SRI/USEPA-GHG-VR-11
September 2001

Environmental Technology Verification Report

MIRATECH Corporation
GECO^{TM} 3001 Air/Fuel Ratio Controller (Manufactured by Woodward Governor Company)

Prepared by:

Greenhouse Gas Technology Center
Southern Research Institute

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

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Greenhouse Gas Technology Center

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

Environmental Technology Verification Report

MIRATECH Corporation
GECO™ 3001 Air/Fuel Ratio Controller

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ACKNOWLEDGMENTS

The Greenhouse Gas Technology Center wishes to thank personnel at the natural gas transmission station where testing was conducted for hosting this verification. The name and location of the host site are omitted at their request. 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.

ACRONYMS/ABBREVIATIONS

acf	actual cubic feet
ADQ	audit of data quality
BHp	brake horsepower
BHp-hr	brake horsepower-hour
Btu/ft^3	British thermal units per cubic foot
Btu/hr	British thermal units per hour
CEM	Continuous Emissions Monitoring systems
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
cSt	centistokes
DP	differential pressure
DQI	data quality indicator goal
DQO	data quality objective
dscf/MMBtu	dry standard cubic feet per million British thermal units
ECU	engine control unit
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification program
^oF	degrees Fahrenheit
FID	flame ionization detector
FS	full scale
ft-lbs	foot-pounds
ft^2	square feet
ft^3/min	cubic feet per minute
g	grams
g/BHp-hr	grams per brake horsepower-hour
GC	gas chromatograph
GHG Center	Greenhouse Gas Technology Center
GHGs	greenhouse gases
HI	heat input
H_2S	hydrogen sulfide
hr	hours
in.	inches
lb	pounds
lb/dscf	pounds per dry standard cubic foot
lb/hr	pounds per hour
lb/kW-hr	pounds per kilowatt-hour
LHV	fuel lower heating value
MAG	magnetic pickup engine speed
MAP	manifold air pressure
MAT	manifold air temperature
MIRATECH	MIRATECH Corporation
N_2	nitrogen
NDIR	nondispersive infrared spectroscopy
NIST	National Institute for Standards and Technology

(continued)

ACRONYMS/ABBREVIATIONS
(continued)

NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
O_2	oxygen
O_3	ozone
ORD	EPA's Office of Research and Development
Phi	air/fuel ratio
ppm	parts per million
ppmv	parts per million by volume
ppmvd	parts per million by volume dry
psia	pounds per square inch absolute
psig	pounds per square inch gauge
QA/QC	Quality Assurance/Quality Control
QMP	Quality Management Plan
RH	relative humidity
rpm	revolutions per minute
RTD	resistance temperature detector
scfm	standard cubic feet per minute
SRI	Southern Research Institute
TCD	thermal conductivity detector
TCS	Technical Compressor Services, Inc.
temp.	temperature
Test Plan	Test and Quality Assurance Plan
THC	total hydrocarbon
TSA	technical systems audit
UEGO	universal exhaust gas oxygen
VOCs	volatile organic compounds

1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (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 several verification organizations operating under ETV. The GHG Center is managed by the U.S. 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 Test Plans (Test Plans) 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 GHG Center's Oil and Gas Industry Stakeholder Group offers advice on technologies that have the potential to improve operation and efficiency of natural gas transmission activities. They also assist in selecting verification factors and provide guidance to ensure that the performance evaluation is based on recognized and reliable field measurement and data analysis procedures.

In the natural gas industry, transmission pipeline operators use internal combustion (IC) gas-fired engines to provide the mechanical energy needed to drive pipeline gas compressors. As such, owners and operators of compressor stations are interested in the performance of these engines with regard to engine fuel consumption, reliability, availability, and emissions. MIRATECH Corporation has developed a technology that has the potential to improve engine performance and has committed to participate in a verification of this technology. MIRATECH's GECO 3001 Air/Fuel Ratio Controller (Controller) is designed to balance lean-burn engine fuel mixtures and improve fuel economy, maintenance requirements, and emissions performance.

A verification test was carried out at a natural gas processing station in the southern U.S. This station employs several reciprocating engines in support of its gas processing and transmission activities. The design of the Controller is applicable to two of the lean-burn engines at this facility, and these units were used for evaluation of the technology.

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, MIRATECH Corporation GECO™ 3001Air/Fuel Ratio Controller* (SRI 2001). It can be downloaded from the GHG Center's Web site (www.sri-rtp.com). The Test Plan describes the rationale for the experimental design, the testing methods and instrument calibration procedures planned for use, and the specific QA/QC goals and procedures. The Test Plan was reviewed and revised based on comments received from MIRATECH, selected members of the GHG Center's stakeholder groups, and the EPA Quality Assurance Team. The Test Plan meets the requirements of the GHG Center's Quality Management Plan (QMP), and thereby satisfies ETV QMP requirements. In some cases, deviations from the Test Plan were required. These deviations and the alternative procedures selected for use are discussed in this report.

The remaining discussion in this section describes the Controller 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. Section 4, provided by MIRATECH, provides additional information regarding the Controller. Information provided in Section 4 has not been independently verified by the GHG Center.

1.2 GECO™ 3001 AIR/FUEL RATIO CONTROLLER DESCRIPTION

As engine operations and conditions change over time, engine performance and emissions can be affected by these changes. Variables such as engine speed and load, fuel gas quality, and ambient air conditions can have significant effects on engine operation and the air/fuel ratio in the cylinders. The Controller is an air/fuel ratio controller designed to improve performance of natural-gas-fired, four-cycle, lean-burn reciprocating engines by optimizing and stabilizing the air/fuel ratio over a range of engine operations and conditions.

This device was first introduced in 1997, and currently there are about 25 units in operation in the gas transmission industry. The technology uses a closed-loop feedback system to continuously optimize the air/fuel mixture introduced to the engine. This system provides the potential to improve engine fuel consumption and reduce engine emissions, particularly when changes in engine load, fuel quality, or ambient conditions occur. Optimized and stabilized air/fuel ratios may also improve engine performance, reduce lubrication oil degradation, and help minimize wear to major engine components, thereby reducing engine maintenance. The Controller can be configured to operate based on engine exhaust oxygen (O_2) feedback, or generator output (kW) feedback (for engines used to drive electrical generators). Using either approach, the controller monitors the O_2 or kW sensor inputs and controls the air-to-fuel ratio generated by the carburetor. This verification test addressed only the exhaust O_2 feedback system because the test engine was not used to drive a generator.

The Controller uses relationships between excess air in the combustion chamber, measured exhaust gas O_2 concentrations, and engine emissions to calculate optimum air/fuel ratios at various engine loads. Typical relationships between excess air and emissions in lean-burn, gas-fired engines are illustrated in Figure 1-1. Using exhaust gas O_2, intake manifold air pressure (MAP), intake manifold air temperature (MAT), and magnetic pickup engine speed (MAG) as primary indicators of engine operation, the Controller continuously adjusts air/fuel ratios in the engine by adjusting and controlling fuel flow to the carburetor. Fuel flow is adjusted using a full-authority fuel valve that is supplied by the vendor and installed directly into the engine fuel line upstream of the carburetor/mixer. Figure 1-2 presents a schematic of the GECO Controller. Table 1-1 summarizes the components that are included in a typical Controller installation and their function.

Figure 1-1. Relationship of Excess Air and Exhaust Gas Characteristics

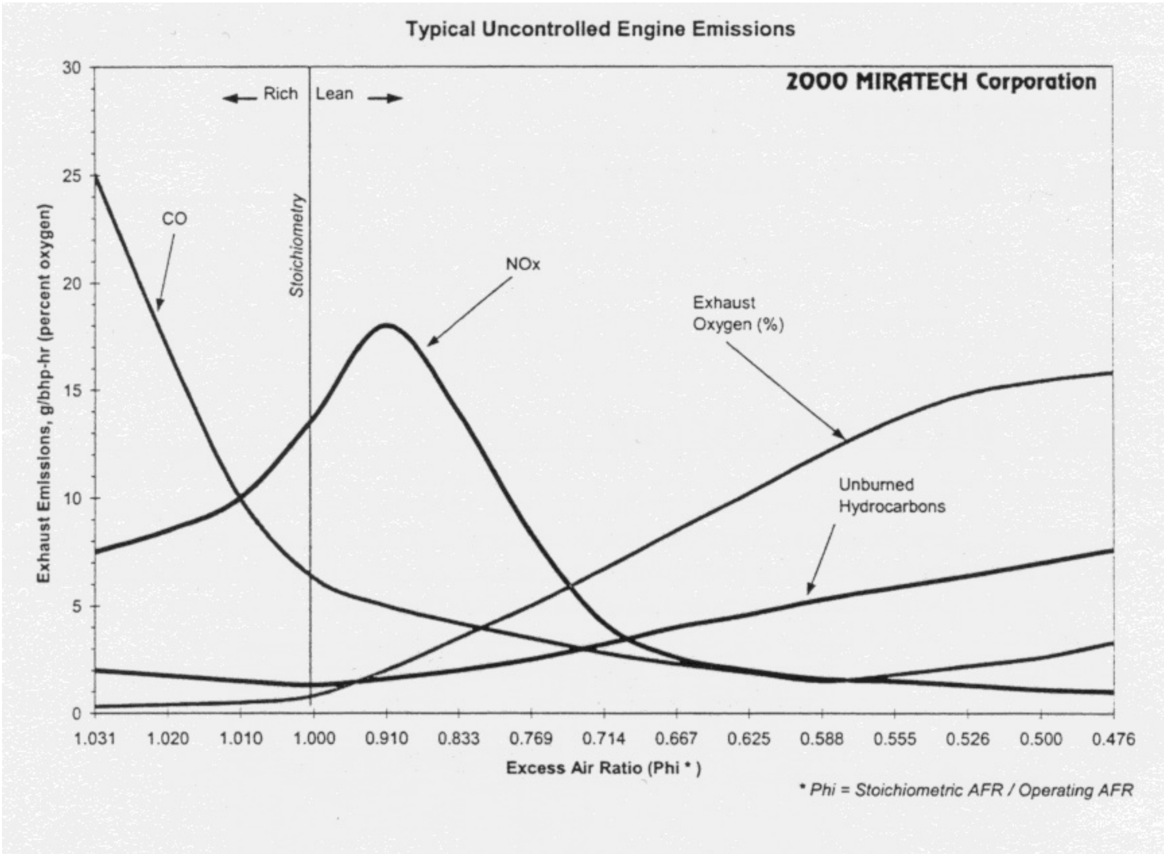

Typical Uncontrolled Engine Emissions
2000 MIRATECH Corporation
Rich
Lean
Stoichiometry
CO
NOx
Exhaust
Oxygen (%)
Unburned
Hydrocarbons
Exhaust Emissions, g/bhp-hr (percent oxygen)
30
25
20
15
10
5
0
1.031
1.020
1.010
1.000
0.910
0.833
0.769
0.714
0.667
0.625
0.588
0.555
0.526
0.500
0.476
Excess Air Ratio (Phi *)
* Phi = Stoichiometric AFR / Operating AFR

