SRI/USEPA-GHG-VR-16
June 2002

Environmental Technology Verification Report

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

Prepared By:

Greenhouse Gas Technology Center
Southern Research Institute

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

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

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Phase II

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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.

1.0 INTRODUCTION

1.1 BACKGROUND

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

The Greenhouse Gas Technology Center (GHG Center) is one of six verification organizations operating under ETV. The GHG Center is managed by the 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 Test and Quality Assurance 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 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.

Performance testing of the Controller 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. The verification was executed in two phases of testing. Phase I evaluated Controller installation requirements, and changes in fuel consumption and engine emission rates realized through use of the Controller. Phase II evaluated changes in lubrication oil degradation rates realized by using the Controller. Details on the verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures for both phases of testing can be found in the Test Plan titled *Test and Quality Assurance Plan, MIRATECH Corporation GECO™ 3001Air/Fuel Ratio Controller* (SRI 2001a). Results of the Phase I testing are documented in a separate report titled *Environmental Technology Verification Report, MIRATECH Corporation GECO™ 3001Air/Fuel Ratio Controller (Manufactured by Woodward Governor Company)* (SRI 2001b). Both can be downloaded from the GHG Center's Web site (www.sri-rtp.com). This report presents results of the Phase II testing for evaluation of lubrication oil degradation rates.

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 Phase II verification test results, and Section 3 assesses the quality of the data obtained. Section 4, provided by MIRATECH, provides additional information regarding the Controller. The GHG Center has not independently verified information provided in Section 4.

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/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 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

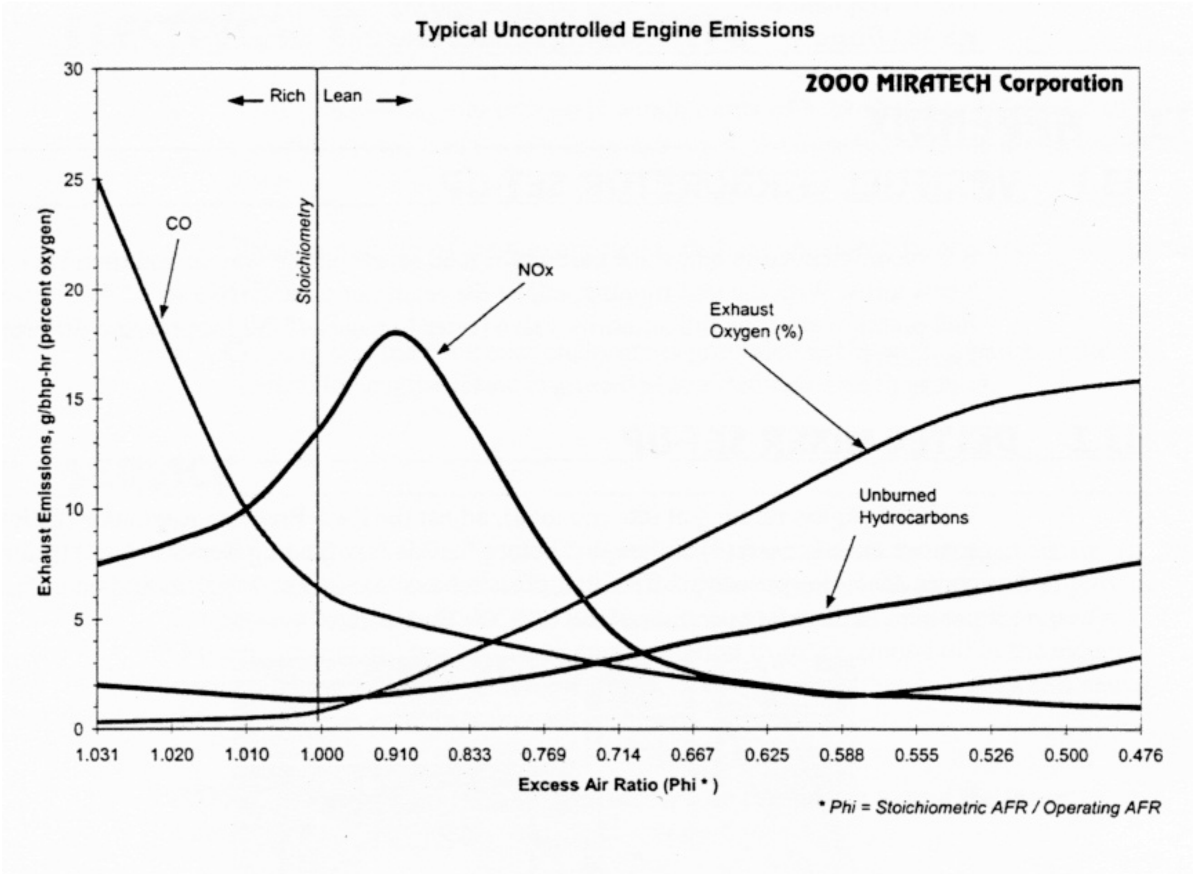


Figure 1-2. Schematic of the GECO 3001 Controller (provided by MIRATECH Corporation)

