EPRI

# Formaldehyde and VOC Emissions from a Siemens-Westinghouse 501F Combustion Turbine with Lean Pre-Mix Combustors and SCR and CO Catalysts

*Technical Report*

# Formaldehyde and VOC Emissions from a Siemens-Westinghouse 501F Combustion Turbine with Lean Pre-Mix Combustors and SCR and CO Catalysts

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# PRODUCT DESCRIPTION

This report presents a summary of flue gas formaldehyde and volatile organic compounds (VOCs) measurements conducted at a Siemens-Westinghouse 501F gas-fired combustion turbine with lean pre-mix low-$NO_x$ combustors and selective catalytic reduction (SCR) and carbon monoxide (CO) catalysts.

## Results & Findings

Formaldehyde concentrations, as measured by the CARB (California Air Resources Board) 430 method using DNPH (dinitrophenylhydrazine) impingers, averaged 10 ppb in the turbine exhaust before the SCR and CO catalysts and 5 ppb at the stack. As measured by Fourier Transform Infrared (FTIR) Spectroscopy, formaldehyde concentrations averaged 47 ppb at the turbine exhaust, and 42 ppb at the stack over the same time periods. The discrepancy between the FTIR and the "traditional" CARB 430 method could not be resolved based on the limited measurements and methods comparison. It is not known which, if either, method is providing accurate measurements.

Measurements of VOCs at full operating load were below the method detection limit using both FTIR and the traditional summa canister method (EPA TO-14A). Emissions of formaldehyde, benzene, other VOCs, $NO_x$, and CO were higher at low loads than at full operating load but did not track each other well enough to use one to predict the other. Based on measurements using the CARB 430 method, formaldehyde removal across the CO and SCR catalysts was measured to be at least 50% at full load and 90% at 60% unit load.

## Challenges & Objectives

The objectives of this study were:

- To characterize formaldehyde emissions from "utility-size" combustion turbines with state-of-the-art lean premix low $NO_x$ combustors
- To evaluate the impact of CO catalyst on formaldehyde removal
- To evaluate the FTIR technique along with the traditional CARB 430 and EPA TO-14A methods.

The most significant challenges faced by this research were the complexities of trace organic measurements at low ppb levels.

## Applications, Values & Use

The results are relevant to permitting new combustion turbines.

## EPRI Perspective

These results summarize formaldehyde and VOC emissions data from a lean premix combustion turbine operating at several operating loads and transient conditions. The formaldehyde results from the FTIR did not compare well with the traditional CARB 430 method. Base full-load measurements of formaldehyde were 9 ppb at the turbine exhaust and 5 ppb at the catalyst outlet (stack) as measured by CARB 430, and 47 ppb at the turbine exhaust and 42 ppb at the catalyst outlet, as measured by FTIR. Since the quality assurance/quality control (QA/QC) for both methods does not indicate any issues or concerns, there is no specific data or results to determine which set of results accurately represents formaldehyde emissions. Previous work by others has indicated some potential biases between FTIR and CARB 430. However, these biases are much lower in magnitude than those measured in this study.

Measurements at lower loads and transient conditions indicated increased emissions of formaldehyde and VOCs. It should be noted that these operating conditions represent a small fraction of the operating time for most, if not all, turbines. Measurements for transient start-up and shutdown are extremely difficult due to the short durations (about 5-10 minutes) of these conditions. In addition, there is uncertainty in regards to the reliability of the continuous FTIR results, based on the lack of consistency with the traditional methods.

Additional trace organic measurements are planned to characterize other combustion turbine designs.

## Approach

Investigators measured formaldehyde and VOC emissions at the turbine exhaust and downstream of SCR and CO catalysts using two different sampling and analytical approaches, FTIR and “traditional” methods, specifically CARB 430 and EPA TO-14A.


## Keywords

Air toxics
Formaldehyde
Combustion turbines
FTIR
CO catalyst

# ABSTRACT

An emission testing program was conducted on a combined-cycle Siemens-Westinghouse 501F gas-fired combustion turbine with lean pre-mix low- $NO_x$ combustors, and a selective catalytic reduction (SCR) and carbon monoxide (CO) catalysts. The program included measurement of emissions of formaldehyde, benzene and other volatile organic compounds, as well as $NO_x$ and CO. Tests were conducted to characterize emissions at base load, at lower load rates, and during load transients including startup and shutdown of the gas turbine. The results of standard reference methods were compared with the results from the FTIR. Formaldehyde emissions were measured using California Air Resources Board (CARB) Method 430 using DNPH (dinitrophenylhydrazine) reagent and using Fourier Transform Infrared (FTIR) spectroscopy. The two methods did not compare well, although the methods for measurement of other pollutants compared more closely to the FTIR results. The QA/QC for both methods did not indicate any issues or concerns, thus it is not possible to determine which, if either, set of results accurately represents the actual formaldehyde emissions. The tests did provide results for emissions at various unit loads during startup and during operation at base load and 60% load.