Figure 1-2. Schematic of the GECO 3001 Controller

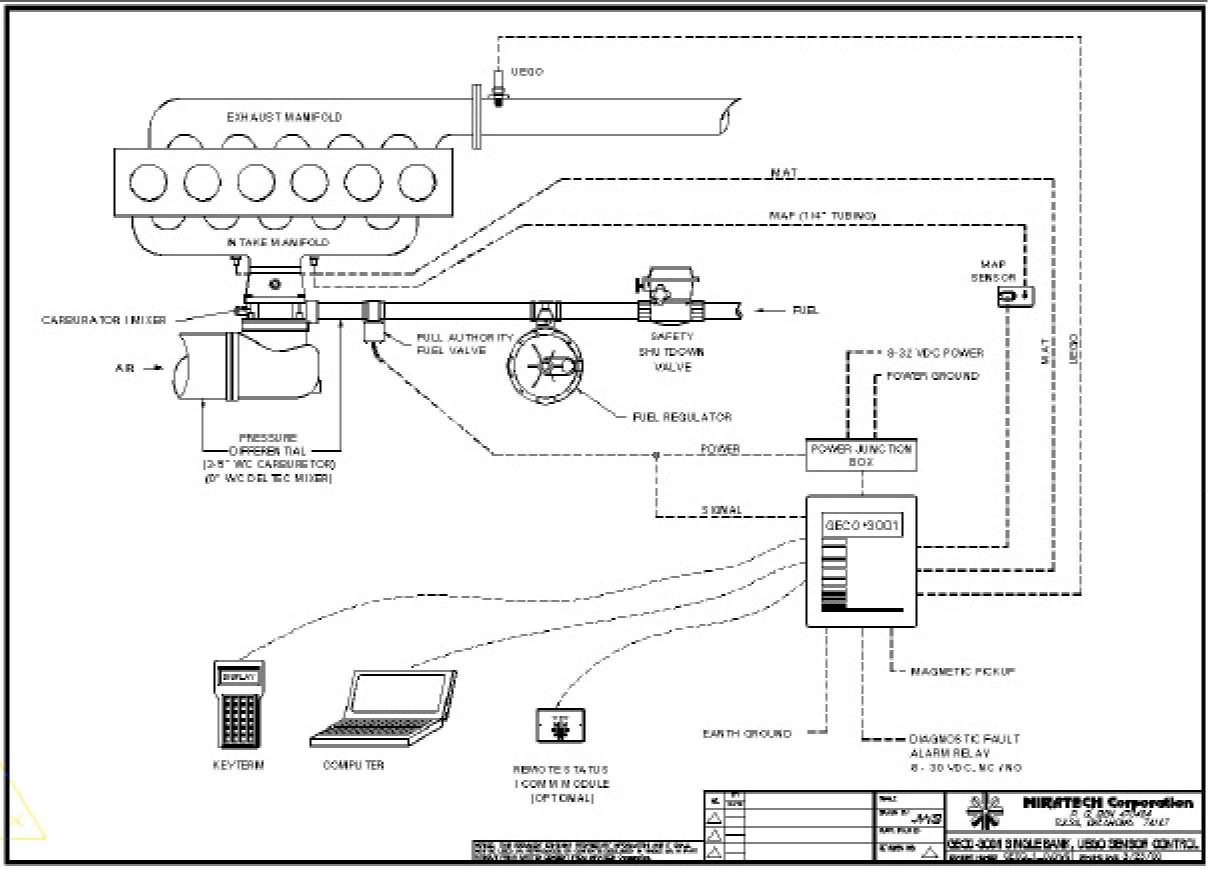


Table 1-1. GECO Air/Fuel Controller System Components	
Component	**Function**
Engine Control Unit (ECU) Control Board	Includes the microprocessor controller and all electronics associated with power regulation, signal inputs and filtering, controlled outputs, and communications. Also includes the closed-loop enable switch.
Keyterm	A terminal useful for communication with the Controller in applications where a PC is not available.
User Interface Module	Allows the user to view Controller status using three LED displays including Controller power, shutdown relay, and fault relay
Full-Authority Fuel Valve	An electronically actuated, full-authority valve used to control fuel flow to the air/fuel carburetor/mixer.
Manifold Temperature Sensor	A thermal resistor used to monitor intake MAT to determine M-dot air and calculations (M-dot air is a default air temperature setpoint used during engine start-up).
Manifold Pressure Sensor	A 5-volt reference pressure sensor used to monitor intake MAP from 0 to 43 psia, used as an indicator of engine load.
Engine Speed Sensor	A MAG-pickup sensor used to determine engine speed (RPM) by counting pins on the flywheel.
Exhaust Oxygen Sensor	A universal exhaust gas oxygen (UEGO) sensor used to continuously monitor the oxygen concentration in the exhaust gas.
GECO Diagnostic Software	Provides advanced troubleshooting capabilities using diagnostic fault codes, oscilloscope plotting, and data logging.

Figure 1-2 and Table 1-1 show that the four input variables to the Controller during operation are exhaust gas O_2 content, MAP, MAT, and MAG-pickup. The O_2 signal indicates the excess air level, the MAP signal is used by the Controller to estimate engine load, the MAT signal is used to calculate the intake air flow breakpoint (a preprogrammed exhaust gas O_2 threshold level that disables the Controller during engine start-up), and the MAG-pickup sensor monitors engine speed. After all system components are installed on an engine and confirmed to be functional, the Controller must then be programmed to control air/fuel ratios to levels most desirable for a specific engine and application. During programming, the engine air/fuel ratios are varied while monitoring emissions to determine the optimum ratios with respect to engine NO_X emissions or fuel consumption. The optimum air/fuel ratio value is identified as Phi-desired. The engine is then operated at a range of loads and, while monitoring the input variables (O_2, MAT, MAP, and engine speed or rpm) to the Controller, the fuel valve is adjusted to achieve the Phi-desired ratio at each load. The valve positions and input variables at each operating point are stored by the Controller as the Phi-target table. When in operation, the Controller produces a continuous valve command that controls valve position, and subsequently, the air/fuel ratio.

The Controller can be used in three different modes of operation: open-loop, closed-loop, and manual. When the engine is started, the Controller sets the fuel valve to a default valve position. The valve remains in this position until the engine reaches 400 rpm, at which point the Controller goes into its closed-loop mode of operation. Once in closed-loop mode, the Controller uses input signals for engine speed and air pressure (the MAG-pickup and MAP sensors) to look up the Phi-target valve positions from the preprogrammed valve table, and set the valve at that position to optimize the air/fuel ratio. Manual mode is primarily a troubleshooting tool that allows the user to disable the Controller and manually control the fuel valve to observe the sensor and emissions responses and to program the controller during system installation and setup.

1.3 TEST FACILITY DESCRIPTION

The facility that hosted this verification is a natural gas plant where gas is extracted and processed for subsequent transport and sale. The plant recovers hydrocarbons of C_2 and heavier from the natural gas, then compresses the residual gas for transport and subsequent sale. The plant has a capacity of greater than 20 million cubic feet of gas per day, and is equipped with five internal combustion engines including two Caterpillar Model 3516-LE recompressors that were used to conduct this verification.

One engine was equipped with the Controller and designated as the Test Engine. The twin engine without the Controller was designated as the Control Engine and used for comparison of engine oil conditions. Both units were exchanged during a scheduled overhaul with zero-hour units (engines with no run time) during the first week of August 2000. Shortly before field testing was conducted, both engines received scheduled maintenance including fresh lubricating oil, a tune-up, and other routine maintenance.

Both engines have a rated power output of 1,085 BHp and each consume approximately 7,200 cubic feet per hour (cfh) natural gas from a common fuel header during normal operation. During normal plant operations, plant residual gas used to fuel the engines is very uniform in composition with methane concentrations of approximately 91 percent and LHV between 980 and 990 Btu/scf. Engine fuel composition can change in response to plant upsets or changes in station operations, but these occurrences are rare. The engines are lean-burn design and no additional emission controls are employed. Both engines drive reciprocating gas compressors that elevate pipeline gas pressure from approximately 250 to 850 psig. The compressors are Ariel Model JGK two-stage units. The two engine/compressor sets operate on the same schedule and load during normal station operation. Engine speed may vary somewhat between the engines depending on inlet gas volumes. Under normal operations, the engines run at or near full capacity with an average annual utilization of approximately 96 percent. The engines were operated at reduced operating loads for short periods in order to facilitate the testing planned for this verification. Load changes were conducted by adjusting the compressor pockets. Load reductions of approximately 20 percent were measured on the compressor during the testing. The station monitors engine operations continuously, but has limited data acquisition capabilities. Therefore, engine operating parameters that were key to this verification were monitored by the GHG Center using procedures described in Section 1.4.1 of this report and detailed in Section 2.2.1 of the Test Plan.

For this verification, one GECO Air/Fuel Ratio Controller was installed on the designated Test Engine by MIRATECH on May 8, 2001. GHG Center personnel were on-site to observe and document installation activities and requirements. On the day immediately preceding the verification testing, MIRATECH personnel programmed the Controller using the procedures outlined in Section 1.2 to operating conditions specific to the Test Engine.

1.4 OVERVIEW OF VERIFICATION PARAMETERS AND EVALUATION STRATEGIES

This verification was designed to quantify changes in engine fuel consumption rates, criteria pollutant and greenhouse gas (GHG) emissions, and oil degradation rates that occur with the use of the Controller. The evaluation was designed to characterize, via measurements and other means, the following verification parameters:

- Changes in fuel consumption rates (Btu/BHp-hr)
- Changes in emissions of NO_X, CO, THC, CO_2, and CH_4 emissions (g/BHp-hr)
- Controller installation requirements (labor and capital)
- Lubrication oil degradation rates (extended Phase II evaluation)

Changes in fuel consumption rate and engine emissions were evaluated over a 4-day period after completion of Controller installation, shake-down, and start-up activities. Evaluation of oil degradation rates will continue over an additional 3- to 4-month period and be reported separately (Phase II). To verify the effects of the Controller on engine performance, each of the parameters was evaluated with and without the use of the Controller on the Test Engine. The verification parameters were evaluated using the following comparisons:

- Engine fuel consumption rate, engine emissions, and emissions reductions were evaluated by conducting a series of tests at different engine operating setpoints. During each test, measurements were collected with the Controller enabled, and then repeated with the Controller disabled.

- An extended evaluation of lubrication oil degradation rates will be conducted by comparing the oil characteristics of the engine equipped with the Controller (Test Engine) to the oil in an identical engine (Control Engine) that is not equipped with a Controller.

Because the primary verification parameters were to quantify changes in fuel consumption rate and emissions, it was anticipated that small changes in these parameters would be difficult to quantify. This is because actual measurements such as fuel consumption rate are large numbers (fuel consumption rate is approximately 9,000 Btu/BHp-hr), and changes in this value caused by use of the Controller might be small enough so as to approach the sensitivity of the instrumentation used to quantify the parameter. As such, fairly generous data quality objectives (DQOs) were proposed in the Test Plan (± 20 percent for changes in fuel consumption rate and ± 13 percent for changes in NO_x emissions). The DQOs for each verification parameter are discussed in detail in Section 3.0.

Table 1-2 summarizes the verification approach. Figure 1-3 provides a schematic of the measurement system used during the testing. More detail regarding evaluation of each of the verification parameters is presented in the following sections.

Table 1-2. Verification Strategy

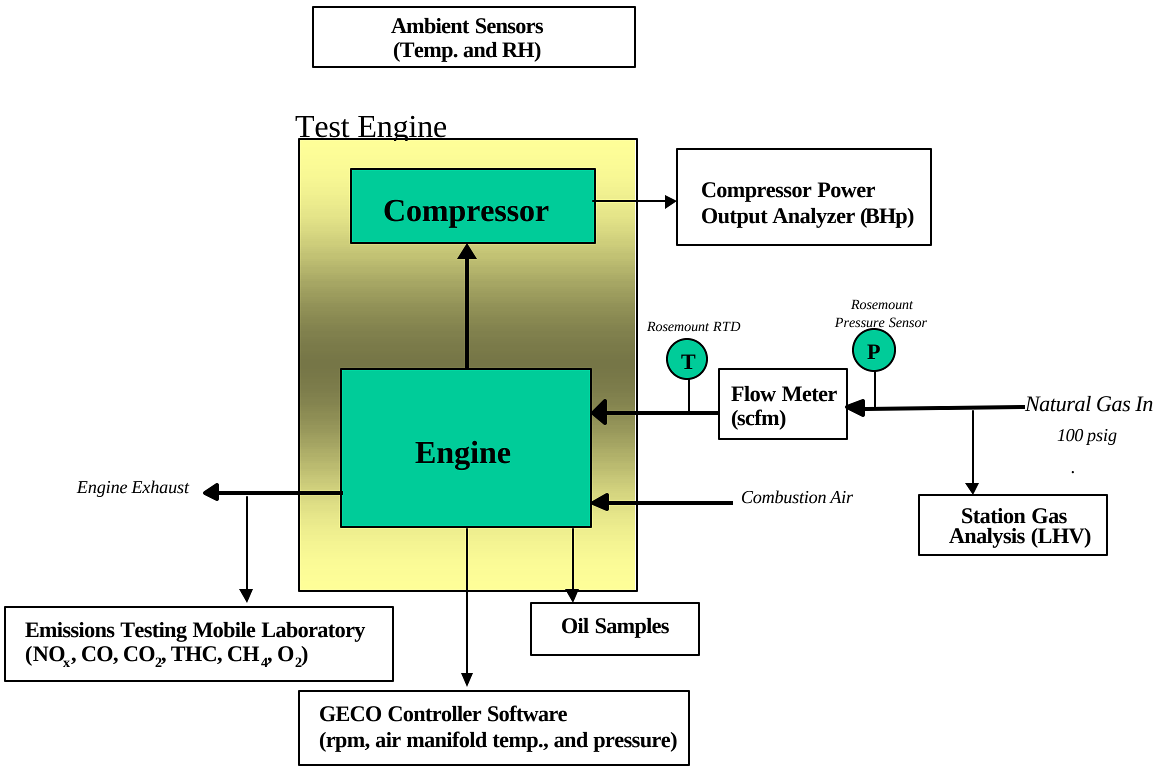
Verification Parameters	Data Used to Determine Changes Due to Controller		
	Test Engine with Controller Enabled	**Test Engine with Controller Disabled**	**Control Engine**
Fuel Consumption Rates	Fuel input and power output metering	Fuel input and power output metering	--
Changes to Criteria Pollutant and GHG Emission Rates	Emission testing	Emission testing	--
Installation Requirements	Station records and on-site observations	--	--
Lube Oil Degradation	Oil sampling	--	Oil sampling

Fuel consumption rates and emissions performance were evaluated on the engine equipped with the Controller by comparing results of a series of tests conducted with the Controller enabled and disabled. During each of the tests, data were collected during discrete measurement periods (runs) of equal duration. The Controller's closed-loop mode of operation was used for all of the tests conducted with the Controller enabled. During these tests, fuel flow to the engine was regulated by the full-authority fuel valve according to the valve learn table programmed into the Controller by MIRATECH engineers after installation.

Immediately following each closed-loop test, the Controller was disabled to simulate an engine that is not equipped with a Controller. At the host plant, air/fuel ratios are set to meet NO_X emission regulations by manually adjusting the carburetor while monitoring emissions. Typically, these adjustments are made during scheduled engine maintenance or overhauls (the most recent being the first week of June 2001). Air/fuel ratios then remain static (but not necessarily optimized) until the carburetor is again manually adjusted. To simulate this during the verification, the Controller was placed into manual mode and the full authority fuel valve was locked in full-open position. With the Controller disabled, air/fuel ratios were static, controlled by the carburetor only, and were not optimized after changes in engine operation, fuel quality, ambient conditions, or any other conditions that might affect engine performance. This scenario was used to represent operation of the engine without a Controller.

