GRI-96 / 0009.1

Topical Report

Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities

Volume I

Prepared by:
Gunseli Sagun Shareef
Kathy R. Ferry
Mahesh Gundappa
Chad A. Leatherwood
Larry D. Ogle
Lisa M. Campbell
Radian Corporation

Gas Research Institute

Environment & Safety Research
February 1996

MEASUREMENT OF AIR TOXIC EMISSIONS FROM NATURAL GAS-FIRED INTERNAL COMBUSTION ENGINES AT NATURAL GAS TRANSMISSION AND STORAGE FACILITIES

VOLUME I

TOPICAL REPORT

Prepared by:

Gunseli Sagun Shareef, Kathy R. Ferry
Mahesh Gundappa, Chad A. Leatherwood,
Larry D. Ogle, and Lisa M. Campbell

RADIAN CORPORATION
P.O. Box 13000
Research Triangle Park, North Carolina 27709

Prepared for:

GAS RESEARCH INSTITUTE
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

GRI Contract No. 5091-254-2293

GRI Project Managers
James M. Evans
Senior Technology Manager
and
James M. McCarthy
Senior Technology Manager

February 1996

GRI DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI-96/0009.1	2.	3. Recipient's Accession No.

4. Title and Subtitle

Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities

5. Report Date
January 1996

6.

7. Author(s)
Gunseli Sagun Shareef, Kathy R. Ferry, Mahesh Gundappa,
Chad A. Leatherwood, Larry D. Ogle, and Lisa M. Campbell

8. Performing Organization Rept. No.
275-114-06-93

9. Performing Organization Name and Address
Radian Corporation
P.O. Box 13000
Research Triangle Park, North Carolina 27709

10. Project Task/Work Unit No.
275-114

11. Contract(C) or Grant(G) No.

(C) 5091-254-2293

12. Sponsoring Organization Name and Address

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

13. Type of Report & Period Covered

Topical Report
September 1993 - December 1995

14.

15. Supplementary Notes

16. Abstract (limit: 200 words)

This report presents the results of a preliminary field study to evaluate air emissions from natural gas-fired internal combustion engines and turbines. The primary focus of the study was to quantify and speciate emissions of hazardous air pollutants (HAPs). Emissions data were collected at six natural gas transmission and storage facilities in four campaigns. Through this effort, 16 different natural gas-fired reciprocating engines and one natural gas-fired turbine were tested. A higher priority was placed on collecting data from reciprocating engines than turbines based on preliminary data from an earlier phase of the program that indicated that air toxic concentrations in natural gas-fired turbine exhaust were very low (and much lower than that of engines).

Of the 47 volatile and semi-volatile compounds examined during the study, formaldehyde was the only HAP present in engine exhausts at sufficient levels to potentially exceed the EPA's 10 ton/yr major source threshold in some cases. Emission rates ranged from <0.1 to 0.5 g/hp-hr, and appear to depend on both engine design and operating characteristics.

Exhaust concentrations of air toxic compounds were lower for the natural gas-fired turbine than the engines. Acetaldehyde was the HAP measured at the highest concentration with measured formaldehyde levels lower. The acetaldehyde emission factor for this turbine was 0.020 g/hp-hr; formaldehyde emissions were non-detectable (<0.2 ppmv). The mechanism that favors acetaldehyde formation over formaldehyde has not yet been identified.

17. Document Analysis

a. Descriptors
Air toxics
Hazardous air pollutants
Emissions
Internal combustion engines

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement: Unlimited distribution	**19. Security Class (This Report)** Unclassified	**21. No. of Pages**
	20. Security Class (This Page) Unclassified	**22. Price**

RESEARCH SUMMARY

TITLE	Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities
CONTRACTOR	Radian Corporation GRI Contract Number: 5091-254-2293
PRINCIPAL INVESTIGATORS	Gunseli Sagun Shareef, Kathy R. Ferry, Mahesh Gundappa, Chad A. Leatherwood, Larry D. Ogle, and Lisa M. Campbell
REPORT PERIOD	Data covers period from September 1993 to December 1995.
OBJECTIVE	To develop data to identify both major air toxic emissions sources and those that are not significant emitters, to establish baseline emission levels for potential control strategy development, and to refine and apply sampling/analytical methodology that will allow simultaneous measurement of a wide variety of air toxic species and sources.
TECHNICAL PERSPECTIVE	Until 1991, there were only limited efforts to identify air toxic emissions data associated with natural gas industry sources, primarily through the use of publicly available information. This type of technical information is needed to assist the gas industry in proactively responding to the upcoming federal National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations scheduled for promulgation in 1996 for oil and gas production sources and in the year 2000 for stationary internal combustion engines and stationary gas turbines.
TECHNICAL APPROACH	The results of an earlier Phase I study were used in conjunction with input from the Industry Work Group to establish the research priorities for the Phase II efforts. One of the highest priorities was to evaluate air toxic emissions from internal combustion engines. Emissions testing was conducted at six natural gas transmission facilities, in four campaigns, to investigate emissions of air toxic compounds from natural gas-fired reciprocating engines and turbines.

TECHNICAL APPROACH (Continued)

Through this effort, 16 different engines and one gas turbine were tested, all firing natural gas. The engines included the most common manufacturers (Cooper-Bessemer, Clark, Ingersoll-Rand, and Waukesha) of engines used in the natural gas industry, and provided data on 13 unique models. A higher priority was placed on collecting data from reciprocating engines than from turbines based on preliminary data from an earlier phase of the program that indicated that air toxic concentrations in turbine exhaust were very low (and much lower than that of engines).

Engine design was anticipated to impact emissions; therefore, the engine models and test results were separated into five broad engine "families" based on design differences. These families included 2-stroke lean-burn, 2-stroke clean-burn (low-NO_x), 4-stroke lean-burn, 4-stroke rich-burn, and 4-stroke clean-burn (low-NO_x). The engine family designations were reviewed and approved by the industry advisors and used in the site selection process to ensure data were collected on a wide range of engines representative of the natural gas industry.

A list of target compounds was developed based on EPA's list of 189 hazardous air pollutants (HAPs) and selected state air toxics regulations. Fourier transform infrared (FTIR) spectroscopy and manual methods were used for measurement of volatile organic compounds and aldehydes, while manual methods were used to measure emissions of semi-volatile organic compounds, particulate matter, and metals. For monitoring concentrations of nitrogen oxides, carbon monoxide, carbon dioxide, and total hydrocarbons, a continuous emission monitoring (CEM) system was employed. In July 1995, FTIR was approved by EPA as a valid method for measuring aldehydes as well as several other compounds.

RESULTS

Of the 47 volatile and semi-volatile compounds examined during the study, formaldehyde was the only HAP present in engine exhausts at sufficient levels to potentially exceed the EPA's 10 ton/yr major source threshold. Emission rates ranged from <0.1 to 0.5 g/hp-hr, and appear to depend on both engine design and operating conditions.

Of the operating factors studied, torque appeared to have the strongest influence on formaldehyde emissions, with emissions

RESULTS (Continued)

increasing as torque was reduced. Other operating variables, such as speed and air-to-fuel (A/F) ratio, may also influence formaldehyde levels; however, in most cases, it was not possible to vary these parameters over a sufficiently wide range to distinguish emission changes associated with their impact from normal engine variability.

The impact of emission controls, such as clean-burn (low-NO_x) combustion modifications, was investigated at sites where such controls were available. Full clean-burn modifications (including a precombustion chamber, increased A/F ratio, and improved mixing) appeared to increase formaldehyde emissions. The cause of this increase is likely the reduced bulk gas temperatures in the cylinders associated with the high A/F ratios. When A/F ratios were maintained at standard lean-burn levels, little or no increase in formaldehyde was observed; however, NO_x reductions were also less substantial.

Exhaust concentrations of air toxic compounds were lower in the turbine than in the engines. Acetaldehyde was the HAP measured at the highest concentration in the turbine, with formaldehyde levels lower. Acetaldehyde emission factors for the turbine tested were constant at 0.020 g/hp-hr; formaldehyde was not detectable. The mechanism which favors acetaldehyde formation over formaldehyde has not yet been identified nor has this phenomena been verified through measurement on other turbines.

PROJECT IMPLICATIONS

Based on the industry survey conducted in Phase I of this program, a critical need for information on emissions from various gas industry equipment, specifically engines and turbines, was identified. The information presented in this document allows the natural gas industry to characterize emissions from their engines and turbines without conducting costly field testing. Additionally, these data will serve as the basis for industry interaction with EPA's regulatory development including informing EPA of industry equipment and operations where problems do not exist as well as providing data on equipment relative to Title III status.

GRI Project Managers
James M. McCarthy
Sr. Technology Manager

James M. Evans
Sr. Technology Manager

ACKNOWLEDGEMENTS

Gas Research Institute (GRI) wishes to acknowledge the technical and cofunding support provided by the host sites where the field measurement campaigns were conducted and the cofunding provided by the U.S. Environmental Protection Agency towards collection of criteria pollutant emissions data. GRI also wishes to acknowledge the guidance and feedback provided by the members of the Industry Work Group throughout the entire program.

EXECUTIVE SUMMARY

Introduction

Because U.S. Environmental Protection Agency (EPA) and state regulations governing emissions of toxic air pollutants could have significant impacts on the natural gas industry, and because there are critical gaps in the publicly available data on air toxic emissions from gas industry operations, the Gas Research Institute (GRI) has initiated a multiphase research program. In Phase I of this program, a preliminary assessment of the gas industry was conducted to identify potential emissions sources and determine the associated emissions. Based on the limited information available, critical research needs for collecting emissions data and developing emission measurement technologies were identified. Therefore, Phase II of the program focused on meeting these critical research needs by initiating a field measurement effort in conjunction with an air toxics measurement method development and validation study. The specific objectives of the Phase II efforts were to:

- Refine and apply sampling and analytical methodology that will allow simultaneous measurement of a wide variety of air toxic species and sources;
- Identify potential air toxic emissions sources in the gas industry and the pollutants associated with these sources;
- Develop data to identify both potential major emissions sources and those that are not significant emitters, and establish baseline levels for potential control strategy development;
- Enhance technology transfer to the industry via analytical tools (e.g., software products), project involvement by the Industry Work Group, reports, technical bulletins, and papers; and
- Determine the industry's needs for further research.

The results of the Phase I study were used in conjunction with input from the Industry Work Group to establish the research priorities for the Phase II efforts. One of the highest priorities in Phase II was to evaluate air toxic emissions from internal combustion engines operating at natural gas transmission and storage facilities. Emissions testing was conducted at six facilities, in four campaigns, to investigate emissions of air toxic compounds from natural gas-fired reciprocating engines and turbines at natural gas transmission and storage facilities. Through this effort, 16 different engines and one gas turbine were tested. The engines included the most common manufacturers (Cooper-Bessemer, Clark, Ingersoll-Rand, and Waukesha) of engines used in the natural gas industry, and provided data on 13 unique models. A higher priority was placed on collecting data from reciprocating engines than gas turbines based on preliminary data collected in Phase I of the program which indicated that air toxic concentrations in turbine exhausts were very low (and much lower than that of engines).

Another priority for the Phase II testing efforts was to evaluate air toxic emissions from natural gas-fired reciprocating engines and turbines, as well as process equipment, at natural gas processing facilities. For this effort, emissions testing was conducted at four facilities, two sweet gas plants and two sour gas plants, in four campaigns. Internal combustion engines were segregated between transmission and processing service due to potential differences in operating and maintenance practices at the different facilities. Preliminary data indicate that these differences in operation and maintenance may have an effect on air toxic emissions. Results from the testing conducted at these processing facilities will be published in a separate report entitled *Measurement of Air Toxic Emissions from Combustion Equipment at Natural Gas Processing Plants* (GRI-96/0010).

Engine design was anticipated to impact emissions; therefore, the engine models and test results were separated into five broad engine "families" based on design differences. These families included:

- 2-stroke lean-burn;
- 2-stroke clean-burn (low-NO_x);
- 4-stroke lean-burn;
  - direct injected
  - port injected
- 4-stroke rich-burn; and
- 4-stroke clean-burn (low-NO_x).

The engine family designations were reviewed and approved by the industry advisors and used in the site selection process to ensure data were collected on a wide range of engines representative of the natural gas industry.

A list of target compounds was developed based on EPA's list of 189 hazardous air pollutants (HAPs) and selected state air toxics regulations. Manual measurement methods and Fourier transform infrared (FTIR) spectroscopy were used to quantify aldehyde and volatile organic compound concentrations. Emissions of semi-volatile organics (polynuclear aromatic hydrocarbons--PAHs), particulate matter less than or equal to 10 micrometers in diameter (PM_{10}), and metals were measured using manual methods. A continuous emissions monitoring (CEM) system was employed to measure concentrations of nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and total hydrocarbons (THC).

Because there were no EPA-validated sampling and analytical methods for measuring formaldehyde and other aldehydes present in natural gas-fired internal combustion engine and turbine exhaust, GRI conducted a study for validating the extractive FTIR method according to EPA Method 301--"Field Validation of Pollutant Measurement Methods from Various Waste Media." Method 301 is a set of procedures to be followed in validating a proposed test method for a particular emission source/category; it is not a measurement method. The EPA Method 301 validation for FTIR was approved in July 1995 by EPA.

For reciprocating engines, the only HAP measured at levels of possible significance was formaldehyde. The average formaldehyde emission factors for full-load operation [$\geq$90 percent rated torque, $\geq$95 percent rated revolutions per minute (rpm)] ranged from 0.04 g/hp-hr for 4-stroke lean-burn (direct injected) engines to 0.24 g/hp-hr for 4-stroke clean-burn engines. Assuming 8,760 hours of annual operation and these emission rates, the 10 ton/yr maximum achievable control technology (MACT) major source level for HAPs equates to 25,900 and 4,100 total site horsepower, for 4-stroke lean-burn (direct injected) engines and 4-stroke clean-burn engines, respectively. Although engines typically do not operate for 8,760 hr/yr, this level of operation is commonly used to calculate potential-to-emit. Because other HAPs were measured at lower or non-detectable concentrations, the 25 ton/yr major source threshold for cumulative HAP emissions is not a concern for engines.

For the turbine, exhaust concentrations of air toxic compounds were lower than for the engines. Acetaldehyde was the HAP measured at the highest concentration in the two runs conducted on the turbine. Formaldehyde emissions were non-detectable (<0.2 ppm). A mechanism that favors acetaldehyde formation over formaldehyde has not yet been identified nor has this phenomena been verified through measurement on other turbines. Acetaldehyde emission factors were 0.020 g/hp-hr for both run conditions.

Making the same assumptions as above for engines, the 10 ton/yr MACT major source level for acetaldehyde is equivalent to 51,800 total site horsepower for turbines. All other HAPs were at considerably lower or non-detectable concentrations.

Based on the identification of formaldehyde as the HAP of concern in engine exhaust, the data collection and analysis effort focused on gaining a better understanding of formaldehyde emissions from reciprocating engines. Since the test sites had limited flexibility due to operational constraints, the range of operating conditions available for testing was narrow. However, engine design and operating parameters were evaluated including engine family, torque, speed, cylinder temperature, air-to-fuel (A/F) ratio, cylinder bore and stroke, and ignition timing.

Of the operating factors studied, torque appeared to have the strongest influence on formaldehyde emissions, with emissions increasing as torque was reduced. Other operating variables, such as speed and A/F ratio, may also influence formaldehyde levels; however, in most cases, it was not possible to vary these parameters over a sufficiently wide range to distinguish emission changes associated with their impact from normal engine variability.

The impact of emission controls, such as clean-burn combustion modification, was investigated at sites where such controls were available. Full clean-burn modifications (including a precombustion chamber, increased A/F ratio, and improved mixing) appear to increase formaldehyde emissions. The cause of this increase is likely the reduced bulk gas temperatures in the cylinders associated with the high A/F ratios. When A/F ratios in a clean-burn unit were maintained at standard lean-burn levels, little or no increase in formaldehyde was observed; however, NO_x reductions were also less substantial. The limited data collected on catalytic controls indicate reductions in formaldehyde may be possible with certain oxidation catalysts.

To gain a better understanding of formaldehyde emissions from reciprocating engines several areas of additional research are recommended as follows:

- Conducting measurements under a wider range of engine operating conditions to gain a more fundamental understanding of the parameters that influence formaldehyde emissions. Tests of engines in the field with more operational flexibility and in a test stand environment would be helpful.

- Collecting additional field data on other engine models/units in those engine families that have exhibited higher formaldehyde levels and for which little data are available (i.e., 2-stroke clean-burn, 4-stroke lean-burn, and 4-stroke clean-burn). The current database is very limited and needs to be expanded.

- Evaluating potential formaldehyde reduction strategies, including reductions possible via process or combustion modifications and add-on controls. The availability, effectiveness, durability and cost of the controls should also be investigated.

- Further investigating aldehyde emissions from natural gas-fired turbines. This would help determine the validity of the limited data indicating a higher level of acetaldehyde emissions than formaldehyde emissions. In addition, the significance of acetaldehyde emissions from a turbine to total site emissions could be clarified. If identified as a pollutant of concern, a better understanding of the mechanisms that influence acetaldehyde emissions would be helpful.

- Development of a risk screening tool should be considered. Such a tool should be compatible with existing GRI software (e.g., HAPCalc™) and allow the user the opportunity to perform sensitivity analyses on key variables.

Ongoing GRI research will likely pursue a portion of this work, with a near term focus on the characterization of the impacts of operating conditions on formaldehyde emissions from reciprocating engines.

Table of Contents

Page

VOLUME I

Table of Contents
(Continued)

Page

Table of Contents
(Continued)

Page

List of Figures

List of Tables

Acronyms and Abbreviations

A/F	Air-to-Fuel
ACFM	Actual cubic feet per minute
ACT	Alternative Control Techniques
BMEP	Brake mean effective pressure
BS	Blower scavenged
BTDC	Before top dead center
BTEX	Benzene, toluene, ethyl benzene, xylenes
Btu	British thermal unit
CAAA	Clean Air Act Amendment
CARB	California Air Resources Board
C-B	Cooper-Bessemer
CEM	Continuous emissions monitoring
CO	Carbon monoxide
DNPH	2,4-Dinitrophenylhydrazine
DSCFM	Dry standard cubic feet per minute
EPA	Environmental Protection Agency
F_d	Fuel factor (dry basis)
FID	Flame ionization detector
FTIR	Fourier transform infrared spectroscopy
GC	Gas chromatography
GPA	Gas Processors Association
GRI	Gas Research Institute
HAP	Hazardous air pollutant
HHV	Higher heating value
HP	Horsepower
IC	Internal combustion
I-R	Ingersoll-Rand
LSD	Least significant difference
MACT	Maximum achievable control technology
MMBtu	Million British thermal units
MMscfd	Million standard cubic feet per day
MS/MSD	Matrix spike/matrix spike duplicate
NA	Not applicable

Acronyms and Abbreviations
(Continued)

ND	Non-detect
NESHAP	National emission standards for hazardous air pollutants
NM	Not measured
NMEHC	Non-methane, non-ethane hydrocarbon
NMHC	Non-methane hydrocarbon
NSCR	Nonselective catalytic reduction
NO_x	Oxides of nitrogen
NSCR	Nonselective catalytic reduction
PCC	Pre-combustion chamber
PM_{10}	Particulate matter smaller than 10 micrometers in diameter
PPMV	Parts per million, volume basis
PS	Piston scavenged
QA/QC	Quality assurance/quality control
RACT	Reasonable available control technology
RPM	Revolutions per minute
RSD	Relative standard deviation
S/V	Surface-to-volume
SCR	Selective catalytic reduction
TC	Turbocharged
THC	Total hydrocarbon
VOC	Volatile organic compound
VOST	Volatile organic sampling train

1.0 INTRODUCTION

1.1 Background

In Title III of the 1990 Clean Air Act Amendments (CAAA), Congress included provisions to reduce emissions of hazardous air pollutants (HAPs) considered to pose a risk to human health or the environment. The U.S. Environmental Protection Agency (EPA) has defined a schedule for developing maximum achievable control technology (MACT)-based regulations for several source categories including the oil and gas production industry category and the fuel combustion category, including stationary internal combustion (IC) engines and stationary combustion turbines. In addition, the gas industry is faced with meeting the requirements of Title V - Operating Permit regulations. At the state level, there are several air toxic programs in place or in the developmental phase that may affect the gas industry (e.g., California, Texas, Louisiana, Colorado, New Mexico, and Kentucky). Because these regulations could have economic and operational impacts on the gas industry, and because there are critical data gaps on air toxics emissions, the Gas Research Institute (GRI) is conducting a multiphase research program to identify potential sources of air toxic emissions, the quantities of total air toxics and individual species emitted, and the potential risk they pose. Further research on prevention and control of air toxic emissions and development of mitigation technologies as needed is also planned.

In Phase I of this program, information available from other GRI programs, GRI member companies, EPA databases, and state agencies was used to perform a preliminary assessment of the gas industry to identify potential air toxic emissions sources and determine the associated emissions.[1] An Industry Work Group was established to provide guidance and feedback on industry's needs and priorities. Based on the limited information available from these sources, critical research needs for collecting emissions data and developing measurement technologies were identified:

- Development or adaptation of better air toxics sampling and analytical instrumentation for gas industry sources, especially engines;
- Full speciation of HAP emissions from gas industry sources; and
- Development of emissions data to determine the level of air emissions sources within the gas industry.

Phase II of the program focused on meeting these critical research needs by initiating a field measurement effort in conjunction with an air toxics measurement method development and validation study. The results of the Phase II program are summarized in three separate reports. The first report presents the results from the validation testing of the Fourier transform infrared (FTIR) spectroscopy method for measuring air toxics and other species which received EPA approval in July 1995.[2] This report, *"Measurement of Air Toxics Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities,"* presents the results from measurements collected on engines from four field campaigns at six natural gas transmission facilities, including limited data from one natural gas-fired turbine. A third report is planned that will summarize the test results from four campaigns conducted at two sour gas plants and two sweet gas plants focusing on combustion sources (e.g., IC engines, combustion turbines, incinerators, heaters, and boilers.)[3]

The objectives of this study and the approach used are presented in the remainder of this section. A brief description of formaldehyde formation/destruction pathways and discussion of the engine classifications are included in Section 2. Section 3 summarizes the sampling and analytical methods utilized for data collection. Test site selection criteria and a description of host sites is included in Section 4. A detailed discussion of the formaldehyde measurement results is presented in Section 5. Section 6 summarizes the emission factor data for all of the pollutants measured, followed by Section 7 where an overview of the quality assurance/quality control (QA/QC) procedures and results is presented. Conclusions from the study and recommendations for further research are described in Section 8. Finally, a list of references is provided in Section 9, with supporting information presented in Appendices A through E.

1.2 Objectives

The goals of the GRI Air Toxics program are to characterize the natural gas industry's air toxic emissions/sources, and provide the data, technology, and tools that will help the gas industry to proactively respond to possible regulatory development activities. The specific objectives of the Phase II efforts are to:

- Refine and apply sampling/analytical methodology that will allow simultaneous measurement of a wide variety of air toxic species and sources;

- Identify potential air toxic emission sources in the gas industry and the pollutants associated with these sources;
- Develop data to identify both potential major emission sources and those that are not significant emitters, and establish baseline levels for potential control strategy development;
- Enhance technology transfer to the industry via analytical tools (e.g., software products), project involvement by the Industry Work Group, reports, technical bulletins, and papers; and
- Determine the industry's needs for further research (e.g., emission reduction/control technology alternatives, calculational/database tools, basic understanding of emissions issues).

1.3 Approach

To accomplish the objectives of the Phase II effort, the results from the Phase I study were used, in conjunction with input from the Industry Work Group, to identify and prioritize those emission sources that may exceed the major source threshold levels for HAP emissions (i.e., 10 ton/yr for a single HAP or 25 ton/yr for a mixture of HAPs). Research programs were established to evaluate emissions from gas industry sources. The projects completed under this contract focused on emissions from combustion sources. In addition, other GRI contracts under the Air Toxics Program investigated glycol dehydrators, amine gas removal units, fugitive emissions, and storage tanks. The glycol dehydrator program has conducted field measurements to establish emissions levels and developed a predictive model to estimate emissions.[4,5] Amine units were studied to evaluate BTEX and VOC emissions.[6] In the fugitive emissions study, leak rates were measured and gas samples were collected from field equipment to develop emission factors and correlations for estimating total and speciated emissions from equipment leaks.[7] The recently initiated storage tanks program is focusing on emission levels from storage tanks containing flashing liquids.

The combustion source work to date has included eight field campaigns. Since engines were identified as high-priority sources for emissions characterization, four of the eight field campaigns focused on transmission and storage stations, and four campaigns were conducted at gas plants. The host sites were selected based on specific criteria developed with guidance from the Industry Work Group to ensure that the critical data needs of the industry were satisfied. These criteria included:

- Presence of multiple engines of various makes/models/families;
- Range of engine size and age;
- Flexible operating load; and
- Presence of controlled and uncontrolled units.

The target compounds selected for measurement were identified by reviewing EPA's list of 189 HAPs, as well as lists from selected states, and by examining emissions data collected in Phase I. Only compounds that were included in previous test programs, and compounds that possibly could be present in the natural gas or in the exhaust, were included as target compounds. In some cases, compounds (e.g., metals) were included in the measurements to test whether expectations of negligible emissions were in fact true. Analysis of the target compounds was accomplished using a variety of sampling and analytical techniques. Manual measurement methods and FTIR were used for quantifying the air toxic compounds listed in Table 1-1. Continuous emission monitors were used to measure nitrogen oxides (NO_x), carbon monoxide (CO), oxygen (O_2), carbon dioxide (CO_2), and total hydrocarbons (THC) in the engine exhaust. Selection of the FTIR method was based on its ability to:

- Measure several compounds on a continuous and real-time basis;
- Adapt quickly to changing process conditions;
- Provide adequate sensitivity to measure HAP compounds at levels commensurate with determining major source applicability; and
- Provide data that can be reprocessed at any time after collection to quantify additional compounds of interest.

For FTIR measurements, a protocol specifically developed for this program and approved by EPA was implemented, while established procedures specified in the state and federal methods were followed for the other measurements.[8]

Table 1-1

List of Target Air Toxic Compounds

Compound	EPA HAP^a	Compound	EPA HAP^a
Aldehydes		**Semi-Volatile Organic Compounds**	
Formaldehyde	Y	Acenaphthene	Y
Acetaldehyde	Y	Acenaphthylene	Y
Acrolein	Y	Anthracene	Y
Butyr/Isobutyraldehyde	N	Benz(a)anthracene	Y
Propionaldehyde	Y	Benzo(a)pyrene	Y
Volatile Organic Compounds		Benzo(b)fluoranthene	Y
1,2,3-Trimethylbenzene	N	Benzo(e)pyrene	Y
1,2,4-Trimethylbenzene	N	Benzo(g,h,i)perylene	Y
1,3-Butadiene	Y	Benzo(k)fluoranthene	Y
1,3,5-Trimethylbenzene	N	Biphenyl	Y
2,2,4-Trimethylpentane	Y	Chrysene	Y
Acetylene	N	Dibenz(a,h)anthracene	Y
Benzene	Y	Fluoranthene	Y
Cyclohexane	N	Fluorene	Y
Cyclopentane	N	Indeno(1,2,3-c,d)pyrene	Y
Ethyl benzene	Y	2-Methylnaphthalene	Y
Ethylene	N	Naphthalene	Y
n-Hexane	Y	Perylene	Y
Isobutane	N	Phenanthrene	Y
Methanol	Y	Phenol	Y
Methylcyclohexane	N	Pyrene	Y
n-Nonane	N	**Sulfur Compounds**	
n-Octane	N	Hydrogen sulfide	N
Propylene	N	Carbonyl sulfide	Y
Styrene	Y	Carbon disulfide	Y
Toluene	Y	Methyl mercaptan	N
Xylenes	Y	Ethyl mercaptan	N

Table 1-1

List of Target Air Toxic Compounds
(Continued)

Compound	EPA HAP[a]
Metals	
Antimony	Y
Arsenic	Y
Beryllium	Y
Cadmium	Y
Chromium	Y
Cobalt	Y
Lead	Y
Manganese	Y
Mercury	Y
Nickel	Y
Selenium	Y

[a] Compound is on EPA's proposed list of 189 regulated HAPs in 40 CFR Part 63.

The process data collection and verification procedures used to characterize engine operating conditions evolved as information from the initial campaigns was reviewed and interpreted. At the start of this project, the objective was to obtain data from gas industry sources in an "as found" condition. During Campaign 1, the engines were tested under normal operating conditions, as defined by the facility. In addition, process measurements, such as engine horsepower and fuel flow, were obtained from station monitoring equipment without any independent or direct measurements for comparison. Due to problems identified with the accuracy of the horsepower and fuel flow measurements collected from the Campaign 1 station monitoring equipment, no values are presented in this document for the engines at this site that rely upon either of these parameters. To minimize such problems during Campaigns 3, 4, and 6, an engine consultant was added to the project team. (Note that Campaigns 2, 5, 7 and 8 were conducted at gas plants and will be reported in the gas plant report).

In Campaign 3, the engine consultant performed a visual inspection of the engines to be tested to identify any major maintenance/operational problems; however, he did not observe or participate in the testing. The engines tested at this site were equipped with centrifugal compressors which complicate direct measurement of horsepower. Therefore, all horsepower data were obtained from the station control system. Insufficient documentation on sensor calibrations was available from the site to quantify the level of accuracy associated with the horsepower data. However, when compared to fuel flow measurements and expected heat rates for these engine models, the horsepower values correlated well.

During Campaigns 4 and 6, the engine consultant was present during testing and worked with engine analysts to identify and correct any major maintenance or operational conditions that would significantly affect engine performance. Where present, all pocket unloaders were inspected to insure proper operation and tight seals. All horsepower measurements were collected directly off the compressor during each test run. In addition, horsepower measurements were performed directly on the individual power cylinders to check engine balance at least once for each engine. Following these procedures, the horsepower and torque measurements are expected to be accurate within ±5 percent.

2.0 FORMALDEHYDE FORMATION AND NATURAL GAS-FIRED IC ENGINES

Formaldehyde is a predominant intermediate in the combustion of natural gas and most other hydrocarbon fuels. The engine exhaust measurements conducted in this program have consistently found formaldehyde to be the HAP present at the highest concentration. For these reasons, an understanding of formaldehyde formation and destruction pathways, and the influence of engine design and operating characteristics on those pathways, is needed. While research to elucidate the reaction mechanisms that predominate in the formation and destruction of formaldehyde in a reciprocating engine was not part of the Phase II study, a review of the literature offered considerable insight, as described below. In addition to briefly summarizing the literature review results on formaldehyde formation and dissociation, this section describes the classification of the engines in the industry into five broad categories or "families" according to design differences.

2.1 Formaldehyde Reactions During Methane Oxidation[9-15]

Methane combustion kinetic models indicate nearly 100 elementary reactions in a complex, interconnected network. Formaldehyde is a predominant intermediate present in these reactions. However, very little data are available on the combustion of methane and formaldehyde formation in IC engines.