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# 1
# INTRODUCTION

The Avogadro Group, LLC (Avogadro) and URS-Radian Corporation (URS) were contracted by the Electric Power Research Institute (EPRI) to perform a series of emission tests on a combined-cycle gas turbine with lean pre-mix low-$NO_X$ combustors. The unit tested included a Siemens-Westinghouse 501F combustion turbine with lean pre-mix low-$NO_X$ combustors, a heat recovery steam generator (HRSG), and selective catalytic reduction (SCR) and oxidation catalysts.

Tests were conducted at the gas turbine exhaust (i.e. upstream from any catalysts) and at the HRSG stack. The testing program was performed to meet several objectives, the most important of which were:

- To characterize formaldehyde and VOC emissions during operation at base load and lower load conditions, and during transients between loads.
- To provide data for use in regulatory and permitting applications for gas turbines.

In September 2003, EPA promulgated a final rule for formaldehyde emissions from new/reconstructed combustion turbines, requiring the combustion turbine to reduce the concentration of formaldehyde in the exhaust to 91 parts per billion by volume dry basis (ppbvd) or less, at 15 percent oxygen. This rule is available from EPA's web site, http://www.epa.gov/ttn/atw//turbine/turbinepg.html.

URS provided monitoring of concentrations of formaldehyde, VOC and other gases using a Fourier Transform Infrared (FTIR) spectroscopy in accordance to pertinent sections of EPA Test Method 320 "Measurement of Vapor Phase Organic and Inorganic Emissions by Extractive Fourier Transform Infrared (FTIR) Spectroscopy."

Avogadro provided the "conventional" reference method sampling and analysis for measurement of formaldehyde and VOC, as well as continuous monitoring of $NO_X$, CO, Total Hydrocarbon, $O_2$ and $CO_2$ concentrations.

The tests were conducted on October 9 through 14, 2002. The Avogadro test team included Kevin Crosby and Jimmy Chan. The URS team included Walt Gray and Steve Hill. Process operations and data collection were coordinated by Leonard Angello of EPRI.

The results of the tests are presented in this report, which includes descriptions of the facility and the sampling locations, descriptions of the testing procedures, calculations and results, and a summary of quality assurance procedures.

# 2
# EMISSION SOURCE INFORMATION

## Facility Description

The gas turbine unit is a Siemens-Westinghouse 501F combustion gas turbine with dry low-$NO_x$ combustors, and with a heat recovery steam generator (HRSG). The HRSG includes supplementary duct burners (with low-$NO_x$ burners) for additional steam production, and SCR and oxidation catalysts for control of emissions.

## Test Site Description, Gas Turbine Exhaust Duct

The gas turbine exhausts into the HRSG through a horizontal, rectangular duct that expands from 13 feet tall by 13 feet wide to 14 feet tall by 15 feet wide over a length of 13 feet (approximate dimensions). There is a single sampling port on the top of the duct. The port is a 1½-inch pipe section with a cap, and is located near the centerline of the duct. Access to the port was gained by ladder to a temporary scaffold across the top of the duct, and the probes were inserted vertically. A sketch of the duct layout is included in Figure 2-1.

A total of 8 sampling traverse points were located in the vertical cross-section of the duct according to EPA Method 1.

## Test Site Description, Turbine / HRSG Stack

The turbine/HRSG exhausts through a vertical, cylindrical stack that is 99 feet tall. The stack has an inside diameter of 19 feet and has four sampling ports, located 90 degrees apart in the same horizontal plane. The ports are 6-inch pipe sections with flanges (150 psi rating type) and caps. Access to the ports is by stairway to the top of the HRSG, then by ladder the last 16 feet to a permanent platform approximately 84 feet above ground level. The ports are approximately 32 feet (1.7 stack diameters) downstream from (or above) the HRSG duct transition to the stack, and 9 feet (0.5 diameters) upstream from the top of the stack. A sketch of the stack layout is included in Figure 2-2.

A total of 12 sampling traverse points were located according to EPA Method 1 for a traverse to determine the amount of stratification of the stack gases. Three points were used in each of four sampling ports.