During all test periods (with the Controller in either closed-loop or manual operation), the O_2, MAP, MAT, and MAG-pickup sensor signals were logged using the Controller's software and collected by GHG Center personnel to document test conditions.

Figure 1-3. Schematic of Measurement System



The Controller is designed to stabilize engine performance during normal operation and after engine operation, fuel quality, or environmental changes occur. Therefore, the performance evaluations were conducted while operating at full load, and after reducing engine load, which is the only operational parameter that is fully controllable. Loads were reduced to approximately 80 percent of capacity by opening the compressor pocket. The Test Plan proposed evaluations at three different operating loads but, because of heavy gas demand in the pipeline system, the Test Engine could not be operated at loads less than 80 percent of capacity.

The Test Plan also proposed conducting a series of tests during a cool weather period (spring of 2001) and repeating the testing during warm weather. However, delays in coordinating installation of the Controller with the host facility precluded conducting testing during the cool spring months; consequently, only the warm summer weather testing was conducted.

During all test periods, engine operational parameters including engine speed, horsepower, fuel pressure, ambient air temperature and humidity, the fuel LHV, and other engine parameters were monitored. This was done to ensure that engine operations remained relatively constant during each test period. These data also were used to confirm that operating conditions were steady as the Controller was enabled or disabled, allowing valid engine performance comparisons to be made. The source of these data and the logging frequencies for each variable during the test periods are summarized in Table 1-3.

Table 1-3. Summary of Engine Operating Parameters Logged During Testing			
Engine Operating Parameter (units)	**Instrumentation**	**Data Logging Method**	**Frequency of Reading**
Speed (rpm)	GECO Controller MAG-pickup sensor	Logged by Controller internal software	Once per minute
Power (BHp)	Dynalco Model 9240 Compressor Analyzer	Logged by analyzer internal software	2 to 3 measurements during each test, averaged over each test period
Air Manifold Pressure (psig)	GECO Controller MAP sensor	Logged by Controller internal software	Once per minute
Air Manifold Temperature (°F)	GECO Controller MAT sensor	Logged by Controller internal software	Once per minute
Exhaust Gas O_2 (%)	Teledyne Model 3290 O_2 sensor	Logged by Emissions Testing data logging system	Once per minute
Fuel Pressure (psig)	Rosemount 3095 mass flow meter	Meter transmitter – Manual Logging	1-minute readings, and averaged over duration of each run
Fuel Flow (scfm)	Rosemount 3095 mass flow meter	Meter transmitter – Manual Logging	1-minute readings, and averaged over duration of each run
Pipline Gas Temperature (°F)	Rosemount 3095 mass flow meter	Meter transmitter – Manual Logging	Once every 5 minutes, manually
Fuel Heating Value (Btu/scf)	Station Gas Analyzer	Station Control System	Once per hour
Suction and Discharge Pressures (psig)	Station pressure gauges	Manual gauge readings	Once every 5 minutes, manually
Ambient Temperature (°F) and Humidity (%)	Vaisala Model HMP 35C	Logged by Campbell data logger	Once per minute

Following the guidelines provided in *ASME Performance Test Code (PTC 17) for Reciprocating Internal Combustion Engines* (ASME 1997), variability limits in key parameters were used to evaluate engine stability during test periods. The variability limits are summarized in Table 1-4.

Table 1-4. Maximum Allowable Variability in Operating Parameters During Test Periods	
Engine Operating Parameter	**Maximum Deviation of Individual Observations From Average Value During Test Period**
Engine Power Output (BHp)	± 3 %
Engine Speed (rpm)	± 1 %
Ambient Air Intake Temperature (°F)	± 10 °F
Fuel Heat Value (Btu/scf)	± 2 %
Fuel Gas Pressure (psig)	± 2 %

Before and during each test, GHG Center personnel confirmed that the engine was under steady operating conditions at each of the desired operating setpoints by documenting that the engine operating parameters listed in Table 1-4 were stable (within the deviation criteria listed) for a period of at least 15 minutes. At each test condition, approximately 30 to 60 minutes of data were collected after engine stabilization to determine engine emissions and engine fuel consumption rate with the Controller enabled and disabled.

A primary indicator of engine load and performance is power output in units of brake-horsepower (BHp). During this testing, a balanced pressure compressor performance analyzer was used to make direct and accurate measurements (± 1 percent) of the indicated power (i.e., work being conducted by the compressor), and relate the measured indicated power to net engine power output.

During each of the tests, engine BHp was measured by Technical Compressor Services, Inc. using a Dynalco Recip-Trap Model 9240 Engine/Compressor Analyzer and following guidelines provided by *ASME PTC 19.8 Measurement of Indicated Power* (ASME 1985). PTC 19.8 provides guidance for determining indicated engine power through direct measurement of pressures into and out of the gas compressors. The Dynalco analyzer, coupled with Dynalco's RT software, determines the indicated power using the balanced-pressure approach defined in PTC 19.8. The analyzer includes pressure sensors that are mounted on the suction and discharge sides of each compressor cylinder (two cylinders for the test engine compressor) and then continuously monitors these pressures. The software then calculates the total work performed by the compressor and reports this work as BHp. Repeated measurements were collected during each run at intervals of approximately 30 minutes, and averaged for each run. The BHp values were also used to confirm stable engine load during each test, to calculate fuel consumption rate, and to normalize measured engine emissions to engine power output.

Engine operating parameters logged by the Controller include engine speed, intake air temperature, and intake air manifold pressure. These data were recorded and stored during each run using the oscilloscope plotting function built into the Controller software. Pipeline gas temperature and compressor suction and discharge pressures were logged manually by GHG Center personnel during the test periods at 5-minute intervals on data logs. These data were used to further document the stability of engine operations during the test periods.

Ambient temperature and humidity were monitored using a Vaisala, which was positioned near the engine air intake, recorded, and stored at 1-minute intervals. These meteorological data were not used in determining the verification parameters, but they did document the stability of ambient conditions during each of the test periods. The temperature/humidity probe was factory-calibrated to a NIST-traceable standard prior to use in this verification, and reasonableness checks were conducted with a hand-held thermocouple and psychrometer.

The following sections present each of the verification parameters in more detail, and present the method of determination for each. Additional details regarding measurement procedures and sampling and analytical details are in the Test Plan.

1.4.1 Fuel Consumption Rate

Evaluation of the Controller's ability to reduce fuel consumption was based on comparison of the fuel consumed at each of the operating loads with the Controller enabled and disabled. Fuel consumption rates were determined as described in ASME PTC 17. Average fuel consumption during each test run was calculated using the following equation:

Fuel Consumption Rate (Btu/BHp-hr) = [Heat input to engine (Btu/hr) / indicated power (BHp)]

where: Heat input to engine (Btu/hr) = Fuel flow (scfm) * fuel LHV (Btu/scf), and
Indicated power (BHp) = average of engine power measurements during the run.

Fuel flow to the engine was monitored during each test period using a Rosemount Model 1195 orifice meter equipped with Model 3095 transmitter. The meter was mounted in a 1.5 in. inside diameter fuel line at a point in the line upstream of the Controller, and in accordance with Rosemount installation guidelines. The meter was equipped with a resistance temperature detector (RTD) to monitor fuel temperature and a pressure sensor to monitor absolute pressure of the fuel. With these measurements, the meter continuously compensated the fuel flow measured at site conditions for temperature and pressure, and reported mass flow at standard conditions (60 ^{o}F, 14.7 psia). Individual 1-minute meter signals were recorded throughout each test period, and averaged over the duration of each test run.

The measured fuel flow rates were used in conjunction with the LHV of the fuel to determine energy input to the engine during each test period. Fuel composition analyses are conducted by the host on an hourly basis using an on-site gas chromatograph/thermal conductivity detector (GC/TCD). Gas compositional analyses are conducted in accordance with ASTM Specification D1945 with quantification of methane (C1) to hexanes plus (C6+), N_2, O_2, CO_2, and H_2S. Sample gas is injected into a gas chromatograph equipped with a TCD, where gas components are physically separated in the columns and the resultant areas compared to the corresponding calibration data. The range of the detectable concentrations (mole percent) is specified in Table 1 of the method (D1945). These data are then used in conjunction with ASTM Specification D3588 to calculate the LHV in units of British thermal units per standard cubic foot (Btu/scf). The measured LHVs were multiplied by the corresponding average fuel flow rate values for each test period to calculate engine heat input in units of Btu/hr.

1.4.2 Emissions Performance

Determination of the emissions performance of the engine is an important variable in evaluation of the performance of the Controller. Pollutant concentration and emission rate measurements for NO_X, CO, THC, CO_2, and CH_4 were conducted on the engine exhaust stack during each test period. All of the test procedures used in the verification are U.S. EPA Reference Methods, which are well documented 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 (40CFR60, Appendix A). Table 1-5 summarizes the standard Test Methods that were followed.

Table 1-5. Summary of Emission Testing Methods

Pollutant/ Parameter	Reference Method	Principle of Detection	Analytical Range
O_2	3A	Electrochemical Cell	0-25 %
CO_2	3A	NDIR	0-20 %
NO_X	7E	Chemiluminescence	0-500 ppm
CO	10	NDIR-Gas Filter Correlation	0-1,000 ppm
CH_4	18	GC/FID	0-1,000 ppm
THC	25A	Flame Ionization	0-1,000 ppm

During each test, sampling was conducted at a single point near the center of the engine exhaust stack for the duration of the test. Results of the instrumental testing are reported in units of parts per million by volume dry (ppmvd). The emissions testing was conducted by Cubix Corporation of Austin, Texas, 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.

In order for the CO_2, O_2, NO_X, and CO 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 turbine exhaust gas stream through a stainless steel probe and heated sample line and transported to ice-bath condensers 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 series of analyzers. For determination of CO_2 concentrations, a Fuji Model 3300 analyzer with nondispersive infrared spectroscopy (NDIR) was used. The CO_2 analyzer range was set at 0 to 20 percent. A Teledyne Model 3290 equipped with an electrochemical cell O_2 sensor was used to monitor O_2 concentrations. The O_2 analyzer range was set at 0 to 25 percent.

NO_X concentrations were determined utilizing a Thermo Environmental Model 10 chemilumenescence 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 on a range of 0 to 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. These two values are "correlated," based upon the known concentrations of CO in the filter, to determine the concentration of CO in the sample gas. The CO analyzer was operated on a range of 0 to 1,000 ppm.

THC concentrations in the exhaust gas were measured using a JUM Model 5-100 with flame ionization detector. 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 on a range of 0 to 1,000 ppm.

Concentrations of CH_4 content in the exhaust gas stream were measured using a gas chromatograph (GC) with a VICI 6-port gas loop injection system and a flame ionization detector (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 the GC/FID after calibration of the FID. All samples submitted were analyzed in duplicate. The average difference between duplicate analytical results was 0.1 percent.

The instrumental testing for CO_2, O_2, NO_X, CO, and THCs yielded concentrations in units of parts per million by volume (ppmv). EPA Method 19 was followed to convert the concentration values into exhaust gas emission rates in units of pounds per hour (lb/hr). The method is applicable to the determination of emission rates from combustion sources. The accuracy of this procedure is dependent upon the accuracy of measured variables used in the calculations. These measurements include system heat input, fuel composition, and exhaust gas O_2 content. The fundamental principle of Method 19 is based upon F-factors, which are the ratio of combustion gas volume to the heat content of the fuel, and are calculated as a volume/heat input value (e.g., standard cubic feet per million Btu). This method includes all calculations required to compute the F-factors and provides guidelines on their use. The F-factors used to determine emission rates during each run were calculated using the actual gas compositional values obtained from the host facility GC results. Equation 19-13 of Method 19 was followed to calculate the F-factors in units of dry standard cubic feet per million Btu (dscf/MMBtu). After converting measured pollutant concentrations from a ppm basis to lb/dscf, the calculated F-factor was used in conjunction with the measured heat input to the engine (MMBtu/hr) and the O_2 volumetric concentration (dry basis; percent $O_{2,d}$) to report emission rates in terms of lb/hr using the following equation.

$$\textit{Mass Emission Rate (lb/hr)} = HI * Concentration * F\text{-}Factor * [20.9 / (20.9 - \% O_{2,d})]$$

Where:

HI = heat input (MMBtu/hr), determined using fuel flow rate measurements and fuel analyses for heat content
Concentration = measured pollutant concentration (lb/dscf)
F-factor = calculated exhaust gas flow rate (dscf/MMBtu), determined using fuel composition analyses
$O_{2,d}$ = measured oxygen level in exhaust stack, dry basis (%)

The mass emission rates in lb/hr were then normalized to total power output by dividing the rate by the average BHp measured during each test, and are also reported as pounds per brake horsepower-hour (lb/BHp-hr).

1.4.3 GECO Controller Installation Requirements

The GHG Center observed and documented installation and programming of the Controller. The total labor hours expended in the installation, programming, shakedown, and start-up of the GECO controller were recorded in the field and confirmed using labor records from the installation contractor. The cost of the Controller and components was also documented. The controller system was installed by an installation contractor familiar with the system, with supervision and guidance provided by MIRATECH engineers and plant personnel. Labor records and hourly rates obtained from the installation contractor were used to calculate the cost of Controller installation.