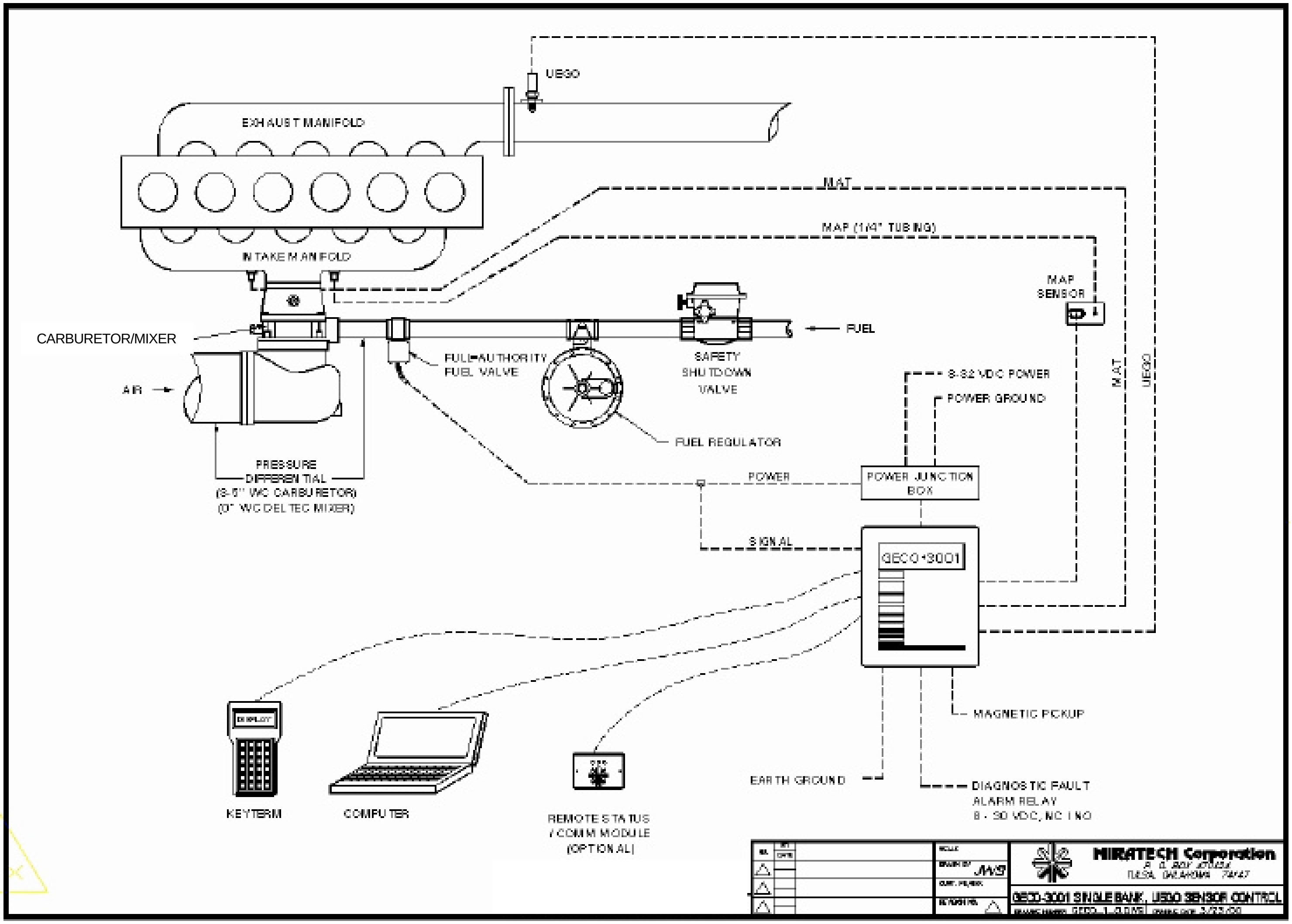


Table 1-1. GECO Air/Fuel Controller System Components	
Component	**Function**
Engine Control Unit (ECU) Control Board	Includes the microprocessor controller and all electronics associated with power regulation, signal inputs and filtering, controlled outputs, and communications. Also includes the closed-loop enable switch.
Keyterm	A terminal useful for communication with the Controller in applications where a computer is not available.
User Interface Module	Allows the user to view the 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 crank default position that can be preset as desired. The valve remains in this position until the engine reaches 400 rpm, at which point the Controller goes into open-loop mode and sets valve positions according to a preprogrammed valve learn table. The Controller will operate in open-loop mode until the preprogrammed target air/fuel ratio is surpassed, at which point the Controller will go into 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 (IC) 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 lubrication oil, a tune-up, and other routine maintenance.

Both engines have a rated power output of 1,085 brake horsepower (bhp) and each consumes 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 fuel lower heating value (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. 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 (SRI 2001a).

For this verification, one 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 during Phase I testing over a 4-day period after completion of Controller installation, shakedown, and start-up activities on the Test Engine. The performance evaluation approach and test procedures for those evaluations are detailed in the Phase I report and are not repeated here.

1.4.1 Changes in Lubrication Oil Degradation Rate

Evaluation of oil degradation rates continued over an additional 8-month period from June 2001 through February 2002. This extended evaluation was 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 was not equipped with a Controller and operated under similar conditions.