2.1.1 Formaldehyde Formation

The oxidation of methane begins with the production of methyl radicals (CH_3). Methyl radicals are formed via thermal decomposition of methane, hydrogen abstraction, or reactions with other radicals (OH, O, H, and HO_2). These methyl radicals are consumed through one of three general paths: methyl radical oxidation, methyl radical/radical reaction, or methyl radical recombination. Each of these paths leads to the production of formaldehyde as shown in Figure 2-1.

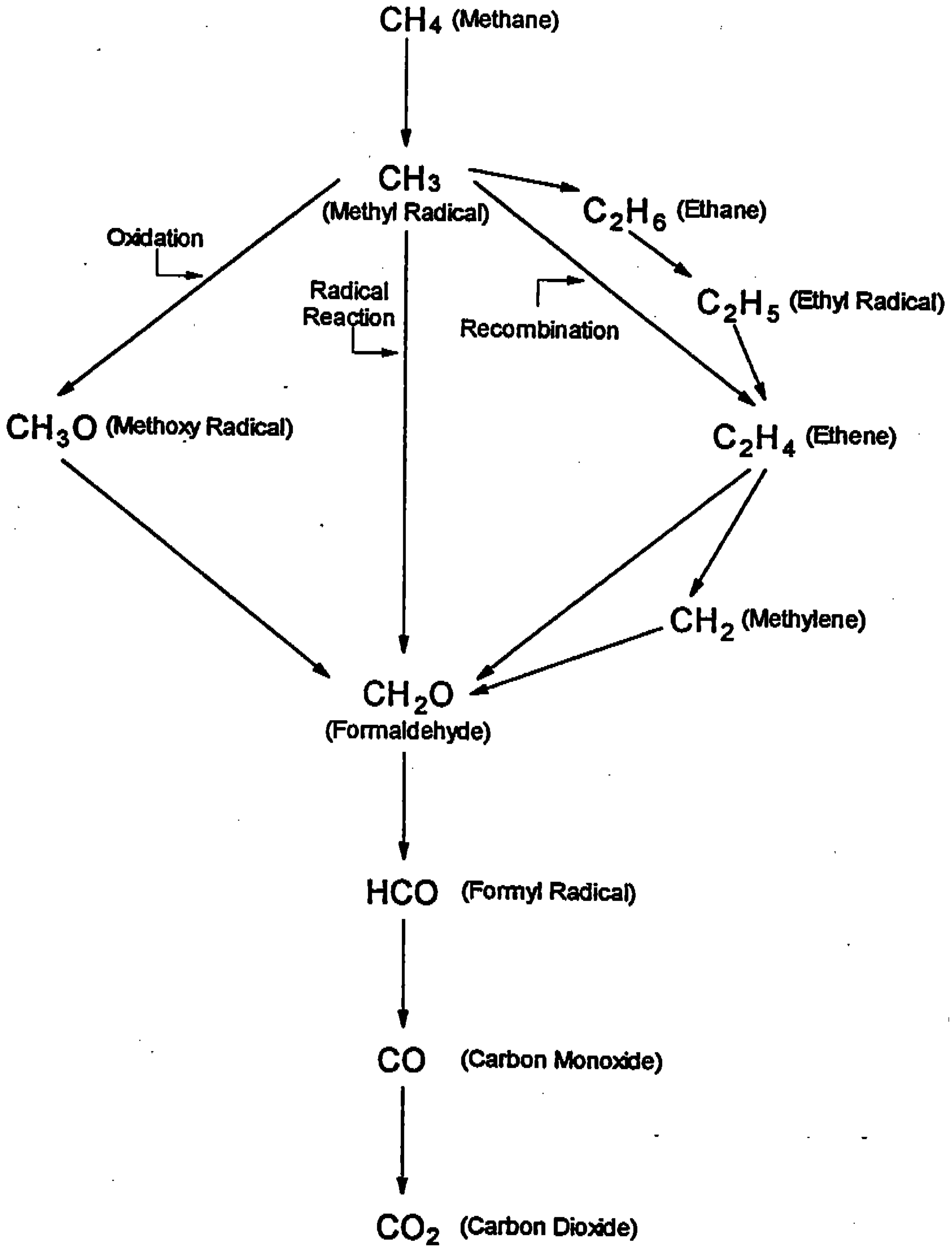


Figure 2-1. Methane Combustion Chemistry/Formaldehyde Formation

Methyl Radical Oxidation

Methyl radicals can oxidize to form methoxy radicals (CH_3O) in fuel-lean conditions, as shown in the following equation:

$$CH_3 + O_2 = CH_3O + O \tag{1}$$

Methyl radical oxidation is a slow reaction relative to methyl radical/radical reactions and is therefore expected to be dominant only when sustained residence time is available. The subsequent decay of the methoxy radical results in the formation of formaldehyde (CH_2O):

$$CH_3O + O_2 = CH_2O + HO_2 \tag{2}$$

$$CH_3O + M^* = CH_2O + H + M \tag{3}$$

$$CH_3O + H = CH_2O + H_2 \tag{4}$$

The methoxy radical oxidation reaction (2) occurs very rapidly at low temperatures and fuel-lean conditions. Reactions 3 and 4 are dominant for fuel-rich mixtures at high temperatures.

Methyl Radical/Radical Reactions

The methyl radicals also react with O and OH radicals to form formaldehyde directly.

$$CH_3 + O = CH_2O + H \tag{5}$$

$$CH_3 + OH = CH_2O + H_2 \tag{6}$$

The methyl radical/radical reactions are fast relative to the oxidation reaction (1) and may tend to dominate when residence times at sustained temperatures are relatively short.

---

[*] M represents all the collision partners, principally methane (CH_4), active in thermal decomposition.

Methyl Radical Recombination

In fuel-rich mixtures, the methyl radicals can recombine to form higher-order hydrocarbons, particularly ethyl radicals (C_2H_5) or ethane (C_2H_6), which further breaks down to ethyl radicals. The ethyl radicals then break down and/or react with O or OH radicals to form formaldehyde via several possible pathways.

2.1.2 Formaldehyde Dissociation

Formaldehyde is consumed primarily by reactions with OH, H, and O radicals to produce formyl radicals.

$$CH_2O + OH = HCO + H_2O \quad (7)$$

$$CH_2O + H = HCO + H_2 \quad (8)$$

$$CH_2O + O = HCO + OH \quad (9)$$

In fuel-rich environments, reaction of formaldehyde with the hydrogen radical via Reaction 8 is the main reaction pathway. In fuel-lean conditions, Reactions 7 and 9 are favored.

Additionally, two possible pathways for formaldehyde thermal dissociation include:

$$CH_2O + M = HCO + H + M \quad (10)$$

$$CH_2O + M = CO + H_2 + M \quad (11)$$

Most studies support the first path (10); however, it is probable that both paths occur at the same time during high-temperature dissociation. It appears from modeling analyses and other flame and shock tube studies that, when formaldehyde exists only as an intermediate, the thermal decomposition reaction is not important and may in fact proceed in the reverse direction. The reactions between formaldehyde and radical species are dominant in most situations.[9] The potential implications for engine families and subgroups may be that air-to-fuel (A/F) ratio and mixing characteristics may be as or more important than temperature in the combustion chamber.

2.2 Formaldehyde Emission Trends In Methanol-Fueled Engines

Although little information is available on formaldehyde formation/destruction mechanisms in natural gas-fired engines, there are a number of studies investigating formaldehyde emissions from methanol-fueled engines.[9,16,17] While methanol oxidation reaction mechanisms differ from methane oxidation, formaldehyde is an important intermediate in both cases and insight into formaldehyde decay in methane combustion may be gained from investigation of methanol studies.

For methanol combustion, the available pathways for formaldehyde dissociation are essentially the same as those presented for methane combustion. Therefore, the general formaldehyde emission trends observed in methanol-fueled engines may be similar in natural gas-fired engines.

From the available literature, general trends observed between formaldehyde emissions and engine operating conditions for methanol-fueled, automotive engines include:[16]

- Formaldehyde emissions increase as the A/F ratio is increased;
- Formaldehyde emissions decrease as combustion/exhaust temperatures are increased; and
- Any operating conditions that cause an increase in THC also result in higher formaldehyde emissions.

Although these trends were observed in methanol-fueled, automotive engine studies, there may be similarities in stationary, natural gas-fired engines.

Based on the formaldehyde formation/dissociation chemistry combined with the studies conducted on methanol-fueled engines, several bulk gas conditions may affect formaldehyde emissions, including temperature, O_2 level, and residence time. In addition to these bulk properties, localized conditions in the combustion chamber may play a significant role in formaldehyde formation.[17,18] In some cases, a small volume of unburned or partially burned fuel/air mixture can remain in crevice volumes, such as those formed between the piston rings and cylinder walls, or in the quench layer formed along chamber walls. Depending on the level of mixing present, the gas mixture could remain trapped until after the bulk gas temperature has dropped below the conditions necessary for complete combustion, leading to increased hydrocarbon emissions.

2.3 Engine Designs and the Potential Relationships to Formaldehyde Emissions[16,19-22]

For the purposes of this study, natural gas-fired engines used in the gas industry were classified into five broad categories or "families" according to design differences that may lead to differences in emissions characteristics. These broad categories include:

- 2-stroke lean-burn engines;
- 2-stroke clean-burn (low-NO_x) engines;
- 4-stroke lean-burn engines;
    - direct-injected
    - port-injected
- 4-stroke rich-burn engines; and
- 4-stroke clean-burn (low-NO_x) engines.

Following is a discussion of the engine families, with each family comprising combustion units that share similar operational and design characteristics. While this classification scheme is used for this study, design differences between manufacturers may provide more insights into formaldehyde emission characteristics. Table 2-1 presents engine makes/models from each category, based on the engines tested in this program. Table 2-2 presents a summary of the combustion conditions observed during testing.

Table 2-1

Engines Tested in Each of the Engine Families[a]

Air Scavenging	2-Stroke Lean-burn	2-Stroke Clean-burn	4-Stroke Lean-burn	4-Stroke Rich-burn	4-Stroke Clean-burn
Turbocharged	Cooper GMVC-10 (2) Cooper GMWC-10 (1)	Clark TCV-10 (1) Cooper 10V-275 (1) Cooper GMVC-10C (1)	Cooper LSV-16 (2) Ingersoll-Rand KVS-412 (1)	---[b]	Ingersoll-Rand KVS-412 (1)
Blower scavenged	Cooper GMVA-10 (2)	---[c]	---[d]	---[e]	---[c]
Piston scavenged	Clark BA-5 (1) Clark HBA-5 (1)	---[c]	---[d]	---[e]	---[c]
Naturally aspirated	---[f]	---[c]	---[d]	Ingersoll-Rand KVG-103 (2) Waukesha L7042GU (1)	---[c]

[a] Values in parenthesis represent the number of units tested.

[b] No engines of this design were tested.

[c] All clean-burn engines are turbocharged.

[d] No engines of this design were identified.

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

[f] All 2-stroke engines utilize scavenging air.

Table 2-2

Summary of Combustion Conditions for Engines Tested

Engine Family	Exhaust O_2 (% by volume)	Stack Exhaust Temperature (°F)	Cylinder Exhaust Temperature (°F)
2-stroke lean-burn	11.4 - 15.7	440 - 660	430 - 950
2-stroke clean-burn	15.3 - 17.1	440 - 540	510 - 665
4-stroke lean-burn			
- Direct-injected	8.3 - 8.6	780	860 - 950
- Pre-mixed	9.3 - 11.0	920 - 980	NA[a]
4-stroke rich-burn	0.04 - 10.1	640 - 950	NA
4-stroke clean-burn	11.1 - 11.6	720 - 770	610 - 940

[a] NA = Not available.

2.3.1 2-Stroke Engines

A 2-stroke engine completes the power cycle in one revolution of the crankshaft. The first stroke begins with the piston at the top of the cylinder. At this time, the combustion chamber contains a compressed mixture of air and fuel. This mixture is ignited by a spark that causes a sudden increase in temperature and pressure. The increased pressure forces the piston downward, transferring power to the crankshaft. As the piston continues its downward motion, exhaust ports are uncovered or opened by exhaust valves, which let the combustion gases exit. Immediately after the exhaust ports are opened, air inlets are opened. Fresh air is forced into the cylinder to remove, or scavenge, the cylinder of remaining combustion gases and to provide oxygen for the next cycle. During the second stroke, the air and exhaust ports close as the piston begins its upward motion. After all ports are closed, gas is injected into the cylinder. The piston continues its upward motion, compressing the air and fuel mixture. When the piston reaches the top of the cylinder, the compressed fuel/air mixture is ignited and the cycle begins again.

Due to the scavenging air used to sweep the cylinder of exhaust gases, 2-stroke engines operate with an overall A/F ratio that is greater than stoichiometric (e.g., fuel lean conditions). As such, all 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 exhaust temperatures normally ranging from 550 to 850°F.

Relative to stoichiometric combustion, 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. The exhaust concentrations of formaldehyde also tend to be higher because the formaldehyde dissociation reaction rates are reduced at lower temperatures.

All 2-stroke lean-burn engines are direct-injected (i.e., fuel is injected directly into the cylinder) and exhibit 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 that have carbureted (premixed) fuel delivery systems. Because of the potential for nonuniform mixing of the air and fuel, 2-stroke engines may tend to have higher THC and formaldehyde levels than 4-stroke carbureted engines.

2-Stroke Clean-Burn Engines

The term "clean-burn" refers to engines that are designed to reduce NO_x through combustion modifications. Clean-burn engines use turbochargers to force more air into the combustion chamber. The increased A/F ratio reduces bulk gas and combustion temperatures, resulting in less NO_x formation. However, the reduced temperatures may also increase THC, CO, and formaldehyde emissions.

Engines with a large cylinder bore 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 precombustion chamber (PCC) design is utilized. Although PCC designs vary among manufacturers, the PCC is typically a small volume antechamber that ignites a fuel-rich mixture. The ignited mixture from the PCC propagates into the main cylinder and ignites the very lean combustion charge. The high 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 as compared to an open-chamber design.

2.3.2 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 and fuel mixture in the cylinder. As the piston finishes its upward stroke, the fuel/air mixture is ignited by a spark, causing a sudden increase in temperature and pressure. The increased pressure drives the piston downward (i.e., the third stroke), delivering power to the crankshaft. Finally, the piston moves upwards 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, or fuel-rich, and have an exhaust O_2 concentration ranging from nearly zero to five percent. Rich-burn engines include all naturally aspirated and nonscavenged, turbocharged 4-stroke engine models. A/F ratios for rich-burn engines typically range between 16:1 to 20:1. Because of the low levels of O_2 present, bulk combustion temperatures, and consequently exhaust temperatures, are higher than for lean-burn engines.

In the high-temperature environment associated with fuel-rich combustion, formaldehyde dissociation reactions are favored. Therefore, relative to lean-/clean-burn families, lower exhaust concentrations of formaldehyde are expected from rich-burn engines.

4-Stroke Lean-Burn Engines

Four-stroke lean-burn engines are available in two basic designs: direct injected and premixed (carbureted or port-injected). The conditions in the combustion zone for these two designs can be very different. 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 the conditions present in a rich-burn engine. The pre-mixed 4-stroke lean-burn engines combust a homogenous air/fuel mixture, which leads to a cooler combustion zone.

The additional mixing in 4-stroke engines reduces the presence of high fuel concentration and temperature gradients in the cylinder during combustion 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 times at elevated temperatures should favor formaldehyde dissociation and, therefore, may result in lower formaldehyde emissions compared to 2-stroke lean-burn engines. However, when compared to 4-stroke rich-burn engines, the increased A/F ratio in 4-stroke lean-burn engines reduces combustion and exhaust temperatures which should lead to higher formaldehyde concentrations in the exhaust.

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 premixed.

Four-stroke clean-burn injected engines are characterized by either a direct-injected or port-injected fuel delivery system. Compared to the premixed fuel/air design, the injected clean-burn design is expected to exhibit higher fuel concentration gradients, leading to nonuniform temperature distribution in the combustion chamber. The "cool" areas of this nonhomogeneous combustion temperature profile can lead to decreased formaldehyde dissociation reaction rates and increased formaldehyde emissions.

Four-stroke carbureted engines are characterized by premixing the air and fuel prior to charging the combustion cylinder. Because of the homogeneity of the air/fuel mixture during the combustion process, the premixed design provides a relatively uniform combustion temperature profile. Compared to uncontrolled 4-stroke engines, the pre-mix clean-burn design exhibits lower combustion and exhaust temperatures due to the higher A/F ratio. Therefore, formaldehyde emission levels may tend to be higher than for a comparable size and model uncontrolled 4-stroke engine.

2.4 Gas Turbines

A gas turbine is an internal combustion engine that 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.

3.0 SAMPLING AND ANALYTICAL METHODS

This section describes the approach employed in gathering the field measurement data, including the methods used to measure target compound concentrations in the engine/turbine exhaust streams and to collect the pertinent process data (e.g., fuel flow rate, horsepower). Also described in this section is how data collection and verification procedures evolved as information from the initial campaigns was reviewed. Some of the problems encountered during the field measurements are also described in this section.

3.1 Measurement Approach

Table 3-1 summarizes the measurement methods used during the field campaigns to quantify emissions of the target compounds listed in Table 1-1. As indicated in Table 3-1, sampling and analysis of the target compounds was accomplished using a variety of sampling and analytical techniques based on manual (single point/time integrated) or continuous measurements. For measurement of volatile organic compounds and aldehydes, FTIR and manual methods were used, while only manual methods were used to measure emissions of semi-volatile organic compounds, PM_{10}, and metals. For monitoring concentrations of NO_x, CO, CO_2, O_2, and THC, a continuous emission monitoring (CEM) system was employed. Table 3-2 presents the specific measurement methods employed during the field campaigns for each target compound, including "criteria" pollutants (e.g., NO_x, CO, and non-methane hydrocarbons). Results of the criteria pollutant emissions measurements are also summarized in a separate GRI/EPA report entitled "*Criteria Pollutant Emissions from Internal Combustion Engines in the Natural Gas Industry*" (GRI-95/0270).[26]

Also indicated in Table 3-2 is the measurement method selected for use in developing the emission factors described in Sections 5 and 6. The following criteria were used in selection of a particular method for emission factor development:

- Most accurate results; and
- No other validated measurement method available.

Table 3-1

Target Parameters and Sampling Methods[a]

Location	Parameter	Collection Method	Sampling and Analytical Method
Stack	Exhaust Flow Rate	Manual, Traverse	EPA Method 2
		Based on Fuel Flow	EPA Method 19
	Molecular Weight	Extractive Probe (Dry)	EPA Method 3A
	Moisture Content	Manual, Single Point	EPA Method 4
	Volatile Organics	SUMMA® Canisters	EPA Method TO-14
		Manual, Single Point	SW-846 Method 0030
		Extractive Probe (Wet)	FTIR
	Semi-volatile Organics	Manual, Traverse	SW-846 Method 0010; CARB Method 429
	C1-C6 Organics	Extractive Probe (Wet)	EPA Method 18
	Aldehydes	Manual, Single Point	CARB Method 430; SW-846 Method 0011
		Extractive Probe (Wet)	FTIR
	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
	PM_{10}	Manual, Single Point	EPA Method 201A/202
	Metals	Manual, Traverse	SW-846 Method 0012
Fuel Sample	HHV	Pressurized Cylinders	GPA Method 2261
	Fuel Composition	SUMMA® Canisters	EPA Method TO-14
Ambient Air	Barometric Pressure	Barometer	
	Temperature	Thermometer	
	Relative Humidity	Humidistat	
Process Data[b]	Fuel Flow Rate	Orifice Flowmeter	
	Horsepower	Engine Analyst	
	Engine Speed	Engine Analyst	

[a] HHV = Higher Heating Value; CARB = California Air Resources Board; GPA = Gas Processors Association.

[b] Engine analyst on-site during all campaigns except Campaigns 1 and 3A. During Campaign 3A, engine horsepower data were obtained from the station's control system. For Campaign 6B, turbine horsepower data were obtained from the station's control system.

Table 3-2

Target Compounds and Measurement Methods

Compound	Measurement Methods Used in Testing	Measurement Method Used to Develop Emission Factors
Aldehydes		
Formaldehyde	FTIR CARB Method 430 SW-846 Method 0011	FTIR
Acetaldehyde	FTIR CARB Method 430 SW-846 Method 0011	FTIR
Acrolein	FTIR CARB Method 430 SW-846 Method 0011	FTIR
Butyr/Isobutyraldehyde	CARB Method 430 SW-846 Method 0011	CARB Method 430
Volatile Organic Compounds		
1,2,3-Trimethylbenzene	EPA Method TO-14	EPA Method TO-14
1,2,4-Trimethylbenzene	EPA Method TO-14	EPA Method TO-14
1,3-Butadiene	EPA Method TO-14	EPA Method TO-14
1,3,5-Trimethylbenzene	EPA Method TO-14	EPA Method TO-14
2,2,4-Trimethylpentane	EPA Method TO-14	EPA Method TO-14
Acetylene	EPA Method TO-14 FTIR	EPA Method TO-14
Benzene	EPA Method TO-14 SW-846 Method 0030	EPA Method TO-14
Butane	EPA Method TO-14	EPA Method TO-14
Cyclohexane	EPA Method TO-14	EPA Method TO-14
Cyclopentane	EPA Method TO-14	EPA Method TO-14
Ethane	EPA Method TO-14 EPA Method 18	Method 18
Ethyl benzene	EPA Method TO-14 SW-846 Method 0030	EPA Method TO-14
Ethylene	EPA Method TO-14 FTIR	EPA Method TO-14
n-Hexane	EPA Method TO-14	EPA Method TO-14
Isobutane	EPA Method TO-14	EPA Method TO-14
Methane	EPA Method 18	EPA Method 18

Table 3-2

Target Compounds and Measurement Methods (Continued)

Compound	Measurement Methods Used in Testing	Measurement Method Used to Develop Emission Factors
Volatile Organics Compounds (Continued)		
Methanol	EPA Method TO-14 FTIR	FTIR
Methylcyclohexane	EPA Method TO-14	EPA Method TO-14
n-Nonane	EPA Method TO-14	EPA Method TO-14
n-Octane	EPA Method TO-14	EPA Method TO-14
n-Pontane	EPA Method TO-14	EPA Method TO-14
Propane	EPA Method TO-14	EPA Method TO-14
Propylene	EPA Method TO-14 FTIR	EPA Method TO-14
Styrene	EPA Method TO-14 SW-846 Method 0030	EPA Method TO-14
Toluene	EPA Method TO-14 SW-846 Method 0030	EPA Method TO-14
Xylenes	EPA Method TO-14 SW-846 Method 0030	EPA Method TO-14
Semi-Volatile Organic Compounds		
Acenaphthene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Acenaphthylene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Anthracene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benz(a)anthracene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benzo(a)pyrene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benzo(e)pyrene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benzo(b)fluoranthene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benzo(g,h,i)perylene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Benzo(k)fluoranthene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Biphenyl	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429

Table 3-2

Target Compounds and Measurement Methods (Continued)

Compound	Measurement Methods Used in Testing	Measurement Method Used to Develop Emission Factors
Semi-Volatile Organic Compounds (Continued)		
Chrysene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Dibenz(a,h)anthracene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Fluoranthene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Fluorene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Indeno(1,2,3-c)pyrene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
2-Methylnaphthalene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Naphthalene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Perylene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Phenanthrene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Phenol	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Pyrene	SW-846 Method 0010 CARB Method 429	SW-846 Method 0010 or CARB Method 429
Metals	SW-846 Method 0012	SW-846 Method 0012
"Criteria" Pollutants		
NO_x	EPA Method 7E FTIR	EPA Method 7E
CO	EPA Method 10 FTIR	EPA Method 10
PM_{10}	EPA Method 201A/202	EPA Method 201A/202
THC	EPA Method 25A	EPA Method 25A
NMHC and NMEHC	EPA Method 25A (for THC) EPA Method 18 (for methane and ethane)	EPA Method 25A and EPA Method 18

NMHC = non-methane hydrocarbons; NMEHC = non-methane, non-ethane hydrocarbons.

3.1.1 Exhaust Gas Flow Rate

Exhaust gas flow rates were estimated using EPA Methods 2 and 19. Method 2 uses pitot tube velocity measurements and temperature data to calculate volumetric flow rate, while Method 19 employs a factor based on combustion stoichiometry that relates the amount of fuel burned to the exhaust gas flow rate. Accuracy of Method 2 data can be affected by the pulsations caused by the noncontinuous flow from each piston, whereas the accuracy of Method 19-based flow rates is dependent on reliable fuel flow rate data. For most of the test runs, emission rates were determined using Method 19, except where accurate fuel flow rate data were unavailable.

3.1.2 Procedures

FTIR measurements were conducted according to procedures described in a protocol document prepared for this field measurement program.[8] Results from FTIR validation testing performed under a separate effort have been reviewed by EPA and the FTIR method has been approved as a valid method for measuring concentrations of formaldehyde, acetaldehyde, acrolein, NO_x, CO, CO_2, and H_2O in engine exhaust. A copy of the EPA approval letter is included as an attachment to this volume.

Measurements for other target compounds were conducted according to established procedures specified in the state and federal methods (see Appendix B for detailed description of the methods).

As the data collection effort was refined based on review of information from initial campaigns, some of the measurements were discontinued. For example, metal emission measurements were conducted only during Campaign 1. Similarly, measurement of PM_{10} emissions (particulate and condensible) was not conducted after Campaign 4.

3.1.3 CARB Method 430 Formaldehyde Measurements

As indicated above, measurements of formaldehyde and other aldehydes were conducted via the FTIR method and CARB Method 430 during all campaigns. In some campaigns, SW-846 Method 0011 was also used to measure aldehydes. Differences between the FTIR method and the two manual methods were observed in some of the test results. Both manual methods are based on quantifying the amount of derivatization occurring between the aldehydes and 2,4-dinitrophenylhydrazine (DNPH) in impinger solutions. In several cases where aldehydes were measured above detection limits using the FTIR, they were not observed in the analysis of the samples performed by manual methods. In several of these cases, trace amounts of the aldehydes were found in the field blanks. Impinger solutions were observed to be clear instead of the orange color typically associated with DNPH, indicating potential cross-reactions that consumed the reagent.

Recent results reported in the literature indicate that potential interferences for the DNPH measurement methods may be caused by nitrogen dioxide (NO_2) present in the exhaust gas.[22,23] GRI has conducted laboratory tests investigating the potential impacts of NO_2 on measurement of formaldehyde using DNPH-based methods. Results of this study are documented in the gas plant report.[3]

3.1.4 Measurement System Description (Extractive)

A schematic of the exhaust gas sample extraction and analysis system used during the field measurements is shown in Figure 3-1. Samples were extracted from the engine/turbine stacks using a stainless steel filter and probe assembly. Sample gas was transferred through a heat-traced line to the mobile laboratory using a heated-head pump, followed by delivery to the insulated sample manifold for further distribution. Sample gas was then conditioned, if required, by passing it through a series of chillers. Conditioned gas was delivered to the NO_x, CO, CO_2, and O_2 analyzers, while unconditioned gas was delivered to the FTIR, GC, and THC analyzers. A listing of the instruments used during the field measurements is shown in Table 3-3.

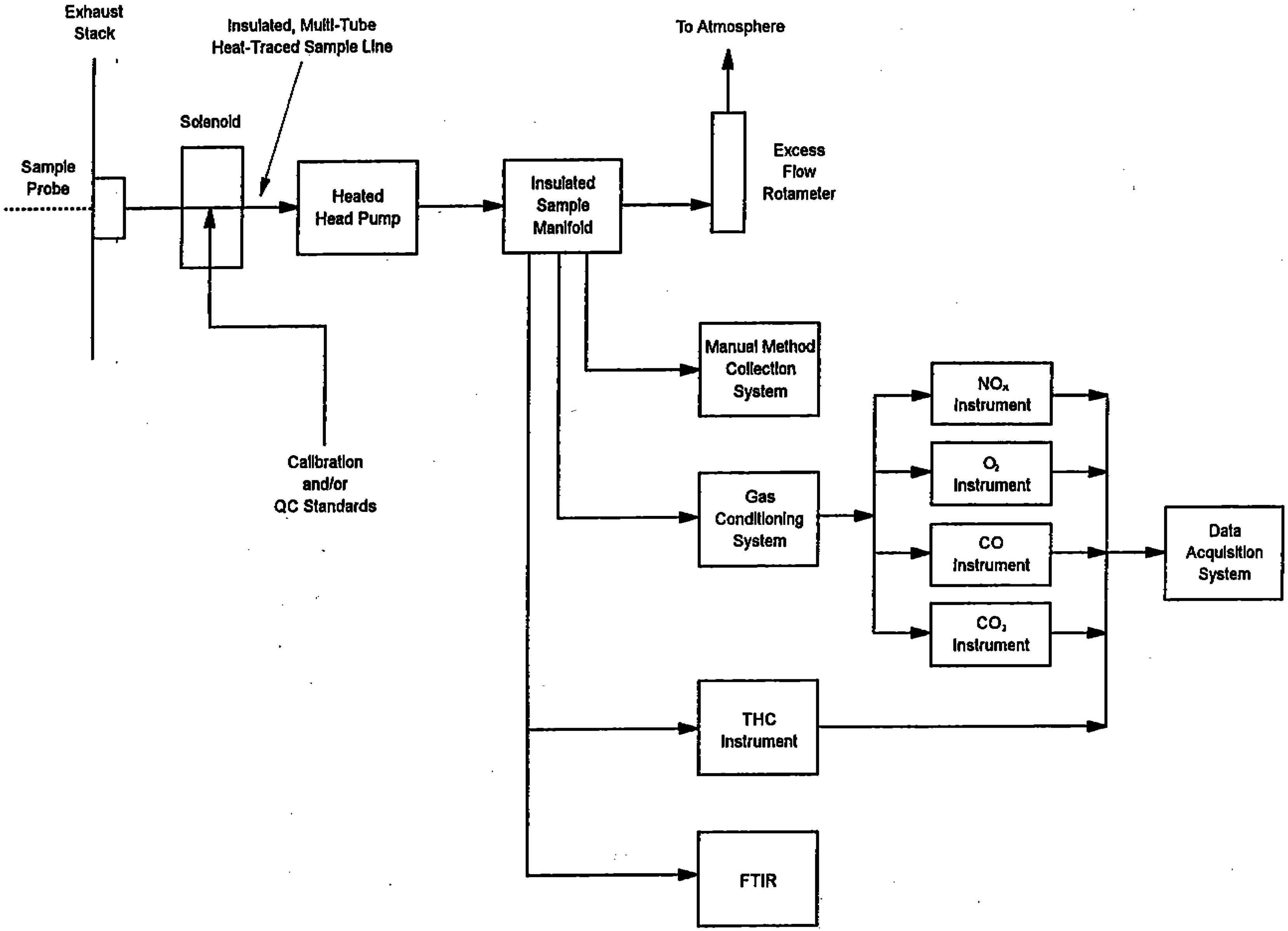


Figure 3-1, Sample Extraction System Schematic

Table 3-3

Instruments Used During Testing

Parameter	Manufacturer/Model	Campaign No.
Air Toxics	Nicolet Model RS-3 (FTIR)	All
Volatile Organic Compounds	HP Model 5890 (GC/FID)	All
NO_x	TECO Model 10A/R	All
O_2	Servomex Model 1400	All
CO	TECO Model 48H	All
CO_2	Horiba Model PIR-2000	1,3,4
	Servomex Model 1400	6
THC	Ratfische Model RS-55	1,3,4
	J.U.M. Model VE7	6

3.2 Process Data Collection

Process data collection and verification procedures used to characterize engine operating conditions were refined as information from the initial campaigns was reviewed. During Campaign 1, no independent evaluation of the engines was performed to ensure that they were operating in a manner typical for the industry. Additionally, horsepower and fuel flow rate data were obtained from the host site's monitoring system without any direct or independent measurements for comparison. Due to problems identified with the accuracy of the horsepower and fuel flow measurements collected from the Campaign 1 station monitoring equipment, no values are presented in this document for the engines at this site that rely upon either of these parameters.

