EPA-600/R-96-020a
GRI-95/0270.1
February 1996

Criteria Pollutant Emissions from Internal Combustion Engines in the Natural Gas Industry

Volume I. Technical Report

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EPA Contract No. 68-D2-0160
Work Assignment No. 33

GRI Contract No. 5091-254-2293

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Washington, DC 20460

EPA Review Notice

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Abstract

This report contains emissions data for nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), ethane (C_2H_6), nonmethane hydrocarbons (NMHC), and nonmethane-ethane hydrocarbons (NMEHC) from stationary internal combustion (IC) engines and gas turbines used in the natural gas industry. The emission factors were calculated from test results based on five test campaigns conducted as part of the Gas Research Institute's air toxics study, three of which were cofunded by the EPA. Test results for individual engines tested are presented, along with full load engine family-specific factors, and the calculated emissions factors are evaluated relative to the emission factors published in EPA report AP-42. Units tested included eleven 2-stroke engines and five 4-stroke engines, with and without controls, and two gas turbines. The data will enhance the current database in AP-42 for stationary IC engines. It will not only enlarge the population of engine types covered, but will enhance the emission factor quality of several engine categories which have a limited data set.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Executive Summary

Background

One function of the Air Pollution Prevention and Control Division (APPCD) of the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development is improving current air pollutant emission inventory methodologies, especially for those pollutants associated with tropospheric ozone formation. As part of the improvement to emission inventory methodologies, APPCD supports field emission measurement efforts. These data are used by EPA's Office of Air Quality Planning and Standards (OAQPS) to enhance their reference document "Compilation of Air Pollutant Emission Factors" (AP-42), which contains emission factors for oxides of nitrogen (NO_x), carbon monoxide (CO), methane (CH_4), ethane (C_2H_6), nonmethane hydrocarbon (NMHC), and nonmethane-ethane hydrocarbon (NMEHC) emissions from the large, stationary internal combustion (IC) reciprocating engines and turbines used in the natural gas industry. In AP-42, emission factors for some types of engines, especially those with air pollution controls, are based on an inadequate amount of emissions test data. To improve the understanding of emissions from these sources, additional testing is needed to enhance the emissions database, giving OAQPS the ability to revise AP-42.

Emissions characterization of IC engines in the natural gas industry is currently underway through a program sponsored by the Gas Research Institute (GRI), with the primary focus on determining the potential for air toxics emissions. Since information on NO_x, CO, CH_4, C_2H_6, NMHC, and NMEHC emissions is needed to completely characterize the IC engine emissions, EPA/APPCD provided cofunding to the GRI program to support gathering such data for enhancement of the emissions database currently used in AP-42 for the development of emission factors. The work described in this document was conducted as part of this joint effort between GRI and EPA and involved the following:

- Field measurements of NO_x, CO, CH_4, C_2H_6, and total hydrocarbon (THC) emissions at three test sites (GRI Campaigns 4, 5, and 6);

- Incorporation of field data collected at two earlier test sites (Campaigns 2 and 3) by GRI into the data set for evaluation; and
- Evaluation of all test data for use in enhancing the emissions database currently in AP-42.

Results

Table S-1 presents a summary of full load emission factors for NO_x, CO, CH_4, C_2H_6, THC, NMHC, and NMEHC expressed in grams per horsepower-hour (g/hp-hr) and pounds per million British thermal units (lb/MMBtu). The emission factors were averaged by engine family, and are presented for 2-stroke, lean-burn; 2-stroke, clean-burn; 4-stroke, lean-burn; 4-stroke, clean-burn; and 4-stroke, rich-burn engines; and gas turbines. Separate emission factors were calculated for engines using emission control equipment, e.g., nonselective catalytic reduction (NSCR), or selective catalytic reduction (SCR), CO oxidation catalyst, or pre-combustion chamber (PCC). Only data from test periods during which the engines were operated within 90 percent of rated load and 95 percent of rated speed were used to calculate the average emission factors, except when the engine tested was the only one of a particular classification included in the test program, and the engine did not meet the minimum load and speed criteria during any of the test periods.

Oxides of nitrogen, CO, and THC emission factors are based on continuous emissions monitoring system (CEMS) measurements while the methane and ethane emission factors are based on gas chromatography (GC). Emission factors expressed as NMHC and NMEHC are calculated by subtracting the methane and methane/ethane concentrations, respectively, from the THC concentrations. In some cases, the difference between the measured THC and methane/ethane concentrations was less than the analytical precision of the instruments. In these cases, NMHC/NMEHC emissions were not quantified.

Except for the 2-stroke, lean-burn engine family, the information presented in Table S-1 is considered limited since the emission factors are based on tests conducted on only one to three engines/turbines. As expected, there are differences between the emission factors calculated in this study and those in AP-42. The differences between the data from this study and AP-42 can be attributed to the variability associated with the population of engines tested, and differences in the type of instrumentation used during the two studies.

Table S-1. Full Load Average Emission Factors

Engine Family	Emission Control	No. of Engines/ Runs[a]	Units	NO_x	CO	CH_4	C_2H_6	THC	NMHC	NMEHC
2-stroke; lean-burn	–	7/16	(g/hp-hr)[b]	14	0.63	4.6	0.31	5.7	1.1	0.80
			(lb/MMBtu)	3.4	0.15	1.1	0.077	1.4	0.28	0.19
2-stroke; clean-burn	–	1/3	(g/hp-hr)	0.48	1.4	NA	0.38[c]	6.8	–[c]	–[c]
			(lb/MMBtu)	0.14	0.41	NA	0.11[c]	2.0	–[c]	–[c]
	CO catalyst	1/1	(g/hp-hr)	0.54	0.11	NA	NA	6.3	–[c]	–[c]
			(lb/MMBtu)	0.17	0.030	NA	NA	1.9	–[c]	–[c]
4-stroke; lean-burn	–	3/6	(g/hp-hr)	14	0.83	5.5	0.16	4.1	–[c,d]	–[c,d]
			(lb/MMBtu)	3.7	0.21	1.5	0.044	1.1	–[c,d]	–[c,d]
	SCR catalyst	1/2	(g/hp-hr)	5.0	0.43	NA	0.15	2.7	–[c,d]	–[c,d]
			(lb/MMBtu)	1.3	0.11	NA	0.036	0.69	–[c,d]	–[c,d]
4-stroke; clean-burn	PCC	1/1	(g/hp-hr)	0.56	2.0	NA	NA	8.0	–[c]	–[c]
			(lb/MMBtu)	0.14	0.51	NA	NA	2.0	–[c]	–[c]
4-stroke; rich-burn	–	1[e]/1	(g/hp-hr)	18	15	NA	NA	3.0	–[c]	–[c]
			(lb/MMBtu)	5.2	4.2	NA	NA	0.85	–[c]	–[c]
	NSCR catalyst	1[f]/2	(g/hp-hr)	0.050	0.26	NA	NA	1.7	–[c]	–[c]
			(lb/MMBtu)	0.015	0.075	NA	NA	0.49	–[c]	–[c]
Gas turbine	–	2/4	(g/hp-hr)	1.4	0.16[g]	ND	ND	ND	ND	ND
			(lb/MMBtu)	0.31	0.038[g]	ND	ND	ND	ND	ND

NA = Not available. ND = Not detected. NSCR = nonselective catalytic reduction. SCR = selective catalytic reduction.
PCC = Pre-combustion chamber.

[a]For some pollutants, the number of engines/runs used in the average is less than the total number tested.
[b]There is uncertainty in the horsepower measurements made by the engine analyst for 4 of the 16 runs.
[c]GC hardware malfunction during Campaign 4 prevented collection of data for methane and/or ethane.
[d]Difference between recorded methane and THC measurements was less than the precision of either instrument.
[e]Based on one engine tested at 91 percent speed and below 90 percent load.
[f]Based on one engine tested at 90 percent speed.
[g]Test results below the detection limits were averaged as zero.

Conclusions

Based on examination of the test results from this study, the following conclusions are offered to enhance the emissions database currently in AP-42:

- Incorporate emissions data used to develop the emission factors for uncontrolled 2-stroke, lean-burn; 4-stroke, lean-burn; and 4-stroke, rich-burn engines; and gas turbines into the current AP-42 emissions database. Although the current factors are "A" quality, incorporation of these data will broaden the population of the engines covered.

- Incorporate the data used to develop the emission factors for 2-stroke, clean-burn engines into the current AP-42 emissions database. The current AP-42 factors are "C" quality. The additional data may upgrade the emission factor quality rating for this category.

- Use data for the NSCR-controlled 4-stroke, rich-burn engine, PCC-controlled 4-stroke, lean-burn engine, and the 2-stroke, clean-burn engine with a CO oxidation catalyst to build and/or improve an emissions database for these categories.

- The current version of AP-42 has separate emission factors for "clean-burn" and "PCC" controlled engines. "Clean-burn" is a trade name used by one manufacturer to describe modifications to a lean-burn engine to lower emissions. A PCC is a primary component of the "clean-burn" modification to these engines. An engine equipped with PCC may also have all of the other clean-burn modifications, as did the one engine with PCC tested under this program. Consideration should be given to combining the emissions database for these control scenarios under a single generic description.

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Acronyms and Abbreviations

APPCD	Air Pollution Prevention and Control Division
ASSET	Air Sciences and Engine Technology, Inc.
BMEP	Brake mean effective pressure
C-B	Cooper-Bessemer
CEMS	Continuous emissions monitoring system
CO	Carbon monoxide
CH_4	Methane
C_2H_6	Ethane
EPA	Environmental Protection Agency
F_d	F factor (dry basis)
FID	Flame ionization detector
g/hp-hr	Gram per horsepower-hour
GC	Gas chromatography
GC/MD	Gas chromatography with multiple detectors
GPA	Gas Processors Association
GRI	Gas Research Institute
HHV	Higher heating value
hp	Horsepower
IC	Internal combustion
I-R	Ingersoll-Rand
LHV	Lower heating value
lb/MMBtu	Pounds per million British thermal units
NMEHC	Nonmethane-ethane hydrocarbon
NMHC	Nonmethane hydrocarbon
NO_x	Oxides of nitrogen
NSCR	Nonselective catalytic reduction
PCC	Pre-combustion chamber
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
SCR	Selective catalytic reduction
THC	Total hydrocarbon

Section 1.0
Introduction

1.1 Background

One function of the Air Pollution Prevention and Control Division (APPCD) of the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development is improving current air pollutant emission inventory methodologies, especially for those pollutants associated with tropospheric ozone formation. As part of the improvement to emission inventory methodologies, APPCD supports field emission measurement efforts. These data are used by EPA's Office of Air Quality Planning and Standards (OAQPS) to enhance their reference document "Compilation of Air Pollutant Emission Factors" (AP-42), which contains emission factors for oxides of nitrogen (NO_x), carbon monoxide (CO), methane (CH_4), ethane (C_2H_6), nonmethane hydrocarbon (NMHC), and nonmethane-ethane hydrocarbon (NMEHC) emissions from the large, stationary internal combustion (IC) reciprocating engines and turbines used in the natural gas industry.[1] In AP-42, emission factors for some types of engines, especially those with air pollution controls, are based on an inadequate amount of emissions test data. To improve the understanding of emissions from these sources, additional testing is needed to enhance the emissions database, giving OAQPS the ability to revise AP-42.

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1.2 Objectives and Approach

The primary objectives of this study were to:

- Characterize emissions of NO_x, CO, CH_4, C_2H_6, and total hydrocarbons (THCs) from IC engines including turbines;
- Evaluate the emissions data for use in enhancing the emissions database currently in AP-42.

The scope of this joint effort covered measurements conducted as part of the following field campaigns:

- Campaign 4--Compressor station (four engines);
- Campaign 5--Sweet gas plant (one turbine);
- Campaign 6A--Compressor station (two engines);
- Campaign 6B--Compressor station (one turbine); and
- Campaign 6C--Compressor station (four engines).

Additionally, field data collected as part of previous GRI efforts are also included in this document:

- Campaign 2--Sour gas plant (two engines);
- Campaign 3A--Compressor station (two engines); and
- Campaign 3B--Sweet gas plant (two engines).

The host sites for the field measurements were selected according to criteria developed for the GRI program. These criteria included engine make/model, family (type), size, age, presence of controls, and operating load flexibility to ensure the data collected would be applicable to a broad population of units in the industry. Emissions data collection and reduction for Campaigns 4, 5, and 6 were conducted according to procedures documented in the Quality Assurance Project Plan (QAPP) prepared for EPA and the test plans prepared for GRI and EPA. During the engine testing, the GRI program engine consultant, Jon Tice of Air Sciences and Engine Technology, Inc., and engine analyst(s) were on-site to ensure the operation of the engines being tested was satisfactory and to measure and confirm engine operating data (e.g., horsepower, fuel flow).

For Campaigns 2 and 3, emissions data collection and reduction were performed according to test plans prepared for GRI, similar to those prepared for both GRI and EPA in Campaigns 4, 5, and 6. Engine horsepower measurements were performed by host site engine analysts for Campaigns 2 and 3B, with the GRI program's engine consultant (Jon Tice of ASSET) providing initial engine operation assessment for Campaign 3.

1.3 Report Contents

Section 2.0 presents an overview of broad engine categories, followed by a summary of emission factors calculated from the test data tabulated according to engine classification. Section 3.0 gives detailed test results for each engine characterized as part of this effort, including descriptions of the test sites. Descriptions of the test methods used during the measurement campaigns are included in Section 4.0, with the summary of the quality assurance (QA) and quality control (QC) procedures used, and documentation of the data quality indicators presented in Section 5.0. Section 6.0 presents the average emission factors calculated from the test data by engine classification including a comparison of these factors with current AP-42 emission factors. Evaluation of the data for enhancing the emissions database used in AP-42 to improve the emission factors for large, stationary internal combustion engines is also included in Section 6.0. Finally, Section 7.0 lists the references, and supporting data are presented in Volume II of this document in Appendices A through I.

Section 2.0
Summary of Emission Factors

2.1 Engine Families[2-4]

Natural gas-fired reciprocating engines can be classified into five broad categories or "families" according to design differences which may lead to differences in emission characteristics. These families include:

- 2-stroke; lean-burn;
- 2-stroke; clean-burn;
- 4-stroke; lean-burn;
- 4-stroke; clean-burn; and
- 4-stroke; rich-burn.

Following is a brief description of the engine families, with each family composed of units that share typical engine power cycles, air-to-fuel (A/F) ratios, and combustion and exhaust temperatures. Table 2-1 presents the engines tested in this study by engine family. In addition, two gas turbines, a Westinghouse 191 and a Solar Taurus T-6502, were also tested in this study.

2.1.1 2-Stroke Engines

A 2-stroke engine completes the power cycle in one revolution of the crankshaft. In the first stroke, air or an air and fuel mixture is drawn or forced into the cylinder as the piston begins the compression stroke. Near the end of the compression stroke, the mixture is ignited, which forces the piston downward through the cylinder and begins the second stroke.

Table 2-1. Engines Tested in Each Family

Air Scavenging	2-Stroke Lean-burn	2-Stroke Clean-burn	4-Stroke Lean-burn	4-Stroke Clean-burn	4-Stroke Rich-burn
Turbocharged	Cooper GMVC-10 (2) Cooper GMWC-10	Cooper GMVC-10C[a]	Cooper LSV-16 (2) Ingersoll Rand KVS-412[c]	Ingersoll Rand KVS-412	--[e]
Blower scavenged	Cooper GMVA-10 (2) Cooper GMWA-8	--[b]	--[d]	--[b]	--[f]
Piston scavenged/ Naturally aspirated	Clark BA-5 Clark BA-6 Clark HBA-5 Cooper GMV-10TF	--[b]	--[d]	--[b]	Waukesha L7042GU[g]

[a]Equipped with CO oxidation catalyst.

[b]All clean-burn engines are turbocharged.

[c]Equipped with selective catalytic reduction control.

[d]No engines of this design were identified.

[e]No engines of this design were tested.

[f]4-stroke, rich-burn engines do not utilize scavenging air.

[g]Equipped with nonselective catalytic reduction control.

During the second stroke, power is transferred to the crankshaft. As the piston continues to move downward, the piston passes and uncovers exhaust ports (or exhaust valves open), and the combustion gases exit. Intake ports then open, and the fresh fuel and air mixture is forced into the cylinder, displacing the remainder of the combustion gases. Finally, the exhaust ports are closed, and the cycle begins again.

Because scavenging air is used to sweep the cylinder of exhaust gases, 2-stroke engines operate with an overall A/F ratio that is greater than the stoichiometric ratio. This is also referred to as a fuel-lean condition. As such, 2-stroke engines are classified as having lean-burn combustion. Newer model 2-stroke engines are designed to utilize turbochargers and high-energy ignition systems to achieve stable combustion at even higher A/F ratios. The high A/F ratio lowers bulk combustion temperatures and, thereby, reduces NO_x formation. Due to the reduced NO_x levels, these models are commonly called "clean-burn" engines.