2.0 VERIFICATION RESULTS

2.1 OVERVIEW

Installation and programming of the Controller was completed on June 19, 2001. The field testing for fuel consumption and engine emissions was conducted from June 20 to 23, 2001. Table 2-1 summarizes the ambient conditions encountered during each test as well as engine operating conditions during the test periods. A total of 13 tests were conducted to compare engine performance with the Controller enabled and disabled. Six of these tests (Runs 1, 2, 10, 11, 12, and 13) were confirmed to have occurred during normal engine and station operations. The engine was maintained in a stable mode of operation during each of the test runs. The PTC17 variability criteria described in Section 1.4 and presented later in Section 3.2.1 were used as a guideline to verify that the tests were conducted during stable operation. The engine was allowed to stabilize for at least 15 minutes after changing loads before testing was started.

The values summarized in Table 2-1 are average values for the test periods. Although the GHG Center was not able to conduct cool weather testing as initially planned, Table 2-1 shows that some variability in ambient temperatures was encountered during the testing period. Therefore, some effects on engine operation may have been experienced (ambient temperatures during test periods ranged from 73 to 98 ^{o}F).

Around mid-day on June 21, the fuel composition and LHV changed to levels that are atypical for this engine. The change in gas composition was caused by a large reduction in the total plant gas flow, and a subsequent decrease in the plant's ability to recover heavy hydrocarbons from the gas. Total gas flow through the plant was reduced from approximately 920,000 to 720,000 cubic feet per hour. Gas flow was intentionally reduced by the station operator to accommodate maintenance activities being conducted at an associated gas transmission facility. Due to this change in plant operation and gas composition, fuel gas LHV values were well above the normal range of 980 to 990 Btu/scf, ranging from approximately 998 to 1067 Btu/scf. In addition, CH_4 concentrations in the gas (normally approximately 91 percent) were reduced to approximately 83 percent due to the increased level of heavy hydrocarbons in the gas (Table 2-1).

Six comparison tests were conducted during this period and, due to the upset in operations described above, results of these tests were invalidated. This verification was designed to evaluate Controller performance during normal operations, so results of these tests are not detailed here. The total volume of gas flowing through the plant and the LHV levels returned to normal on June 23, and four more comparisons were conducted.

The first test conducted on June 21 (Test 3) was invalidated because a slight adjustment was made to the engine carburetor before starting the test. This adjustment was made to set the engine to its optimum air/fuel mixture for that particular day, which contradicts the testing strategy outlined in the Test Plan. The strategy was to conduct all of the testing on a well-tuned engine without making any additional changes to the uncontrolled air/fuel ratio, and observe engine performance over a range of operating loads and ambient temperatures. During the first test conducted with the Controller disabled on June 20 (Test 1), exhaust gas O_2 content was 7.9 percent. This level of excess air in the system was determined to be the engine's baseline operating condition. Prior to Test 3, the excess air level had drifted, resulting in a stack O_2 reading of 7.7 percent, and the carburetor was incorrectly adjusted slightly to return to the baseline excess air level of 7.9 percent O_2 before testing resumed, invalidating test 3.

Table 2-1. Summary of Test Conditions

Test Identification			Controller Operating Mode	Ambient Conditions			Engine/Compressor Operations				
Test ID	Date	Test Period		Temp. (°F)	Relative Humidity (%)	Pressure (in. Hg)	Engine Speed (rpm)	Engine Power (BHp)	Fuel LHV[a] (Btu/cf)	Fuel CH_4 Content[b] (%)	Suction/ Discharge Press.(psig)
1	6/20/01	1135-1235	Enabled	92.1	28.0	27.60	1202	831	981.2	91.5	242/796
		1647-1747	Disabled	97.8	17.4	27.59	1202	856	980.7	91.2	242/804
2[d]	6/20/01	1305-1405	Enabled	94.7	22.4	27.65	1203	722	975.3	91.4	241/797
		1515-1615	Disabled	97.9	18.2	27.60	1219	739	979.0	91.7	243/800
3	6/21/01	0915-1015	Disabled	85.3	46.8	27.69	1211	845	980.6	91.4	237/796
		1040-1140	Enabled	89.1	38.0	27.69	1205	839	985.4	90.6	238/800
4[c,d]	6/21/01	1230-1315	Enabled	89.9	32.5	27.68	1198	725	1059.1	83.5	239/806
		1337-1410	Disabled	91.7	27.8	27.64	1198	714	1059.1	83.5	236/795
5[c]	6/21/01	1527-1555	Enabled	94.9	24.5	27.62	1205	826	997.9	87.7	224/800
		1600-1630	Disabled	95.1	23.8	27.61	1203	823	997.9	87.7	225/798
6[c]	6/22/01	0757-0825	Disabled	75.5	60.7	27.68	1202	830	1047.8	84.1	231/798
		0828-0900	Enabled	77.0	58.1	27.69	1203	832	1039.2	87.4	230/803
7[c,d]	6/22/01	0930-1010	Enabled	78.3	55.3	27.69	1194	710	1048.2	84.0	236/803
		1015-1045	Disabled	80.3	51.8	27.69	1199	701	1048.2	84.0	236/800
8[c,d]	6/22/01	1135-1205	Disabled	82.7	46.5	27.69	1208	714	1057.8	83.4	234/794
		1208-1230	Enabled	83.9	44.8	27.69	1206	713	1057.8	83.4	234/796
9[c]	6/22/01	1315-1345	Enabled	86.0	40.8	27.65	1202	817	1067.4	82.8	229/800
		1350-1420	Disabled	87.3	38.2	27.62	1206	808	1067.4	82.8	230/799
10	6/23/01	0817-0840	Enabled	72.9	81.4	27.63	1202	843	988.3	91.4	240/800
		0847-0915	Disabled	73.6	80.3	27.64	1203	843	985.0	91.0	240/805
11	6/23/01	0925-0950	Enabled	74.9	74.9	27.64	1193	817	987.8	91.2	240/805
		0955-1017	Disabled	77.3	68.4	27.64	1190	813	987.8	91.2	240/803
12[d]	6/23/01	1030-1055	Disabled	78.1	68.1	27.64	1204	722	985.6	90.9	240/798
		1058-1123	Enabled	77.2	69.4	27.64	1202	724	985.6	90.9	240/799
13[d]	6/23/01	1126-1150	Disabled	74.8	73.2	27.64	1202	720	986.3	91.1	241/799
		1150-1220	Enabled	75.5	70.6	27.64	1204	724	986.3	91.1	242/799

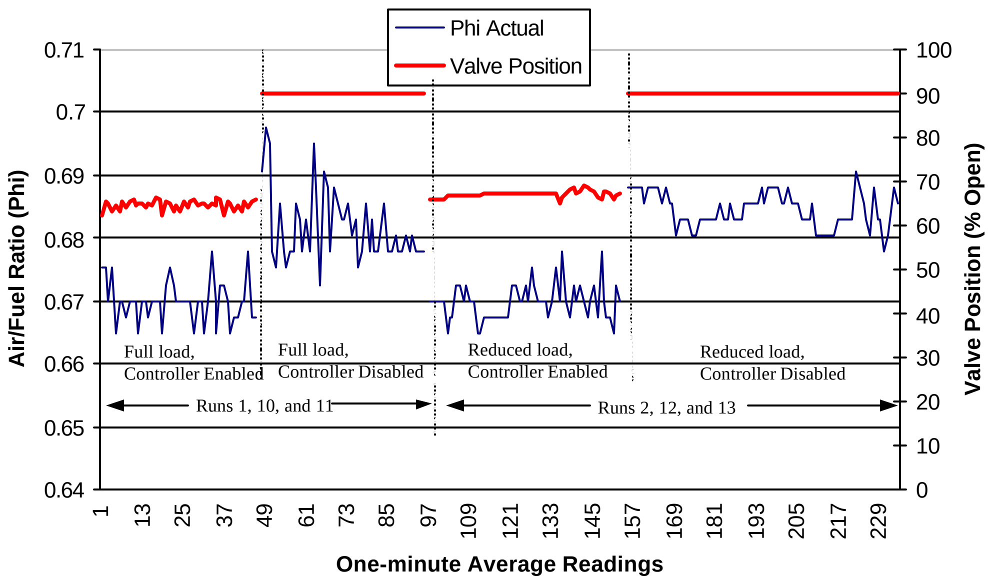
[a] LHV values greater than 1,000 Btu/cf indicate atypical engine fuel composition.
[b] Methane values lower than 90 percent indicate atypical engine fuel composition.
[c] Indicate runs invalidated due to atypical engine fuel qualities.
[d] Tests conducted at reduced load (approximately 80 % of capacity).

The engine was allowed to stabilize for several hours, no further adjustments were made to the carburetor, and testing resumed the following day (June 22).

The remaining four tests were conducted during normal operation, validated, and divided into two operating regimes including full load with normal LHV levels in the fuel and reduced load with normal LHV. Three separate comparison tests were conducted at each of these loads and included individual test runs with the Controller enabled (operating in closed loop mode) and disabled (placed in manual with the valve fully open).

In general, operation of the Controller in closed loop mode resulted in a leaner air/fuel mixture to the engine. Recalling Figure 1-1, the excess air ratio (Phi) is calculated as the stoichiometric air/fuel ratio divided by the actual air/fuel ratio and can have a large impact on engine operations, particularly emission rates. The average Phi with the Controller in closed loop was 0.670, while the average Phi with the Controller disabled was 0.683. As illustrated in Figure 2-1, changes in Phi during the test periods correspond to Controller valve positions. With the Controller in manual mode, the valve was locked at the full open position (90 percent). System design limits the valve to a full open position of 90 percent. With the Controller in closed loop mode, the valve position is regulated by the Controller according to sensor feedback and the preprogrammed valve-learn table

Figure 2-1. Air/Fuel Ratios During Test Periods



The tests were designed to evaluate the effects of these changes in air/fuel ratio on engine operations. Test results for changes in fuel consumption rates and engine emissions are provided for each individual comparison test, and also averaged for the three comparisons conducted at each condition.

Detailed discussions of the test results are presented below:

2.1.1 Changes in Fuel Consumption Rate

Results of the fuel consumption rate testing are summarized in Table 2-2 for all valid test runs. Three test run comparisons were conducted with the engine operating at full load and another three with the engine at reduced load.

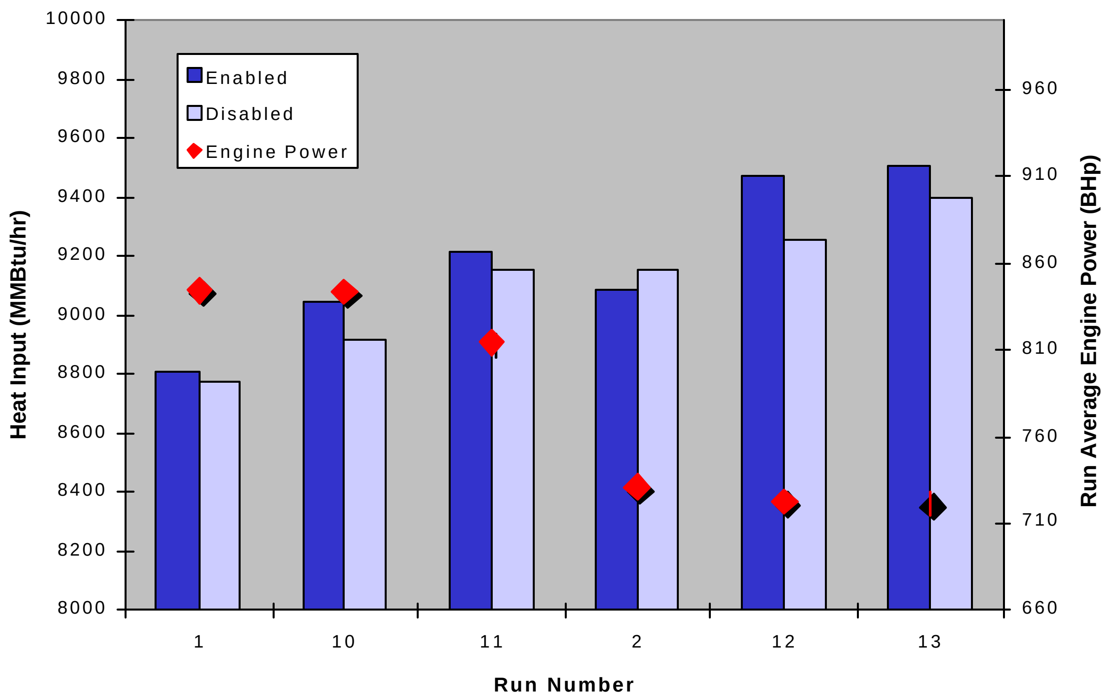
Table 2-2. Fuel Consumption Rate Test Results

Test Number	Controller Mode of Operation	Engine Power Output (BHp)	Fuel LHV (Btu/scf)	Fuel Flow (scfm)	Heat Input (MMBtu/hr)	Fuel Consumption Rate (Btu/BHp-hr)	Percent Reduction[a]
Change in fuel consumption rate at full load with normal LHV							
1	Enabled	831	981.2	124.3	7.318	8805.7	(0.4)
	Disabled	856	980.7	127.6	7.510	8772.8	
10	Enabled	843	988.3	128.7	7.628	9049.2	(1.5)
	Disabled	843	985.0	127.1	7.514	8913.7	
11	Enabled	817	987.8[b]	127.0	7.524	9209.8	(0.6)
	Disabled	813		125.6	7.442	9153.7	
Average							**(0.8)**
Change in fuel consumption rate at reduced load with normal LHV							
2	Enabled	722	975.3	112.1	6.558	9082.4	0.8
	Disabled	739	979.0	115.2	6.765	9153.6	
12	Enabled	724	985.6[b]	115.9	6.856	9469.5	(2.3)
	Disabled	722		113.0	6.680	9251.8	
13	Enabled	724	986.3[b]	116.3	6.885	9509.4	(1.2)
	Disabled	720		114.3	6.766	9397.0	
Average							**(0.9)**

[a] Percent change = [(consumption with controller disabled – consumption with controller enabled) / consumption with controller disabled] * 100, values in parentheses indicate percent increases.
[b] One fuel analysis was conducted during both the Controller enabled and disabled runs.