An engine consultant was subcontracted for Campaigns 3, 4, and 6. In Campaign 3, the consultant performed a visual inspection of the engines during the pretest site survey to identify any major maintenance or operational problems. No urgent maintenance requirements were identified. The engines tested at site 3A during Campaign 3 were equipped with centrifugal compressors which complicate direct measurement of horsepower. Therefore, all horsepower data were obtained from the station control system. Insufficient documentation on sensor calibrations was available from the site to quantify the level of accuracy associated with the horsepower data. However, when compared to fuel flow measurements and expected heat rates for these engine models, the horsepower values correlated well. During Campaigns 4 and 6, the engine consultant was on-site and worked with the engine analysts to identify and correct any major maintenance and operational conditions that would significantly affect engine performance and emissions. Where present, all pocket unloaders were inspected to insure proper operation and tight seals. The engines to be tested were checked for balance and, if needed, balanced at maximum load conditions. In a few cases, some fuel valves and/or spark plugs were replaced before tests were conducted. All horsepower measurements were collected directly off the compressor during each test run. In addition, horsepower measurements were performed directly on the individual power cylinders to check engine balance at least once for each engine. Following these procedures, the horsepower and torque measurements are expected to be accurate within ±5 percent.

4.0 DESCRIPTION OF HOST SITES

4.1 Site Selection Criteria

Criteria were established for selecting suitable sites for testing to ensure that the measurements would be performed on representative engine types and provide data for a broad population of engines in compression/transmission service in the gas industry. The criteria were prioritized in order of relative importance with respect to the objectives of the measurement effort. The candidate sites were evaluated relative to the established criteria, as described below in Table 4-1.

Table 4-1

Prioritization of Site Selection Criteria

Parameter	Selection Criteria	Priority Level
Engine Family	2-stroke lean-burn 2-stroke clean-burn 4-stroke rich-burn 4-stroke lean-burn 4-stroke clean-burn	High
Engine Manufacturer	Cooper-Bessemer, Ingersoll-Rand, Clark	High
Engine Size	1,000-5,000 hp	Medium
Engine Operating Load	Flexibility to vary load during testing	Medium-Low
Engine Age	Mix of "new" (post-1970) and "old" (pre-1970)	Medium
Gas Turbine	Gas turbine at site	Low
Other Emissions Control	Catalytic oxidation Selective catalytic reduction Nonselective catalytic reduction	Low

4.1.1 Engine Family

Engines representing as many of the five engine families as possible at a site was a high-priority selection criteria. The population of reciprocating engines in gas transmission service is about equally divided between 2- and 4-stroke engines (53 percent versus 47 percent, respectively).[1] Because 4-stroke engines are further subdivided into lean- and rich-burn categories, the 2-stroke lean-burn engine family is the largest single engine group. Furthermore, for the 4-stroke engine classification, both rich- and lean-burn models were desirable for testing, since the A/F ratio and fuel/air mixing characteristics are likely to affect emissions.

Air toxic emissions from engines with NO_x controls, either combustion modifications or add-on controls, are potentially different from those without any controls. Since clean-burn and other NO_x control alternatives are being required in response to the NO_x reasonably available control technology (RACT) rules in development by individual states in ozone nonattainment areas, information on the effect of NO_x controls on air toxic emissions is of interest to the gas industry. Additionally, since clean-burn retrofit may be required to meet RACT emission limits in several states, the investigation of clean-burn technology (both 2- and 4-stroke clean-burn) on air toxic emissions was considered a high priority. Ideally, to allow a direct comparison of uncontrolled versus controlled (clean-burn) emissions, two identical models with and without clean-burn technology were desirable.

4.1.2 Engine Manufacturer/Model

Another high-priority selection criteria was that sites selected should have engines representative of the most common engines in use in the gas industry. The largest manufacturer of engines is Cooper-Bessemer, with about 30 percent of the engines in transmission service. Ingersoll-Rand and Clark each represent about 15 percent of the engine population and are the second and third largest manufacturers, respectively. The reciprocating engine models selected to meet the criteria of representing as many of the engine families as possible should also represent these top three engine manufacturers where feasible.

4.1.3 Engine Size and Age

Because of the large variability in the size range and age of engines in use in the industry, selection of engines in a size range (e.g., 1,000 to 5,000 hp) that represents the majority of engines in transmission service was assigned a medium priority. Due to differences in design, air toxic emissions are potentially different between "old" (pre-1970) and "new" (post-1970) engines. Thus age was also assigned a medium priority as selection criteria.

4.1.4 Operating Load

During the initial test campaigns, operating load flexibility was given a low priority. The objective of these earlier campaigns focused on collecting screening level emissions data at base operating conditions. As the program evolved and potential relationships between operating load and air toxic emissions were identified, the importance of load flexibility increased.

4.1.5 Other Selection Criteria

Gas turbines were given a low priority since characterization of gas turbine emissions was being conducted as part of another GRI program. Gas turbines represent about 10 percent of the total prime mover population and 30 percent of the total installed horsepower in transmission service. Another low-priority selection criterion was the presence of add-on emission controls (catalytic oxidation, selective catalytic reduction, and nonselective catalytic reduction) on candidate engines. Some types of add-on controls are expected to affect air toxic emissions; however, very few existing engines utilize catalytic controls.

4.2 Campaign 1--Compressor Station

Table 4-2 summarizes the characteristics of the engines tested during Campaign 1. This compressor station employs six mainline compressor engines and typically handles 350 MMscfd or more of natural gas for transmission to end users. At any one time, at least four of the six engines are in operation. Gas is generally collected from fields south of the plant and dehydrated before compression and transmission to the end users. All of the engines on site fire pipeline-quality gas.

Table 4-2

Engines Tested At Campaign 1

Engine Make/Model	Number of Units Tested	Unit Size (hp)	Year Installed	Engine Family	Emission Controls
Ingersoll Rand KVG-103	2	1,100	1962	4-stroke rich-burn; naturally aspirated	None
Clark TCV-10	1	4,200	1992	2-stroke lean-burn; turbocharged	Clean-burn
Cooper 10V-275	1	3,400	1969	2-stroke lean-burn; turbocharged	Clean-burn (retrofit)

4.3 Campaign 3—Compressor Station 3A

Station 3A operates four Cooper LSV-16 four-stroke, turbocharged engines for compression and transmission of natural gas. These engines are rated at 3,500 hp; however, the site operates the units at maximum brake mean effective pressure (BMEP) that results in a full load horsepower level of 4,200 hp. Only two of these engines were tested. Three of the four engines at the site are typically in operation at any given time. All on-site equipment fire pipeline-quality natural gas.

Testing was also conducted during this campaign at a sweet gas plant. However, as discussed in Section 1.3, data collected at gas processing plants will be presented in a separate report.

4.4 Campaign 4—Storage Facility

Table 4-3 summarizes the characteristics of the engines tested during Campaign 4, which was conducted at a natural gas storage station. The engines are used for compression of gas during injection to and withdrawal from the storage reservoir. All of the engines at the station fire pipeline-quality gas.

Table 4-3

Engines Tested in Campaign 4

Engine Make/Model	Number of Units Tested	Unit Size (hp)	Year Installed	Engine Family	Emission Control
Cooper-Bessemer GMVC-10C	1	1,800	1956	2-stroke lean-burn; turbocharged	Clean-burn[a] (retrofit)
Ingersoll-Rand KVS-412	1	2,000	1956	4-stroke lean-burn; turbocharged	PCC[b] (retrofit)
Ingersoll-Rand KVS-412	1	2,000	1956	4-stroke lean-burn; turbocharged	SCR[c] (retrofit)
Waukesha L7042GU	1	896	1982	4-stroke rich-burn; naturally aspirated	NSCR[d] (retrofit)

[a] Engine also has CO oxidation catalyst.

[b] Precombustion chamber.

[c] Selective catalytic reduction.

[d] Nonselective catalytic reduction.

As shown in Table 4-3, all four engines tested are equipped with NO_x emission controls (clean-burn, precombustion chamber, selective catalytic reduction, and nonselective catalytic reduction). In addition, a CO oxidation catalyst is in use on the clean-burn Cooper GMVC-10C engine. The clean-burn/CO catalyst and nonselective catalytic reduction controls have been recently retrofitted on the Cooper GMVC-10C and Waukesha L7042GU engines, respectively. During the tests, measurements were conducted both upstream and downstream of the catalytic emission control equipment. In addition, a limited number of parametric test runs varying torque and ignition timing were conducted on the Ingersoll-Rand KVS-412 unit with PCC control.

4.5 Campaign 6--Compressor Stations 6A, 6B, and 6C

Table 4-4 presents a description of all of the engines and the turbine tested under Campaign 6. These units are used in natural gas transmission and burn pipeline-quality gas.

Compressor Station 6A has eleven Clark BA-5 engines and one Clark HBA-5 engine. Testing was conducted on the single Clark HBA-5 unit and one of the Clark BA-5 units. Compressor Station 6B is equipped with one Solar Taurus Model T6502 gas turbine, and Compressor Station 6C employs 15 Cooper-Bessemer engines including 11 GMVA-10 units, 2 GMVC-10 units, and 2 GMWC-10 units. A total of four engines were tested at Station 6C, including one GMVA-10, two GMVC-10, and one GMWC-10. Most of the units were tested at only one or two loads; however, a limited number of parametric test runs varying torque and speed, were conducted on two of the engines at Station 6C.

Table 4-4

Engines Tested in Campaign 6

Station	Engine Make/Model	Number of Units Tested	Unit Size (hp)	Year Installed	Engine Family	Emission Controls
6A	Clark BA-5	1	911	1948	2-stroke lean-burn; piston scavenged	None
6A	Clark HBA-5	1	1,000	1951	2-stroke lean-burn; piston scavenged	None
6B	Solar Taurus T6502	1	5,419	1993	Gas turbine	None
6C	Cooper GMVA-10	1	1,235	1954	2-stroke lean-burn; blower scavenged	None
6C	Cooper GMVC-10	2	1,800	1957; 1963	2-stroke lean-burn; turbocharged	None
6C	Cooper GMWC-10	1	3,500	1960	2-stroke lean-burn; turbocharged	None

5.0 ENGINE DATA ANALYSIS

This section presents an analysis of the data collected on the engines tested during Campaigns 1, 3, 4, and 6, focussing on formaldehyde because, of the toxic species measured in the engine exhaust, it had the highest concentration levels. Section 5.1 presents a summary of the data collected (Note: More detailed test summaries are included in Appendix D). The effects of engine design and operating variables on formaldehyde emissions are discussed in Sections 5.2 and 5.3. The effects of emission controls are discussed in Section 5.4. Finally, relationships between formaldehyde emissions and other pollutant emissions are examined in Section 5.5.

5.1 Engine Process and Emissions Data

Table 5-1 shows a breakdown of the data collected for each of the five broad engine categories or "families" discussed in Section 2.0. The categories include 2-stroke clean-burn, 2-stroke lean-burn, 4-stroke clean-burn, 4-stroke lean-burn, and 4-stroke rich-burn engines. As shown in Table 5-1, 58 data points were collected on 16 individual engines representing 13 models. Over one-third of these data were collected from 2-stroke lean-burn engines.

Table 5-1

Breakdown of Engine Test Data

Engine Family	No. of Engine Models	No. of Engines	No. of Data Points
2-stroke lean-burn	5	6	21
2-stroke clean-burn	3	3	10
4-stroke rich-burn	2	3	10
4-stroke lean-burn	2	3	8
4-stroke clean-burn	1	1	9
Total	**13**	**16**	**58**

Tables 5-2 and 5-3 show the key engine process data and exhaust emissions data for all the engines. The data are average values obtained under steady-state engine operating conditions. The key engine parameters shown in Table 5-2 include air supply system design, engine horsepower, speed, torque, fuel flow, heat rate, ignition timing, engine cylinder dimensions, and engine exhaust duct and cylinder temperatures. With the exception of the Cooper LSV-16 engines (ID Nos. 41-45), all of the horsepower data presented in Table 5-2 were measured directly off the compressor by an engine analyst. The horsepower data for the LSV-16 engines was collected from the station control system. The last column in the table indicates whether an engine analyst and consultant were present on-site during the testing to assess engine operating condition. During Campaigns 4 and 6, the engine analyst and consultant worked together to identify and correct minor maintenance problems on the engines tested.

Data reduction procedures are described in Appendix A. Engine test torque is expressed as a percentage of rated torque. Heat rates were calculated based on the higher heating value of fuel samples collected at each station. As indicated in the table, horsepower and/or fuel flow were not measured on some engines because these engines were not equipped with adequate instrumentation for these measurements. Consequently, torque and/or heat rate values could not be calculated for these tests.

The cylinder exhaust temperatures shown in Table 5-2 were measured by thermocouples located near the exhaust ports of each cylinder. Although these temperatures are indicative of cylinder bulk gas temperatures, differences in temperature measured among the various engine models could result from differences in cooling system design and operation, differences in the location of the thermocouples, and measurement errors. Therefore, these data should be used with care when analyzing the effect of temperature on formaldehyde emissions from different engines. In the following analyses, the temperature data were used only to assess the effect of temperature for a particular engine.

The data presented in Table 5-3 include exhaust measurements of NO_x, CO, THC, formaldehyde, and O_2. Ambient temperature, barometric pressure, and relative humidity are also included. As indicated earlier, because engine horsepower was not measured for some of the engine tests in earlier campaigns, exhaust emissions

Table 5-2

Summary of Engine Design and Process Data

Engine Test ID	Engine Make/Model	Exhaust Emission Controls (a)	Date of Test	Engine Parameters														Engine Analyst/ Consultant On-site
				Air Supply (b)	Rated hp	Rated rpm	Test hp (c)	Test rpm	Test Torque (%)	Test rpm (%)	Fuel Flow (dscfm)	Heat Rate (Btu/hp-hr)	Engine Bore (in.)	Engine Stroke (in.)	Ignition Timing (°btdc)	Exhaust Temp (°F)	Cylinder Temp Range (°F)	
2-Stroke, clean-burn																		
1	Clark TCV-10		11/03/93	TC	4,200	330	NM (d)	331	NM	100	NM	NM	17.0	19.0	7	445	540-665	N/N
2	Clark TCV-10		11/03/93	TC	4,200	330	NM	331	NM	100	NM	NM	17.0	19.0	7	442	510-660	N/N
3	Cooper 10V-275		11/01/93	TC	3,750	275	NM	250	NM	91	NM	NM	18.0	20.0	4	503	NM	N/N
4	Cooper 10V-275		11/02/93	TC	3,750	275	NM	276	NM	100	NM	NM	18.0	20.0	4	543	NM	N/N
5	Cooper GMVC-10C	CO cat	08/26/94	TC	1,800	300	1,600	300	89	100	203	7,699	14.0	14.0	5	517	550-610	Y/Y
6	Cooper GMVC-10C	CO cat	08/26/94	TC	1,800	300	1,773	299	99	100	211	7,199	14.0	14.0	5	517	550-615	Y/Y
7	Cooper GMVC-10C	pre-CO cat	08/25/94	TC	1,800	300	1,732	299	97	100	211	7,368	14.0	14.0	5	574	545-615	Y/Y
8	Cooper GMVC-10C	pre-CO cat	08/26/94	TC	1,800	300	1,674	300	93	100	213	7,706	14.0	14.0	5	517	550-620	Y/Y
9	Cooper GMVC-10C	pre-CO cat	08/30/94	TC	1,800	300	1,422	299	79	100	185	7,880	14.0	14.0	5	507	525-600	Y/Y
10	Cooper GMVC-10C	pre-CO cat	08/30/94	TC	1,800	300	1,705	299	95	100	212	7,550	14.0	14.0	5	506	535-605	Y/Y
2-Stroke, lean-burn																		
11	Clark BA-5		11/04/94	PS	911	300	851	299	94	100	161	11,627	17.0	17.0	11	458	585-650	Y/Y
12	Clark BA-5		11/04/94	PS	911	300	725	301	80	100	147	12,468	17.0	17.0	11	436	565-620	Y/Y
13	Clark BA-5		11/05/94	PS	911	300	910	299	100	100	174	11,737	17.0	17.0	11	455	590-660	Y/Y
14	Clark HBA-5		11/04/94	PS	1,000	300	741	297	75	99	140	11,612	17.0	17.0	11	540	430-530	Y/Y
15	Clark HBA-5		11/05/94	PS	1,000	300	839	301	84	100	150	10,947	17.0	17.0	11	592	440-590	Y/Y
16	Cooper GMVA-10		11/11/94	BS	1,235	300	1,078	299	88	100	168	9,511	14.0	14.0	8	576	550-690	Y/Y
17	Cooper GMVA-10		11/12/94	BS	1,235	300	1,232	300	100	100	174	8,631	14.0	14.0	8	586	570-720	Y/Y
18	Cooper GMVA-10		11/12/94	BS	1,235	300	1,234	300	100	100	173	8,566	14.0	14.0	8	590	580-710	Y/Y
19	Cooper GMVC-10 (A)		11/10/94	TC	1,800	300	1,827	300	102	100	266	8,900	14.0	14.0	8	581	570-780	Y/Y
20	Cooper GMVC-10 (A)		11/10/94	TC	1,800	300	1,830	300	102	100	266	8,884	14.0	14.0	8	576	575-780	Y/Y
21	Cooper GMVC-10 (A)		11/11/94	TC	1,800	300	1,523	299	85	100	265	10,667	14.0	14.0	8	552	560-755	Y/Y
22	Cooper GMVC-10 (B)		11/15/94	TC	1,800	300	1,465	284	86	95	199	8,323	14.0	14.0	8	561	585-695	Y/Y
23	Cooper GMVC-10 (B)		11/15/94	TC	1,800	300	1,569	301	87	100	217	8,474	14.0	14.0	8	569	590-705	Y/Y
24	Cooper GMVC-10 (B)		11/15/94	TC	1,800	300	1,724	285	101	95	224	7,961	14.0	14.0	8	583	610-725	Y/Y
25	Cooper GMVC-10 (B)		11/15/94	TC	1,800	300	1,799	300	100	100	236	8,038	14.0	14.0	8	592	610-725	Y/Y
26	Cooper GMVC-10 (B)		11/15/94	TC	1,800	300	1,669	292	95	97	221	8,113	14.0	14.0	8	576	605-715	Y/Y
27	Cooper GMWC-10		11/14/94	TC	3,500	250	3,172	249	91	100	440	8,527	18.0	20.0	8	621	620-865	Y/Y
28	Cooper GMWC-10		11/14/94	TC	3,500	250	2,822	230	88	92	389	8,481	18.0	20.0	8	615	610-840	Y/Y
29	Cooper GMWC-10		11/14/94	TC	3,500	250	3,352	250	96	100	459	8,423	18.0	20.0	8	653	640-890	Y/Y
30	Cooper GMWC-10		11/14/94	TC	3,500	250	3,054	230	95	92	421	8,478	18.0	20.0	8	651	635-875	Y/Y
31	Cooper GMWC-10		11/14/94	TC	3,500	250	3,092	240	92	96	426	8,474	18.0	20.0	8	617	620-855	Y/Y

a CO cat = carbon monoxide oxidation catalyst; NSCR = nonselective catalytic reduction.
b TC = turbocharged; PS = piston scavenged; BS = blower scavenged; PI = Port Injection; DI = Direct Injection; NA = naturally aspirated.
c For all engines except the LSV-16 engines, horsepower was measured directly by an engine analyst and is accurate to within ±5 percent. For the LSV-16 engines, hp was recorded from the station's control system.
d NM = not measured

Table 5-2

Summary of Engine Design and Process Data (Continued)

Engine Test ID	Engine Make/Model	Exhaust Emission Controls (a)	Date of Test	Engine Parameters														Engine Analyst/ Consultant On-site
				Air Supply (b)	Rated hp	Rated rpm	Test hp (c)	Test rpm	Test Torque (%)	Test rpm (%)	Fuel Flow (dscfm)	Heat Rate (Btu/hp-hr)	Engine Bore (in.)	Engine Stroke (in.)	Ignition Timing (°btdc)	Exhaust Temp (°F)	Cylinder Temp Range (°F)	
4-Stroke, clean-burn																		
32	Ingersoll KVS-412		08/27/94	TC	2,000	330	1,783	330	89	100	272	9,239	15.3	18.0	8	741	640-925	Y/Y
33	Ingersoll KVS-412		08/27/94	TC	2,000	330	1,640	330	82	100	253	9,340	15.3	18.0	8	719	655-930	Y/Y
34	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,783	335	88	102	276	9,375	15.3	18.0	8	762	635-925	Y/Y
35	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,693	329	85	100	265	9,477	15.3	18.0	8	739	615-910	Y/Y
36	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,687	333	87	101	254	9,116	15.3	18.0	11	749	620-895	Y/Y
37	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,846	330	92	100	267	8,757	15.3	18.0	8	746	625-900	Y/Y
38	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,656	327	84	99	276	10,094	15.3	18.0	5	756	635-940	Y/Y
39	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,708	323	88	98	277	9,819	15.3	18.0	5	766	640-925	Y/Y
40	Ingersoll KVS-412		08/30/94	TC	2,000	330	1,621	333	80	101	247	9,226	15.3	18.0	11	733	610-905	Y/Y
4-Stroke, lean-burn																		
41	Cooper LSV-16 (A)		06/15/94	TC/PI	4,200	327	4,202	325	101	99	497	8,145	15.5	22.0	18/22	976	NM	N/Y
42	Cooper LSV-16 (A)		06/15/94	TC/PI	4,200	327	3,364	302	87	92	412	8,440	15.5	22.0	18/22	968	NM	N/Y
43	Cooper LSV-16 (B)		06/15/94	TC/PI	4,200	327	3,311	303	85	93	423	8,800	15.5	22.0	18/22	922	NM	N/Y
44	Cooper LSV-16 (B)		06/16/94	TC/PI	4,200	327	4,117	325	99	99	486	8,126	15.5	22.0	18/22	970	NM	N/Y
45	Cooper LSV-16 (B)		06/16/94	TC/PI	4,200	327	4,056	321	98	98	478	8,118	15.5	22.0	18/22	962	NM	N/Y
46	Ingersoll KVS-412		08/28/94	TC/DI	2,000	330	1,764	330	88	100	261	8,950	15.3	18.0	12	779	NM	Y/Y
47	Ingersoll KVS-412		08/29/94	TC/DI	2,000	330	1,840	332	91	101	272	8,978	15.3	18.0	12	779	NM	Y/Y
48	Ingersoll KVS-412		08/29/94	TC/DI	2,000	330	1,830	331	91	100	266	8,821	15.3	18.0	12	779	860-950	Y/Y
4-stroke, rich-burn																		
49	Ingersoll KVG-103 (A)		10/29/93	NA	1,100	330	NM	327	NM	99	NM	NM	15.3	18.0	4	945	NM	N/N
50	Ingersoll KVG-103 (A)		10/29/93	NA	1,100	330	NM	327	NM	99	NM	NM	15.3	18.0	4	945	NM	N/N
51	Ingersoll KVG-103 (A)		10/30/93	NA	1,100	330	NM	291	NM	88	NM	NM	15.3	18.0	4	798	NM	N/N
52	Ingersoll KVG-103 (A)		10/30/93	NA	1,100	330	NM	328	NM	99	NM	NM	15.3	18.0	4	940	NM	N/N
53	Ingersoll KVG-103 (B)		10/31/93	NA	1,100	330	NM	328	NM	99	NM	NM	15.3	18.0	4	775	NM	N/N
54	Ingersoll KVG-103 (B)		10/31/93	NA	1,100	330	NM	328	NM	99	NM	NM	15.3	18.0	4	842	NM	N/N
55	Waukesha L7042GU	NSCR	08/23/94	NA	896	1,000	692	809	95	81	88	7,717	9.4	8.5	22	796	NM	Y/Y
56	Waukesha L7042GU	NSCR	08/23/94	NA	896	1,000	671	811	92	81	85	7,646	9.4	8.5	22	796	NM	Y/Y
57	Waukesha L7042GU	pre-NSCR	08/23/94	NA	896	1,000	644	813	88	81	83	7,809	9.4	8.5	22	796	NM	Y/Y
58	Waukesha L7042GU	pre-NSCR	08/24/94	NA	896	1,000	362	779	52	78	55	9,185	9.4	8.5	22	641	NM	Y/Y

a CO cat = carbon monoxide oxidation catalyst; NSCR = nonselective catalytic reduction.

b TC = turbocharged; PS = piston scavenged; BS = blower scavenged; PI = Port Injection; DI = Direct Injection; NA = naturally aspirated.

c For all engines except the LSV-16 engines, horsepower was measured directly by an engine analyst and is accurate to within ±5 percent. For the LSV-16 engines, hp was recorded from the station's control system.

d NM = not measured

Table 5-3

Summary of Engine Emissions Data

Engine Test ID	Engine Make/Model	Exhaust Emission Controls (a)	Date of Test	Emissions Data (ppmvd @ 15% O2) NOx	CO	THC	CH2O	Emissions Data (g/hp-hr) NOx	CO	THC	CH2O	O2 (%)	Ambient Conditions Ambient Temp (°F)	Barometric Pressure (in. Hg)	Relative Humidity (%)
2-Stroke, clean-burn															
1	Clark TCV-10		11/03/93	73	601	2,960	49	NM (b)	NM	NM	NM	17.1	NM	NM	NM
2	Clark TCV-10		11/03/93	69	628	3,168	51	NM	NM	NM	NM	17.1	NM	NM	NM
3	Cooper 10V-275		11/01/93	232	155	843	13	NM	NM	NM	NM	16.9	NM	NM	NM
4	Cooper 10V-275		11/02/93	197	138	727	17	NM	NM	NM	NM	16.2	NM	NM	NM
5	Cooper GMVC-10C	CO cat	08/26/94	36	14	1,837	5.3	0.4	0.1	7.9	0.04	15.5	86	29	43
6	Cooper GMVC-10C	CO cat	08/26/94	47	15	1,559	8.8	0.5	0.1	6.3	0.07	15.4	84	29	48
7	Cooper GMVC-10C	pre-CO cat	08/25/94	43	179	1,446	22	0.5	1.3	5.9	0.17	15.5	85	29	38
8	Cooper GMVC-10C	pre-CO cat	08/26/94	37	195	1,817	24	0.5	1.5	7.8	0.19	15.4	89	29	41
9	Cooper GMVC-10C	pre-CO cat	08/30/94	22	260	2,317	28	0.3	2.0	10.2	0.23	15.5	84	29	45
10	Cooper GMVC-10C	pre-CO cat	08/30/94	39	186	1,624	16	0.5	1.4	6.8	0.13	15.3	85	29	29
2-Stroke, lean-burn															
11	Clark BA-5		11/04/94	805	76	NM	16	14.9	0.9	NM	0.20	14.2	62	26	63
12	Clark BA-5		11/04/94	367	94	NM	23	7.3	1.1	NM	0.29	14.9	51	26	93
13	Clark BA-5		11/05/94	1,195	83	943	16	22.3	0.9	6.1	0.20	14.3	62	29	29
14	Clark HBA-5		11/04/94	559	258	NM	38	10.3	2.9	NM	0.45	15.7	51	26	92
15	Clark HBA-5		11/05/94	1,053	202	1,457	27	18.4	2.2	8.9	0.31	15.1	71	26	23
16	Cooper GMVA-10		11/11/94	302	70	2,856	19	4.6	0.6	15.0	0.19	15.1	65	27	46
17	Cooper GMVA-10		11/12/94	368	63	1,360	17	5.1	0.5	6.5	0.15	14.6	57	26	86
18	Cooper GMVA-10		11/12/94	358	62	1,311	17	4.9	0.5	6.2	0.15	14.5	59	26	83
19	Cooper GMVC-10 (A)		11/10/94	560	71	1,044	18	7.9	0.6	5.2	0.17	15.0	53	27	47
20	Cooper GMVC-10 (A)		11/10/94	620	69	1,000	18	8.8	0.6	4.9	0.16	14.8	58	27	36
21	Cooper GMVC-10 (A)		11/11/94	306	84	1,538	25	5.2	0.9	9.1	0.27	15.5	53	27	63
22	Cooper GMVC-10 (B)		11/15/94	380	77	1,219	18	5.0	0.6	5.6	0.15	15.3	57	27	26
23	Cooper GMVC-10 (B)		11/15/94	326	82	1,384	20	4.4	0.7	6.5	0.18	15.3	55	27	29
24	Cooper GMVC-10 (B)		11/15/94	1,338	53	903	14	17.0	0.4	4.0	0.11	14.6	55	27	29
25	Cooper GMVC-10 (B)		11/15/94	857	63	1,012	16	11.0	0.5	4.5	0.14	14.9	50	27	34
26	Cooper GMVC-10 (B)		11/15/94	745	64	1,027	15	9.6	0.5	4.6	0.13	14.9	51	27	36
27	Cooper GMWC-10		11/14/94	1,226	107	1,951	29	16.7	0.9	9.2	0.25	15.1	55	27	43
28	Cooper GMWC-10		11/14/94	1,432	95	1,895	27	19.3	0.8	8.9	0.23	15.0	64	27	24
29	Cooper GMWC-10		11/14/94	1,606	108	1,739	28	21.5	0.9	8.1	0.25	14.7	62	27	26
30	Cooper GMWC-10		11/14/94	1,971	111	1,756	29	26.6	0.9	8.3	0.25	14.6	66	27	21
31	Cooper GMWC-10		11/14/94	1,464	104	1,902	28	19.8	0.9	8.9	0.25	15.1	51	27	53

a CO cat = carbon monoxide oxidation catalyst; NSCR = nonselective catalytic reduction.

b NM = not measured.