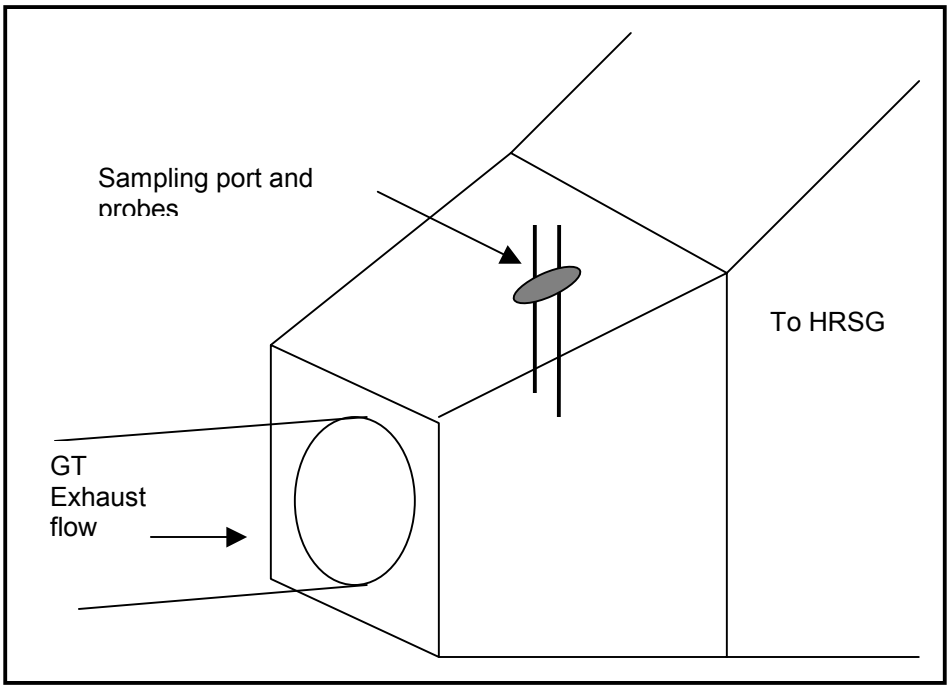



**Figure 2-1**
**Sampling Location, Gas Turbine Exhaust**

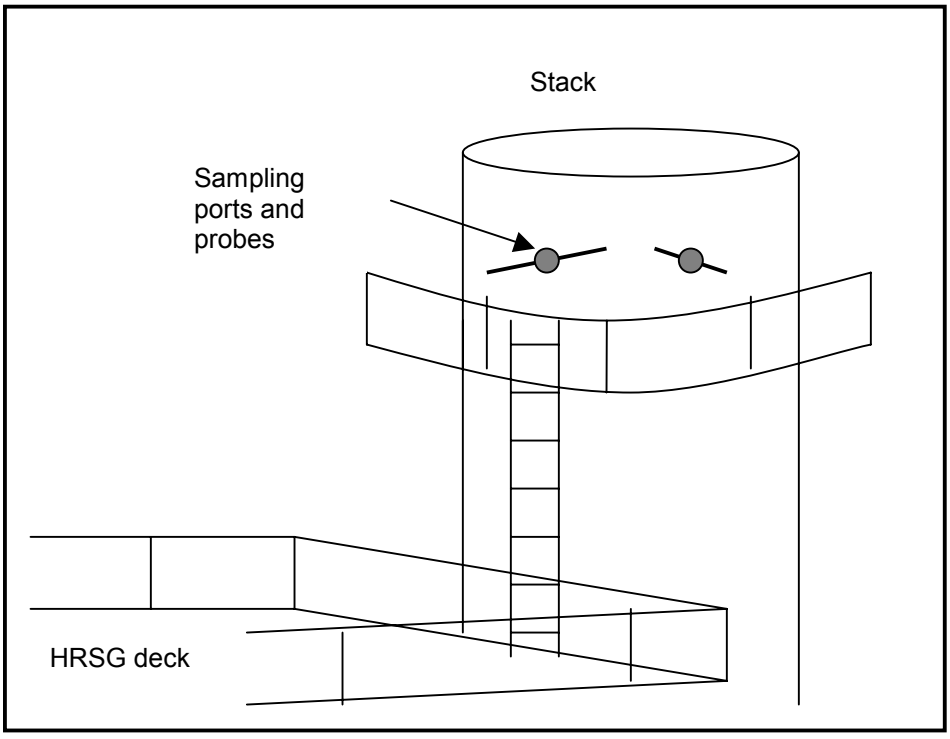



**Figure 2-2**
**Sampling Location, HRSG Stack**

# 3
# TEST PROGRAM DESCRIPTION

## Program Objective

The testing program was performed to meet several objectives, the most important of which were:

- To provide data for use by EPRI and EPA in evaluating MACT standards for gas turbines.
- To characterize emissions during operation at base load and lower load conditions, and to provide data using two test methods that are proposed by EPA for use in determining compliance with the MACT standard.

The first objective was met by testing during operation of the unit at base load. The second objective was enhanced by using both instrumental (FTIR) and "conventional" (DNPH/HPLC, GC, etc.) reference methods for measuring the emissions of formaldehyde ($H_2CO$) and other volatile organic compounds (VOC). The monitoring and testing of formaldehyde and VOC emissions were of critical importance in meeting the objectives. The monitoring and testing of the emissions of other compounds were of secondary importance; these compounds included $NO_X$ (NO and $NO_2$), CO, $NH_3$, $CH_4$, $H_2O$ and $CO_2$.