Users of IC engines typically collect oil samples from the engines at routine intervals and analyze the samples for compounds that can corrode and degrade combustion equipment. These analyses are a useful preventive maintenance tool for operators and can help to evaluate the performance and condition of the engines. The test host site typically performs these oil analyses every 45 days. Poor fuel quality, excessive fuel blow-by (unburned fuel passing the piston rings and entering the crankcase), unstable air/fuel ratios, and fuel mixtures that are too rich or lean can all accelerate the rate of oil degradation. In support of this verification, oil samples were collected and analyzed for both the Test and Control Engines each month to evaluate if use of the Controller on the Test Engine slowed the oil degradation process.

Both engines were equipped with fresh oil in June 2001, approximately 2 weeks prior to the verification test period. The first set of samples was collected on June 23 immediately after completion of the Phase I testing. For the remainder of the Phase II verification period through February 4, 2002, the Test Engine was operated with the Controller operating in closed-loop mode (air/fuel ratios were continuously controlled). Samples were then collected on a monthly basis for the duration of the 8-month verification period to enable the development of oil degradation profiles for each engine. Engine operators collected the samples from a sampling port in each engine oil system located at a point between the oil filters and the oil cooler. The Test Plan specified that duplicate samples would be collected each month in order to increase the size of the dataset. However, instead of collecting duplicate samples, the GHG Center extended the verification period to 8 months in order to generate additional data and improve the oil quality profiles.

Samples were shipped to CTC Analytical Laboratories in Phoenix, Arizona, each month after collection to quantify each of parameters listed in Table 1-2. Station operating logs were used to document the operating hours of both engines during the verification period. In order to make a meaningful comparison of oil degradation rates on the two engines, operating hours needed to be similar. Typically, the engines operate on the same schedule so long as equipment malfunctions do not occur.

Table 1-2. Lubrication Oil Analyses			
Analyte	**Reference Method**	**Principle of Analysis**	**Reporting Units**
Oxidation	Not Specified	Fourier-Transform Infra-red Spectroscopy	absorbance per centimeter (cm)
Nitration	Not Specified	Fourier-Transform Infra-red Spectroscopy	absorbance per centimeter (cm)
Viscosity @ 40°C	ASTM-D445	Kinematic	centistokes (cSt)
Total Acid Number	ASTM-D974	Potentiometric Titration	mg KOH/g

The analytes listed in the table are indicators of oil condition and often times related. Oil nitration, quantified in units of absorbance per centimeter (cm), is a result of piston blow-by and fuel and/or combustion products mixing with the engine oil. The products of nitration are highly acidic and therefore have an obvious impact on total acid numbers, but also can increase or accelerate the effects of oxidation, and increase the oil viscosity. Oxidation, also quantified as absorbance per cm, is a chemical change in oil composition caused by nitration and high-temperature operation. Oxidation can also increase oil viscosity and reduce the oil's ability to lubricate engine components.

Viscosity, quantified as centistokes (cSt), is a measure of the thinness of the oil and is used as a primary indicator of the oil's lubricating abilities. Abnormally high or low oil viscosity can be caused by dilution, contamination, or oxidation and can be damaging to engine components. Total base and total acid numbers are also indicators of oil condition and contamination. Most oils contain alkaline additives to help neutralize the effects of acidic products that accumulate in the oil over time. In an engine experiencing excessive blow-by, improper air/fuel ratios, or poor fuel quality, the total acid number can increase dramatically over time, thereby reducing ability of the oil to maintain neutral pH.

The trends observed in the viscosity, oxidation, nitration, and total acid levels between the oil in the two engines were used to develop degradation profiles, and identify differences that developed between the Test and Control Engines. The operator that hosted this test has a strict policy of changing engine oil whenever abnormal analytical parameters are reported, or every 4 months, whichever occurs first. During planning of this test, the GHG Center recognized that, in a 4-month period, oil degradation may not have been severe enough to observe conclusive trends regarding how use of the Controller impacts the condition of the oil, or reduced oil degradation. During this verification, the laboratory's recommendation to change oil occurred after the fourth monthly samples were collected, and therefore coincided with the facility's policy of changing after a 4-month period. Both engines were charged with fresh oil after two consecutive 4-month periods.

QA/QC procedures specified in the above referenced analytical methods were followed by the laboratory, including instrument calibrations and performance checks. In addition, duplicate analyses were conducted on two samples from each engine to demonstrate analytical repeatability. A detailed discussion of the data quality of the oil sampling is provided in Section 3.0 of this report.

2.0 VERIFICATION RESULTS

2.1 OVERVIEW

The Test and Control Engines were charged with fresh lubricating oil on June 2, 2001. Installation and programming of the Controller was completed on June 19, 2001. The Phase I field testing for fuel consumption and engine emissions was conducted from June 20 to 23, 2001. The first set of oil samples was collected on June 23 at the conclusion of the Phase I test period. Samples were then collected each month through February 2002, except during January 2002 when site operators did not collect samples.

Station operating logs were used to document the operating hours of both engines during the verification period. Engine operating hours and sample collection dates are summarized in Table 2-1.

