SRI/USEPA-GHG-VR-14
April 2002

Environmental Technology Verification Report

JCH Fuel Solutions, Inc.
JCH Enviro Automated Fuel Cleaning and Maintenance System

Prepared by:

Greenhouse Gas Technology Center
Southern Research Institute

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

EPA REVIEW NOTICE

SRI/USEPA-GHG-VR-14
April 2002

Greenhouse Gas Technology Center

A U.S. EPA Sponsored Environmental Technology Verification (ET✓) Organization

Environmental Technology Verification Report

JCH Fuel Solutions, Inc.
JCH Enviro Automated Fuel Cleaning and Maintenance System

Prepared by:
Greenhouse Gas Technology Center
Southern Research Institute
PO Box 13825
Research Triangle Park, NC 27709 USA
Telephone: 919/806-3456

Under EPA Cooperative Agreement CR 826311-01-0

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711 USA

EPA Project Officer: David A. Kirchgessner

TABLE OF CONTENTS

Page
APPENDICES iii
LIST OF FIGURES iii
LIST OF TABLES iii
ACKNOWLEDGMENTS iv

1.0 INTRODUCTION 1-1
- 1.1 BACKGROUND 1-1
- 1.2 JCH ENVIRO AUTOMATED FUEL CLEANING AND MAINTENANCE SYSTEM DESCRIPTION 1-2
- 1.3 TEST FACILITY DESCRIPTION 1-6
- 1.4 OVERVIEW OF VERIFICATION PARAMETERS AND EVALUATION STRATEGIES 1-8
  - 1.4.1 Emissions Performance 1-11
  - 1.4.2 Fuel Properties for Contaminated and Cleaned Fuel 1-15
    - 1.4.2.1 Fuel Consumption Rate for Contaminated and Cleaned Fuel 1-15
    - 1.4.2.2 Fuel Heating Value and Fuel Quality for Contaminated and Cleaned Fuel 1-16
  - 1.4.3 Emissions Performance of Contaminated and Cleaned Fuel 1-18
  - 1.4.4 Fuel Cleaning Performance 1-19

2.0 VERIFICATION RESULTS 2-1
- 2.1 OVERVIEW 2-1
- 2.2 ENGINE OPERATION AND FUEL CLEANING PROCEDURES 2-2
  - 2.2.1 Engine Operation 2-2
  - 2.2.2 Fuel Cleaning Procedures 2-4
- 2.3 ENGINE EMISSIONS AND EMISSIONS PERFORMANCE 2-5
  - 2.3.1 Engine Emissions 2-5
  - 2.3.2 Emissions Performance 2-8
- 2.4 FUEL QUALITY AND FUEL CLEANING PERFORMANCE 2-9
  - 2.4.1 Fuel Quality 2-9
  - 2.4.2 Fuel Cleaning Performance 2-12

3.0 DATA QUALITY ASSESSMENT 3-1
- 3.1 DATA QUALITY OBJECTIVES 3-1
- 3.2 RECONCILIATION OF DQOS AND DQIS 3-2
  - 3.2.1 Emission Measurements 3-4
    - 3.2.1.1 Exhaust Gas Flow Rate and TPM Emissions 3-4
    - 3.2.1.2 Gaseous Pollutant Emissions 3-5
    - 3.2.1.3 Propagation of Errors for Emission Rate Measurements 3-7
  - 3.2.2 Fuel Quality Performance 3-8
  - 3.2.3 Ambient Measurements 3-11
- 3.3 AUDITS 3-11

4.0 REFERENCES 4-1

APPENDICES

Page

APPENDIX A Table A-1. Analyzer Spans and Calibration Gas Values A-2
Table A-2. Summary of System Bias and Drift Checks A-2

APPENDIX B Appendix B-1. SwRI Fuel Sample Handling Procedures B-2
Appendix B-2. SwRI Fuel Analysis QA/QC Procedures B-4

LIST OF FIGURES

Page

Figure 1-1 JCH Fuel Treatment and Cleaning Process Flow 1-3
Figure 1-2 JCH Portable Cart-Mounted System 1-4
Figure 1-3 JCH Floor-Mounted System 1-5
Figure 1-4 Test Engine and Fuel Day Tank 1-8
Figure 1-5 Verification Strategy 1-10
Figure 1-6 Schematic of Verification Measurement System 1-11
Figure 1-7 Sampling Location for Contaminated and Treated Fuel 1-17
Figure 2-1 Ambient Temperature and Relative Humidity During Test Periods 2-4
Figure 2-2 Engine Filter after Operation with Contaminated Fuel 2-13

LIST OF TABLES

Page

Table 1-1 Onan/Cummins Model 200DGFC 1-6
Table 1-2 Summary of Emission Testing Methods 1-12
Table 1-3 Fuel Properties Test Methods 1-16
Table 2-1 Average Generator and Engine Operation During Test Periods 2-2
Table 2-2 Generator and Engine Parameters and Permissible Variation During Test Periods 2-3
Table 2-3 Enviro System Fuel Cleaning Activities During Verification Testing 2-4
Table 2-4 Pollutant Concentrations and Emission Rates 2-6
Table 2-5 Engine Emissions Normalized to Fuel Consumption and Heat Input 2-7
Table 2-6 Genset Fuel Consumption Rates 2-8
Table 2-7 Differences in Emission Rates 2-9
Table 2-8 Fuel Quality for Contaminated and Treated Fuel 2-10
Table 2-9 Differences in Fuel Properties for Contaminated and Treated Fuel 2-10
Table 2-10 Results of Microbial Contamination Tests 2-11
Table 3-1 Verification Parameters and Data Quality Objectives 3-2
Table 3-2 Summary of Data Quality Goals and Results 3-3
Table 3-3 Results of Additional TPM Emissions Testing QA/QC Checks 3-4
Table 3-4 Exhaust Gas Flow and Particulate Emission Rate Error Propagation 3-5
Table 3-5 Results of Additional Gaseous Pollutant Emissions Testing QA/QC Checks 3-6
Table 3-6 Particulate and Gaseous Pollutant Emission Rate Error Propagation 3-7
Table 3-7 Summary of Fuel Properties Data Quality Indicators 3-9

ACKNOWLEDGMENTS

The Greenhouse Gas Technology Center wishes to thank Mike Myer and Cummins Intermountain for hosting this verification and providing the genset used to conduct the testing. Additionally, Garry Schaap and Matt Sanchez, both of Cummins Intermountain, provided assistance to GHG Center staff during the field testing that was instrumental to the verification. Thanks are also extended to the members of the GHG Center's Oil and Gas Industry Stakeholder Group for reviewing and providing input on the testing strategy and this verification report.

1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and innovative environmental technologies. ETV is funded by Congress in response to the belief that there are many viable environmental technologies that are not being used for the lack of credible third-party performance data. With performance data developed under ETV, technology buyers, financiers, and permitters in the United States and abroad will be better equipped to make informed decisions regarding environmental technology purchase and use.

The Greenhouse Gas Technology Center (GHG Center) is one of six verification organizations operating under ETV. The GHG Center is managed by the EPA's partner verification organization, Southern Research Institute (SRI), which conducts verification testing of promising GHG mitigation and monitoring technologies. The GHG Center's verification process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other test data, obtaining independent peer review input, and reporting findings. Performance evaluations are conducted according to externally reviewed verification Test and Quality Assurance Plans (Test Plan) and established protocols for quality assurance.

The GHG Center is guided by volunteer groups of stakeholders. These stakeholders offer advice on specific technologies most appropriate for testing, help disseminate results, and review Test Plans and Verification Reports. The GHG Center's stakeholder groups consist of national and international experts in the areas of climate science and environmental policy, technology, and regulation. Members include industry trade organizations, technology purchasers, environmental technology finance groups, governmental organizations, and other interested groups. In certain cases, industry specific stakeholder groups and technical panels are assembled for technology areas where specific expertise is needed. The stakeholder technical panel members provide guidance on the verification testing strategy and peer review key documents that are related to their areas of expertise.

JCH Fuel Solutions, Inc. (JCH), located in North Las Vegas, NV, requested the GHG Center to perform an independent third-party performance verification of a diesel fuel treatment and filtration system. Many types of facilities operate stationary and mobile equipment powered by diesel-fueled internal combustion (IC) engines. These facilities often maintain their own diesel fuel storage tanks at central locations. Diesel fuel is best used immediately after manufacture, or at least within a few months from the time it was manufactured. In practice, however, a given inventory of fuel can remain in a storage tank for long periods. The fuel can become contaminated during long storage periods in a clean tank. This contamination decreases fuel quality and may increase engine emissions when the fuel is ultimately consumed. JCH's technology treats and cleans contaminated fuel.

This Verification Report specifically addresses the JCH Enviro Automated Fuel Cleaning and Maintenance System, Model 4 (Enviro System). The Enviro System incorporates the JCH/Algae-X Model 46-LG-X1500 magnetic fuel conditioner and the JCH/Algae-X Fuel Catalyst AFC-705. Details on the verification test design, measurement test procedures, and Quality Assurance/Quality Control

(QA/QC) procedures can be found in the Test Plan titled *Testing and Quality Assurance Plan for the JCH Fuel Solutions, Inc. Enviro Automated Fuel Cleaning and Maintenance System* (SRI, 2001). It can be downloaded from the GHG Center (sri-rtp.com) or ETV (www.epa.gov/etv) Web sites. The Test Plan describes the rationale for the experimental design, the planned test methods and instrument calibration procedures, and specific QA/QC goals and procedures. The Test Plan was reviewed and revised based on comments received from JCH, selected members of the GHG Center's stakeholder groups, and the EPA Quality Assurance Team. The Test Plan met the requirements of the GHG Center's Quality Management Plan (QMP), and thereby satisfied ETV QMP requirements. In some cases, the verification required deviations from the Test Plan. These deviations and the alternative procedures used are discussed in this report.

The remaining discussion in this section describes the Enviro System technology, presents the operating schedule of the test facility, and lists the performance verification parameters that were quantified. Section 2 presents the verification test results, and Section 3 assesses the quality of the data obtained.

1.2 JCH ENVIRO AUTOMATED FUEL CLEANING AND MAINTENANCE SYSTEM DESCRIPTION

Facilities using diesel-fired engines often maintain their own diesel fuel storage tanks at central locations. Stationary engines draw their fuel supply through direct piping to the central storage tanks, or they may operate from integral tanks (day tanks) mounted on the engine chassis. Although diesel fuel is best used within a few months from when it was manufactured, a given inventory of fuel can often remain in a storage tank for long periods. For example, a hospital or hotel with a diesel-powered emergency electric generating plant may keep the same tank of fuel for a long time before using it up. Some facilities buy fuel months or even years in advance of projected needs to take advantage of favorable pricing.

The fuel can become contaminated during long storage periods even when it is stored in a clean tank. This contamination decreases fuel quality and may increase engine emissions when it is ultimately consumed.

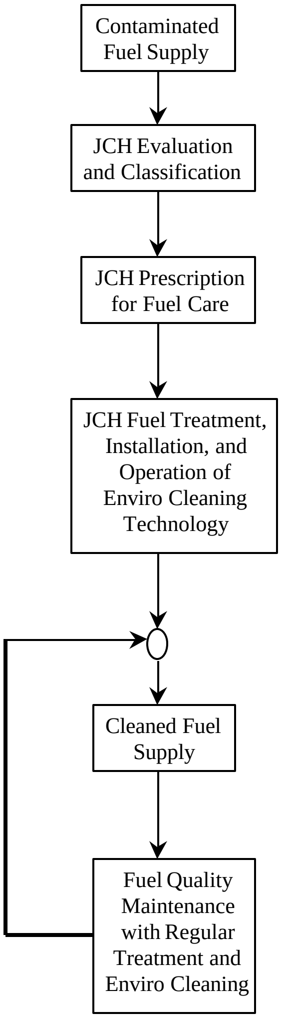
During storage, diesel fuel may:

- acquire water from atmospheric condensation and separation
- grow colonies of algae and fungi
- form clouds and gels
- oxidize into gums and resins
- accumulate other particles (e.g., ambient dust, rust, other fines)

Each of these contaminants can alter diesel fuel properties and thereby potentially harm the precision mechanisms of a diesel engine, increase wear, clog filters, and reduce combustion quality. Contaminated fuel may therefore increase fuel consumption and emissions.

JCH's Enviro System technology treats and cleans contaminated fuel. It also maintains the treated fuel while in storage. Figure 1-1 depicts the process flow of the Enviro System.

Figure 1-1. JCH Fuel Treatment and Cleaning Process Flow

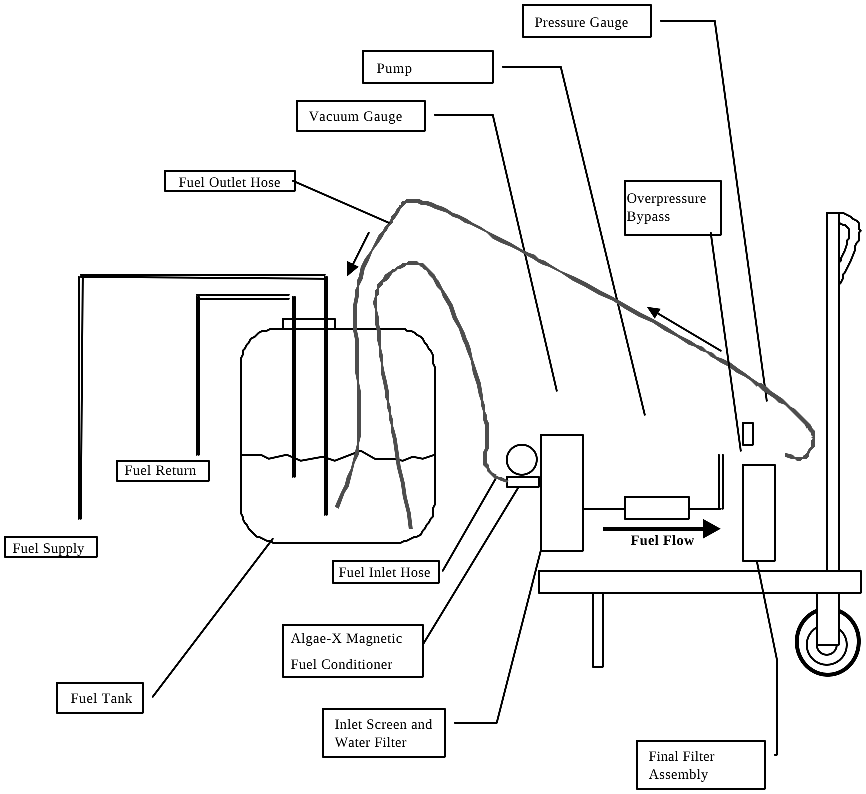


When an operator requires a solution to a fuel contamination problem, JCH initially collects a fuel sample for field testing and laboratory classification of contaminants. The field test equipment yields a quick qualitative evaluation of the fuel for sediment and water, microorganisms, appearance, clarity/brightness, and debris/contamination. The JCH representative rates the fuel for each of these factors on a qualitative scale from 1 to 10: 1 is no observable contamination, and 10 indicates heavy contamination. The field tests roughly correspond to standard laboratory [ASTM International (ASTM)] methods, and are sufficient for most customers' applications. JCH then develops a prescription of care for fuel treatment and filtration.

The first step of treatment consists of the application of the proper amount of Algae-X AFC-705 fuel catalyst. The AFC-705 solution contains detergents, lubricity enhancers, a corrosion inhibitor, and a demulsifier to drop out entrained water. The solution also provides a preservative and dispersant to stabilize fuel in storage by retarding gum formation. The tank owner adds the fuel treatment directly to the stored fuel. One gallon of AFC-705 solution treats approximately 5,000 gallons of fuel.

JCH then installs an Enviro System at or near the storage tank. JCH manufactures and markets approximately 12 Enviro models in various sizes and capacities. Figure 1-2 shows a schematic of a portable cart-mounted system that can be moved from tank to tank. Figure 1-3 depicts a larger capacity system intended to be permanently floor- or wall-mounted at a single storage tank.