Avogadro provided measurements by "conventional" test methods:

- Sampling and analysis for formaldehyde and VOC emissions using CARB Method 430 and EPA Method TO-14A,
- Monitoring of concentrations and emissions of $NO_X$, CO, and total hydrocarbon using standard continuous emission monitoring analyzers,
- Monitoring of concentrations of $O_2$ and $CO_2$ using standard continuous emission monitoring analyzers.

URS provided measurements by FTIR:

- Monitoring of formaldehyde and VOC concentrations,
- Monitoring of concentrations of NO, $NO_2$, CO, $CH_4$, $NH_3$, and $H_2O$,
- Monitoring of concentrations of $CO_2$ by FTIR, and of $O_2$ with a standard continuous emission monitoring analyzer.

This draft report presents the results of the emission measurements at full load, at lower load rates, and during transient conditions.

## Process Conditions

Most of the tests were conducted during operation of the gas turbine at base load, with no duct burner firing in the HRSG. Tests were also conducted during unit shutdown and startup, and during operation at approximately 60%, 15% and 3% load conditions. The process conditions were determined and controlled by the facility's operators. Coordination of the testing and operation schedule was provided by EPRI.

## Test Schedule

The test schedule was adapted to fit the operation schedule of the gas turbine as shown in Table 3-1.

**Table 3-1**
**Testing Schedule**

| 1. Date | 2. Testing Activity, Reference Methods | 3. Testing Activity, FTIR |
|---|---|---|
| October 9, 2002 | 1117-1135 Preliminary Traverse<br>1500-1800 Base Load Test, GT Exhaust<br>1505-1805 Base Load Test, GT / HRSG | 1522-1810 Base Load Test, GT Exhaust<br><br>1953-2339 Base Load Test, GT Exhaust |
| October 9 to 10 | 2345-0107 Shutdown Test, GT Exhaust ($NO_x$, CO, THC only) | 2344-0130 Shutdown Test, GT Exhaust |
| October 10 | Unit Down | Unit Down |
| October 11 | 1858-2053 Startup Test, GT Exhaust ($NO_x$, CO, THC only)<br>1927-1932 Startup Formaldehyde Test<br>1950, 1954, 1958 Startup VOC Tests<br>2004-2009 25 MW "Level-off" Formaldehyde Test<br>2242-0042 95 MW Test, GT Exhaust<br>2236-0036 95 MW Test, GT / HRSG | 1858-2053 Startup Test, GT Exhaust<br><br><br><br><br>2058-0901 95 MW Test, GT Exhaust |
| October 12 | 1450-1750 Base Load Test, GT Exhaust<br>1445-1745 Base Load Test, GT / HRSG<br><br>1817-2117 Base Load Test, GT Exhaust<br>1811-2111 Base Load Test, GT / HRSG | 1420-2359 Base Load Test, switching between GT Exhaust and HRSG Stack |
| October 13 | -- | 0000-1429 Base Load Test, switching between GT Exhaust and HRSG Stack<br>2139-2359 Base Load Test, HRSG Stack |
| October 14 | -- | 0000-1007 Base Load Test, HRSG Stack |

# 4
# REFERENCE METHOD TESTING

## Overview

The testing program conducted by Avogadro included measurement of the emissions of criteria pollutants and toxic air contaminants. The tests included the measurement of gaseous emissions from the gas turbine exhaust duct and from the gas turbine/HRSG stack. Some samples were taken from both locations concurrently, but most were taken from one location or the other.

Avogadro provided measurements by "conventional" test methods:

- Sampling and analysis for formaldehyde and VOC emissions,
- Monitoring of concentrations and emissions of $NO_X$, CO, and total hydrocarbons using standard continuous emission monitoring analyzers,
- Monitoring of concentrations of $O_2$ and $CO_2$ using standard continuous emission monitoring analyzers.

## 4.1 Test Methods

Avogadro used standard EPA or CARB reference methods for the measurements made during the program. A list of the test methods is provided in Table 4-1.