Table 2-1. Schedule of Lubrication Oil Sampling

Date	Activity (Both Engines)	Operating Hours on Current Oil Charge	
		Test Engine	Control Engine
06/02/01*	1st Oil Change	na	na
06/23/01	Samples Collected	496	497
07/12/01		945	946
08/08/01		1590	1594
09/05/01		2252	2251
10/10/01		3054	3051**
10/11/01*	2nd Oil Change	na	na
11/08/01	Samples Collected	722	722
12/12/01		1526	1549
02/04/02		2736**	2808**

* An oil change with fresh lubricant occurred on both engines.
** Based on the analytical results from these samples, the laboratory recommended that the engine oil be changed.
na = Not applicable

For samples collected on October 10, analytical results indicated that only the oil in the Control Engine had degraded to abnormal levels. The laboratory flags oil analysis results as abnormal (or critical in some cases), when values exceed industry-accepted standards. For the oil parameters examined here, abnormal values include total acid numbers greater than 3.0 mg KOH/g oil, nitration greater than 35 absorbance units in cm, and oxidation greater than 25 cm.

The engine oil was changed with fresh lubricant on both engines on October 11, 2001, even though results of the oil analysis on the Test Engine were within normal tolerances. This is because the host site changes oil if abnormal values are indicated, or after 4 months have elapsed since the last oil change. Results of the samples collected on February 4 indicated abnormal oil conditions (i.e., elevated total acid, nitration, and oxidation levels) on both engines. At this time, the oil in both engines was changed again and the verification testing was concluded.

The operational hours presented in Table 2-1 show that both engines operated on nearly identical schedules during the period following the first oil change (June to October 2001). The Control Engine operated 72 hours longer than the Test Engine during the second period, about 3 percent longer. Site operators confirmed that the Test Engine's Controller remained in closed-loop mode for the entire test period, continuously trying to optimize the air/fuel mixture introduced to the engine.

2.2 RESULTS OF OIL PROPERTIES MEASUREMENTS

In the Test Plan, the GHG Center proposed to prepare degradation "profiles" or graphical plots of viscosity, oxidation, nitration, and total acid. These profiles would be used to identify significant differences in the rate of oil degradation between the Test and Control Engines (e.g., accelerated degradation in one engine compared to the other). It was envisioned that, if significant differences in the oil properties for both engines occurred, they would be revealed using graphical profiles, but it was recognized that these differences might be small and/or obscured by the variability that commonly occurs in oil analyses.

Graphical profiles for each oil parameter are shown in the sections that follow. With the possible exception of nitration, these graphs suggest that clear and significant differences were not evident in the rate of oil degradation between the Test and Control Engines. However, some trends observed in the profiles are identified and analyzed in the following section. Following this graphical assessment is a more traditional numerical analysis of the data.

2.2.1 Degradation Profiles: Lubrication Oil Nitration and Oxidation

Each of the samples was analyzed for nitration and oxidation to develop degradation profiles for the Test and Control Engines. Results of the nitration and oxidation analyses are presented in Figures 2-1 and 2-2.

Figure 2-1. Oil Nitration During Verification Period

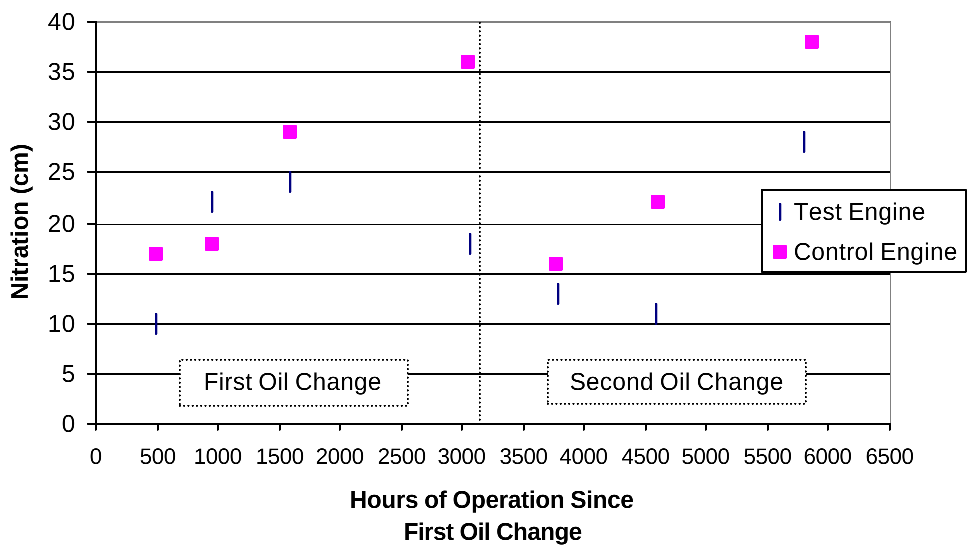
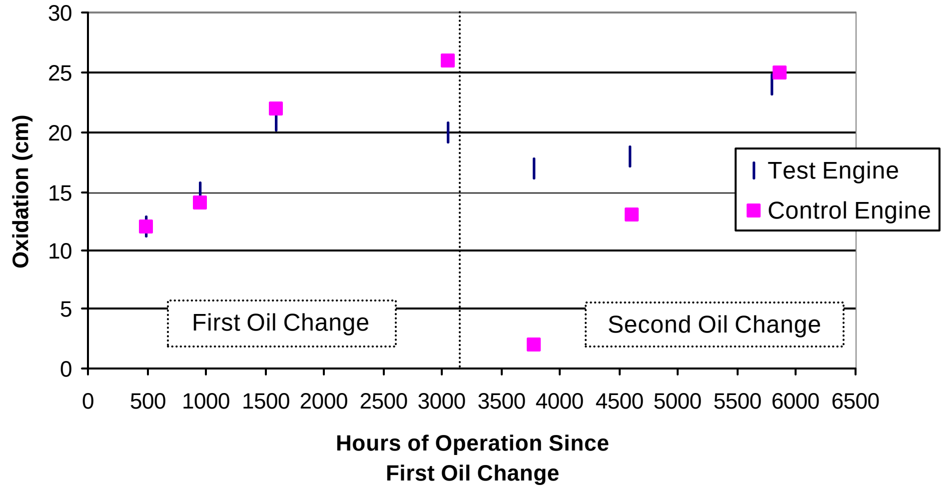