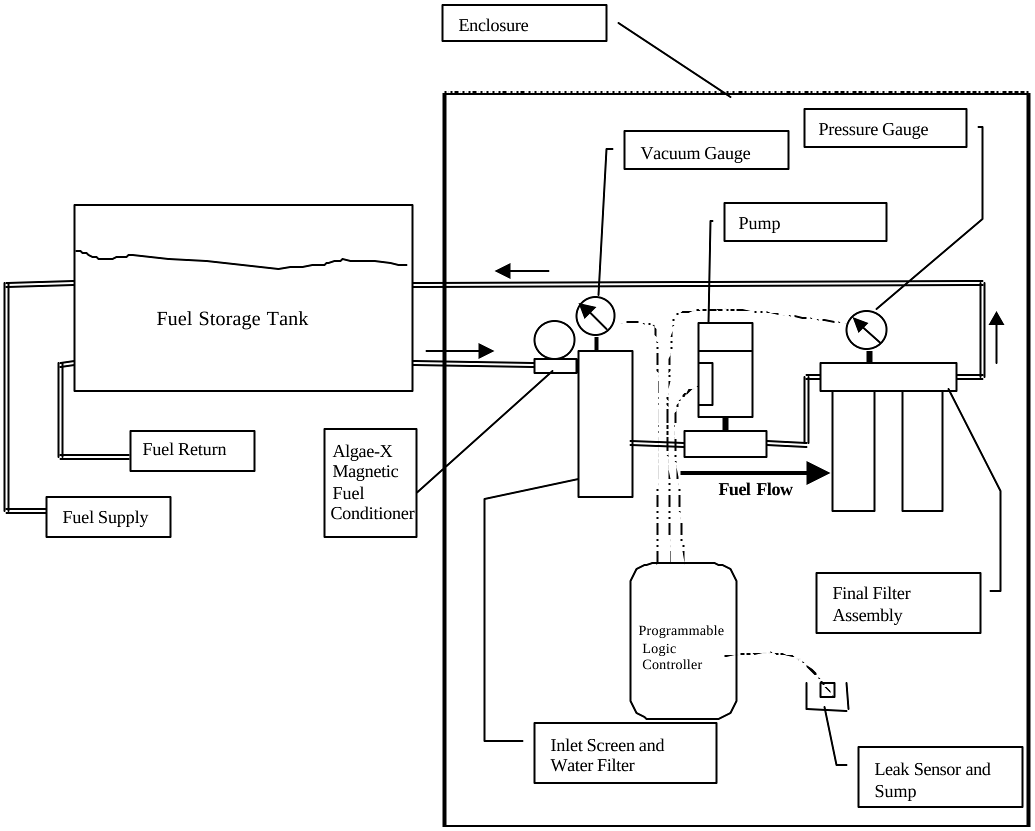
Figure 1-2. JCH Portable Cart-Mounted System



Each system consists of several components. An electric pump moves fuel from the tank through an Algae-X magnetic fuel conditioner, a multistage filter train, and then back to the tank. The Algae-X fuel conditioner is designed to eliminate and prevent problems related to fuel deterioration, repolymerization, stratification, and organic debris and acid buildup. Most portable Enviro models (Figure 1-2) employ two-stage filtration. The first stage is a cartridge-type coarse particulate screen and bulk water separator. The second stage is a 2-µm particulate filter that also removes emulsified water. Depending on pumping capacity, a typical portable unit is 49 x 21 x 19 in. (height/width/depth) and weighs about 175 pounds.

The larger, permanently mounted units (Figure 1-3) are housed in an enclosure and use three-stage filtration. Stage 1 is a 150-µm particulate and bulk water separator cartridge. Stage 2 is a 10-µm particulate filter which removes 95 percent of entrained water. Stage 3 is a 2-µm particulate filter which removes emulsified water. The stage 2 and 3 filters are spin-on canister-type elements. These systems are plumbed directly into the tanks which they serve. Inlet piping conveys the fuel from the lowest point of the tank to the inlet screen and water filter. The electric pump circulates the fuel through the final filter train and back to the storage tank.

Figure 1-3. JCH Floor-Mounted System



The system size and pumping capacity is selected based on the size of the tank to be served. The Enviro 2 is intended for use on tanks up to 2,000 gallons and has a 3 gallons per minute (GPM) pump. Its wall-mounted enclosure is 24 x 24 x 10 in. (h/w/d), and the entire unit weighs 150 pounds. The largest model, the Enviro 9, monitors and maintains tanks up to 80,000 gallons with a 40 GPM pump. It is in a 40 x 54 x 26 in. (h/w/d) floor-mounted enclosure and weighs 750 pounds.

During this verification, a Model 4 was specified based on the capacity of the day tank used to store fuel for the test engine (275 gallons). During initial treatment and cleaning activities, JCH qualitatively monitors the fuel quality using field test equipment to determine when to end a treatment. Once a contaminated lot of fuel is satisfactorily treated, its quality must be maintained by regular operation of the Enviro System. JCH recommends that at least one tank volume per week be circulated through the Enviro System. Portable systems are operated manually: the operator moves the cart to the tank to be treated, installs the inlet and outlet hoses through the tank fill cap, and runs the system for the time required.

For wall-mounted systems, a programmable logic controller (PLC) provides for unattended operation. The operator programs the PLC according to the pumping capacity of the Enviro System and the size of the tank.

The PLC also monitors vacuum and pressure gauge readings. A vacuum gauge alarm alerts the operator of the need to clean or replace the inlet screen and filter. A differential pressure (DP) gauge alarm indicates the need to change the final filter elements. The PLC shuts the system off during overpressure conditions (e.g., final filter becoming clogged). It also monitors the leak sump and pump motor, shutting the system down or triggering alarms as appropriate.

System maintenance includes draining water and sludge from the inlet screen and filter into an adsorbent to stabilize it. The 10- and 2-µm filter canisters must be changed periodically. Enviro System users must transfer the used canisters and spent adsorbent media to a Class I landfill for ultimate waste disposal.

1.3 TEST FACILITY DESCRIPTION

This verification was hosted by the Cummins Intermountain (CI) facility located in North Las Vegas, NV. CI is a full-service Cummins engine dealer that maintains a large inventory of diesel-driven generator (genset) rental equipment. The unit selected for testing was an Onan Model 200DGFC 200 kilowatt (kW) trailer-mounted genset, with a Cummins Model 6CTAA8.3-G1 6-cylinder, direct injected, turbocharged engine (Onan, 2001). The genset was connected to a Loadtec Model OTT3-1505.1 Portable Resistive Load Bank to provide a controlled electrical load. Table 1-1 shows factory performance and emissions data for the test engine. The emissions data in the table are manufacturer rated values and served as starting estimates for the field determinations.

Table 1-1. Onan/Cummins Model 200DGFC
(Engine/Generator Emissions Data: Prime Power Service)

Description	Predicted Value
Brake Horsepower (Bhp) @ 1800 rpm (60 Hz)	285 Bhp
* Carbon Dioxide (CO_2) Emissions	*285.8 lb/hr
Carbon Monoxide (CO) Emissions	5.34 lb/hr
Fuel Consumption	13.3 gal/hr
Nitrogen Oxides (NO_X) Emissions	4.34 lb/hr
Prime Power Generating Capacity (480 VAC)	180 kW
* Sulfur Dioxide (SO_2) Emissions	*0.50 lb/hr
Total Unburned Hydrocarbons, as Methane (CH_4)	0.63 lb/hr

* Factory data unavailable; estimate based on AP-42 "Emission Factors of Uncontrolled Gasoline and Diesel Industrial Engines" (U.S. EPA, 1995)

During test development and planning, the GHG Center reviewed this engine's size and generation capacity with representatives from Cummins, Inc., Caterpillar, Inc., International Truck and Engine Co., John Deere & Co., and several diesel fuel experts, including the chairman of the ASTM D-975 fuels committee. The consensus was that this engine/generator combination is a good selection for the test campaign for several reasons. First, diesel engines of all sizes must achieve EPA Tier I emissions requirements. More restrictive Tier II regulations are phasing in from 2001 to 2006. Most manufacturers are using similar technologies (e.g., direct injection, turbocharging, computerized engine control) to meet the requirements. The increasingly stringent emissions regulations are forcing a convergence in engine design and operation across all manufacturers, regardless of size. Emissions from engines of different manufacturers are reported to be very similar for a given horsepower (hp) range.

Second, the 180 kW engine/generator combination is representative of a large number of installed gensets. In the fourth quarter of 2000 alone, the Electrical Generating Systems Association reported sales of 4461 gensets of between 150 and 4000 kW capacity (EGSA, 2001). Of these, 60 percent were between 150 and 750 kW.

Third, a generator with a resistive load provides a consistent, predictable load for the engine. The constant 100 percent prime-power load cycle represents normal operating conditions for genset engines. The only differences which arise when compared with other service classes are the load rating of the engine and the operating time allowed at that load. For example, this genset can supply 200 kW of emergency power for the duration of a normal power interruption. Net emissions per hour at the higher rating will be greater because the engine is working harder and burning more fuel. The normalized emission rates at both power ratings ($lb_{pollutant}/lb_{fuel}$), however, will be virtually the same.

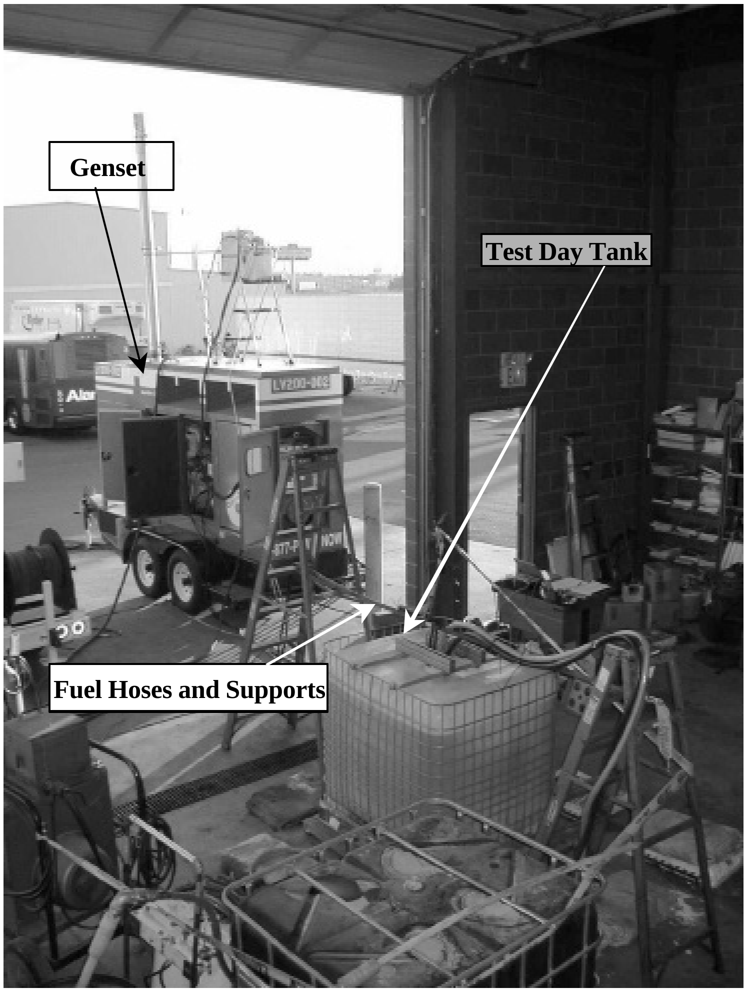
Finally, this genset represented a good compromise between a large engine which would have required a large amount of test fuel, and a small engine which would have presented emissions testing and fuel flow measuring difficulties. Figure 1-4 is a photograph of the fuel day tank and the test engine.

To help maintain steady engine operations during the verification, an adjustable load bank (Loadtec Portable Resistive Load Bank, Model OTT3-1505.1) was used to provide a steady state, pure resistive load for the genset at a target load of 100 ± 5 percent of the prime power capacity (180 kW). In the load bank, fan-cooled resistor arrays convert electrical energy into heat. Various resistors can be switched into and out of the circuit to provide the appropriate load for each generator phase.

The engine was also fitted with a custom fabricated test duct installed on the engine exhaust to facilitate proper emissions measurements. The temporary test duct was a 6-inch diameter stainless steel tube, 10 feet long, with an adaptor for the genset’s rain cap. Appropriate ports for gaseous and particulate emissions sampling were installed on the stack.

The test engine was equipped with a standard fuel cleaning system that included a two-stage fuel filter. Both stages were rated at 20-µm nominal filtration; the primary stage included a water separator element. This compares with the 10- and 2-µm filters in the Enviro equipment described in Section 1.2.

Figure 1-4. Test Engine and Fuel Day Tank



1.4 OVERVIEW OF VERIFICATION PARAMETERS AND EVALUATION STRATEGIES

This verification was designed to evaluate the following fuel and engine performance characteristics:

- Mass emission rates of criteria air pollutants and greenhouse gases (GHGs) from the engine while combusting contaminated and treated fuel:
  Carbon Dioxide (CO_2), lb/hr
  Carbon Monoxide (CO), lb/hr
  Methane (CH_4), lb/hr
  Nitrogen Oxides (NO_X), lb/hr
  Sulfur Dioxide (SO_2), lb/hr
  Total Hydrocarbons (THCs), quantified as CH_4, lb/hr
  Total Particulate Matter (TPM), lb/hr

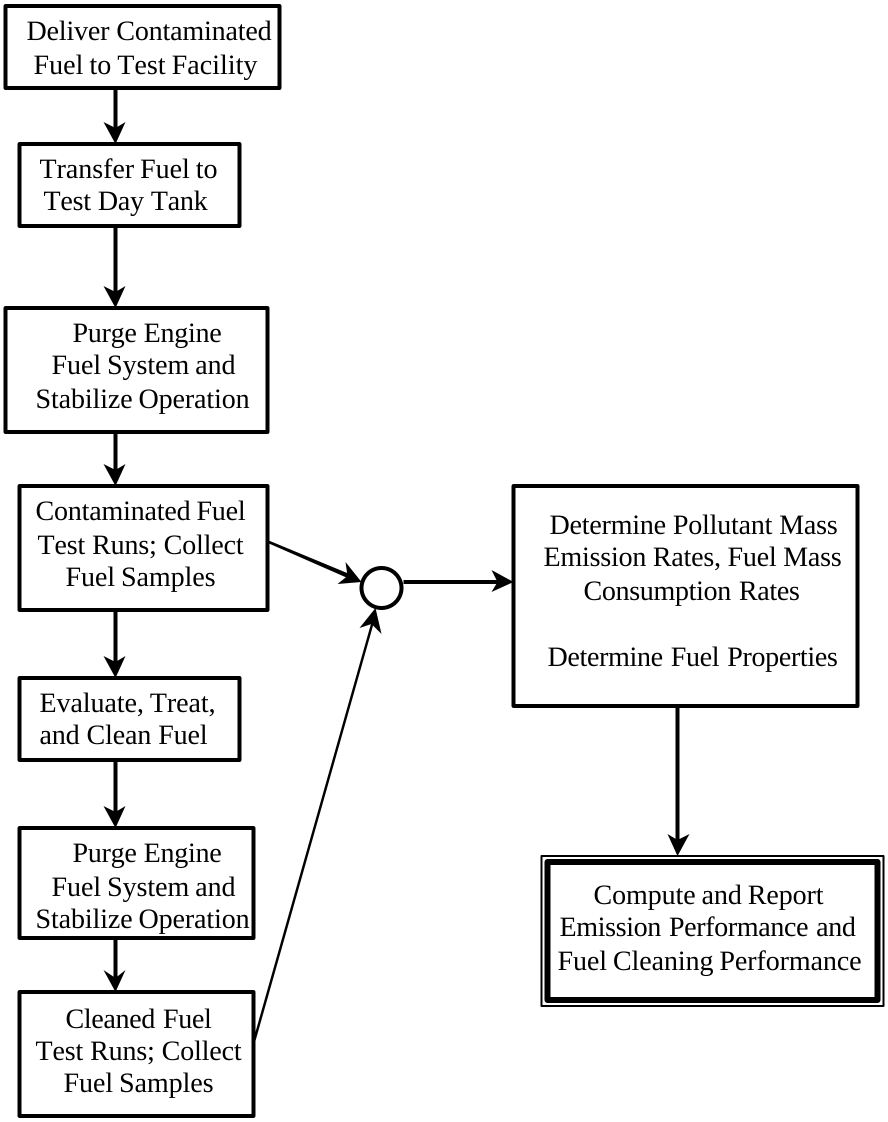
- Fuel properties for contaminated and treated fuel:
  - Fuel consumption rate, lb/hr
  - Fuel lower heating value (LHV), Btu/lb
  - Fuel quality properties:
    - API Gravity
    - Ash, vol %
    - Cetane Number
    - Flash Point, °C
    - Gums and Resins, mg/L
    - Lubricity
    - Microbial Contamination
    - Particulate Matter, mg/L
    - Water and Sediment, vol %

- Emissions performance in terms of the percent change in mass emission rates between contaminated and treated fuel. Emission rates were normalized as pounds of pollutant per pound of fuel ($lb_{pollutant}/lb_{fuel}$) and as pounds of pollutant per million Btu of heat input ($lb_{pollutant}/10^6 Btu$).

- Fuel cleaning performance: Percent change resulting from fuel treatment for each fuel property.

Figure 1-5 is a schematic of the verification strategy. This verification strategy was to conduct a set of tests for emissions, fuel quality, and fuel consumption while operating the engine on the contaminated fuel, and then to repeat the tests after treating the same lot of fuel using the Enviro System and running the engine on the treated fuel. During each test period, engine load was maintained at near- steady state using the load bank. The emissions tests conformed to well-documented EPA reference methods, and fuel measurements were conducted according to ASTM test specifications and other protocols as described in following sections. The results of these measurements allowed emissions performance and cleaning performance comparisons between the two fuel conditions.