2-Stroke, Lean-Burn Engines

A lean-burn engine is classified as one with an A/F ratio operating range that is greater than stoichiometric, and cannot be adjusted to operate with an exhaust O_2 concentration of less than 1 percent. A/F mass ratios for lean-burn engines range from 20:1 to 60:1, with stack temperatures normally ranging from 550 to 850°F. All 2-stroke engines and 4-stroke, scavenged, turbocharged engines operate under lean-burn conditions due to scavenging air; however, some engines may have fuel-rich combustion zones.

The higher air content in lean-burn combustion increases the heat capacity of the mixture in the combustion chamber, which lowers combustion temperatures and generally results in increased THC emissions due to the high quench volume in the cylinder.

All 2-stroke, lean-burn engines are direct-injected (i.e., fuel is injected directly into the cylinder) and experience nonuniform mixing of the air and fuel prior to combustion. Therefore, thermal and concentration gradients are more prominent in the combustion chamber for 2-stroke engines than 4-stroke engines which have carbureted (pre-mixed) fuel delivery systems. Because of the potential for nonuniform mixing of the air and fuel, 2-stroke engines tend to have higher THC levels than 4-stroke carbureted engines.

2-Stroke, Clean-burn Engines

Clean-burn engines use turbochargers to force more air into the combustion chamber, with the increased A/F ratio reducing bulk gas temperatures and combustion temperatures, resulting in lower NO_x formation. However, the reduced temperatures can also increase THC and CO emissions.

Engines with large cylinder bores and conventional ignition systems cannot reliably ignite and sustain combustion at the higher A/F ratios used in clean-burn designs. In these cases, a pre-combustion chamber (PCC) design is utilized. Although PCC engine designs vary among manufacturers, the PCC is typically a small volume antechamber in which a fuel-rich mixture is ignited. The ignited mixture from the PCC propagates into the main cylinder and ignites a very lean combustion charge. The exit velocity of the combustion products from the PCC has a torch-like effect that creates multiple ignition fronts and promotes mixing in the main chamber. Both of these factors create a more stable and cooler temperature profile in the main combustion chamber with a PCC design than with an open-chamber design. Although the lower temperatures and leaner A/F ratios reduce NO_x emissions, they may result in higher levels of THC in the exhaust stream of a PCC engine.

2.1.2 4-Stroke Engines

A 4-stroke engine completes the power cycle in two full revolutions of the crankshaft. During the intake stroke, the downward motion of the piston draws air into the cylinder. The second stroke compresses the air, or air and fuel mixture, and begins to increase cylinder temperatures. The third-stroke begins with ignition of the gases, which causes the gases to expand, driving the piston downward and delivering power to the crankshaft. Finally, the piston moves upward and forces the exhaust gases out of the cylinder. Four-stroke engines are available in three basic configurations:

- 4-stroke, rich-burn;
- 4-stroke, lean-burn; and
- 4-stroke, clean-burn.

4-Stroke, Rich-Burn Engines

Rich-burn engines operate with an A/F ratio that is near stoichiometric (approximately 16:1 to 20:1), or fuel-rich, and have an exhaust O_2 concentration ranging from nearly zero to about five percent. Rich-burn engines include all naturally aspirated and non-scavenged, turbocharged 4-stroke engine models. Because of the low levels of O_2 present, combustion temperatures and consequently exhaust temperatures are higher than for lean-burn engines. Exhaust temperatures for rich-burn engines typically range from 1,000 to 1,250°F.

4-Stroke, Lean-Burn Engines

Four-stroke, lean-burn engines are available in two basic designs: direct injected and pre-mixed (carbureted or port injected). The conditions in the combustion zone for these two designs can be very distinct. The direct injected 4-stroke, lean-burn engines have a hot combustion zone before the flame front mixes with the remainder of the combustion air. This hot zone is similar to conditions present in a rich-burn engine. The pre-mixed 4-stroke, lean-burn engines combust a homogeneous air/fuel mixture which leads to a cooler combustion zone, similar to a 2-stroke engine.

The additional mixing in 4-stroke engines reduces the presence of high concentration and temperature gradients in the cylinder during combustion when compared to 2-stroke engines. In addition, the residence time of combustion products in the cylinder of a 4-stroke engine is up to twice that of a 2-stroke engine operating at the same speed. The longer residence time at elevated temperatures typically results in lower THC emissions compared to 2-stroke, lean-burn engines.

4-Stroke, Clean-burn Engines

As with 2-stroke engines, newer model 4-stroke engines are frequently designed with very high A/F ratios to minimize NO_x formation. Four-stroke, clean-burn engines can be classified into two subcategories: injected and carbureted.

Four-stroke, clean-burn injected engines are characterized by either a direct-injected or port-injected fuel delivery system. Compared to the carbureted air/fuel design, the injected clean-burn design is expected to have higher fuel concentration gradients, leading to nonuniform temperature distribution in the combustion chamber.

Four-stroke, carbureted engines are characterized by pre-mixing the air and fuel prior to charging the combustion cylinder. Because of the homogeneity of the A/F mixture during the combustion process, the pre-mix design provides a relatively uniform combustion temperature profile. Compared to uncontrolled rich- or lean-burn, 4-stroke engines, the carbureted clean-burn design exhibits lower combustion and exhaust temperatures due to the higher A/F ratio.

2.1.3 Gas Turbines[5]

A gas turbine is an internal combustion engine which uses rotary rather than reciprocating motion to generate shaft horsepower. Three primary sections are present in gas turbines: the compressor, the combustor, and the turbine. The compressor draws in ambient air, compresses it with a compression ratio of up to 30:1, and directs the compressed air into the combustion zone. Fuel is injected and combusted in the combustor. Flame temperatures can reach 3,600°F; however, additional ambient air is quickly added to reduce temperatures to around 2,000 to 2,300°F before the gases enter the turbine section. The turbine recovers the energy released during combustion in the form of shaft horsepower.

Combustion in a gas turbine takes place under fuel lean conditions; however, due to imperfect mixing, fuel rich zones frequently occur in the combustor. By maintaining overall fuel lean conditions, NO_x formation is minimized.

2.2 Full Load Emission Factors

2.2.1 Emission Factors

Table 2-2 presents a summary of emission factors for NO_x, CO, CH_4, C_2H_6, THC, NMHC, and NMEHC expressed in grams per horsepower-hour (g/hp-hr) and pounds per million British thermal units (lb/MMBtu), based on the higher heating value of fuel. In cases where individual engines were tested during more than one test period, an average emission factor for the engine is reported in the table. Only data from test periods during which the engines were operated within 90 percent of rated load and 95 percent of rated speed were used to determine average emission factors to represent engines operated at or near full load conditions. There are a few cases where data from engines tested at slightly lower loads or speeds are included. In these cases, the engines tested were the only ones of their particular

Table 2-2. Summary of Emission Factors

Campaign	Engine Make/Model	No. of Test Periods	Load (%)	Units	NO_x	CO	CH_4	C_2H_6	THC	NMHC[a]	NMEHC[b]
2-stroke; lean-burn											
6	Clark BA-5, Unit 10	2	94-100	(g/hp-hr)	19	0.90	3.8	0.13	6.1[c]	1.8[c]	1.7[c]
				(lb/MMBtu)	3.6	0.17	0.73	0.025	1.2[c]	0.35[c]	0.32[c]
3	Cooper-Bessemer GMV-10TF, Unit 2	3	104	(g/hp-hr)[d]	13	0.53	2.4[e]	0.86[e]	3.5	1.1	0.23
				(lb/MMBtu)	3.3	0.10	0.57[e]	0.21[e]	0.87	0.27	0.054
6	Cooper-Bessemer GMVA-10, Unit 9	2	100	(g/hp-hr)	5.0	0.52	5.0	0.24	6.4	1.4	1.1
				(lb/MMBtu)	1.3	0.14	1.3	0.060	1.7	0.35	0.29
6	Cooper-Bessemer GMVC-10, Unit 11	3	95-101	(g/hp-hr)	13	0.47	3.8[f]	0.19[f]	4.4	0.56	0.35
				(lb/MMBtu)	3.5	0.13	1.0[f]	0.050[f]	1.2	0.14	0.091
6	Cooper-Bessemer GMVC-10, Unit 15	2	102	(g/hp-hr)	8.4	0.60	3.6[f]	0.18[f]	5.0	1.5	1.3
				(lb/MMBtu)	2.1	0.15	0.89[f]	0.043[f]	1.3	0.37	0.32
3	Cooper-Bessemer GMWA-8, Unit 4	1	98	(g/hp-hr)[d]	17	0.40	NA	NA	6.0	–	–
				(lb/MMBtu)	4.3	0.10	NA	NA	1.5	–	–
6	Cooper-Bessemer GMWC-10, Unit 13	3	91-96	(g/hp-hr)	19	0.87	7.6	0.34	8.8	1.1	0.76
				(lb/MMBtu)	5.1	0.23	2.0	0.087	2.3	0.29	0.20
2-stroke; clean burn											
4	Cooper-Bessemer GMVC-10C (before CO catalyst), Unit 4	3	93-97	(g/hp-hr)	0.48	1.4	NA	0.38[g]	6.8	–	–
				(lb/MMBtu)	0.14	0.41	NA	0.11[g]	2.0	–	–
4	Cooper-Bessemer GMVC-10C (after CO catalyst), Unit 4	1	99	(g/hp-hr)	0.54	0.11	NA	NA	6.3	–	–
				(lb/MMBtu)	0.17	0.030	NA	NA	1.9	–	–
4-stroke; lean-burn											
3	Cooper-Bessemer LSV-16, Unit 101	2	98-99[h]	(g/hp-hr)	9.5	1.1	5.6	0.17	5.3	–[i]	–[i]
				(lb/MMBtu)	2.6	0.30	1.5	0.048	1.5	–[i]	–[i]
3	Cooper-Bessemer LSV-16, Unit 102	2	98-101[h]	(g/hp-hr)	12	0.90	5.3	0.15	4.7	–[i]	–[i]
				(lb/MMBtu)	3.2	0.20	1.5	0.041	1.3	–[i]	–[i]

Table 2-2. (Continued)

Campaign	Engine Make/Model	No. of Test Periods	Load (%)	Units	NO_x	CO	CH_4	C_2H_6	THC	NMHC[a]	NMEHC[b]
4	Ingersoll-Rand KVS-412 (before SCR catalyst), Unit 9	2	91	(g/hp-hr)	22	0.55	NA	NA	2.5	--	--
				(lb/MMBtu)	5.4	0.14	NA	NA	0.64	--	--
4	Ingersoll-Rand KVS-412 (after SCR catalyst), Unit 9	2	90	(g/hp-hr)	5.0	0.43	NA	0.15[j]	2.7	--	--
				(lb/MMBtu)	1.3	0.11	NA	0.036[j]	0.69	--	--
4-stroke; clean burn											
4	Ingersoll-Rand KVS-412, Unit 8	1	92	(g/hp-hr)	0.56	2.0	NA	NA	8.0	--	--
				(lb/MMBtu)	0.14	0.51	NA	NA	2.0	--	--
4-stroke; rich-burn											
4	Waukesha L7042GU (before NSCR catalyst)	1	88[k]	(g/hp-hr)	18	15	NA	NA	3.0	--	--
				(lb/MMBtu)	5.2	4.2	NA	NA	0.85	--	--
4	Waukesha L7042GU (after NSCR catalyst)	2	92-95[k]	(g/hp-hr)	0.050	0.26	NA	NA	1.7	--	--
				(lb/MMBtu)	0.015	0.075	NA	NA	0.49	--	--
Gas Turbine											
6	Solar Taurus T-6502[l]	2	95	(g/hp-hr)	1.3	ND	ND	ND	ND	ND	ND
				(lb/MMBtu)	0.30	ND	ND	ND	ND	ND	ND
5	Westinghouse 191[m]	2	Full	(g/hp-hr)	1.5	0.33	ND	ND	ND	ND	ND
				(lb/MMBtu)	0.32	0.075	ND	ND	ND	ND	ND

NA = Not available. ND = Not detected. NSCR = nonselective catalytic reduction. SCR = selective catalytic reduction.
[a] Calculated as THC minus methane.
[b] Calculated as THC minus methane and ethane.
[c] Emission factors based on Test Period 2 only.
[d] Uncertainty in the horsepower measurements by the engine analyst for these runs.
[e] Emission factors based on Test Periods 2 and 3 (not 4).
[f] Instrument drift exceeded specified limit.
[g] Based on GC data from Test Period 7.
[h] Rating based on operation at maximum brake mean effective pressure (BMEP).
[i] Difference between THC and methane measurement is less than precision of the instruments.
[j] Based on GC data from Test Period 15.
[k] Engine speed is 81% of the rated speed.
[l] Detection limits are as follows: CO: 1 ppm; CH_4: 2 ppm; C_2H_6: 2 ppm; and THC: 1 ppm.
[m] Detection limits are as follows: CH_4: 1 ppm; C_2H_6: 1 ppm; and THC: 10 ppm.

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family included in the test program. [Note: See Section 3.0 for details on the test data presented in Table 2-2. Data for low load and low speed test conditions are included in the appendices.]

Oxides of nitrogen, CO, and THC emission factors are based on continuous emissions monitoring system (CEMS) data, whereas methane and ethane emission factors are based on gas chromatography (GC). Emission factors for NMHC and NMEHC were calculated by subtracting the methane and methane plus ethane concentrations from the THC concentrations, respectively. In some cases, the difference between the measured THC and methane/ethane concentrations was less than the analytical precision of one or both of the instruments. This is not unusual for combustion sources where THC emissions are composed of high fractions of methane and ethane. In these cases, NMHC and NMEHC emissions were not quantified.

2.2.2 Test Engines/Turbines

The engines/turbines tested under Campaigns 2, 3B, and 5 were located at gas processing plants, while the others were located at pipeline transmission/storage stations. Discussions with industry representatives have indicated differences in operating and maintenance practices at gas processing and transmission/storage stations which may impact engine emission rates. Engines at gas processing plants tend to be run continuously year-round, and are rarely shut down for maintenance unless engine problems are affecting production rates. Engines at transmission/storage stations have more operating flexibility, because the stations do not run at full capacity all year long, and most engines used at transmission stations are subject to regular shutdowns which allow the opportunity for repairs and preventive maintenance. Therefore, on average, engines used at transmission/storage stations tend to be in better physical condition than those used at gas processing plants.

Neither of the two engines tested at a sour gas processing plant under Campaign 2 was included in the engine family emission factor averages. Test data from these two engines were excluded from the averages because they were both running at less than 90 percent load, and one of the engines appeared to be operating especially poorly, as described in Section 3.0.

Except for the 2-stroke lean-burn family, the information presented in Table 2-2 for each category is limited, as it is based on test(s) conducted on only one to three engines.

The data for the 2-stroke lean-burn engine family are from seven engines, representing two manufacturers and six models, encompassing a broader population of engines than represented by the data for the other engine families. Two manufacturers and two models (three engines) are represented with the data on 4-stroke lean-burn engine category. Of the two 4-stroke lean-burn engine models tested, the Cooper-Bessemer LSV-16 engines use a port injection system, while the Ingersoll-Rand KVS-412 engines use direct injection. This difference in injection techniques accounts for some of the difference in emission levels between these two engine models.

As shown in Table 2-2, three of the engines tested were equipped with catalytic emission controls: selective catalytic reduction (SCR) for NO_x control, nonselective catalytic reduction (NSCR) for THC, NO_x, and CO control, and CO oxidation catalyst. The CO and NSCR catalysts had recently been installed on the Cooper GMVC-10C and Waukesha L7042GU engines, respectively.

2.2.3 *Operating Data*

For all but four engines in Table 2-2, the emission factors were calculated using horsepower measurements performed by an engine analyst and exhaust flow rates derived from fuel flow measurement data. The horsepower data were based on measurements of actual pressure changes in each cylinder of the compressor. For the Cooper LSV-16 engines in the 4-stroke lean-burn family, the horsepower data were calculated from site-specific performance curves. Although the horsepower during the Cooper GMV-10TF and GMWA-8 engine testing was measured by an engine analyst, calculations based on fuel flow rate data indicate the horsepower data may be about 10 to 15 percent high.

Gas turbine test data are based on one model from each of two turbine manufacturers. The process data for the Solar turbine were provided by the host site, while the load during the tests on the Westinghouse 191 turbine was estimated based on exhaust flow rate data and discussions with the manufacturer.