Table 5-3

Summary of Engine Emissions Data (Continued)

				Emissions Data									Ambient Conditions		
				(ppmvd @ 15% O2)				(g/hp-hr)							
Engine Test ID	Engine Make/Model	Exhaust Emission Controls (a)	Date of Test	NOx	CO	THC	CH2O	NOx	CO	THC	CH2O	O2 (%)	Ambient Temp (°F)	Barometric Pressure (in. Hg)	Relative Humidity (%)
4-Stroke, clean-burn															
32	Ingersoll KVS-412		08/27/94	43	216	1,336	21	0.6	1.9	6.9	0.20	11.3	91	29	33
33	Ingersoll KVS-412		08/27/94	37	240	2,308	28	0.6	2.2	12.0	0.28	11.4	86	29	35
34	Ingersoll KVS-412		08/30/94	37	240	1,854	28	0.6	2.2	9.7	0.27	11.2	86	29	41
35	Ingersoll KVS-412		08/30/94	33	263	2,534	31	0.5	2.4	13.4	0.31	11.5	78	29	56
36	Ingersoll KVS-412		08/30/94	40	240	1,317	27	0.6	2.1	6.7	0.26	11.1	89	29	38
37	Ingersoll KVS-412		08/30/94	40	232	1,631	26	0.6	2.0	8.0	0.23	11.3	73	29	66
38	Ingersoll KVS-412		08/30/94	31	230	2,964	31	0.5	2.3	16.7	0.32	11.6	82	29	47
39	Ingersoll KVS-412		08/30/94	35	205	2,033	27	0.5	2.0	11.2	0.27	11.4	85	29	43
40	Ingersoll KVS-412		08/30/94	34	278	2,305	31	0.5	2.5	11.9	0.30	11.3	90	29	36
4-Stroke, lean-burn															
41	Cooper LSV-16 (A)		06/15/94	850	111	1,002	16	11.1	0.9	4.6	0.14	9.4	83	29	73
42	Cooper LSV-16 (A)		06/15/94	442	132	1,097	19	6.0	1.1	5.2	0.17	9.9	80	29	87
43	Cooper LSV-16 (B)		06/15/94	154	124	1,540	20	2.2	1.1	7.6	0.18	11.0	84	30	72
44	Cooper LSV-16 (B)		06/16/94	785	131	1,105	16	10.2	1.0	5.0	0.13	9.3	89	29	58
45	Cooper LSV-16 (B)		06/16/94	671	134	1,167	17	8.7	1.1	5.3	0.15	9.5	80	29	78
46	Ingersoll KVS-412		08/28/94	1,566	64	517	NM	22.6	0.6	2.6	NM	8.3	94	29	28
47	Ingersoll KVS-412		08/29/94	1,454	68	524	NM	21.0	0.6	2.6	NM	8.6	77	29	52
48	Ingersoll KVS-412		08/29/94	1,567	59	493	4.7	22.3	0.5	2.4	0.04	8.3	91	29	32
4-stroke, rich-burn															
49	Ingersoll KVG-103 (A)		10/29/93	492	1,879	94	1.2	NM	NM	NM	NM	4.3	NM	NM	NM
50	Ingersoll KVG-103 (A)		10/29/93	475	2,123	95	1.3	NM	NM	NM	NM	4.1	NM	NM	NM
51	Ingersoll KVG-103 (A)		10/30/93	537	1,273	114	1.4	NM	NM	NM	NM	2.0	NM	NM	NM
52	Ingersoll KVG-103 (A)		10/30/93	562	1,466	84	1.2	NM	NM	NM	NM	4.8	NM	NM	NM
53	Ingersoll KVG-103 (B)		10/31/93	917	47	335	7.1	NM	NM	NM	NM	10.1	NM	NM	NM
54	Ingersoll KVG-103 (B)		10/31/93	1,015	39	132	5.9	NM	NM	NM	NM	8.8	NM	NM	NM
55	Waukesha L7042GU	NSCR	08/23/94	2.3	19	217	<0.01	0.1	0.3	1.6	<0.0002	0.04	87	30	35
56	Waukesha L7042GU	NSCR	08/23/94	2.4	20	228	<0.01	0.1	0.3	1.7	<0.0002	0.1	87	29	40
57	Waukesha L7042GU	pre-NSCR	08/23/94	819	1,070	381	6.6	18.3	14.5	3.0	0.10	0.4	74	30	65
58	Waukesha L7042GU	pre-NSCR	08/24/94	730	772	504	7.0	10.8	7.0	2.6	0.07	0.4	87	30	37

a CO cat = carbon monoxide oxidation catalyst; NSCR = nonselective catalytic reduction.

b NM = not measured.

expressed in units of grams per horsepower-hour (g/hp-hr) could not be calculated for these engines. Emissions data for air toxics other than formaldehyde are presented in Section 6 and Appendix D.

To indicate the variability in emissions for a typical test condition, an example time trace of measured formaldehyde, O_2, NO_X, THC, and CO concentrations is shown in Figure 5-1. The data were collected at 1-minute intervals on a Clark TCV-10 engine (Engine Test ID No. 1 in Table 5-3). For formaldehyde, the measured concentrations varied between 35 to 38 ppmv and averaged 37 ppmv (all at measured O_2). The relative standard deviation (RSD) value was calculated at about 2 percent.

5.2 Effect of Engine Design on Formaldehyde Emissions

5.2.1 Effect of Engine Family

The formaldehyde emissions data, expressed in parts per million by volume, dry basis (ppmvd) at 15 percent O_2 and in g/hp-hr, are presented in Figures 5-2 and 5-3 for each engine, segregated by family. Measurements made downstream of the catalyst on the Cooper-Bessemer GMVC-10C (Engine Test ID Nos. 5 and 6 in Tables 5-2 and 5-3) and the Waukesha L7042GU (Test ID Nos. 55 and 56) engines are not included in the figure. The differences in formaldehyde emissions within engine families reflect the effect of differences in engine design, operating parameters, and maintenance history. The effects of such variables are discussed in subsequent sections, and the differences in formaldehyde emissions between engine families are discussed in this section. When calculating average formaldehyde emission values for engine families, the data collected when the engines were operated at "normal" operating conditions ($\geq$90 percent of rated torque, $\geq$95 percent of rated rpm, and normal ignition timing) were considered.

The three 2-stroke clean-burn engines are equipped with PCCs for NO_X emissions control. The formaldehyde emissions varied from 17 to 51 ppmv.[a] The highest formaldehyde emission levels of 51 ppmv and 49 ppmv were measured on a Clark TCV-10 engine (Test ID Nos. 1 and 2) during Campaign 1. To minimize NO_x

---

[a] All emission concentrations presented in Section 5.0 are on a dry basis and adjusted to 15 percent O_2, unless otherwise noted.

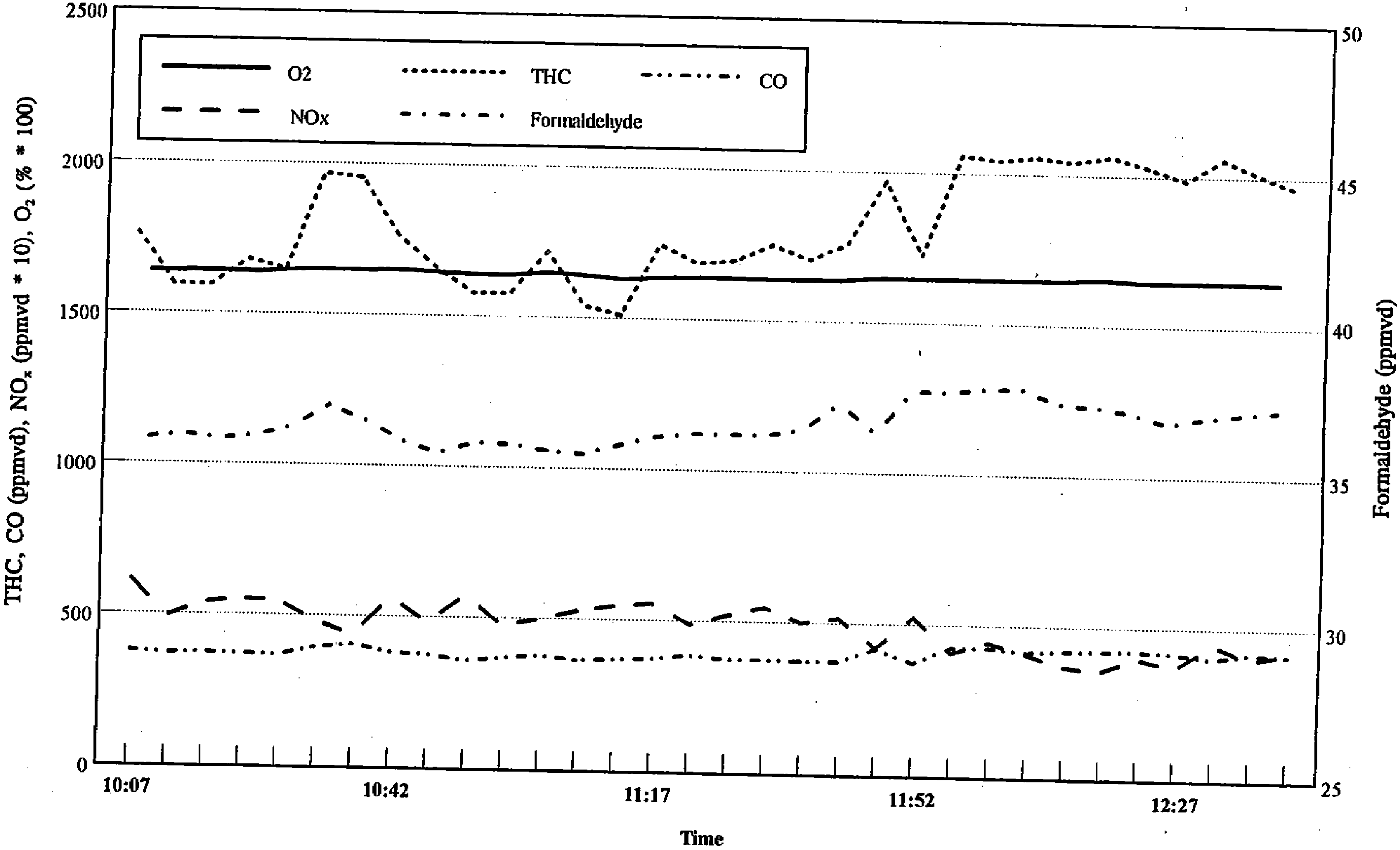


Figure 5-1. Example Time Trace of Measured Emissions Data

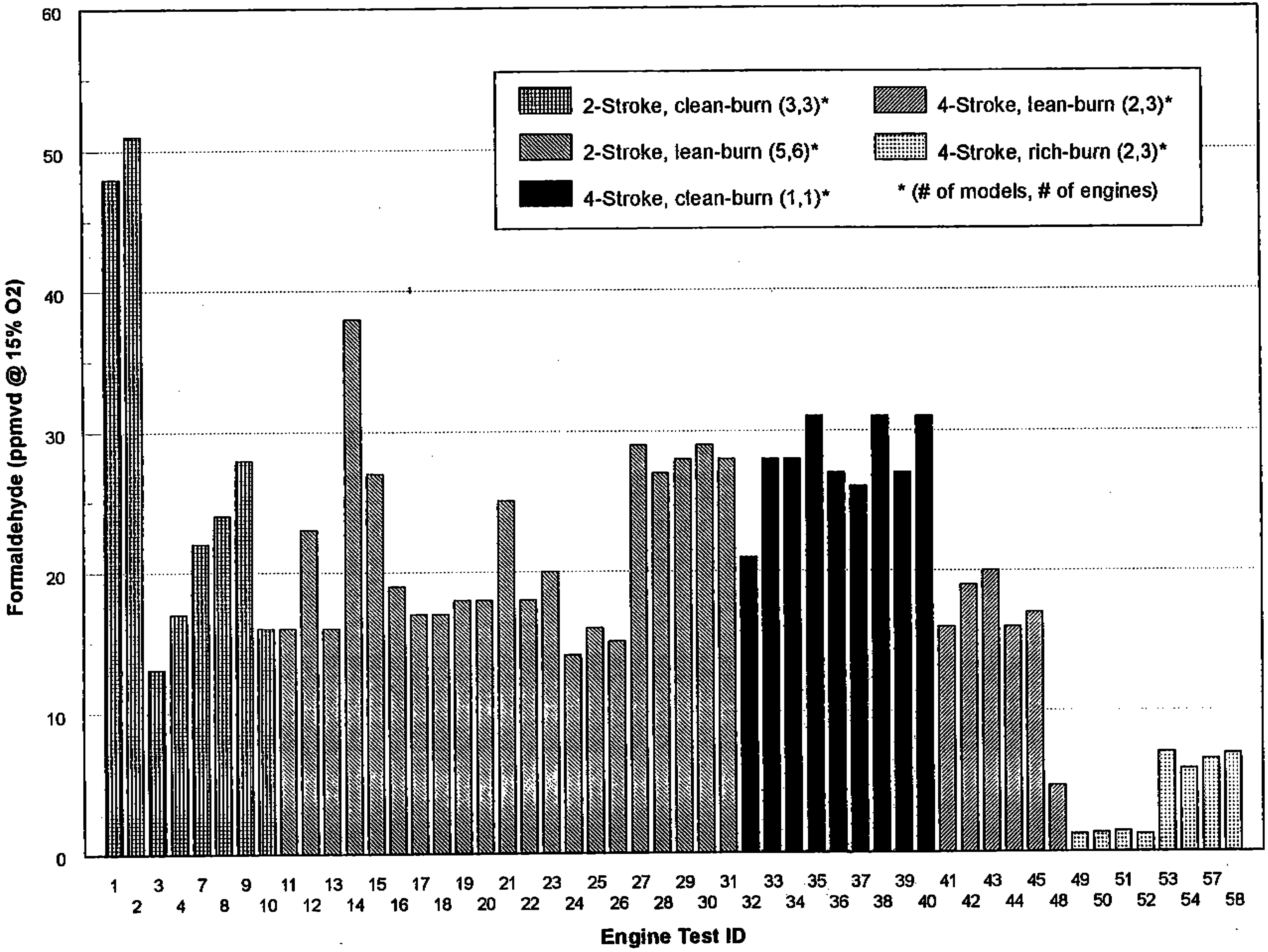


Figure 5-2. Formaldehyde Emission Concentrations

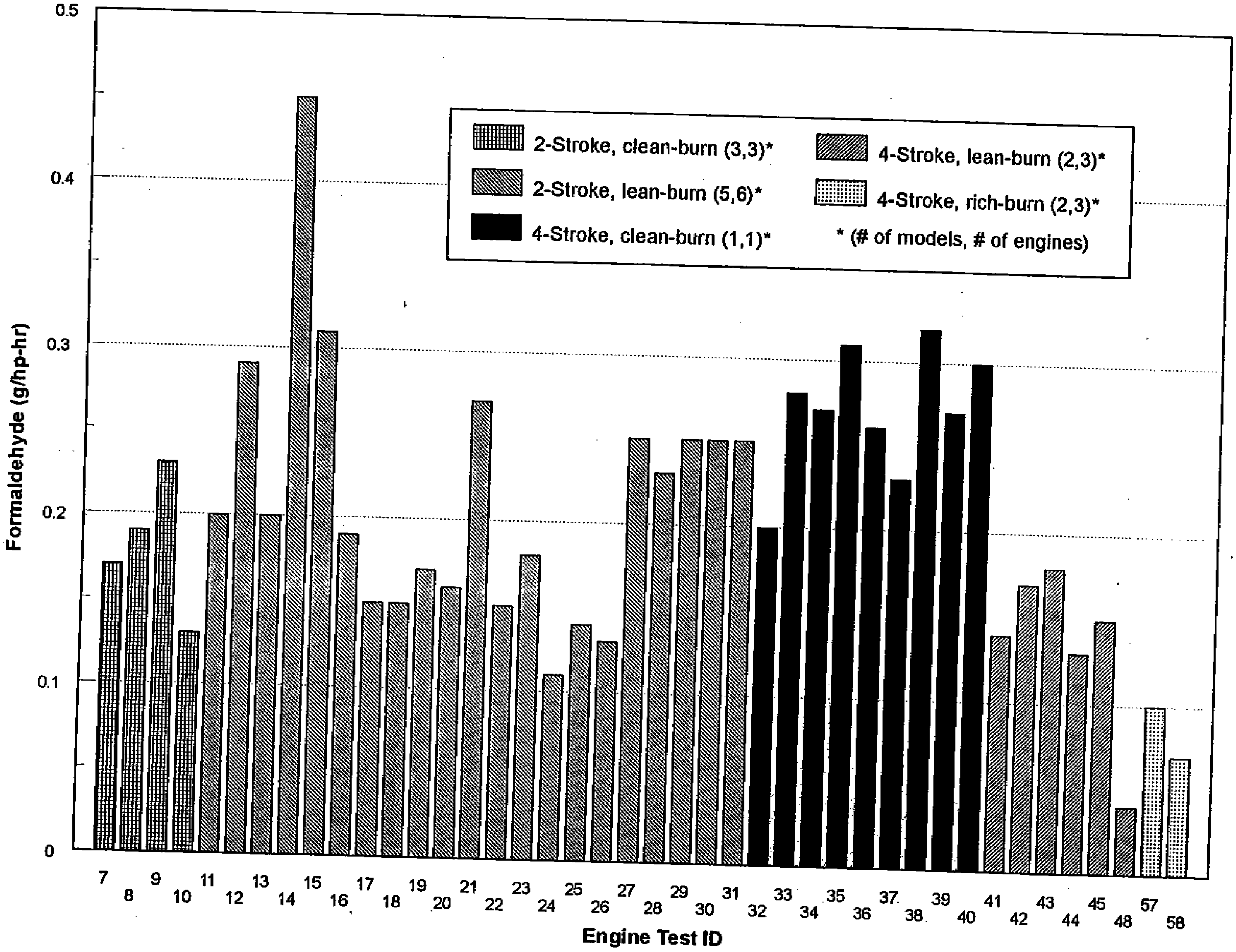


Figure 5-3. Formaldehyde Emission Factors

emissions, station personnel operate this engine at A/F ratios that are significantly higher than the manufacturer's recommended values. By operating under extremely lean conditions, mean combustion temperatures are reduced, and flame quenching is increased relative to standard operation. Both of these conditions result in a greater proportion of unoxidized and partially oxidized fuel (including formaldehyde) exiting the cylinder.[14] Excluding this data point, the average formaldehyde emissions for the engines operating under normal conditions was 21 ppmv (0.16 g/hp-hr).

The 2-stroke lean-burn engine family data include measurements made on six engines representing four piston-scavenged, one blower-scavenged, and three turbocharged engine models. The formaldehyde emissions varied between 14 and 38 ppmv. The variability in the data reflects the effect of differences in engine design, maintenance, and operating conditions. The formaldehyde emission concentrations for the engines operating under normal conditions averaged 19 ppmv (0.18 g/hp-hr).

Only one 4-stroke clean-burn engine (Ingersoll-Rand KVS-412) was tested. Formaldehyde emissions varied from 21 to 31 ppmv during the nine runs conducted on the engine. Under normal operating conditions, formaldehyde emissions averaged 26 ppmv (0.23 g/hp-hr).

Formaldehyde emissions for the three 4-stroke lean-burn engines varied from 5 to 20 ppmv. Formaldehyde emissions for the two Cooper-Bessemer LSV-16 engines were similar at 16-20 ppmv. The 5 ppmv level was measured on an Ingersoll-Rand KVS-412 engine. Differences in the fuel injection mechanism on the two models were the likely cause of the divergent emissions levels. The LSV-16 engines are port-injected, which allows some premixing of the fuel and air prior to the combustion cylinder. The KVS-412 model is direct-injected. Direct-injection leads to large temperature and concentration gradients between the combustion zone and the remainder of the cylinder. The combustion zone is effectively fuel-rich and is likely to exhibit high temperatures more characteristic of rich-burn engines. The premixing of fuel and air in the LSV-16 engines tends to reduce temperature gradients in the combustion cylinder and leads to lower bulk gas temperatures. As discussed in Section 5.3.2, formaldehyde emissions generally increase as bulk cylinder temperatures decrease. The average formaldehyde levels under normal operating conditions for the port-injected and direct-injected 4-stroke lean-burn engines tested are 17.6 ppmv (0.16 g/hp-hr) and 5 ppmv (0.04 g/hp-hr), respectively.

Among the five engine families, the lowest formaldehyde emissions were measured for the 4-stroke rich-burn engines. This is likely due to higher combustion and exhaust temperatures associated with the lower A/F ratios characteristic of this class of engines. Assuming that unoxidized and partially oxidized fuel in poorly mixed zones (e.g., trapped within crevice volumes) govern formaldehyde emissions, the higher bulk temperatures characteristic of the lower A/F ratio is likely sufficient to complete oxidation of the unoxidized pockets upon release/mixing with the bulk gas volumes. The formaldehyde emissions varied between 1 and 7 ppmv and averaged 4 ppmv (0.10 g/hp-hr). Note that the average value for this engine family was calculated at reduced torque and reduced speed due to limited data availability at full torque, full speed conditions.

The ranges and average values of the formaldehyde emissions data suggest that differences might exist among the various engine families. To determine whether these differences are statistically significant, a least significant difference (LSD) test was performed on a data set containing the formaldehyde measurements at normal conditions for the 2-stroke clean-burn, 2-stroke lean-burn, and the 4-stroke lean-burn engine families. The 4-stroke clean-burn and 4-stroke rich-burn engine families were excluded from this analysis because of the minimal data available for these families. In the LSD test, the smallest difference that would be declared significant is computed and the absolute value of each observed difference is compared to it.[25] The results of this analysis for the three engine families showed that, at a 95 percent confidence level, the average formaldehyde emission values are not statistically different from each other when the ppmv emission data were analyzed. For the g/hp-hr data, the LSD test was only performed on the 2- and 4-stroke lean-burn families because only one engine in the 2-stroke clean-burn family had g/hp-hr data. The results of this test also showed no significant difference between the 2- and 4-stroke lean-burn engine families at a 95 percent confidence level. However, these results are influenced by differences in the number of engines/models tested and in engine operating conditions, and may change if more data become available for the statistical analysis.

5.2.2 Effect of Engine Cylinder Bore and Stroke

To assess the effect of engine cylinder bore and stroke, the formaldehyde emissions from the Cooper GMVC-10 and the larger bore GMWC-10 engines are plotted as a function of torque in Figure 5-4. The data were measured on

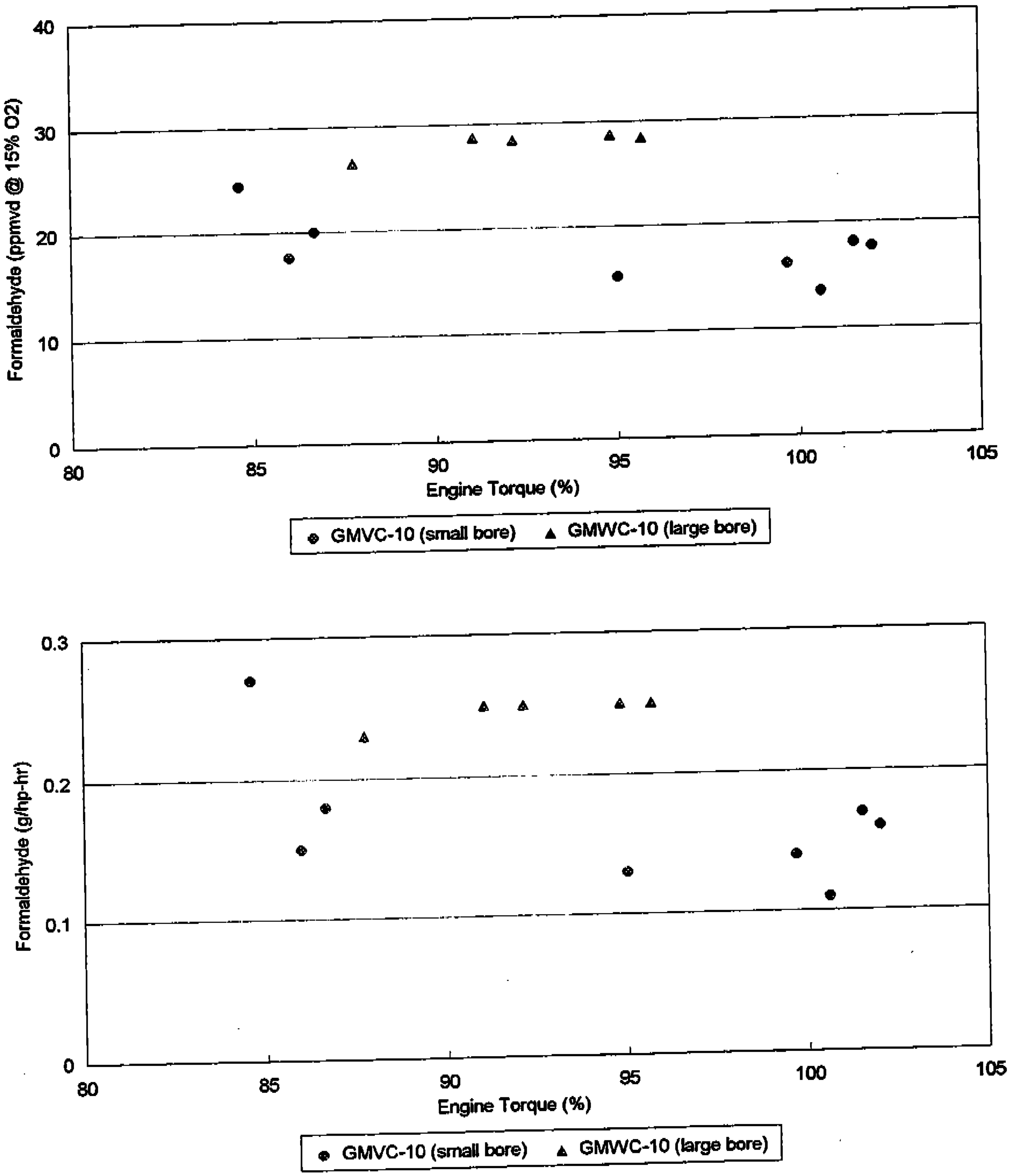


Figure 5-4. Effect of Cylinder Bore and Stroke on Formaldehyde Emissions

two GMVC-10 (Test ID Nos. 19 - 26) engines and one GMWC-10 (Test ID Nos. 27 - 31) engine. The GMWC-10 engine has a larger displacement (bore = 18 in.; stroke = 20 in.) than the GMVC-10 (bore = 14 in.; stroke = 14 in.). Both engine models are equipped with a turbocharger mounted in-series with a blower. All three engines were tested at the same station and were fueled from the same header. Consequently, the fuel composition should be the same for both engine models. In addition, the two models were operated at similar A/F ratios (exhaust O_2 = 14.6-15.5 percent for GMVC-10 and 14.6-15.1 percent for GMWC-10).

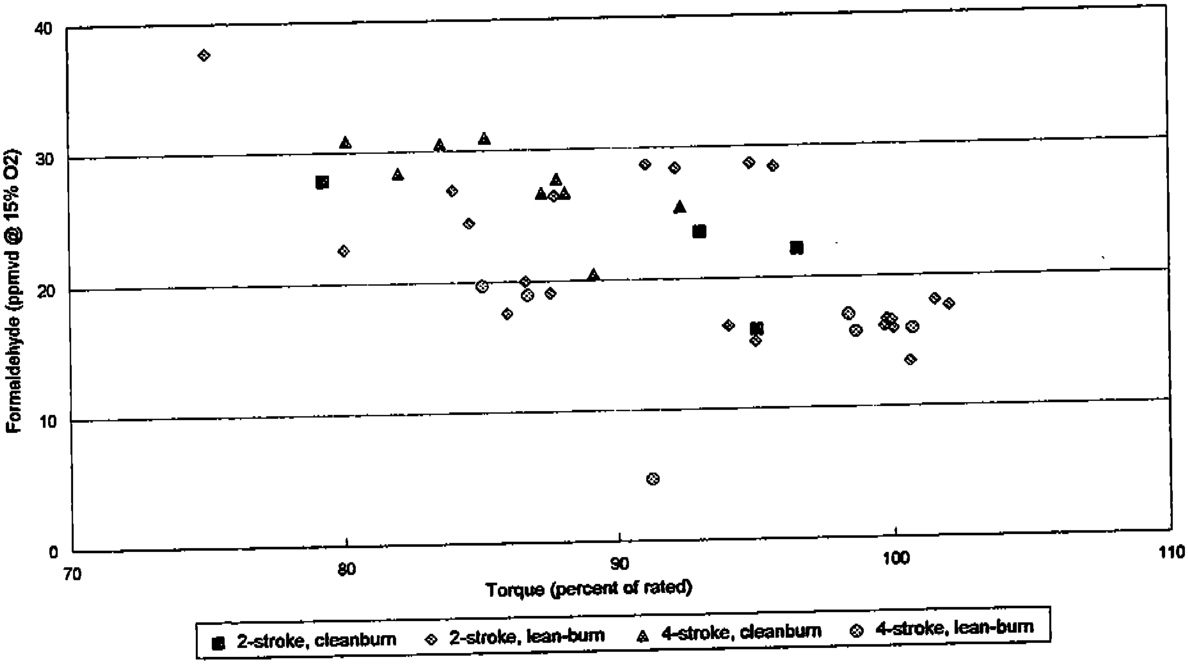
As seen in Figure 5-4, formaldehyde emissions are consistently higher for the larger bore GMWC-10 engine. Assuming formaldehyde formation along the cylinder wall and in cylinder crevices predominates, formaldehyde emissions would be expected to be lower for the larger-bore engines because of the lower surface to volume (S/V) ratio for these engines. The lower S/V ratio provides a relatively smaller surface area to cool the bulk gas, which is expected to result in a smaller fraction of the fuel-air mixture to remain unoxidized on the cylinder walls due to flame quenching. However, bulk mixing effects may also impact formaldehyde emissions. Reduced mixing between air and fuel in the combustion chamber may lead to a greater relative volume of unburned or partially oxidized fuel pockets exiting the engine cylinder. As shown in Table 5-3, the exhaust THC emissions are higher for the GMWC-10 than for the GMVC-10 engine.

To study the effect of cylinder geometry, correlations between formaldehyde emissions and various engine design parameters were examined. These parameters included the cylinder crevice volume/displacement volume ratio, the cylinder surface area/displacement volume ratio, and the cylinder stroke/bore ratio. However, due to a lack of detailed design data on engine/cylinder geometry for each engine, firm conclusions on the effect of these variables on formaldehyde emissions could not be made.

