Environmental Technology Verification

Test Report of Mobile Source Emission Control Devices

Flint Hills Resources, LP
CCD15010 Diesel Fuel Formulation with HiTEC4121 Additive

Prepared by

Southwest Research Institute

RTI International

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

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MOBILE DIESEL ENGINE AIR POLLUTION CONTROL**
APPLICATION:	**CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE WITH DIESEL FUEL FORMULATION**
TECHNOLOGY NAME:	**CCD15010 FUEL WITH HITEC4121 ADDITIVE**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

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

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

ETV TEST DESCRIPTION

All tests were performed in accordance with the *Test/QA Plan for the Verification Testing of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Heavy Duty Diesel Engines and Light Duty Gasoline Engines and Vehicles* and the *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Flint Hills Resources for the CCD15010 Diesel Fuel Formulation*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management, QA, procedures for product selection, auditing of the test laboratories, and test reporting format.

The mobile diesel engine air pollution control fuel formulation was tested October 18-27, 2006, at Southwest Research Institute. The performance verified was the percentage emission reduction achieved by the fuel formulation for particulate matter (PM), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) relative to the performance of the same baseline engine with standard ultra-low sulfur diesel (ULSD) fuel. Operating conditions were documented and ancillary performance measurements were also made. A summary description of the ETV test is provided in Table 1.

Table 1. Summary Description of the ETV Test

Test type	Highway Transient Federal Test Procedure (FTP) and Supplemental Emissions Test (SET)
Engine family	MDD12.7FZAK
Engine make–model year	Detroit Diesel Corp (DDC) – 1991 Series 60, 6067GU60
Service class	Highway, heavy-duty diesel engine
Engine rated power	365 bhp @ 1800 rpm
Engine displacement, type	12.7 L, six-cylinder
Technology	CCD15010 with HiTEC4121
Technology description	Diesel fuel formulation with additive
Test cycle or mode description	One cold-start and three hot-start tests plus supplemental emissions tests according to FTP test
Baseline fuel description	Ultra-low-sulfur diesel (ULSD) fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO_x, HC, and CO
Ancillary measurements	Carbon dioxide, exhaust backpressure, and fuel consumption

VERIFIED TECHNOLOGY DESCRIPTION

This verification statement describes the performance of the tested technology, CCD15010 diesel fuel formulation with HiTEC4121 additive, on the diesel engine identified in Table 1.

VERIFICATION OF PERFORMANCE

The *CCD15010 fuel formulation with HiTEC4121 additive* achieved the reduction in tailpipe emissions shown in Table 2 compared to baseline operation without the additive.

Table 2. Verified Emissions Reductions

Technology	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	PM	NOx	HC	CO	PM	NOx	HC	CO
CCD15010+HiTEC4121	-0.74 [a]	8.2	17	9.6	– [b]	7.3 to 9.0	– [b]	5.3 to 14

[a] Negative reduction indicates increase in emissions.
[b] The emissions reduction can not be distinguished from zero with 95% confidence.

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

This verification statement verifies the emissions characteristics of the *CCD15010 fuel formulation with HiTEC4121 additive* 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 *CCD15010 fuel formulation with HiTEC4121 additive* within the range of applicability of the statement.

Original signed by S. Gutierrez *5/16/07*

Sally Gutierrez Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by A. R. Trenholm *5/14/07*

Andrew R. Trenholm Date
Director
Air Pollution Control Technology Verification Center

Environmental Technology Verification Report

Mobile Source Emission Control Devices

Flint Hills Resources, LP
CCD15010 Diesel Fuel Formulation
with HiTEC4121 Additive

Prepared by

RTI International
Southwest Research Institute

EPA Cooperative Agreement No. CR831911-01-1

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Notice

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute (SwRI), with partial funding from Cooperative Agreement No. CR831911-01-1 with the U.S. Environmental Protection Agency (EPA). The document has been submitted to RTI's and EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

Foreword

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

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

Fuel formulations and additives used to control emissions from mobile diesel engines are among the technologies evaluated by the APCT Center. The center developed (and EPA approved) the *Generic Verification Protocol for Determination of Emissions Reductions Obtained by Use of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Diesel Engines and Light Duty Gasoline Engines and Vehicles* 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 Flint Hills Resources, LP, CCD15010 diesel fuel formulation with HiTec4121 additive. ETV testing of this technology was conducted in October 2006 at SwRI. All testing was performed in accordance with an approved test/QA plan that implements the requirements of the generic verification protocol at the test laboratory.

Availability of Report

Copies of this verification report are available from:

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

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

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

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Acronyms/Abbreviations

APCT Center	Air Pollution Control Technology Verification Center
bhp	brake horsepower
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
C-B	carbon balance
CFR	Code of Federal Regulations
cm	centimeter(s)
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampler
DDC	Detroit Diesel Corporation
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FHR	Flint Hills Resources, LP
FTP	Federal Test Procedure
ft	foot (feet)
g	gram(s)
HC	hydrocarbon(s)
HDDE	heavy duty diesel engine
hp	horsepower
kW	kilowatt(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
lb-ft	pound foot (feet)
m	meter(s)
mm	millimeter(s)
NCDC	National Clean Diesel Campaign
NO_x	nitrogen oxides
OTAQ	Office of Transportation and Air Quality
PM	particulate matter

QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SET	supplemental emissions test
SwRI	Southwest Research Institute
TCEQ	Texas Commission on Environmental Quality
ULSD	ultra-low sulfur diesel