2.3 Engine Family-Specific Emission Factors

The emission factors calculated from engine tests have been averaged by engine family, as shown in Table 2-3. For the 2-stroke, clean-burn; 4-stroke, clean-burn; and 4-stroke, rich-burn categories, the emission factors are the same as those presented in

Table 2-3. Average Emission Factors

Engine Family	Emission Control	No. of Engines/ Runs[a]	Units	NO_x	CO	CH_4	C_2H_6	THC	NMHC	NMEHC
2-stroke; lean-burn	--	7/16	(g/hp-hr)[b]	14	0.63	4.6	0.31	5.7	1.1	0.80
			(lb/MMBtu)	3.4	0.15	1.1	0.077	1.4	0.28	0.19
2-stroke; clean-burn	--	1/3	(g/hp-hr)	0.48	1.4	NA	0.38	6.8	--[c]	--[c]
			(lb/MMBtu)	0.14	0.41	NA	0.11	2.0	--[c]	--[c]
	CO catalyst	1/1	(g/hp-hr)	0.54	0.11	NA	NA	6.3	--[c]	--[c]
			(lb/MMBtu)	0.17	0.030	NA	NA	1.9	--[c]	--[c]
4-stroke; lean-burn	--	3/6	(g/hp-hr)	14	0.83	5.5	0.16	4.1	--[c,d]	--[c,d]
			(lb/MMBtu)	3.7	0.21	1.5	0.044	1.1	--[c,d]	--[c,d]
	SCR catalyst	1/2	(g/hp-hr)	5.0	0.43	NA	0.15	2.7	--[c,d]	--[c,d]
			(lb/MMBtu)	1.3	0.11	NA	0.036	0.69	--[c,d]	--[c,d]
4-stroke; clean-burn	PCC	1/1	(g/hp-hr)	0.56	2.0	NA	NA	8.0	--[c]	--[c]
			(lb/MMBtu)	0.14	0.51	NA	NA	2.0	--[c]	--[c]
4-stroke; rich-burn	--	1[e]/1	(g/hp-hr)	18	15	NA	NA	3.0	--[c]	--[c]
			(lb/MMBtu)	5.2	4.2	NA	NA	0.85	--[c]	--[c]
	NSCR catalyst	1[f]/2	(g/hp-hr)	0.050	0.26	NA	NA	1.7	--[c]	--[c]
			(lb/MMBtu)	0.015	0.075	NA	NA	0.49	--[c]	--[c]
Gas turbine	--	2/4	(g/hp-hr)	1.4	0.16[g]	ND	ND	ND	ND	ND
			(lb/MMBtu)	0.31	0.038[g]	ND	ND	ND	ND	ND

NA = Not available. ND = Not detected. NSCR = nonselective catalytic reduction. SCR = selective catalytic reduction. PCC = Pre-combustion chamber.

[a]For some pollutants, the number of engines/runs used in the average is less than the total number tested.
[b]There is uncertainty in the horsepower measurements made by the engine analyst for 4 of the 16 runs.
[c]GC hardware malfunction during Campaign 4 prevented collection of data for methane and/or ethane.
[d]Difference between recorded methane and THC measurements was less than the precision of either instrument.
[e]Based on one engine tested at 91 percent speed and below 90 percent load.
[f]Based on one engine tested at 90 percent speed.
[g]Test results below the detection limits were averaged as zero.

Table 2-2, since only one engine was tested in each of these categories. For the 2-stroke, lean-burn; 4-stroke, lean-burn; and gas turbine categories, the emission factors are based on seven, three, and two units, respectively. In calculating the engine/turbine family average emission factors, data from all test periods collected on units that fall in the particular family were included. Table 2-4 provides an indication of the range of the emission factors for individual test periods in these three categories. The largest range was observed for NO_x data in the 2-stroke, lean-burn category, where the most models were tested.

Table 2-4. Emission Factor Range (g/hp-hr)

Pollutant	2-Stroke Lean-burn (7 engines/16 runs)	4-Stroke Lean-burn (3 engines/6 runs)	Gas Turbines (2 turbines/4 runs)
NO_x	4.9 - 22 (14)	8.7 - 22 (14)	1.2 - 1.6 (1.4)
CO	0.40 - 0.94 (0.63)	0.51 - 1.1 (0.83)	ND - 0.35 (0.16)
CH_4	2.3 - 8.0 (4.6)	4.7 - 6.0 (5.5)	ND
C_2H_6	0.090 - 0.88 (0.31)	0.13 - 0.17 (0.16)	ND
THC	3.5 - 9.2 (5.7)	2.4 - 5.3 (4.1)	ND
NMHC	0.29 - 1.8 (1.1)	-- --	ND
NMEHC	0.087 - 1.8 (0.80)	-- --	ND

Note: The number in parenthesis is the average (mean) emission factor.

Section 3.0
Test Results

3.1 Overview

This section presents results from the individual engine/turbine tests conducted during Campaigns 2 through 6 and provides a brief description of the host sites for these campaigns. Campaigns 2 and 3 were conducted before EPA Work Assignment No. 33 was initiated. Data from these two test campaigns, therefore, were collected using the procedures established in the GRI program. No methane or ethane emissions data were collected during Campaign 2, because such measurements were beyond the scope of the GRI program at that time.

Table 3-1 describes the engines/turbines tested in this effort (e.g., make/model, size, speed, family, controls) including information on the test runs conducted. All engines/turbines listed in Table 3-1 were tested at 90 percent of full load (or higher) and 95 percent of full speed (or higher), except as noted in the table and explained in the text. Only data that meet these criteria are included in this section, with low load and low speed data presented in the appendices.

Full load for reciprocating engines was determined on the basis of torque. Torque at full load was taken to be the manufacturer's rated power divided by the manufacturer's rated speed except at Station 6A, where torque was based on the site-rated power and manufacturer's rated speed. For the turbines, load was taken as a percentage of maximum available power calculated as the manufacturer's rating, adjusted for site elevation and temperature. For most test periods, stack gas flow rate was monitored via both EPA Method 2 and EPA Method 19. EPA Method 2 may be unreliable when used on reciprocating engines because of possible pulsations in the exhaust gas flow. EPA Method 19 calculations, based on fuel flow to the engine/turbine and exhaust oxygen content, were used to calculate emission rates except as noted in the tables and text.

Table 3-1. Engines Tested

Campaign	Engine Make/Model	Unit No.	Rated Power (hp)	Rated Speed (rpm)	Year Installed	Engine Family	Emission Control	Test Date	Sample Location	Test Period No.	Test Time Period
2	Cooper-Bessemer[a] GMVA-10	2	1,350	300	1966	2-stroke, lean-burn; BS	None	3/12/94	stack	7	1042-1550
2	Clark BA-6[a]	1	1,140	300	1982	2-stroke, lean-burn; PS	None	3/13/94	stack	8	1240-1810
3A	Cooper-Bessemer LSV-16	102	4,200[b]	327	1957	4-stroke, lean-burn; TC	None	6/14/94	stack	1	1600-2100
								6/15/94	stack	2	0832-1315
3A	Cooper-Bessemer LSV-16	101	4,200[b]	327	1955	4-stroke, lean-burn; TC	None	6/16/94	stack	2	0915-1415
								6/16/94	stack	3	1415-1806
3B	Cooper-Bessemer GMWA-8	4	2,000	250	1958	2-stroke, lean-burn; BS	None	6/18/94	stack	1	0925-1115
3B	Cooper-Bessemer GMV-10TF	2	1,100	300	1945	2-stroke, lean-burn; PS	None	6/19/94	stack	2	1105-1428
								6/19/94	stack	3	1630-2018
								6/20/94	stack	4	1240-1747

Table 3-1. (Continued)

Campaign	Engine Make/Model	Unit No.	Rated Power (hp)	Rated Speed (rpm)	Year Installed	Engine Family	Emission Control	Test Date	Sample Location	Test Period No.	Test Time Period
4	Waukesha L7042GU	--	896	1,000	1982	4-stroke, rich-burn; NA	NSCR	8/23/94	after catalyst	1	1146-1345
								8/23/94	after catalyst	2	1424-1722
								8/23/94	before catalyst	3	1805-2028
4	Cooper-Bessemer GMVC-10C	4	1,300	300	1956	2-stroke, clean-burn; TC	Clean-burn and CO catalyst	8/25/94	before catalyst	7	1705-1906
								8/26/94	after catalyst	8	1051-1226
								8/26/94	before catalyst	9	1310-1537
								8/30/94	before catalyst	H	1605-1630
4	Ingersoll-Rand KVS-412	8	2,000	330	1956	4-stroke, clean-burn; TC	PCC	8/30/94	stack	A	0745-0815
4	Ingersoll-Rand KVS-412	9	2,000	330	1956	4-stroke, lean-burn; TC	SCR	8/29/94	before catalyst	14	0858-0932
								8/29/94	after catalyst	15	0959-1330
								8/29/94	after catalyst	16	1413-1549
								8/29/94	before catalyst	17	1613-1700

Table 3-1. (Continued)

Campaign	Engine Make/Model	Unit No.	Rated Power (hp)	Rated Speed (rpm)	Year Installed	Engine Family	Emission Control	Test Date	Sample Location	Test Period No.	Test Time Period
5	Westinghouse 191 (Turbine)	--	20,000	--	--	--	None	10/5/94	stack	3	1230-1755
								10/5/94	stack	4	1843-2133
6A	Clark BA-5	10	911	300	1948	2-stroke, lean-burn; PS	None	11/5/94	stack	2	936-1209
6A	Clark HBA-5	12	1,000	300	1951	2-stroke, lean-burn; PS	None	11/5/94	stack	5	1345-1802
6B	Solar Taurus T-6502 (Turbine)	--	5,419	14,300	1993	--	None	11/7/94	stack	6	1709-1823
								11/8/94	stack	7	915-1344
6C	Cooper-Bessemer GMVC-10	15	1,800	300	1963	2-stroke, lean-burn; TC	None	11/10/94	stack	9	1030-1500
								11/10/94	stack	10	1546-1801
6C	Cooper-Bessemer GMVA-10	9	1,235	300	1954	2-stroke, lean-burn; BS	None	11/12/94	stack	13	1000-1405
								11/12/94	stack	14	1515-1645
6C	Cooper-Bessemer GMWC-10	13	3,500	250	1960	2-stroke, lean-burn; TC	None	11/13/94	stack	15	1030-1130
								11/14/94	stack	18	1855-1925
								11/14/94	stack	23	2025-2100
6C	Cooper-Bessemer GMVC-10	11	1,800	300	1957	2-stroke, lean-burn; TC	None	11/15/94	stack	19	1020-1120
								11/15/94	stack	20	1622-1655
								11/15/94	stack	24	1730-1813

BS = Blower scavenged. PS = Piston scavenged. TC = Turbocharged.

NSCR = Nonselective catalytic reduction. SCR = Selective catalytic reduction. NA = Naturally aspirated. PCC = Pre-combustion chamber.

[a]Loads greater than 90 percent could not be achieved for these engines.

[b]Manufacturer's rated hp is 3,500; however, site operates unit at maximum brake mean effective pressure (BMEP) equivalent to 4,200 hp.

Continuous emissions monitoring data for NO_x, CO, and THC were collected for all units. Gas chromatography measurements for methane and ethane were performed on all units except in following cases:

- Campaign 2 (Cooper-Bessemer GMVA-10, Clark BA-6);
- Campaign 3 (Cooper-Bessemer GMWA-8); and
- Campaign 4 [Waukesha L7042GU, Cooper-Bessemer GMVA-10, and Ingersoll-Rand KVS-412 (Unit 8)].

3.2 Campaign 2

3.2.1 Site Description

The site tested during GRI Campaign 2 was a sour gas processing plant. Raw natural gas containing carbon dioxide (CO_2) and hydrogen sulfide (H_2S) is treated with a monoethanolamine absorption unit to remove acid gases. The sweetened gas is dehydrated using triethylene glycol absorption and a molecular sieve unit prior to treatment in a cryogenic extraction unit for removal of nonmethane hydrocarbons. The site utilizes IC engines for recompression of refrigerants for the cryogenic plant and for recompressing the treated natural gas prior to transfer to a pipeline. Two IC engines were tested in this campaign. All of the engines on-site burn treated natural gas from the processing plant; however, due to an equipment malfunction, a small amount of raw, high Btu natural gas may have bypassed treatment and mixed with the treated gas fired during the testing.

3.2.2 Operating Conditions and Measurement of O_2, CO_2, CO, THC, and NO_x

Cooper-Bessemer GMVA-10

The Cooper-Bessemer GMVA-10 engine is used to power a refrigeration compressor used in the cryogenic extraction unit. This 2-stroke, lean-burn engine is rated at 1,350 horsepower (hp) and 300 rpm, and was operating at 77 percent load during the tests. Horsepower measurements were performed by the host site engine analyst. The NO_x measurements failed to meet the QA requirement for daily calibration drift. The data from this engine are not included in the average emission factor calculations because of the operating load level during the tests (see Appendix B for test data).

Clark BA-6

The Clark BA-6 engine is used to compress the natural gas leaving the cryogenic extraction unit. This 2-stroke, lean-burn engine is rated at 1,140 hp and 300 rpm, and was operating at 89 percent load during the tests. As for the Cooper-Bessemer GMVA-10 engine, the horsepower measurements were performed by the host site engine analyst. A stack gas temperature of 1,092°F and visible exhaust suggest that the engine's operation may not be representative (see Section 2.1.1 typical stack temperatures). Due to the low load and stack gas temperature, the data from this engine are excluded from the average emission factor calculations (see Appendix B for test data).

3.3 Campaign 3

3.3.1 Site Description

Testing was performed at a natural gas transmission station and a sweet gas processing plant. The engines tested at Station 3A include two Cooper-Bessemer LSV-16 4-stroke, lean-burn, turbocharged engines which are used to drive compressors for natural gas transmission in a pipeline. All equipment on-site fire pipeline-quality natural gas.

The engines tested at Sweet Gas Plant 3B are used to compress the raw natural gas at the inlet to the extraction plant. These engines include a Cooper-Bessemer GMV-10TF, 2-stroke, lean-burn, piston-scavenged model and a Cooper-Bessemer GMWA-8, 2-stroke, lean-burn, piston-scavenged model. Both of these engines fire raw gas from a sweet gas field which has a high Btu natural gas.

3.3.2 Operating Conditions and Measurement of O_2, CO_2, CO, THC, and NO_x

During this campaign, CEMS and GC data were collected, except on Engine 4 (GMWA-8) at Sweet Gas Plant 3B, which did not include GC measurements. For all test periods, the accuracy of the Method 19 calculations for determination of stack gas flow rate was confirmed with host site staff and the GRI program engine consultant. Therefore, the emission rate calculations are based on Method 19 results. During 8 of the 12 test periods, at least one manual sampling test requiring a full duct traverse was performed, thereby allowing an independent calculation of the stack gas volumetric flow rate by EPA Method 2. Volumetric flow rate of the stack gas during the other four test periods was estimated using differential pressure measurements made at a single point in the duct. Both Method 2 and Method 19 results are shown in the summary tables.

Cooper-Bessemer LSV-16

The Cooper-Bessemer LSV-16 engines tested at Station 3A are turbocharged 4-stroke engines, rated at 4,200 hp and 327 rpm, based on operation at maximum brake mean effective pressure (BMEP). Two test runs were performed on each engine at full load. Operating parameters and results of the CEMS measurements for NO_x, CO, THC, O_2, and CO_2 are presented in Tables 3-2 and 3-3.

Engine fuel flow rate and horsepower data were obtained from the host site's computer control system. The engine power was calculated from site-specific performance curves for the engines. Heat content of the natural gas fuel was based on two canister samples taken from the fuel supply header--one taken on June 14, and one taken on June 16. The fuel composition data from the canister analyses were used to determine the higher heating value (HHV) for engine heat input calculations.

Engine 102 at Station 3A was tested by the host site approximately one week prior to the Campaign 3 testing. The Campaign 3 full-load results show good agreement with this data set. The NO_x and THC values measured in this program were somewhat higher than the earlier results, approximately 20 percent and 5 percent, respectively, although the remaining pollutant measurements agree within 1 percent. One possible explanation for the higher NO_x values may be the higher ambient temperatures during this testing (85°F versus 67°F).

The Method 2 volumetric flow rates measured at Station 3A were lower than expected based on the earlier testing and Method 19 calculations; however, the Method 19 values from the two sets of test data agree well. Follow-up discussions with the site personnel and the GRI program engine consultant, and subsequent calculations have confirmed the accuracy of the fuel flow measurements. As noted in Tables 3-2 and 3-3, the Method 19 values were used to calculate all mass emission rates.

Table 3-2. Station 3A: Engine Operating Conditions and CEMS Results, Engine 102, Cooper-Bessemer LSV-16

Test Period	1	2
Load Condition	98%	101%
Date	6/14/94	6/15/94
Test Time	1600 - 2100	0832 - 1314
Ambient Conditions		
Barometric Pressure (in Hg)	29.2	29.2
Ambient Temperature (°F)	87	83
Relative Humidity (%)	62	73
Absolute Humidity (lb H_2O/1000 lb dry air)	17.9	18.4
Engine Operation Conditions		
Horsepower (hp)[a]	4,055	4,202
Load (%)[b]	98	101
Engine Speed (rpm)	321	325
Fuel Flow (scf/min)	487	497
Heat Input (MMBtu/hr)[c]	33.3	33.7
NG HHV (Btu/scf)	1,159	1,148
NG LHV (Btu/scf)	1,049	1,039
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	7,381	6,947
Vol. Flow (dscfm) - M19, F_d[d]	8,735	8,678
Stack Gas Temperature (°F)	976	976
Moisture (%V)	13.0	14.1
O_2 (%V)	9.6	9.4
CO_2 (%V)	7.0	7.3
NO_x (ppmvd)	1,749	1,657[e]
CO (ppmvd)	203	217
THC (ppmvw)	1,666	1,677
Exhaust Emissions		
NO_x (lb/hr)	109	103
NO_x (g/hp-hr)	12.2	11.1
NO_x (lb/MMBtu)	3.3	3.1
CO (lb/hr)	7.7	8.2
CO (g/hp-hr)	0.9	0.9
CO (lb/MMBtu)	0.2	0.2
THC (lb/hr)	41.7	42.2
THC (g/hp-hr)	4.7	4.6
THC (lb/MMBtu)	1.2	1.3

[a] Based on site-specific load performance curves.