Figure 2-2. Oil Oxidation During Verification Period



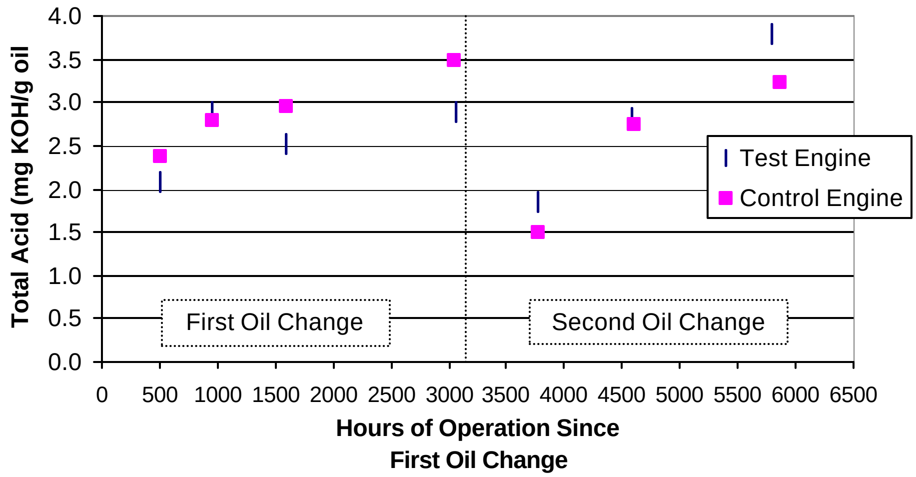
Both the Test and Control Engines operated nearly continuously as expected, and nitration and oxidation in both engines increased over time. It is generally accepted in the industry that fuel combustion products cause increases in nitration, and that nitration can accelerate the oil oxidation process. One cause of nitration is fuel mixtures that are either too rich or too lean, and exposure of lubrication oil to combustion products that contain acid gases like NO_X.

With the Controller maintaining optimum air/fuel ratios and lower NO_X formation on the Test Engine, it is possible that nitration rates, and subsequently oxidation rates, could be reduced. The data in Figure 2-1suggest that oil degradation, as expressed by increases in nitration (an oxidation precursor), is lower on the Test Engine. The Test Engine often had lower nitration values than the Control Engine. It should be noted that both the nitration and oxidation figures are skewed somewhat by the presence of data outliers, which are identified and examined more closely in Section 2.2.4.

2.2.2 Degradation Profile: Lubrication Oil Total Acid Number

Most nitration products formed in the oil are highly acidic and, therefore, whenever nitration levels increase, as was the case in these samples, the oil's total acid number is also likely to increase. Increasing oil acidity is evident for both engines during this verification, as illustrated in Figure 2-3.

Figure 2-3. Oil Total Acid Number Throughout the Verification Period

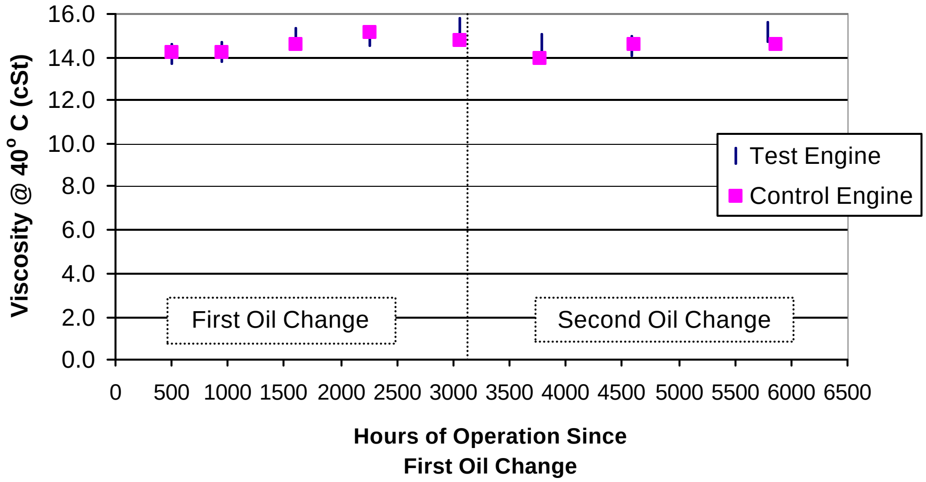


Acidity in the Control Engine oil after about 3,000 hours of operation was identified by the laboratory as abnormal prior to the second oil change, while the acidity in the Test Engine oil was at a narrowly acceptable level. Near the end of the second oil charge, the acid number for the oil in both engines was identified as abnormal after approximately 2,700 hours. The profile for total acid in the graph above does not present a clear indication that one engine's oil was acidifying more than the other.