Figure 1-5. Verification Strategy



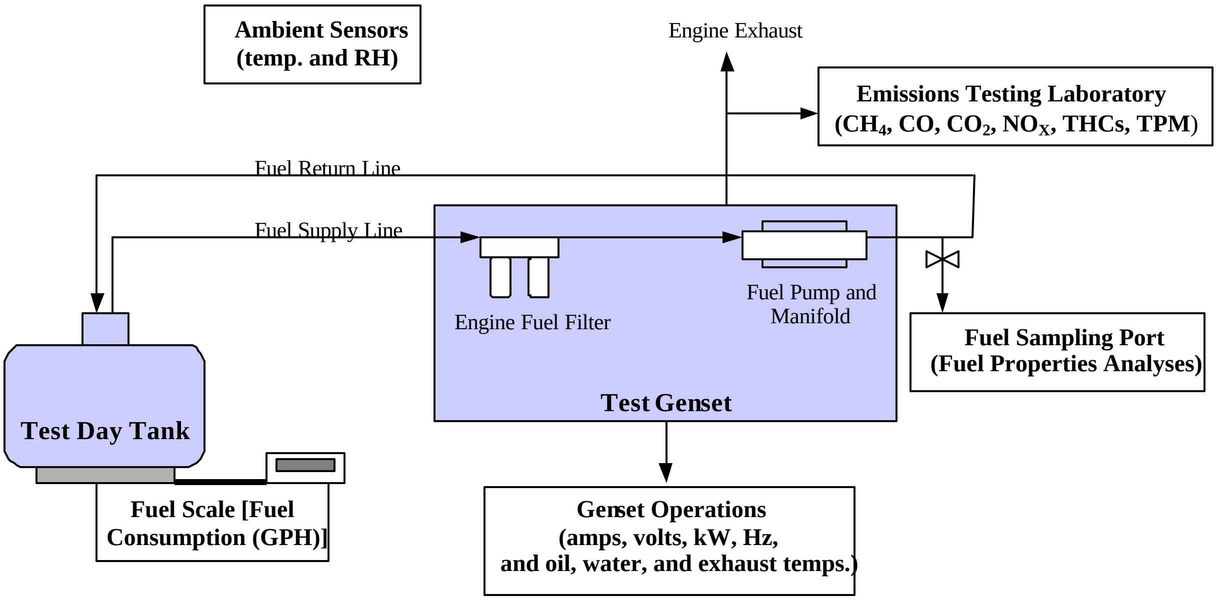
JCH provided a contaminated lot of fuel for this test, provided the test day tank which contained the test fuel, and performed all fuel transfers. The fuel in the test day tank was agitated before and during all testing to prevent stratification and to ensure that the mixed fuel supplied to the engine during testing was representative of the contaminated fuel.

GHG Center personnel obtained fuel samples from the as-received test fuel prior to the first test run. The Field Team Leader transferred the as-received sample from the test day tank into two 2.5 liter aluminum sample bottles with a suction pump while the fuel was being agitated. The suction pump inlet hose used to collect this sample was placed adjacent to the fuel hose to obtain a sample which would be representative of the fuel that the engine would consume.

The engine's fuel hoses and the circulation pump hoses were positioned such that they would not have contact with the tank walls or floor, thereby causing weight fluctuations (the genset's integral fuel tank was disconnected from the engine). The fuel return hose had a tee fitting and a ball valve connected to a short length of hose for fuel sample collection.

Verification testing commenced after collection of the as-received fuel sample and installation of the fuel delivery and sampling system. A series of tests were conducted for each of the verification parameters listed above while combusting the contaminated fuel. The fuel was then treated using the Enviro System, and the tests were repeated while combusting the treated fuel. Figure 1-6 is a schematic of the measurement system used during the testing. Specific procedures used to document test conditions and to determine each of the parameters are presented in Sections 1.4.1 through 1.4.4. Additional details regarding these procedures can be found in the Test Plan.

Figure 1-6. Schematic of Verification Measurement System



Engine and generator operations were monitored during each of the test periods. Parameters recorded included engine oil temperature, water temperature, exhaust temperature, generator amperes (amps), volts, and hertz (Hz). In addition to these engine/generator parameters, ambient temperature and relative humidity (RH) were also monitored. These data were used to document stable engine operation and test conditions during the test periods by comparing the variability in the measurements to allowable variations specified in the test engine Operation and Maintenance and Troubleshooting and Repair Manuals (Cummins, 1991a and 1991b).

1.4.1 Emissions Performance

Determination of the emissions performance of the engine is a primary verification parameter for evaluation of the performance of the Enviro System. Pollutant concentration and emission rate measurements for CH_4, CO, CO_2, NO_X, SO_2, THCs, and TPM were conducted on the engine exhaust stack during each test period. All of the test procedures used in the verification are EPA Reference Methods, which are contained in the Code of Federal Regulations. The Reference Methods include procedures for selecting measurement system performance specifications and test procedures, quality control procedures, and emission calculations (U.S. EPA, 1999). Table 1-2 summarizes the standard Test Methods that were followed.

Table 1-2. Summary of Emission Testing Methods

Pollutant/ Parameter	Reference Method	Principle of Detection	Analytical Range (Span)
CH_4	18	GC/FID	0 to 500 ppmv
CO	10	NDIR – Gas Filter Correlation	0 to 408 ppmv
CO_2	3A	NDIR	0 to14 %
NO_X	7E	Chemiluminescence	0 to 2,500 ppmv
O_2	3A	Fuel Cell	0 to 25 %
SO_2	6	Barium-thorin Titration	0 to 1,500 ppmv
THCs	25A	Flame Ionization	0 to 500 ppmv
TPM	5/202	Isokinetic Sampling/Gravimetric	not applicable

The emissions testing was conducted by Cubix Corporation of Albuquerque, New Mexico, under the on-site supervision of the GHG Center Field Team Leader.

A mobile laboratory was used to house the instruments and record emissions data throughout the testing periods. A detailed description of the sampling system used to determine the concentrations of criteria pollutants, GHGs, and O_2 is provided in the Test Plan and is not repeated in this report. A brief description of key features is provided below.

Sampling for gaseous pollutants (CH_4, CO, CO_2, NO_X, O_2, and THCs) was conducted by extracting a continuous stream of engine exhaust gas from a single point in the 4.75-inch diameter stack and directing the gas to the mobile laboratory. In order for the CO, CO_2, NO_X, and O_2 instruments used to operate properly and reliably, the flue gas must be conditioned prior to introduction into the analyzers. The gas conditioning system used for this test was designed to remove water vapor and/or particulate from the sample. Gas was extracted from the exhaust gas stream through a stainless steel probe and heated sample line, and transported to two ice-bath condensers, one on each side of a sample pump. The condensers removed moisture from the gas stream. The clean, dry sample was then transported to a flow distribution manifold where sample flow to each analyzer was controlled. Calibration gases were routed through this manifold and to the sample probe to perform bias and linearity checks.

For CO_2 and O_2 determination, a continuous sample was extracted from the emission source and passed through a Servomex Model 1400 analyzer. For determination of CO_2 concentrations, the Model 1400 was equipped with a nondispersive infrared spectrometer (NDIR). The CO_2 analyzer range was set at 0 to 14 percent. The same Model 1400 is also equipped with a micro-fuel-cell O_2 sensor. The fuel cell technology used by this instrument determines levels of O_2 based on partial pressures. The O_2 analyzer range was set at 0 to 25 percent.

NO_X concentrations were determined utilizing a Thermo Environmental Model 10AR chemiluminescence analyzer. This analyzer catalytically reduces NO_X in the sample gas to nitrogen oxide (NO). The gas is then converted to excited nitrogen dioxide (NO_2) molecules by oxidation with ozone (O_3) (normally generated by ultraviolet light). The intensity of the emitted energy from the excited NO_2 is proportional to the concentration of NO_2 in the sample. The efficiency of the catalytic converter for converting NO to NO_2 is checked as an element of instrument setup and checkout. The NO_X analyzer was operated with a range of 0 to 2,500 parts per million (ppm).

A Thermo Environmental Model 48H gas filter correlation analyzer with an optical filter arrangement was used to determine CO concentrations. This method provides high specificity for CO. Gas filter correlation uses a constantly rotating filter with two separate 180-degree sections (much like a pinwheel). One section of the filter contains a known concentration of CO, and the other section contains an inert gas without CO. Based upon the known concentrations of CO in the filter, these two values are correlated to determine the concentration of CO in the sample gas. The CO analyzer was operated within a range of 0 to 408 ppm.

THC concentrations in the exhaust gas were measured using a JUM Model 3-300 flame ionization detector (FID). This detector analyzes gases on a wet, unconditioned basis. Therefore, a second heated sample line was used to deliver unconditioned exhaust gases directly to the THC analyzer. All combustible hydrocarbons were being analyzed and reported, and the emission value was calculated on a CH_4 basis. The THC analyzer was operated within a range of 0 to 500 ppm.

Concentrations of CH_4 in the exhaust gas stream were measured using a gas chromatograph (GC) with a VICI 6-port gas loop injection system and a FID that was calibrated with appropriate certified calibration gases. Integrated gas samples were collected in Tedlar bags and returned to the emission testing contractor's laboratory for analysis. In the laboratory, samples were directed to a GC/FID after calibration of the FID.

Concentrations of SO_2 were determined following EPA Reference Method 6. This method was selected in lieu of the planned instrumental method (Method 6C) because it has the potential to provide a lower detection limit, and SO_2 concentrations were expected to be very low. The principle of Method 6 is to extract a gas stream from the stack at a known flow rate and pass the gas through impingers containing 3 percent hydrogen peroxide (H_2O_2) solution to absorb any SO_2 in the gas stream. After collecting the samples, the solutions are returned to the laboratory where analyses are conducted using barium-thorin titration procedures. Test results reported by the laboratory indicated that SO_2 concentrations were not detectable, but laboratory results for the fuel samples indicate that small levels of sulfur were found in the fuel. This indicates that some SO_2 (approximately 15 ppm) should have been detected in the exhaust gas. For this reason, the SO_2 results reported in Section 2.3 are based on fuel sulfur analyses and calculations. This is discussed in more detail in Section 2.3.

The testing for all of the gaseous pollutants (CH_4, CO, CO_2, NO_X, SO_2, and THCs) yielded concentrations in units of parts per million by volume (ppmv). Engine exhaust gas volumetric flow rates (determined using EPA Methods 2 through 4 as described below) were used to convert the concentration values into exhaust gas emission rates in units of pounds per hour (lb/hr) using Equation 1.

$$E_{poll,i} = C_{poll,i} K_{poll} Q_{stack,std,i} \qquad \text{(Eqn. 1)}$$

Where:

$E_{poll,i}$ = Emission rate for test run i, lb/hr
$C_{poll,i}$ = Average analyzer concentration for test run i (where i=1 to 3), ppmv
K_{poll} = ppmv to lb/dscf conversion factor
$Q_{stack,std,i}$ = Stack dry volumetric flow rate, dscf/hr (dscfm*60), corrected to standard conditions (60 ^{o}F, 29.92 in. Hg) for test run i

Emissions of TPM were determined in accordance with EPA Method 5/202 using an isokinetic sampling system. Stack gas velocity, temperature, and moisture content determinations were included in the TPM testing following Methods 2, 3, and 4. A standard-type pitot tube and thermocouple were located at the center of the 4.75-inch diameter stack to record DP and gas temperature throughout each test. These data were used to calculate the average stack gas velocity. Moisture was determined gravimetrically by withdrawing a measured stack gas sample through a probe and passing it through a chilled impinger train to condense the water. Oxygen (O_2) and CO_2 concentrations required to calculate the stack gas molecular weight were obtained using Method 3A as described above. These data, along with the physical measurement of the test duct area, were used to determine the average dry volumetric flow rate at standard conditions (dscfm) for each test run. These values were correlated with measured pollutant concentrations to calculate pollutant emission rates.

For TPM determination, the stack gas and its entrained particulate matter pass through the heated, glass-lined probe and through a filter maintained at 250 ± 25 ^{o}F. The filter collected particulate (usually inorganic matter) which condensed above that temperature; the rest of the stack gas and condensible particulate passed through the filter. The weights of particulate collected on the filter and deposited in the probe and nozzle were correlated with the total volume of stack gas collected and comprised the front half particulate concentration.

The stack gas then passed into a chilled impinger train charged with distilled water. Stack gas moisture and condensible particulate (usually organic matter) dropped out in the impinger train for recovery at the end of the test run. Test operators forwarded the recovered samples to the laboratory for extraction with methylene chloride and gravimetric analyses. The condensed impinger particulate was correlated with the total volume of stack gas collected and comprised the back half particulate concentration.

TPM results were reported as the sum of the front half and back half concentrations in units of grains per dry standard cubic foot (gr/dscf), as shown in Equation 2.

$$C_{TPM} = \frac{(m_{filter} + m_{condens} - m_{blank}) / 64.799}{VM_{std}} \qquad \text{(Eqn. 2)}$$

Where:

C_{TPM} = Particulate mass concentration, gr/dscf
m_{filter} = Mass of particulate collected on the filter, mg
$m_{condens}$ = Mass of particulate collected in impingers, mg
m_{blank} = Total mass of filter, probe rinse, back half, and extraction reagent blanks, mg
VM_{std} = Volume of collected stack gas, corrected to dry standard conditions (68 ^{o}F, 29.92 in. Hg), dscf
64.799 = conversion factor, mg/gr

Total particulate emission rates are reported as shown in Equation 3.

$$E_{TPM,i} = C_{TPM,i} Q_{stack,std,i} * 1.429 \times 10^{-4} \qquad \text{(Eqn. 3)}$$

Where:

$E_{TPM,i}$ = Particulate emission rate, lb/hr
$C_{TPM,i}$ = Mass concentration of particulate matter for run i (where i = 1 to 3), gr/dscf
$Q_{stack,std,i}$ = Stack dry volumetric flow rate, dscf/hr (dscf•60) corrected to standard conditions (60 °F, 29.92 in. Hg)
1.429×10^{-4} = conversion factor, gr/lb

1.4.2 Fuel Properties for Contaminated and Cleaned Fuel

This verification included determination of fuel consumption rates, heating values, and fuel quality for contaminated and cleaned fuel as burned in the engine. These measurements were used to evaluate the quality of fuel combusted in the engine and to correlate the data with the engine emissions for the two fuel conditions. The fuel properties evaluation included examination of engine fuel consumption rate, fuel heating value, and fuel quality while operating the engine on contaminated and cleaned fuel. The testing was designed to evaluate the quality of the fuel as combusted in the engine.

1.4.2.1 Fuel Consumption Rate for Contaminated and Cleaned Fuel

Diesel engines use their fuel for cooling and lubrication of fuel system components. Engine-operated pumps constantly circulate fuel from the storage tank, through the engine galleries and past the injectors, and back to the storage tank. The Cummins test engine circulates approximately 55 gallons per hour (gal/hr) under normal conditions. The injectors actually use only a portion of the total flow depending on the engine load and revolutions per minute (rpm). For this engine, fuel consumption was expected to be about 13 gal/hr at 100 percent of prime power load (180 kW).

Gravimetric determination was selected as the optimum way to monitor the fuel consumed. The 275-gallon polyethylene day tank was placed on a Fairbanks platform scale (Model IQ-5900C, 2000 pound capacity, serial number B39991) to obtain fuel mass consumption data. The engine pulled its fuel from the day tank, and the return fuel was circulated back to the same tank. For each test run conducted, the GHG Center personnel recorded fuel starting and ending weights on field data forms.

At the beginning of each test run, test operators recorded the time, the weight of the tank and fuel, and initial fuel temperature. At least three scale readings were collected at 15-minute intervals during each test run. The total fuel used during the run is shown in Equation 4.

$$FuelRate = (Wt_1 - Wt_2)\left(\frac{60}{T_{elapse}}\right) \qquad \text{(Eqn. 4)}$$

Where:

FuelRate = Mass fuel consumption rate, lb/hr
Wt_1 = Initial tank/fuel weight at the beginning of the test run, lb
Wt_2 = Final tank/fuel weight at the end of the test run, lb
T_{elapse} = Run elapsed time, as recorded by the instrumental analyzer operator, min

1.4.2.2 Fuel Heating Value and Fuel Quality for Contaminated and Cleaned Fuel

To determine the fuel cleaning performance of the Enviro System, fuel samples were collected and submitted to a laboratory for analysis of fuel quality properties. These data were used to form comparisons between the contaminated and cleaned fuel combusted in the engine. The samples were collected in conjunction with the emissions testing. As specified in the Test Plan, all samples were collected downstream of the engine fuel filtering system so that evaluation of the fuel actually being introduced to the engine could be examined.

The selection of fuel quality properties was based on input from engine manufacturing representatives (i.e., Association of Engine Manufacturers, Cummins, Caterpillar, International Truck and Engine, John Deere), fuel biological contamination experts, the chairman of the ASTM D-975 fuels committee, and several testing laboratories.

JCH's treatment and filtration technology was expected to affect properties such as water, sediment, particulate, API gravity, and microbial contamination. There was also interest in determining if the technology might affect other properties such as LHV, flash point, gums and resins, cetane number, or lubricity.