[b] Rating based on operation at maximum brake mean effective pressure (BMEP).

[c] Based on HHV.

[d] Used in emission rate calculations.

[e] Analyzer calibration drift exceeded quality criteria for this test by 1 percent.

Table 3-3. Station 3A: Engine Operating Conditions and CEMS Results, Engine 101, Cooper-Bessemer LSV-16

Test Period	2	3
Load Condition	98%	99%
Date	6/16/94	6/16/94
Test Time	0915 - 1405	1415 - 1806
Ambient Conditions		
Barometric Pressure (in Hg)	29.4	29.2
Ambient Temperature (°F)	80	89
Relative Humidity (%)	78.0	58.0
Abs. Humidity (lb H_2O/lb dry air)	17.58	17.90
Engine Operation Conditions		
Horsepower (hp)[a]	4,056	4,117
Load (%)[b]	98	99
Engine Speed (rpm)	321	325
Fuel Flow (scf/min)	478	486
Heat Input (MMBtu/hr)[c]	32.4	33.0
NG HHV (Btu/scf)	1,148	1,148
NG LHV (Btu/scf)	1,039	1,039
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	7,195	7,319
Vol. Flow (dscfm) - M19, F_4[d]	8,421	8,409
Stack Gas Temperature (°F)	962	970
Moisture (%V)	13.5	13.5
O_2 (%V)	9.5	9.3
CO_2 (%V)	7.2	7.3
NO_x (ppmvd)	1,297[e]	1,544[e]
CO (ppmvd)	258	258
THC (ppmvw)	1,950	1,881
Exhaust Emissions		
NO_x (lb/hr)	78.2	93.0
NO_x (g/hp-hr)	8.7	10.2
NO_x (lb/MMBtu)	2.4	2.8
CO (lb/hr)	9.5	9.4
CO (g/hp-hr)	1.1	1.0
CO (lb/MMBtu)	0.3	0.3
THC (lb/hr)	47.3	45.5
THC (g/hp-hr)	5.3	5.0
THC (lb/MMBtu)	1.5	1.4

[a]Based on site-specific load performance curves.
[b]Rating based on operation at maximum brake mean effective pressure (BMEP).
[c]Based on HHV.
[d]Used in emission rate calculations.
[e]Analyzer calibration drift exceeded quality criteria for this test by 1 percent.

Cooper-Bessemer GMWA-8

One Cooper-Bessemer GMWA-8 engine, Engine 4, was tested at Sweet Gas Plant 3B. This engine is a 2-stroke, blower-scavenged engine, rated at 2,000 hp and 250 rpm. One test run was performed on this engine at full load on June 18 as shown in Table 3-4. Fuel flow rate data were obtained from the plant's computer control system, with the horsepower measurements collected by the host site engine analyst.

An on-line gas analysis system was used by the host site to measure the composition and calculate the heat content of the natural gas fuel. The results from this system were averaged over each test period. Two gas samples were also taken in sample bombs for analysis by Southern Petroleum Laboratories (SPL) to confirm the accuracy of the station's analysis system. The results from SPL agreed within 4 percent of the station analyses.

The exhaust flow measurements for this engine agreed well between the two methods (Method 2 and Method 19), with differences on the order of 1 percent. Since the accuracy of the fuel flow rate measurements was confirmed by follow-up discussions with host site personnel and the GRI program engine consultant, Method 19 results were used to calculate mass emission rates.

Cooper-Bessemer GMV-10TF

One Cooper-Bessemer GMV-10TF engine, Engine 2, was tested at Sweet Gas Plant 3B. This is a 2-stroke, piston-scavenged engine, rated at 1,100 hp and 300 rpm. Three test runs were performed on this engine at full load--two on June 19 and one on June 20--with the test results shown in Table 3-5. Engine operating parameters, including horsepower, speed, fuel flow, and fuel heat content were measured as described above for the Cooper-Bessemer GMWA-8 engine tested at the same station.

3.3.3 Measurement of Methane and Ethane Emissions

On-site analysis for methane and ethane was performed for Engines 101, 102, and 2 using a GC with a flame ionization detector (FID). Results are shown in Tables 3-6 and 3-7 for the full (or highest) load conditions. Note that the differences between the measured THC and methane/ethane concentrations were less than the analytical precision of the instruments for the results presented in Table 3-6 for the Cooper-Bessemer LSV-16 engines.

Table 3-4. Sweet Gas Plant 3B: Engine Operating Conditions and CEMS Results, Engine 4, Cooper-Bessemer GMWA-8

Test Period	1
Load Condition	98%
Date	6/18/94
Test Time	0925 - 1115
Ambient Conditions	
Barometric Pressure (in Hg)	29.3
Ambient Temperature (°F)	85
Relative Humidity (%)	66.0
Abs. Humidity (lb H_2O/lb dry air)	17.72
Engine Operation Conditions	
Horsepower (hp)[a]	1,958
Load (%)	98
Engine Speed (rpm)	249
Fuel Flow (scf/min)	244
Heat Input (MMBtu/hr)[b]	17.4
NG HHV (Btu/scf)	1,206
NG LHV (Btu/scf)	1,098
Exhaust Gas Conditions	
Vol. Flow (dscfm) - M2	8,665
Vol. Flow (dscfm) - M19, F_d[c]	8,290
Stack Gas Temperature (°F)	645
Moisture (%V)	9.3
O_2 (%V)	14.7
CO_2 (%V)	4.2
NO_x (ppmvd)	1,246
CO (ppmvd)	53
THC (ppmvw)	1,129
Exhaust Emissions	
NO_x (lb/hr)	74.0
NO_x (g/hp-hr)	17.1
NO_x (lb/MMBtu)	4.3
CO (lb/hr)	1.9
CO (g/hp-hr)	0.4
CO (lb/MMBtu)	0.1
THC (lb/hr)	25.7
THC (g/hp-hr)	6.0
THC (lb/MMBtu)	1.5

[a]There is some uncertainty in the horsepower measurement by the engine analyst.

[b]Based on HHV.

[c]Used in emission rate calculations.

Table 3-5. Sweet Gas Plant 3B: Engine Operating Conditions and CEMS Results, Engine 2, Cooper-Bessemer GMV-10TF

Test Period	2	3	4
Load Condition	104%	104%	104%
Date	6/19/94	6/19/94	6/20/94
Test Time	1105 - 1428	1630 - 2018	1240 - 1747
Ambient Conditions			
Barometric Pressure (in Hg)	29.4	29.4	29.4
Ambient Temperature (°F)	91	91	91
Relative Humidity (%)	51.0	54.0	51.0
Abs. Humidity (lb H_2O/lb dry air)	16.74	17.72	16.71
Engine Operation Conditions			
Horsepower (hp)[a]	1,145	1,142	1146
Load (%)	104	104	104
Engine Speed (rpm)	300	300	300
Fuel Flow (scf/min)	146	146	141
Heat Input (MMBtu/hr)[b]	10.4	10.4	10.1
NG HHV (Btu/scf)	1,204	1,204	1205
NG LHV (Btu/scf)	1,095	1,095	1096
Exhaust Gas Conditions			
Vol. Flow (dscfm) - M2	3,377	3,391	3217
Vol. Flow (dscfm) - M19, F_d[c]	3,885	3,890	3868
Stack Gas Temperature (°F)	661	660	651
Moisture (%V)	10.3	9.3	7.8
O_2 (%V)	13.0	13.0	13.2
CO_2 (%V)	d	5.0	5.1
NO_x (ppmvd)	1,287	1,366	994
CO (ppmvd)	81.0	80.4	83.7
THC (ppmvw)	828	818	865
Exhaust Emissions			
NO_x (lb/hr)	35.8	38.1	27.5
NO_x (g/hp-hr)	14.2	15.1	10.9
NO_x (lb/MMBtu)	3.5	3.7	2.7
CO (lb/hr)	1.4	1.4	1.4
CO (g/hp-hr)	0.5	0.5	0.6
CO (lb/MMBtu)	0.1	0.1	0.1
THC (lb/hr)	8.9	8.7	9.0
THC (g/hp-hr)	3.5	3.5	3.6
THC (lb/MMBtu)	0.9	0.8	0.9

[a]There is uncertainty in horsepower measurements by the engine analyst.
[b]Based on HHV.
[c]Used in emission rate calculations.
[d]CO_2 concentration not reported because analyzer calibration drift exceeded quality criteria for this test period.

Table 3-6. Station 3A: GC Results

Engine Make/Model	Unit No.	Test Period	Load (%)	Pollutant	Stack Conc (ppmvd)	Emission Rate/Factor		
						(lb/hr)	(g/hp-hr)	(lb/MMBtu)
C-B LSV-16	102	1	98	Methane	1,924	42	4.7	1.3
				Ethane	28	1.1	0.13	0.034
C-B LSV-16	102	2	101	Methane	2,566	55	6.0	1.7
				Ethane	39	1.6	0.17	0.047
C-B LSV-16	101	2	98	Methane	2,339	49	5.5	1.5
				Ethane	37	1.5	0.16	0.045
C-B LSV-16	101	3	99	Methane	2,444	51	5.6	1.6
				Ethane	38	1.5	0.17	0.050

Table 3-7. Sweet Gas Plant 3B: GC Results

Engine Make/Model	Unit No.	Test Period	Load (%)	Pollutant	Stack Conc (ppmvd)	Emission Rate/Factor		
						(lb/hr)	(g/hp-hr)	(lb/MMBtu)
C-B GMV-10TF	2	2	104	Methane	604	5.9	2.3	0.56
				Ethane	117	2.1	0.84	0.20
C-B GMV-10TF	2	3	104	Methane	626	6.1	2.4	0.58
				Ethane	121	2.2	0.88	0.21

This is not unusual for combustion sources where a large fraction of THC emissions is composed of methane/ethane. No methane/ethane data were collected for Engine 4.

3.4 Campaign 4

3.4.1 Site Description

The host site for Campaign 4 was a storage station where engines are used to pump natural gas to and from storage fields. The engines characterized during this campaign included a Cooper-Bessemer GMVC-10C 2-stroke, clean-burn engine, two Ingersoll-Rand KVS-412 4-stroke, lean-burn engines, and a Waukesha L7042GU 4-stroke, rich-burn engine. All of the engines burn pipeline-quality natural gas. As shown in Table-3-1, three of the engines were equipped with catalytic controls on the exhaust gas streams.

3.4.2 Operating Conditions and Measurement of O_2, CO_2, CO, THC, and NO_x

Tables 3-8 through 3-14 present the engine operating conditions and results from the CEMS testing performed at this site. During each test period, CEMS and GC data were collected at the inlet and outlet of the control devices for engines equipped with catalytic controls. Fuel flow rates were measured by the station control system and confirmed by the GRI program engine consultant. The Method 19 volumetric flow rate estimates were used in the emission rate calculations except where noted, under the recommendation of the GRI program engine consultant. Both Method 2 and Method 19 flow rate estimates are shown in the result summary tables. Heat content of the fuel was based on samples taken daily from the fuel supply header and analyzed by the host site's laboratory. The heat content of individual fuel samples varied less than 0.3 percent from the average during the testing period.

Engine horsepower measurements were conducted by an engine analyst under subcontract to Radian. Prior to testing, minimal maintenance was performed where needed to balance the engine cylinders at maximum load conditions.

Table 3-8. Campaign 4: Operating Conditions and CEMS Results, Waukesha L7042GU (Tests 1 and 2)

Test Period	1	2
Load Condition	95%	92%
Sampling Location	After NSCR	After NSCR
Date	8/23/94	8/23/94
Test Time	1146 - 1345	1424 - 1722
Ambient Conditions		
Barometric Pressure (in Hg)	29.5	29.5
Ambient Temperature (°F)	87	87
Relative Humidity (%)	35.2	40.1
Abs. Humidity (lb H_2O/1000 lb dry air)	10.1	11.3
Engine Operating Conditions		
Horsepower (hp)	692	671
Load (%)	95	92
Engine Speed (rpm)	809	811
Fuel Flow (scf/min)[a]	88.0	84.6
Heat Input (MMBtu/hr)[b]	5.3	5.1
NG HHV (Btu/scf)	1,011	1,011
NG LHV (Btu/scf)	911	911
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2[c]	1,274	1,274
Vol. Flow (dscfm) - M19, Fd	746	718
Stack Gas Temperature (°F)	796	796
Moisture (%V)	20.7	20.7
O_2 (%V)	0.04	0.06
CO_2 (%V)	11.7	11.7
NO_x (ppmvd)	8.03	8.38
CO (ppmvd)	68.5	69.5
THC (ppmvw)	607	640
Exhaust Emissions		
NO_x (lb/hr)	0.07	0.08
NO_x (g/hp-hr)	0.05	0.05
NO_x (lb/MMBtu)	0.01	0.02
CO (lb/hr)	0.38	0.39
CO (g/hp-hr)	0.25	0.26
CO (lb/MMBtu)	0.07	0.08
THC (lb/hr)	2.4	2.6
THC (g/hp-hr)	1.6	1.7
THC (lb/MMBtu)	0.46	0.51

[a]Fuel flow rate is suspect.

[b]Based on HHV.

[c]Used in emission rate calculations.

Table 3-9 Campaign 4: Operating Conditions and CEMS Results, Waukesha L7042GU (Test 3)

Test Period	**3**
Load Condition	**88%**
Sampling Location	**Before NSCR**
Date	**8/23/94**
Test Time	**1805 - 2028**
Ambient Conditions	
Barometric Pressure (in Hg)	29.5
Ambient Temperature (°F)	74
Relative Humidity (%)	65.4
Abs. Humidity (lb H_2O/1000 lb dry air)	12.0
Engine Operating Conditions	
Horsepower (hp)	644
Load (%)	88
Engine Speed (rpm)	813
Fuel Flow (scf/min)[a]	82.8
Heat Input (MMBtu/hr)[b]	5.0
NG HHV (Btu/scf)	1,011
NG LHV (Btu/scf)	911
Exhaust Gas Conditions	
Vol. Flow (dscfm) - M2[c]	1,274
Vol. Flow (dscfm) - M19, F_d[a]	716
Stack Gas Temperature (°F)	796
Moisture (%V)	20.7
O_2 (%V)	0.42
CO_2 (%V)	11.2
NO_x (ppmvd)	2,843
CO (ppmvd)	3,714
THC (ppmvw)	1,048
Exhaust Emissions	
NO_x (lb/hr)	25.9
NO_x (g/hp-hr)	18.3
NO_x (lb/MMBtu)	5.2
CO (lb/hr)	20.6
CO (g/hp-hr)	14.5
CO (lb/MMBtu)	4.2
THC (lb/hr)	4.2
THC (g/hp-hr)	3.0
THC (lb/MMBtu)	0.85

[a]Fuel flow rate is suspect.

[b]Based on higher heating value (HHV).

[c]Used in emission rate calculations.

Table 3-10. Campaign 4: Operating Conditions and CEMS Results, Engine 4, Cooper-Bessemer GMVC-10C (Tests 7, 9, and H)

Test Period	7	9	H
Load Condition	97%	93%	95%
Sampling Location	Before Catalyst	Before Catalyst	Before Catalyst
Date	8/25/94	8/26/94	8/30/94
Test Time	1705 - 1906	1310 - 1537	1605 - 1630
Ambient Conditions			
Barometric Pressure (in Hg)	29.4	29.5	29.4
Ambient Temperature (°F)	85	89	85
Relative Humidity (%)	37.8	40.5	29.4
Abs. Humidity (lb H_2O/1000 lb dry air)	10.1	12.4	8.0
Engine Operating Conditions			
Brake horsepower (hp)	1,732	1,674	1,705
Load (%)	97	93	95
Engine Speed (rpm)	299	300	299
Fuel Flow (scf/min)	211	213	212
Heat Input (MMBtu/hr)[a]	12.6	12.7	12.7
NG HHV (Btu/scf)	1,009	1,009	1,011
NG LHV (Btu/scf)	910	910	911
Exhaust Gas Conditions			
Vol. Flow (dscfm) - M2	8,486	NA	8,338
Vol. Flow (dscfm) - M19, F_d[b]	6,920	6,866	6,633
Stack Gas Temperature (°F)	574	517	506
Moisture (%V)	7.26	7.30	8.20
O_2 (%V)	15.5	15.4	15.3
CO_2 (%V)	2.86	2.96	2.92
NO_x (ppmvd)	39.2	34.1	36.9
CO (ppmvd)	162	181	178
THC (ppmvw)	1,218	1,559	1,426
Exhaust Emissions			
NO_x (lb/hr)	1.94	1.68	1.75
NO_x (g/hp-hr)	0.51	0.45	0.47
NO_x (lb/MMBtu)	0.15	0.13	0.14
CO (lb/hr)	4.89	5.41	5.15
CO (g/hp-hr)	1.28	1.47	1.37
CO (lb/MMBtu)	0.39	0.43	0.41
THC (lb/hr)	22.6	28.8	25.6
THC (g/hp-hr)	5.93	7.79	6.82
THC (lb/MMBtu)	1.80	2.26	2.02

[a]Based on HHV.