2.2.3 Degradation Profile: Lubrication Oil Viscosity

Many variables can impact oil viscosity, including nitration, oxidation, and acidity of the lubrication oil. Therefore, whenever levels of these three parameters increase, the oil's viscosity is likely to degrade. On both engines, viscosity increased over time at similar rates as illustrated in Figure 2-4. The viscosity data do not present a clear indication that one engine's oil was degrading more significantly than the other.

Figure 2-4. Oil Viscosity Throughout the Verification Period



2.2.4 Numerical Data Analysis

In addition to the trends described above, an analysis of the profiles revealed the presence of several apparent outliers. To assess the validity of these apparent outliers, the data's reasonableness was assessed based on input from experts at the oil analysis laboratory, and an assessment of data trends and oil properties for both engines. The outliers identified and actions taken are outlined below.

- Test Engine: In Figure 2-1 (nitration data), the fourth data point for the Test Engine appears unreasonably low, especially considering the previous two samples had significantly higher nitration values, and nitration levels should not be reduced with added exposure to engine operations. Dilution with large quantities of fresh oil could cause such a large reduction in nitration, but evidence of a large dilution is not apparent in the other results, and if additions did occur, site operators indicate they would be small (under 4 percent of total volume per month). Later in this section, the average difference in nitration values between the Test and Control Engines is calculated. When this is done, the questionable fourth data point for the Test Engine (October 10, 2001) is considered invalid and not used in the calculations. To avoid biasing average results for the Control Engine, the corresponding October 10, 2001, sample for this engine was also invalidated and not used.

- Control Engine: In Figure 2-2 (oxidation data), the fifth oxidation data point in the chart for the Control Engine appears unreasonably low (2.0 cm). This oxidation sample was the first one collected after the second engine oil change occurred and, in comparison with other samples collected soon after an oil change, the 2.0 cm value is much lower. Specifically, the initial oxidation values for the Test Engine are 6 to 8 times higher, and the initial oxidation value for the Control Engine in June 2001 is 6 times higher. As such, the questionable fifth oxidation data point for the Control Engine (November 8, 2001) is considered invalid, and is not used in determining the average difference in oxidation values between the Test and Control Engines. To avoid biasing average results for the Test Engine, the corresponding November 8, 2001, sample collected for this engine was also invalidated and not used.

After removing the outliers as described above, differences between the Test and Control Engine oil properties were examined further. For each sample pair collected on the same day, the GHG Center subtracted oil properties measured for the Test Engine from the same oil properties measured on the

Control Engine. The average of these differences is calculated and reported in Table 2-2 for each oil parameter (Average Difference). Separate Average Difference values are reported, one including all valid samples collected following the first oil change, and one including all valid samples collected following the second oil change.

Table 2-2 presents the results described above. In addition, the Overall Average Difference is reported near the end of the table for each oil parameter. It is calculated by averaging all of the differences reported in Table 2-2 for that parameter. Finally, the Overall Average Percent difference is calculated and presented at the end of the table. This value provides an indication of the significance of any differences found, and was calculated by dividing the Overall Average Difference, calculated as described above, by the overall average value of that oil parameter for the Control Engine. The example below illustrates this calculation.

Overall Average Percent Difference For Viscosity =

100*[average of all viscosity differences/average of all Control Engine viscosity values]

= 100*[0.21 cSt / 14.52 cSt]

= 1.4 %

Table 2-2. Results of Analysis of Oil Properties

Date of Sample	Viscosity @ 40°C (cSt)			Oxidation (cm)			Nitration (cm)			Total Acid Number (mg KOH/g)		
	Control Engine	Test Engine	Difference	Control Engine	Test Engine	Difference	Control Engine	Test Engine	Difference	Control Engine	Test Engine	Difference
6/2/01	First Oil Change											
6/23/01	14.23	14.11	-0.12	12	12	0	17	10	-7	2.37	2.09	-0.28
7/12/01	14.26	14.26	0.00	14	15	1	18	22	4	2.80	2.88	0.08
8/8/01	14.59	14.72	0.13	22	21	-1	29	24	-5	2.96	2.51	-0.45
9/5/01	15.18	15.01	-0.17	see footnote a								
10/10/01	14.75	15.35	0.60	26	20	-6	36[b]	18[b]	na	3.50	2.90	-0.60
10/11/01	Second Oil Change											
11/8/01	13.94	14.60	0.66	2[b]	17[b]	na	16	13	-3	1.50	1.86	0.36
12/12/01	14.57	14.55	-0.02	13	18	5	22	11	-11	2.74	2.81	0.07
2/4/02	14.64	15.20	0.56	25	24	-1	38	28	-10	3.23	3.79	0.56
Average Difference (1st oil change)			0.09			-2			-3			-0.31
Average Difference (2nd oil change)			0.40			2			-8			0.33
Overall Average Difference			0.21			-0.3			-5			-0.04
Overall Average Percent Difference			1.4			-2			-21			-1.4

[a] Sampling data unavailable: analyses of these parameters were not specified on the chain of custody forms submitted by site operators.