Table 2-2 lists the average change in fuel consumption rate at the two operating loads tested. Changes in fuel consumption rate were calculated in units of Btu/BHp-hr and are based on the fuel flow to the engine, the LHV of the fuel, and the power output produced by the engine during each of the tests. As shown in the table, changes in fuel consumption rate were so small that the GHG Center is unable to state with certainty the level of fuel use change that occurs with the use of the Controller. Figure 2-2 demonstrates the similarity in fuel consumption with the Controller enabled and disabled. The data quality assessment presented in Section 3.0 of this report details the accuracy that was achieved in each of the measurements used to determine fuel consumption rate (fuel flow, fuel LHV, and engine power output). This is significant here because fuel consumption rate is so similar, and any differences observed during the tests could be due to measurement error or bias. After propagating errors in the individual measurements, a maximum uncertainty in changes in fuel consumption rate of approximately ± 92.4 Btu/BHp-hr was achieved for fuel consumption measurements. Reported changes in fuel consumption rate averaged approximately 80 Btu/BHp-hr, meaning that overall uncertainty in the reported results is greater than the average change.

Figure 2-2. Run Average Engine Fuel Consumption During Each Test



The Center conducted additional statistical evaluations to confirm that the average fuel consumption rates with the Controller enabled and disabled were not statistically different. Tables 2-3, 2-4, and supporting calculations summarize this analysis.

Table 2-3. Fuel Consumption Rate Confidence Intervals (Btu/Bhp-hr)				
Engine Load Condition	**Controller Enabled**		**Controller Disabled**	
	Mean ± 95% Confidence Interval	**Std. Dev.**	**Mean ± 95% Confidence Interval**	**Std. Dev.**
100 %	9021.6 ± 505.6	203.5	8946.7 ± 478.5	192.6
80 %	9353.7 ± 586.1	235.9	9267.5 ± 304.2	122.4

Mean fuel consumption rates in Table 2-3 are slightly less for disabled controller operations. But, examination of the confidence intervals shows that fuel consumption rates overlap significantly for both enabled and disabled controller conditions. Computation of a test statistic, *t*, allows the analyst to decide whether or not a statistically significant difference exists between the means. The base hypothesis is that the means are the same; i.e., the difference between them is zero. The *t*-test was computed as follows:

$$t = \frac{\overline{X}_{enabled} - \overline{X}_{disabled}}{\sqrt{s_p{}^2\left(\frac{1}{n_{enabled}} + \frac{1}{n_{disabled}}\right)}}$$

$$s_p{}^2 = \frac{(n_{enabled} - 1)s^2{}_{enabled} + (n_{disabled} - 1)s^2{}_{disabled}}{n_{enabled} + n_{disabled} - 2}$$

Where:

t = Test statistic
X = Mean fuel consumption
s_p = Pooled sample standard deviation
n = Number of test runs
s = Sample standard deviation

If the test statistic (t) is > 2.776 (assuming a 95 percent confidence level and four degrees of freedom), we can reject the hypothesis that the mean fuel consumption is the same for the two controller conditions. Table 2-4 presents the test statistics for the 100 and 80 percent engine loads and shows that, whether or not the Controller is enabled, the mean fuel consumption rate is statistically the same.

Table 2-4. Controller Enabled/Disabled Test Statistics

Load Condition	t
100 %	0.463
80 %	1.304

2.2 EMISSIONS PERFORMANCE

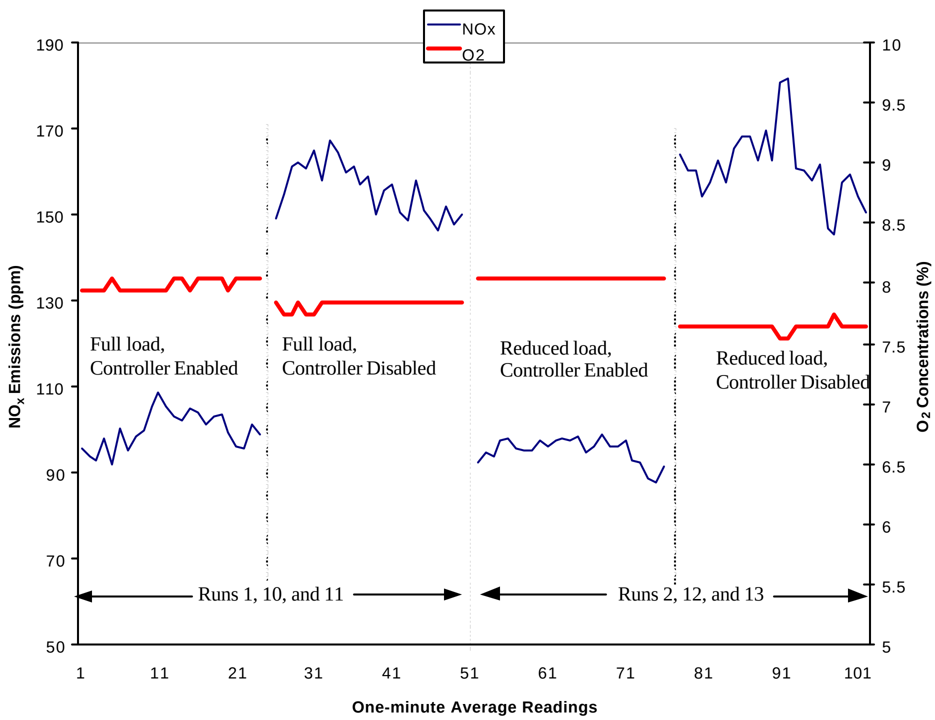
Emissions were tested to determine engine emission rates for criteria pollutants (NO_X, CO, and THCs) and greenhouse gases (CO_2 and CH_4). All testing was conducted in accordance with EPA Reference Methods as described in the Test Plan, and as listed in Table 1-5. Emissions testing was conducted concurrently with each of the validated fuel consumption tests summarized in Table 2-2.

Results of the emissions tests are reported in units of ppm for NO_X, CO, THCs, and CH_4, and percent for O_2 and CO_2. The concentration and volume percent data were converted to mass emission rates using computed exhaust stack flow rates, and are reported in units of pounds per hour (lb/hr). The emission rates are also reported in units of grams per brake horsepower-hour (g/BHp-hr), and were computed by dividing the mass emission rate by the measured power delivered by the compressor.

To ensure the collection of accurate emissions data, sampling system QA/QC checks were conducted in accordance with Test Plan specifications including analyzer linearity tests, sampling system bias and drift checks, interference tests, and audit gases. Results of the QA/QC checks are discussed in Section 3.2.3 of this report, and will show that the DQOs for these measurements were satisfied. A complete summary of emissions testing equipment calibration data is presented in Appendix A.

Table 2-5 summarizes the emission results for each run and the percent reduction or increase in emissions realized through operation of the Controller in closed loop. Reductions in NO_X emissions were the most significant change observed throughout the testing. Average NO_X reductions measured at the two engine operating loads were 30.5 percent at full load and 30.0 percent at reduced load. Reductions in NO_X were a result of the Controller's maintaining a leaner air/fuel mixture (as illustrated earlier in Figure 2-1). With the exception of the first comparison conducted, exhaust gas O_2 levels were higher during each of the tests conducted with the Controller enabled, indicating leaner fuel mixtures. This is illustrated in Figure 2-3 where NO_X and O_2 concentrations in the engine exhaust are plotted for the test runs.

Figure 2-3. Engine Exhaust NO_X and O_2 Concentrations During Test Periods



NO_X emissions were also less variable with the Controller in closed loop mode. Average variability in NO_X concentrations during these tests with the Controller enabled was 9.14 ppm, while average variability in the data with the Controller disabled was 14.11 ppm.

Changes in emissions of other pollutants were less significant. However, operation of the Controller in closed loop did result in a consistent decrease in CO emissions. Average reductions in CO emissions were 5.1 percent at full load and 2.4 percent at reduced load. This is significant because, with many types of emission controls, reductions in NO_X emissions commonly result in higher CO emissions.

Table 2-5. Changes in Engine Emissions

Test ID	Engine Load	Controller Mode	O_2 Content (%)	NO_x Emissions (g/BHp-hr)	NO_x Emissions % Reduction	CO Emissions (g/BHp-hr)	CO Emissions % Reduction	THC Emissions (g/BHp-hr)	THC Emissions % Reduction	CH_4 Emissions (g/BHp-hr)	CH_4 Emissions % Reduction	CO_2 Emissions (g/BHp-hr)	CO_2 Emissions % Reduction
1	Full Load with Typical LHV	Enabled	7.84	1.18	18.1	1.27	9.9	1.67	22.3	1.51	23.0	451	(0.9)
		Disabled	7.93	1.44		1.41		2.15		1.96		447	
10		Enabled	8.10	0.62	38.6	1.25	3.1	3.07	(11.6)	2.77	(11.7)	468	(1.1)
		Disabled	7.81	1.01		1.29		2.75		2.48		463	
11		Enabled	8.07	0.69	34.9	1.28	2.3	3.15	(4.3)	2.84	(4.0)	478	(0.2)
		Disabled	7.91	1.06		1.31		3.02		2.73		477	
Averages Reductions or (Increases)					**30.5**		**5.1**		**(2.1)**		**(2.4)**		**(0.7)**
2	Reduced Load with Typical LHV	Enabled	7.95	1.27	19.1	1.35	3.6	2.84	(9.2)	2.60	(8.8)	463	0.6
		Disabled	7.88	1.57		1.40		2.60		2.39		466	
12		Enabled	8.09	0.68	38.2	1.30	2.2	3.66	(14.0)	3.30	(13.8)	487	(1.9)
		Disabled	7.69	1.10		1.33		3.21		2.90		478	
13		Enabled	8.09	0.68	32.7	1.29	1.5	3.45	(9.9)	3.11	(9.9)	494	(1.2)
		Disabled	7.77	1.01		1.31		3.14		2.83		488	
Averages Reductions or (Increases)					**30.0**		**2.4**		**(11.0)**		**(10.8)**		**(0.8)**

Note: Values in parenthesis indicate percent increases.

Emissions of THCs and CH_4 did increase in all but the first comparison with the Controller in closed loop. Increases in THC emissions ranged from approximately 4.3 to 14.0 percent. Slight increases in CO_2 emissions were also observed with the Controller in closed loop during all but one comparison test. Average increases in CO_2 emissions were 0.7 percent at full load and 0.8 percent at reduced load. Measured increases in THCs, CH_4, and CO_2 are likely attributable to the small increases in fuel consumption rates that were measured when the Controller was disabled. During these test periods, additional carbon was introduced into the engine fuel system.

As stated earlier, several tests were conducted during a period of atypical station operation. Specifically, station residual gas (used as engine fuel) had abnormally high levels of ethane, propane, and butane and subsequently a much higher gas LHV. This verification was designed to evaluate Controller performance during normal operations, so results of these tests are not detailed here. However, data collected during these tests indicate that operation of the Controller in closed loop has potentially greater benefits during upset conditions than during the normal operations used for this verification, particularly with regard to reductions of NO_X emissions. NO_X emission reductions greater than 60 percent were observed during some of these periods, and emission rate variability was significantly lower with the Controller enabled.

2.2.1 GECO Controller Installation Requirements

The Controller was installed by a qualified installation contractor on May 9, 2001, under the supervision of MIRATECH personnel. All of the key components of the Controller including system hardware and software, engine sensors and cables, fuel valve, and power supply were provided by MIRATECH. Table 2-6 summarizes the system components needed for this application and where they were installed on the engine.

Table 2-6. GECO 3001 Air/Fuel Ratio Controller Component Installation

System Component	Location Installed
GECO Controller electronic control unit and enclosure	Engine control panel
GECO Controller software	Controller and station operator personal computer
24-volt DC power supply	Engine enclosure
Full-authority fuel valve and valve adapters	Engine fuel line, downstream of a regulator (reduces fuel pressure to 10 psig) and upstream of fine regulator (reduces fuel pressure)
UEGO oxygen sensor and cable	Engine exhaust stack approximately 2 diameters downstream of exhaust manifold
MAP air pressure sensor and cable	Tapped into an existing combustion air manifold pressure gauge
MAT air temperature sensor and cable	Tapped into combustion air manifold upstream of carburetor
Magnetic engine speed pickup and cable	Mounted adjacent to engine flywheel

In accordance with station safety procedures, all of the sensor signal cables and connections to the power supply were installed in intrinsically safe conduit. The conduit was supplied and installed by the installation contractor. The Controller was programmed by MIRATECH personnel on June 19, prior to verification testing.

Four technicians from the installation contractor were on site to install the system components, the power supply, and conduit. A total of 24 contractor manhours were spent installing the system. A significant portion of this time (approximately 60 percent) was involved in cutting, bending, and installing the conduit around the engine components to run the signal cables to the Controller. Applications with existing conduit or less complicated installation configurations may require less installation labor. Other applications may also have existing 24-volt DC power available on-site which would further reduce labor requirements. Programming of the Controller required approximately 4 hours of labor by the MIRATECH engineer. Additionally, emissions measurements were required during programming activities. In this case, the emissions testing contractor was on site for the verification testing and provided this service. Otherwise, a portable emissions analyzer and operator would be required to assist with the programming.