[b]Used in emission rate calculations.

Table 3-11. Campaign 4: Operating Conditions and CEMS Results, Engine 4, Cooper-Bessemer GMVC-10C (Test 8)

Test Period	**8**
Load Condition	**99%**
Sampling Location	**After Catalyst**
Date	**8/26/94**
Test Time	**1051 - 1226**
Ambient Conditions	
Barometric Pressure (in Hg)	29.5
Ambient Temperature (°F)	84
Relative Humidity (%)	47.8
Abs. Humidity (lb H_2O/1000 lb dry air)	12.5
Engine Operating Conditions	
Horsepower (hp)	1,773
Load (%)	99
Engine Speed (rpm)	299
Fuel Flow (scf/min)	211
Heat Input (MMBtu/hr)[a]	12.6
NG HHV (Btu/scf)	1,009
NG LHV (Btu/scf)	910
Exhaust Gas Conditions	
Vol. Flow (dscfm) - M2	8,751
Vol. Flow (dscfm) - M19, F_d[b]	6,696
Stack Gas Temperature (°F)	517
Moisture (%V)	7.3
O_2 (%V)	15.4
CO_2 (%V)	3.0
NO_x (ppmvd)	44.0
CO (ppmvd)	14.2
THC (ppmvw)	1,358
Exhaust Emissions	
NO_x (lb/hr)	2.11
NO_x (g/hp-hr)	0.54
NO_x (lb/MMBtu)	0.17
CO (lb/hr)	0.41
CO (g/hp-hr)	0.11
CO (lb/MMBtu)	0.03
THC (lb/hr)	24.4
THC (g/hp-hr)	6.25
THC (lb/MMBtu)	1.94

[a]Based on HHV.

[b]Used in emission rate calculations.

Table 3-12. Campaign 4: Operating Conditions and CEMS Results, Engine 8, I-R KVS-412 (PCC)

Test Period	**A**
Load Condition	**92%**
Sampling Location	**Stack**
Date	**8/30/94**
Test Time	**0745 - 0815**
Ambient Conditions	
Barometric Pressure (in Hg)	29.4
Ambient Temperature (°F)	73
Relative Humidity (%)	66.4
Abs. Humidity (lb H_2O/1000 lb dry air)	11.7
Engine Operating Conditions	
Horsepower (hp)	1,846
Load (%)	92
Engine Speed (rpm)	330
Fuel Flow (scf/min)	267
Heat Input (MMBtu/hr)[a]	15.9
NG HHV (Btu/scf)	1,009
NG LHV (Btu/scf)	910
Exhaust Gas Conditions	
Vol. Flow (dscfm) - M2	4,531
Vol. Flow (dscfm) - M19, F_d[b]	4,927
Stack Gas Temperature (°F)	746
Moisture (%V)	12.0
O_2 (%V)	11.3
CO_2 (%V)	5.19
NO_x (ppmvd)	64.6
CO (ppmvd)	378
THC (ppmvw)	2,333
Exhaust Emissions	
NO_x (lb/hr)	2.28
NO_x (g/hp-hr)	0.56
NO_x (lb/MMBtu)	0.14
CO (lb/hr)	8.10
CO (g/hp-hr)	1.99
CO (lb/MMBtu)	0.51
THC (lb/hr)	32.5
THC (g/hp-hr)	8.0
THC (lb/MMBtu)	2.04

[a]Based on HHV.

[b]Used in emission rate calculations.

Table 3-13. Campaign 4: Operating Conditions and CEMS Results, Engine 9, I-R KVS-412 (Tests 14 and 17)

Test Period	14	17
Load Condition	91%	91%
Sampling Location	Before SCR	Before SCR
Date	8/29/94	8/29/94
Test Time	0858 - 0932	1613 - 1700
Ambient Conditions		
Barometric Pressure (in Hg)	29.5	29.4
Ambient Temperature (°F)	77	91
Relative Humidity (%)	52.1	31.7
Abs. Humidity (lb H_2O/1000 lb dry air)	10.6	10.3
Engine Operating Conditions		
Horsepower (hp)	1,840	1,830
Load (%)	91	91
Engine Speed (rpm)	332	331
Fuel Flow (scf/min)	272	266
Heat Input (MMBtu/hr)[a]	16.3	15.9
NG HHV (Btu/scf)	1,011	1,011
NG LHV (Btu/scf)	911	911
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	4,259	4,259
Vol. Flow (dscfm) - M19, F_d[b]	3,914	3,754
Stack Gas Temperature (°F)	779	779
Moisture (%V)	14.4	14.4
O_2 (%V)	8.56	8.33
CO_2 (%V)	6.93	7.10
NO_x (ppmvd)	3,042	3,339
CO (ppmvd)	141	126
THC (ppmvw)	938	900
Exhaust Emissions		
NO_x (lb/hr)	85.2	89.7
NO_x (g/hp-hr)	21.0	22.3
NO_x (lb/MMBtu)	5.24	5.65
CO (lb/hr)	2.41	2.06
CO (g/hp-hr)	0.59	0.51
CO (lb/MMBtu)	0.15	0.13
THC (lb/hr)	10.7	9.8
THC (g/hp-hr)	2.63	2.44
THC (lb/MMBtu)	0.66	0.62

[a]Based on HHV.

[b]Used in emission rate calculations.

Table 3-14. Campaign 4: Operating Conditions and CEMS Results, Engine 9, I-R KVS-412 (Tests 15 and 16)

Test Period	15	16
Load Condition	90%	90%
Sampling Location	After SCR	After SCR
Date	8/29/94	8/29/94
Test Time	0959 - 1330	1413 - 1549
Ambient Conditions		
Barometric Pressure (in Hg)	29.5	29.4
Ambient Temperature (°F)	87	93
Relative Humidity (%)	33.1	31.8
Abs. Humidity (lb H_2O/1000 lb dry air)	9.3	11.2
Engine Operating Conditions		
Horsepower (hp)	1,809	1,800
Load (%)	90	90
Engine Speed (rpm)	331	331
Fuel Flow (scf/min)	270	265
Heat Input (MMBtu/hr)[a]	16.1	15.8
NG HHV (Btu/scf)	1,011	1,011
NG LHV (Btu/scf)	911	911
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	4,259	4,259
Vol. Flow (dscfm) - M19, F_d[b]	3,890	3,804
Stack Gas Temperature (°F)	779	779
Moisture (%V)	14.4	14.4
O_2 (%V)	8.6	8.6
CO_2 (%V)	6.8	6.8
NO_x (ppmvd)	677	775
CO (ppmvd)	103	102
THC (ppmvw)	949	1,001
Exhaust Emissions		
NO_x (lb/hr)	18.8	21.1
NO_x (g/hp-hr)	4.73	5.3
NO_x (lb/MMBtu)	1.2	1.3
CO (lb/hr)	1.8	1.7
CO (g/hp-hr)	0.44	0.42
CO (lb/MMBtu)	0.11	0.11
THC (lb/hr)	10.7	11.1
THC (g/hp-hr)	2.7	2.8
THC (lb/MMBtu)	0.67	0.70

[a]Based on HHV.

[b]Used in emission rate calculations.

Waukesha L7042GU

One Waukesha L7042GU engine equipped with NSCR control was tested. This model is a naturally-aspirated, 4-stroke, rich-burn engine, rated at 896 hp and 1,000 rpm. The test results are included in this section because it is the only 4-stroke, rich-burn engine tested in this effort. Two runs were performed downstream of the catalyst bed, and one run was performed upstream of the catalyst bed. Operating parameters and results of the CEMS measurements for NO_x, CO, CO_2, THC, and O_2 are presented in Tables 3-8 and 3-9. As noted in these two tables, the fuel flow rate data for this engine are suspect. Therefore, the emission rate calculations are based on Method 2 results.

Cooper-Bessemer GMVC-10C

One Cooper-Bessemer GMVC-10C engine (Engine 4) retrofitted with clean-burn modifications for NO_x control and an oxidation catalyst for CO control was tested. This is a 2-stroke, turbocharged engine rated at 1,800 hp and 300 rpm. Engine 4 was tested at full load, upstream and downstream of the CO catalyst. Operating parameters and CEMS measurements are summarized in Tables 3-10 and 3-11.

Ingersoll-Rand KVS-412

One Ingersoll-Rand KVS-412 engine (Engine 8) equipped with a PCC for NO_x control was tested. This is a 2-stroke, turbocharged engine rated at 2,000 hp and 330 rpm. In addition, measurements were conducted on a sister unit, Engine 9, which has been retrofitted with SCR for NO_x control. Engine 9 was tested upstream and downstream of the SCR catalyst at full load. During the tests on Engine 9, the SCR system was operating under a condition of excess ammonia injection, creating ammonia slip through the SCR catalyst. This condition is not typical for SCR operation, and the ammonia slip may have caused NO_x measurements downstream of the catalyst for this engine to be biased high. Operating parameters and CEMS measurements for these two units are summarized in Tables 3-12 through 3-14.

3.4.3 Measurement of Methane and Ethane Emissions

On-site analysis for methane and ethane was performed using a GC/FID system which was calibrated specifically for methane and ethane, among other straight chain hydrocarbons. Due to instrument failure, no GC data were collected on August 23, 1994. Therefore no methane/ethane data are available for the Waukesha engine. For the remaining engines, methane measurements were not collected due to an instrument malfunction. This malfunction did not affect readings for ethane, as summarized in Table 3-15. Since no methane data were available, it was not possible to calculate NMHC and NMEHC emission factors for this campaign.

Table 3-15. Campaign 4: GC Results (Ethane)

Engine Make/Model	Unit No.	Test Period	Load (%)	Sample Location	Stack Conc. (ppmvd)	Emission Rate/Factor		
						(lb/hr)	(g/hp-hr)	(lb/MMBtu)
C-B GMVC-10C	4	7	97	Before CO catalyst	44	1.4	0.37	0.11
C-B GMVC-10C	4	9	93	Before CO catalyst	45	1.5	0.39	0.11
I-R KVS-412	8	11	99	Stack	60	1.4	0.36	0.086
I-R KVS-412	9	13	88	Before SCR	29	0.50	0.13	0.032
I-R KVS-412	9	15	90	After SCR	32	0.58	0.15	0.037

3.5 Campaign 5

3.5.1 Site Description

The sweet gas plant tested in Campaign 5 is a cryogenic expansion plant which is designed to remove 90 percent of the ethane and 100 percent of the propane and higher molecular weight hydrocarbons from raw natural gas. The plant fractionates the hydrocarbons extracted from the raw natural gas along with a mix of hydrocarbons purchased from outside the facility. The facility's products include: ethane, propane, butane, isobutane, and natural gasoline.

A natural gas-fired Westinghouse 191 (20,000 hp) combustion turbine is used to power two refrigeration compressors at the facility. The first of the compressors is a propane compressor rated at 10,800 hp, and the second is an ethylene compressor rated at 4,865 hp.

3.5.2 Test Results

Two full load test runs were conducted on the turbine. The CEMS was used to gather NO_x, CO, CO_2, O_2, and THC concentration data during both test periods, while methane and ethane data were collected only during the first test period.

Table 3-16 summarizes the operating parameters and the CEMS measurements collected during the two test periods. No actual measurement of brake horsepower of the turbine was available because of instrumentation limitations at the facility. Based on discussions with the turbine manufacturer, the measured fuel flow and the exhaust flow rates (Method 2 and Method 19) were considered representative of full load operation for the turbine.

Measurements of the methane and ethane concentrations in the gas turbine exhaust were conducted using a GC/FID system. As consistent with the THC measurements, neither methane nor ethane were detected in the exhaust gas, resulting in NMHC and NMEHC concentrations below detection limits as well.

Table 3-16. Campaign 5: Operating Conditions and CEMS Results, Westinghouse 191

Test Period	3	4
Load Condition	Full	Full
Date	10/05/94	10/05/94
Test Time	1230 - 1755	1843 - 2133
Ambient Conditions		
Barometric Pressure (in Hg)	29.3	29.4
Ambient Temperature (°F)	57.24	51.48
Relative Humidity (%)	51.26	75.12
Absolute Humidity (lb H_2O/1000 lb dry air)	5.11	6.04
Operating Conditions		
Horsepower (hp)[a]	20,000	20,000
Fuel Flow (scf/min)	3,298	3,298
Heat Input (MMBtu/hr)[b]	203	203
NG HHV (Btu/scf)	1,026	1,026
NG LHV (Btu/scf)	924	924
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2[c]	232,503	214,147
Vol. Flow (dscfm) - M19	185,603	184,460
Stack Gas Temperature (°F)	239[d]	430
Moisture (%V)	4.03	4.46
O_2 (%V, dry)	17.7	17.6
CO_2 (%V, dry)	2.00	2.00
NO_x (ppmvd)	41.4	39.6
CO (ppmvd)	13.2	16.6
THC (ppmvw)	ND[e]	ND[e]
Exhaust Emissions		
NO_x (lb/hr)	68.9	60.7
NO_x (g/hp-hr)	1.56	1.38
NO_x (lb/MMBtu)	0.34	0.30
CO (lb/hr)	13.4	15.5
CO (g/hp-hr)	0.30	0.35
CO (lb/MMBtu)	0.07	0.08
THC (lb/hr)	ND	ND
THC (g/hp-hr)	ND	ND
THC (lb/MMBtu)	ND	ND

[a]Estimated to be at full load.
[b]Based on higher heating value (HHV).
[c]Used in emission rate calculations.
[d]Temperature reading suspect.
[e]Detection limit: 10 ppm.

3.6 Campaign 6

3.6.1 *Site Description*

Testing was performed at three natural gas transmission stations (6A, 6B, and 6C) where the engines and the turbine characterized in these tests are used to drive compressors for gas transmission. Station 6A operates several Clark BA-5 engines and one Clark HBA-5 engine. As shown in Table 3-1, testing was conducted on one of the Clark BA-5 units (Engine 10) and the single Clark HBA-5 unit (Engine 12). At Station 6B, there is one Solar Taurus T-6502 gas turbine, which was tested during this campaign. Station 6C operates several engines, including Cooper-Bessemer GMVA-10, Cooper-Bessemer GMVC-10, and GMWC-10 engines. Four engines were tested at Station 6C, including one Cooper-Bessemer GMVA-10 (Engine 9), two Cooper-Bessemer GMVC-10 (Engines 11 and 15), and one Cooper-Bessemer GMWC-10 (Engine 13).

3.6.2 *Engine Operating Conditions and Measurement of O_2, CO_2, CO, THC, and NO_x*

During each test period, concentrations of O_2, CO_2, CO, THC, and NO_x in the stack gas were measured using the CEMS. Methane and ethane concentrations were measured by GC/FID.

For all engines, horsepower was measured by the host site's engine analyst under the direction of GRI program's engine consultant. For the turbine at Station 6B, horsepower and other process data were obtained from the host site control system. Pressure readings from an orifice meter on the fuel header were used to calculate fuel flow rates at Stations 6A and 6B. At Station 6C, the orifice meters on the fuel headers were monitored by the station's data acquisition system, and the calculated fuel flow rates were available from the station computer. Heat content of the natural gas fuel was based on samples taken daily from the fuel supply header and analyzed by the host site.

Clark BA-5

A Clark BA-5 engine, Engine 10, was tested at 93 percent load on November 4, and at 100 percent load on November 5. This model is a naturally-aspirated, 2-stroke, lean-burn engine, rated at 911 hp at 300 rpm at site conditions. Operating parameters and results of the CEMS measurements for O_2, CO_2 CO, THC, and NO_x are presented in Table 3-17.

Table 3-17. Station 6A: Operating Conditions and CEMS Results, Engine 10, Clark BA-5

Test Period	1	2
Load Condition	94%	100%
Sampling Location	Exhaust	Exhaust
Date	11/04/94	11/05/94
Test Time	1000 - 1224	0936 - 1209
Ambient Conditions		
Barometric Pressure (in Hg)	26.4	29.3
Ambient Temperature (°F)	62	62
Relative Humidity (%)	62.7	29.3
Abs. Humidity (lb H_2O/1000 lb dry air)	8.2	3.5
Engine Operating Conditions		
Brake horsepower (hp)	851	910
Load (%)	94	100
Engine Speed (rpm)	299	299
Fuel Flow (scf/min)	161	174
Heat Input (MMBtu/hr)[a]	9.8	10.5
NG HHV (Btu/scf)	1,025	1,021
NG LHV (Btu/scf)	928	924
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	7,163	7,493
Vol. Flow (dscfm) - M19, F_d[b]	4,272	4,679
Stack Gas Temperature (°F)	458	455
Moisture (%V)	10.4	8.0
O_2 (%V)	14.2	14.3
CO_2 (%V)	4.3	4.4
NO_x (ppmvd)	914	1,337
CO (ppmvd)	86.3	92.6
THC (ppmvw)	NA[c]	970
Exhaust Emissions		
NO_x (lb/hr)	28.0	44.8
NO_x (g/hp-hr)	14.9	22.3
NO_x (lb/MMBtu)	2.87	4.26
CO (lb/hr)	1.61	1.89
CO (g/hp-hr)	0.86	0.94
CO (lb/MMBtu)	0.16	0.18
THC (lb/hr)	--	12.3
THC (g/hp-hr)	--	6.12
THC (lb/MMBtu)	--	1.17

[a]Based on higher heating value (HHV).
[b]Used in emission rate calculations.
[c]Not available due to instrument failure.