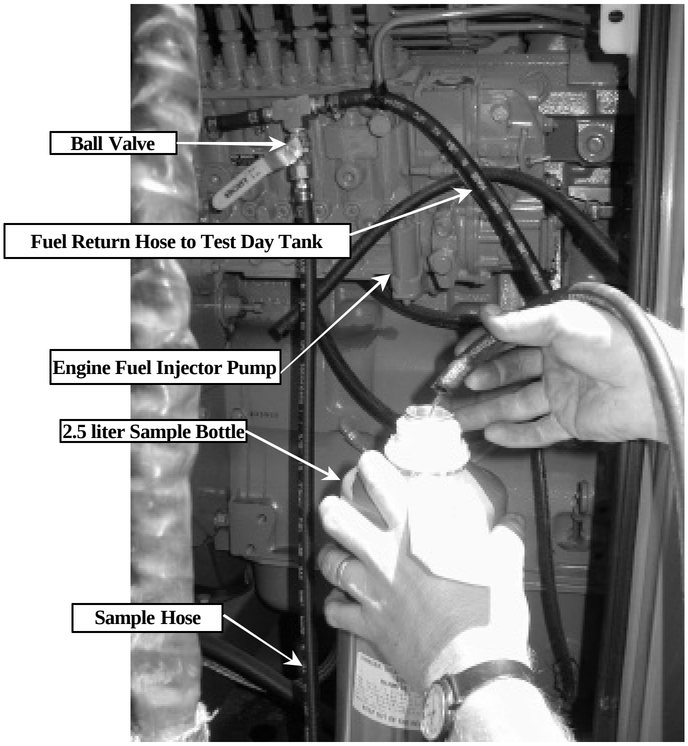
ASTM D-975, "Standard Specification for Diesel Fuel Oils" specifies some of these properties and lists the associated test methods (ASTM, 1999). Other properties of interest were analyzed with additional ASTM test methods not specified in D-975. Table 1-3 outlines the consensus selection of fuel properties evaluated, the D-975 specifications and test methods where applicable, and other methods used.

Table 1-3. Fuel Properties Test Methods

Description	D-975 Method	Test Plan Method	Principle of Detection	Method Accuracy
API Gravity	--	D-4052	Density by densitometer	± 0.22 % of reading
Ash	D-482	D-482	Gravimetric after incineration	± 21 % of reading
Bacterial and Fungal Contamination	--	LiquiCult	Colorimetric evaluation of fuel culture on agar	± 1 $\log_{10}$ of reading
Cetane Number	D-613	D-613	Audible knock in test engine	± 5.2 % of reading
Flash Point	D-93	D-93	Closed-cup heating with ignition source	± 5 % of reading
Gums and Resins	--	D-381	Gravimetric after evaporation of volatile compounds	± 6 mg/100 mL
LHV	--	D-4809	Calorimetric	± 97.1 Btu/lb
Lubricity	--	D-6079	Reciprocating scuffing pad	± 21.3 % of reading
Particulate Matter	--	D-6217	Gravimetric after filtering	varies; ± 25.3 % at 10 mg/l
Water and Sediment	D-2709	D-2709	Volumetric after centrifugal separation	varies; ± 9.4 % at 3 % vol. conc.

All fuel samples were collected from the fuel return hose downstream of the engine (and the engine filtering system). This sampling location had a tee fitting and a ball valve connected to a short length of hose. Figure 1-7 illustrates the fuel return connections at the engine and the collection of a sample. When the valve was in the closed position, all return fuel was routed back to the test day tank. When test personnel opened the valve, part of the return was diverted into the fuel sample hose. The Field Team Leader regulated the valve such that approximately 10 minutes was required to fill each sample bottle.

Figure 1-7. Sampling Location for Contaminated and Treated Fuel



Procedures detailed in the Test Plan were followed during all of the fuel sampling. The Field Team Leader first filled a 2.5-liter sample container with fuel. A 5.0-mL syringe was then filled from the sample remaining in the hose, and the contents were injected into a LiquiCult™ vial for bacterial and fungal microbial contamination analysis. The Field Team Leader then filled a second 2.5-liter container to complete the sample collection for Runs 1 and 3 for cleaned, and contaminated fuel. The Field Team Leader subsequently filled a third 2.5-liter container for Run 2 for each fuel condition so that the laboratory would have sufficient sample volume to conduct duplicate analyses on those samples. After filling, the Field Team Leader immediately sealed and labeled each sample container and entered the proper information on the Fuel Sample Collection Log form. Samples were forwarded to Southwest Research Institute's Petroleum Products Research Department (SwRI) for analysis. Standard chain of custody procedures were followed in the field and at the analytical laboratory operated by SwRI. After each sample collection, filled sample bottles were tagged with numbers, placed into shipping containers (four per container) and, before the containers were sealed, a signed chain of custody form, complete with laboratory handling instructions, was included. At the SwRI laboratory, the technician combined appropriate samples into a single container from which aliquots were drawn for analysis for each run. The technician handled each group of samples individually, so that all the containers were not open at one time, but only those containers for the current sample group. Laboratory identification numbers were applied to the combined sample containers, providing traceability to their original containers shipped from the field.

At the laboratory, samples were analyzed for each of the fuel quality parameters listed in Table 1-3. The Field Team Leader retained the LiquiCult samples for analysis at the proper times. These analyses were conducted at 30 ± 3 hours and 72 ± 3 hours after the sample was collected for bacterial and fungal contamination, respectively. Additional details regarding each of the fuel analyses are presented in the Test Plan and are not repeated here.

1.4.3 Emissions Performance of Contaminated and Cleaned Fuel

Emission rate measurements described above were used to report emissions performance as the percent change in emission rates for each pollutant between contaminated and treated fuel. To accomplish this, pollutant mass emissions were normalized using average diesel fuel mass consumption rates and LHVs. Results were computed in two forms:

- Percent change of mass of pollutant emitted per mass of fuel consumed (percent change, $lb_{pollutant}/lb_{fuel}$)
- Percent change of mass of pollutant emitted per million Btu heat input (percent change, $lb_{pollutant}/10^6 Btu$)

The calculation of emissions in terms of $lb_{pollutant}/lb_{fuel}$ requires the emission rate for each pollutant (Section 1.4.1) and the fuel consumption rate (Section 1.4.2). Equation 5 was used to determine normalized emissions.

$$E_{norm,i} = \frac{E_i}{FuelRate_i} \qquad \text{(Eqn. 5)}$$

Where:

$E_{norm,i}$ = Normalized emission rate of the given pollutant or greenhouse gas for run i, lb/lb of fuel
E_i = Emission rate of the given pollutant or greenhouse gas, for run i (where i = 1 to 3), lb/hr
$FuelRate_i$ = Fuel consumption rate for run i, lb/hr

The calculation of emissions in terms of pounds of a pollutant per million Btu of fuel heat input requires the emission rate for each pollutant (Section 1.4.1), the fuel consumption rate (Section 1.4.2), and the LHV (Section 1.4.2) of the fuel according to Equation 6.

$$E_{normheat,i} = \frac{E_i}{(FuelRate_i * LHV_i / 1{,}000{,}000)} \qquad \text{(Eqn. 6)}$$

Where:

$E_{normheat,i}$ = Normalized emission rate of the given pollutant or greenhouse gas for run i, lb/10^6Btu
E_i = Emission rate of the given pollutant or greenhouse gas, for run i (where i = 1 to 3), lb/hr
$FuelRate_i$ = Fuel consumption rate for run i, lb/hr
LHV_i = Fuel net heating value for run i, Btu/lb
1,000,000 = Conversion factor, Btu/10^6Btu

To report the emissions performance (i.e., the percent change in emissions between contaminated and cleaned fuel) a statistically significant difference in emissions must exist. Analysts computed t-statistics according to the procedure described in the following section.

1.4.4 Fuel Cleaning Performance

Fuel cleaning performance of the Enviro System was defined in the Test Plan as the percent change in fuel parameters between contaminated fuel and the same fuel when it has been treated and cleaned. The laboratory results for contaminated and cleaned fuel properties (Section 1.4.2) were used to develop the fuel quality comparisons. As described in Section 1.4.2, all of the fuel quality samples were collected downstream of the engine filtering system so that the results would represent the quality of fuel being combusted (Figure 1-6). However, this approach did not allow a quantitative evaluation of the quality of the fuel in the fuel tank before and after treatment. Therefore, this verification does not include a true evaluation of the Enviro System performance regarding the quality of fuel in the tank before and after treatment. Instead, this study reports only the quality of the fuel as combusted. More details regarding the Enviro System's fuel cleaning ability is provided in Section 2.4.

Fuel quality results were evaluated for statistically significant differences for each fuel quality parameter to allow a meaningful computation of the percent change between cleaned and contaminated fuel. The GHG Center tested the hypothesis that average fuel properties for the two fuel conditions were different by computing the following test statistic, as shown in Equations 7 and 8.

$$t = \frac{(X_{cleaned} - X_{contam})}{\sqrt{s_p{}^2\left(\frac{1}{n_{cleaned}} + \frac{1}{n_{contam}}\right)}} \qquad \text{(Eqn. 7)}$$

$$s^2{}_p = \frac{(n_{cleaned} - 1)s^2{}_{X,cleaned} + (n_{contam} - 1)s^2{}_{X,contam}}{n_{cleaned} + n_{contam} - 2} \qquad \text{(Eqn. 8)}$$

Where:

t = Test statistic
X = Average laboratory value for the fuel property (LHV, °API, etc.; see Section 2.4)
s_p = Pooled sample standard deviation
s = Sample standard deviation for cleaned and contaminated fuel conditions
n = Number of available results (3)

For parameters where the test statistic (t) was > 2.776 (assuming a 95 percent confidence level and 4 degrees of freedom), it was accepted that the average values were different. The data determined to be statistically different were then processed to calculate the percent change.

The percent change in each fuel property is as shown in Equation 9.

$$\%Change_X = \left(\frac{X_{cleaned} - X_{contam}}{X_{contam}} \right) * 100 \qquad \text{(Eqn. 9)}$$

Where:

$\%$ Change$_x$ = Percent change of fuel property, X
X$_{cleaned}$ = Average laboratory value of property, X (LHV, ^{o}API, etc.) for cleaned fuel
X$_{contam}$ = Average laboratory value of property, X for contaminated fuel

2.0 VERIFICATION RESULTS

2.1 OVERVIEW

The verification testing was conducted at the CI facility in North Las Vegas, NV, on July 17 and 18, 2001. During this period, engine emissions, fuel consumption, and fuel quality were evaluated with contaminated and cleaned fuel.

To facilitate this verification, JCH representatives obtained the contaminated fuel from a Nortel facility in Laughlin, NV, while servicing a storage tank. An independent hauler transferred the fuel from the service location to a 275-gallon polyethylene storage tank and a 55-gallon drum located at JCH's South Las Vegas facility. Total fuel available for the tests was approximately 300 gallons; approximately 250 gallons in the polyethylene tank and 50 gallons in the drum. JCH transferred the fuel to a new 275-gallon polyethylene tank which was placed in a trailer. JCH cleaned the original polyethylene storage tank because it was to be used as the test day tank at the CI test site. The Field Team Leader and JCH noted that both tanks were clean before any fuel was transferred into them. At the test site the test day tank was placed on a scale, and the fuel was transferred into it. It was anticipated that some fuel would be consumed during test preparations. The fuel in the drum was kept in reserve to top up the test day tank immediately prior to the start of testing.

The Test Plan specified that a propeller-type stirrer would agitate the fuel during testing. This was to prevent stratification and to ensure that the mixed fuel supplied to the engine during testing was representative of the contaminated fuel. At the test site, however, JCH and Cummins personnel became concerned that a propeller could breach the walls of the test day tank and suggested using a recirculating pump for this purpose instead. GHG Center personnel concurred and, for both sets of tests, JCH installed a 10-GPM recirculating pump. When the pump was switched on, the Field Team Leader observed vigorous rolling circulation at the surface of the fuel. Once the fuel delivery system was in place and the fuel agitation pump was running, the GHG Center began testing activities.

At least three valid test runs were conducted for engine emissions for each fuel condition. The first particulate and instrumental analyzer run for contaminated fuel lasted 60 minutes, but the particulate sample volume was slightly less than that specified in the Test Plan (i.e., 31.45 instead of 31.8 dscf). The remaining particulate/instrumental analyzer test runs were 70 minutes each to ensure collection of sufficient particulate sample volume.

The NO_X analyzer had excessive drift during Run 3 for contaminated fuel; the THC analyzer had excessive drift during Run 2 for contaminated fuel and Run 5 for cleaned fuel. Testers conducted additional instrumental analyzer runs (designated 3a and 6a for contaminated and cleaned fuels, respectively). Each of these runs was 30 minutes in duration.

Fuel quality sampling and fuel consumption determinations were conducted in conjunction with each test run. After completing the contaminated fuel testing, JCH personnel conducted fuel treatment activities using the Enviro System. The testing was then repeated the following day while combusting the cleaned fuel. Details regarding engine operation during testing activities, fuel cleaning activities, and test results are presented in the following subsections:

Section 2.1 – Engine Operation and Fuel Cleaning Procedures
Section 2.2 – Engine Emissions and Emissions Performance
Section 2.3 – Fuel Quality and Fuel Cleaning Performance

An assessment of the quality of data collected throughout all verification testing is provided in Section 3.0. The data quality assessment is used to demonstrate whether the data quality objectives (DQOs) introduced in the Test Plan were met.

2.2 ENGINE OPERATION AND FUEL CLEANING PROCEDURES

2.2.1 Engine Operation

To purge the engine of fuel from previous activities prior to beginning both sets of tests, Cummins personnel started the genset and operated the engine at 50 to 80 percent of prime power capacity while placing the engine's fuel return line in a waste container. A 10-minute run purged approximately 5 gallons of fuel through the engine, which was deemed sufficient because the engine's fuel system holds approximately 1 gallon of fuel.

The engine fuel return line was then connected to the test day tank, and the engine was operated at 100 percent prime power during all test periods. As had been anticipated in the Test Plan, the engine's fuel filters tended to bind and clog while the engine combusted the contaminated fuel. Prior to the start of the first test run, the engine ran for approximately 2.5 hours at full load on contaminated fuel when the engine fuel filter clogged, and the engine stalled. Cummins personnel installed a new set of engine fuel filters, and the contaminated fuel test runs were started. According to the Test Plan, the filters were changed between every test run to prevent engine shutdowns or damage to the engine.

To ensure stable operations during all test periods, the GHG Center logged generator amperage, voltage, frequency, engine oil, water, and exhaust temperatures. Table 2-1 summarizes engine operations during the test periods and indicates stable operation throughout the test periods.

Table 2-1. Average Generator and Engine Operation During Test Periods

	Generator Parameters				Engine Parameters		
Run ID	**Current, amps**	**Voltage**	**Power, kW**	**Frequency, Hz**	**Oil Temp, ^{o}F**	**Water Temp, ^{o}F**	**Exhaust Temp, ^{o}F**
Contaminated 1	499.8	208.0	180.0	60.0	205	189	889
Contaminated 2	501.1	208.0	180.6	60.0	208	192	881
Contaminated 3	497.7	208.0	179.3	60.0	215	195	898
Contaminated 3a	497.6	208.0	179.3	60.0	218	197	902
Cleaned 1	500.1	208.0	180.2	59.9	205	190	874
Cleaned 2	496.0	208.0	178.7	59.9	212	193	895
Cleaned 3	500.9	208.0	180.5	60.0	216	196	903
Cleaned 3a	495.8	208.0	178.6	60.0	212	198	902

The Test Plan specified expected values and permissible variations for each of these generator and engine parameters based on preliminary information. For example, the Test Plan assumed that generator nominal voltage and current were 483 volts alternating current (VAC) and 215 amps, respectively. The Test Plan allowed a 2.5 percent permissible variation for each of these parameters. Actual generator voltage was 208 VAC. For the generator to supply 180 kW at 208 VAC, the current must be 499.6 amps.

Similarly, the oil temperature, water temperature, exhaust temperature, and their permissible variation observed in the field were different from those specified in the Test Plan. GHG Center personnel revised the expected values and their permissible variations based on specifications in the engine operating and troubleshooting manuals (Cummins, 1991a and 1991b). Table 2-2 presents the revised values.