Acknowledgments

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

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Section 1.0
Introduction

This report reviews the performance of the CCD15010 diesel fuel formulation, containing the additive HiTEC4121, submitted for testing by Flint Hills Resources, LP (FHR). Environmental technology verification (ETV) testing of this technology was conducted October 18-27, 2006, during a series of tests by Southwest Research Institute (SwRI), under contract with the Air Pollution Control Technology Verification Center (APCT Center). The APCT Center is operated by RTI International (RTI)[†] in partnership with the U.S. Environmental Protection Agency's (EPA) ETV Program. The objective of the APCT Center and the ETV Program is to verify, with high-quality data, the performance of air pollution control technologies, including those designed to control air emissions from diesel engines. With the assistance of a technical panel of experts assembled for the purpose, RTI has established an air pollution control technology program area specifically to evaluate the performance of alternative fuels, additives, emulsions, and lubricants as control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Determination of Emissions Reductions Obtained by Use of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Diesel Engines and Light Duty Gasoline Engines and Vehicles*[1] was developed. This protocol was chosen as the best guide to verify the immediate performance effects of the CCD15010 fuel formulation with HiTEC4121 additive. To determine these effects, emissions results from a highway heavy-duty diesel engine using ultra-low sulfur diesel (ULSD) fuel were compared to emissions results obtained operating the same engine under the same conditions but with the CCD15010 fuel formulation containing the HiTEC4121 additive. The specific test/quality assurance (QA) plan addendum for the ETV test of the technology submitted by FHR was developed and approved in August 2006.[2] The goal of the test was to measure the emissions control performance of the CCD15010 fuel formulation with HiTEC4121 additive and its emissions reduction relative to the same engine using ULSD fuel.

A description of the FHR fuel formulation is presented in Section 2. Section 3 documents the procedures and methods used for the test and the conditions under which the test was conducted. The results of the test are summarized and discussed in Section 4, and references are presented in Section 5.

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

This verification statement describes the performance of the tested technology, CCD15010 diesel fuel formulation with HiTEC4121 additive, on the tested diesel engine. Testing was conducted in October 2006 at SWRI.

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

Section 2.0
Product Description

The FHR CCD15010 diesel fuel formulation has an aromatic content below the nationwide average diesel fuel. It contains the HiTEC4121 additive with cetane-improving components.

Emissions were quantified with two separate diesel fuels, a baseline fuel and a candidate fuel. FHR palletized approximately 200 gallons of both fuels for transport to SwRI in sealed 55-gallon drums. As shown in Figure 1, drums of baseline fuel were labeled "NatAvBaseline" (coded by SwRI as EM-6049-F), and drums of candidate fuel were labeled "CCD15010" (coded by SwRI as EM-6048-F). SwRI extracted a one-gallon sample of the baseline and candidate fuels for chemical analyses. The composition and properties of the CCD15010 fuel and the composition and concentration of the HiTEC4121 additive in the fuel are proprietary and will be provided to the EPA National Clean Diesel Campaign (NCDC) and to the Texas Council on Environmental Quality (TCEQ) as confidential business information. The properties of the baseline fuel are given in Table 1.

Figure 1. Sealed drums of Flint Hills Resources diesel fuels

Table 1. Selected Fuel Properties and Specifications

	Code of Federal Regulations (CFR) Specification[a]		Test Fuel
	ASTM	Type 2D	EM-6049-F (baseline)
Cetane number	D613	40–50	45.1
Cetane index	D976	40–50	–[b]
Distillation range:			
Initial boiling point, ºC (ºF)	D86	171–204 (340–400)	194 (382)
10% Point, ºC (ºF)	D86	204–238 (400–460)	215 (419)
50% Point, ºC (ºF)	D86	243–282 (470–540)	256 (492)
90% Point, ºC (ºF)	D86	293–332 (560–630)	316 (601)
End point, ºC (ºF)	D86	321–366 (610–690)	352 (666)
Gravity (American Petroleum Institute)	D287	32–37	–[b]
Specific gravity	–	–	0.8542[c]
Total sulfur, ppm	D2622	7-15	5.1[d]
Hydrocarbon composition:			
Aromatics (minimum), %	D5186	27	36.4
Paraffins, naphthenes, and olefins, %	D5186	–[e]	
Flash point (minimum), ºC (ºF)	D93	54 (130)	–[b]
Viscosity, centistokes at 40 ºC	D445	2.0–3.2	–[b]

[a] 40 CFR 86.1313-2007(b)(2) for the year 2007 and beyond for heavy-duty diesel engines.

[b] Not tested

[c] Measured per ASTM D1298.

[d] Measured per ASTM D7039. This method is an acceptable substitute for ASTM D2622.

[e] Remainder of the hydrocarbons

Section 3.0
Test Documentation

The ETV testing took place during October 2006 at SwRI under contract to the APCT Center. Testing was performed in accordance with:

- *Generic Verification Protocol for Determination of Emissions Reductions Obtained by Use of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Diesel Engines and Light Duty Gasoline Engines and Vehicles*[1]
- *Test/QA Plan for the Verification Testing of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Heavy Duty Diesel Engines and Light Duty Gasoline Engines and Vehicles*[5]
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Flint Hills Resources for the CCD15010 Diesel Fuel Formulation*.[2]

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

3.1 Engine Description

The ETV testing was performed on an inline six-cylinder, 12.7 L, 1991 model year, Detroit Diesel Corporation (DDC) Series 60 highway heavy-duty diesel engine (model 6067GU60, SN: 06RE001123). The rating of this model engine is 272 kW (365 bhp) in "prime" power service at 1800 rpm. The engine was owned by SwRI and has been used in a number of test programs at SwRI. Table 2 provides the engine identification details. The engine belongs to on-highway engine family box OH-4 as categorized by EPA.