Clark HBA-5

One Clark HBA-5 engine, Engine 12, was tested at 84 percent load on November 5. This was the highest achievable load under the pipeline pressure conditions during the testing at Station 6A. This model is a piston-scavenged, 2-stroke, lean-burn engine, rated at 1,000 hp at 300 rpm. Because the engine was tested at a load below 90 percent, operating parameters and CEMS results are summarized in Appendix B.

Solar Taurus T-6502

Two test runs were performed on a Solar Taurus T-6502 gas turbine at 95 percent load, on November 7 and 8. The turbine has a site power rating of 5,419 hp. Although the loads are similar for the two full load tests, ambient conditions and pipeline suction and discharge pressures were slightly different. Operating parameters and CEMS results are summarized in Table 3-18.

Cooper-Bessemer GMVC-10

A Cooper-Bessemer GMVC-10 engine, Engine 15, was tested twice at 102 percent load on November 10. This model is a turbocharged, 2-stroke, lean-burn engine, rated at 1,800 hp at 300 rpm. Operating parameters and results of the CEMS measurements for O_2, CO_2, CO, THC, and NO_x are presented in Table 3-19. A second Cooper-Bessemer GMVC-10 engine, Engine 11, was tested three times at 95-101 percent load on November 15. Operating parameters and results of the CEMS measurements for O_2, CO_2, CO, THC, and NO_x are presented in Table 3-20 for Engine 11. Note that only one of the three tests was conducted at 100 percent speed (Test Period 19). As indicated in the tables, the emission rates for the three tests were affected by the different engine speeds.

Cooper-Bessemer GMVA-10

A Cooper-Bessemer GMVA-10 engine, Engine 9, was tested twice at 100 percent load on November 12. This model is a blower scavenged, 2-stroke, lean-burn engine, rated at 1,235 hp at 300 rpm. Operating parameters and results of the CEMS measurements for O_2, CO_2, CO, THC, and NO_x are presented in Table 3-21.

Table 3-18. Station 6B: Operating Conditions and CEMS Results, Solar Taurus T-6502

Test Period	6	7
Load Condition	95%	95%
Sampling Location	Exhaust	Exhaust
Date	11/07/94	11/08/94
Test Time	1709 - 1823	0915 - 1344
Ambient Conditions		
Barometric Pressure (in Hg)	26.5	26.5
Ambient Temperature (°F)	69	76
Relative Humidity (%)	44.2	47.2
Abs. Humidity (lb H_2O/1000 lb dry air)	7.5	10.4
Engine Operating Conditions		
Horsepower (hp)	4,803	4,709
Percent Load[a]	95	95
Turbine Speed (rpm)	12,458	12,250
Fuel Flow (scf/min)	709	745
Heat Input (MMBtu/hr)[b]	42.8	45.0
NG HHV (Btu/scf)	1,020	1,021
NG LHV (Btu/scf)	924	925
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	29,192	30,964
Vol. Flow (dscfm) - M19, F_d[c]	25,757	26,581
Stack Gas Temperature (°F)	954	941
Moisture (%V)	6.40	6.50
O_2 (%V dry)	16.0	15.9
CO_2 (%V dry)	3.2	3.2
NO_x (ppmvd)	71.5	70.8
CO (ppmvd)	ND[d]	ND[d]
THC (ppmvw)	ND[e]	ND[e]
Exhaust Emissions		
NO_x (lb/hr)	13.2	13.5
NO_x (g/hp-hr)	1.2	1.3
NO_x (lb/MMBtu)	0.3	0.3
CO (lb/hr)	ND	ND
CO (g/hp-hr)	ND	ND
CO (lb/MMBtu)	ND	ND
THC (lb/hr)	ND	ND
THC (g/hp-hr)	ND	ND
THC (lb/MMBtu)	ND	ND

[a]Turbine load is based on available power at ambient conditions during testing.
[b]Based on higher heating value (HHV).
[c]Used in emission rate calculations.
[d]Detection limit: 1 ppm.
[e]Detection limit: 1 ppm.

Table 3-19. Station 6C: Operating Conditions and CEMS Results, Engine 15, Cooper-Bessemer GMVC-10

Test Period	9	10
Load Condition	102%	102%
Sampling Location	Exhaust	Exhaust
Date	11/10/94	11/10/94
Test Time	1030 - 1500	1546 - 1801
Ambient Conditions		
Barometric Pressure (in Hg)	26.7	26.6
Ambient Temperature (°F)	53	58
Relative Humidity (%)	46.5	36.2
Abs. Humidity (lb H_2O/1000 lb dry air)	4.4	4.2
Engine Operating Conditions		
Horsepower (hp)	1,827	1,830
Load (%)	102	102
Engine Speed (rpm)	300	300
Fuel Flow (scf/min)	266	266
Heat Input (MMBtu/hr)[a]	16.0	16.0
NG HHV (Btu/scf)	1,020	1,020
NG LHV (Btu/scf)	924	924
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	7,570	7,588
Vol. Flow (dscfm) - M19, F_d[b]	7,972	7,749
Stack Gas Temperature (°F)	581	576
Moisture (%V)	7.0	7.0
O_2 (%V)	15.0	14.8
CO_2 (%V)	3.68	3.69
NO_x (ppmvd)	560	638
CO (ppmvd)	71.2	71.1
THC (ppmvw)	971	957
Exhaust Emissions		
NO_x (lb/hr)	31.9	35.4
NO_x (g/hp-hr)	7.93	8.77
NO_x (lb/MMBtu)	1.99	2.21
CO (lb/hr)	2.47	2.40
CO (g/hp-hr)	0.61	0.59
CO (lb/MMBtu)	0.15	0.15
THC (lb/hr)	20.7	19.9
THC (g/hp-hr)	5.15	4.92
THC (lb/MMBtu)	1.29	1.24

[a]Based on higher heating value (HHV).

[b]Used in emission rate calculations.

Table 3-20. Station 6C: Operating Conditions and CEMS Results, Engine 11, Cooper-Bessemer GMVC-10

Test Period	19	20	24
Load Condition	100%	101%	95%
Sampling Location	Exhaust	Exhaust	Exhaust
Date	11/15/94	11/15/94	11/15/94
Test Time	1020 - 1120	1622 - 1655	1730 - 1813
Ambient Conditions			
Barometric Pressure (in Hg)	27.0	26.9	26.9
Ambient Temperature (°F)	50	55	51
Relative Humidity (%)	33.5	29.3	36.2
Abs. Humidity (lb H_2O/1000 lb dry air)	2.8	2.9	3.1
Engine Operating Conditions			
Brake horsepower (hp)	1,799	1,724	1,669
Load (%)	100	101	95
Engine Speed (rpm)	300	285	292
Fuel Flow (scf/min)	236	224	221
Heat Input (MMBtu/hr)[a]	14.2	13.5	13.3
NG HHV (Btu/scf)	1,021	1,021	1,021
NG LHV (Btu/scf)	925	925	925
Exhaust Gas Conditions			
Vol. Flow (dscfm) - M2	7,501	7,019	7,172
Vol. Flow (dscfm) - M19, F_d[b]	6,983	6,312	6,528
Stack Gas Temperature (°F)	592	583	576
Moisture (%V)	6.7	7.0	6.8
O_2 (%V)	14.9	14.6	14.9
CO_2 (%V)	3.8	3.9	3.7
NO_x (ppmvd)	870	1,426	757
CO (ppmvd)	63.6	57.0	65.3
THC (ppmvw)	958	895	973
Exhaust Emissions			
NO_x (lb/hr)	43.5	64.5	35.4
NO_x (g/hp-hr)	11.0	17.0	9.6
NO_x (lb/MMBtu)	3.05	4.77	2.65
CO (lb/hr)	1.94	1.57	1.86
CO (g/hp-hr)	0.49	0.41	0.50
CO (lb/MMBtu)	0.14	0.12	0.14
THC (lb/hr)	17.9	15.1	17.0
THC (g/hp-hr)	4.51	3.98	4.61
THC (lb/MMBtu)	1.25	1.12	1.27

[a]Based on higher heating value (HHV).

[b]Used in emission rate calculations.

Table 3-21. Station 6C: Operating Conditions and CEMS Results, Engine 9, Cooper-Bessemer GMVA-10

Test Period	13	14
Load Condition	100%	100%
Sampling Location	Exhaust	Exhaust
Date	11/12/94	11/12/94
Test Time	1000 - 1405	1515 - 1645
Ambient Conditions		
Barometric Pressure (in Hg)	26.5	26.5
Ambient Temperature (°F)	57	59
Relative Humidity (%)	85.6	82.9
Abs. Humidity (lb H_2O/1000 lb dry air)	9.3	10.0
Engine Operating Conditions		
Horsepower (hp)	1,232	1,234
Load (%)	100	100
Engine Speed (rpm)	300	300
Fuel Flow (scf/min)	174	173
Heat Input (MMBtu/hr)[a]	10.5	10.4
NG HHV (Btu/scf)	1,020	1,020
NG LHV (Btu/scf)	928	928
Exhaust Gas Conditions		
Vol. Flow (dscfm) - M2	4,715	4,690
Vol. Flow (dscfm) - M19, F_d[b]	4,845	4,756
Stack Gas Temperature (°F)	586	590
Moisture (%V)	8.3	8.4
O_2 (%V)	14.6	14.5
CO_2 (%V)	3.91	3.95
NO_x (ppmvd)	396	391
CO (ppmvd)	67.6	67.1
THC (ppmvw)	1,342	1,309
Exhaust Emissions		
NO_x (lb/hr)	13.7	13.3
NO_x (g/hp-hr)	5.06	4.89
NO_x (lb/MMBtu)	1.31	1.28
CO (lb/hr)	1.43	1.39
CO (g/hp-hr)	0.53	0.51
CO (lb/MMBtu)	0.14	0.13
THC (lb/hr)	17.7	16.9
THC (g/hp-hr)	6.50	6.22
THC (lb/MMBtu)	1.69	1.62

[a]Based on higher heating value (HHV).
[b]Used in emission rate calculations.

Cooper-Bessemer GMWC-10

A Cooper-Bessemer GMWC-10 engine, Engine 13, was tested three times on November 14. This model is a turbocharged, 2-stroke, lean-burn engine, rated at 3,500 hp at 250 rpm. Tests were conducted at 91, 92, and 96 percent load. Operating parameters and results of the CEMS measurements for O_2, CO_2, CO, THC, and NO_x are presented in Table 3-22.

3.6.3 *Measurement of Methane and Ethane Emissions*

On-site analysis for methane and ethane was performed using a GC/FID system, which was calibrated daily using a certified mixture of methane and ethane. Methane and ethane concentrations as measured on the GC/FID system and the emission rate/factor for each test run are presented in Table 3-23. As noted in the table, the instrument drift exceeded the specified limit for runs conducted on the two Cooper-Bessemer GMVC-10 units (Engines 11 and 15). For the two runs on the Solar gas turbine, methane and ethane concentrations were below the detection limits, as consistent with the THC concentrations measured at non-detect levels.

Table 3-22. Station 6C: Operating Conditions and CEMS Results, Engine 13, Cooper-Bessemer GMWC-10

Test Period	15	18	23
Load Condition	96%	91%	92%
Sampling Location	Exhaust	Exhaust	Exhaust
Date	11/14/94	11/14/94	11/14/94
Test Time	1030 - 1130	1855 - 1925	2025 - 2100
Ambient Conditions			
Barometric Pressure (in Hg)	26.8	26.8	26.9
Ambient Temperature (°F)	62	55	51
Relative Humidity (%)	24.0	42.7	52.5
Abs. Humidity (lb H_2O/1000 lb dry air)	3.2	4.3	4.5
Engine Operating Conditions			
Horsepower (hp)	3,352	3,172	3,092
Load (%)	96	91	92
Engine Speed (rpm)	250	249	240
Fuel Flow (scf/min)	459	440	426
Heat Input (MMBtu/hr)[a]	27.8	26.6	25.8
NG HHV (Btu/scf)	1,025	1,025	1,025
NG LHV (Btu/scf)	928	928	928
Exhaust Gas Conditions			
Vol. Flow (dscfm) - M2	14,164	13,942	13,360
Vol. Flow (dscfm) - M19, F_d[b]	13,104	13,514	12,978
Stack Gas Temperature (°F)	653	621	617
Moisture (%V)	6.91	6.77	6.85
O_2 (%V)	14.7	15.1	15.1
CO_2 (%V)	3.84	3.68	3.72
NO_x (ppmvd)	1,695	1,204	1,449
CO (ppmvd)	114	105	103
THC (ppmvw)	1,710	1,785	1,754
Exhaust Emissions			
NO_x (lb/hr)	159	116	135
NO_x (g/hp-hr)	21.5	16.7	19.8
NO_x (lb/MMBtu)	5.72	4.37	5.22
CO (lb/hr)	6.53	6.16	5.82
CO (g/hp-hr)	0.88	0.88	0.85
CO (lb/MMBtu)	0.23	0.23	0.23
THC (lb/hr)	60.0	64.4	60.9
THC (g/hp-hr)	8.11	9.21	8.93
THC (lb/MMBtu)	2.16	2.42	2.36

[a]Based on higher heating value (HHV).

[b]Used in emission rate calculations.

Table 3-23. Campaign 6: GC Results

Engine Make/Model	Unit No.	Test Period	Load (%)	Pollutant	Stack Conc. (ppmvd)	Emission Rate/Factor (lb/hr)	(g/hp-hr)	(lb/MMBtu)
Clark BA-5	10	2	100	Methane	739	8.6	4.3	0.82
				Ethane	14.7	0.32	0.16	0.031
Clark BA-5	10	1	94	Methane	593	6.3	3.4	0.64
				Ethane	8.7	0.17	0.093	0.018
Solar Taurus T-6502	-	6	95	Methane	ND[a]	--	--	--
				Ethane	ND[a]	--	--	--
Solar Taurus T-6502	-	7	95	Methane	ND[a]	--	--	--
				Ethane	ND[a]	--	--	--
C-B GMVA-10	9	13	100	Methane	1185	14	5.3	1.4
				Ethane	29	0.66	0.24	0.063
C-B GMVA-10	9	14	100	Methane	1067	13	4.7	1.2
				Ethane	28.3	0.63	0.23	0.060
C-B GMVC-10	11	19	100	Methane[b]	908	16	4.0	1.1
				Ethane[b]	23.0	0.75	0.19	0.053
C-B GMVC-10	11	20	101	Methane[b]	895	14	3.7	1.04
				Ethane[b]	24.2	0.71	0.19	0.053
C-B GMVC-10	11	24	95	Methane[b]	852	14	3.8	1.04
				Ethane[b]	23.7	0.72	0.20	0.054
C-B GMVC-10	15	9	102	Methane[b]	772	15	3.8	0.95
				Ethane[b]	19.9	0.74	0.18	0.046
C-B GMVC-10	15	10	102	Methane[b]	695	14	3.3	0.84
				Ethane[b]	18.6	0.68	0.17	0.042
C-B GMWC-10	13	15	96	Methane	1597	52	7.1	1.9
				Ethane	35.8	2.2	0.30	0.079
C-B GMWC-10	13	18	91	Methane	1651	56	8.0	2.1
				Ethane	40.0	2.5	0.36	0.095
C-B GMWC-10	13	23	92	Methane	1636	53.0	7.8	2.1
				Ethane	38.8	2.4	0.35	0.091

[a]Detection limit: 2 ppm.

[b]Instrument drift exceeded specified limit.

Section 4.0
Sampling and Analytical Methods

The sampling and analytical methods used in the test campaigns are described in this section. The list of target parameters and measurement methods used is presented in Table 4-1, with a schematic of the measurement system shown in Figure 4-1.