Table 2-2. Generator and Engine Parameters and Permissible Variation During Test Periods

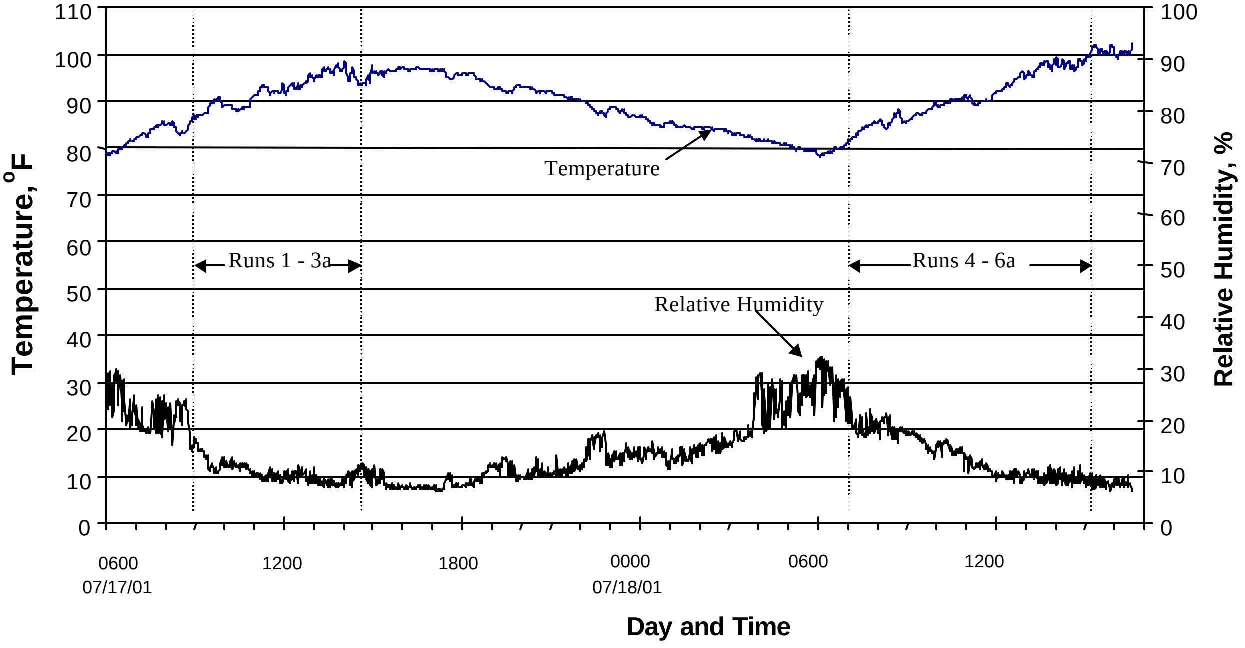
Description	Expected Value	Permissible Variation During Test Period
Generator Ammeter, Each Phase	499.6 amps	± 12.5 amps
Generator Voltmeter, Each Phase	208.0 VAC	± 5.2 VAC
Generator Frequency Meter	60.0 Hz	± 1.2 Hz
Engine Oil Temperature	260 °F	+0, -50 °F
Engine Water Temperature	212 °F	+0, -54 °F
* Engine Exhaust Temperature	925 °F	n/a

* This instrument was not a standard engine accessory. The engine's manuals did not specify a permissible range for this parameter.

Data acquired during all tests conformed to these permissible variations except for lubricating oil temperatures during Runs 1 and 2 for contaminated fuel and Run 1 for cleaned fuel. The Cummins technician on site stated that this is normal for engines operating under the conditions found during the tests, and would not materially affect the engine's performance.

Because engine performance and emissions characteristics can vary with changing ambient conditions, the GHG Center monitored ambient temperature and RH data during each test run with a Vaisala Model HMP 35C meter connected to a Campbell datalogger. These data are shown in Figure 2-1 and indicate similar ambient conditions during the 2-day test period. Temperatures on July 17 ranged from approximately 86 to 98 °F, and RH ranged from approximately 18 to 7 percent during the test periods. On July 18, temperature ranged from approximately 82 to 100 °F (testing started earlier in the day), and RH ranged from approximately 24 to 7 percent.

Figure 2-1. Ambient Temperature and Relative Humidity During Test Periods



2.2.2 Fuel Cleaning Procedures

At the conclusion of the contaminated fuel test runs, JCH administered the AFC-705 fuel catalyst (9 ounces in this case) and began operating the Enviro System fuel cleaning equipment. Table 2-3 shows the Enviro System fuel cleaning schedule performed by JCH for this verification.

Table 2-3. Enviro System Fuel Cleaning Activities During Verification Testing

Time (Date)	Process Description
1530 (07-17-01)	Start Enviro System fuel cleaning equipment
1640	Change 10- and 2-µm filters due to pressure alarm; clean water strainer due to high vacuum
1700	Restart
1800	Clean water strainer due to high vacuum and restart
1900	Change 10-µm filter due to high DP
1910	Restart
1930	Clean water strainer
0345 (07-18-01)	Stop Enviro System equipment. Purge 5 gallons cleaned fuel through engine fuel system
0400	Start genset for 2 hour burnout run by CI technician
0600	Shut down engine, change fuel filters, prepare for cleaned fuel emissions test runs by CI technician

The water strainer cleaning and filter change procedures conformed generally to JCH's normal field practices. However, the overall treatment and cleaning procedure departed from normal in two respects:

- JCH administered approximately twice the normal amount of AFC-705 additive (i.e., dilution was 1:2500 instead of 1:5000). JCH was concerned that a treated batch of fuel usually has a significant resting time to allow the additive to work. They recommended the increased dosage because, for the verification tests, the cleaned fuel tests would start immediately after cleaning. According to the Algae-X additive manufacturer, it is not unusual to administer a double dose of AFC-705 additive to a batch of fuel when it is heavily contaminated. This provides a "shock treatment" to quickly control contamination, and is useful when the fuel must be used soon after treatment.
- After the conclusion of the test campaign, JCH stated that their normal practice is to collect the water and sediment fractions from the bottom of the tank with a separate probe and suction pump prior to starting the Enviro System. This was not done during the verification testing. Section 2.4.2 discusses the effect this may have had on the test results.

2.3 ENGINE EMISSIONS AND EMISSIONS PERFORMANCE

2.3.1 Engine Emissions

Testing was conducted to determine engine emissions of CH_4, CO, CO_2, NO_X, O_2, SO_2, THCs, and TPM while combusting contaminated and cleaned fuel. Testers conducted three TPM test runs in conjunction with three instrumental analyzer runs for CH_4, CO, CO_2, NO_X, O_2, and THCs for contaminated and cleaned fuel. Table 2-4 presents results of the emissions testing in concentration units (ppm or %) and mass emission rates as lb/hr. Table 2-5 presents emission rates normalized to engine fuel consumption ($lb_{pollutant}/lb_{fuel}$) and heat input ($lb/10^6Btu$).

As noted in Tables 2-4 and 2-5, excessive drift in the analyzers invalidated the THC measurements for Runs 2 and 5, and the NO_X measurement for Run 3. The post-test drift checks exceeded the Reference Method criteria (3 percent of span). To make up for the invalidated runs, additional test runs (Runs 3a and 6a) were conducted only for the instrumental measurements. Fuel sampling and TPM emissions testing was not repeated during Runs 3a and 6a.

Tables 2-4 and 2-5 also note that SO_2 emissions are based on values calculated using the fuel analyses. The Method 6 tests were invalidated because the laboratory returned results for each run that were below the method detection limit of approximately 0.5 ppmv, while the fuel analyses clearly show small concentrations of sulfur in the fuel. All of the Method 6 QA/QC criteria were met (Section 3.2.1.2) so the reason for the non-detectable results is not clear. SO_2 emissions were calculated using Equation 10.

$$E = S_f * Q_f * r \qquad \text{(Eqn. 10)}$$

Where:
E = SO_2 emission rate, lb/hr
S_f = sulfur content in fuel, lb_{sulfur}/lb_{fuel}
Q_f = fuel consumption, lb/hr
r = lb-mole ratio of SO_2:S, 32:16

Table 2-4. Pollutant Concentrations and Emission Rates

Run ID	Fuel Condition	Engine Power, kW	TPM Emissions		NO_x Emissions		CO Emissions		SO_2 Emissions[a]		THC Emissions		CH_4 Emissions		CO_2 Emissions	
			gr/dscf	lb/hr	ppm	lb/hr	ppm	lb/hr	ppm	lb/hr	ppm	lb/hr	ppm	lb/hr	%	lb/hr
1	Contam-inated	180.0	0.0269	0.113	1213	4.25	72.3	0.154	15.0	0.0732	83.8	0.102	2.30	0.0028	8.83	296
2		180.6	0.0330	0.139	1202	4.22	80.3	0.172	15.3	0.0749	invalidated[b]	invalidated[b]	1.90	0.0023	9.00	302
3		179.3	0.0399	0.165	invalidated[b]	invalidated[b]	85.1	0.179	15.4	0.0741	94.8	0.114	1.70	0.0020	9.24	305
3a[c]		179.3			1353	4.67	88.3	0.186			94.2	0.113	1.90	0.0023	9.25	306
AVG		**179.8**	**0.0333**	**0.139**	**1256**	**4.38**	**81.5**	**0.173**	**15.2**	**0.0741**	**90.9**	**0.110**	**1.95**	**0.0024**	**9.08**	**302**
4	Cleaned	180.2	0.0399	0.167	1195	4.18	81.9	0.174	15.6	0.0761	61.4	0.075	2.30	0.0028	8.90	298
5		178.7	0.0290	0.119	1285	4.40	85.6	0.179	15.6	0.0744	invalidated[b]	invalidated[b]	1.80	0.0021	9.06	297
6		180.5	0.0273	0.112	1254	4.30	92.3	0.192	15.4	0.0733	105	0.125	1.40	0.0017	9.26	304
6a[c]		178.6			1190	4.08	94.7	0.197			102	0.122	1.90	0.0023	9.22	302
AVG		**179.5**	**0.0321**	**0.133**	**1231**	**4.24**	**88.6**	**0.186**	**15.5**	**0.0746**	**89.5**	**0.107**	**1.85**	**0.0022**	**9.11**	**300**

[a] SO_2 emission rates calculated based on fuel analyses for sulfur content.

[b] Any tests exceeding the analyzer drift requirements are labelled as invalidated.

[c] Test runs conducted to replace invalidated runs.

Table 2-5. Engine Emissions Normalized to Fuel Consumption and Heat Input

	Test Conditions			TPM Emissions		NO$_x$ Emissions		CO Emissions		SO$_2$ Emissions [a]		THC Emissions		CH$_4$ Emissions		CO$_2$ Emissions	
Run ID	Fuel Consumption (lb$_{fuel}$/hr)	Fuel LHV (Btu/lb$_{fuel}$)	Heat Input (10^{6}Btu/hr)	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu	lb$_{pollutant}$ / lb$_{fuel}$	lb/10^{6}Btu
1	88.8	18328	1.63	0.00127	0.0694	0.0479	2.61	0.00174	0.0947	0.000824	0.0450	0.00115	0.0627	0.00003	0.0017	3.33	182
2	90.9	18347	1.67	0.00153	0.0833	0.0464	2.53	0.00189	0.103	0.000824	0.0449	invalidated [b]	invalidated [b]	0.00003	0.0014	3.32	181
3	89.7	18363	1.65	0.00184	0.100	invalidated [b]	invalidated [b]	0.00199	0.109	0.000826	0.0450	0.00127	0.0691	0.00002	0.0012	3.40	185
3a[c]	88.6	18363	1.63			0.0527	2.87	0.00209	0.114			0.00128	0.0695	0.00003	0.0014	3.45	188
AVG	**89.5**	**18350**	**1.64**	**0.00155**	**0.0843**	**0.0490**	**2.67**	**0.00193**	**0.105**	**0.000825**	**0.045**	**0.00123**	**0.0671**	**0.00003**	**0.0014**	**3.38**	**184**
4	89.5	18302	1.64	0.00187	0.102	0.0467	2.55	0.00195	0.107	0.000850	0.0464	0.00084	0.0456	0.00003	0.0017	3.33	182
5	88.2	18290	1.61	0.00135	0.0738	0.0499	2.73	0.00202	0.111	0.000844	0.0461	invalidated [b]	invalidated [b]	0.00002	0.0013	3.37	184
6	85.2	18306	1.56	0.00131	0.0718	0.0504	2.76	0.00226	0.123	0.000860	0.0470	0.00147	0.0802	0.00002	0.0011	3.56	195
6a[c]	88.0	18306	1.61			0.0463	2.53	0.00224	0.123			0.00138	0.0754	0.00003	0.0014	3.43	188
AVG	**87.7**	**18301**	**1.61**	**0.00151**	**0.0825**	**0.0484**	**2.64**	**0.00212**	**0.116**	**0.000851**	**0.047**	**0.00123**	**0.0671**	**0.00003**	**0.0014**	**3.42**	**187**

[a] SO$_2$ emission rates calculated based on fuel analyses for sulfur content.

[b] Any tests exceeding the analyzer drift requirements are labelled as invalidated.

[c] Test runs conducted to replace invalidated runs.

The results in Tables 2-4 and 2-5 indicate that for the majority of pollutants, the fuel cleaning process did not result in a statistically significant impact on engine emissions. Average emissions rates for all of the pollutants were consistent throughout all of the contaminated and cleaned fuel test periods. As discussed in Section 2-4, the likely explanation is that after passing through the engine's fuel filters, the contaminated fuel's quality was essentially the same as the quality of the cleaned fuel.

2.3.2 Emissions Performance

In addition to the emission rates, the engine's fueling and heat rates are required to determine the emissions performance in terms of $lb_{pollutant}/lb_{fuel}$. Table 2-6 presents the fueling and heat rates for each of the test runs.

Table 2-6. Genset Fuel Consumption Rates

Fuel Condition	**Run ID**	**Fuel Consumption Rate, lb/hr**	**Heat Rate, 10^6 Btu/hr**
Contaminated Fuel	1	88.80	1.6275
	2	90.94	1.6686
	3	89.66	1.6464
	3a	88.60	1.6269
	Average	**89.50 ± 1.25**	**1.6423 ± 0.0231**
Treated Fuel	4	89.49	1.6378
	5	88.20	1.6132
	6	85.20	1.5597
	6a	88.00	1.6109
	Average	**87.72 ± 2.13**	**1.6054 ± 0.0386**

Average fuel consumption and heat rates were similar for contaminated and cleaned fuels. The value measured during Run 6 (85.2 lb/hr) is considerably lower than all other tests, but the GHG Center cannot identify the reason for this difference. Based on 95 percent confidence intervals of the means, and the overall measurement uncertainty in the measurements, the average values presented in the table overlap, indicating that fuel treatment using the Enviro System did not significantly affect engine fuel consumption. Also, the mass of contaminants collected on the engine filters while burning contaminated fuel may have affected these measurements slightly because the mass of contaminated fuel drawn from the day tank during each test is likely slightly higher than the mass of filtered fuel consumed.

As discussed in the previous section and shown in Table 2-5, emission rates were nearly uniform for combustion of both contaminated and treated fuel. For each pollutant, a t-statistic was computed to determine if measured differences in emission rates between contaminated and cleaned fuel were statistically significant. This t-statistic, compared to a Student's T distribution value for a 95 percent confidence level, indicates whether or not a statistically valid difference in average emission rates of each pollutant exists. The Student's T value depends on the number of test runs (n_p) for both contaminated and cleaned fuel. If the t-statistic is less than the corresponding Student's T value, then it is 95 percent certain that there is no statistically significant difference between emission rates for contaminated and cleaned fuel. Table 2-7 summarizes the t-statistics for each of the pollutants examined.

T-statistics for emission performance in terms of $lb_{pollutant}/10^6$Btu are similar to those in Table 2-7, and are not presented here.

Table 2-7. Differences in Emission Rates

Pollutant	Average Emission Rate – Contaminated Fuel, $lb_{pollutant}/lb_{fuel}$	Average Emission Rate – Treated Fuel, $lb_{pollutant}/lb_{fuel}$	Average Difference[a], %	n_p[b]	$T_{0.025,np}$	t-statistic
CO	0.00193	0.00212	-9.6	6	2.447	-1.7
CO_2	3.38	3.42	-1.4	6	2.447	-0.77
NO_X	0.0490	0.0484	1.3	5	2.571	0.31
SO_2	0.000825	0.000851	-3.2	4	2.776	5.7
THCs	0.00123	0.00123	0.1	4	2.776	0.006
TPM	0.00155	0.00151	2.4	4	2.776	0.16

[a] Average Difference = (contaminated rate – treated rate) / contaminated rate * 100

[b] n_p = (number of valid contaminated fuel test runs) + (number of valid cleaned fuel test runs) – 2

Because the t-statistics are less than the Student's T values for all pollutants other than SO_2, differences in emission rates cannot be considered statistically significant. Because emissions testing results for SO_2 emissions were invalidated, the reported rates were calculated from fuel sulfur content. The fuel sulfur content was approximately 3.4 percent higher after treatment of the fuel. This difference accounts for the apparent significance of the increase in calculated SO_2 emission rates during the tests conducted with treated fuel. As described below, the increase in fuel sulfur was likely related to the AFC-705 fuel additive used. The small predicted increase in SO_2 emissions is meaningful only to the extent that the fuel sulfur increase is representative.

The data also indicate a 9.6 percent increase in CO emissions after treatment, but this increase is not statistically significant based on a 95 percent confidence interval (largely due to variability in the individual test run results). The CO increase is only statistically valid based on a confidence interval of 85 percent.

2.4 FUEL QUALITY AND FUEL CLEANING PERFORMANCE

2.4.1 Fuel Quality

The fuel quality testing was conducted in conjunction with the emissions testing and included determination of fuel properties and generator fuel consumption rates. Documentation of sample collection logs, laboratory results, certifications, and ASTM method control charts is maintained at the GHG Center.

Fuel quality properties were evaluated by submitting contaminated and treated fuel samples collected during each test run to SwRI for analysis. Table 2-8 summarizes the results of these analyses.