Table 2. Engine Identification Information

Engine serial number	06RE001123
Make	Detroit Diesel Corp. (DDC)
Model year	1991
Model	Series 60, 6067GU60
Engine displacement and configuration	12.7 L, six-cylinder
Service class	Highway heavy-duty diesel engine (HDDE)
EPA engine family identification	MDD12.7FZAK
Certification standards (g/hp-hr)	HC 1.30/CO 15.50/NOx 5.00/PM 0.250
Rated power	365 bhp @ 1800 rpm
Rated torque	1400 lb-ft @ 1200 rpm
Certified emission control system	Detroit Diesel electronic control (DDEC)-II
Aspiration	Turbocharger and laboratory charge air cooler
Fuel system	Direct injection

3.2 Engine Fuel Description

All baseline emissions testing was conducted with ULSD fuel meeting the 40 CFR §86.1313-2007 specification for emissions certified fuel.[6] Baseline testing was conducted using fuel from a single batch identified as EM-6049-F. All candidate emissions testing was conducted with FHR CCD15010 diesel fuel formulation, containing the HiTEC4121 additive, from a single batch identified as EM-6048-F.

In accordance with SwRI standard operating procedures, each fuel change included thoroughly flushing fuel lines, heat exchangers, and the day tank. To fully purge the engine, the Series 60 was run with its return-fuel diverted into a slop container as new fuel was supplied. After the previous fuel was fully purged and the engine was running on the selected fuel, a set of fresh fuel filters was installed and the return-fuel was routed into the day tank. Each fuel change effort consumed approximately 16 gallons of diesel fuel.

3.3 Summary of Emissions Measurement Procedures

The ETV tests consisted of baseline tests with ULSD fuel and candidate tests with the fuel formulation. Engine operation and emissions sampling adhered to techniques developed by EPA in 40 CFR, Part 86, Subpart N.[7] Emissions were measured over triplicate runs of the highway transient test cycle and the supplemental emissions test (SET) for the baseline and candidate exhaust configurations. Baseline testing is conducted at the beginning and end of the verification series, and the complete test sequence is repeated for the candidate fuel, as shown in Table 3.

Table 3. Overview of Verification Test Sequence

Description	Fuel	Engine	Test Sequence
Baseline 1	EM-6049-F [a]	1991 DDC Series 60 HDDE	Cold + 3 hots + SET
Candidate 1	EM-6048-F [b]	1991 DDC Series 60 HDDE	Cold + 3 hots + SET
Candidate 2	EM-6048-F	1991 DDC Series 60 HDDE	Cold + 3 hots + SET
Baseline 2	EM-6049-F	1991 DDC Series 60 HDDE	Cold + 3 hots + SET

[a] FHR fuel identified as "NatAvBaseline" conforming to 40 CFR §86.1313-2007
[b] CCD15010 fuel formulation with HiTEC4121 additive

The DDC Series 60 engine was operated in an engine dynamometer test cell, with exhaust sampled using full-flow dilution constant volume sampling (CVS) techniques to measure regulated emissions of hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM), as well as carbon dioxide (CO_2). 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 2 depicts the sampling system and related components. The system is designed to comply with the requirements of 40 CFR, Part 86.[7]