Table 4-1. Target Parameters and Measurement Methods

Location	Parameter	Collection Method	Sampling and Analytical Method
Stack	Gas Flow Rate	Manual, Traverse	EPA Method 2; EPA Method 19
	Gas Molecular Weight	Extractive Probe (Dry)	EPA Method 3A
	Gas Moisture Content	Manual, Single Point	EPA Method 4
	Methane	Extractive Probe (Wet)	EPA Method 18
	Ethane	Extractive Probe (Wet)	EPA Method 18
	Oxygen	Extractive Probe (Dry)	EPA Method 3A
	Carbon Dioxide	Extractive Probe (Dry)	EPA Method 3A
	Total Hydrocarbons	Extractive Probe (Wet)	EPA Method 25A
	Oxides of Nitrogen	Extractive Probe (Dry)	EPA Method 7E
	Carbon Monoxide	Extractive Probe (Dry)	EPA Method 10
Fuel Header	Gas Composition and Heating Value	Sample Bombs	GPA Method 2261[a]
Ambient Air	Barometric Pressure	Barometer	
	Temperature	Thermometer	
	Relative Humidity	Wet Bulb/Dry Bulb	
Process Data	Fuel Flow Rate	Orifice Meter	
	Brake Horsepower	Engine Analyst[b]	
	Engine Speed	Engine Analyst[b]	

[a]GPA = Gas Processors Association. This method was used in all campaigns except in Campaign 3B where EPA Method TO-14 was used.

[b]An engine analyst measured engine horsepower except in the following cases: Campaign 3A: site-specific performance curves were used to determine brake horsepower; Campaign 5: turbine brake horsepower was not measured; and Campaign 6B: turbine brake horsepower data were obtained from the station's control system.

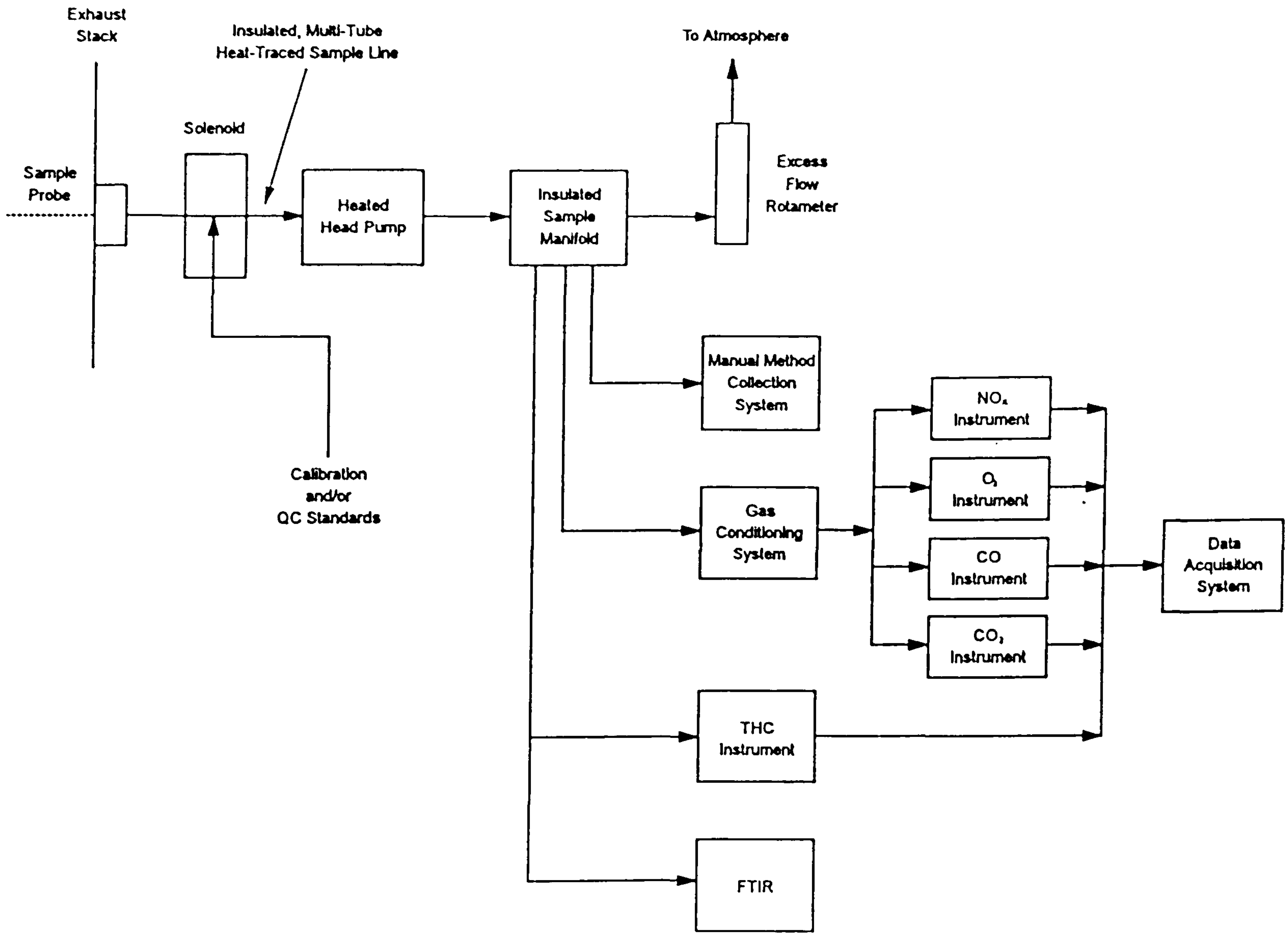

Figure 4-1. Measurement system schematic

4.1 Sampling Traverse Point Determination

The procedures specified in EPA Method 1 were used to determine the number and location of sampling points required for estimating an average gas velocity. EPA Method 1 parameters are based on the length of duct separating the sampling ports from the closest downstream and upstream flow disturbances. The minimum number of total traverse points for a duct is specified in Method 1 based on the duct size and distance from the nearest flow disturbances.

4.2 Exhaust Gas Flow Rate

The volumetric flow rate of the exhaust streams was estimated using EPA Methods 2 and 19. In EPA Method 2, a Type S pitot tube is used to measure the velocity of the exhaust gas, and a Type K thermocouple is used to measure exhaust gas temperature. During the measurements, the thermocouple and pitot tube were incorporated into a single stainless steel sheathed probe. An oil manometer or calibrated electronic pressure transducer was used to measure the pressure drop across the pitot tube, while a calibrated barometer was used to obtain barometric pressure readings. During some runs, the pitot tube and thermocouple readings were made in conjunction with other manual tests conducted as part of the GRI test program.

In EPA Method 19 exhaust flow rate calculations, the theoretical volume of combustion products is estimated from the fuel flow rate and the resulting volumetric flow rate is corrected for excess air based on the O_2 concentration in the exhaust gas. In this study, the fuel flow rate data were used in conjunction with higher heating value of the fuel, exhaust O_2 concentration, and the F_d factor for natural gas to estimate exhaust gas flow rates. The higher heating value and the F_d factor were based on fuel analysis results, while the O_2 concentrations were obtained from the CEMS measurements. The F_d factor is the ratio of the gas volume of the products of combustion to the heat content of the fuel. The "d" subscript indicates that it is calculated on a dry basis and includes all components of combustion less water.

4.3 Exhaust Gas Molecular Weight

The molecular weight of the exhaust gas was determined based on analysis of the major components of the gas stream. The concentrations of O_2 and CO_2 in the exhaust gas were determined using continuous analyzers as specified in EPA Method 3A. The remainder of the gas composition was assumed to be moisture and nitrogen, for the purposes of molecular weight determination. Moisture content of the gas stream was determined by EPA Method 4 (see below).

4.4 Exhaust Gas Moisture Content

The moisture content of the exhaust gases was determined using the procedures specified in EPA Method 4. In this method, moisture is condensed from a metered volume of gas in a series of chilled impingers, and the remainder is absorbed in silica gel. The total mass of the water collected and the total sample gas volume are used to determine the moisture content of the gas.

In most cases, the EPA Method 4 tests were completed in conjunction with other manual tests conducted as part of the GRI program, using chilled impingers and silica gel as specified in Method 4. In some cases, the approximation method using midget impingers, as described in Method 4, was used for moisture content determination.

4.5 Fuel Gas Composition and Heating Value

Natural gas samples for composition analysis and heating value calculations were collected in evacuated stainless steel containers during Campaigns 2, 4, 5, and 6; and at Compressor Station 3A of Campaign 3. Mechanical flow controllers were used to fill the containers at line pressure over a five-minute period. The sample containers were analyzed using Gas Processors Association (GPA) Method 2261.

In Campaign 3B, a modified version of EPA Method TO-14 was used to collect and analyze canister samples of the natural gas for composition analysis. Samples were collected in evacuated SUMMA® polished stainless steel canisters, using mechanical flow controllers for time-integrated samples over a one- to two-hour period. Analysis was performed on a gas chromatograph with multiple detectors (GC/MD).

4.6 Exhaust Gas Composition

In determining the emissions of the pollutants of interest, a CEMS including O_2, CO_2, CO, THC, and NO_x analyzers, and a GC/FID were used.

4.6.1 Sample Gas Extraction and Transfer

Samples were extracted from the engine/turbine exhaust stack using a stainless steel filter and probe assembly. Sample gas was pulled through a heat-traced sample line to the mobile sampling laboratory using a heated head pump. The sample gas was then delivered to an insulated sample manifold for further distribution. The total sample extraction flow rate was controlled by a flow control valve located at the exit of the heated head pump. Sample gas was then conditioned, if required, by passing it through a series of chilled cyclones. Conditioned gas was delivered to the O_2, CO_2, CO, and NO_x analyzers, while unconditioned gas was delivered to the GC and THC analyzers.

A rotameter located at the exit of the sample manifold was used to set the overall sample extraction flow rate prior to monitoring, and also as a visual flow indicator to ensure an adequate flow of sample gas was maintained.

4.6.2 Calibration and Quality Control Standard Delivery

The calibration and QC gas standards consisting of target analytes contained in high-pressure gas cylinders were introduced into the sampling system through a dedicated tube in the multi-tube heat-traced sample line. A solenoid valve located at the exit of the sampling probe was actuated to allow the gas standards to flow through the heat-traced sample line, the heated head pump, the insulated sample manifold, and the gas conditioner as appropriate. Gas standards were delivered at a flow rate in excess of the total sample extraction flow rate.

4.6.3 Measurement of O_2, CO_2, CO, THC, and NO_x Concentrations

Measurement of O_2 and CO_2 concentrations in the sample gas was conducted according to EPA Method 3A. A Servomex Model 1400 analyzer with a range of 0-25 percent O_2 was used for O_2 measurements, except during part of Campaign 2. The Servomex analyzer uses a paramagnetic cell to produce a linearized voltage signal proportional to the ratio of the oxygen concentration of a reference gas to the oxygen concentration of the sample. An Ametek Model WDG-III O_2 analyzer was used during part of Campaign 2. The Ametek O_2 analyzer uses an electrochemical cell to produce a linearized voltage signal proportional to the ratio of oxygen concentrations of the sample and a reference gas. The instrument range was 0 to 25 percent O_2.

Three different analyzers were used for measurement of CO_2 concentrations during this study. A Beckman Model 865-23 analyzer was used during Campaign 2. A Horiba CO_2 analyzer was used during Campaigns 3 and 4 while a Servomex Model 1400 analyzer was used during Campaigns 5 and 6. All three analyzers use a nondispersive infrared test cell to determine CO_2 concentrations based on the infrared light absorption of the gas sample. The analyzer range for each instrument was 0 to 20 percent CO_2.

Measurement of NO_x was conducted according to EPA Method 7E. A TECO Model 10AR analyzer was used during all test campaigns to measure total concentrations of NO_x in the gas streams. The analyzer operation is based on the chemiluminescence principle, where all nitrogen oxides in the sample are converted to nitric oxide (NO), followed by reaction of the NO with ozone in a photomultiplier tube, providing a signal proportional to the NO_x concentration in the sample. The instrument was calibrated over a range suitable for concentration of NO_x at the particular source being tested.

Measurement of CO was conducted according to EPA Method 10. A TECO Model 48H analyzer was used during all test campaigns to measure CO in the exhaust gas stream. The instrument was calibrated over a range suitable for concentrations of CO at the particular source being tested. The analyzer uses a non-dispersive infrared test cell to determine CO concentration from the infrared light absorption of the gas sample, based on a gas filter correlation technique to eliminate interferences from other gaseous compounds present in the sample gas.

Measurement of THC was conducted according to EPA Method 25A. A Ratfisch Model RS-55 analyzer was used during all test campaigns except for Campaign 6, where a J.U.M. Model VE7 analyzer was used. The instruments were calibrated over a range suitable for concentrations of THC at the particular source being tested. Both instruments use an FID to detect THC as it is combusted in a hydrogen flame. The FID for each instrument was calibrated using certified concentrations of methane in air.

4.6.4 On-Site GC Analysis

Analysis of the exhaust gas by GC was implemented at four of the five campaigns included in this report. Sampling and analysis of the methane and ethane concentrations in the exhaust gases was conducted according to EPA Method 18, using a Hewlett-Packard Model 5890 GC with an FID detector at Campaigns 3, 4, 5, and 6. The instrument was calibrated with a mixture of straight-chain hydrocarbons, including methane and ethane, in air prior to testing. Unconditioned sample gas was delivered directly to the GC from the sample gas distribution manifold through a heated sample line. The sample gas was passed continuously through a heated six-port sampling valve. The valve was used for injecting sample into the GC on a sequential basis during each testing period. Sampling frequency was determined by the total cycle time for sample analysis, which includes the retention time of the sample in the GC column and the time for the GC oven temperature to return to the initial value. Typical cycle time was 15-20 minutes.

Section 5.0
Quality Assurance/Quality Control and Documentation

The QA/QC procedures used during the test campaigns were largely based on the procedures described in the QAPP. This section describes the QA/QC procedures used in the field and laboratory, with the supporting information presented in the appendices.

5.1 Process Data Quality

Where available, process data were recorded at approximately 30-minute intervals during each test period. At the end of each day, the process data collected for each engine tested was reviewed by the Radian field engineer. In addition, an engine analyst was available at all test sites except at Station 3A during Campaign 3, Campaign 5, and Station 6B during Campaign 6. The GRI program engine consultant was on-site during Campaigns 4 and 6 (except at Station 6B), and during startup testing at Station 3A. [Note: Campaigns 5 and 6B involved turbine testing.]

The engine horsepower data for Station 3A were based on site-specific performance curves, while the engine horsepower measurements at Sweet Gas Plant 3B were conducted by the host site engine analyst. Horsepower estimates for the turbine tested during Campaign 5 were based on the manufacturer's rating since direct horsepower measurements were not possible because of instrument limitations. The horsepower data for the turbine characterized during Campaign 6B were based on the station's data acquisition system.

Power outages were experienced during some of the testing conducted under Campaign 4. Time periods during which facilities experienced power outages or other operational problems were excluded from data analysis. The results from one Cooper-Bessemer GMVA-10 engine tested at Campaign 4 have been excluded from all analysis in this report. This engine was not part of the original Campaign 4 test matrix, and upon review of the fuel flow measurements, the data was considered highly suspect.

5.2 Continuous Emission Monitors Data Quality

Quality assurance procedures for the CEMS were implemented according to the reference methods. These specifications include requirements to determine calibration drift and error of the instruments. The primary method of measuring these parameters was daily analysis of control standards.

5.2.1 CEMS Calibration

All continuous analyzers were calibrated at the beginning and end of each test day. Certified calibration gases were introduced at the probe and transferred through the entire CEMS. Each analyzer was calibrated at two points, using pure nitrogen as a zero gas and a certified span gas chosen at a concentration appropriate to the instrument range and expected exhaust gas composition. Instrument voltage responses to the calibration gases were recorded for each instrument during the calibration routine, along with the slope and intercept coefficients from the linear calibration equation. The equations established during the calibration routine were used by the data acquisition computer to calculate pollutant concentrations based on instrument voltage responses. Instruments were recalibrated whenever the range was changed, or when adjustments were made to the instrument linearizer potentiometers. All range changes and potentiometer adjustments were recorded in the field log.

5.2.2 CEMS Drift Checks

At the end of each test day, or at intermediate instrument calibrations, the calibration drift of each instrument was determined by calculating the difference between the pre-sampling and post-sampling responses to the zero and span calibration gases, as percentages of the full-scale reading of the analyzer. This calculation is simplified by the fact that the response to the calibration gases is mathematically set to the actual concentration values in the pretest calibration routine. The equation is thus:

$$D = \frac{100 \times (R_{post} - C)}{FS} \qquad (5\text{-}1)$$

where

D = calibration drift, in percent;
R_{post} = post-test response, in ppm or percent;
C = certified gas concentration, in ppm or percent; and
FS = full scale value (range) of instrument, in ppm or percent.

The calibration drift for each instrument was tabulated for each day or partial day. Drifts during Campaigns 4, 5, and 6 were all below the ±5 percent limit specified in the QAPP. In Campaigns 3 and 2, drift in excess of specified limits was experienced. The NO_x analyzer experienced drift in excess of 6 percent during testing of the two Cooper-Bessemer LSV-16 engines on June 15 and 16, 1994, during Campaign 3A. The drift for the CO_2 analyzer during the June 19 (Campaign 3B) test on the Cooper-Besemer GMV-10TF engine was higher than the specified limit. Data collected during these test days are flagged accordingly in the results tables.

Additionally, the NO_x analyzer experienced drift in excess of 10 percent during testing of the Cooper-Bessemer GMVA-10 engine on March 12, 1994, during Campaign 2. The data were not used in the calculation of average emission factors because the tests were conducted at less than 90 percent load.