5.3 Effect of Engine Operating Conditions on Formaldehyde Emissions

5.3.1 Effect of Torque

Figure 5-5 shows the variation of formaldehyde emissions with engine torque. Only data measured at ≥95 percent of rated rpm and at normal ignition timing are shown in the figure. Since there are no full-speed data, the 4-stroke rich-burn engine



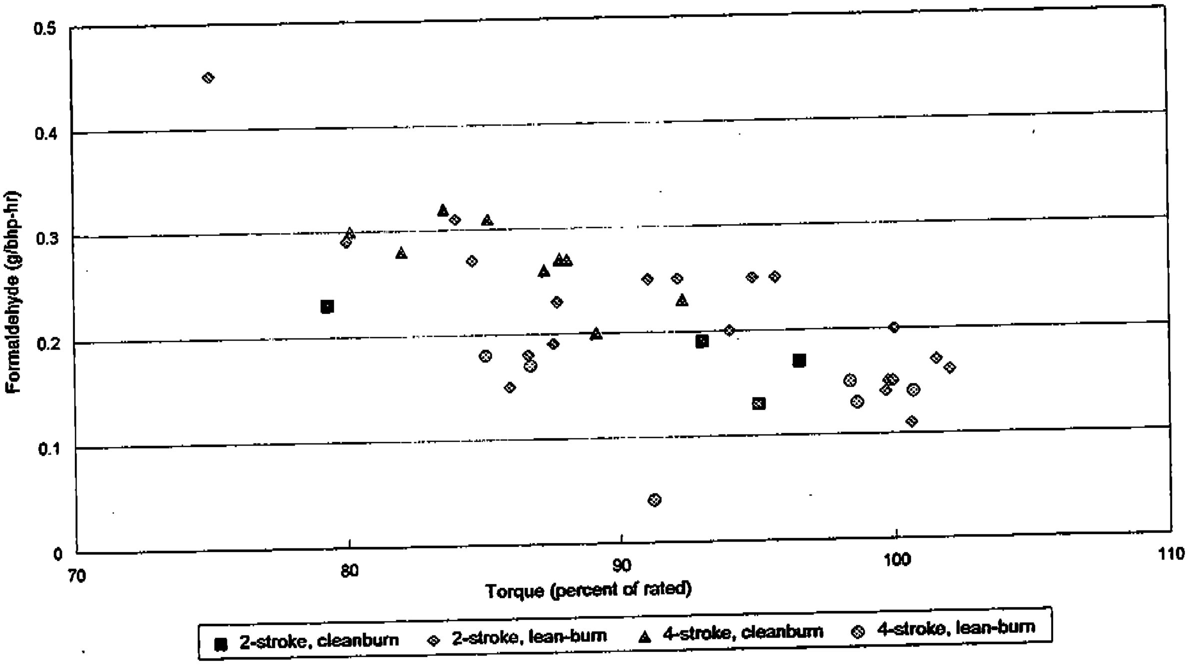


Figure 5-5. Effect of Torque on Formaldehyde Emissions

family is not represented on the figure. Although there is significant scatter in the data, the figure shows the expected trend of an increase in formaldehyde emissions as engine torque decreases. It is likely that the increase in formaldehyde emissions at reduced torque shown in Figure 5-5 is due to lower cylinder bulk gas temperatures, which reduces the likelihood that intermediate species like formaldehyde will be oxidized before being exhausted from the cylinder. For example, when torque was reduced from 100 to 87 percent on one of the Cooper GMWC-10 engines at Campaign 6 (Test ID Nos. 23 and 25), average cylinder exhaust temperatures decreased by 20°F, and formaldehyde concentrations rose from 16 to 20 ppmv.

To determine whether there is a statistically significant difference between the average formaldehyde emissions measured at torque levels greater than and less than 90 percent of rated torque, a *t*-test was performed between average formaldehyde levels for the high (≥90 percent) and low (<90 percent) torque cases. To calculate the averages, only data collected at engine speeds ≥95 percent of rated rpm and at normal ignition timing were used. Average values were calculated for the entire data set (all five engine families) and for a subset of these data containing the 2-stroke lean-burn engines. Similar tests were not performed within other engine families because of the small sample size in these cases. The *t*-test was performed both on the formaldehyde emissions data expressed in ppmv and in g/hp-hr. A 95 percent confidence level was assumed in each case.

The *t*-test results indicated that for both the entire data set and the 2-stroke lean-burn data subset, the differences between the high and low torque cases on a g/hp-hr basis are significant at a 95 percent confidence level. The *t*-test also indicated a significant difference between the high and low torque cases across the entire data set on a ppmv basis at a 95 percent confidence level. For the 2-stroke lean-burn concentration data, the difference is statistically significant at an 87 percent confidence level.

5.3.2 Effect of Cylinder Temperature

No direct measure of bulk cylinder gas temperature was available; therefore, cylinder exhaust temperature was used as a surrogate. As mentioned in Section 5.1, an analysis of cylinder exhaust temperature could be affected by differences in cooling system performance, thermocouple locations, and by measurement errors among the engines. However, these effects are minimized when considering the effects of cylinder exhaust temperature on an individual engine. The engine used for this analysis was the 4-stroke Ingersoll-Rand KVS-412 clean-burn engine (Test ID Nos. 32-40 in Tables 5-2 and 5-3).

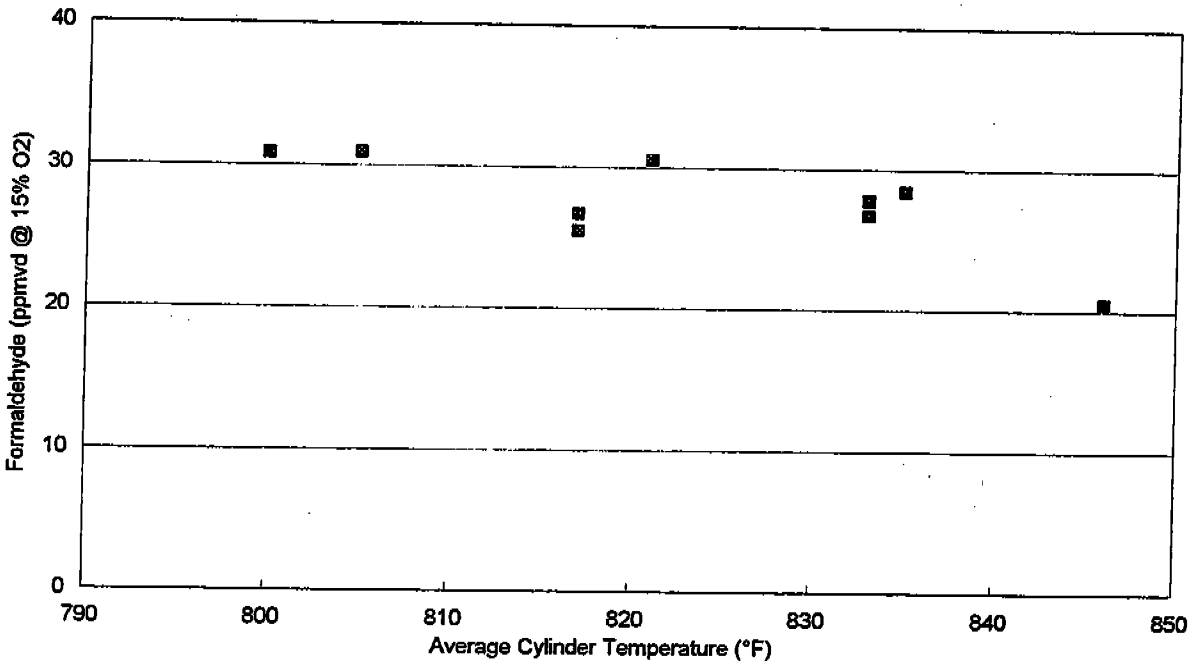
In Figure 5-6, formaldehyde emissions are plotted against the average cylinder exhaust temperatures for the Ingersoll-Rand KVS-412 clean-burn engine. As shown in the figure, formaldehyde emissions tend to decrease as the average cylinder exhaust temperature increases, indicating that there is greater oxidation of formaldehyde at higher temperatures. Higher cylinder exhaust temperatures, which are indicative of higher bulk temperatures, increase the likelihood for unoxidized fuel trapped in crevices or in the oil layers along the cylinder walls to be completely oxidized when it is released and mixed with the bulk gas during expansion and exhaust blowdown.

5.3.3 Effect of A/F Ratio

Due to station control system limitations, no attempt was made to vary A/F ratio directly during Campaigns 1 through 6; however, many operating and design parameters that were evaluated influenced A/F ratios. The five engine families each have a characteristic A/F ratio operating range. In addition, variables such as torque and rpm impact A/F ratios in some engines.

In Figure 5-7, formaldehyde emissions are plotted against exhaust O_2 levels for all of the test runs. Exhaust O_2 levels were used as a surrogate measure of the actual A/F ratio in the combustion cylinder due to measurement limitations. Although scavenging air rates influence the measured O_2 levels, the impact does not significantly obscure general trends in the data.

As shown in the figure, formaldehyde emissions increase with increasing exhaust O_2 levels. Higher A/F ratios increase the heat capacity of the combustion mixture in the cylinder, and lead to reduced bulk gas temperatures. As A/F ratios increase and bulk gas temperatures decrease, the formaldehyde destruction reaction rates are slowed. At extremely high A/F ratios, flame quenching may occur, resulting in significant quantities of partially oxidized fuel (frequently in the form of formaldehyde) being emitted from the engine.



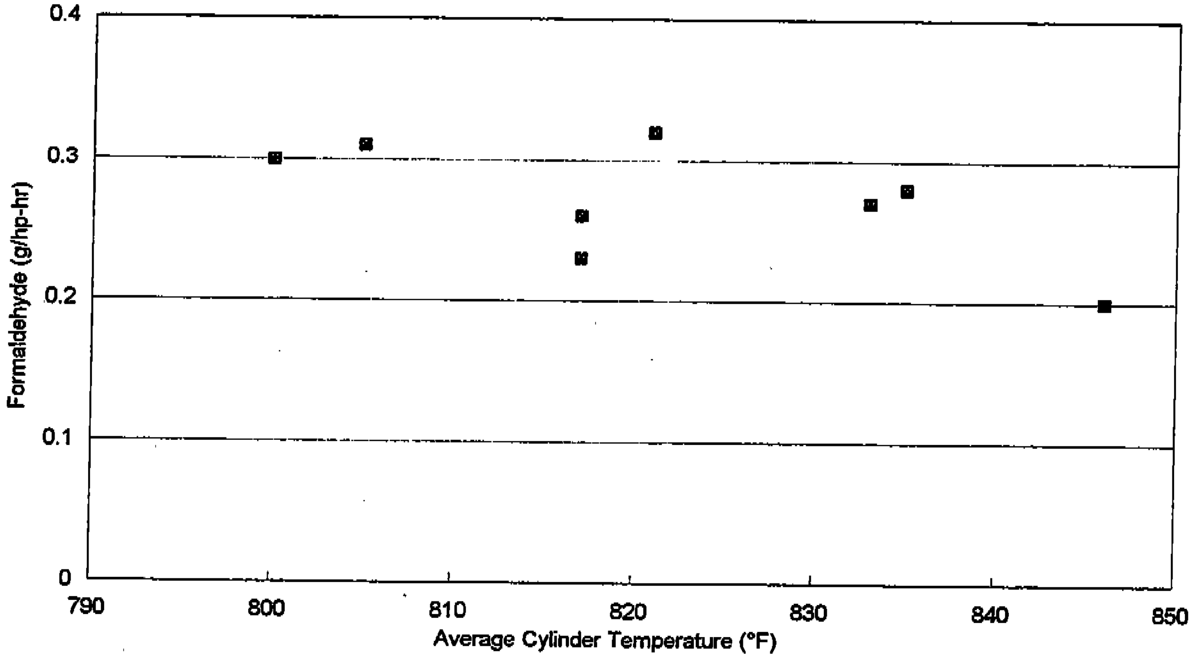


Figure 5-6. Effect of Engine Cylinder Temperature on Formaldehyde Emissions

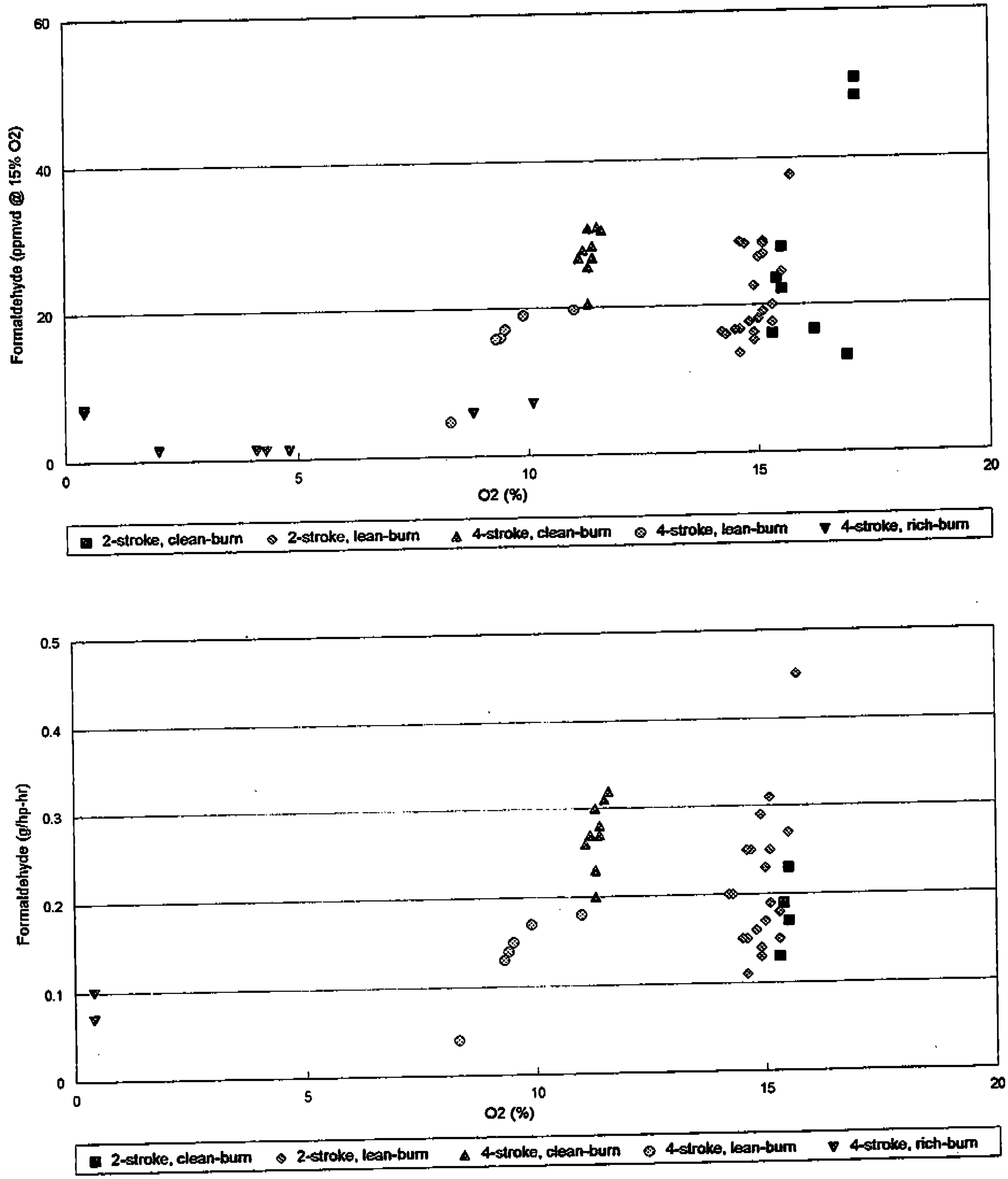


Figure 5-7. Formaldehyde vs. A/F Ratio

5.3.4 Effect of Ignition Timing

Limited parametric runs were conducted on one Ingersoll-Rand KVS-412 during Campaign 4 to evaluate the impact of torque and ignition timing on emissions (Test ID Nos. 34-40). A time trace of the formaldehyde and THC concentrations during these runs is shown in Figure 5-8. Normal operation for the unit was at an ignition timing of 8 degrees before top-dead-center (btdc). Measurements were collected at the base level, and at 3 degrees each of timing advance and timing retard (to 11° btdc and 5° btdc, respectively). Figure 5-9 displays the run-averaged formaldehyde and THC measurement data versus torque.

Both figures indicate only slight changes (1-2 ppmv decrease) in formaldehyde emissions when timing is retarded from 8° btdc to 5° btdc. A slightly larger decrease (~10 percent) was observed in advancing the timing from 8° btdc to 11° btdc; formaldehyde concentrations changed from 31 to 27 ppmv (45 to 41 ppmv at actual O_2 levels). Based on this limited data, formaldehyde levels do not appear to be strongly influenced by ignition timing.

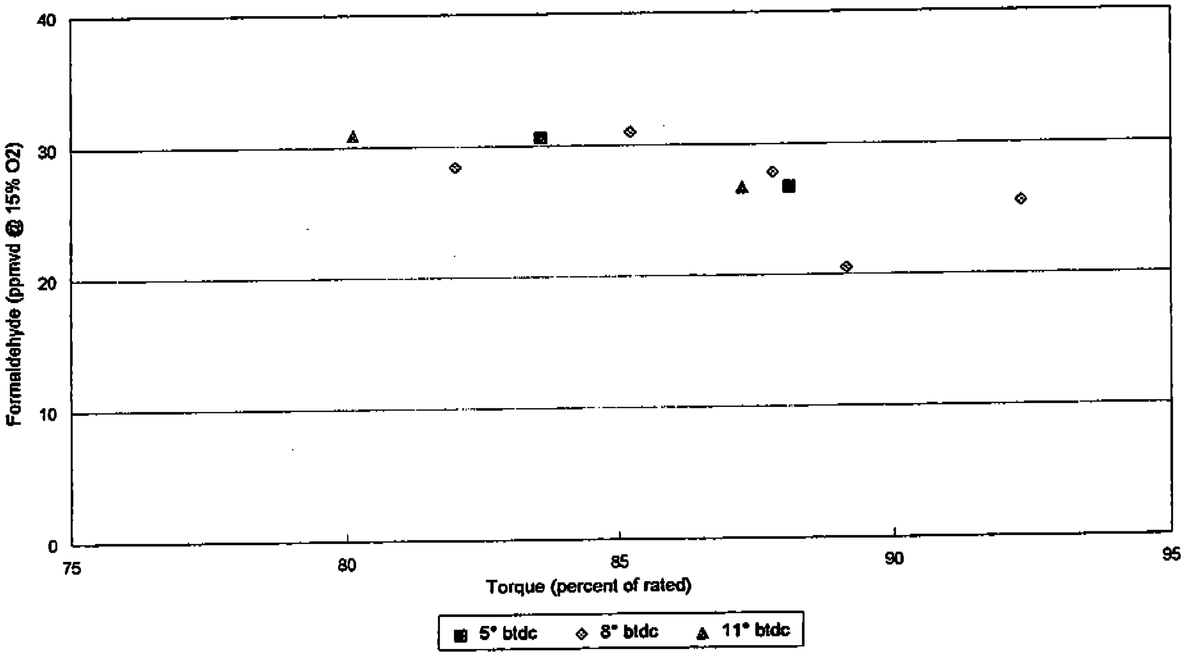
5.3.5 Combined Effect of Engine Design and Operating Conditions on Formaldehyde Emissions

Of the parameters evaluated, formaldehyde emissions appear to be the most strongly correlated with engine torque. In an attempt to identify a stronger relationship, the effect of torque was combined with other operating and design parameters (i.e., speed, ignition timing, cylinder exhaust temperature) to evaluate correlations with formaldehyde levels. However, the range of conditions tested for these other variables was too small to distinguish the influence of the parameter from normal engine-to-engine variability. A separate study designed to evaluate parametric relationships between engine operation and formaldehyde emissions is recommended.

5.4 Effect of Emission Controls

5.4.1 Effect of Low NO_x Combustion Designs

A combination of a PCC, improved mixing, and increased A/F ratio is used in many clean-burn engine designs to reduce NO_x emissions. The PCC provides a



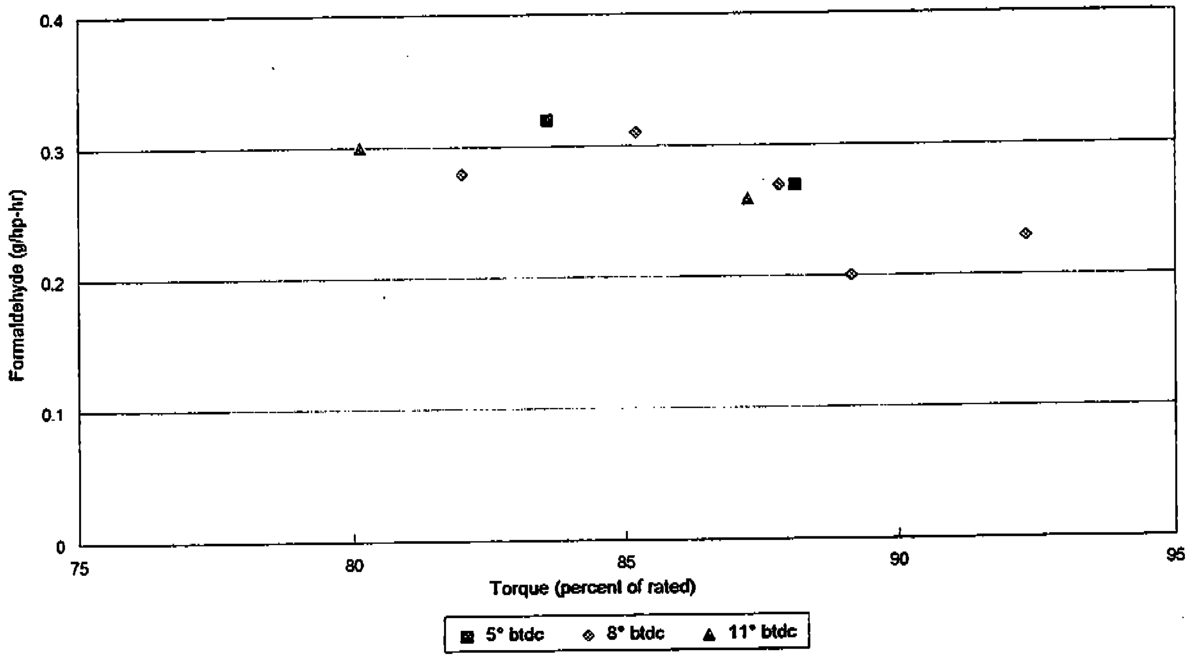


Figure 5-8. Effect of Ignition Timing on Formaldehyde Emissions

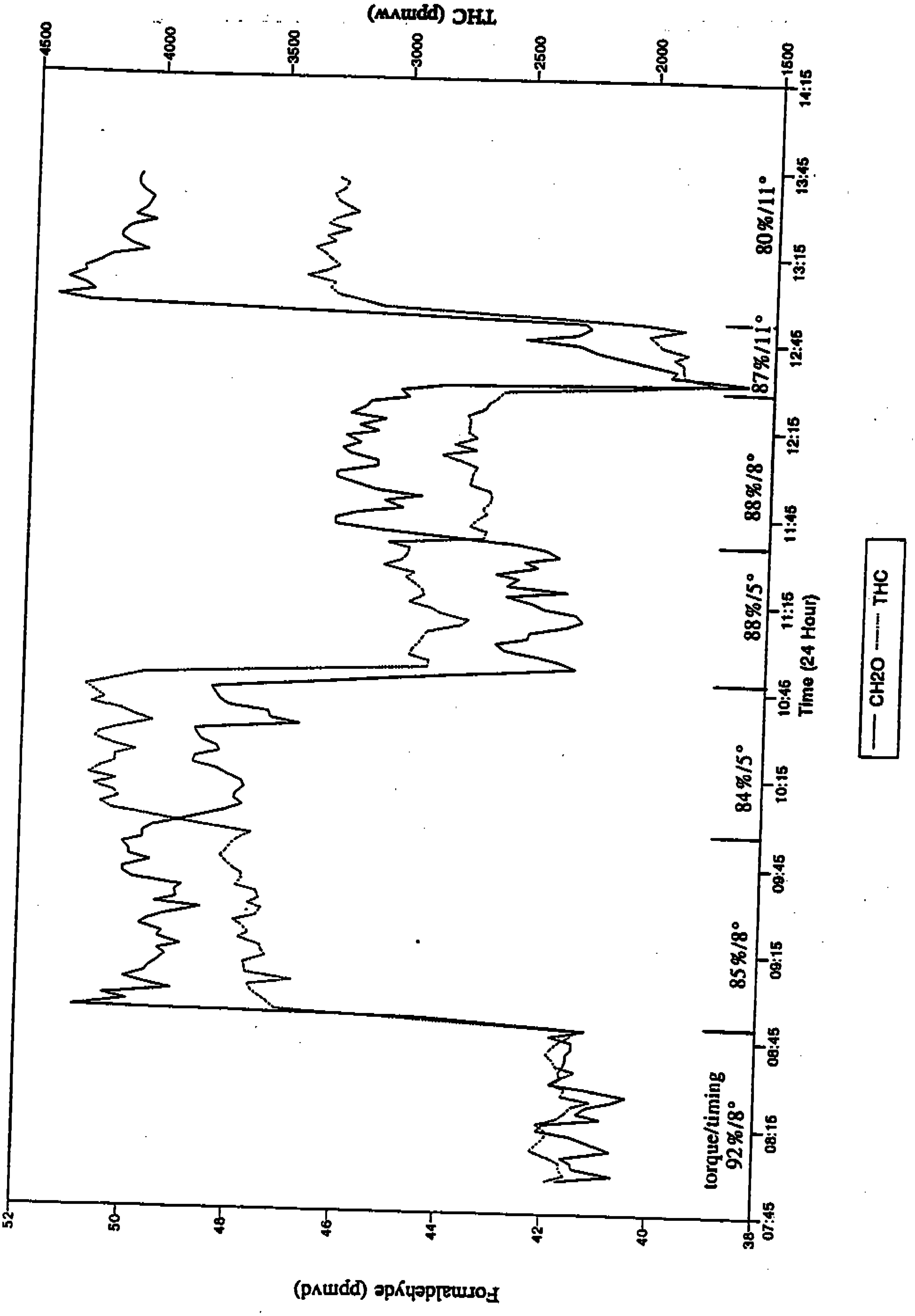


Figure 5-9. Concentration vs. Time for Formaldehyde and THC

localized and discreet, fuel-rich mixture for ignition. By maintaining fuel-rich conditions at the point of ignition, insufficient O_2 is present to participate in NO_x formation reactions. Once ignition takes place, the improved mixing and high A/F ratio work together to disperse the high-temperature combustion gases from the PCC. The remainder of the fuel/air mixture is combusted at the lower bulk gas temperature, thereby, retarding NO_x formation in the main cylinder.

These factors can also combine to influence formaldehyde emissions. The effect of clean-burn combustion can be observed in the emissions from the 4-stroke, Ingersoll-Rand KVS-412 engines. A comparison between the data point on the lean-burn KVS-412 (Test ID No. 48) and the data for the clean-burn KVS-412 (Test ID Nos. 32 - 40) indicates that formaldehyde emissions increased from about 5 ppmv (0.04 g/hp-hr) to an average of nearly 26 ppmv (0.23 g/hp-hr) at normal operating conditions. The primary contributor to increased formaldehyde emissions appears to be the higher A/F ratio (and, consequently, lower bulk gas temperatures) associated with clean-burn combustion. In this case, the lean-burn engine operated with an exhaust O_2 level of 8.3 percent, while the clean-burn engine averaged 11.3 percent O_2. The average cylinder exhaust temperatures for the two engines were 900°F and 823°F, respectively.

In contrast, three Cooper-Bessemer GMVC-10 engines were also tested, one with a clean-burn conversion and the other two of standard lean-burn design. However, these three engines were operated at very similar A/F ratios. The clean-burn unit (Test ID Nos. 5-10) had exhaust O_2 levels ranging from 15.3 to 15.5 percent and an average cylinder exhaust temperature of 578°F at full load. The two lean-burn engines (Test ID Nos. 19-26) exhibited exhaust O_2 concentrations ranging from 14.6 to 15.5 percent, and an average cylinder exhaust temperature of 652°F. Formaldehyde levels at high load averaged 21 ppmv (0.16 g/hp-hr) for the clean-burn engine and 16 ppmv (0.14 g/hp-hr) for the lean-burn units, respectively. The smaller change in formaldehyde emissions observed in these Cooper-Bessemer engines as compared to the Ingersoll-Rand KVS units suggests that formaldehyde formation is governed more by the A/F ratio, temperatures, and mixing properties in the main cylinder than by the presence or lack of a PCC.

5.4.2 Effect of Exhaust Emission Controls

Three engines equipped with catalysts for exhaust emissions control were tested:

- 2-stroke clean-burn Cooper-Bessemer GMVC-10C engine equipped with a catalytic oxidation system for carbon monoxide control (Test ID Nos. 5-10);
- 4-stroke lean-burn Ingersoll-Rand KVS-412 engine equipped with an SCR catalyst for NO_x control; and
- 4-stroke rich-burn Waukesha L7042GU engine equipped with an NSCR catalyst for NO_x control (Test ID Nos. 55-58).