**Table 4-1**
**Reference Test Methods and Detection Limits**

| Parameter | Reference Methods | Principle | Detection Limit |
|---|---|---|---|
| $NO_x$ | EPA 7E | Chemiluminescent Analyzer | 0.2 ppm vol dry |
| CO | EPA 10 (modified) | NDIR / Gas Filter Correlation Analyzer | 0.2 ppm vol dry |
| Total Hydrocarbons | EPA 25A | Flame Ionization Detector Analyzer | 0.2 ppm vol dry |
| $O_2$ | EPA 3A | Electrochemical Cell Analyzer | 0.05 % vol dry |
| $CO_2$ | EPA 3A | NDIR Analyzer | 0.05 % vol dry |
| Volumetric Flow Rate and Emission Rates | EPA 19 | Calculated from Stoichiometric Fuel Factor and measured Fuel Flow | N/A |
| Formaldehyde | CARB 430 | Absorption in DNPH solution,<br>Analysis by HPLC | 2 to 7 ppb vol dry<br>(CARB DL 7 ppb vol dry)<br>(CARB Reporting Limit 75 ppb vol dry) |
| Benzene | EPA TO-14A | Sampling into SUMMA Canister,<br>Analysis by GC/FID/MS | 0.3 ppb vol dry |
| Toluene,<br>Ethylbenzene,<br>*m* + *p* Xylenes<br>*o*-Xylenes | EPA TO-14A | Sampling into SUMMA Canister,<br>Analysis by GC/PID/MS | 0.5 ppb vol dry<br>0.3 ppb vol dry<br>0.5 ppb vol dry<br>0.4 ppb vol dry |

### *4.1.1 Gaseous Emissions / Diluent Gases*

$NO_X$, CO, $CO_2$, and $O_2$ concentrations were quantified by means of an extractive continuous emission monitoring (CEM) system maintained in a mobile laboratory. The CEM system is comprised of four basic subsystems. These subsystems are: 1) the sample conditioning and delivery system, 2) the calibration gas system, 3) the electronic analyzers, and 4) the data recording and acquisition system.

The sample conditioning and delivery system includes components to extract a representative sample from the source, remove the moisture and particulate matter from the sample stream, and transport the sample to the analyzers. The primary components of this subsystem are: 1) A stainless steel or glass probe - heated or insulated as necessary to avoid condensation, 2) Teflon tubing - connecting the probe to the sample conditioner and the sample conditioner to the analyzer manifold - heated or insulated as necessary to avoid condensation, 3) sample conditioner - glass or stainless steel flasks immersed in an ice bath to remove the moisture from the sample gas stream, 4) vacuum pump - a leak-free pump with Teflon diaphragm to transport the sample gas through the system, 5) sample manifold - a distribution system, constructed of stainless steel and Teflon tubing, to direct sample gas to the analyzers, and 6) sample flow rate control - a series of rotameters, vacuum gauges and pressure gauges connected to the manifold used to maintain the appropriate sample flow rates.

The calibration gas system utilizes only US EPA Protocol One gases to verify the operation, linearity, and range settings of the electronic analyzers. The sample gas system allows for the introduction of the protocol gases to the analyzers either directly through the manifold (calibration error check - performed once daily) or through the sampling system (system bias check - performed with each run).

The electronic analyzers are rack mounted and are maintained in the mobile lab. The data recording and acquisition system is based on a digital system known as STRATA. It includes software for controlling the collection of calibration and emission monitoring data, and hardware for connection of the analyzer outputs to the recording system. Test results can be provided in three forms; on-site printouts of the digitized data, diskette recordings of the digitized data, and printouts of strip charts from the monitoring data.

### *4.1.2 Total Hydrocarbons (THC)*

Concentrations of THC were monitored using a direct flame ionization detector (FID) analyzer according to EPA Method 25A. Sample was drawn from the sampling probe through a length of heated Teflon tubing by the analyzer's internal heated pump. Calibration gases were introduced through a "tee" at the connection between the probe and the heated Teflon line.

### 4.1.3 Formaldehyde

The concentrations of formaldehyde were measured using CARB Method 430. The sampling apparatus included a probe of quartz glass tubing (supported inside stainless steel tubing) connected by a length of 1/8 inch diameter Teflon tubing to a series of midget impingers immersed in an ice bath. The probe was inserted into the stack or duct and sample gas was drawn through the apparatus at a known flow rate using a vacuum pump and a calibrated critical orifice. The first two impingers contained DNPH solution and the third impinger contained silica gel. Field blank and field spike samples were taken in the same manner as the samples except that no sample gas was drawn through the blank and spike impingers. The DNPH solution was prepared and analyzed by Air Toxics, Ltd. of Folsom, CA using HPLC.

The sample volume and sampling time for each test run was determined using the pre-test planning calculations of Method 430. The test runs at base load were 3 hours in duration and collected approximately 70 liters of sample gas. The test runs at low load rates were of shorter duration, some only 5 minutes. The test results were calculated using the blank-corrected value rather than the CARB Method reporting limit.

### 4.1.4 Volatile Organic Compounds (VOC)

Concentrations of volatile organic compounds were measured using EPA Compendium Method TO-14A. Samples were drawn into evacuated SUMMA canisters, which were shipped to the laboratory for analysis. The GC/FID/PID/MS analyses included benzene, toluene, ethylbenzene and xylenes (BTEX).