5.2.3 CEMS Bias Checks

After completion of the calibration routine for each instrument, at least one QC gas standard at the approximate concentration expected in the stack gas was introduced to the instrument through the entire sampling system. For each QC gas (O_2, CO, CO_2, and NO_x), the difference between the measured concentration of the QC standard and the known value was calculated as a percentage of the full-scale value of the instrument range to estimate the measurement bias (accuracy). For THC, the bias was calculated relative to the QC standard gas concentration. This procedure was repeated periodically throughout each test day. The equation used to calculate bias is similar to Equation 5-1:

$$B = \frac{100 \times (R_{QC} - C)}{FS} \qquad (5\text{-}2)$$

where

B = bias, in percent; and
R_{QC} = response to the QC gas, in ppm or percent.

The measurement bias data for each test are tabulated in Appendix I. Bias measurements during Campaigns 4, 5, and 6 were all below the ± 10 percent limit. One bias test of the CO_2 analyzer used to monitor emissions from the Cooper-Bessemer GMV-10TF tested during Campaign 3B showed a bias of approximately 10 percent. The affected CO_2 measurements are flagged in the data tables and are not used in any subsequent calculations.

5.2.4 *CEMS Precision*

The relative standard deviation (RSD) was calculated for the multiple QA/QC checks to provide an indication of the precision (repeatability) of the species measurements. The RSD is calculated by taking the ratio of response standard deviation to the average of the response values times 100. The RSD values for all the tests were less than 5 percent except on June 19, 1994 during Campaign 3B where the RSD for CO_2 measurements was approximately 9 percent, and the RSD for NO_x measurements was approximately 6 percent. Additionally, on August 23, 1994 during Campaign 4, the RSD on THC measurements was 5.1 percent.

5.2.5 *Other CEMS QC*

Each time the CEMS was set up at a new location, a leak check was performed on the sampling system by sending pure nitrogen through the system at the probe, and checking the oxygen monitor for signs of inleaking air. No tests were performed until a satisfactory leak check with an overall O_2 concentration at the analyzer less than 0.5 percent was achieved. Additionally, instrument response time was checked each time the system was set up at a new location. The response time was less than 2 minutes for each test.

The efficiency of the NO_2 converter on the NO_x analyzer was checked periodically to ensure that it was operating correctly. The converter was replaced if the NO_2-to-NO conversion efficiency dropped below 90 percent.

5.3 Manual Sampling Methods Data Quality

Quality control procedures for the manual sampling and analysis methods consisted of the following:

- All sampling equipment passed a thorough visual and functional check prior to and after shipment to ensure clean and operable parts. Equipment which failed the checks was not used in the field.
- Manometers were leveled and zeroed before measuring the differential pressure across the Type S pitot tubes.
- The temperature measurement system was capable of measuring the ambient temperature prior to each traverse to within $\pm$ 2°C of the average measured ambient temperature.
- Type S pitot tubes were measured and passed the inspection criteria specified in EPA Method 2.
- The pitch and yaw angles of the Type S pitot tube were maintained within 10 degrees of perpendicular to the flow velocity traverses.
- Each leg of the Type S pitot tube achieved the leak criteria specified in EPA Method 2.
- The field personnel reviewed sampling and traverse data forms daily on-site during testing.
- Any unusual occurrences during testing were noted on the field data sheets or log book.

5.4 Method 18 Data Quality

The quality control procedures specified in Method 18 were followed. The retention times of the analytes of interest were determined using certified calibration gases, and multipoint calibration curves were developed for use in quantitation.

No GC data were collected during Campaign 2 since collection of methane/ethane data was outside the scope of the GRI program at that time. During Campaign 4, hardware problems on the gas chromatograph caused all the methane readings to be off-scale, with no methane data available for the engines tested during Campaign 4. Most of the ethane data for this test campaign was of good quality based on the QA criteria.

During Campaign 6, on November 10, response to the high-level calibration standard (1,000 ppmv) was unusually low. Data generated using this standard were not used in preparing the calibration curve for this day, and the GC was calibrated at only two points. On November 12, 14, and 15, weighted (1/x) least squares curves were used to generate the calibration curves. This was required because a higher level standard of 2,000 ppmv was used, and because response to the 1,000 ppmv standard was variable. The weighing routine minimized the influence of the two high standards and improved the accuracy of measurements at the lower end of the calibration range. Use of the higher level standard and weighing routine are not expected to affect the final data quality.

Section 6.0
Evaluation and Comparison of Emission Factors

Section 3.2 of the fifth edition of AP-42 lists emission factors for heavy-duty, natural gas-fired pipeline compressor engines. The emission factors in AP-42 are grouped in tables according to engine classification and emission control equipment. This section presents the emission factors calculated for the engines/turbines tested under this joint effort, in tables with their AP-42 counterparts, to allow a direct comparison between the data collected during this project and the emission factors listed in AP-42. [Note: The emission factors presented in this section are from Table 2-3, except where footnoted.] Additionally, recommendations are presented on how the data from this study can be used to enhance the emissions database used in AP-42, thereby improving the emission factors for large internal combustion engines.

6.1 Uncontrolled Engines/Gas Turbines

Tables 6-1 and 6-2 show emission factors for uncontrolled units where Table 6-1 contains emission factors for turbines and 2-stroke engines, and Table 6-2 contains emission factors for 4-stroke engines. Emissions listed as "THC" in the tables correspond to total organic carbon (TOC) emission factors in AP-42. Emissions listed as "NMHC" in the tables correspond to total nonmethane organic compounds (TNMOC) emission factors in AP-42. There are no emission factors currently listed in AP-42 for NMEHC. The NMEHC factors are listed in the tables in this report because the EPA excludes methane and ethane from its definition of volatile organic compounds (VOCs) (40 CFR 51). The AP-42 emission factors are derived from measurements conducted by Southwest Research Institute in the late '70s and early '80s and cover a wide population of engines.

As expected, there are differences between the emission factors calculated in this study and those in AP-42. For 2-stroke, lean-burn engines, the NO_x emission factor is higher than the AP-42 factor by about 25 to 30 percent (14 vs. 11 g/hp-hr) while the CO

Table 6-1. Emission Factors for Uncontrolled Natural Gas Prime Movers: Gas Turbines and 2-Stroke Engines

	Gas Turbines					2-Stroke Lean-Burn				
	GRI/EPA Tests[a]		AP-42			GRI/EPA Tests[b]		AP-42		
Pollutant	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[c]	(lb/hp-hr)	(lb/MMBtu)	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[c]	(lb/hp-hr)	(lb/MMBtu)
NO_x	1.4	0.31	1.3	2.87E-03	0.34	14	3.4	11	0.024	2.7
CO	0.16	0.038	0.83	1.83E-03	0.17	0.63	0.15	1.5	3.31E-03	0.38
CH_4	ND	ND	0.17	3.75E-04	0.051	4.6	1.1	5.6	0.012	1.4
C_2H_6	ND	ND	NA	NA	NA	0.31	0.077	NA	NA	NA
THC	ND	ND	0.18	3.97E-04	0.053	5.7	1.4	6.1	0.013	1.5
NMHC	ND	ND	0.01	2.20E-05	0.002	1.1	0.28	0.43	9.48E-04	0.11
NMEHC	ND	ND	NA	NA	NA	0.80	0.19	NA	NA	NA

[a]Based on two turbines.

[b]Based on seven engines.

[c]g/hp-hr emission factors are calculated from the AP-42 lb/hp-hr factors.

Table 6-2. Emission Factors for Uncontrolled Natural Gas Prime Movers: 4-Stroke Engines

	4-Stroke Lean-Burn					4-Stroke Rich-Burn				
	GRI/EPA Tests[a]		AP-42			GRI/EPA Tests[b]		AP-42		
Pollutant	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[c]	(lb/hp-hr)	(lb/MMBtu)	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[c]	(lb/hp-hr)	(lb/MMBtu)
NO_x	14	3.7	12	0.026	3.2	18	5.2	10	0.022	2.3
CO	0.83	0.21	1.6	3.53E-03	.42	15	4.2	8.6	0.019	1.6
CH_4	5.5	1.5	4.1	9.04E-03	1.1	NA	NA	1.1	2.43E-03	0.24
C_2H_6	0.16	0.044	NA	NA	NA	NA	NA	NA	NA	NA
THC	4.1	1.1	4.9	0.011	1.2	3.0	0.85	1.2	2.65E-03	0.27
NMHC	NA	NA	0.72	1.59E-03	0.18	NA	NA	0.14	3.09E-04	0.03
NMEHC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

[a]Based on three engines

[b]Based on one engine tested at 81 percent speed.

[c]g/hp-hr emission factors are calculated from the lb/hp-hr factors.

emission factor is less than half of the AP-42 factor. Although the THC emission factors are similar (5.7 vs. 6.1 g/hp-hr), the methane values from this study are lower by about 20 percent (4.6 vs. 5.6 g/hp-hr), resulting in NMHC factors being different (1.1 vs. 0.43 g/hp-hr). In the 4-stroke, lean-burn category, the NO_x and CO emission factors show the same trend described for the 2-stroke, lean-burn category. However, the methane emission factor is higher (5.5 vs. 4.1 g/hp-hr) and the THC factor is lower (4.1 vs. 4.9 g/hp-hr) than the AP-42 factor. The largest differences are observed for 4-stroke, rich-burn engines, where the emission factors from this study are based on data from one engine only. The 4-stroke, rich-burn engine tested was an intermediate speed engine rated at 1,000 rpm, but was tested at approximately 810 rpm.

The differences between the limited data from this study and AP-42 may largely be attributed to the variability associated with the smaller population of engines tested. Another likely contributing factor is the type of sampling/analysis instrumentation employed during the two studies.

For turbines, the NO_x emission factors are similar, however, the CO emission factor from this study is 20 percent of the AP-42 factor. Methane and THC emissions were found at non-detect levels while the respective AP-42 values are 0.17 and 0.18 g/hp-hr.

6.2 Controlled Engines

The data for controlled engines in this report are limited because the information is based on tests of single engines in each category. These engines were all tested during Campaign 4, where problems with the GC hardware prevented collection of data for methane emissions. Therefore, only NO_x, CO, and THC emission factors are included in this comparison.

Tables 6-3 and 6-4 list the emission factors based on single engine testing for NSCR-controlled 4-stroke, rich-burn engines and SCR-controlled 4-stroke, lean-burn engines, respectively, including the AP-42 factors. The NSCR-controlled 4-stroke, rich-burn emission factors for NO_x and CO are 50 and 40 times smaller (0.050 vs. 2.5 g/hp-hr; 0.26 vs. 10 g/hp-hr) than the AP-42 factors, respectively, while the THC emission factor is larger than the AP-42 factor (1.7 vs 0.2 g/hp-hr). Note that the data in this study are based on a recently installed NSCR catalyst.

Table 6-3. Emission Factors for Controlled Natural Gas Prime Movers: NSCR On 4-Stroke Rich-Burn Engines

	Inlet					Outlet				
	GRI/EPA Tests[a]		AP-42			GRI/EPA Tests[a]		AP-42		
Pollutant	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[b]	(lb/hp-hr)	(lb/MMBtu)	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[b]	(lb/hp-hr)	(lb/MMBtu)
NO_x	18	5.2	7.8	0.017	1.8	0.050	0.015	2.5	5.51E-03	0.58
CO	15	4.2	12	0.026	2.8	0.26	0.075	10	0.022	2.4
THC	3.0	0.85	0.33	7.28E-04	0.079	1.7	0.49	0.2	4.41E-04	0.047

[a]Based on one engine tested at 81 percent rated speed.

[b]g/hp-hr emission factors are calculated from the AP-42 lb/hp-hr factors.

Table 6-4. Emission Factors for Controlled Natural Gas Prime Movers: SCR On 4-Stroke Lean-Burn Engines

	Inlet					Outlet				
	GRI/EPA Tests[a]		AP-42			GRI/EPA Tests[a,c]		AP-42		
Pollutant	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[b]	(lb/hp-hr)	(lb/MMBtu)	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[b]	(lb/hp-hr)	(lb/MMBtu)
NO_x	22	5.4	19	0.042	6.4	5.0	1.3	3.6	7.94E-03	1.2
CO	0.55	0.14	1.2	2.65E-03	0.38	0.43	0.11	1.1	2.43E-03	0.37
THC	2.5	0.64	NA	NA	NA	2.7	0.69	NA	NA	NA

[a]Based on one engine.

[b]g/hp-hr emission factors are calculated from the AP-42 lb/hp-hr factors.

[c]Data suspect due to excess NH_3 injection.

For the SCR-controlled engine, the outlet NO_x emission factor is higher (5.0 vs. 3.6 g/hp-hr) and the CO emission factor is lower (0.43 vs. 1.1 g/hp-hr) than the AP-42 factor. The SCR system used on this engine was operating under a condition of excess ammonia injection, creating ammonia slip through the catalyst. The ammonia slip may have interfered with the NO_x measurements, causing them to be biased high, hence making the data suspect.

Table 6-5 presents the emission factors generated from testing a single 2-stroke, lean-burn engine recently retrofitted with clean-burn. When the factors for the 2-stroke clean-burn category are compared, the NO_x emission factor is much smaller than the AP-42 factor (0.48 vs. 2.3 g/hp-hr), while the CO emission factor at approximately the same level as the AP-42 factor. The THC emission factor is significantly larger than the AP-42 factor (6.8 vs. 2.5 g/hp-hr).

Table 6-5. Emission Factors for Controlled Natural Gas Prime Movers: "Clean Burn" On 2-Stroke Lean-Burn Engines

	GRI/EPA Tests[a]		AP-42		
Pollutant	(g/hp-hr)	(lb/MMBtu)	(g/hp-hr)[b]	(lb/hp-hr)	(lb/MMBtu)
NO_x	0.48	0.14	2.3	5.07E-03	0.83
CO	1.4	0.41	1.1	2.43E-03	0.30
THC	6.8	2.0	2.5	5.51E-03	0.77

[a] Based on one engine.

[b] g/hp-hr emission factors are calculated from the AP-42 lb/hp-hr factors.

6.3 Other

AP-42 currently has no listing of emission factors for 4-stroke engines equipped with PCC. Emission factors generated from the testing on such an engine are shown in Table 6-6. Another emission control scenario not addressed in AP-42 is the presence of a CO catalyst in conjunction with clean-burn on a 2-stroke, lean-burn engine. Table 6-7 shows the emission factors based on testing on a single engine.

Table 6-6. Emission Factors for Controlled Natural Gas Prime Movers: "Pre-combustion Chamber (PCC)" On 4-Stroke Lean-Burn Engines

Pollutant	GRI/EPA Tests[a]	
	(g/hp-hr)	(lb/MMBtu)
NO_x	0.56	0.14
CO	2.0	0.51
THC	8.0	2.0

[a]Based on one engine.

Table 6-7. Emission Factors for Controlled Natural Gas Prime Movers: "Clean Burn" and CO Catalyst On 2-Stroke Lean-Burn Engines

Pollutant	GRI/EPA Tests[a]	
	(g/hp-hr)	(lb/MMBtu)
NO_x	0.54	0.17
CO	0.11	0.030
THC	6.3	1.9

[a]Based on one engine.

6.4 Conclusions

Based on examination of the test results from this study, the following conclusions are presented to enhance the emissions database currently in AP-42:

- Incorporate emissions data used to develop the emission factors presented in Tables 6-1 and 6-2 for uncontrolled 2-stroke, lean-burn; 4-stroke, lean-burn; and 4-stroke, rich-burn engines; and gas turbines into the current AP-42 emissions database. Although the current factors are "A" quality, incorporation of these data will broaden the population of the engines covered.

- Incorporate the emissions data used to develop the emission factors in Table 6-5 for 2-stroke, clean-burn engines into the current AP-42 emissions database. The current AP-42 factors are "C" quality. The additional data may upgrade the emission factor quality rating for this category.

- Use data shown in Tables 6-3, 6-6, and 6-7 for an NSCR-controlled 4-stroke, rich-burn engine, PCC-controlled 4-stroke, lean-burn engine, and a 2-stroke, clean-burn engine with a CO oxidation catalyst, respectively, to build and/or improve an emissions database for these categories.

- The current version of AP-42 has separate emission factors for "clean-burn" and "PCC" controlled engines. "Clean-burn" is a trade name used by one manufacturer to describe modifications to a lean-burn engine to lower emissions. A PCC is a primary component of the "clean-burn" modification to these engines. An engine equipped with PCC may also have all of the other clean-burn modifications, as did the one engine with PCC tested under this program. Consideration should be given to combining the emissions databases for these control scenarios under a single generic description. The emission factor resulting from this incorporation may be more representative of this class of engines.

In summary, full load engine emissions test data following the QA/QC approved procedures were obtained during 36 test runs for eight of the 11 tested 2-stroke engines, five 4-stroke engines, and two gas turbines. These data will enhance the current database in AP-42 for stationary IC engines. These emissions data will not only enhance the population of engine types covered, but will also upgrade the emission factor quality of several engine categories which have a limited data set.

Section 7.0
References

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