At the time of testing, the CO catalyst was newly installed on the Cooper-Bessemer GMVC-10C engine. The catalyst system was supplied by Johnson Matthey and consists of eight square (2 ft. sides) metal monolith modules mounted in two rows (four modules per row) in the catalyst housing. The system is designed to provide 80 percent CO conversion at an operating temperature of 500°F. Exhaust gas temperatures were approximately 500°F at the inlet to the catalyst during the tests, indicating that the catalyst reactor temperatures were close to design. Formaldehyde measurements made upstream and downstream of the catalyst are shown in Figure 5-10. The data show that the CO catalyst reduced formaldehyde from upstream levels of 16 to 24 ppmv at full load (0.13 to 0.19 g/hp-hr) to below 10 ppmv (~0.07 g/hp-hr) in the exhaust stack. At full load, formaldehyde levels were reduced by about 60 percent. CO levels at full load were reduced from an average level of 187 ppmv to 15 ppmv (Test ID Nos. 5-8, and 10), which corresponds to a 90 percent reduction. **Note that this catalyst was recently installed and no data were obtained on possible degradation of performance over time.**

The SCR catalyst system on the Ingersoll-Rand KVS-412 engine had been in operation for several years at the time of testing. Measurements were made upstream and downstream of the catalyst. For the SCR system, ammonia (NH_3) is injected in the exhaust duct upstream of the catalyst to facilitate the reduction of NO_x to N_2. Based on downstream NH_3 concentrations, the unit tested was operated at atypical NH_3 injection rates. The high NH_3 levels led to interference in the FTIR measurements of

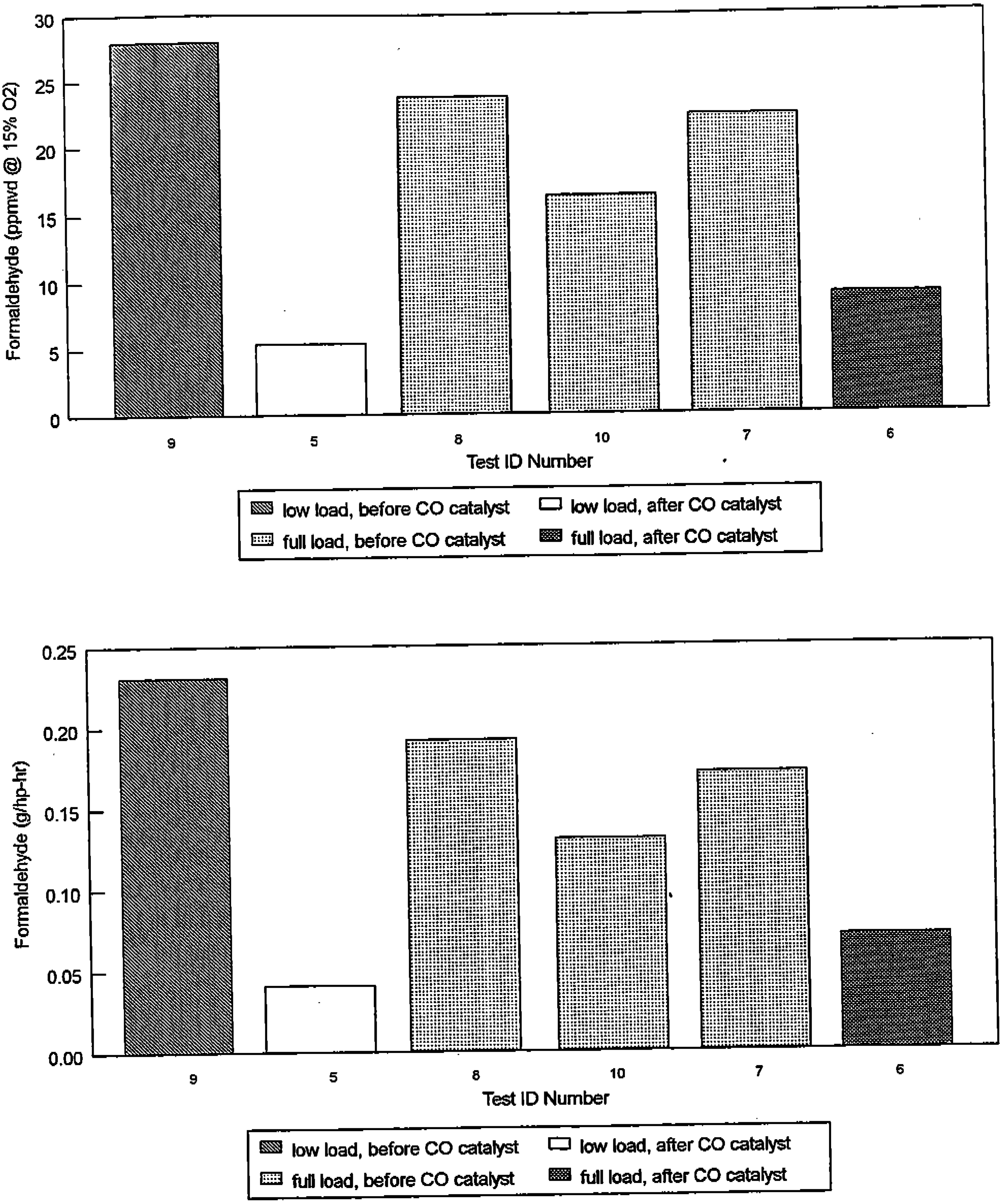


Figure 5-10. Effect of the CO Catalyst on Formaldehyde Emissions

formaldehyde downstream of the catalyst. In addition, no reliable NH_3 flow rate data were available during testing. Therefore, no data are presented for pollutant concentrations downstream of the SCR catalyst.

At the time of testing, the NSCR catalyst was newly installed in the exhaust duct of the Waukesha L7042GU engine for NO_x control. This is a 4-stroke rich-burn engine with exhaust O_2 concentrations of <0.5 percent. Exhaust temperatures upstream of the catalyst were approximately 950°F to 1000°F during the higher load (88 to 95% torque) tests and approximately 850°F during the 52% torque run. Formaldehyde levels upstream of the catalyst were 7 ppmv. At the downstream sampling location, formaldehyde levels were below detection limits (<0.2 ppmv). Emission reductions across the catalyst were on the order of 99 percent for NO_x, 98 percent for CO, and 40 percent for THC.

Although formaldehyde reductions were significant across the NSCR catalyst, the uncontrolled formaldehyde levels were already low. NSCR catalysts are designed for operation at very low O_2 levels. The purpose of the catalyst is to simultaneously reduce NO_x and oxidize CO and THC. However, NSCR is designed for use on units with A/F ratios near stoichiometric.[26] Thus, NSCR catalyst control would not be appropriate for lean- or clean-burn engines. **Note that this catalyst was recently installed, and no data were obtained on possible degradation of performance over time.**

5.5 Relationships between Formaldehyde and Other Pollutant Emissions

Engine design and operating conditions impact emissions of THC, CO, and NO_x, as well as formaldehyde. Central to these interrelationships are combustion temperature and O_2, both of which are influenced by engine torque and other engine conditions. This section discusses the correlation between formaldehyde and these other emission parameters.

5.5.1 Formaldehyde and THC

As discussed in Section 2, decomposition of methane (the primary component in THC emissions from natural gas-fired sources) to formaldehyde and other combustion products depends on temperature and the availability of oxidation radicals. Because of its refractory nature, methane is one of the more difficult hydrocarbon compounds to decompose (The thermal light-off temperature, the temperature at which a compound will spontaneously react with oxygen, is 1,170°F for methane versus 860°F for formaldehyde). As a result, methane destruction efficiency provides a conservative estimator of formaldehyde destruction.

Figure 5-11 shows the relationship between formaldehyde and THC for all five engine families. Considering all of the engines as a group, there is a positive correlation between formaldehyde and THC. However, there are also distinct characteristics for several of the engine families. For example, the low THC and formaldehyde emissions associated with the rich-burn engines is consistent with the near stoichiometric A/F ratio and higher bulk gas temperatures of rich-burn engines.

Note also that most of the scatter (apparent outliers) in the data are associated with 2-stroke lean-burn, scavenged engines. However, this scatter appears to reflect variations between engines and the increase in A/F ratio as engine torque decreases. For example, at low torque on the Cooper-Bessemer GMVA-10 (Test ID No. 16 ~2,800 ppmv THC and 19 ppmv formaldehyde), there is a significant increase in THC but only a small increase in formaldehyde compared to the rated torque tests (Test ID Nos. 17 and 18 ~1,300 ppmv THC and 17 ppmv formaldehyde). These data suggest that the change in A/F ratio and cylinder exhaust gas temperature associated with decreases in torque for scavenged engines is sufficient to significantly reduce THC (i.e., methane) destruction, but remains high enough to still achieve high formaldehyde destruction. This same trend of large increases in THC accompanied by small increases in formaldehyde also appears to exist for the individual 4-stroke lean-burn and clean-burn engines.

For the turbocharged 2-stroke lean-burn and clean-burn engines, however, the increases in THC and formaldehyde as a function of torque changes appear to be relatively small, but are approximately equal, percentage wise. For example, emissions from the Cooper GMVC-10 increase from ~900 ppmv THC and 14 ppmv formaldehyde at 101 percent torque (Test ID No. 24) to 1,400 ppmv THC and 20 ppmv formaldehyde at 87 percent torque (Test ID No. 23), an increase of ~50 percent for both pollutants. This suggests that the turbocharger control system on these engines is able to maintain a more uniform A/F ratio over the range of engine operating conditions.

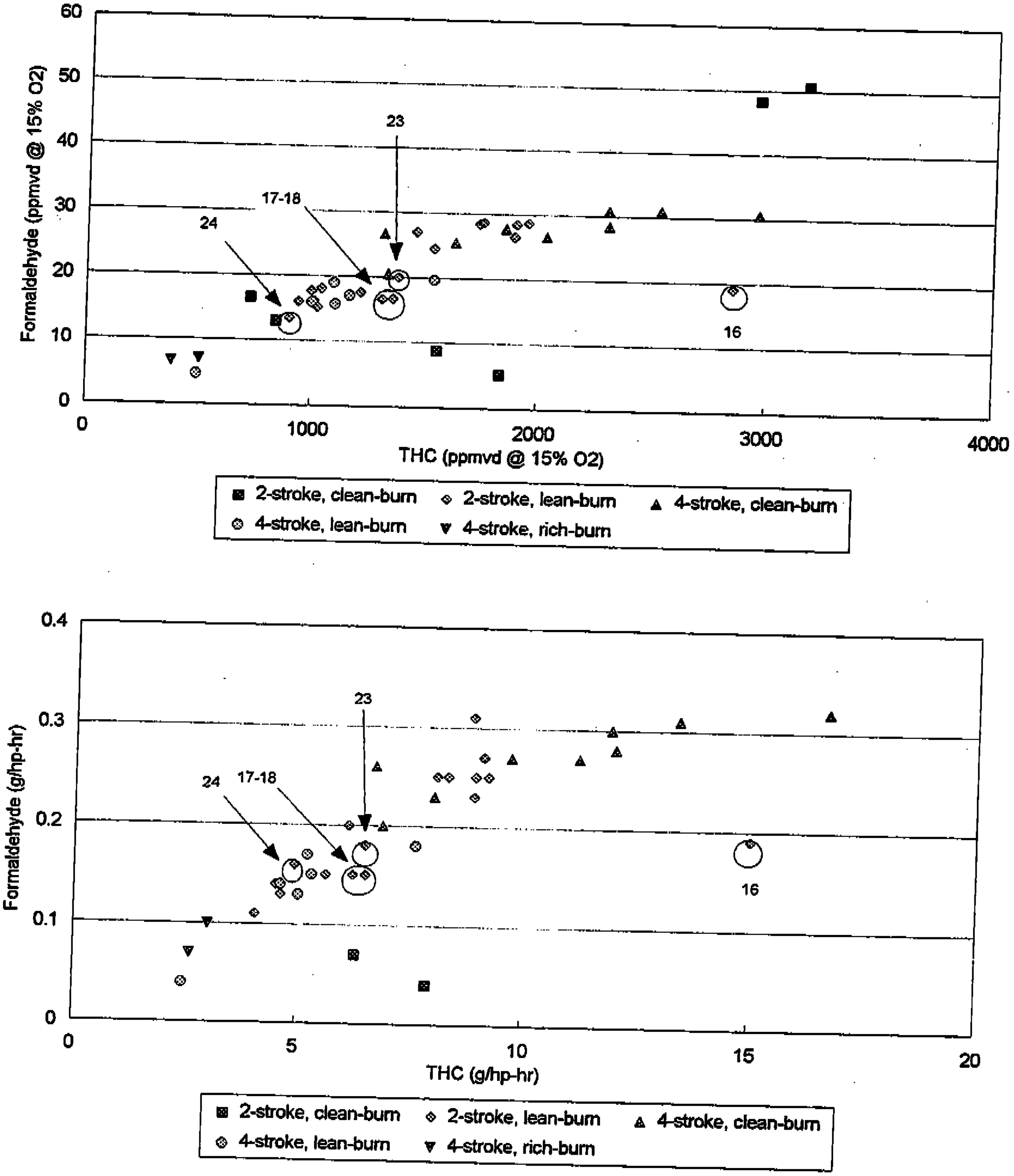


Figure 5-11. Relationship Between Formaldehyde and THC Emissions

The highest formaldehyde level measured during any of the tests was for a 2-stroke clean-burn engine (Test ID Nos. 1 and 2) operating at A/F ratios higher than the manufacturer's design point to further reduce NO_x emissions. The high hydrocarbon emissions during these tests (3,000 ppmv THC and 50 ppmv formaldehyde) suggests that gas temperatures at the time of exhaust port opening may have been low enough to result in reduced destruction of both THC and formaldehyde.

5.5.2 Formaldehyde and CO

The oxidation of CO to CO_2 depends on the availability of oxygen in the combustion gas mixture as well as high temperatures. However, when compared to the decomposition of THC, the oxidation of CO is more dependent on oxygen availability. As a result, rich-burn engines can exhibit high CO emissions even when temperatures are high and hydrocarbon emissions are low.

Figure 5-12 shows the relationship between formaldehyde and CO for all five engine families. Two distinct trends exist--one for lean-burn engines and one for rich-burn engines. As shown for the three rich-burn engines tested, formaldehyde emissions remained low over a wide range of CO levels (the two Ingersoll-Rand KVG-103 engines tested are designed for rich-burn, but were operating with up to 11 percent O_2 in the exhaust gas).

The lean-burn data, shown using an expanded scale in Figure 5-13, appears to exhibit two distinct positive correlations between formaldehyde and CO. One of these correlations (the steeper data cluster to the left) includes all of the 2-stroke turbocharged and most of the 2-stroke scavenged lean-burn engines. The second correlation (the somewhat flatter data cluster to the right) includes the 4-stroke lean-burn, 4-stroke clean-burn, and 2-stroke clean-burn tests, plus two tests of 2-stroke scavenged lean-burn engines conducted at reduced torque (both tests of the Clark HBA-5). This difference in slopes appears to correlate with the difference in A/F ratio of lean-burn versus clean-burn engines. To reduce NO_x emissions, clean-burn engines are designed to operate at higher A/F ratios and lower average combustion gas temperatures than lean-burn engines. At these lower temperatures, the rate of CO oxidation is reduced, resulting in higher CO emissions.

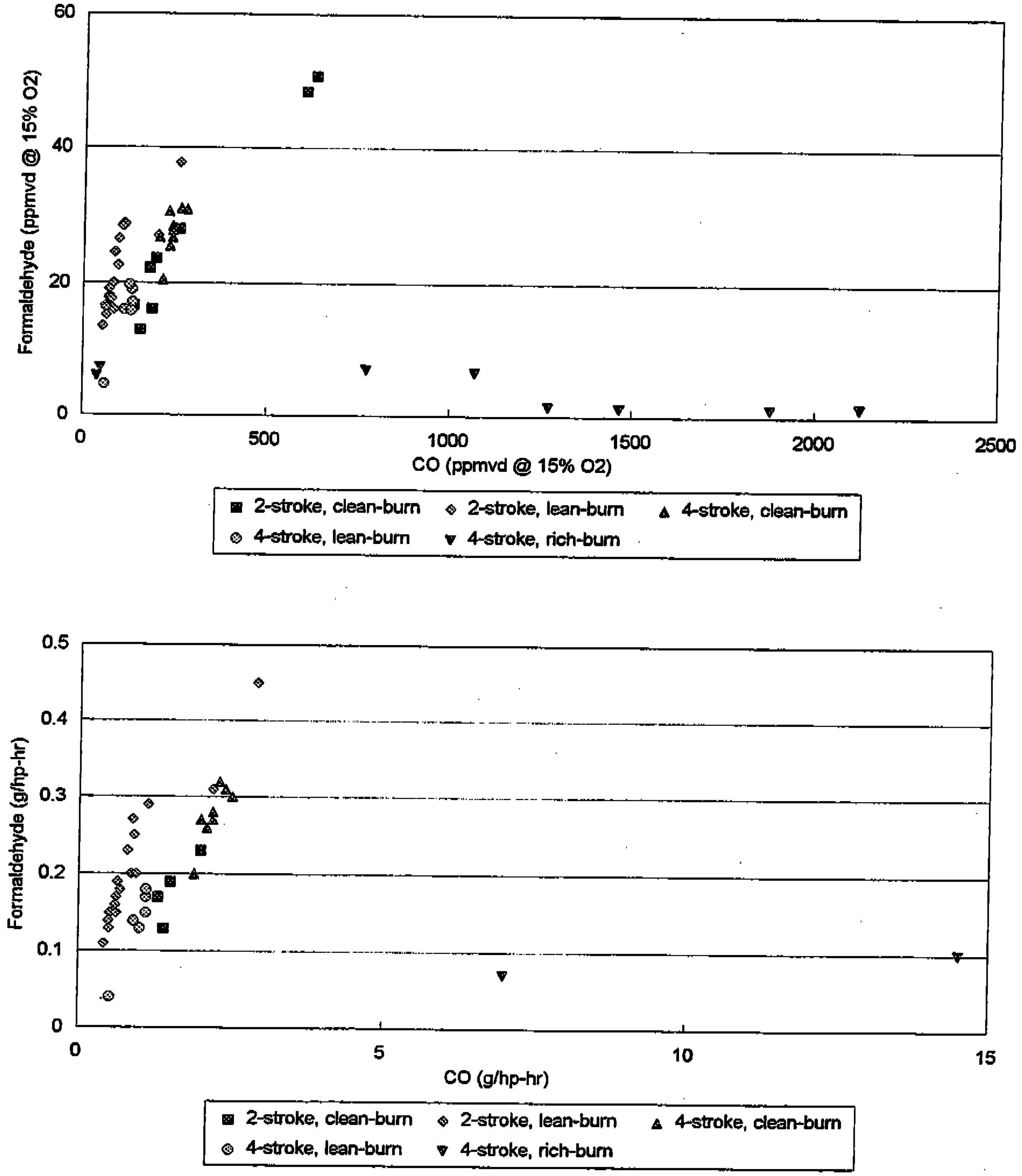
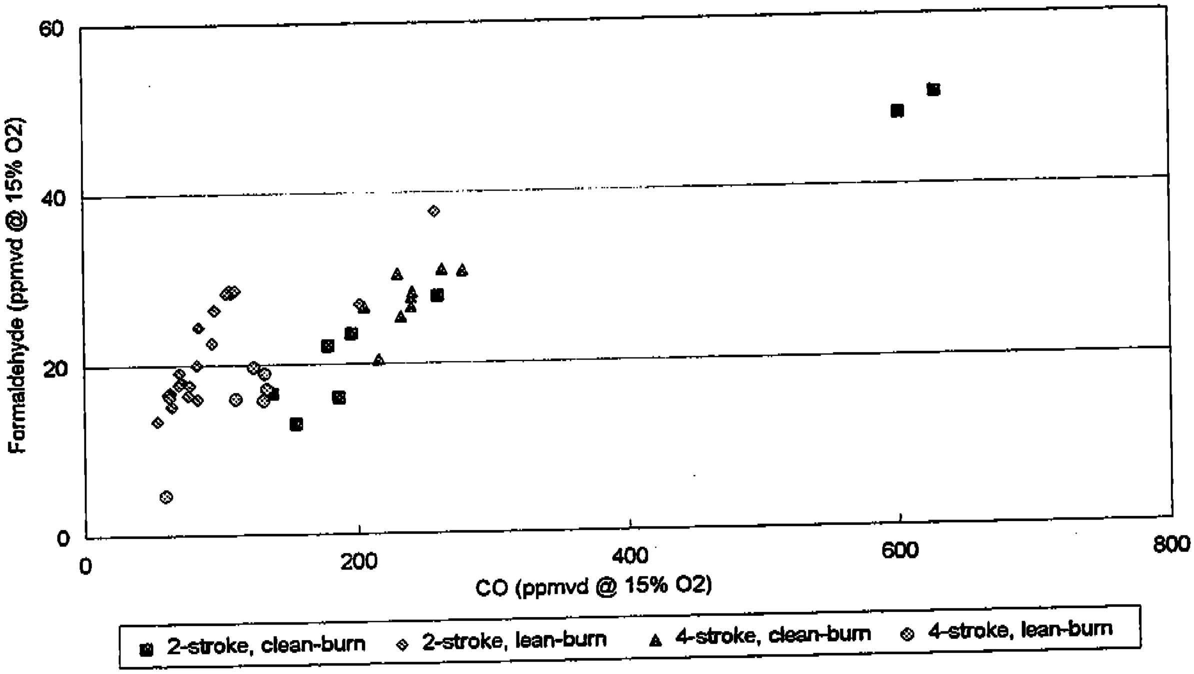


Figure 5-12. Relationship Between Formaldehyde and CO Emissions for All Engines



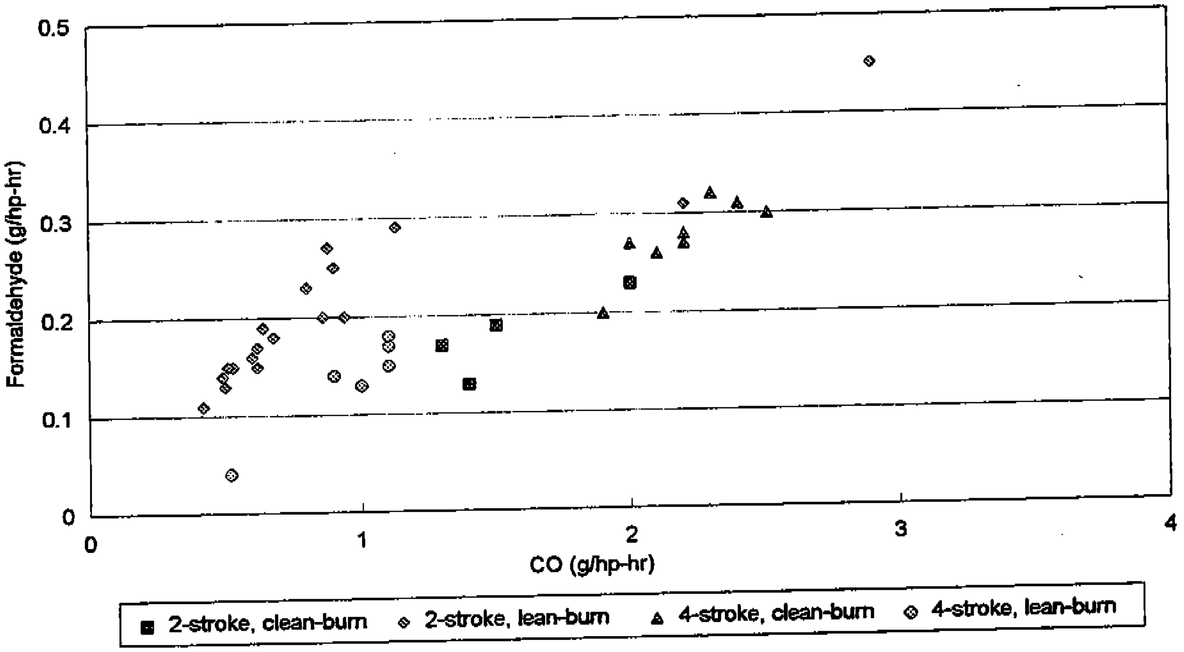


Figure 5-13. Relationship Between Formaldehyde and CO Emissions for Lean-burn and Clean-burn Engines

Generally, these lower temperatures are still sufficient to achieve significant formaldehyde destruction. However, as indicated by the higher formaldehyde emissions from the Clark TCV-10 clean-burn engine (Test ID Nos. 1 and 2), operating at too high an A/F ratio to reduce NO_x emissions can result in elevated formaldehyde and CO emissions.

6.0 EMISSION FACTORS

One of the objectives of the field measurement campaigns was to generate emission factors for the target compounds. This section describes the approach used to organize the available data to develop the desired emission factors. The emission factors developed from the field testing for aldehydes, volatile organic compounds, semi-volatile organic compounds, and criteria pollutants are presented and compared with other published emission factors. An evaluation of plant size (station horsepower) at which the 10 ton/yr major source threshold level would be triggered is included. Additionally, results from limited tests where PM_{10} and metal emissions were measured are briefly summarized.

6.1 Emission Factor Development

Emission data for target compounds from all engines and turbines tested were converted into emission factors with units of g/hp-hr and grouped into the following categories, as consistent with the discussions in Section 2.0:

- 2-stroke lean-burn;
- 2-stroke clean-burn;
- 4-stroke rich-burn;
- 4-stroke lean-burn;
  - direct-injected
  - port-injected
- 4-stroke clean-burn; and
- Turbines.

As discussed in Section 5.3, engine operating load is expected to influence emissions. In general, reductions in load lead to lower combustion temperatures, resulting in increased emissions of products of incomplete combustion, including THC, volatile organic compounds, formaldehyde, and other hydrocarbons, with reduced NO_x

emissions. Load for engines was determined on the basis of torque. Percent torque was calculated by dividing operating horsepower by rated horsepower then multiplying by the ratio of rated speed to operating speed:

$$\text{Load (\%)} = (\text{hp/rated hp})\ (\text{rated speed/speed}) \times 100$$

For turbines, load was taken as a percentage of available horsepower. Maximum available horsepower for each turbine was calculated as the manufacturer's rating, adjusted for site elevation and ambient conditions during testing.

Within these five categories, the emission factors were separated into two groups based on load. Emission factors from tests when an engine was operating at or greater than 90 percent torque and 95 percent rated speed were classified as "full-load" and considered for average emission factor development. Tests that did not meet these criteria were considered to represent "low-load" conditions. An exception was made to these criteria in the case of the Waukesha L7042GU engine tested in Campaign 4 at 52 and 88 percent load upstream of the NSCR catalyst. Because there is no other uncontrolled, 4-stroke rich-burn engine emission information available in the test data set, the 88 percent load test was used for 4-stroke rich-burn engines. Test data from engines operating at less than 95 percent of rated speed were not considered in average emission factor development, except for the Waukesha L7042GU engine, since most engines operate at or near rated speed.

Average emission factors for the low-load case were not developed since low-load tests varied over a wide range of load conditions (52 to 89 percent) and data collected using manual methods were very limited.

6.1.1 Average Emission Factors

Emission factors for each test run were averaged to generate representative emission factors for each category. There are some engine categories from which no data were available for various target compounds and thus no emission factors could be developed for these compounds. For tests where target compound concentrations were not detected, a value of 0.0 was used for averaging purposes. Average emission factors for some target compounds are 0.0 due to finding nondetectable levels of species measured in all tests. Note that in all cases, non-detect levels were confirmed to result in emission levels much less than 10 ton/yr.

Full-load average emission factors for the categories listed above are presented in Tables 6-1 through 6-7 at the end of this section grouped under the following classifications:

- Aldehydes;
- Volatile organic compounds;
- Semi-volatile organic compounds; and
- Criteria pollutants.

Included with each average emission factor are the number of test runs, the number of individual engines tested, and the maximum and minimum value contained in each set of data. Due to the number of tables, all tables are at the end of this section, following the text.

6.1.2 Emission Factor Comparisons

Full-load emission factors developed from the data obtained during this study were compared with previously published emission factors (see Tables 6-8 through 6-13 at the end of this section for the categories listed above). The published emission factors were taken from the following:

- Literature data [*Preliminary Assessment of Air Toxics Emissions in the Natural Gas Industry* (GRI-94/0268); GRI-HAPCalc™ Version 1.0];[1] and
- EPA AP-42 (Section 3.2).[27]

Although EPA's Alternative Control Techniques (ACT) documents for NO_x emissions from engines and turbines were reviewed, the information presented in these documents was not included in the emission factor comparisons mainly due to different engine grouping and emission factors provided only by manufacturers.

All emission factors in Tables 6-8 to 6-13 are presented in g/hp-hr. For cases where the published emission factors were given in pounds per million British thermal units (lb/MMBtu), the conversion was made using average heat rate values Btu per horsepower-hour (Btu/hp-hr) for each category calculated from the field data obtained during this study. A limited amount of data in AP-42 are given in units of lb/MMBtu with corresponding engine heat rates and, for these cases, the given heat rates were used for the conversion.

The only comparisons between the GRI and AP-42 formaldehyde emission factors can be made with the 2-stroke lean-burn and 4-stroke rich-burn families (see Tables 6-8 and 6-10, respectively). For the 2-stroke lean-burn family, the AP-42 factor (1.3 g/hp-hr) is approximately one order of magnitude higher than the GRI test data factor (0.18 g/hp-hr). The opposite is true for the 4-stroke rich-burn emission factors (AP-42: 0.0072 g/hp-hr vs. GRI: 0.10 g/hp-hr). The EPA formaldehyde data are primarily based on smaller, field-operated units compared to those in the GRI data set. In addition, the GRI information is based on FTIR measurements while the EPA data are based on CARB Method 430 measurements.

Criteria pollutant emission factors generated under this field program are comparable in magnitude with AP-42 emission factors for the uncontrolled categories. For the controlled categories, there is disagreement with no set of factors consistently higher or lower. These data are discussed in more detail in the joint GRI-EPA report entitled "*Criteria Pollutant Emissions from Internal Combustion Engines in the Natural Gas Industry*" (GRI-95/0270).[24]

6.1.3 Considerations Regarding the Use of IC Engine Formaldehyde Emission Factors for Emission Inventory and Permitting Purposes

Emission factors are typically used to estimate emission rates for emission inventories and permit applications, as opposed to direct emissions testing. For these uses, emission factors are generally expressed in units which require the user to only supply easily obtained unit-specific information in order to derive an emission rate. Depending on the units of the emission factors, different assumptions must be considered to both minimize variability in emissions estimates and maximize permitting flexibility.

All of the emission factors in this report are presented in units of grams/horsepower-hour (g/hp-hr). These values can be converted into a mass emission rate (e.g., lb/hr, ton/yr, etc.) or concentration (e.g., ppmvd at 15% O_2) for inclusion in emission inventories and/or permit applications. Care should be taken to evaluate the operating conditions under which the emission factors were developed to ensure the estimates properly reflect not only the typical operations for the equipment of interest, but also the range of those operations. The primary factors to consider are those that may impact the combustion efficiency and/or the emissions characteristics of the unit (e.g., operating load extremes, ambient conditions, A/F ratio changes, maintenance history, etc).

As an example, the average formaldehyde emission factor for 2-stroke lean-burn engines tested under this program is 0.18 g/hp-hr for operating conditions $\geq$90 percent rated torque and $\geq$95 percent rated speed. Based on an average higher heating value heat rate of 9,700 Btu/hp-hr (i.e., brake specific fuel consumption), this emission factor equates to a concentration of 17.0 ppmvd at 15% O_2 and emission rate of 0.041 lb/MMBtu heat input; for a 2,000 hp engine, these values would result in a mass emission rate of 0.79 lb/hr and annual emissions of 3.47 tons.

Note, however, that the range of heat rates measured in this program varied from 7,960 Btu/hp-hr to 11,740 Btu/hp-hr. Compared to the 9,700 Btu/hp-hr average heat rate, a less efficient engine (with a heated rate of 11,740 Btu/hp-hr) could only emit formaldehyde in concentrations less than 14.1 ppmvd at 15% O_2 to maintain emissions below 0.18 g/hp-hr. Similarly, a more efficient engine (with a heat rate of 7,960 Btu/hp-hr) could operate with exhaust concentrations of formaldehyde nearing 21 ppmvd at 15% O_2 while staying under the 0.18 g/hp-hr factor.

This issue becomes further complicated when evaluating emissions under off-load operating conditions. For most combustion equipment, load reductions typically result in lower total exhaust flow rates, reduced fuel efficiency, and increased concentrations of products of incomplete combustion, such as formaldehyde. Depending on the relative impact of changes in these parameters, mass emission rates may increase, decrease, or remain essentially unchanged.