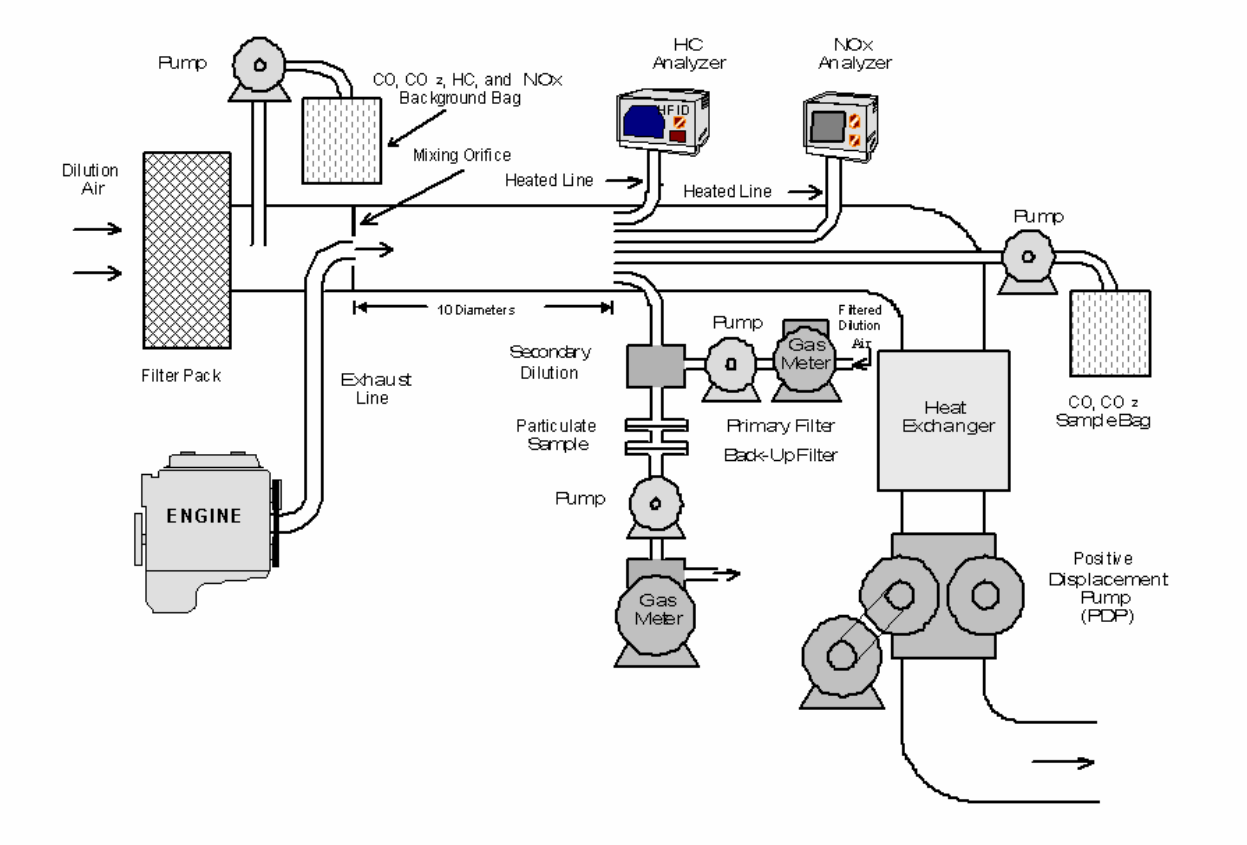

Figure 2. Schematic of emissions sampling system at SwRI.

The verification protocol requires that engines used for verification testing must not exceed 110% of the certification standards for emissions from that engine category.[8] For 1991-1992 highway engines, the certification standards are defined in EPA's on-highway engine family box OH-4[9]. Furthermore, the Office of Transportation and Air Quality (OTAQ) assumes 5% reduction in PM emissions due to the use of ULSD fuel.

Therefore, the criteria established to indicate that the test engine was acceptable and that the verification testing could proceed were that the baseline emissions from the engine using ULSD fuel could not exceed 110% of OH-4 (1.1 x OH-4) for HC, CO, and NO_x, and also could not exceed 110% of [(OH-4)-5%], or (1.045 x OH-4) for PM. Table 4 presents the required emission performance of the test engine, as well as the certification standards and baseline results for comparison.

Table 4. Test Engine Baseline Emissions Requirement for 1991 DDC Series 60

	HC		CO		NO_x		PM	
	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr
OH-4	1.74	1.30[a]	20.79	15.50[a]	6.71	5.00[a]	0.335	0.250[a]
Acceptance criteria	1.92	1.43	22.86	17.05	7.38	5.50	0.350	0.261
Baseline results	0.07	0.05	3.67	2.74	6.91	5.15	0.240	0.179

[a] 40 CFR §86.091-11, Certification standards for EPA engine family box OH4 for 1991-1992 highway engines

3.4 Deviations from the Test/QA Plan

There was one deviation from the test/QA plan. Following the initial baseline testing, an erratic NOx signal was noted on several subsequent tests. These tests were voided and not included in the results. Diagnostic tests indicated that the NOx pump's motor-to-pump coupling had allowed the pump to turn, usually without interruption, but occasionally slipped, producing intermittent flow losses that resulted in an erratic analyzer response. The coupling was replaced and testing resumed without incident after a stable NOx signal was achieved.

3.5 Documented Test Conditions

Engine Performance

Figure 3 shows torque map information measured on the DDC Series 60 engine using the ULSD fuel.

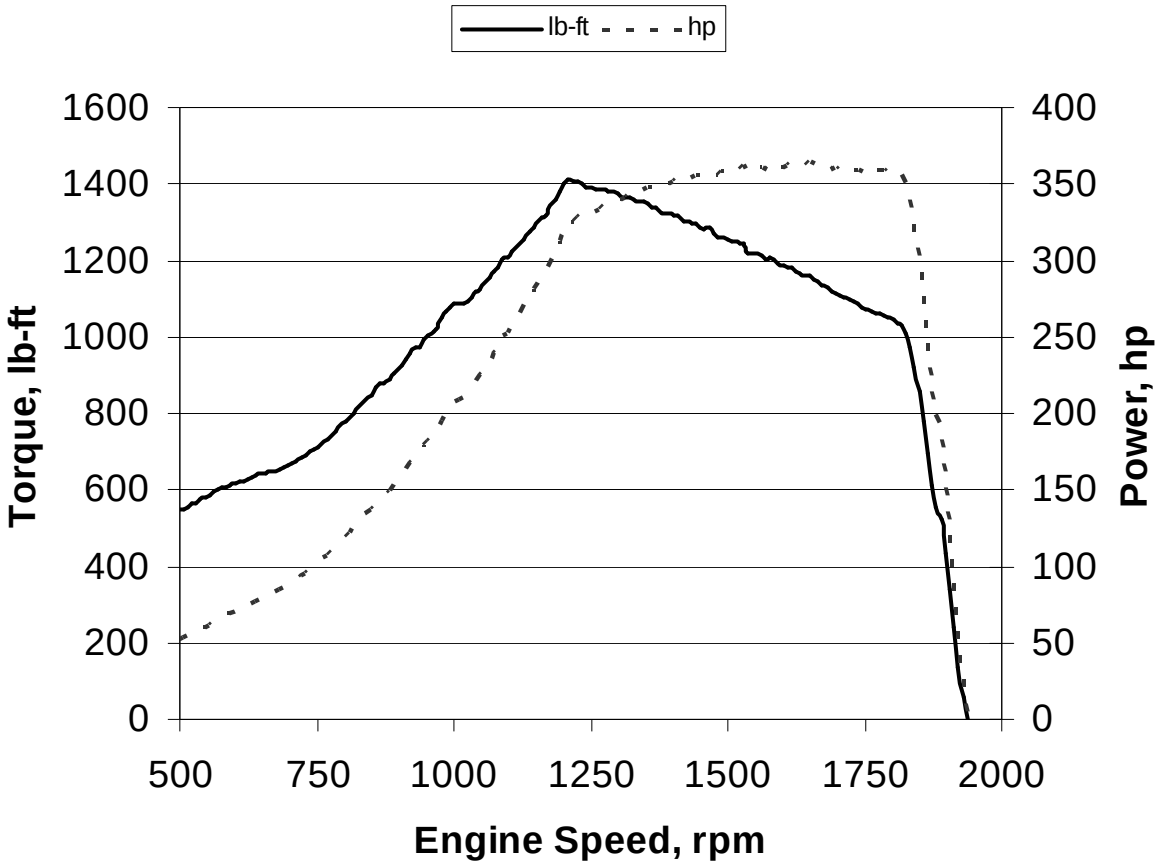

Figure 3. Torque map of 1991 DDC Series 60 engine using ULSD baseline fuel.