Capital costs associated with procurement and installation of the Controller were provided by MIRATECH and are summarized as follows:

Controller and all system components listed in Table 2-6:	$9,750
24-volt DC power supply (application specific):	$750
Conduit and other miscellaneous materials (application specific):	no charge
Installation contractor labor (24 hours at $48/hr)	$1,152
Total system installation cost:	$11,652

For engines that drive generators, the Controller can be configured to use a kW feedback sensor in place of the UEGO O_2 sensor. The cost of this system is approximately $500 less. Engines with dual carburetors will require two fuel valves, and engines with dual exhausts will require two feedback sensors (O_2 or kW). Controller component and installation costs for these systems were not verified here, but would be somewhat higher.

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 occurs in the final results. Data quality objectives (DQOs) were specified for the following verification parameters: changes in fuel consumption rate, NO_X emission reductions, and emission reduction for other pollutants. Table 3-1 lists the uncertainty levels targeted for these parameters.

Table 3-1. Data Quality Objectives

Verification Parameter	Units	DQO
Changes in Fuel Consumption Rates	Btu/BHp-hr	± 20 %
Emission Reductions (NO_X)	g/BHp-hr	± 13 %
Emission Reductions (CO_2, CO, THCs, CH_4)	g/BHp-hr	± 24 %

In this verification, the primary quantitative objectives were to verify the performance of the Controller with respect to savings or reductions in engine fuel consumption and emissions. The DQOs in Table 3-1 were developed based on anticipated levels of reduction (approximately 5 percent for fuel consumption and 10 percent for NO_X emissions). It was expected that uncertainty in the final test results would vary depending on the magnitude of reductions measured. For example, as the reductions in fuel consumption or NO_X emissions increased, the level of uncertainty in the reductions would decrease as a percent of the total reduction. This is because measurement error has a smaller impact on the larger values.

The target levels of uncertainty presented in Table 3-1 were developed by propagating and compounding the maximum potential error in each of the measurement parameters used to determine the reductions. For example, the uncertainty presented in the table for engine fuel consumption rate improvements were propagated using the maximum error expected for fuel flow, gas heat content, and engine power output measurements. The verification parameters listed in Table 3-1 required measurement of several different variables in the field. So, to ensure that the DQOs were met for each verification parameter, data quality indicator goals (DQIs) were established for each variable measured. The DQIs specified in Table 3-2 contain accuracy and completeness goals presented in the Test Plan. The DQIs for each of the measurement variables were evaluated through factory, laboratory, and/or field calibrations as indicated in the table. The achieved DQIs were then compounded and propagated to determine overall uncertainty in the verification parameters and, based on these uncertainties, to assess if the DQOs were met.

The following discussion illustrates that the accuracy goals were met or exceeded for each of the measurement variables. As such, the uncertainty objective for emissions changes listed in Table 3-1 was satisfied. However, changes in fuel consumption rate were very small; therefore, the objectives were not met, even though the measurement accuracy goals were met.

3.2 EVALUATION OF DATA QUALITY INDICATORS

Table 3-2 includes the range of measurements observed in the field, the accuracy and completeness goals, and the accuracy and completeness achieved for each measurement variable. The completeness goals

Table 3-2. Summary of Data Quality Indicators for Critical Measurements

Measurement Variable		Instrument Type / Manufacturer	Instrument Range	Measurement Range Observed	Frequency of Measurements	DQI Goal	DQI Achieved	How Verified / Determined	Completeness Achieved
Fuel Consumption	Gas Flow Rate	Mass Flow Meter / Rosemount 3095 w/ 1195 orifice	0 to 150 scfm	0 to 125 scfm	once every minute during test periods	± 1.0 % of reading	± 1.0 % of reading	Reviewed manufacturer calibration certificates, conducted reasonableness checks in field	100 percent
	Gas Pressure	Pressure Transducer / Rosemount or equiv.	0 to 250 psig	0 to 120 psig		± 0.75% FS	± 0.75% FS		
	Gas Temperature	RTD / Rosemount Series 68	-58 to 752 ^{o}F	60 to 100 ^{o}F	every 5 minutes during test periods	± 0.09% reading	± 0.09% reading	Reviewed manufacturer calibration certificates	
	Engine Power Output	Dynalco Recip-Trap Analyzer (pressure transducers)	0 to 1,500 psig	200 to 850 psig	twice per test	± 1.0 % reading	± 0.1 % reading		
	LHV	Gas Chromatograph /thermal conductivity detector	0 to 100 % CH_4	85 to 95% CH_4	once per hour	± 0.2% for CH_4	± 0.1% for CH_4	Calibrated GC/TCD with gas standard	50 percent
Exhaust Stack Emissions	NO_X Levels	Chemiluminescence / TECO Model 10	0 to 500 ppm	89 to 200 ppm	5-second readings compiled as 1-minute averages during each test period	Bias ≤ 5.0% range	Bias ≤ 2.8% range	Calculated following EPA Reference Method field calibrations	100 percent
	CO Levels	NDIR / TECO Model 48	0 to 1,000 ppm	290 to 429 ppm		Bias ≤ 5.0% range	Bias ≤ 2.4% range		
	THC Levels	FID / JUM Model 3-300	0 to 1,000 ppm	231 to 467 ppm		Bias ≤ 5.0% range	Bias ≤ 2.7% range		
	CO_2 Levels	NDIR / Teledyne Model 731R	0 to 20 %	7.0 to 8.0 %		Bias ≤ 5.0% range	Bias ≤ 1.7% range		
	CH_4 content	GC / FID HP Model 5890	0 to 1,000 ppm	200 to 450 ppm		± 5%	± 2%		
	O_2 Levels	Teledyne Model 320 AR	0 to 25 %	6.8 to 8.1 %		Bias </= 5.0% range	Bias </= 1.0% range		
Ambient Meteorological Conditions	Ambient Temperature	RTD / Vaisala Model HMP 35A	50 to 110 ^{o}F	72 to 98 ^{o}F	once per minute	0.2 ^{o}F	0.2 ^{o}F	Reviewed manufacturer calibration certificates	100 percent
	Relative Humidity	Vaisala Model HMP 35A	0 to 100 % RH	17 to 82 % RH		± 2% (0 to 90% RH) ± 3% (90 to 100% RH)	± 2% (0 to 90% RH) ± 3% (90 to 100% RH)		

were to obtain 1-minute readings for fuel flow rates and emission rate data for each test conducted, and to analyze two gas samples during each hour. These goals were met, except that the natural gas samples were collected approximately once per hour according to station sampling intervals. The accuracy results for each measurement are discussed below.

3.2.1 Monitoring Engine Operation

During each test period, stable engine operations were evaluated using measurement variability guidelines provided in ASME PTC17. Table 3-3 summarizes the maximum variations observed in engine power output, engine speed, fuel gas pressure, and ambient (intake air) temperature during the tests. Variability in fuel heat value is discussed in Section 3.2.2. As shown in the table, the PTC 17 guidelines for engine speed were exceeded during runs 1, 2, and 12, and guidelines for fuel pressure were exceeded during runs 1 and 2. Variability in all the other measurements was within the guidelines. Exceedances were small and were not considered grounds to invalidate certain tests for the following reasons. Engine speed can be controlled manually, and the variability could have been reduced during the test periods; however, for this verification, it was preferred to allow the engine to run uninhibited during the test periods to observe its reaction to Controller operations. Regarding fuel pressure, the pressure at the point of measurement (the location of fuel flow meter) was approximately 105 psig. However, the pressure is regulated down to less than 1 psig just upstream of the carburetor, so the measured pressures were not indicative of actual variability in pressures at the engine.

Table 3-3. Maximum Variability Observed in Operating Conditions

Measured Parameter (units of measurement)	Maximum Variability Allowed Under PTC 17[a]	Actual Maximum Variability Observed in Field Measurements (%)[b] (Individual Test Run Number)					
		1	2	10	11	12	13
Power Output (BHp)	± 3 %	2	0	0	3	1	0
Engine Speed (rpm)	± 1 %	3	2	1	1	2	1
Fuel Pressure (psig)	± 2 %	4	3	2	2	2	2
Inlet Air Temperature (°F)	± 10 °F	3	4	1	2	2	1

[a] = (Average of Test Run – Maximum Observed Value) / Average of Test Run * 100
[b] Variation in inlet air temperature is in units of °F

3.2.2 Changes in Fuel Consumption Rate

The DQO for changes in fuel consumption rates was identified in Table 3-1 as having an overall parameter uncertainty of ± 20 percent. This uncertainty was derived based on an anticipated reduction in fuel use of approximately 5 percent, and the accuracy goals (DQIs) for the three measurements used to calculate fuel consumption rate (fuel flow, fuel LHV, and engine power output). Table 3-2 and the following discussions show that the DQI goals for each of these three variables were met or exceeded during the test periods. The average fuel consumption rate during the test periods was approximately 9,147 Btu/BHp-hr with a propagated uncertainty of approximately ± 92.4 Btu/BHp-hr. However, measured changes in fuel consumption rate were less than 1 percent, averaging approximately 80 Btu/BHp-hr. Therefore the average uncertainty in changes in fuel consumption rate achieved during the tests was greater than the average differences. The following paragraphs discuss the data quality evaluations associated with each variable measured to determine the change in fuel consumption rates.

3.2.2.1 Fuel Flow Rate

The Test Plan specified the use of an integral orifice meter (Rosemount Model 3095) to measure the flow of natural gas supplied to the test engine. The integral orifice meter was factory-calibrated prior to installation in the field, and its calibration records were reviewed to ensure that the ± 1.0 percent instrument accuracy goal was satisfied. QC checks (sensor diagnostics) listed in Table 3-4 were conducted to ensure proper function in the field.

Sensor diagnostic checks consisted of zero flow verification by isolating the meter from the flow, equalizing the pressure across the differential pressure (DP) sensors, and reading the pressure differential and flow rate. The sensor output must read zero flow during these checks. Transmitter analog output checks, known as the loop test, consist of commanding the transmitter to produce 4 and 20 mA currents. The current output levels are verified with a Fluke multimeter to ensure that 4 and 20 mA signals are indeed produced. These results were found to be within ± 0.01 mA. Reasonableness checks revealed that measured flow rates were within the range specified by Caterpillar for this model engine.

Table 3-4. Results of Additional Fuel Consumption Rate QC Checks

Measurement Variable	QA/QC Check	When Performed/Frequency	Allowable Result	Results Achieved
Mass Flow Rate	Sensor Diagnostics (zero check and loop tests)	Beginning and end of verification testing	Pass	Passed all sensor diagnostic checks
	Reasonableness checks	Throughout test	Readings should be between 100 and 120 scfm at full load	All readings within specified range

3.2.2.2 Engine Power Output

Accurate input of compressor cylinder design (bore and stroke dimensions) and accurate pressure measurements on the compressors was required to achieve the target DQI for engine power output. The transducers were factory-calibrated and accurate to within 0.1 percent of reading. In accordance with the Test Plan, the Center relied on these factory calibrations to evaluate the accuracy of the transducer measurements. Also, the suction and discharge pressures measured by Technical Compressor Services, Inc. (TCS) were consistent with the station gauge readings (reasonableness checks). Cylinder bore and stroke dimensions obtained from design drawings from the compressor manufacturer are assumed to be 100 percent accurate; therefore, the data quality goal for engine power output was met.

3.2.2.3 Fuel Lower Heating Value (LHV)

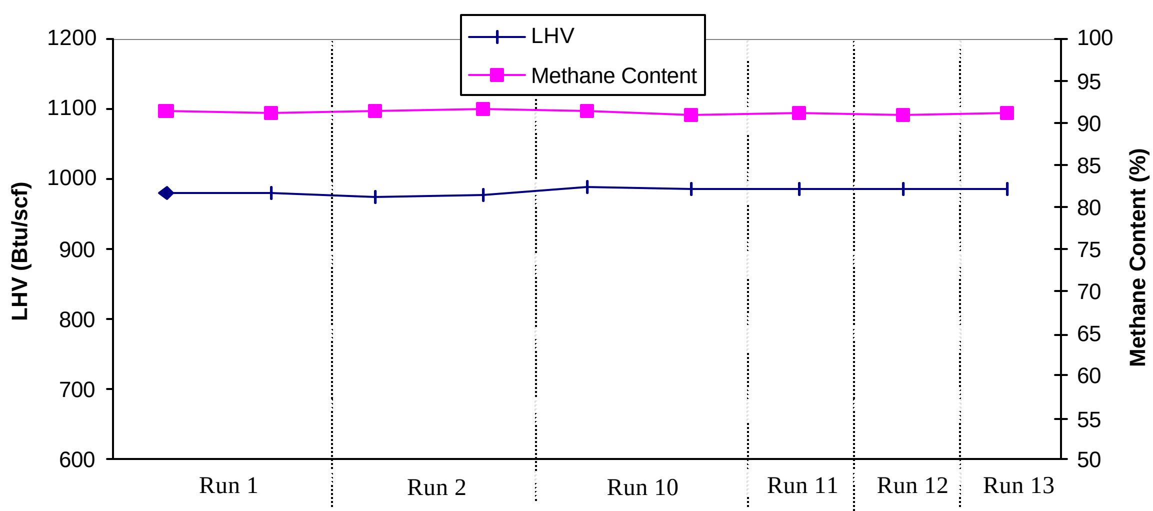
Station fuel gas is sampled hourly by the host to determine composition and LHV. Full documentation of sample collection date, time, and results is maintained by the host site. The station owners generate revenue based on the LHV of residual gas pumped by this station; therefore, this is a very important value for the station. Analyses are conducted via direct injections of station residual gas into the GC/TCD analyzer. The data quality indicator goal was to measure CH_4 concentrations that were within ± 0.2 percent of a NIST-traceable calibration gas.