To illustrate one potential effect, an example is shown below with data at several load conditions summarized for an 1,800 hp, 2-stroke lean-burn, Cooper GMVC-10 engine (Engine Test ID 19 to 21; detailed data for which is contained in Tables 5-2 and 5-3).

Test Conditions				Formaldehyde Emissions			
% Torque	Test HP	Fuel Flow, dscfm	Heat Rate, Btu/hp-hr	ppmvd, at 15% O_2	lb/MMBtu	g/hp-hr	lb/hr
85	1,523	265	10,667	25	0.056	0.27	0.91
102	1,827	266	8,900	18	0.042	0.17	0.68
102	1,830	266	8,884	18	0.040	0.16	0.65

In this case, at nominal base load conditions (102% torque and 1,830 hp), formaldehyde concentrations were on the order of 18 ppmvd at 15% O_2, corresponding to a full load emission factor of 0.16 g/hp-hr, with mass emission rates of 0.65 lb/hr (2.8 ton/yr).

For this particular engine and test conditions, the off-load test showed a significant increase in formaldehyde concentrations, resulting in an exhaust concentration of 25 ppmvd at 15% O_2. However, the competing effects of decreased engine torque and horsepower (85% torque and 1,523 hp, respectively) and increased brake specific fuel consumption (10,667 Btu/hp-hr) resulted in increased formaldehyde mass emissions of 0.91 lb/hr (3.97 ton/yr). The corresponding emission factor for the off-load test condition is 0.27 g/hp-hr. This illustrates that for this particular engine operating at off-load conditions, the formaldehyde emission factor increased by approximately 70 percent and the mass emissions increased by 40 percent over the full-load conditions. For this case, if a full-load emission factor were chosen to calculate mass emission rates for permitting purposes, it would underestimate emission rates at off-load conditions and potentially create a compliance issue if the unit normally operated at off-load conditions.

These types of off-load effects on formaldehyde emissions illustrated by the single example above may vary between engine families, and even engine-to-engine within a family, manufacturer, and model. In addition, other effects due to changes in A/F ratio, ambient conditions, and engine health/maintenance history could also result in variability in formaldehyde exhaust concentrations and/or emission factors.

Therefore, the selection of a formaldehyde emission factor should be made based upon the fullest practical understanding of both the test engine's operating conditions and those of the engine to which the factor is applied.

In summary, emission factors in general, including those contained in this report, are applicable for *estimating average emissions* based upon average equipment operations and performance. Because of that, these formaldehyde emission factors should be used as the basis for an emission estimate or limit only after careful evaluation of the design, operating conditions, and performance of both the test engine(s) and the engine in question, and normal unit-to-unit and day-to-day variations have been properly considered.

6.2 Major Source Criteria

Based on the formaldehyde emission factors generated in this study, an evaluation was performed to determine the plant size (station horsepower) at which the MACT threshold level of 10 ton/yr would potentially be reached. Assuming 8,760 hr/yr of operation, Table 6-14 presents the horsepower at which a plant would be considered a major source. Depending on the engine family, the threshold plant size varies from about 4,500 hp to over 25,000 hp. Formaldehyde levels were nondetectable for the turbine tested. However, based on an acetaldehyde emission factor of 0.020 g/hp-hr, the major source threshold plant size is approximately 52,000 hp.

6.3 Emissions of Benzene, Toluene, Ethyl Benzene, and Xylenes (BTEX) and Semi-volatile Organic Compounds

BTEX emission factors were estimated using canister data since the FTIR detection limits for these target compounds are high due to presence of moisture and CO_2 in the exhaust stream. As shown in Tables 6-1, 6-2, 6-4, 6-5 and 6-7 for the 2-stroke lean-burn, 2-stroke clean-burn, and 4-stroke lean-burn engine families and gas turbine categories, respectively, the individual BTEX emission factors ranged from nondetectable levels to 3 x 10^{-3} g/hp-hr. Converted to an annual emission rate, this is equivalent to less than 0.15 ton/yr, much lower than the MACT threshold level of 10 ton/yr, for a 5,000 hp engine assuming 8,760 hours of operation.

Data on semi-volatile organic compounds were collected using manual methods on engines representing the 2-stroke lean-burn, 2-stroke clean-burn, and 4-stroke lean-burn families, and gas turbines (see Tables 6-1, 6-2, 6-4, 6-5, and 6-7, respectively). The highest emission factor is associated with biphenyl at 8 x 10^{-4} g/hp-hr, with naphthalene and phenol measured at lower levels (10^{-6} - 10^{-4} g/hp-hr). All other target semi-volatile organic compounds were found at lower levels. For a 5,000-hp engine operating continuously, annual biphenyl emissions are estimated at less than 0.05 ton/yr, which is insignificant when compared with the MACT threshold level of 10 ton/yr.

6.4 PM_{10} and Metal Emissions

Limited tests for PM_{10} emissions were conducted during Campaigns 3 and 4. Data collected from eight engines are presented in Table 6-15, where the particulate and condensible portions of the PM_{10} emissions are shown. For all the engines tested, including the Cooper GMVC-10C and Waukesha L7042GU engines with catalytic controls, the particulate fraction ranged from 0.006 to 0.03 ton/yr while the condensibles fraction ranged from 0.47 to 2.0 ton/yr. In almost all of the tests, the condensibles fraction was largely comprised of organic compounds, suggesting less than optimal combustion conditions.

Metal emission tests were conducted only during Campaign 1. As shown in Table 6-16, these tests were conducted on two 2-stroke clean-burn engines and one 4-stroke rich-burn engine. Emission factors were not calculated for these tests due to unreliable exhaust flow and horsepower measurements. Exhaust concentration measurements for lead and manganese were higher than the other metal species measured. Lead levels ranged from 0.015 to 0.21 micrograms per dry standard cubic foot (μg/dscf) and manganese levels ranged from 0.095 to 0.56 μg/dscf. Since rough estimates of annual emission rates indicated very low levels (less than 0.01 ton/yr for a specific metal species), collection of metal emissions data was discontinued following Campaign 1.

Table 6-1

Emission Factors
2-Stroke Lean-Burn

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	1.8×10^{-1}	12	5	2.5×10^{-1}	1.1×10^{-1}
Acetaldehyde	1.0×10^{-2}	12	5	4.0×10^{-2}	0.0
Acrolein	0.0	12	5	0.0	0.0
Butyr/Isobutyraldehyde	2.8×10^{-3}	3	3	7.6×10^{-3}	0.0
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	1.0×10^{-4}	3	3	1.6×10^{-4}	0.0
1,2,4-Trimethylbenzene	5.5×10^{-4}	3	3	6.9×10^{-4}	3.1×10^{-4}
1,3-Butadiene	0.0	3	3	0.0	0.0
1,3,5-Trimethylbenzene	3.0×10^{-5}	3	3	9.0×10^{-5}	0.0
2,2,4-Trimethylpentane	1.7×10^{-3}	3	3	3.0×10^{-3}	1.2×10^{-4}
Acetylene	0.0	3	3	0.0	0.0
Benzene	3.7×10^{-3}	3	3	6.0×10^{-3}	1.6×10^{-3}
Butane	2.0×10^{-2}	3	3	3.2×10^{-2}	1.1×10^{-2}
Cyclohexane	1.3×10^{-3}	3	3	1.9×10^{-3}	9.2×10^{-4}
Cyclopentane	3.3×10^{-4}	3	3	4.9×10^{-4}	2.0×10^{-4}
Ethane	2.2×10^{-1}	12	5	3.6×10^{-1}	9.0×10^{-2}
Ethyl benzene	1.9×10^{-4}	3	3	2.3×10^{-4}	1.3×10^{-4}
Ethylene	0.0	3	3	0.0	0.0
n-Hexane	2.4×10^{-3}	3	3	3.6×10^{-3}	1.6×10^{-3}
Isobutane	1.6×10^{-2}	3	3	2.4×10^{-2}	9.9×10^{-3}
Methane	4.9	12	5	8.0	3.3
Methanol	1.0×10^{-2}	12	5	2.0×10^{-2}	6.0×10^{-3}
Methylcyclohexane	1.1×10^{-3}	3	3	1.6×10^{-3}	7.1×10^{-4}
n-Nonane	2.4×10^{-5}	3	3	5.3×10^{-5}	0.0
n-Octane	1.5×10^{-4}	3	3	2.0×10^{-4}	1.2×10^{-4}
n-Pentane	6.0×10^{-3}	3	3	9.6×10^{-3}	3.7×10^{-3}
Propane	1.2×10^{-1}	3	3	1.9×10^{-1}	7.5×10^{-2}
Propylene	0.0	3	3	0.0	0.0
Styrene	2.4×10^{-4}	3	3	4.6×10^{-4}	7.5×10^{-5}
Toluene	2.2×10^{-3}	3	3	2.7×10^{-3}	1.4×10^{-3}
Xylenes	4.6×10^{-4}	3	3	5.9×10^{-4}	3.9×10^{-4}

Table 6-1

Emission Factors
2-Stroke Lean-Burn
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	4.3×10^{-6}	2	2	5.7×10^{-6}	2.8×10^{-6}
Acenaphthylene	8.9×10^{-6}	2	2	1.2×10^{-5}	5.8×10^{-6}
Anthracene	1.6×10^{-6}	2	2	2.3×10^{-6}	9.4×10^{-7}
Benz(a)anthracene	7.0×10^{-7}	2	2	1.4×10^{-6}	0.0
Benzo(a)pyrene	0.0	2	2	0.0	0.0
Benzo(e)pyrene	0.0	2	2	0.0	0.0
Benzo(b)fluoranthene	0.0	2	2	0.0	0.0
Benzo(g,h,i)perylene	0.0	2	2	0.0	0.0
Benzo(k)fluoranthene	0.0	2	2	0.0	0.0
Biphenyl	1.2×10^{-5}	2	2	1.5×10^{-5}	8.0×10^{-6}
Chrysene	1.5×10^{-6}	2	2	2.9×10^{-6}	0.0
Dibenz(a,h)anthracene	0.0	2	2	0.0	0.0
Fluoranthene	1.3×10^{-6}	2	2	1.7×10^{-6}	9.2×10^{-7}
Fluorene	5.5×10^{-7}	2	2	1.1×10^{-6}	0.0
Indeno(1,2,3-c)pyrene	0.0	2	2	0.0	0.0
2-Methylnaphthalene	6.4×10^{-5}	2	2	9.0×10^{-5}	3.8×10^{-5}
Naphthalene	1.3×10^{-4}	2	2	1.9×10^{-4}	7.1×10^{-5}
Perylene	0.0	2	2	0.0	0.0
Phenanthrene	9.8×10^{-6}	2	2	1.4×10^{-5}	5.6×10^{-6}
Phenol	1.1×10^{-4}	2	2	1.4×10^{-4}	7.3×10^{-5}
Pyrene	1.8×10^{-6}	2	2	2.3×10^{-6}	1.3×10^{-6}
Criteria Pollutants					
NO_x	$1.3 \times 10^{+1}$	12	5	$2.2 \times 10^{+1}$	4.9
CO	6.7×10^{-1}	12	5	9.4×10^{-1}	4.1×10^{-1}
THC	6.2	11	5	9.2	4.0
NMHC	1.1	11	5	1.8	2.9×10^{-1}
NMEHC	9.0×10^{-1}	11	5	1.7	8.7×10^{-2}

Table 6-2

Emission Factors
2-Stroke Clean-Burn

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	1.6×10^{-1}	3	1	1.9×10^{-1}	1.3×10^{-1}
Acetaldehyde	6.7×10^{-3}	3	1	2.0×10^{-2}	0.0
Acrolein	2.0×10^{-2}	3	1	3.0×10^{-2}	0.0
Butyr/Isobutyraldehyde	6.1×10^{-4}	1	1	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	0.0	1	1	NA	NA
1,2,4-Trimethylbenzene	1.2×10^{-4}	1	1	NA	NA
1,3-Butadiene	4.2×10^{-4}	1	1	NA	NA
1,3,5-Trimethylbenzene	0.0	1	1	NA	NA
2,2,4-Trimethylpentane	6.8×10^{-4}	1	1	NA	NA
Acetylene	NM	NA	NA	NA	NA
Benzene	1.0×10^{-3}	1	1	NA	NA
Butane	NM	NA	NA	NA	NA
Cyclohexane	NM	NA	NA	NA	NA
Cyclopentane	3.6×10^{-4}	1	1	NA	NA
Ethane	3.8×10^{-1}	2	1	3.9×10^{-1}	3.7×10^{-1}
Ethyl benzene	0.0	1	1	NA	NA
Ethylene	NM	NA	NA	NA	NA
n-Hexane	2.7×10^{-3}	1	1	NA	NA
Isobutane	NM	NA	NA	NA	NA
Methane	NM	NA	NA	NA	NA
Methanol	7.0×10^{-3}	3	1	1.0×10^{-2}	3.0×10^{-3}
Methylcyclohexane	1.6×10^{-3}	1	1	NA	NA
n-Nonane	2.1×10^{-4}	1	1	NA	NA
n-Octane	6.3×10^{-4}	1	1	NA	NA
n-Pentane	6.0×10^{-3}	1	1	NA	NA
Propane	1.0×10^{-1}	1	1	NA	NA
Propylene	NM	NA	NA	NA	NA
Styrene	0.0	1	1	NA	NA
Toluene	9.0×10^{-4}	1	1	NA	NA
Xylenes	4.0×10^{-4}	1	1	NA	NA

Table 6-2

Emission Factors 2-Stroke Clean-Burn (Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	1.2×10^{-7}	1	1	NA	NA
Acenaphthylene	3.6×10^{-7}	1	1	NA	NA
Anthracene	7.7×10^{-8}	1	1	NA	NA
Benz(a)anthracene	3.0×10^{-8}	1	1	NA	NA
Benzo(a)pyrene	2.1×10^{-8}	1	1	NA	NA
Benzo(e)pyrene	8.1×10^{-8}	1	1	NA	NA
Benzo(b)fluoranthene	2.8×10^{-8}	1	1	NA	NA
Benzo(g,h,i)perylene	8.7×10^{-8}	1	1	NA	NA
Benzo(k)fluoranthene	1.4×10^{-8}	1	1	NA	NA
Biphenyl	NM	NA	NA	NA	NA
Chrysene	6.2×10^{-8}	1	1	NA	NA
Dibenz(a,h)anthracene	0.0	1	1	NA	NA
Fluoranthene	2.3×10^{-7}	1	1	NA	NA
Fluorene	2.1×10^{-7}	1	1	NA	NA
Indeno(1,2,3-c)pyrene	3.4×10^{-8}	1	1	NA	NA
2-Methylnaphthalene	1.6×10^{-6}	1	1	NA	NA
Naphthalene	6.4×10^{-6}	1	1	NA	NA
Perylene	1.6×10^{-8}	1	1	NA	NA
Phenanthrene	7.0×10^{-7}	1	1	NA	NA
Phenol	NM	NA	NA	NA	NA
Pyrene	3.4×10^{-7}	1	1	NA	NA
Criteria Pollutants					
NO_x	4.8×10^{-1}	3	1	5.1×10^{-1}	4.5×10^{-1}
CO	1.4	3	1	1.5	1.3
THC	6.8	3	1	7.8	5.9
NMHC	NM	NA	NA	NA	NA
NMEHC	NM	NA	NA	NA	NA

NA = Not applicable.

NM = Not measured.

Table 6-3

Emission Factors
4-Stroke Rich-Burn

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	1.0×10^{-1}	1	1	NA	NA
Acetaldehyde	0.0	1	1	NA	NA
Acrolein	0.0	1	1	NA	NA
Butyr/Isobutyraldehyde	3.0×10^{-4}	1	1	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	NM	NA	NA	NA	NA
1,2,4-Trimethylbenzene	NM	NA	NA	NA	NA
1,3-Butadiene	NM	NA	NA	NA	NA
1,3,5-Trimethylbenzene	NM	NA	NA	NA	NA
2,2,4-Trimethylpentane	NM	NA	NA	NA	NA
Acetylene	NM	NA	NA	NA	NA
Benzene	NM	NA	NA	NA	NA
Butane	NM	NA	NA	NA	NA
Cyclohexane	NM	NA	NA	NA	NA
Cyclopentane	NM	NA	NA	NA	NA
Ethane	NM	NA	NA	NA	NA
Ethyl benzene	NM	NA	NA	NA	NA
Ethylene	NM	NA	NA	NA	NA
n-Hexane	NM	NA	NA	NA	NA
Isobutane	NM	NA	NA	NA	NA
Methane	NM	NA	NA	NA	NA
Methanol	2.0×10^{-2}	1	1	NA	NA
Methylcyclohexane	NM	NA	NA	NA	NA
n-Nonane	NM	NA	NA	NA	NA
n-Octane	NM	NA	NA	NA	NA
n-Pentane	NM	NA	NA	NA	NA
Propane	NM	NA	NA	NA	NA
Propylene	NM	NA	NA	NA	NA
Styrene	NM	NA	NA	NA	NA
Toluene	NM	NA	NA	NA	NA
Xylenes	NM	NA	NA	NA	NA

Table 6-3

Emission Factors
4-Stroke Rich-Burn
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	NM	NA	NA	NA	NA
Acenaphthylene	NM	NA	NA	NA	NA
Anthracene	NM	NA	NA	NA	NA
Benz(a)anthracene	NM	NA	NA	NA	NA
Benzo(a)pyrene	NM	NA	NA	NA	NA
Benzo(e)pyrene	NM	NA	NA	NA	NA
Benzo(b)fluoranthene	NM	NA	NA	NA	NA
Benzo(g,h,i)perylene	NM	NA	NA	NA	NA
Benzo(k)fluoranthene	NM	NA	NA	NA	NA
Biphenyl	NM	NA	NA	NA	NA
Chrysene	NM	NA	NA	NA	NA
Dibenz(a,h)anthracene	NM	NA	NA	NA	NA
Fluoranthene	NM	NA	NA	NA	NA
Fluorene	NM	NA	NA	NA	NA
Indeno(1,2,3-c)pyrene	NM	NA	NA	NA	NA
2-Methylnaphthalene	NM	NA	NA	NA	NA
Naphthalene	NM	NA	NA	NA	NA
Perylene	NM	NA	NA	NA	NA
Phenanthrene	NM	NA	NA	NA	NA
Phenol	NM	NA	NA	NA	NA
Pyrene	NM	NA	NA	NA	NA
Criteria Pollutants					
NO_x	$1.8 \times 10^{+1}$	1	1	NA	NA
CO	$1.5 \times 10^{+1}$	1	1	NA	NA
THC	3.0	1	1	NA	NA
NMHC	NM	NA	NA	NA	NA
NMEHC	NM	NA	NA	NA	NA

NA = Not applicable.

NM = Not measured.

Table 6-4

Emission Factors
4-Stroke Lean-Burn, Direct-Injected

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	4.0×10^{-2}	1	1	4.0×10^{-2}	4.0×10^{-2}
Acetaldehyde	2.0×10^{-2}	1	1	2.0×10^{-2}	2.0×10^{-2}
Acrolein	0.0	1	1	0.0	0.0
Butyr/Isobutyraldehyde	NM	NA	NA	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	NM	NA	NA	NA	NA
1,2,4-Trimethylbenzene	NM	NA	NA	NA	NA
1,3-Butadiene	NM	NA	NA	NA	NA
1,3,5-Trimethylbenzene	NM	NA	NA	NA	NA
2,2,4-Trimethylpentane	NM	NA	NA	NA	NA
Acetylene	NM	NA	NA	NA	NA
Benzene	NM	NA	NA	NA	NA
Butane	NM	NA	NA	NA	NA
Cyclohexane	NM	NA	NA	NA	NA
Cyclopentane	NM	NA	NA	NA	NA
Ethane	NM	NA	NA	NA	NA
Ethyl benzene	NM	NA	NA	NA	NA
Ethylene	NM	NA	NA	NA	NA
n-Hexane	NM	NA	NA	NA	NA
Isobutane	NM	NA	NA	NA	NA
Methane	NM	NA	NA	NA	NA
Methanol	5.0×10^{-3}	1	1	5.0×10^{-3}	5.0×10^{-3}
Methylcyclohexane	NM	NA	NA	NA	NA
n-Nonane	NM	NA	NA	NA	NA
n-Octane	NM	NA	NA	NA	NA
n-Pentane	NM	NA	NA	NA	NA
Propane	NM	NA	NA	NA	NA
Propylene	NM	NA	NA	NA	NA
Styrene	NM	NA	NA	NA	NA
Toluene	NM	NA	NA	NA	NA
Xylenes	NM	NA	NA	NA	NA

Table 6-4

Emission Factors
4-Stroke Lean-Burn, Direct-Injected
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	NM	NA	NA	NA	NA
Acenaphthylene	NM	NA	NA	NA	NA
Anthracene	NM	NA	NA	NA	NA
Benz(a)anthracene	NM	NA	NA	NA	NA
Benzo(a)pyrene	NM	NA	NA	NA	NA
Benzo(e)pyrene	NM	NA	NA	NA	NA
Benzo(b)fluoranthene	NM	NA	NA	NA	NA
Benzo(g,h,i)perylene	NM	NA	NA	NA	NA
Benzo(k)fluoranthene	NM	NA	NA	NA	NA
Biphenyl	NM	NA	NA	NA	NA
Chrysene	NM	NA	NA	NA	NA
Dibenz(a,h)anthracene	NM	NA	NA	NA	NA
Fluoranthene	NM	NA	NA	NA	NA
Fluorene	NM	NA	NA	NA	NA
Indeno(1,2,3-c)pyrene	NM	NA	NA	NA	NA
2-Methylnaphthalene	NM	NA	NA	NA	NA
Naphthalene	NM	NA	NA	NA	NA
Perylene	NM	NA	NA	NA	NA
Phenanthrene	NM	NA	NA	NA	NA
Phenol	NM	NA	NA	NA	NA
Pyrene	NM	NA	NA	NA	NA
Criteria Pollutants					
NO_x	$2.2 \times 10^{+1}$	2	1	$2.2 \times 10^{+1}$	$2.1 \times 10^{+1}$
CO	5.5×10^{-1}	2	1	5.9×10^{-1}	5.1×10^{-1}
THC	2.5	2	1	2.6	2.4
NMHC	NM	NA	NA	NA	NA
NMEHC	NM	NA	NA	NA	NA

NA = Not applicable.

NM = Not measured.

Table 6-5

Emission Factors
4-Stroke Lean-Burn, Port-Injected

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	1.4×10^{-1}	3	2	1.5×10^{-1}	1.3×10^{-1}
Acetaldehyde	0.0	3	2	0.0	0.0
Acrolein	0.0	2	1	0.0	0.0
Butyr/Isobutyraldehyde	NM	NA	NA	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	NM	NA	NA	NA	NA
1,2,4-Trimethylbenzene	0.0	2	2	0.0	0.0
1,3-Butadiene	0.0	2	2	0.0	0.0
1,3,5-Trimethylbenzene	0.0	2	2	0.0	0.0
2,2,4-Trimethylpentane	0.0	2	2	0.0	0.0
Acetylene	NM	NA	NA	NA	NA
Benzene	2.1×10^{-4}	2	2	3.1×10^{-4}	1.0×10^{-4}
Butane	2.0×10^{-3}	2	2	2.2×10^{-3}	1.8×10^{-3}
Cyclohexane	0.0	1	1	0.0	0.0
Cyclopentane	0.0	1	1	0.0	0.0
Ethane	1.6×10^{-1}	4	2	1.7×10^{-1}	1.3×10^{-1}
Ethyl benzene	0.0	1	1	0.0	0.0
Ethylene	NM	NA	NA	NA	NA
n-Hexane	5.1×10^{-5}	2	2	7.2×10^{-5}	2.9×10^{-5}
Isobutane	NM	NA	NA	NA	NA
Methane	5.5	4	2	6.0	4.7
Methanol	4.0×10^{-3}	3	2	4.0×10^{-3}	4.0×10^{-3}
Methylcyclohexane	0.0	1	1	0.0	0.0
n-Nonane	NM	NA	NA	NA	NA
n-Octane	0.0	2	2	0.0	0.0
n-Pentane	2.4×10^{-4}	2	2	2.6×10^{-4}	2.1×10^{-4}
Propane	1.5×10^{-2}	2	2	1.8×10^{-2}	1.2×10^{-2}
Propylene	NM	NA	NA	NA	NA
Styrene	2.5×10^{-5}	2	2	4.9×10^{-5}	0.0
Toluene	0.0	2	2	0.0	0.0
Xylenes	0.0	2	2	0.0	0.0

Table 6-5

Emission Factors
4-Stroke Lean-Burn, Port-Injected
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	0.0	2	2	0.0	0.0
Acenaphthylene	0.0	2	2	0.0	0.0
Anthracene	0.0	2	2	0.0	0.0
Benz(a)anthracene	0.0	2	2	0.0	0.0
Benzo(a)pyrene	0.0	2	2	0.0	0.0
Benzo(e)pyrene	0.0	2	2	0.0	0.0
Benzo(b)fluoranthene	0.0	2	2	0.0	0.0
Benzo(g,h,i)perylene	0.0	2	2	0.0	0.0
Benzo(k)fluoranthene	0.0	2	2	0.0	0.0
Biphenyl	7.8×10^{-4}	2	2	9.2×10^{-4}	6.4×10^{-4}
Chrysene	0.0	2	2	0.0	0.0
Dibenz(a,h)anthracene	0.0	2	2	0.0	0.0
Fluoranthene	0.0	2	2	0.0	0.0
Fluorene	3.7×10^{-5}	2	2	5.0×10^{-5}	2.3×10^{-5}
Indeno(1,2,3-c)pyrene	0.0	2	2	0.0	0.0
2-Methylnaphthalene	0.0	2	2	0.0	0.0
Naphthalene	3.8×10^{-5}	2	2	4.5×10^{-5}	3.1×10^{-5}
Perylene	0.0	2	2	0.0	0.0
Phenanthrene	0.0	2	2	0.0	0.0
Phenol	8.9×10^{-5}	2	2	1.4×10^{-4}	3.7×10^{-5}
Pyrene	0.0	2	2	0.0	0.0
Criteria Pollutants					
NO_x	$1.1 \times 10^{+1}$	4	2	$1.2 \times 10^{+1}$	8.7
CO	9.8×10^{-1}	4	2	1.1	9.0×10^{-1}
THC	4.9	4	2	5.3	4.6
NMHC	0.0	4	2	0.0	0.0
NMEHC	0.0	4	2	0.0	0.0

NA = Not applicable.

NM = Not measured.

Table 6-6

Emission Factors
4-Stroke Clean-Burn

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	2.3×10^{-1}	1	1	NA	NA
Acetaldehyde	0.0	1	1	NA	NA
Acrolein	2.0×10^{-2}	1	1	NA	NA
Butyr/Isobutyraldehyde	NM	NA	NA	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	NM	NA	NA	NA	NA
1,2,4-Trimethylbenzene	NM	NA	NA	NA	NA
1,3-Butadiene	NM	NA	NA	NA	NA
1,3,5-Trimethylbenzene	NM	NA	NA	NA	NA
2,2,4-Trimethylpentane	NM	NA	NA	NA	NA
Acetylene	NM	NA	NA	NA	NA
Benzene	NM	NA	NA	NA	NA
Butane	NM	NA	NA	NA	NA
Cyclohexane	NM	NA	NA	NA	NA
Cyclopentane	NM	NA	NA	NA	NA
Ethane	NM	NA	NA	NA	NA
Ethyl benzene	NM	NA	NA	NA	NA
Ethylene	NM	NA	NA	NA	NA
n-Hexane	NM	NA	NA	NA	NA
Isobutane	NM	NA	NA	NA	NA
Methane	NM	NA	NA	NA	NA
Methanol	1.0×10^{-2}	1	1	NA	NA
Methylcyclohexane	NM	NA	NA	NA	NA
n-Nonane	NM	NA	NA	NA	NA
n-Octane	NM	NA	NA	NA	NA
n-Pentane	NM	NA	NA	NA	NA
Propane	NM	NA	NA	NA	NA
Propylene	NM	NA	NA	NA	NA
Styrene	NM	NA	NA	NA	NA
Toluene	NM	NA	NA	NA	NA
Xylenes	NM	NA	NA	NA	NA

Table 6-6

Emission Factors
4-Stroke Clean-Burn
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Engines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	NM	NA	NA	NA	NA
Acenaphthylene	NM	NA	NA	NA	NA
Anthracene	NM	NA	NA	NA	NA
Benz(a)anthracene	NM	NA	NA	NA	NA
Benzo(a)pyrene	NM	NA	NA	NA	NA
Benzo(e)pyrene	NM	NA	NA	NA	NA
Benzo(b)fluoranthene	NM	NA	NA	NA	NA
Benzo(g,h,i)perylene	NM	NA	NA	NA	NA
Benzo(k)fluoranthene	NM	NA	NA	NA	NA
Biphenyl	NM	NA	NA	NA	NA
Chrysene	NM	NA	NA	NA	NA
Dibenz(a,h)anthracene	NM	NA	NA	NA	NA
Fluoranthene	NM	NA	NA	NA	NA
Fluorene	NM	NA	NA	NA	NA
Indeno(1,2,3-c)pyrene	NM	NA	NA	NA	NA
2-Methylnaphthalene	NM	NA	NA	NA	NA
Naphthalene	NM	NA	NA	NA	NA
Perylene	NM	NA	NA	NA	NA
Phenanthrene	NM	NA	NA	NA	NA
Phenol	NM	NA	NA	NA	NA
Pyrene	NM	NA	NA	NA	NA
Criteria Pollutants					
NO_x	5.6×10^{-1}	1	1	NA	NA
CO	2.0	1	1	NA	NA
THC	8.0	1	1	NA	NA
NMHC	NM	NA	NA	NA	NA
NMEHC	NM	NA	NA	NA	NA

NA = Not applicable.

NM = Not measured.