Table 2-8. Fuel Quality for Contaminated and Treated Fuel[a]

Test Parameter	Contaminated Fuel Samples				Treated Fuel Samples			
	Run 1	Run 2	Run 3	Average	Run 4	Run 5	Run 6	Average
Density (° API)	34.2	34.2	34.2	**34.2**	34.2	34.1	34.1	**34.1**
Flash Point (°F)	163	163	165	**164**	165	165	167	**166**
Sulfur (mass %)	0.0412	0.0412	0.0413	**0.0412**	0.0425	0.0422	0.0430	**0.0426**
Ash (mass %)	< 0.001	< 0.001	< 0.001	**< 0.001**	< 0.001	< 0.001	< 0.001	**< 0.001**
Lubricity (mm scar)	0.410	0.345	0.370	**0.375**	0.375	0.355	0.370	**0.367**
Cetane Number	46.7	46.7	46.7	**46.7**	48.4	47.8	47.8	**48.0**
Gums and Resins (mg/100 mL)	46.4	39.3	47.0	**44.2**	72.1	75.1	63.0	**70.1**
Water and Sediment[b] (volume %)	0.023	0.025	0.045	**0.031**	0.130	0.075	0.028	**0.078**
Particulate Matter (mg/L)	24.3	5.2	9.2	**12.9**	3.8	10.4	7.1	**7.1**
LHV[b](Btu/lb)	18328	18347	18363	**18346**	18302	18290	18306	**18299**

[a] All samples were collected after fuel filtering by the engine filtering system, and the filters were changed prior to each test

[b] Values represent the average of duplicate analyses conducted on each sample

Section 1.4.4 described the procedure used by the GHG Center to determine if significant or statistically valid differences in the physical properties were evident after treatment by the Enviro System. Using the results presented in Table 2-8, this statistical analysis was conducted for each parameter, and the results are summarized in Table 2-9.

Table 2-9. Differences in Fuel Properties for Contaminated and Treated Fuel

Test Parameter	Average Value – Contaminated Fuel	Average Value – Treated Fuel	Average Difference	t-statistic	n_p	$T_{0.025,\ np}$
Density (° API)	34.2	34.1	-0.10	2.000	4	2.776
Flash Point (°F)	163.7	165.7	2.00	-2.120	4	2.776
Sulfur (mass %)	0.0412	0.0426	0.0014	-5.657	4	2.776
Ash (mass %)	0	0	0	0	4	2.776
Lubricity (mm scar)	0.375	0.367	-0.008	0.420	4	2.776
Cetane number	46.7	48.0	1.3	-6.500	4	2.776
Gums and Resins (mg/100 mL)	44.2	70.1	25.9	-5.86	4	2.776
Water and Sediment (volume %)	0.031	0.078	0.047	-1.342	4	2.776
Particulate Matter (mg/L)	12.9	7.1	-5.8	0.97	4	2.776
LHV (Btu/lb)	18346	18299	-47	4.16	4	2.776

Statistically significant changes in density, flash point, lubricity, water and sediment, and ash were not evident. Fuel quality properties including sulfur content, cetane number, and gums and resins all had statistically significant changes after treatment. Each of these average values was higher after fuel cleaning.

The increase in sulfur is possibly related to the 9 ounces of AFC-705 additive with which JCH dosed the fuel during cleaning and treatment. Algae-X International stated that the AFC-705 contains approximately 1.1 mass percent sulfur. This means that the additive brought approximately 0.0054 pound sulfur to the approximately 1,300 pounds of fuel in the test day tank at the start of JCH's treatment schedule. Based on this rough mass balance calculation, the AFC-705 increased the fuel sulfur by 0.0004 percent, compared to the 0.0014 percent average shown in Table 2-8. This is about a third of the reported sulfur increase at the reported level of additive. No other source of added sulfur in the fuel was apparent.

The increase in cetane number, although small, is also consistent with the AFC-705 additive. Algae-X International publications state that, at normal treatment levels (0.5 ounce per 20 gallons, or 1:5000), the additive increases the cetane number by approximately 0.7. This is consistent with the 1.3 cetane number increase reported here at a treatment level of approximately 2 times the normal treatment level.

The gums and resins analyses were also higher after treatment. This may be due to the operations of the engine's fuel filters as they filter particulate, asphaltines, gums and resins, and other contaminants from the fuel. The GHG Center believes that the unexpected increases in gums and resins are the result of the samples' being collected downstream of the engine filtering system.

The sampling protocol used during this verification prevented the GHG Center from conducting a true evaluation of fuel properties before and after treatment. A more detailed discussion of this sampling problem and the true fuel cleaning performance of the Enviro System is presented in Section 2.4.2.

Microbial contamination of the fuel was evaluated by visual inspection of the Liqui-cult samples after the required incubation time (30 hours for bacterial growth and 72 hours for fungal growth). Results of the tests are summarized in Table 2-10.

Table 2-10. Results of Microbial Contamination Tests

Sample ID	Incubation Time, hrs		Visual Condition [a]		Corresponding Count Number	
	Bacterial	Fungal	Bacterial	Fungal	Bacterial	Fungal
Contaminated 1	36	75	Heavy	Heavy	10^5	10^6
Contaminated 2	33	74	Moderate	Heavy	10^4	10^6
Contaminated 3	33	72	Slight	Heavy	10^3	10^6
Treated 1	31	74	Slight	Slight	10^3	10
Treated 2	28	75	Slight	Slight	10^3	10
Treated 3	38	75	Slight	Slight	10^2	10

[a] Visual condition is determined by comparison of sample appearance to Liqui-cult reference charts

Test results show that bacterial contamination in the contaminated fuel varied from slight to heavy, and that fungal contamination was heavy in all samples. After fuel treatment, bacterial and fungal contaminations were slight in all samples collected, indicating that the Enviro System treatment was effective in reducing these contaminants.

2.4.2 Fuel Cleaning Performance

The Test Plan specified an evaluation of the fuel cleaning performance of the Enviro System by examining the fuel properties test results before and after treatment, and computing the percent difference where statistically significant differences were observed. However, to make a sound evaluation of the effect of fuel cleaning on engine emissions, the Test Plan specified that all fuel samples would be collected downstream of the engine fuel filtering system (thereby examining the fuel quality as combusted by the engine before and after cleaning). Upon review of the test results, JCH and the GHG Center determined that a true evaluation of the Enviro System's fuel cleaning performance would have required that samples be collected upstream of the engine's fuel filter to examine properties of the fuel in the tank, prior to being filtered by the engine's filters. Because samples were not collected upstream of the engine filters during the test campaign, this verification parameter could not be evaluated. In fact, for this reason fuel quality parameters appear to be relatively similar, whether dirty or cleaned fuel was present in the tank (i.e., the engine's filters cleaned the dirty fuel before sampling occurred).

The fuel quality properties analyses discussed in Section 2.4.1 indicated that the gums/resins values for samples collected in the return line were higher after treatment with the Enviro System. But after reviewing field notes recorded during the testing and photographs of the engine filters before and after fuel treatment, it is visually clear that the Enviro System does provide significant fuel cleaning. Moreover, while combusting contaminated fuel prior to the beginning of testing, the engine could only run at full load for about 2.5 hours before the engine filters clogged and stalled the engine. In anticipation of this problem, the Test Plan specified that the engine's filters be changed before all test runs.

Results for water and sediment content in the fuel were very low for both the contaminated and cleaned fuel runs, and as such, differences between these two cases are not significant. It is important to address why some individual cleaned-fuel test runs showed apparent increases for these parameters. Three considerations may explain these increases, as well as the increases in gums and resins. First, it is possible that, as the test day tank emptied, small amounts of water that had not been collected by the Enviro System were circulated into the fuel intake hose. After the test campaign was completed, JCH personnel stated that their normal field practice is to collect the water and sediment that settles to the bottom of a fuel tank with a separate probe and suction pump prior to treating the fuel with the Enviro System. This procedure was not followed during the test campaign, and some water may have remained in the test day tank during the cleaned fuel test runs. Thus, as the fuel was consumed and the level in the test day tank was drawn down, residual water could have been circulated past the fuel intake hose.

Second, the ASTM D-2709 test method's uncertainty becomes very large when water and sediment concentrations are small. The method's 0.041 percent reproduceability is a significant fraction of the highest concentrations found (0.130 volume percent) and could completely obscure the lower concentrations (0.005 to 0.025 volume percent).

Third, the Enviro System's fuel cleaning filters have particle size cut points of 10 and then 2 µm, compared to the genset's 20-µm cut point for the fuel cleaning filters. It stands to reason that the engine filters would not experience clogging or even significant caking of material from particulate, gums and resins, water and sediment, and other insoluble contaminants after fuel cleaning using the Enviro filters. Photographs of the filters used during the verification support this (very little material is visually evident on the filters after fuel cleaning with the Enviro System).

Conversely, during combustion of contaminated fuel, each engine fuel filter showed significant material lodged on the filter pleats. Depending on levels of contamination, eventual clogging of the secondary filter and starvation of the engine's fuel supply could occur. This did occur after approximately 2.5 hours of run time the day prior to the start of testing. Additionally, caking of the secondary filter may reduce the cut point of the filter, actually increasing its efficiency and accelerating the clogging process. Figure 2-2 shows one of the filters used during the verification while combusting the contaminated fuel. A large amount of contaminants is visually apparent on this filter after only approximately 1.5 hours of genset operation at full load.

Figure 2-2. Engine Filter after Operation with Contaminated Fuel

Conversations with the engine manufacturer, fuel testing laboratory, and two filter manufacturer representatives indicated that this could be an explanation for these data. It may have been possible for the filter cake, which built up very quickly while filtering the contaminated fuel, to have increased the filter's efficiency, reduced the cut point, and reduced the amount of contaminants appearing in the fuel samples. This is consistent with research performed by Hastings Filters, Inc. on a Fleetguard FS-1000 spin-on fuel-filter/water-separator similar to those used on the test engine. SAE J905 performance tests showed a 18.9 percent increase in mass filtering efficiency from beginning to end of life for this filter (Hastings, 2001).

After cleaning, the remaining contaminants would have been those which would pass the Enviro System's 2-µm filter. Such contaminants would also have easily passed through a new filter's 20-µm pores and been retained in the fuel as it was combusted.

3.0 DATA QUALITY ASSESSMENT

3.1 DATA QUALITY OBJECTIVES

In verifications conducted by the GHG Center and EPA-ORD, measurement methodologies and instruments are selected to ensure that a desired level of data quality exists in the final results. DQOs are established for key verification parameters before testing commences. These objectives must be achieved in order to draw conclusions with the desired level of confidence. The primary JCH verification parameters were based on comparisons of engine emissions while combusting contaminated and cleaned fuel, and the quality of contaminated fuel and fuel cleaned using the Enviro System.

The process of establishing DQOs for stack emissions performance starts with identifying the measurement variables that affect the verification parameters. For example, determination of changes in NO_X emissions in units of $lb_{pollutant}/lb_{fuel}$ first requires determination of NO_X emissions from cleaned and contaminated fuels.

Each of these two determinations requires measurement of three separate variables: NO_X concentrations, exhaust gas flow rate, and fuel consumption. The errors associated with each of these measurements must be accounted for to determine their cumulative effect on emissions performance. The Test Plan did this by assuming that measurement errors are not random, and that these errors can be combined to produce a worst-case overall error in the verification parameter. For NO_X, assuming a 10 percent reduction in stack gas concentration, the resulting emissions performance in terms of $lb_{pollutant}/lb_{fuel}$ would be -9.5 ± 5.4 percent. Note that the accumulated uncertainty is more than half the emissions performance. This shows how smaller emissions performances resulting from smaller changes in stack gas concentration would be obscured by the inherent measurement uncertainty. In this case, ± 5.4 percent is the DQO for NO_X emissions performance.

For fuel cleaning performance, the DQO is based on the associated ASTM method's uncertainty for each fuel property. In the simplest case, the DQO is twice the method error. LHV measurement error, for example, is ± 0.53 percent. The difference between contaminated and cleaned fuel must be at least twice that value to achieve the DQO.

Table 3-1 recapitulates the Test Plan's DQOs.

Table 3-1. Verification Parameters and Data Quality Objectives

Verification Parameters		DQO, %
Changes in Engine Emissions (DQO represents the maximum error in propagated measurements, based on a 10 percent reduction in emission rates in units of $lb_{pollutant}/lb_{fuel}$).	CH_4	± 7.30
	CO	± 7.50
	CO_2	± 7.50
	NO_X	± 5.40
	SO_2	± 7.60
	THCs	± 7.40
	TPM	± 4.50
Fuel Cleaning Performance (DQO represents the minimum percent change in each fuel quality parameter needed to draw valid conclusions from the results).	° API	± 0.44
	Ash	± 42.00
	Cetane Number	± 15.90
	Flash Point	± 10.00
	Gums and Resins	± 60.00
	LHV	± 1.05
	Lubricity	± 43.00
	Particulate	± 57.20
	Water and Sediment	± 23.30

To determine whether the DQOs listed above were met during the verification testing, data quality indicator (DQI) goals were established for each key measurement performed in the verification test. The DQI goals, specified in Tables 3-2 (fuel consumption and emissions) and 3-6 (fuel quality), contain accuracy and completeness levels that must be achieved to ensure that DQOs were met. Reconciliation of DQIs is conducted by performing independent performance checks in the field and/or laboratory, by following reference method QA/QC procedures, and factory-calibrating the instruments prior to use where applicable. The following discussion illustrates that most DQI goals were achieved and, therefore, the measurements data are reliable. A true reconciliation with the DQOs could not be made, however, because the DQOs were based on changes in emissions and fuel quality. Verification results presented in Section 2.0 showed that changes in these values were either statistically insignificant, or lower than the thresholds specified in Table 3-1. Further discussion of this and other data quality results is provided below.

3.2 RECONCILIATION OF DQOS AND DQIS

Tables 3-2 and 3-7 summarize the range of measurements observed in the field and the completeness goals. Completeness is defined as the number of valid determinations expressed as a percent of the total tests or readings conducted. The completeness goals were to obtain 1 hour of valid emissions data for a total of three test runs with contaminated and cleaned fuel, and to collect one fuel properties sample during each test run. Table 3-2 also includes accuracy goals of measurement instruments that are used to compute DQOs for key verification parameters. Measurement accuracy was evaluated using instrument calibrations conducted by manufacturers, field calibrations, reasonableness checks, and/or independent performance checks with a second instrument. The accuracy results for each measurement, and their effects on the DQOs, are detailed in the following subsections.

The following discussion illustrates that the accuracy goals were met or exceeded for each of the measurement variables. However, changes in emissions and fuel properties were very small and, therefore, the data quality objectives were not met, even though the measurement accuracy goals were met.

Table 3-2. Summary of Data Quality Goals and Results

Measurement Variable		Instrument Type or Principle of Detection	Instrument Range	Range Observed in Field	Accuracy			Completeness	
					Goal	**Actual**	**How Verified / Determined**	**Goal**	**Actual**
Fuel Consumption	Fuel Tank Weight	Fairbanks Model IQ-5900C Platform Scale	2,000 lb	600 to 2,000 lb	± 0.1 % of reading	± 0.1 % of reading	Field verification with NIST-traceable standard	100 % for each emissions test	100 %
Ambient Conditions	Ambient Temperature	RTD / Vaisala Model HMP 35A	-50 to 150 °F	82 to 100 ° F	± 0.2 °F	±0.2 °F	Instrument calibration from manufacturer	1-minute readings for all runs	1-minute readings for all runs
	RH	Vaisala Model HMP 35A	0 to 100 % RH	7 to 24 % RH	± 2 % (0 to 90 % RH)	± 2 % (0 to 90 % RH)			
Genset Emissions	NO_X Levels	Chemiluminescent/ Monitor Labs 8840	0 to 5,000 ppmvd	1,150 to 1,275 ppmvd	± 5 % FS[a]	≤ ± 4.9 % FS[b]	Calculated following EPA Reference Method calibrations (before and after each test run)	3 valid runs per condition	4 valid runs per condition
	CO Levels	NDIR / Monitor Labs 8830	0 to 500 ppmvd	70 to 95 ppmvd	± 5 % FS	≤ ± 0.54 % FS			
	CO_2 Levels	NDIR / Nova Model 372WP	0 to 20 %	8.80 to 9.93 %	± 5 % FS	≤ ± 0.71 % FS			
	O_2 Levels	Paramagnetic / California Analytical 100P	0 to 25 %	8.50 to 9.20 %	± 5 % FS	≤ 0.0 % FS			
	CH_4 Levels	GC/FID	0 to160 ppmvd	0 to 3 ppmvd	± 2 % of reading	± 1.8 % of reading			3 valid runs per condition
	THC Levels	FID/California Analytical 300M	0 to 500 ppmvd	60 to 110 ppmvd	± 5 % FS	± 1.0 % FS			
	Stack Gas Flow	Pitot and thermocouple	not specified	28706 to 29410 scfm	± 5 % of reading	± 3.88 % of reading[c]			
	TPM Levels	Gravimetric	not specified	0.026 to 0.040 gr/dscf	± 5 % of reading	± 4.38 % of reading[c]			
	SO_2 Levels	Barium-thorin titration	Detection limit of 0.5 ppmv	< 0.05 ppmv	± 5 % of reading	± 2.0 % of reading[c]			all runs invalidated

[a] Full scale
[b] Contaminated fuel Run 3 drift was 4.9 percent of span. Average NO_X value is the mean of Runs 1, 2, and 3a for contaminated fuel
[c] Total accumulated error (Shigehara et al., 1970)

3.2.1 Emission Measurements

The DQOs for emissions performance (defined as changes in emission rates) were based on anticipated reductions in emission rates (10 percent) and the accuracy goals (DQIs) for each of the measurements used in this determination (including pollutant concentration, exhaust gas flow rate, fuel consumption, and fuel LHV). Table 3-2 and the discussions below show that the DQI goals were met for emission concentration measurements. However, overall uncertainty in emission rate changes are a function of not only measurement accuracy, but also the magnitude of the changes realized through use of the Enviro System. Since no statistically significant changes in emission rates were measured, uncertainty in changes in emission rates could not be evaluated. The following paragraphs discuss the data quality evaluations associated with each variable measured to determine the pollutant emission rates.