Engine Exhaust Backpressure

The engine backpressure for the 1991 DDC Series 60 engine was set in accordance with the engine manufacturer specifications before the first baseline test. Maximum backpressure observed during testing did not exceed the manufacturer's specifications.

Brake Specific Fuel Consumption

The fuel consumption was not measured explicitly during the engine testing. Rather, a calculated "carbon-balance" (C-B) fuel consumption rate was determined based on the measured exhaust flow rate and the carbon content (i.e., the CO and the CO_2) in the exhaust gas analysis. The weighted brake-specific fuel consumption (BSFC) calculations are similar to the weighted emissions calculations explained in Section 4.0. Tables 5 and 6 show the weighted BSFC calculations for the highway Federal Test Procedure (FTP) and SET. Table 7 summarizes the results of these calculations and compares the fuel consumption during the baseline ULSD runs with that measured during the candidate CCD15010 tests. (The weighting for BSFC in Table 7 is the same as that for the combined emissions rates in Tables 11 and 12. A more detailed explanation is given in Section 4.)

Table 5. Brake-Specific Fuel Consumption (by Carbon Balance) for Highway FTP Tests

Test Number	Test Type	Test Date	BSFC		Weighted BSFC	
			lb/bhp-hr	kg/kWh	lb/bhp-hr	kg/kWh
BASELINE 1						
FHR49-C2	Cold-start	10/18/2006	0.408	0.248		
FHR49-H4	Hot-start	10/18/2006	0.390	0.237	0.393	0.239
FHR49-H5	Hot-start	10/18/2006	0.404	0.246	0.405	0.246
FHR49-H6	Hot-start	10/18/2006	0.391	0.238	0.394	0.239
CANDIDATE 1						
FHR48-C6	Cold-start	10/25/2006	0.399	0.243		
FHR48-H19	Hot-start	10/25/2006	0.383	0.233	0.385	0.234
FHR48-H20	Hot-start	10/25/2006	0.380	0.231	0.383	0.233
FHR48-H21	Hot-start	10/25/2006	0.377	0.229	0.380	0.231
CANDIDATE 2						
FHR48-C7	Cold-start	10/26/2006	0.424	0.258		
FHR48-H22	Hot-start	10/26/2006	0.385	0.234	0.391	0.237
FHR48-H23	Hot-start	10/26/2006	0.384	0.233	0.389	0.237
FHR48-H24	Hot-start	10/26/2006	0.382	0.232	0.388	0.236
BASELINE 2						
FHR49-C3	Cold-start	10/27/2006	0.405	0.246		
FHR49-H7	Hot-start	10/27/2006	0.384	0.233	0.387	0.235
FHR49-H8	Hot-start	10/27/2006	0.381	0.232	0.385	0.234
FHR49-H9	Hot-start	10/27/2006	0.381	0.232	0.385	0.234

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

Test Number	Test Type	Weighted BSFC	
		lb/bhp-hr	kg/kWh
FHR49-SET-4	Baseline 1	0.334	0.203
FHR48-SET-4	Candidate 1	0.324	0.197
FHR48-SET-6	Candidate 2	0.320	0.195
FHR49-SET-5	Baseline 2	0.332	0.202

Table 7. Summary of Fuel Consumption Reduction

Combined weighted BSFC	lb/bhp-hr	kg/kWh
BASELINE		
B1	0.384	0.233
B2	0.394	0.240
B3	0.385	0.234
B4	0.379	0.230
B5	0.377	0.229
B6	0.377	0.229
MEAN	**0.383**	**0.233**
CANDIDATE		
C1	0.376	0.229
C2	0.374	0.227
C3	0.372	0.226
C4	0.380	0.231
C5	0.379	0.230
C6	0.378	0.230
MEAN	**0.377**	**0.229**
% Reduction		1.58
95% Confidence Limits		1.58 to 1.59

Section 4.0
Summary and Discussion of Emission Results

Table 8 reports the emissions from cold- and hot-start tests that were conducted with the baseline and candidate fuels. The concentration measurements were converted to units of total grams per test for all species.