The host facility calibrates the GC/TCD on a monthly basis to confirm the accuracy of the analyses, using calibration materials meeting Gas Processing Association (GPA) Standards for analysis of natural gas (GPA 2000). Table 3-5 summarizes results of the calibrations conducted before and after the testing period. The results for all gas species were within the ASTM specified levels, including CH_4, which was within the GHG Center's specified level. The Test Plan specified that LHV readings be collected every 30 minutes. However, it was later learned that the station gas composition analyzer operates automatically and samples the residual gas at 1-hour intervals. Therefore, the completeness goal for LHV was not met. During normal station operation, gas composition is uniform and, because all test results reported here were obtained during normal and stable station operation, this reduction in the frequency of LHV measurements is not believed to significantly affect the findings of this verification (Figure 3-1).

Table 3-5. GC/TCD Calibration Results

Gas Component	Calibration Standard Value (%)	Analyzer Responses (%)	
		June 2001	July 2001
Nitrogen	3.997	4.00	4.01
Methane	88.872	88.97	88.96
Ethane	3.075	3.08	3.08
Carbon Dioxide	0.501	0.50	0.50
Propane	2.026	2.02	2.02
Isobutane	0.404	0.40	0.40
N-Butane	0.903	0.90	0.90
Isopentane	0.101	0.10	0.10
N-Pentane	0.101	0.10	0.10

Figure 3-1. Variation in Fuel Quality During Test Periods



3.2.2.4 Propagation of Errors for Fuel Consumption Rate Measurements

The measurement errors listed above for the three different measurements were propagated to yield the overall uncertainty of the average fuel consumption rate. The estimate of the compounded error (*Shigehara et al. 1970*) is:

$$3\sigma = \left[\sum_{i=1}^{n} (err_i)^2 \right]^{1/2}$$

Where:

3σ = Compounded measurement error within 3 standard deviations of the mean
n = Total number of contributing parameters
err = Individual measurement error for each parameter

Using this equation, the propagated error for the fuel consumption rate determinations is ± 1.01 percent. Using the compounded error, the mean fuel consumption rate during all valid test runs was 9,147 ± 92.4 Btu/Bhp-hr.

3.2.3 Exhaust Stack Emission Measurements

The DQO for changes in emission rates was set at 13 percent uncertainty for NO_X and 24 percent for the other pollutants. These DQOs were based on anticipated reductions in emission rates (10 percent for NO_X) and the accuracy goals (DQIs) for each of the measurements used in this determination (including pollutant concentration, exhaust gas O_2 content, fuel flow rate, engine power output, 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 is a function of not only measurement accuracy, but also the magnitude of the changes realized through use of the Controller. Uncertainty in changes in emission rates was evaluated by propagating the error in variable measurements, and applying the propagated error to the average change in emissions observed during the testing. This was done separately for each pollutant at both full and reduced load test conditions: results are summarized in Table 3-6. The table shows that the uncertainty in the results is lower than the goals of 13 percent for NO_X and 24 percent for the other pollutants; therefore, the DQOs for changes in emission rates were met. The following paragraphs discuss the data quality evaluations associated with each variable measured to determine the change in emission rates.

Table 3-6. Summary of Uncertainty in Changes in Emission Rate Results

Test Condition	Determination of Uncertainty	Pollutant				
		NO_X	CO	THCs	CH_4	CO_2
Full Load	Average Change in Emissions (g/BHp-hr, absolute value)	0.34	0.07	0.31	0.28	3
	Propagated Measurement Error (% reading)	± 2.02	± 1.85	±.85	± 5.20	± 1.80
	Uncertainty (g/BHp-hr, absolute value)	± 0.014	± 0.003	± 0.011	± 0.029	± 0.108
	Overall Uncertainty in Results (%)	**4.04**	**3.70**	**3.70**	**10.4**	**3.59**
Reduced Load	Average Change in Emissions (g/BHp-hr, absolute value)	0.35	0.04	0.33	0.30	3
	Propagated Measurement Error (% reading)	±2.17	± 1.92	± 2.06	± 5.20	± 1.81
	Uncertainty (g/BHp-hr)	± 0.015	± 0.002	± 0.014	± 0.031	± 0.109
	Overall Uncertainty in Results (%)	**4.35**	**3.84**	**4.12**	**10.4**	**3.62**

3.2.3.1 Determination of Pollutant Emissions and O_2 Concentrations

Section 3.2.2 demonstrated that the DQI goals for fuel flow rate, engine power output, and LHV were also met. Along with determination of emission rates, the same measurements apply to normalize emission rates to engine output. EPA Reference Methods were used to quantify emission rates of criteria pollutants and GHGs. The Reference Methods specify the sampling and calibration procedures, and data quality checks that must be followed. These Methods ensure that run-specific quantification of instrument and sampling system drift and accuracy occur 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 system bias of ± 5 percent of span or better for each of the pollutants. If system bias checks are within 5 percent of span, the measurement error, after correcting for system bias following reference method procedures, is less than ± 1 percent.

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 is recorded and must 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 NO_X, CO, CO_2, THCs, and O_2 were less than 2.8, 2.4, 2.7, 1.7, and 1.0 percent, respectively. After correcting the measured pollutant concentrations for system bias, the actual bias in the corrected numbers was well within 1 percent of the readings. Following Method 6C specification, the system bias checks were conducted before and after each test period. 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. In conclusion, the system bias goals and drift goals were met for all pollutants.

Another QA/QC check conducted during the verification was analyzer calibration error tests. These were conducted at the beginning of each day of testing. During these calibrations, a suite of calibration gases were introduced directly to each analyzer, and 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: 0, 40 to 60 percent of span, and 80 to 100 percent of span. Four gases were used for CO and THC: 0 and approximately 30, 60, and 90 percent of span. The analyzer calibration errors for all gases were below the allowable levels (2 percent of instrument span) as shown in Table 3-7. Results of each of the analyzer and sampling system calibrations conducted, including instrument calibration error tests and sampling system bias and drift checks, are presented in Appendix A.

Two additional QC checks were performed to better quantify the NO_X data quality. In accordance with Method 20, an interference test was conducted on the NO_X analyzer once before the testing started. This test confirms that the presence of other pollutants in the exhaust gas does 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 zero ± 2 percent of span:

- CO – 600 ppm in balance nitrogen (N_2)
- SO_2 – 255 ppm in N_2
- CO_2 – 10 percent in N_2
- O_2 – 22 percent in N_2

As shown in Table 3-7, the maximum measured value was well below the ± 2 percent of analyzer span required by the method.

The NO_X analyzer converts any NO_2 present in the gas stream to NO prior to gas analysis. The second QC check consisted of determining NO_2 converter efficiency prior to the beginning of emissions testing. This was done by introducing to the analyzer a mixture of mid-level calibration gas and air. 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 to have been either repaired or replaced prior to testing. As shown in Table 3-7, the converter efficiency was measured at 99.3 percent and was above the efficiency level required.

Table 3-7. Results of Additional Emissions Testing QC Checks

Parameter	QA/QC Check	When Performed/Frequency	Expected or Allowable Result	Maximum Result Measured During Load Tests (%)
NO_X	Analyzer interference check	Once before testing begins	± 2 % of analyzer span or less	0.54
	NO_2 converter efficiency	Once before testing begins	98 % efficiency or greater	99.3
NO_X, THCs, CO, CO_2, O_2	Analyzer calibration error test	Daily before testing	± 2 % of analyzer span or less	0.6 for NO_X 1.0 for CO 0.8 for THC 0.8 for CO_2 0.7 for O_2

As shown in Table 3-2, the host facility reported DQI for the methane analyses of approximately 2 percent (based on analyzer calibrations to NIST-traceable calibration standards). Each of the collected samples was analyzed in duplicate: differences between initial and duplicates averaged less than 0.1 percent for all of the valid test runs.

3.2.3.2 Propagation of Errors for Emission Rate Measurements

Emission rate determination required measurement of several parameters as outlined above. Using those measurements, the following equation shows how emission rates in terms of grams per brake horsepower-hour were determined.

$$E = Q[Pc]F_{O2}\left[\frac{20.9}{(20.9 - O_2)}\right]$$

Where:

E = emission rate, g/BHp-hr
Q = heat rate, MMBtu/BHp-hr (derived from fuel flow rate [dscf/hr], heating value [LHV; Btu/dscf], and engine power [BHp])
Pc = pollutant concentration in the stack gas, ppm
F_{O2} = Oxygen-based fuel F-factor, dscf/MMBtu
O_2 = oxygen in the stack gas, %

Each of these variables has associated errors as previously described which compound into the total potential error. For example, the individual contributing errors as determined during the field testing for NO_x emissions were:

Description	Error, %	Basis of Determination
BHp	± 0.10	Factory Calibration
O_2 EPA protocol calibration gas	± 1.00	Cal Gas Certification
O_2 average bias for all test runs	± 0.20	Field Calibrations
Fuel flow rate	± 1.00	Factory Calibration
Fuel lower heating value (LHV)	± 0.10	Field Calibrations
Oxygen F-factor	± 0.10	Field Calibrations
NO_x EPA protocol calibration gas	± 1.00	Cal Gas Certification
NO_x average bias for all test runs	± 1.00	Field Calibrations

Errors were propagated using the same equation as in Section 3.2.2.4. The compounded "3σ" error is the square root of the sum of the errors squared. Total compounded error for the NO_x emission rate determination is therefore ± 2.02 percent.

3.2.4 Ambient Measurements

Ambient temperature and relative humidity 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 relative humidity. 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 relative humidity were met.

3.3 AUDITS

A technical systems audit (TSA) and an audit of data quality (ADQ) were conducted by the GHG Center's QA Manager. The TSA did not include inspection of field activities for this verification, but did involve review of study requirements, procedures, and experimental design during Test Plan preparation to ensure that data quality objectives could be met. 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 TECHNICAL AND PERFORMANCE DATA SUPPLIED BY MIRATECH

The GECO Air/Fuel Ratio Controller utilized during this testing employs closed-loop feedback to keep the engine running accurately at the optimized conditions over varying engine load, ambient conditions, and fuel quality. Thus, the engine emissions and performance are much more stable over time. The Controller has a fast transient response, so it can keep the engine under control during system upsets, and therefore engine misfire and/or detonations are minimized and engine maintenance is reduced.

The details of the GECO Controller system are described in Section 1.2. The system is simple to install, easy to operate, and reliable (with built-in sensor health monitoring and comprehensive diagnostics). It also has several data port options for viewing/logging data or remote monitoring. The controller has adaptive logic and broad control, so it can be set to control the engine for minimum emissions, optimum efficiency, or highest power output.

For this testing, the GECO was set to achieve low NO_x and CO emissions per the site requirements, and was successful at achieving greater than 30 percent NO_x reductions. There was a slight impact on engine efficiency and, as predicted in Figure 1-1, a small increase in unburned hydrocarbons. However, for lean-burn engines, such as the type used in this study, unburned hydrocarbons can be eliminated easily from the exhaust with a relatively inexpensive oxidation catalyst. The removal of NO_x from the exhaust requires a more expensive selective catalytic reduction system. Additional work to optimize the ignition timing could be checked to reduce hydrocarbon emissions and the impact on fuel consumption.

During the relatively short duration of the testing, it was noted that the variability of the emissions was reduced when the GECO Controller was in use. Also, during non-normal plant operations, NO_x emission reductions of greater than 60 percent were observed, thereby demonstrating the value of having air/fuel ratio control in a real-world application.