3.2.1.1 Exhaust Gas Flow Rate and TPM Emissions

In the Test Plan, discussion of DQI accuracy goals were assessed from a worst case perspective; i.e., it was assumed that individual measurement errors would be additive and would occur at their maximum allowed values. Of course this error accumulation rarely occurs, but a conservative approach is used in the planning stage to help ensure that the instruments and procedures put in place will consistently meet or better data quality goals.

Field and laboratory calibrations showed that the test instrumentation errors were significantly smaller than the method's allowed values as summarized in Table 3-3.

Table 3-3. Results of Additional TPM Emissions Testing QA/QC Checks

QA/QC Check	When Performed/Frequency	Expected or Allowable Result	Results Achieved
Minimum Sample Volume	after each test run	corrected vol. ≥ 31.8 dscf	all acceptable except for Run 1 (31.45 dscf)
Percent Isokinetic Rate	after each test run	80 % ≤ I ≤ 120 %	all acceptable (99 to 101 %)
Analytical Balance Calibration	once before analysis	± 0.0001 g	± 0.0001 g
Dry Gas Meter Calibration	once before and once after testing	± 5 %	± 0.3 %
Sampling Nozzle Calibration	once for each nozzle before testing	± 0.004 in.	± 0.0002 in.
Pitot Tube Dimensional Calibration / Inspection	once before and once after testing	see 40CFR60 Method 2, Section 10.0	Pitot acceptable
Thermocouple Calibration	once after testing	± 1.5 % of average stack temperature recorded during final test run	± 0.7 %

As opposed to the conservative approach used in planning, anormally distributed errors rarely compound additively. A more realistic approach is to estimate a "three sigma" error as the square root of the sum of the errors squared (Shigehara et al., 1970). Table 3-4 illustrates this estimation for the exhaust gas flow and particulate emission rates.

Table 3-4. Exhaust Gas Flow and Particulate Emission Rate Error Propagation

Contributing Parameter	As-Found Error, %
Atmospheric Station Pressure (in. Hg)	± 0.35
Pitot Coefficient (dimensionless)	± 0.98
Stack Gas Moisture Content (proportion)	± 0.50
Stack Gas Molecular Weight (lb/lb mol)	± 0.25
Stack Gas Temperature (^{o}F)	± 0.70
Stack Static Pressure (in. H_2O)	± 1.28
Velocity Pressure (in. H_2O)	± 3.40
$\sqrt{\left(\sum err^2\right)}$ **(Exh. Gas Flow, dscf/hr or lb.mol/hr)**	**± 3.88**
Particulate Catch (g)	± 0.42
Sample Volume (dscf)	± 2.00
$\sqrt{\left(\sum err^2\right)}$ **(Particulate Emissions, lb/hr)**	**± 4.39**

The 3.88 percent error found during field testing for exhaust gas flow rate is less than the 5 percent error assumed in the Test Plan. Compounding of the particulate weight and sample volume errors with the exhaust gas flow rate error yields a total estimated TPM emission rate error of 4.39 percent. This is also less than the 5 percent error assumed in the Test Plan.

3.2.1.2 Gaseous Pollutant Emissions

EPA Reference Methods were used to quantify emission rates of criteria pollutants and GHGs. The Reference Methods specify the sampling and calibration procedures, and the data quality checks that must be followed. For the instrumental methods (CO, CO_2, NO_X, O_2, and THCs), these methods ensure that run-specific quantification of instrument and sampling system drift and accuracy occurred for each emissions test. The DQIs specified in the Test Plan were the sampling system bias determinations conducted before and after each test. The methods specify a system bias of ± 5 percent of span or less for each of the pollutants.

These calibrations are conducted by introducing the zero gas and an upscale gas for each parameter into the sampling system at the probe and recording the system response. Sampling system bias was then calculated by comparing the system responses to the analyzer calibration errors determined at the beginning of each day (see discussion below). The system bias was recorded and had to be within 5 percent of instrument span for the system to be acceptable for testing. Measured pollutant concentrations were corrected for system bias in accordance with the reference methods. As shown in Table 3-2, the system bias checks for CO, CO_2, NO_X, O_2, and THCs were less than 0.5, 0.7, 4.9, 0.0, and 1.0 percent, respectively.

Following Method 6C specification criteria, the system bias checks were conducted before and after each test period. In some cases where these criteria were exceeded, the runs were invalidated and repeated. The pre- and post-test system bias calibrations were also used to calculate analyzer drift for each pollutant analyzer. All drift checks for each of the pollutants were well within the specified 3 percent of instrument span for all valid runs. In conclusion, the system bias goals and drift goals were met for all pollutants during validated test periods.

Other QA/QC checks conducted during the verification were analyzer calibration error tests. These were conducted at the beginning of each day of testing. During these calibrations, a suite of calibration gases was introduced directly to each analyzer and the analyzer responses were recorded. EPA Protocol 1 calibration gases were used for these calibrations. Three gases were used for NO_X, CO_2, and O_2, including: 0, 40 to 60 percent of span, and 80 to 100 percent of span. Four gases were used for CO and THC including: 0 and approximately 30, 60, and 90 percent of span. The analyzer calibration errors for all gases other than THC were below the allowable levels (2 percent of instrument span) as shown in Table 3-5. THC error was slightly higher during one calibration (-2.2 percent), but this was not expected to affect test results (note that Reference Method 25A for THC does not specify this additional QA/QC check). Results of each of the sampling system calibrations, including bias and drift checks, are presented in Appendix A-1.

Table 3-5. Results of Additional Gaseous Pollutant Emissions Testing QA/QC Checks

Parameter	QA/QC Check	When Performed/Frequency	Expected or Allowable Result	Maximum Result Measured During Tests (%)
NO_X	Analyzer interference check	once before testing begins	± 2 % of analyzer span or less	0.00
	NO_2 converter efficiency	once before testing begins	98 % efficiency or greater	98.7
CO, CO_2, NO_X, O_2, THCs	Analyzer calibration error test	daily before testing	± 2 % of analyzer span or less	0.7 % for CO -0.1 % for CO_2 0.1 % for NO_X 0.2 % for O_2 -2.2 % for THCs

Two additional QA/QC checks were performed to better quantify the NO_X data quality. An interference test was conducted on the NO_X analyzer once before the testing started to confirm that the presence of other pollutants in the exhaust gas did not interfere with the accuracy of the NO_X analyzer. This test was conducted by injecting the following calibration gases into the analyzer and recording the response of the NO_X analyzer, which must be 0.0 ± 2 percent of span:

- CO – 3980 ppm in balance nitrogen (N_2)
- CO_2 – 8.01 percent in N_2
- O_2 – 8.03 percent in N_2
- SO_2 – 97.8 ppm in N_2

As shown in Table 3-5, no value greater than zero was observed, so the analyzer passed the test.

The NO_X analyzer converts any NO_2 present in the gas stream to NO prior to gas analysis. The second QA/QC check consisted of determining NO_2 converter efficiency prior to beginning emissions testing. This was done by introducing a mixture of mid-level calibration gas and air to the analyzer. The analyzer response was recorded every minute for 30 minutes. If the NO_2 to NO conversion was 100 percent efficient, the response would have been stable at the highest peak value observed. If the response decreased by more than 2 percent from the peak value observed during the 30-minute test period, the converter would have been judged faulty and the analyzer would have needed repair or replacement prior to testing. As shown in Table 3-5, the converter efficiency was measured at 98.7 percent and was above the efficiency level required.

As shown in Table 3-2, the CH_4 analyses reported a DQI of approximately 1.8 percent accuracy. The GC/FID used for CH_4 analyses was fitted with a linear calibration curve developed using analyzer calibrations to four levels of NIST-traceable calibration standards. The calibration curve was then tested using a fifth calibration standard (an audit sample). Accuracy was then defined as the difference between the audit sample and the instrument response, in this case 1.8 percent.

As reported in Section 2.3.1, the Method 6 testing for SO_2 emissions was invalidated due to questionable results (all were below the detection limit of approximately 0.5 ppmv). Following Method 6, several QA/QC checks were conducted in the field and laboratory, and acceptable results were reported for all checks. These included:

- Pre- and post-test dry gas meter calibrations met the method specification
- Sampling train leak checks before and after each test run were all acceptable
- The barium standard solution was standardized to a normality of 0.008247
- Replicate titrations were conducted on each sample, and all were within the specified difference of ± 1 percent

Since all of the method QC criteria were either met or exceeded, it is unclear why test results were non-detectable when small levels of SO_2 were expected. For this reason, the GHG Center invalidated these results and relied on the sulfur content in the fuel to calculate theoretical SO_2 emissions.

3.2.1.3 Propagation of Errors for Emission Rate Measurements

Emission rate determinations for all pollutants in terms of $lb_{pollutant}/lb_{fuel}$ and $lb_{pollutant}/10^6$Btu require the following measurements:

- Stack gas flow rate, lb.mol/hr (for gases) or dscf/hr (for particulate)
- Pollutant concentration, ppmvd (for gases) or lb/dscf (for particulate)
- Fuel mass consumption rate, lb/hr
- Fuel LHV, Btu/lb

Table 3-6 shows how errors in each of these measurements compounded to yield an estimate of the total measurement error.

Table 3-6. Particulate and Gaseous Pollutant Emission Rate Error Propagation

Contributing Parameter	**As-Found Error, %**
Fuel Mass Consumption Rate (lb/hr)	± 0.03
LHV (Btu/lb)	± 0.12
TPM Emission Rate (lb/hr)	± 4.39
$\sqrt{\left(\sum err^2\right)}$ **(Particulate lb/10^6Btu)**	**± 4.39**
Exhaust Gas Flow Rate (lb.mol/hr)	± 3.88
Fuel Mass Consumption Rate (lb/hr)	± 0.03
Gaseous Pollutant Concentration (ppmvd)	± 1.00[a]
LHV (Btu/lb)	± 0.12
$\sqrt{\left(\sum err^2\right)}$ **(Gaseous Pollutant lb/10^6Btu))**	**± 4.01**

[a] Average uncertainty for all pollutant gas measurements was < 1.00 percent

The Test Plan included an example error propagation for NO_X emissions. The analysis concluded that given the method's maximum allowed uncertainty for each contributing parameter, the expected error would be 9.6 percent of the individual NO_X lb/10^6Btu determination. Expected errors for particulate and other gas emissions are similar. The 4.39 and 4.01 percent errors (for particulate and gaseous emissions, respectively) cited in Table 3-6 are less than the expected uncertainties and meet the Test Plan objectives.

3.2.2 Fuel Quality Performance

Fuel cleaning performance was based on the percent change in fuel properties between contaminated and cleaned fuels. Similar to emissions performance, the DQOs listed in Table 3-1 were therefore developed based on anticipated changes in fuel properties. The Test Plan specified a set of ASTM fuel test methods to measure the fuel properties of interest, and each method for each fuel property had an associated error estimate. These error estimates were the DQIs used to develop the DQOs. The DQO for the percent change in each fuel property was therefore based on the estimated measurement error (DQI) for that property, and expected differences in the properties for contaminated and treated fuels.

Table 3-7 summarizes the DQIs for each of the fuel property measurements. Table 3-7 includes the expected or allowable result (based on anticipated levels of change), the range of measurements observed during the testing, and the actual measurement error (DQIs) for each measurement type.

The percent difference between contaminated and cleaned fuel properties must be larger than the values in Table 3-1 to draw valid conclusions. For example, LHV for cleaned fuel must be at least 1.05 percent different from LHV for contaminated fuel to conclude that JCH's technology has an effect.

For all fuel quality analyses, the GHG Center used industry-standard methods developed by ASTM, and believes the QA guidelines required by those standards provide a sound, defensible, and industry-accepted way of ensuring that good quality data were collected. Further, these methods provided an industry-accepted means by which data quality was determined and reported and, thus, are used to judge how close SRI came to achieving its original DQOs for fuel quality.

Table 3-7. Summary of Fuel Properties Data Quality Indicators

Measurement Variable	Calibration - QA/QC Check	When Performed / Frequency	Expected or Allowable Result	Range Observed in Field	Results Achieved (DQIs)
Mass Consumption	Platform scale NIST calibration	Once before testing begins	± 0.1 % of reading	85.2 – 90.9 lb/hr	± 0.0 %
	*Scale field verification	Once before testing begins	± 0.1 % of reading		+ 0.03 % average
		Once after testing ends	± 0.1 % of reading		- 0.04 % average
D-4809 LHV	*Benzoic acid SRM analysis	Once per shift	11308.79 ± 16.63 Btu/lb	18281 - 18373 Btu/lb	11372.4 + 8.1, - 13.4 Btu/lb[a]
	Duplicate sample analysis	Once per shift	± 50 Btu		± 19.3 Btu, average
	Balance verification	Once per sample	± 0.1 mg of Class A mass standard		± 0.1 mg
	Equipment calibrations	Within 6 months	Varies; see Section 2.4	34.1 - 34.2 °API	Satisfactory
D-4052 °API	*Water SRM analysis	Once per shift	0.9999 ± 0.0004		1.0000 ± 0.0000
	*Heptane SRM analysis	Once per shift	0.6885 ± 0.0002		0.6884 ± 0.0001
D-93 Flash Point	*Anisole analysis	Once per shift	117 ± 2 °F	163 - 167 °F	117 + 1 °F
	n-Decane analysis	Within 6 months	127 ± 4 °F		131 °F
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Satisfactory
D-2709 Water and Sediment	Comparison of the two centrifuge tube readings	Once per sample	± 1 scale division	0.005 - 0.150 vol. %	Satisfactory
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Satisfactory
	*Duplicate sample analysis	Once for each Run 2, contaminated and cleaned fuel	at 3% water conc., duplicates must be within ± 0.4%		Satisfactory; largest difference was ± 0.04 %
D-482 Ash	Reference oil analysis	Once per shift	1.675 % (mass) ± 0.148 %	none detected	1.675 + 0.041, - 0.046 %
	Oven temperature record	Once per sample	775 ± 25°C		Not available[b]
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Satisfactory
	Balance verification	Once per sample	± 0.1 mg of Class A mass standard		Not available[c]
	*Duplicate sample analysis	Once for each Run 2, contaminated and cleaned fuel	Duplicates must be within 0.18 ± 0.024 mass %		Satisfactory; all results were below the method detection limit

(continued)

Table 3-7. Summary of Fuel Properties Data Quality Indicators (continued)

Measurement Variable	Calibration / QA/QC Check	When Performed / Frequency	Expected or Allowable Result	Range Observed in Field	Results Achieved (DQIs)
D-6217 Particulate	Tare filter analysis	Once per sample	< 0.5 mg weight gain	3.8 - 24.3 mg/L	Not available[d]
	Balance verification	Once per sample	± 0.1 mg of Class A mass standard		± 0.1 mg, average
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Satisfactory
	*Duplicate sample analysis	Once for each Run 2, contaminated and cleaned fuel	Duplicates must be within 10 ± 3.6 mg/L		At 10.4, duplicate was - 0.8 mg/L
D-613 Cetane Number	*Consensus standard analysis	Once per shift	41.6 ± 0.9 cetane numbers	46.7 - 48.4	41.6 ± 0.5 cetane numbers
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Satisfactory
D-2622 Sulfur	* Standard analysis	Once per shift	± 0.002 wt% at expected conc.	0.041 – 0.043 wt.%	± 0.0015 wt%
D-381 Gums and Resins	Equipment calibrations	Within 6 months	Varies; see Section 2.4	39.1 - 79.1 mg/100 mL	Steam jet calibration within 8 months; others are satisfactory
	Balance verification	Once per sample	± 0.1 mg of Class A mass standard		± 0.1 mg, average
	*Duplicate sample analysis	Once for each Run 2, contaminated and cleaned fuel	Duplicates must be within 20 ± 8.5 mg/L		At 79.1, duplicate was -8.0; at 39.4, duplicate was -0.3 mg/L
D-6079 Lubricity	*Cat 1-H oil analysis	Every 20 samples	0.29 ± 0.08 mm WSD @ 25 °C; 0.41 ± 0.08 mm WSD @ 60 °C	0.345 - 0.410 mm WSD @ 60°C	Satisfactory: 0.38 mm WSD @ 60 °C[e]
	*Isopar solvent/oil analysis	Every 20 samples	0.58 ± 0.08 mm WSD @ 25 °C; 0.62 ± 0.08 mm WSD @ 60 °C		Satisfactory: 0.62 mm WSD @ 60 °C[e]
	Cat 1-H and Isopar duplicate analyses	Every 20 samples	Duplicate results ± 0.08 mm WSD @ 25 and 60 °C		Cat 1H ± 0.005, Isopar ± 0.01 mm WSD @ 60 °C
	Equipment calibrations	Within 6 months	Varies; see Section 2.4		Calibration within 8 months

* Results from these QC checks were used as the primary DQI goals

[a] Certified benzoic acid LHV was 11,373 Btu/lb

[b] Lab oversight. Logging of the oven temperature profile is a non-standard procedure

[c] Although the SwRI formal report did not include the balance verification, it did include the NIST-traceable calibration from May 5, 2001

[d] SwRI did not submit blank filter analyses with the report

[e] Lubricity results reported for 60 °C only

Each ASTM method specified a different combination of QA/QC checks, calibrations, reference material analyses, duplicate sample analyses, and others as indicated. ASTM states that, if each of these QA/QC checks is performed according to the method, the corresponding sample analysis has a specific numerical reproducibility. ASTM further states that method accuracy may be derived from these reproducibility results, and has justified this through extensive inter-laboratory round-robin testing for each method.