### 4.1.5 Volumetric Flow and Emission Rates

Emission rates were calculated in units of lb/MMBTU from the measured concentrations and fuel factors using EPA Method 19. The stack gas volumetric flow rates were calculated from the measured fuel flow rates. The EPA factor Fd (dscf/MMBTU at stoichiometric conditions), the stack gas $O_2$ concentration, and the fuel higher heating value was used in the flow rate calculations. Emission rates were calculated in units of lb/hr where applicable using the measured concentrations and the calculated volumetric flow rates. The daily emission rates were calculated assuming 24-hour operation.

### 4.1.6 Mobile Laboratory

For the purposes of this test program, Avogadro mobilized a mobile laboratory to the site for the testing period. The mobile lab is equipped with storage cabinets and the CEM system, provides a temperature-controlled environment for the CEM instrumentation. There is sufficient room to work in the mobile van with spacious counter tops for sample recovery, calculation of results and completion of the sample chain of custody forms.

## 4.2 Test Results

The results of the emission tests at base load are summarized in Tables 4-2 and 4-3. The results of the tests at lower load rates are provided in Section 7. The symbol "<" denotes that the analyte was detected in some samples or fractions but not in all samples or fractions. The symbol "ND<" denotes that the analyte was not detected at the level stated, which represents the detection limit for that test run. For compounds that result below the detection limit, ½ the reported MDL was used for calculating the average concentrations.

**Table 4-2**
**Emission Test Results, Conventional Test Methods (Criteria Pollutants), Base Load**

| **Base Load** | **Gas Turbine Exhaust** | | | | **HRSG Stack** | | | |
|---|---|---|---|---|---|---|---|---|
| Test number | Run 1 | Run 9 | Run 10 | **Avg** | Run 2 | Run 7 | Run 8 | **Avg** |
| Date 2002 | 10-9 | 10-12 | 10-12 | **--** | 10-9 | 10-12 | 10-12 | **--** |
| Start / Stop time | 1117-1135 | 2012-2042 | 2111-2141 | **--** | 1658-1728 | 1607-1637 | 1643-1713 | **--** |
| $O_2$, % volume dry | 13.77 | 13.65 | 13.62 | **13.68** | 13.40 | 13.78 | 13.86 | **13.68** |
| $CO_2$, % volume dry | N/A | 4.132 | 4.095 | **4.114** | 4.314 | 4.071 | 4.094 | **4.160** |
| Fuel flow, kscfh | 1,939 | 1,936 | 1,936 | **1,937** | 1,939 | 1,938 | 1,938 | **1,939** |
| Stack flow rate, dscfm | 833,873 | 818,390 | 815,353 | **822,539** | 791,979 | 834,359 | 843,603 | **823,313** |
| Turbine Gross Output, MW | 155 | 160 | 160 | **158** | 155 | 161 | 161 | **159** |
| Aqueous Ammonia Rate, Klb/hr | 294 | 304 | 304 | **301** | 294 | 322 | 322 | **313** |
| **CO**, ppm vol dry | 0.7 | 1.1 | 1.0 | **0.9** | <0.2 | <0.2 | <0.2 | **<0.2** |
| ppm @ 15% $O_2$ dry | 0.6 | 0.9 | 0.8 | **0.8** | <0.2 | <0.2 | <0.2 | **<0.2** |
| lb/hr | 2.7 | 3.8 | 3.5 | **3.3** | <0.7 | <0.7 | <0.7 | **<0.7** |
| lb/day | 64 | 92 | 83 | **79** | <17 | <17 | <18 | **<17** |
| lb/MMBtu | 0.0014 | 0.0020 | 0.0018 | **0.0017** | <0.0004 | <0.0004 | <0.0004 | **<0.0004** |
| **$NO_x$**, ppm vol dry | 34 | 35 | 33 | **34** | 3.2 | 3.2 | 3.3 | **3.3** |
| ppm @ 15% O2 dry | 28 | 28 | 27 | **28** | 2.5 | 2.7 | 2.7 | **2.7** |
| lb/hr as $NO_2$ | 204 | 204 | 191 | **200** | 18 | 19 | 20 | **19** |
| lb/day as $NO_2$ | 4900 | 4892 | 4582 | **4792** | 441 | 466 | 474 | **460** |
| lb/MMBtu as $NO_2$ | 0.104 | 0.104 | 0.098 | **0.102** | 0.0094 | 0.0099 | 0.0101 | **0.0098** |
| **THC**, ppm vol dry | -- | 2.2 | <0.2 | **1.2** | -- | -- | -- | **--** |
| ppm @ 15% $O_2$ dry | -- | 1.8 | <0.2 | **0.9** | -- | -- | -- | **--** |
| lb/hr as $CH_4$ | -- | 4.5 | <0.4 | **2.4** | -- | -- | -- | **--** |
| lb/day as $CH_4$ | -- | 108 | <9.8 | **56** | -- | -- | -- | **--** |
| lb/MMBtu as $CH_4$ | -- | 0.0023 | <0.0002 | **0.0012** | -- | -- | -- | **--** |

Note: The symbol "<" denotes detection below the practical detection limit, which is the value shown.