[b] Data considered outlying values are included in the table for information, but not included in the analysis.

na: Not applicable

There appear to be no consistent and significant Average Difference between the oxidation, viscosity, and total acid numbers for the Control Engine, and the values of these parameters for the Test Engine. Small, and often inconsistent, differences can be seen in these parameters and, for several samples, differences reported are within the repeatability of the measurements (repeatability results of 1.11 to 2.18 percent are reported in Chapter 3).

Consistent with the graphical analysis discussed earlier, the data in Table 2-2 suggest that the amount of lubrication oil nitration is significantly less in the Test Engine: 21 percent less than the Overall Average nitration value associated with the Control Engine. This is consistent with the Phase I finding that NO_X emissions were reduced by about 30 percent, and that exposure of lubrication oil to acid gases like NO_X can increase nitration as combustion gases or "blow-by" mix with lubrication oil in the crank case. Table 2-3 shows the NO_X emission reductions verified as part of the Phase I evaluation. The emission changes measured for other air pollutants and GHGs are also shown. More details on the data from Phase I can be obtained from the Phase I report *Environmental Technology Verification Report, MIRATECH Corporation, GECO™ 3001 Air/Fuel Ratio Controller (Manufactured by Woodward Governor Company)* (SRI 2001b). This report can be obtained online at www.sri-rtp.com or www.epa.gov/etv.

Table 2-3. Summary of Changes in Engine Emission Rates from Phase I

Test ID	Engine Operation	Reduction[a] in Engine Emissions (%)				
		NO_X	CO	THC	CH_4	CO_2
1	Full Load	18.1	9.9	22.3	23.0	(0.9)
10		38.6	3.1	(11.6)	(11.7)	(1.1)
11		34.9	2.3	(4.3)	(4.0)	(0.2)
Average Change		**30.5**	**5.1**	**(2.1)**	**(2.4)**	**(0.7)**
2	Reduced Load	19.1	3.6	(9.2)	(8.8)	0.6
12		38.2	2.2	(14.0)	(13.8)	(1.9)
13		32.7	1.5	(9.9)	(9.9)	(1.2)
Average Change		**30.0**	**2.4**	**(11.0)**	**(10.8)**	**(0.8)**

[a] Values in parentheses indicate percent increases.

3.0 DATA QUALITY ASSESSMENT

3.1 DATA QUALITY INDICATORS

3.1.1 Introduction

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. The desired levels of data quality are normally defined as data quality objectives (DQOs). The process of establishing DQOs starts with determining the desired level of confidence in the primary verification parameters (e.g., during Phase I, these were changes in fuel consumption and engine emission rates). The next step is to identify all measured values that impact the primary verification parameters and estimate the level of error that can be tolerated. Prior to testing, error propagation is often used to estimate the cumulative effect of all measured variables on the quality of the verification parameters measured. This allows individual measurement methods and instruments to be chosen which perform well enough to satisfy the DQO for each verification parameter. The technique used to determine if DQOs are met is to identify data quality indicators (DQIs) for each of the required critical measurements. The DQIs usually define the accuracy, precision, and completeness goals for each measured variable.

In the Test Plan, the GHG Center intentionally did not include a DQO for changes in oil degradation rates because degradation rates can vary widely and contain large variation. There are many engine design and operational variables that can contribute to oil degredation. The GHG Center did identify DQIs for each of the oil analysis parameters, to ensure that the measurements were as reliable as possible and consistent with generally accepted industry standards.

3.1.2 Completeness, Accuracy, and Repeatability Results

This section presents the results of all QA/QC checks for the oil analyses methods, and reconciles the DQIs. Table 3-1 summarizes the range of measurements observed in the field, the DQI goals, the achieved DQIs, and completeness goals. In all cases, collected samples were analyzed within 23 days of collection. This deviates from the interval of 1 day specified in the Test Plan but, given the stability of sealed oil samples during storage, this deviation is not expected to affect results.

The completeness goal for the oil analyses was to obtain a valid sample each month during 90 percent of the verification period. Achieved completeness of 78 percent was short of that goal. This was because the September 5, 2001, samples were mistakenly analyzed for viscosity only because the other analyses were not specified on the chain-of-custody form prepared by the host site operators. A second reason for the low completeness was that the host site did not submit samples for January 2002. Both of these omissions contributed to difficulties encountered in interpreting the oil degredation profiles presented in Section 2. However, valid samples were generally available for the preceding and following months, allowing the GHG Center to bound the period where sampling was not conducted. This significantly reduces the impact of losing data, allowing the GHG Center to form reliable conclusions with a reasonable degree of confidence. One exception was the nitration variable where, as a result of the outlier analysis discussed in Section 2.2.4, one sample was removed for the Test Engine. In this case, nitration trends and performance results are reasonably clear in spite of the data loss, the trends observed are consistent with emissions findings in Phase I and, as such, the conclusions reached for nitration are considered reliable.