Table 8. Emissions Data from Highway Transient Tests

Test Number	Test Type	PM	NO_X	HC	CO	CO_2	Work
		g				kg	kWh (bhp-hr)
BASELINE ULSD Fuel on a 1991 DDC Series 60 Engine							
FHR49-C2	Cold-start	4.46	145	2.03	82.4	14.4	18.4 (24.7)
FHR49-H4	Hot-start	4.49	121	1.32	67.2	13.6	18.2 (24.4)
FHR49-H5	Hot-start	4.40	123	1.38	67.3	14.1	18.2 (24.4)
FHR49-H6	Hot-start	4.45	122	1.12	67.4	13.7	18.2 (24.4)
CANDIDATE CCD15010 Fuel and HiTEC4121 Additive on a 1991 DDC Series 60 Engine							
FHR48-C6	Cold-start	4.39	130	1.12	70.1	14.1	18.4 (24.7)
FHR48-H19	Hot-start	4.32	112	0.875	56.7	13.4	18.2 (24.4)
FHR48-H20	Hot-start	4.33	110	0.778	56.5	13.3	18.2 (24.4)
FHR48-H21	Hot-start	4.46	111	0.805	57.3	13.2	18.2 (24.4)
CANDIDATE CCD15010 Fuel and HiTEC4121 Additive on a 1991 DDC Series 60 Engine							
FHR48-C7	Cold-start	4.34	132	1.34	68.7	15.0	18.4 (24.7)
FHR48-H22	Hot-start	4.54	111	1.37	60.1	13.4	18.2 (24.4)
FHR48-H23	Hot-start	4.64	111	0.892	61.0	13.4	18.2 (24.4)
FHR48-H24	Hot-start	4.59	114	1.11	59.4	13.4	18.2 (24.4)
BASELINE ULSD Fuel on a 1991 DDC Series 60 Engine							
FHR49-C3	Cold-start	4.40	146	1.37	77.8	14.3	18.5 (24.8)
FHR49-H7	Hot-start	4.23	125	1.07	62.9	13.4	18.2 (24.4)
FHR49-H8	Hot-start	4.35	122	0.919	62.6	13.3	18.2 (24.4)
FHR49-H9	Hot-start	4.30	122	0.982	62.0	13.4	18.2 (24.4)

Tables 9 and 10 report the emissions from the 13-mode steady-state SET tests that were conducted with the baseline and candidate fuels. The concentration measurements were converted to units of grams per hour for all species. The “bhp from Work” (the integrated measured power during each test period) values are also shown in these tables.

Table 9. Emissions Data from Baseline Supplemental Emissions Tests (SET)

Test Number	Mode	Target %	Weighting Factor	PM [a]	NOx	HC	CO	CO_2	Work
				g				kg	kWh (bhp-hr)
FHR49-SET-4	1	(idle)	0.15	5.24	3.28	0.113	1.20	0.210	0.0218 (0.0292)
	2	100	0.08		41.1	0.163	47.1	3.17	5.02 (6.73)
	3	50	0.10		47.7	0.130	2.28	2.33	3.67 (4.92)
	4	75	0.10		56.2	0.138	10.4	3.39	5.49 (7.36)
	5	50	0.05		19.7	0.0577	1.45	1.01	1.58 (2.12)
	6	75	0.05		23.3	0.0777	12.7	1.52	2.38 (3.19)
	7	25	0.05		12.9	0.0794	0.734	0.564	0.798 (1.07)
	8	100	0.09		59.4	0.230	25.6	4.04	6.56 (8.80)
	9	25	0.10		30.7	0.172	1.77	1.31	1.83 (2.45)
	10	100	0.08		57.9	0.171	9.36	3.73	6.03 (8.08)
	11	25	0.05		16.8	0.105	1.18	0.711	0.947 (1.27)
	12	75	0.05		31.2	0.0871	2.19	1.72	2.83 (3.79)
	13	50	0.05		25.7	0.0839	0.892	1.22	1.88 (2.52)
FHR49-SET-5	1	(idle)	0.15	5.39	3.08	0.0723	1.08	0.230	0.0218 (0.0292)
	2	100	0.08		40.9	0.150	46.1	3.14	5.03 (6.74)
	3	50	0.10		47.2	0.0795	2.14	2.29	3.66 (4.91)
	4	75	0.10		56.3	0.102	9.67	3.38	5.48 (7.35)
	5	50	0.05		19.7	0.0374	1.46	1.02	1.58 (2.12)
	6	75	0.05		25.1	0.0729	12.6	1.63	2.61 (3.50)
	7	25	0.05		12.9	0.0581	0.732	0.567	0.798 (1.07)
	8	100	0.09		58.8	0.163	23.4	4.01	6.55 (8.79)
	9	25	0.10		30.6	0.131	1.78	1.31	1.81 (2.43)
	10	100	0.08		57.9	0.120	8.89	3.71	6.05 (8.11)
	11	25	0.05		16.6	0.0780	1.13	0.710	0.947 (1.27)
	12	75	0.05		30.9	0.0638	2.02	1.74	2.82 (3.78)
	13	50	0.05		25.6	0.0620	0.867	1.22	1.88 (2.52)

[a] PM is not reported mode-by-mode.

Table 10. Emissions Data from Candidate Supplemental Emissions Tests (SET)

Test Number	Mode	Target %	Weighting Factor	PM [a]	NOx	HC	CO	CO_2	Work
				g				kg	kWh (bhp-hr)
FHR48-SET-4	1	(idle)	0.15	4.41	3.26	0.0808	0.959	0.214	0.0224 (0.0301)
	2	100	0.08		40.2	0.147	46.6	3.06	5.00 (6.71)
	3	50	0.10		43.7	0.0912	2.12	2.24	3.66 (4.91)
	4	75	0.10		54.9	0.133	9.19	3.32	5.50 (7.37)
	5	50	0.05		18.8	0.0569	1.38	0.995	1.59 (2.13)
	6	75	0.05		22.5	0.0822	11.2	1.47	2.39 (3.21)
	7	25	0.05		11.4	0.0482	0.675	0.557	0.805 (1.08)
	8	100	0.09		58.9	0.187	23.1	3.95	6.57 (8.81)
	9	25	0.10		26.6	0.117	1.56	1.27	1.84 (2.47)
	10	100	0.08		57.5	0.162	7.97	3.60	6.00 (8.04)
	11	25	0.05		14.3	0.0787	0.953	0.670	0.932 (1.25)
	12	75	0.05		30.5	0.0788	1.92	1.71	2.82 (3.78)
	13	50	0.05		23.8	0.0696	0.858	1.18	1.88 (2.52)
FHR48-SET-6	1	(idle)	0.15	4.97	3.06	0.00	0.652	0.191	0.0312 (0.0418)
	2	100	0.08		39.2	0.107	45.4	3.03	4.99 (6.69)
	3	50	0.10		44.1	0.0533	2.16	2.24	3.65 (4.89)
	4	75	0.10		54.2	0.0733	10.0	3.28	5.50 (7.37)
	5	50	0.05		18.4	0.0164	1.39	0.977	1.58 (2.12)
	6	75	0.05		22.0	0.0447	12.2	1.45	2.39 (3.20)
	7	25	0.05		11.0	0.0202	0.570	0.529	0.790 (1.06)
	8	100	0.09		57.6	0.161	24.9	3.89	6.56 (8.80)
	9	25	0.10		26.3	0.0588	1.36	1.26	1.84 (2.47)
	10	100	0.08		59.3	0.111	9.22	3.75	6.33 (8.49)
	11	25	0.05		14.3	0.0560	0.853	0.668	0.940 (1.26)
	12	75	0.05		30.0	0.0553	2.02	1.68	2.83 (3.79)
	13	50	0.05		23.6	0.0438	0.783	1.17	1.89 (2.54)