**Table 4-3**
**Emission Test Results, Conventional Test Methods (Hazardous Air Pollutants), Base Load**

| **Base Load** | **Gas Turbine Exhaust** | | | | **HRSG Stack** | | | |
|---|---|---|---|---|---|---|---|---|
| Test number | Run 1 | Run 9 | Run 10 | **Avg** | Run 2 | Run 7 | Run 8 | **Avg** |
| Date, 2002 | 10-9 | 10-12 | 10-12 | **--** | 10-9 | 10-12 | 10-12 | **--** |
| Start / Stop time | 1500-1800 | 1450-1750 | 1817-2117 | **--** | 1505-1805 | 1445-1745 | 1811-2111 | **--** |
| $O_2$, % volume dry | 13.40 | 13.82 | 13.64 | **13.62** | 13.40 | 13.82 | 13.64 | **13.62** |
| Fuel flow, kscfh | 1,939 | 1,936 | 1,936 | **1,937** | 1,939 | 1,938 | 1,938 | **1,939** |
| Stack flow rate, dscfm | 791,979 | 834,359 | 818,390 | **814,909** | 791,979 | 834,359 | 818,390 | **814,909** |
| Turbine Gross Output, MW | 155 | 161 | 160 | **159** | 155 | 161 | 160 | **159** |
| Aqueous Ammonia Rate, Klb/hr | 294 | 322 | 304 | **307** | 294 | 322 | 304 | **307** |
| Formaldehyde | | | | | | | | |
| ppb vol dry (raw) | <10.4 | 21.3 | 7.8 | **11.4** | 9.5 | 4.1 | <7.0 | **5.7** |
| ppb @ 15% $O_2$ dry | <8.2 | 17.8 | 6.3 | **9.4** | 7.5 | 3.4 | <5.6 | **4.6** |
| lb/hr | <0.02 | 0.08 | 0.03 | **0.04** | 0.04 | 0.02 | <0.03 | **0.02** |
| lb/day | <0.9 | 2.0 | 0.7 | **1.1** | 0.9 | 0.4 | <0.7 | **0.5** |
| lb/MMBtu | <2.0E-5 | 4.3 E-5 | 1.5 E-5 | **2.3 E-5** | 1.8 E-5 | 0.8 E-5 | <1.4 E-5 | **1.1 E-5** |
| Benzene | | | | **(3 runs)** | | | | **(3 runs)** |
| ppb vol dry (raw) | | | | < 0.3 | | | | < 0.3 |
| ppb @ 15% $O_2$ dry | | | | < 0.25 | | | | < 0.25 |
| lb/hr | | | | <3.1E-5 | | | | <3.1E-5 |
| lb/day | | | | <7.6E-2 | | | | <7.6E-2 |
| lb/MMBtu | | | | <1.6E-6 | | | | <1.6E-6 |

Note: The symbol "<" denotes less than the practical detection limit, which is the value shown. ½ of the detection limit was used for purposes of calculating an average (except Benzene, see below).

Note: Emission rates for Benzene (lb/hr, lb/day, lb/MMBtu) have been calculated at the detection limit shown. Three 20-minute BTEX samples were taken during the period of Runs 7 and 9 to provide the average results shown. The test results at base load for Toluene, Ethylbenzene and Xylenes were all below detection limits, <0.5, <0.3, and <0.5 ppbv, respectively.

# 5
# FTIR MONITORING

## Overview

The testing program conducted by URS included continuous emission monitoring using a Fourier Transform Infrared (FTIR) Spectroscopy. The tests included the measurement of gaseous emissions from the gas turbine exhaust duct or from the gas turbine/HRSG stack. There were no concurrent samples from both locations, as sample could be drawn from just one location at a time.

URS provided measurements by FTIR:

- Monitoring of formaldehyde and VOC concentrations,
- Monitoring of concentrations of NO, $NO_2$, CO, $CO_2$, $CH_4$, $NH_3$, and $H_2O$,
- Monitoring of concentrations of $O_2$ with a standard continuous emission monitoring analyzer.

## 5.1 Introduction

Testing at this facility consisted of monitoring a natural gas-fired combustion turbine at varying loads during the time-span of October 7th through the 14th. The analytes of most interest for this testing were formaldehyde ($H_2CO$) and the "BTEX" VOC compounds (benzene, toluene, ethylbenzene, and the o-, m-, p-xylenes). Testing for formaldehyde was conducted according to pertinent sections of EPA Test Method 320 "Measurement of Vapor Phase Organic and Inorganic Emissions by Extractive Fourier Transform Infrared (FTIR) Spectroscopy." The primary objectives of this testing were:

- Provide data for regulatory and permitting purposes.
- Characterize formaldehyde and VOC emissions for transient conditions.
- Compare FTIR and wet-chemistry based methodologies (i.e., CARB Method 430) for measuring formaldehyde and other volatile organic compounds.