Table 6-7

Emission Factors
Gas Turbine

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Turbines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Aldehydes					
Formaldehyde	0.0	2	1	0.0	0.0
Acetaldehyde	2.0×10^{-2}	2	1	2.0×10^{-2}	2.0×10^{-2}
Acrolein	0.0	2	1	0.0	0.0
Butyr/Isobutyraldehyde	3.8×10^{-4}	1	1	NA	NA
Volatile Organic Compounds					
1,2,3-Trimethylbenzene	NM	NA	NA	NA	NA
1,2,4-Trimethylbenzene	NM	NA	NA	NA	NA
1,3-Butadiene	NM	NA	NA	NA	NA
1,3,5-Trimethylbenzene	NM	NA	NA	NA	NA
2,2,4-Trimethylpentane	NM	NA	NA	NA	NA
Acetylene	NM	NA	NA	NA	NA
Benzene	NM	NA	NA	NA	NA
Butane	NM	NA	NA	NA	NA
Cyclohexane	NM	NA	NA	NA	NA
Cyclopentane	NM	NA	NA	NA	NA
Ethane	0.0	2	1	0.0	0.0
Ethyl benzene	NM	NA	NA	NA	NA
Ethylene	NM	NA	NA	NA	NA
n-Hexane	NM	NA	NA	NA	NA
Isobutane	NM	NA	NA	NA	NA
Methane	0.0	2	1	0.0	0.0
Methanol	0.0	2	1	0.0	0.0
Methylcyclohexane	NM	NA	NA	NA	NA
n-Nonane	NM	NA	NA	NA	NA
n-Octane	NM	NA	NA	NA	NA
n-Pentane	NM	NA	NA	NA	NA
Propane	NM	NA	NA	NA	NA
Propylene	NM	NA	NA	NA	NA
Styrene	NM	NA	NA	NA	NA
Toluene	NM	NA	NA	NA	NA
Xylenes	NM	NA	NA	NA	NA

Table 6-7

Emission Factors
Gas Turbine
(Continued)

Compound	Emission Factor (g/hp-hr)	No. of Tests	No. of Turbines	Emission Factor Range (g/hp-hr)	
				Maximum	Minimum
Semi-Volatile Organic Compounds					
Acenaphthene	0.0	1	1	NA	NA
Acenaphthylene	0.0	1	1	NA	NA
Anthracene	0.0	1	1	NA	NA
Benz(a)anthracene	0.0	1	1	NA	NA
Benzo(a)pyrene	0.0	1	1	NA	NA
Benzo(e)pyrene	0.0	1	1	NA	NA
Benzo(b)fluoranthene	0.0	1	1	NA	NA
Benzo(g,h,i)perylene	0.0	1	1	NA	NA
Benzo(k)fluoranthene	0.0	1	1	NA	NA
Biphenyl	1.0×10^{-4}	1	1	NA	NA
Chrysene	9.5×10^{-7}	1	1	NA	NA
Dibenz(a,h)anthracene	0.0	1	1	NA	NA
Fluoranthene	0.0	1	1	NA	NA
Fluorene	0.0	1	1	NA	NA
Indeno(1,2,3-c)pyrene	0.0	1	1	NA	NA
2-Methylnaphthalene	0.0	1	1	NA	NA
Naphthalene	4.6×10^{-6}	1	1	NA	NA
Perylene	0.0	1	1	NA	NA
Phenanthrene	0.0	1	1	NA	NA
Phenol	1.5×10^{-5}	1	1	NA	NA
Pyrene	0.0	1	1	NA	NA
Criteria Pollutants					
NO_x	1.3	2	1	1.3	1.2
CO	0.0	2	1	0.0	0.0
THC	0.0	2	1	0.0	0.0
NMHC	0.0	2	1	0.0	0.0
NMEHC	0.0	2	1	0.0	0.0

NA = Not applicable.

NM = Not measured.

Table 6-8

Emission Factor Comparison
2-Stroke Lean-Burn
(g/hp-hr)

Compound	GRI Test Data	GRI Literature Data	EPA AP-42
Air Toxics			
Acetaldehyde	1.0×10^{-2}	2.7×10^{-3}	NA
Acrolein	0.0	1.8×10^{-3}	NA
Benzene	3.7×10^{-3}	6.6×10^{-3}	1.6×10^{-3}
Ethyl benzene	1.9×10^{-4}	NA	8.2×10^{-4}
Formaldehyde	1.8×10^{-1}	8.8×10^{-2}	1.3
Naphthalene	1.3×10^{-4}	NA	NA
Propylene	0.0	NA	NA
Toluene	2.2×10^{-3}	1.6×10^{-3}	1.6×10^{-3}
Xylenes	4.6×10^{-4}	NA	2.5×10^{-3}
Criteria Pollutants			
CO	6.7×10^{-1}	NA	1.5
NMHC	1.1	NA	4.3×10^{-1}
NO_x	$1.3 \times 10^{+1}$	NA	$1.1 \times 10^{+1}$
THC	6.2	NA	6.1

NA = Not available.

Table 6-9

Emission Factor Comparison
2-Stroke Clean-Burn
(g/hp-hr)

Compound	GRI Test Data	GRI Literature Data	EPA AP-42
Air Toxics			
Acetaldehyde	6.7×10^{-3}	NA	NA
Acrolein	2.0×10^{-2}	NA	NA
Benzene	1.0×10^{-3}	NA	NA
Ethyl benzene	0.0	NA	NA
Formaldehyde	1.6×10^{-1}	NA	NA
Naphthalene	6.4×10^{-6}	NA	NA
Propylene	NA	NA	NA
Toluene	9.0×10^{-4}	NA	NA
Xylenes	4.0×10^{-4}	NA	NA
Criteria Pollutants			
CO	1.4	NA	1.8
NMHC	NA	NA	5.0×10^{-1}
NO_x	4.8×10^{-1}	NA	2.6
THC	6.8	NA	4.5

NA = Not available.

Table 6-10

Emission Factor Comparison
4-Stroke Rich-Burn
(g/hp-hr)

Compound	GRI Test Data[a]	GRI Literature Data	EPA AP-42
Air Toxics			
Acetaldehyde	0.0	3.9×10^{-3}	2.8×10^{-4}
Acrolein	0.0	3.4×10^{-3}	1.7×10^{-4}
Benzene	NA	4.6×10^{-3}	3.2×10^{-3}
Ethyl benzene	NA	NA	NA
Formaldehyde	1.0×10^{-1}	6.2×10^{-2}	7.2×10^{-3}
Naphthalene	NA	NA	2.2×10^{-4}
Propylene	NA	NA	7.2×10^{-4}
Toluene	NA	1.6×10^{-3}	1.0×10^{-3}
Xylenes	NA	1.4×10^{-3}	2.7×10^{-4}
Criteria Pollutants			
CO	$1.5 \times 10^{+1}$	NA	8.6
NMHC	NA	NA	1.4×10^{-1}
NO_x	$1.8 \times 10^{+1}$	NA	$1.0 \times 10^{+1}$
THC	3.0	NA	1.2

[a]Based on low-load measurements

NA = Not available.

Table 6-11

Emission Factor Comparison
4-Stroke Lean-Burn
(g/hp-hr)

Compound	GRI Test Data Direct-Injected	GRI Test Data Port-Injected	GRI Literature Data	EPA AP-42
Air Toxics				
Acetaldehyde	2.0×10^{-2}	0.0	1.7×10^{-2}	NA
Acrolein	0.0	0.0	7.4×10^{-3}	NA
Benzene	NA	2.1×10^{-4}	4.3×10^{-3}	NA
Ethyl benzene	NA	0.0	NA	NA
Formaldehyde	4.0×10^{-2}	1.4×10^{-1}	1.0×10^{-1}	NA
Naphthalene	NA	3.8×10^{-5}	NA	NA
Propylene	NA	NA	NA	NA
Toluene	NA	0.0	2.7×10^{-2}	NA
Xylenes	NA	0.0	9.0×10^{-4}	NA
Criteria Pollutants				
CO	5.5×10^{-1}	9.8×10^{-1}	NA	1.6
NMHC	NA	0.0	NA	0.72
NO_x	$2.2 \times 10^{+1}$	$1.1 \times 10^{+1}$	NA	$1.2 \times 10^{+1}$
THC	2.5	4.9	NA	4.9

NA = Not available.

Table 6-12

Emission Factor Comparison 4-Stroke Clean-Burn (g/hp-hr)

Compound	GRI Test Data	GRI Literature Data	EPA AP-42
Air Toxics			
Acetaldehyde	0.0	NA	NA
Acrolein	2.0×10^{-2}	NA	NA
Benzene	NA	NA	NA
Ethyl benzene	NA	NA	NA
Formaldehyde	2.3×10^{-1}	NA	NA
Naphthalene	NA	NA	NA
Propylene	NA	NA	NA
Toluene	NA	NA	NA
Xylenes	NA	NA	NA
Criteria Pollutants			
CO	2.0	NA	NA
NMHC	NA	NA	NA
NO_x	5.6×10^{-1}	NA	NA
THC	8.0	NA	NA

NA = Not available.

Table 6-13

Emission Factor Comparison
Gas Turbines
(g/hp-hr)

Compound	GRI Test Data	GRI Literature Data	EPA AP-42
Air Toxics			
Acetaldehyde	2.0×10^{-2}	NA	NA
Acrolein	0.0	NA	NA
Benzene	NA	NA	NA
Ethyl benzene	NA	NA	NA
Formaldehyde	0.0	1.6×10^{-2}	NA
Naphthalene	4.6×10^{-6}	NA	NA
Propylene	NA	NA	NA
Toluene	NA	NA	NA
Xylenes	NA	NA	NA
Criteria Pollutants			
CO	0.0	NA	8.3×10^{-1}
NMHC	0.0	NA	1.0×10^{-2}
NO_x	1.3	NA	1.3
THC	0.0	NA	1.8×10^{-1}

NA = Not available.

Table 6-14

Major Source Criteria

Engine Family	Formaldehyde (g/hp-hr)	Plant Size at 10 ton/yr[a] (hp)	Number of Test/Engines Used In Emission Factor
2-stroke clean-burn	0.16	6,500	3/1
2-stroke lean-burn	0.18	5,800	12/5
4-stroke clean-burn	0.23	4,500	1/1
4-stroke lean-burn (direct injected)	0.04	25,900	1/1
4-stroke lean-burn (port-injected)	0.14	7,400	3/2
4-stroke rich-burn[b]	0.10	10,400	1/1

[a] Major source definition under 40 CFR Part 63.

[b] Based on a low-load test.

Table 6-15

PM_{10} Emission Rates (ton/yr)

Engine Family	Engine Make/Model	Campaign No.	Load[c] (%)	PM_{10} Emissions	
				Particulate	Condensible
2-stroke clean-burn	Cooper GMVC-10C[a]	4	89	0.03	1.66
4-stroke rich-burn	Waukesha L7042GU[b]	4	95	0.03	0.47
4-stroke lean-burn	Cooper LSV-16 (Engine 102)	3	101	0.006	2.01
	Cooper LSV-16 (Engine 101)	3	99	0.02	0.86
	Ingersoll KVS 412 (Engine 8)	4	82	0.02	1.03

[a] After CO catalyst.

[b] After NSCR catalyst.

[c] For all engines except the LSV-16 engines, hp was measured directly by an engine analyst. For the LSV-16 engines, hp was recorded from the station's control system.

Table 6-16

Metal Species Concentrations
(μg/dscf)

Species	Ingersoll KVG-103[a]		Cooper 10V-275[b]	Clark TCV-10[b]
	Test ID 60	Test ID 61	Test ID 4	Test ID 1
Antimony	ND	ND	ND	ND
Arsenic	0.014	0.016	ND	0.006
Beryllium	ND	ND	ND	ND
Cadmium	0.01	0.018	0.0034	0.0012
Chromium	0.055	0.11	0.017	0.064
Cobalt	0.006	0.012	0.001	0.007
Lead	0.21	0.18	0.015	0.2
Manganese	0.022	0.14	0.56	0.095
Mercury	0.0005	0.001	0.001	0.02
Nickel	0.031	0.15	0.034	0.047
Selenium	0.006	ND[c]	ND	0.009

[a] 4-stroke rich-burn.

[b] 2-stroke clean-burn.

[c] ND = Non-detectable.

7.0 QUALITY ASSURANCE/QUALITY CONTROL SUMMARY

The goals of quality assurance/quality control (QA/QC) procedures are to ensure the collection of representative samples, the control of data quality during sample analysis, and the use of valid data handling procedures to provide a link between the analytical results and the physical conditions they represent. This section describes the QA/QC procedures used in the field and laboratory and summarizes the overall QA/QC results. Table 7-1 presents a summary of QA/QC criteria and results from all test campaigns. Specific QA/QC results from each test campaign are given in Appendix C.

7.1 Process Data Quality

Where available, process data were recorded at 15 or 30-minute intervals throughout each test period. At the end of each day, a copy of the process data collected was reviewed by the Radian field engineer. In addition, ambient conditions (e.g., temperature, barometric pressure, relative humidity) were recorded at the beginning and end of each test. With the exception of the data from Campaign 3A, all horsepower data presented in this report were measured directly off the compressor by an engine analyst. Where present, pocket unloaders were inspected to insure proper operation and tight seals. Based on the procedures followed, the horsepower and torque measurements are expected to be accurate within ±5 percent. The engines tested at site 3A during Campaign 3 were equipped with centrifugal compressors which complicate direct measurement of horsepower. Therefore, all horsepower data were obtained from the station control system. Insufficient documentation on sensor calibrations was available from the site to quantify the level of accuracy associated with the horsepower data. However, when compared to fuel flow measurements and expected heat rates for these engine models, the horsepower values correlated well.

Exhaust flow rates were determined through EPA Methods 2 and 19. Method 2 utilizes pitot tube velocity measurements and temperature data to calculate volumetric flow rate. Method 19 uses the fuel flow rate, a conversion based on combustion stoichiometry from amount of fuel burned to exhaust flow rate (F_d factor), and O_2 concentration to determine volumetric flow rate. Accurate pitot tube

Table 7-1

Summary of Quality Control Procedures

Method	Criteria	Control Limits	Percentage of Samples Meeting Criteria
Manual Sampling			
EPA 0012	Percentage Isokinetic	100 ± 10%	100
EPA 0010	Percentage Isokinetic	100 ± 10%	88
CARB 429	Percentage Isokinetic	100 ± 10%	100
EPA 201A	Percentage Isokinetic	100 ± 10%	88
Field Sampling/Analytical Procedures			
EPA 7E EPA 10 EPA 25A EPA 3A	Daily Drift (zero and span)	± 10% of span	100
	Inner-Run QC Check (zero and midrange)	± 10% of span	99
	Multiple Inner-Run QC Checks	$\leq$ 5% RSD[a]	99
	Response Time	Less than 1 minute	100
	Line Leak Check	<0.5% O_2	100
	Manifold Leak Check	<0.5% O_2	100
EPA 7E	NO_2 to NO Conversion Efficiency	>90% Conversion	100
FTIR	Daily QC Checks	± 10% of QC value	87
	Daily Leak Check	Less than 10 torr/minute at 20% of normal operating pressure	100
	Daily Pathlength Check	Pathlength within 5% as measured with Freon standard	100
	Baseline Stability	± 0.1 Absorbance units	100
EPA 18	Linearly Multipoint Calibration	Correlation Coefficient (R)>0.995	88

Table 7-1

Summary of Quality Control Procedures (Continued)

Method	Criteria	Control Limits	Percentage of Samples Meeting Criteria
Laboratory			
EPA 0010	Surrogate Recoveries	QC Parameters within limits specified in EPA Method 8270 (compound dependent)	100
CARB 430	Matrix Spike Samples	70-130% Recovery	83
	Duplicate Analysis	± 20% Relative Percent Difference	87
CARB 429	Field Spike Samples	50-150% Recovery	100
	Calibration Check Compounds	70-130% Recovery	100
	Laboratory control samples	50-150% Recovery	100
	Surrogate Recoveries	50-150% Recovery	100
EPA 0012	Laboratory QC Sample	± 25% of known value	100
EPA 0030	Surrogate Recoveries	QC parameters within limits specified in EPA Methods 5040 and 8240 (compound dependent)	100
	Duplicate Analyses	± 20% Relative Percent Difference	100

[a]RSD = relative standard deviation.

measurements are complicated by the pulsations caused by noncontinuous exhaust flow from each piston in reciprocating engines. Therefore, in most campaigns, Method 19 exhaust flow rates were used to determine emission rates, except when fuel flow rates were not available or considered inaccurate. Fuel flow measurements and current flow meter calibration records were reviewed by the engine consultant.

Jon Tice, with Air Sciences and Engine Technology, was the engine consultant for this project. Mr. Tice conducted a visual inspection of the reciprocating engines for Campaigns 3, 4, and 6 to identify any major mechanical problems. Several engines required minor maintenance (bad spark plugs or leaking fuel valves) or balancing during Campaigns 4 and 6. Mr. Tice also worked with the engine analyst during Campaigns 4 and 6 to properly balance the engines. Final data summaries for Campaigns 3, 4, and 6 were reviewed by Mr. Tice for an overall QA/QC check of the operational results.

Based on evaluation of the quality of certain process data, some engines were not included in the development of emission factors. These include the Clark TCV-10, Cooper 10V-275, and two Ingersoll-Rand KVS-103 engines tested in Campaign 1, as well as one Cooper-Bessemer GMVA-10 engine tested in Campaign 4. Due to problems identified with the accuracy of the horsepower and fuel flow measurements collected from the Campaign 1 station monitoring equipment, no values are presented in this document for the engines at this site that rely upon either of these parameters. The GMVA-10 tested during Campaign 4 was not part of the planned Campaign 4 test matrix and was excluded from all analyses in this report due to suspect fuel flow measurements.

7.2 Continuous Emission Monitors Data Quality

QA procedures for the CEM systems were implemented according to the reference methods. These specifications include requirements to determine calibration drift, relative accuracy, and precision of the instruments. The primary method of measuring these parameters was daily analysis of control standards.

7.2.1 CEM Calibration Check

Analyzer calibration was performed prior to the start of tests each day. Analyzer response for O_2, NO_x, CO, THC, and CO_2 was set using zero and high-level calibration gases introduced through the entire CEM system. After the zero and span checks, the linearity of the instruments was checked through analysis of midrange control standards.

7.2.2 CEM Drift Checks

Between test runs and after the completion of monitoring each day, instrument-specific zero and high-level QA/QC gases were introduced through the entire CEM system and measured by the corresponding instrumentation to evaluate measurement drift. The percent difference, relative to span, between the postsampling measured values for the QA/QC standards and the presampling zero and span settings was calculated to evaluate instrument drift. Calculated drift was less than the specified level of 10 percent for all engine tests.

7.2.3 CEM Relative Accuracy and Precision

Directly after completion of instrument calibration, an instrument-specific midrange QA/QC standard was circulated through the entire CEM system and measured by the corresponding instrumentation. The percent difference between the measured concentration of the QA/QC standard and the known concentration for each species was calculated to quantify measurement bias (accuracy). For O_2, CO_2, CO, and NO_x, the percent difference is calculated relative to instrument span. For THC, the percent difference is calculated relative to the QA/QC input. This procedure was repeated periodically throughout each test day to calculate an average bias for each species measurement. 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 using the ratio of the response standard deviation to the average of the response values and multiplying by 100.

All but two measurement biases were within the specified level of 10 percent. Precision measurements were greater than the specified level of 5 percent for THC and CO_2 on 2 days.

7.2.4 FTIR Method Data Quality

The FTIR instrument does not require introduction of a span gas for instrument calibration. Quantitation is based on reference spectra representing each of the species measured at various temperatures and concentrations. Daily analysis of a representative control standard was used to determine the measurement bias of the FTIR. All but 12 of 94 bias measurements were within the 10 percent range specified in the test plan.

7.3 Manual Sampling Methods Data Quality

QC procedures for the manual sampling and analysis methods consisted of the following procedures: field blank samples, field spiked samples, replicate samples, laboratory matrix spike and matrix spike duplicates (MS/MSD), laboratory control samples, surrogate recoveries, and evaluation of sampling conditions (i.e., isokinetics, leak rates).

7.3.1 CARB Method 429 Data Quality

CARB Method 429 was used during Campaign 4 to measure semi-volatile organic compound levels in engine exhaust. QC procedures for this method include surrogate recoveries and duplicate analyses. During the CARB Method 429 tests, all recoveries met the 50 to 150 percent range specified by the method. Duplicate analyses were all within 20 percent relative percent difference, and isokinetic sampling and leak checks were all within acceptable limits (±10 percent isokinetics, <0.02 acfm leak rate).

7.3.2 CARB Method 430 Data Quality

CARB Method 430 was used to measure aldehyde emission levels. Data on precision of the CARB Method 430 results were obtained by performing duplicate analyses. Of the 90 duplicate analyses performed, 12 were outside the specified 20 percent range. Many of these exceedances were caused by conducting measurements near the method detection limit.

Four different types of spike recovery data were collected for CARB Method 430 QA/QC purposes:

- Laboratory matrix spikes;
- Field spikes;
- Laboratory trip spikes; and
- Laboratory spikes.

In a laboratory matrix spike, a known quantity of spiking solution is added to a sample already recovered in the field to evaluate the presence of interfering constituents in the recovered spike solution. Field spikes are performed on-site by the sampling team as a check of sample recovery quality. A known quantity of formaldehyde is added to a set of impingers that has not been exposed to flue gas. The spiked impinger solutions are then recovered following the standard sample recovery procedure. Laboratory trip spikes are samples shipped to the test site with DNPH solutions, recovered on-site, and shipped back to the laboratory. These spikes can identify possible interferences due to sample handling. The laboratory spike is performed in the laboratory to check the accuracy of analytical equipment.

The results of most of the spike recoveries were acceptable. All but 23 of 132 spiked sample recoveries were within the acceptable 70 to 130 percent range. Many of the poor recoveries were due to matrix effects and spiking at inappropriate levels (e.g., a low-level spike in a high-level sample).

7.3.4 Method 18 Data Quality

Speciation of THC emissions was performed through GC analyses, as specified in EPA Method 18. The QC procedures specified in Method 18 were followed. The retention times of the analytes of interest were determined using certified calibration gases. Calibration curves were developed for the quantitation of all analytes. QA/QC results from the GC show that all but 7 of the 33 linearity checks exhibited correlation coefficients less than 0.995. Three of the seven outliers are attributed to the use of only two points to generate the calibration curve slope, thus no correlation coefficient could be calculated.

7.3.5 SW-846 Method 0010 Data Quality

Data quality for SW-846 Method 0010 for semi-volatile organic compounds measurements was evaluated through surrogate recovery tests and sampling conditions. Surrogate recoveries were measured for 80 samples and none were outside the specified range of 70 to 130 percent. Sampling condition results show that of the 16 tests, 2 isokinetic sampling rates were outside the 90 to 110 percent range and no leak checks were greater than the specified rate of 0.02 acfm.

7.3.6 SW-846 Method 0030 VOST Data Quality

Volatile organic compounds were measured in Campaign 1 using SW-846 Method 0030. QA/QC procedures for this analysis include sample recovery measurements and duplicate analyses. During this campaign, all of the sample recoveries were within the acceptable range of 70 to 130 percent, and relative percent differences and standard deviations for the duplicate analyses were within the specified 20 percent range.

8.0 RECOMMENDATIONS FOR FUTURE RESEARCH

To gain a better understanding of formaldehyde emissions from reciprocating engines, several areas of additional research are recommended as follows:

- Conducting measurements under a wider range of engine operating conditions to gain a more fundamental understanding of the parameters that influence formaldehyde emissions. Tests of engines in the field with more operational flexibility and in a test stand environment would be helpful.
- Collecting additional field data on other engine models/units in those engine families that have exhibited higher formaldehyde levels and for which little data are available (i.e., 2-stroke clean-burn, 4-stroke lean-burn, and 4-stroke clean-burn). The current database is very limited and needs to be expanded.
- Evaluating potential formaldehyde reduction strategies, including reductions possible via process or combustion modifications and add-on controls. The availability, effectiveness, and cost of the controls should also be investigated.
- Further investigating aldehyde emissions from natural gas-fired turbines. This would help determine the validity of the limited data indicating a higher level of acetaldehyde emissions than formaldehyde emissions. In addition, the significance of acetaldehyde emissions from a turbine to total site emissions could be clarified. If identified as a pollutant of concern, a better understanding of the mechanisms that influence acetaldehyde emissions would be helpful.
- Development of a risk screening tool should be considered. Such a tool should be compatible with existing GRI software (e.g., HAPCalc™) and allow the user the opportunity to perform sensitivity analyses on key variables.

Ongoing GRI research will likely pursue a portion of this work, with a near term focus on the characterization of the impacts of operating conditions on formaldehyde emissions from reciprocating engines.

9.0 REFERENCES

1. Campbell, L.M., K.R. Ferry, and G.S. Shareef. *Preliminary Assessment of Air Toxics Emissions in the Natural Gas Industry (Phase I)*. Report No. GRI-94/0268, Chicago, Illinois, August 1994.

2. Ogle, L.D., J.P. LaCosse, and G.S. Shareef. *Fourier Transform Infrared (FTIR) Method Validation at a Natural Gas-Fired Internal Combustion Engine*. Report No. GRI-95/0271, Chicago, Illinois, December 1995.

3. Radian Corporation. *Measurement of Air Toxic Emissions from Combustion Equipment at Natural Gas Processing Plants*, Draft report. Report No. GRI-96/0010, Research Triangle Park, North Carolina.

4. Thompson, P.A., A.P. Espenscheid, D.B. Myers, and C.A. Berry. *Technical Reference Manual for GRI-GLYCalc™: A Program for Estimating Emissions from Glycol Dehydration of Natural Gas (Version 2.0)*. Report No. GRI-94/0228, Chicago, Illinois, July 1994.

5. Radian Corporation. *Results of the Glycol Waste Survey*, Draft report. GRI Contract No. 5088-254-1709, October 1991.

6. Skinner, F.D., D.L. Reif, and A.C. Wilson. *BTEX and Other VOC Emissions from a Natural Gas Amine Treater*, Draft report. GRI Contract No. 5094-220-2796.

7. American Petroleum Institute. *Emission Factors for Oil and Gas Production Operations*. API Publication No. 4615, January 1995.

8. Radian Corporation. *Protocol for Performing Extractive FTIR Measurements to Characterize Various Gas Industry Sources for Air Toxics*, Draft report. GRI Contract No. 5091-254-2293. Revised May 1995.

9. Westbrook, C. K. and F. L. Dryer. "Chemical Kinetic Modeling of Hydrocarbon Combustion." *Progressive Energy Combustion Science*. Volume 10, pp. 1-57, 1984.

10. Dean, A. M. "Shock-Tube Studies of Formaldehyde Oxidation." *Combustion and Flame*. Volume 37, pp. 41-62, 1980.

11. Tabayaski, K. and S. H. Bauer. "The Early Stages of Pyrolysis and Oxidation of Methane." *Combustion and Flame*. Volume 34, pp. 63-83, 1979.

12. Dean, A. M. "Shock-Tube Studies of Formaldehyde Pyrolysis." Presented at the Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1979.

13. Peeters, J. and G. Mahnen. "Reaction Mechanisms and Rate Constants of Elementary Steps in Methane-Oxygen Flames." Presented at the Fourteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1973.

14. Vardanyan, I. A. "Kinetics and Mechanism of Formaldehyde Oxidation - II." *Combustion and Flame*. Volume 22, pp. 153-159, 1974.

15. Tsang, W. and R. F. Hampson. "Chemical Kinetic Data Base for Combustion Chemistry. Part 1. Methane and Related Compounds." *Journal of Physical and Chemical Reference Data*, Volume 5, No. 3, pp. 1087-1279, 1986.

16. Kim, C. and D. E. Foster. *Aldehyde and Unburned Fuel Emission Measurements from a Methanol-Fueled Texaco Stratified Charge Engine*. Society of Automotive Engineers, Paper No. 852120, 1986.

17. Heywood, J. B. *Internal Combustion Engine Fundamentals*. McGraw Hill Inc., 1988.

18. Westbrook, C. K., W. J. Pite, and L. J. Clautman. *Toxic Emissions from Natural Gas Engines*, Draft report. Gas Research Institute, Chicago, Illinois, 1995.

19. Ishiguro, F., et al. "Combustion Characteristics of Neat Methanol in IDI Diesel Engine--Mechanism of Formaldehyde Formation." *JSAE Review*. Volume 14, No. 2, 1993.

20. Wilke, C., et al. *Exhaust Emissions Reduction for Existing Dresser-Rand Gas Engines*. Dresser-Rand Company, Painted Post, New York.

21. U.S. Environmental Protection Agency. "*Alternative Control Techniques Document--NO_x Emissions from Stationary Reciprocating Internal Combustion Engines*. EPA-453/R-93-032, July 1993.

22. Scull, N., C. Kim, and D. E. Foster. *Comparison of Unburned Fuel and Aldehyde Emissions from a Methanol-Fueled Stratified Charge and Homogeneous Charge Engine*. Safety of Automotive Engineers, Paper 861543.

23. Karst, U., A. H. J. Cromping, N. Bindings, U. Witting, and K. Cammann. "Determination of Aldehydes, Ketones, and Nitrogen Oxides in Automobile Exhaust." *American Environmental Laboratory*. Vol. 7, No. 2, pp. 32-33, March 1995.

24. Workman, G.S., R.G. Adams, and G.S. Shareef. *Criteria Pollutant Emissions from Internal Combustion Engines in the Natural Gas Industry*. GRI Report No. GRI-95/0270, December 1995.

25. Steel, R.G and J. H. Torrie, *Disciplines and Procedures of Statistics--A Biometrical Approach*, McGraw Hill Inc.

26. Luhman, D.J. *Emission Control of a Propane Fueled Small Utility Engine Utilizing Air/Fuel Ratio Control and Three-Way Catalyst*. Society of Automotive Engineers, Paper No. 932445, 1993.

27. U.S. Environmental Protection Agency. *Compilation of Air Pollution Emission Factors, 5th Edition. AP-42.* Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina.

Attachment

FTIR Validation Approval Letter

JU 2 9

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

JUL 21 1995

Mr. James M. McCarthy
Senior Technology Manager
Air Quality Research
Gas Research Institute
Chicago, Illinois 60631-3562

Dear Mr. McCarthy:

The "Fourier Transform Infrared (FTIR) Method Validation at a Natural-Gas Fired Internal Combustion Engine," which was submitted by Radian Corporation, can be considered valid according to Method 301 for this source and similar sources.

The Emission Measurement Center noted that the proposed protocol "Measurement of Select Hazardous Air Pollutants, Criteria Pollutants, and Moisture Using Fourier Transform Infrared Spectroscopy" was somewhat different than the procedure used in the 301 validation.

The validation test used an in-stack filter. Spiking was performed after the primary (in-stack) filter and before a secondary filter. The protocol has one external filter. Spiking is performed before the external filter.

Technically, the protocol that has been proposed is different from the procedures used in the 301 validation test. However, we consider spiking before the filter more stringent; therefore, we consider the protocol acceptable. Also, the performance specifications listed in the proposed protocol are more stringent than Method 301 requirements. For future use of the submitted protocol, the burden of proof of a similar source is normally up to the facility. However, as long as these proposed performance specifications are met, we see no need for additional proof of the similar source requirement. Therefore, the protocol you have proposed may be used at any gas-fired facility.

It should also be noted that the Maximum Achievable Control Technology standard for this source category is not scheduled until the year 2000. Therefore, any data submitted will be considered when the Emission Standards Division (ESD) is in the data collection phase of the regulation. The contact person in ESD is Amanda Agnew. The Emission Measurement Center contact for this source category is Foston Curtis. They can be reached at 919-541-5268 and 919-541-1063, respectively.

Sincerely,

David C Misenheimer

for William F. Hunt, Jr.
Director
Emissions, Monitoring, and
Analysis Division

cc: Amanda Agnew (MD-13)
Foston Curtis (MD-19)
Lori Lay (MD-19)