[a] PM is not reported mode-by-mode.

For each cold/hot-start test combination, the composite-weighted transient emission rate for each pollutant was 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-weighted transient 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 brake horsepower hour, bhp-hr
W_{HOT} = hot-start brake horsepower hour, bhp-hr.

For the SET, the emission rate for each pollutant was calculated by applying a weighting factor, specified in 40 CFR 86.1360[10], to the emission rate and work measured at each mode as follows:

$$E_{SET} = \frac{\sum_{i=1}^{j} f_i \bullet E_{MODE_i}}{\sum_{i=1}^{j} f_i \bullet W_{MODE_i}} \qquad \text{(Eq. 2)}$$

where
E_{SET} = emissions rate for SET, g/bhp-hr
f_i = mode weighting factor from 40 CFR 86.1360
E_{MODEi} = pollutant emissions rate during mode *i*, g
W_{MODEi} = brake horsepower hour during mode *i*, bhp-hr.

The composite-weighted highway transient emission rate for each pollutant, E_{COMP}, was then combined with a single SET emission rate as follows to obtain the combined emission rate, E_i, for each pollutant for each of the *n* tests at the test point:

$$E_i = 0.85 \bullet E_{COMPi} + 0.15 \bullet E_{SET} \qquad \text{(Eq. 3)}$$

where
E_i = combined emission rate, g/bhp-hr
E_{COMP} = composite-weighted transient emissions rate, g/bhp-hr
E_{SET} = emission rate for supplemental emissions test
i = 1 to *n* tests required at test point

These combined emissions rates are shown in Tables 11 and 12 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.[2] Equations 4-15 show how the data from Tables 8, 9, and 10, identified by test number, were weighted to provide the combined emissions rates.

B1 = (0.85)[(1/7)(FHR49-C2) + (6/7)(FHR49-H4)] + (0.15)(FHR49-SET-4) (Eq. 4)
B2 = (0.85)[(1/7)(FHR49-C2) + (6/7)(FHR49-H5)] + (0.15)(FHR49-SET-4) (Eq. 5)
B3 = (0.85)[(1/7)(FHR49-C2) + (6/7)(FHR49-H6)] + (0.15)(FHR49-SET-4) (Eq. 6)
B4 = (0.85)[(1/7)(FHR49-C3) + (6/7)(FHR49-H7)] + (0.15)(FHR49-SET-5) (Eq. 7)
B5 = (0.85)[(1/7)(FHR49-C3) + (6/7)(FHR49-H8)] + (0.15)(FHR49-SET-5) (Eq. 8)
B6 = (0.85)[(1/7)(FHR49-C3) + (6/7)(FHR49-H9)] + (0.15)(FHR49-SET-5) (Eq. 9)

C1 = (0.85)[(1/7)(FHR48-C6) + (6/7)(FHR48-H19)] + (0.15)(FHR48-SET-4) (Eq. 10)
C2 = (0.85)[(1/7)(FHR48-C6) + (6/7)(FHR48-H20)] + (0.15)(FHR48-SET-4) (Eq. 11)
C3 = (0.85)[(1/7)(FHR48-C6) + (6/7)(FHR48-H21)] + (0.15)(FHR48-SET-4) (Eq. 12)
C4 = (0.85)[(1/7)(FHR48-C7) + (6/7)(FHR48-H22)] + (0.15)(FHR48-SET-6) (Eq. 13)
C5 = (0.85)[(1/7)(FHR48-C7) + (6/7)(FHR48-H23)] + (0.15)(FHR48-SET-6) (Eq. 14)
C6 = (0.85)[(1/7)(FHR48-C7) + (6/7)(FHR48-H24)] + (0.15)(FHR48-SET-6) (Eq. 15)

Table 11. Combined Emission Rates (U.S. Common Units)

Combined Emissions Rate	PM	NOx	HC	CO	CO_2
	g/bhp-hr				
BASELINE ULSD Fuel on a 1991 DDC Series 60 Engine					
B1	0.171	5.56	0.0542	2.75	550
B2	0.169	5.62	0.0559	2.75	564
B3	0.170	5.58	0.0481	2.76	551
B4	0.163	5.66	0.0419	2.58	543
B5	0.167	5.57	0.0376	2.57	540
B6	0.165	5.58	0.0394	2.55	540
CANDIDATE CCD15010 Fuel with HiTEC4121 Additive on a 1991 DDC Series 60 Engine					
C1	0.163	5.16	0.0354	2.35	539
C2	0.164	5.10	0.0326	2.35	536
C3	0.167	5.10	0.0333	2.36	533
C4	0.171	5.13	0.0498	2.46	544
C5	0.174	5.12	0.0355	2.48	543
C6	0.173	5.20	0.0419	2.43	542