5.0 REFERENCES

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APPENDIX A

Appendix A-1
Summary of Daily Reference Method Calibration Error Determinations

Date:	Gas	Measurement Range	Cal Gas Value	Analyzer Response	Calibration Error (% of Span)
		(ppm for NO_x, CO, THC; % for CO_2, O_2)			
6/20/01	NO_x	500	0.00	0.00	**0.00**
			226.00	226.50	**0.10**
			452.00	453.50	**0.30**
	CO	1000	0.00	-1.00	**-0.10**
			309.00	301.00	**-0.80**
			603.00	599.00	**-0.40**
			907.00	902.00	**-0.50**
	CO_2	20	0.00	0.08	**0.40**
			10.03	10.00	**-0.15**
			11.97	12.10	**0.65**
	O_2	25	0.00	0.00	**0.00**
			9.99	9.95	**-0.16**
			18.01	17.83	**-0.72**
	THCs	1000	0.00	0.00	**na**
			301.00	302.00	**0.33**
			500.00	501.00	**0.20**
			897.00	900.00	**0.33**
6/21/01	NO_x	500	0.00	0.00	**0.00**
			226.00	229.00	**0.60**
			452.00	453.00	**0.20**
	CO	1000	0.00	0.00	**0.00**
			309.00	299.00	**-1.00**
			603.00	599.00	**-0.40**
			907.00	900.00	**-0.70**
	CO_2	20	0.00	0.16	**0.80**
			10.03	10.00	**-0.15**
			11.97	12.00	**0.15**
	O_2	25	0.00	0.00	**0.00**
			9.99	10.00	**0.04**
			18.01	17.83	**-0.72**
	THCs	1000	0.00	0.00	**na**
			301.00	299.00	**-0.66**
			500.00	498.00	**-0.40**
			897.00	890.00	**-0.78**

(continued)

Appendix A-1 (Continued)

Summary of Daily Reference Method Calibration Error Determinations

Date:	Gas	Measurement Range	Cal Gas Value	Analyzer Response	Calibration Error (% of Span)
		(ppm for NO_x, CO, THC; % for CO_2, O_2)			
6/22/01	NO_x	500	0.00	0.00	**0.00**
			226.00	228.00	**0.40**
			452.00	453.50	**0.30**
	CO	1000	0.00	0.00	**0.00**
			309.00	300.00	**-0.90**
			603.00	610.00	**0.70**
			907.00	910.00	**0.30**
	CO_2	20	0.00	0.16	**0.80**
			10.03	9.92	**-0.55**
			11.97	11.98	**0.05**
	O_2	25	0.00	0.00	**0.00**
			9.99	10.00	**0.04**
			18.01	18.00	**-0.04**
	THCs	1000	0.00	0.00	**na**
			301.00	299.00	**-0.66**
			500.00	500.00	**0.00**
			897.00	895.00	**-0.22**
6/23/01	NO_x	500	0.00	0.00	**0.00**
			226.00	224.50	**-0.30**
			452.00	453.50	**0.30**
	CO	1000	0.00	-1.00	**-0.10**
			309.00	301.00	**-0.80**
			603.00	599.00	**-0.40**
			907.00	902.00	**-0.50**
	CO_2	20	0.00	0.08	**0.40**
			10.03	10.00	**-0.15**
			11.97	12.10	**0.65**
	O_2	25	0.00	0.00	**0.00**
			9.99	9.95	**-0.16**
			18.01	17.83	**-0.72**
	THCs	1000	0.00	na	**na**
			301.00	302.00	**0.33**
			500.00	501.00	**0.20**
			897.00	900.00	**0.33**

Appendix A-2. Summary of Reference Method System Bias and Drift Checks (as percent

20-Jun-01

Analyzer Spans: NO_x = 500 ppm, CO = 1000 ppm, THC = 1000 ppm, CO_2 = 20%, O_2 = 25%

Run Number:		Initial	1	2	3	4
NO_x Zero	**System Response (ppm)**	10.0	9.0	5.0	4.0	10.0
	System Error (% of span)	2.0	1.8	1.0	0.8	2.0
	Drift (% of span)	NA	-0.2	-1.0	-1.2	0.0
NO_x Mid	**System Response (ppm)**	442.5	451.0	439.0	447.0	447.5
	System Error (% of span)	-1.9	-0.2	-2.6	-1.0	-0.9
	Drift (% of span)	NA	1.7	-0.7	0.9	1.0
CO Zero	**System Response (ppm)**	0.0	0.0	-1.0	-2.0	-3.0
	System Error (% of span)	0.0	0.0	-0.1	-0.2	-0.3
	Drift (% of span)	NA	0.0	-0.1	-0.2	-0.3
CO Mid	**System Response (ppm)**	605.0	598.0	602.0	598.0	595.0
	System Error (% of span)	0.2	-0.5	-0.1	-0.5	-0.8
	Drift (% of span)	NA	-0.7	-0.3	-0.7	-1.0
O_2 Zero	**System Response (%)**	0.00	0.00	0.00	0.00	0.00
	System Error (% of span)	0.0	0.0	0.0	0.0	0.0
	Drift (% of span)	NA	0.0	0.0	0.0	0.0
O_2 Mid	**System Response (%)**	10.00	10.00	9.98	9.98	9.95
	System Error (% of span)	0.0	0.0	0.0	0.0	-0.2
	Drift (% of span)	NA	0.0	-0.1	-0.1	-0.3
CO_2 Zero	**System Response (%)**	0.20	0.20	0.20	0.20	0.20
	System Error (% of span)	1.0	1.0	1.0	1.0	1.0
	Drift (% of span)	NA	0.0	0.0	0.0	0.0
CO_2 Mid	**System Response (%)**	9.90	9.90	9.87	9.92	9.92
	System Error (% of span)	-0.6	-0.6	-0.8	-0.5	-0.5
	Drift (% of span)	NA	0.0	-0.2	0.1	0.1
THCs Zero	**System Response (ppm)**	3.0	3.0	2.0	1.0	1.0
	System Error (% of span)	0.3	0.3	0.2	0.1	0.1
	Drift (% of span)	NA	0.0	-0.1	-0.2	-0.2
THCs Mid	**System Response (ppm)**	895.0	897.0	890.0	886.0	900.0
	System Error (% of span)	-0.2	0.0	-0.7	-1.1	0.3
	Drift (% of span)	NA	0.2	-0.5	-0.9	0.5

(continued)

Appendix A-2 (Continued) Summary of Reference Method System Bias and Drift Checks (as perce

21-Jun-01

Analyzer Spans: NO_x = 500 ppm, CO = 1000 ppm, THC = 1000 ppm, CO_2 = 20%, O_2 = 25%

Run Number:		Initial	5	6	7	8	9/10
NO_x Zero	System Response (ppm)	1.5	7.0	8.5	10.0	8.5	6.0
	System Error (% of span)	0.3	1.4	1.7	2.0	1.7	1.2
	Drift (% of span)	NA	1.1	1.4	1.7	1.4	0.9
NO_x Mid	System Response (ppm)	453.0	446.0	445.0	450.0	449.0	442.5
	System Error (% of span)	0.2	-1.2	-1.4	-0.4	-0.6	-1.9
	Drift (% of span)	NA	-1.4	-1.6	-0.6	-0.8	-2.1
CO Zero	System Response (ppm)	2.0	-2.0	-9.0	-10.0	-2.0	-5.0
	System Error (% of span)	0.2	-0.2	-0.9	-1.0	-0.2	-0.5
	Drift (% of span)	NA	-0.4	-1.1	-1.2	-0.4	-0.7
CO Mid	System Response (ppm)	600.0	589.0	585.0	579.0	591.0	582.0
	System Error (% of span)	-0.3	-1.4	-1.8	-2.4	-1.2	-2.1
	Drift (% of span)	NA	-1.1	-1.5	-2.1	-0.9	-1.8
O_2 Zero	System Response (%)	0.00	0.00	0.00	0.00	0.00	-0.01
	System Error (% of span)	0.0	0.0	0.0	0.0	0.0	0.0
	Drift (% of span)	NA	0.0	0.0	0.0	0.0	-0.1
O_2 Mid	System Response (%)	9.95	10.00	10.00	10.00	10.00	10.00
	System Error (% of span)	-0.2	0.0	0.0	0.0	0.0	0.0
	Drift (% of span)	NA	0.3	0.3	0.3	0.3	0.3
CO_2 Zero	System Response (%)	0.20	0.20	0.20	0.23	0.25	0.28
	System Error (% of span)	1.0	1.0	1.0	1.2	1.3	1.4
	Drift (% of span)	NA	0.0	0.0	0.2	0.3	0.4
CO_2 Mid	System Response (%)	9.9	10.0	10.0	10.0	10.0	10.0
	System Error (% of span)	-0.6	-0.1	-0.1	-0.1	-0.1	-0.1
	Drift (% of span)	NA	0.5	0.5	0.5	0.5	0.5
THCs Zero	System Response (ppm)	0.0	0.0	0.0	0.0	2.0	2.0
	System Error (% of span)	0.0	0.0	0.0	0.0	0.2	0.2
	Drift (% of span)	NA	0.0	0.0	0.0	0.2	0.2
THCs Mid	System Response (ppm)	900.0	891.0	890.0	880.0	882.0	880.0
	System Error (% of span)	0.3	-0.6	-0.7	-1.7	-1.5	-1.7
	Drift (% of span)	NA	-0.9	-1.0	-2.0	-1.8	-2.0

(continued)

Appendix A-2 (Continued). Summary of Reference Method System Bias and Drift Checks (as percent of span)
22-Jun-01
Analyzer Spans: NO_x = 500 ppm, CO = 1000 ppm, THC = 1000 ppm, CO_2 = 20%, O_2 = 25%

Run Number:		Initial	11/12	13/14	15/16	17/18
NO_x Zero	System Response (ppm)	2.0	7.0	6.0	14.0	6.0
	System Error (% of span)	0.4	1.4	1.2	2.8	1.2
	Drift (% of span)	NA	1.0	0.8	2.4	0.8
NO_x Mid	System Response (ppm)	454.0	450.0	458.0	450.0	447.5
	System Error (% of span)	0.4	-0.4	1.2	-0.4	-0.9
	Drift (% of span)	NA	-0.8	0.8	-0.8	-1.3
CO Zero	System Response (ppm)	0.0	-2.0	-3.0	-8.0	-4.0
	System Error (% of span)	0.0	-0.2	-0.3	-0.8	-0.4
	Drift (% of span)	NA	-0.2	-0.3	-0.8	-0.4
CO Mid	System Response (ppm)	599.0	590.0	590.0	582.0	585.0
	System Error (% of span)	-0.4	-1.3	-1.3	-2.1	-1.8
	Drift (% of span)	NA	-0.9	-0.9	-1.7	-1.4
O_2 Zero	System Response (%)	0.00	0.00	0.00	0.00	0.00
	System Error (% of span)	0.0	0.0	0.0	0.0	0.0
	Drift (% of span)	NA	0.0	0.0	0.0	0.0
O_2 Mid	System Response (%)	9.88	10.00	10.00	10.00	9.95
	System Error (% of span)	-0.4	0.0	0.0	0.0	-0.2
	Drift (% of span)	NA	0.6	0.6	0.6	0.3
CO_2 Zero	System Response (%)	0.20	0.26	0.24	0.20	0.33
	System Error (% of span)	1.0	1.3	1.2	1.0	1.7
	Drift (% of span)	NA	0.3	0.2	0.0	0.7
CO_2 Mid	System Response (%)	10.0	10.0	10.0	10.1	10.0
	System Error (% of span)	-0.1	-0.1	-0.1	0.4	-0.1
	Drift (% of span)	NA	0.0	0.0	0.5	0.0
THCs Zero	System Response (ppm)	0.0	2.0	2.0	0.0	0.0
	System Error (% of span)	0.0	0.2	0.2	0.0	0.0
	Drift (% of span)	NA	0.2	0.2	0.0	0.0
THCs Mid	System Response (ppm)	890.0	881.0	887.0	891.0	870.0
	System Error (% of span)	-0.7	-1.6	-1.0	-0.6	-2.7
	Drift (% of span)	NA	-0.9	-0.3	0.1	-2.0

(continued)

Appendix A-2 (Continued). Summary of Reference Method System Bias and Drift Checks (as percent of span)
23-Jun-01

Analyzer Spans: NO_x = 500 ppm, CO = 1000 ppm, THC = 1000 ppm, CO_2 = 20%, O_2 = 25%

Run Number:		Initial	19/20	21/22	23/24	25/26
NO_x Zero	System Response (ppm)	2.5	10.0	1.5	2.5	2.5
	System Error (% of span)	0.5	2.0	0.3	0.5	0.5
	Drift (% of span)	NA	1.6	-0.1	0.1	0.1
NO_x Mid	System Response (ppm)	450.0	443.5	454.5	454.0	454.0
	System Error (% of span)	-0.4	-1.7	0.5	0.4	0.4
	Drift (% of span)	NA	-2.1	0.1	0.0	0.0
CO Zero	System Response (ppm)	0.0	0.0	-2.0	-2.0	-2.0
	System Error (% of span)	0.0	0.0	-0.2	-0.2	-0.2
	Drift (% of span)	NA	0.0	-0.2	-0.2	-0.2
CO Mid	System Response (ppm)	606.0	598.0	593.0	587.0	587.0
	System Error (% of span)	0.3	-0.5	-1.0	-1.6	-1.6
	Drift (% of span)	NA	-0.1	-0.6	-1.2	-1.2
O_2 Zero	System Response (%)	0.00	0.00	0.00	0.00	0.00
	System Error (% of span)	0.0	0.0	0.0	0.0	0.0
	Drift (% of span)	NA	0.0	0.0	0.0	0.0
O_2 Mid	System Response (%)	9.90	9.88	9.88	9.95	9.95
	System Error (% of span)	-0.4	-0.4	-0.4	-0.2	-0.2
	Drift (% of span)	NA	0.0	0.0	0.3	0.3
CO_2 Zero	System Response (%)	0.20	0.26	0.30	0.30	0.33
	System Error (% of span)	1.0	1.3	1.5	1.5	1.7
	Drift (% of span)	NA	0.3	0.5	0.5	0.7
CO_2 Mid	System Response (%)	10.0	10.0	10.0	10.1	10.1
	System Error (% of span)	-0.1	-0.1	-0.1	0.4	0.4
	Drift (% of span)	NA	0.0	0.0	0.5	0.5
THCs Zero	System Response (ppm)	0.0	1.0	1.0	2.0	2.0
	System Error (% of span)	0.0	0.1	0.1	0.2	0.2
	Drift (% of span)	NA	0.1	0.1	0.2	0.2
THCs Mid	System Response (ppm)	891.0	874.0	899.0	880.0	880.0
	System Error (% of span)	-0.6	-2.3	0.2	-1.7	-1.7
	Drift (% of span)	NA	-1.6	0.9	-1.0	-1.0

NA = Not applicable