The Test Plan approach adopted for this verification was that the DQI goals must be met, and results of specific pre-defined QA/QC checks (e.g., duplicate sample analysis, comparisons with standard reference methods) were used to determine if the DQIs goals were achieved. The data in Table 3-7 clearly show that all of the DQIs were met. A true reconciliation with the DQOs was based on minimum changes in fuel properties. The DQI data show that SwRI's analyses exceeded the methods' requirements for reproducibility. This means that measurement uncertainties were less than those assumed in the Test Plan to develop the DQO. The results for most fuel properties, however, show no statistically significant difference between contaminated and cleaned fuel. For those that were statistically significant, the differences were less than the minimum assumed in the Test Plan. Appendices B-1 and B-2 provide additional detail regarding sample handling, and quality control checks for each analysis. Completeness goals for fuel quality analyses were to obtain three valid samples for both contaminated and treated fuel for each parameter. Completeness goals were met.

3.2.3 Ambient Measurements

Ambient temperature and RH at the test site were monitored throughout the test periods. The instruments used are identified in Table 3-2 along with instrument ranges, data quality goals, and data quality achieved. A Vaisala Model 35HMP probe was used to monitor both temperature and RH. The probe was factory calibrated prior to the verification testing using reference materials traceable to NIST standards. Results of these calibrations indicate that the ± 2 ^{o}F accuracy goal for temperature and ± 3 percent for RH were met.

3.3 AUDITS

An audit of data quality (ADQ) was conducted by the GHG Center's QA Manager. To ensure that data quality objectives could be met, a pre-test audit was also conducted to review procedures and experimental design during Test Plan preparation. The ADQ confirmed that the data handling system and calculations conducted after collecting field data were correct. This was done by selecting a random sample of data and tracing all of the calculations through the data processing sequence for each of the primary verification parameters.

4.0 REFERENCES

American Society for Testing and Materials, *ASTM Specification D 975 - 98b, Standard Specification for Diesel Fuel Oils*, Baltimore, MD, 1999.

Cummins Engine Company, Inc., *Operation and Maintenance Manual - C Series Engines*, Cummins P/N 3810354, Louisville, KY, 1991a.

Cummins Engine Company, Inc., *Troubleshooting and Repair Manual – C Series Engines*, Cummins P/N 3666003, Louisville, KY, 1991b.

Electrical Generating Systems Association (EGSA), *Quarterly Generator Shipment Survey for the Quarter Ended December 31, 2000*, Boca Raton, FL, March 14, 2001.

Hastings Filters, *Performance Testing: Fuel (SAE J905)*, Data Sheet, Kearney, NE, 2001.

Onan Corporation, *DGFC 60 Hz Diesel Generator Set*, Form #S-1131b, Minneapolis, MN, 2001.

Onan Corporation, *EPA Tier 1 Exhaust Emission Compliance Statement, 200DGFC 60 Hz Diesel Generator Set*, Form #EPA1CS-1018A, EDS-177A, Minneapolis, MN, 1999.

Shigehara, R.T., Todd, W.F., and Smith, W.S., *Significance of Errors in Stack Sampling Measurements*, presented at the annual meeting of the Air Pollution Control Association, St. Louis, MO, 1970.

Southern Research Institute (SRI). *Test and Quality Assurance Plan, JCH Fuel Solutions, Inc., Enviro Automated Fuel Cleaning and Maintenance System*, Research Triangle Park, NC, July 2001.

U.S. Environmental Protection Agency. Code of Federal Regulations, Title 40, Part 60 (Appendix A), *Reference Methods for Determination of Emissions Rates*, Washington, DC, 1999.

U.S. Environmental Protection Agency. *Compilation of Air Pollutant Emission Factors, Fifth Edition, Volume 1: Stationary Point and Area Sources*, AP-42 (NTIS PB95-196028), Office of Air Quality Planning and Standards, Research Triangle Park, NC, January 1995.

APPENDIX A

Table A-1 Analyzer Spans and Calibration Gas Values A-2
Table A-2 Summary of System Bias and Drift Checks A-2

Table A-1. Analyzer Spans and Calibration Gas Values

Analyzer	Span	Units	Cal. Gas	Units
NO_X	5000	ppmv	2447	ppmv
CO_2	14	%	12.02	%
O_2	25	%	11.96	%
CO	408	ppmv	87.2	ppmv
THCs	500	ppmv	85.0	ppmv

Table A-2. Summary of System Bias and Drift Checks

	Run:	Initial Calibration	1		2		3		3a	
Analyzer, Gas	**QA/QC Check**		**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
NO_X , Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span			0.00		0.00		0.00		0.00
NO_X , High	System Response, ppm	2447	2447	2447	2447	2447	2447	2200	2200	2200
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	-4.94	-4.94	-4.94
	Drift, % of span			0.00		0.00		-4.94		0.00
CO_2 , Zero	System Response, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span			0.00		0.00		0.00		0.00
CO_2 , High	System Response, %	12.00	11.90	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	System Bias, % of span	-0.14	-0.86	-0.14	-0.14	-0.14	-0.14	-0.14	-0.14	-0.14
	Drift, % of span			0.71		0.00		0.00		0.00
O_2 , Zero	System Response, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span			0.00		0.00		0.00		0.00
O_2 , Mid	System Response, %	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	System Bias, % of span	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	Drift, % of span			0.00		0.00		0.00		0.00
CO, Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span			0.00		0.00		0.00		0.00
CO, Low	System Response, ppm	85.00	87.00	87.00	87.00	87.00	87.00	87.60	87.60	86.90
	System Bias, % of span	-0.54	-0.05	-0.05	-0.05	-0.05	-0.05	0.10	0.10	-0.07
	Drift, % of span			0.00		0.00		0.15		-0.17
THCs, Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span			0.00		0.00		0.00		0.00
THCs, Low	System Response, ppm	85.00	85.00	85.00	82.00	87.00	87.00	85.00	260.00[a]	255.00[a]
	System Bias, % of span	0.00	0.00	0.00	-0.60	0.40	0.40	0.00	-0.20	-1.20
	Drift, % of span			0.00		1.00		-0.40		-1.00

(continued)

Table A-2. Summary of System Bias and Drift Checks (continued)

	Run:	**4**		**5**		**6**		**6a**	
Analyzer, Gas	**QA/QC Check**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
NO_X , Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
NO_X , High	System Response, ppm	2447	2447	2447	2447	2447	2447	2447	2447
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
CO_2 , Zero	System Response, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
CO_2 , High	System Response, %	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	System Bias, % of span	-0.14	-0.14	-0.14	-0.14	-0.14	-0.14	-0.14	-0.14
	Drift, % of span		0.00		0.00		0.00		0.00
O_2 , Zero	System Response, %	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
O_2 , Mid	System Response, %	12.00	12.00	12.00	12.00	12.00	12.00	12.00	12.00
	System Bias, % of span	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	Drift, % of span		0.00		0.00		0.00		0.00
CO, Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
CO, Low	System Response, ppm	86.00	87.00	86.00	87.00	86.00	87.00	86.00	87.00
	System Bias, % of span	-0.29	-0.05	-0.29	-0.05	-0.29	-0.05	-0.29	-0.05
	Drift, % of span		0.25		0.25		0.25		0.25
THCs, Zero	System Response, ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	System Bias, % of span	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Drift, % of span		0.00		0.00		0.00		0.00
THCs, Low	System Response, ppm	85.00	86.00	86.00	82.50	85.00	83.00	87.00	87.50
	System Bias, % of span	0.00	0.20	0.20	-0.50	0.00	-0.40	0.40	0.50
	Drift, % of span		0.20		-0.70		-0.40		0.10

[a] THC Run 3a Calibration Gas was 261.0 ppm

APPENDIX B

Appendix B-1 SwRI Sample Handling Procedures..B-2
Appendix B-2 SwRI Fuel Analysis QA/QC Procedure..B-4

Appendix B-1. SwRI Sample Handling Procedures

August 29, 2001

Dear Mr. Richards:

We received groups of 2.5 liter aluminum cans labeled as follows, accompanied by a chain of custody form. Instructions on the chain of custody form were to combine these samples into containers to be used for the following tests. We were also instructed to note which cans had the locking ring removed. Data was handwritten on the chain of custody form by our technical specialist. He handled each group of samples individually, so that all the containers were not open at one time, but only those containers for the current sample group. The combined samples were given sample ID numbers at this time, and instructions to "Shake well before sampling for each test" were inscribed on the top of each combined sample. The combined samples were put into 2-gallon translucent plastic jugs with handles, making them easy to shake and to pour out for individual tests. These containers still contain sample, and are currently being stored in our cold box to slow deterioration or microbial growth.

Can labels action sample ID

CLN20
CLN22 combined for Run 1 clean fuel 17043

CLN 23
CLN25
CLN26 combined for Run 2 clean fuel 17044

CLN27
CLN29 combined for Run 3 clean fuel 17045

PT02
PT03 combined for "as received fuel" 17046 (open)

CONT01
CONT03 combined for Run 1 contaminated 17047 (open)

CONT04
CONT06
CONT07 combined for Run 2 contaminated 17048

CONT08
CONT10 combined for Run 2 contaminated 17049

The samples 17044 and 17048 contain more fuel than do the other samples, in keeping with their being the 3-container samples.

(continued)

Note in the data report, that many of the test show consistent data for the "as received" and the contaminated fuels, with consistently different data on the clean fuels. These parameters include the sulfur content, which is 0.0411 to 0.0413 in the dirty fuel, while the clean is 0.0422 to 0.0430. The carbon/hydrogen contents are very consistent across the dirty fuels, and show a distinct higher hydrogen, lower carbon value in the clean fuels. All of the gross heats of combustion for the dirty fuels are above 19500, while the clean fuels are all below 19500. The Cetane numbers of the dirty and as received fuels are all 46.7, while the clean fuel shows a consistently higher value, from 47.8 to 48.4. Even the density of the samples is consistent, with the clean samples showing a very slightly heavier (0.8537) value than the dirty and as received samples (0.8535 to 0.8536). Gums and resins also remain consistent among the groups, with values of 39 to 47 for the as received and dirty, and values of 63 to 79.1 for the clean.

These basic fuel properties are consistent with a dirty fuel of a consistent C/H/S make-up which, in the clean fuels, has been dosed with a small amount of sulfur containing material, enough to add about 10 ppm sulfur to those samples. This additive is enough to affect some of the basic fuel properties in a detectable way. The values of water and sediment, or particulate contamination, can easily vary by differences in filtration characteristics of the particular samples we obtained, but the consistent change in basic fuel properties is consistent with an added product containing sulfur. If there are any other identifiable components in the additive, we can further verify the sample identifications by measuring those components. If the product contains sulfur, this may be sufficient.

Please let me know if you have any further questions, or if there is additional information we can provide. We Fed-Exed another copy of the report to you today.

Thanks,

Karen Kohl
Petroleum Products Research Dept.
(210)522-2071 FAX (210)522-4544
kkohl@swri.org

Appendix B-2. SwRI Fuel Analysis QA/QC Procedure

QA Supplement

August 13, 2001

ASTM D 4809 Lower Heating Value

QA documents include control chart for benzoic acid, weight challenge information from the balance, calibration certificate from the balance, calibration certificate from the thermistor, and label from the reference benzoic acid from the instrument manufacturer.

Also included in this section are control charts for the sulfur and carbon-hydrogen analyses used in the heat-of-combustion calculation.

No unusual behavior was observed during testing. The data for this test are the average of two results. In the report table, the two individual data points are shown, followed by the average value underlined.

ASTM D 4052 Density, API Gravity, and Specific Gravity

QA documents consist of a copy of a heptane label and the control charts for heptane and water for the instrument used in the test. The individual daily values for verification of the system are detailed and dated in the table at the top of the control chart. No unusual behavior was observed during testing. All three data points are available from the equipment at the time of analysis, so all three values are shown in the report table.

ASTM D 93 Flash Point

QA documents include the control chart for Anisole, our daily control reference material, a calibration certificate on the flash point analyzer, including temperature control, labels from our Anisole and our decane. The test value for the decane was 131 °F, which is within the allowed 52.8±2.3 °C (122.9 to 131.2 °F). No unusual behavior was observed during testing.

ASTM D 2709 Water and Sediment

QA document consists of the calibration verification certificate on the centrifuge. As no reference material exists for this test, no control chart is available. Since the test does not involve two tubes of sample, the testing was performed in duplicate, with both results being reported. The test results were within the reproducibility of the ASTM test method, which is 0.041 volume percent. The sample labeled Run 1 Clean fuel showed a clear bottom layer with a black interface between that layer and the brown fuel layer. The sample labeled As Received fuel appeared as a tiny black interface with a tiny clear layer under it. The sampled labeled as Run 3 Contaminated fuel appeared to be a very small solid black residue.

(continued)

Appendix B-2. SwRI Fuel Analysis QA/QC Procedure (continued)

ASTM D 482 Ash

QA documents consist of the control chart for the test, the calibration certificate for the furnace used in the procedure, and the calibration certificate for the balance used in the procedure. Weight verification was performed using Ainsworth weight 100.0005 g, serial number 4254-S. Duplicate analyses were performed on two of the samples. All results were < 0.001 mass percent, so all were within expected precision. The only measurable weights occurred with the Run 2 Contaminated fuel, where weights of 0.0002 and 0.0003 g were observed. These would have calculated to 0.0002 and 0.0003 mass percent. All other values were 0.0000 g weight changes. No unusual behavior was observed during testing.

ASTM D 6217 Particulate Contamination

QA documents include verification certifications for the timer, the thermometer, and the balance used in the procedure. A sheet for weight challenge to the balance is also included, along with the certificate for the weights used. Duplicate analyses were performed on two of the samples. These data were within the expected precision for the procedure of within 2.19 at the 10.4 level, and within 1.63 at the 5.8 mg/1000 mL level. The filters have been retained in case you are interested in examining them later. Appearances of the residue varied, and descriptions of each are included below. The duplicate filters were identical in appearance. All of the materials were difficult and slow to filter compared with the usual fresh diesel #2 samples we receive.

17043	Clean Run 1 - Solid dark brown stain
17044	Clean Run 2 - Solid medium brown with small amount of debris particles
17045	Clean Run 3 - Solid dark brown stain with small amount of debris
17046	As Received Fuel - Medium brown deposit with some powder texture and some flaking
17047	Contaminated 1 - Very dark brown deposit with dried mud pattern on filter
17048	Contaminated 2 - Medium brown deposit with small areas showing dried mud pattern
17049	Contaminated 3 - Dark brown film with flaking

ASTM D 613 Cetane Number

QA documents include a control chart for the engine, engine maintenance documents, and calibration certifications for the thermometers and timers used with the engines. The consensus value for the check fuel used is 41.3. The test value for the shift where the test samples were run was 41.6. No unusual behavior was observed during testing.

(continued)

Appendix B-2. SwRI Fuel Analysis QA/QC Procedure (continued)

ASTM D 381 Gums and Resins

QA documents include a weight verification data sheet and calibration certificates for the temperature readout, the gum block, and the balance used. Since no reference material is available for this test, no control chart is available. Duplicate analyses were performed on two of the samples. Precision for the repeat data was within the expected repeatability for an aviation turbine fuel for the test (i.e., 79 ± 20.3 mg/100 mL and 39 ± 10.3 mg/100 mL). No unusual behavior was observed during testing.

ASTM D 6079 Lubricity

QA documents include the control charts for the Isopar solvent and the Cat 1-H oil analyses performed every 20 samples, and the certificate of calibration for the equipment. The duplicate Isopar analyses for 8/1/01 were 0.620 and 0.630 mm, and for the Cat 1-H on 8/1/01, 0.380 and 0.375 mm.

Descriptions of each wear scar are as follows:

17043	evenly abraded oval
17044	oval inside an oval
17045	oval inside an oval
17046	oval inside an oval
17047	hourglass-shaped scar inside lightly worn oval
17048	two circular scars; one more abraded inside the outer, less worn scar
17049	hourglass-shaped, lightly abraded scar inside lightly worn oval