Table 12. Combined Emission Rates (Metric Units)

Combined Emissions Rate	PM	NOx	HC	CO	CO_2
	g/kW-hr				
BASELINE ULSD Fuel on a 1991 DDC Series 60 Engine					
B1	0.229	7.46	0.0727	3.69	738
B2	0.227	7.54	0.0750	3.69	756
B3	0.228	7.48	0.0645	3.70	739
B4	0.219	7.59	0.0562	3.46	728
B5	0.224	7.47	0.0504	3.45	724
B6	0.221	7.48	0.0528	3.42	724
CANDIDATE CCD15010 Fuel with HiTEC4121 Additive on a 1991 DDC Series 60 Engine					
C1	0.219	6.92	0.0475	3.15	723
C2	0.220	6.84	0.0437	3.15	719
C3	0.224	6.84	0.0447	3.16	715
C4	0.229	6.88	0.0668	3.30	730
C5	0.233	6.87	0.0476	3.33	728
C6	0.232	6.97	0.0562	3.26	727

The combined emission rates from Tables 11 and 12 are the key values for the verification test. Tables 13 and 14 summarize that information. The first line shows the baseline engine results; the emissions in all categories are below the Table 3 threshold.

Table 13. Summary of Verification Test Data (U.S. Common Units)

Test Type	Fuel	Mean Composite Weighted Emission Value				
		PM	NOx	HC	CO	CO_2
		g/bhp-hr				
BASELINE	ULSD	0.179	5.15	0.0496	2.74	561
CANDIDATE	CCD15010+HiTEC4121	0.183	4.68	0.0412	2.46	553

Table 14. Summary of Verification Test Data (Metric Units)

Test Type	Fuel	Mean Composite Weighted Emission Value				
		PM	NOx	HC	CO	CO_2
		g/kW-hr				
BASELINE	ULSD	0.240	6.91	0.0665	3.67	752
CANDIDATE	CCD15010+HiTEC4121	0.245	6.28	0.0553	3.30	742

Table 15 summarizes the emissions reductions that were achieved by the use of the CCD15010 fuel formulation with HiTEC4121 additive. These are the "verified emissions reductions" reported in Table 2 of the ETV Joint Verification Statement.

Table 15. Summary of Verification Test Emission Reductions

Technology	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
	PM	NOx	HC	CO	PM	NOx	HC	CO
CCD15010+HiTEC4121	-0.74 [a]	8.2	17	9.6	– [b]	7.3 to 9.0	– [b]	5.3 to 14

[a] Negative reduction indicates increase in emissions.
[b] The emissions reduction can not be distinguished from zero with 95% confidence.

4.1 Quality Assurance

The environmental technology verification of the CCD15010 fuel formulation with HiTEC4121 additive for highway heavy-duty diesel engines was performed in accordance with the approved test/QA plan and the test-specific addendum.[2] An audit of data quality included the review of equipment, personnel qualifications, procedures, record keeping, data validation, analysis, and reporting. Preliminary, in-process, and final inspections, and a review of 10% of the data showed that the requirements stipulated in the test/QA plan[5] were achieved. The SwRI, APCT Center, and EPA quality managers reviewed the test results and the QC data and concluded that the data quality objectives given in the generic verification protocol were attained. EPA and RTI QA staff conducted audits of SwRI's technical and quality systems in April 2002 and found no deficiencies that would adversely impact the quality of results. The equipment was appropriate for the verification testing, and it was operating satisfactorily. SwRI's technical staff was well qualified to perform the testing and conducted themselves in a professional manner.

Section 5.0
References

1. RTI International. 2003. *Generic Verification Protocol for Determination of Emissions Reductions Obtained by Use of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Diesel Engines and Light Duty Gasoline Engines and Vehicles*. Research Triangle Park, NC, September. Available: http://www.epa.gov/etv/pdfs/vp/05_vp_fuel.pdf

2. RTI International. 2006. *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Flint Hills Resources for the CCD15010 Diesel Fuel Formulation*. Research Triangle Park, NC, September 22.

3. Southwest Research Institute. 2006. *Environmental Technology Verification of Diesel Fuel Formulation FHR-CCD15010*. Final Report. San Antonio, TX, December.

4. Southwest Research Institute. 2006. *Audit of Data Quality for Environmental Technology Verification of Diesel Fuel Formulation FHR-CCD15010*. San Antonio, TX, December.

5. RTI International. 2006. *Test/QA Plan for the Verification Testing of Alternative or Reformulated Liquid Fuels, Fuel Additives, Fuel Emulsions, and Lubricants for Highway and Nonroad Use Heavy Duty Diesel Engines and Light Duty Gasoline Engines and Vehicles*. Research Triangle Park, NC, September. Available: http://www.epa.gov/etv/pdfs/vp/05_tp_diesel.pdf.

6. 40 CFR §86.1313-2007 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Fuel Specifications), Table N07-2. Available: http://www.epa.gov/epahome/cfr40.htm (updated September 6, 2006).

7. 40 CFR, Part 86 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines), Subpart N.

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

9. 40 CFR §86.091-11 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Emission standards for 1991 and later model year diesel heavy-duty engines). Available: http://www.epa.gov/epahome/cfr40.htm (updated June 26, 2006).

10. 40 CFR §86.1360-2007 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Supplemental emission test; test cycle and procedures). Available: http://www.epa.gov/epahome/cfr40.htm (updated June 26, 2006).