Instrument calibration and performance data supplied by the laboratory were reviewed to document proper instrument operation, and to qualitatively verify achievement of instrument accuracy DQI goals for viscosity, nitration, and oxidation. These records were obtained and reviewed by the GHG Center, and they revealed that the accuracy-related DQI goals were achieved for the three parameters listed above. Instrument performance data for total acid number were not obtained and reviewed. The CTC Analytical Laboratory maintains continuous QA/QC procedures as standard operation for all of the instrumentation used in these analyses. Oxidation and nitration levels are determined using a Perkin Elmer Model 1600 Fourier Transformation Infrared Spectrometer (FTIR). The instrument has background checks run every half-hour during use and is internally standardized to an accuracy of ± 1-cm absorbance or lower. Viscosity is determined in accordance with the American Society for Testing and Materials (ASTM) D445 using a Houllion Viscometer. This instrument measures sample viscosity under controlled conditions (100 °C). A Statistical Process Control (SPC) standard sample is checked daily to verify that the viscometer has an accuracy of ± 0.05 cSt. For total acid number (ASTM D974), the method uses a color indicator to indicate the titration endpoint, and the titrant is certified for its normality. Triplicate titrations were conducted on each sample. In addition, daily calibration is conducted using an SPC sample which yields a method accuracy of ± 0.5 percent of reading.

Duplicate analyses for all the oil variables examined were conducted to confirm the achievement of the repeatability DQI goal for the total acid number method, and to provide important repeatability characterizations for the other three methods used. Many Phase II performance assessments involve the calculation of a difference between two measured parameters (e.g., the Test Engine nitration minus the Control Engine nitration), so repeatability is perhaps more important than accuracy or bias as an indicator of data reliability (measurement bias would tend to cancel out when measured values are subtracted).

Duplicate analyses were carried out on four of the samples submitted, and these results are presented in Table 3-2. For samples with duplicate analyses, the average value of the two results was used to report results in Section 2.2. The DQI goal for total acid number was to demonstrate repeatability of ± 5 percent using duplicate analyses and, as Tables 3-1 and 3-2 show, this goal was achieved (1.7 percent was achieved). Repeatability results for the other three methods ranged from about 1 percent for the viscosity and oxidation methods, to about 2 percent for the nitration method. The Test Plan called for duplicate analyses on every sample collected. This was not conducted on every sample by the laboratory but, given the results of the duplicates conducted, demonstrated repeatability is acceptable.

Table 3-1. Summary of Data Quality Indicators for Lubrication Oil Analyses

Measurement Variable		Instrument Type / Manufacturer	Instrument Rated Accuracy	Measurement Range Observed	Frequency of Measurements	DQI Goal	DQI Achieved	How Verified / Determined	Completeness Achieved
Lubrication Oil Analyses	Viscosity	Kinematic Capillary Viscometer	± 0.05 cSt	13.95 to 15.35 cSt	Once every month for duration of verification period	± 0.05 cSt	± 0.05 cSt	Reviewed laboratory calibration records	78 percent (this excludes outliers removed as discussed in Section 2.2.4)
	Nitration	Nicolet FTIR Spectrometer	± 1 cm	10 to 38 cm		± 1 cm	± 1 cm		
	Oxidation			2 to 26 cm					
	Total Acid Number	Automatic Karl Fischer (KF) Titrator	± 0.5 % of reading	1.50 to 3.79 mg KOH/g oil		± 5 % repeatability	± 1.6 % repeatability	Duplicate analyses	

Table 3-2. Results of Duplicate Oil Analyses					
Parameter	**Analytical Results (initial/duplicate)**				**Average Repeat-ability (%)**
	6/23/01, Test Engine	**6/23/01, Control Engine**	**8/8/01, Test Engine**	**8/8/01, Control Engine**	
Viscosity (cSt)	14.12 / 14.09	14.18 / 14.27	14.56 / 14.87	14.48 / 14.69	1.1
Nitration (cm)	10 / 10	17 / 17	23 / 25	29 / 29	2.1
Oxidation (cm)	12 / 12	12 / 12	21 / 21	21 / 22	1.2
Total Acid (mg KOH)	2.07 / 2.10	2.36 / 2.37	2.56 / 2.45	2.95 / 2.96	1.7

3.2 AUDITS

The GHG Center's QA Manager conducted an audit of data quality (ADQ). The ADQ confirmed that all data handling and calculations were adequate and correct. This was done by selecting a random sample of verification results, duplicating all the calculations performed to determine those results, confirming the proper extraction and tabulation of measurements data by examining a section of raw data reports supplied by the laboratory, and confirming the proper use and interpretation of laboratory-supplied duplicate analysis results. A field activities technical systems audit (TSA) was not conducted on this portion of the verification because samples were collected only at 1-month intervals.

4.0 REFERENCES

ASTM D445. American Society for Testing and Materials, *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity* (D445-01), West Conshohocken, PA, 2001.

ASTM D974. American Society for Testing and Materials, *Standard Test Method for Acid and Base Number by Color-Indicator Titration* (D974-01), West Conshohocken, PA, 2001.

SRI 2001a. Southern Research Institute. *Test and Quality Assurance Plan, MIRATECH Corporation, GECO™ 3001 Air/Fuel Ratio Controller*, Research Triangle Park, NC, February 2001.

SRI 2001b. Southern Research Institute. *Environmental Technology Verification Report, MIRATECH Corporation GECO™ 3001 Air/Fuel Ratio Controller (Manufactured by Woodward Governor Company),* SRI/USEPA-GHG-VR-11, Research Triangle Park, NC, September 2001.