Of critical importance in meeting these objectives were the monitoring of formaldehyde and VOC emissions from the gas turbine during normal (base load) operation and start-up and shutdown procedures. Of secondary importance was the monitoring of other compounds such as $NH_3$, $NO_X$ [nitric oxide (NO) and nitrogen dioxide ($NO_2$)], methane ($CH_4$), and carbon monoxide (CO). The major constituents in combustion exhaust, water ($H_2O$) and carbon dioxide ($CO_2$), were also monitored via FTIR. To achieve these objectives, the following tasks were conducted:

- A laboratory study to document the performance of the FTIR system to monitor the analytes of interest and to determine the minimum detection limits (MDLs) for each.
- Data collection in accordance with EPA Method 320 guidelines to document the formaldehyde emissions from the gas turbine.
- Data collection using a sample conditioning system (for water and carbon dioxide removal) to monitor for the BTEX compounds.
- Develop a functioning FTIR analysis method to quantify all other constituents of interest.

Sampling of the exhaust gas stream was performed on a continuous basis using an extractive FTIR system. This sampling technique enables highly sensitive, real-time monitoring of all target compounds simultaneously. In addition to Method 320, pertinent sections of URS's ISO 9001 document "Protocol for Extractive FTIR Monitoring"[1] and its accompanying "Extractive FTIR System Checklist" were followed to ensure data were collected at a known quality. Descriptions of the FTIR method and calibration data obtained before continuous monitoring commenced at the test site, discussion of the validation results, sampling data collected, and the special considerations noted throughout testing are provided below.

## 5.2 Principles of Extractive FTIR Monitoring

Almost every chemical compound has a unique absorption pattern of infrared (IR) light that can be used to identify and quantify that species in a complex mixture of gases. As governed by Beer's Law, the magnitude of a compound's IR absorbance is directly proportional to the product of its concentration in the mixture and the sample cell optical path length. The extractive FTIR instrument is able to achieve parts-per-billion (ppb) detection levels because a cell is used that reflects the IR beam between a series of mirrors before it reaches the detector. The optical path that the gas sample is exposed to can then be set to a desired length before measurements are taken. The path length, once field calibrated, is an important parameter in the infrared spectrum analysis method used to determine compound concentrations.

### *5.2.1 Spectrum Analysis Method*

An infrared spectrum analysis is performed by matching the features of an observed spectrum to those of reference standards. If more than one feature is present in the same region, a linear combination of references is used to match the compound features. The standards are scaled to match the observed band intensities; this scaling also matches the unknown concentrations. The scaled references are added together to produce a composite that represents the best match with the sample. A classical least squares mathematical technique is used to match the standards' absorption profiles with those of the observed spectrum in specified spectral analysis regions.

1 Radian International LLC, *Protocol for Extractive FTIR Monitoring*. DCN 96-133-403-01 Revision 1.0. Austin, Texas, Oct. 1996.

Compounds of interest and any known compounds expected to present spectral interference are included in the analysis region.

An infrared spectrum can be collected and analyzed in approximately one second, but data are typically averaged over a five-minute integration period to produce adequate signal-to-noise and ppb level detection limits.

### *5.2.2 Creating the Spectrum Analysis Method*

The spectrum analysis method used for the turbine testing was developed by selecting the spectral regions and sub-regions that minimize interference from the primary IR absorbers ($H_2O$ and $CO_2$, in this case) while also optimizing the detection of the target compounds. Typically, an analysis method will be iteratively refined by using it to analyze a representative set of infrared spectra, while varying the method. The optimum method is indicated when both the error bars and the bias on the individual compounds are minimized. Table 5-1 summarizes the references used in the method (described in terms of the compound's concentration and cell path length used when the reference was recorded). In addition to the compounds listed in Table 5-1, formic acid ($HCO_2H$) and hydrochloric acid (HCl) were also observed during the routine spectral analysis done as part post-test data QC.

Of the compounds listed in Table 5-1, all but $H_2O$, $CO_2$, and CO had periods where their concentrations fell below the detection limit of the FTIR. For those compounds, which were observed near the instrument's noise level, MDLs were calculated. This was achieved by analyzing sets of spectra from the turbine exhaust when only interferants were present (the compounds of interest were absent by spectral investigation). When applied to this series, the analytical method should return a set of values centered about zero. The MDL is then estimated by taking three times the standard deviation of that data scatter. If the data scatter is scattered about a non-zero value, it is indicative of a method bias and bias correction procedures are invoked. These field MDL results obtained for each target compound are provided below.

**Table 5-1**
**FTIR Analysis Method Parameters**

| Analyte | Reference Used |
|---|---|
| CO (carbon monoxide) | 50 ppm @ 10.0 m |
| $CH_4$ (methane) | 2000 ppm @6.0 m |
| NO (nitric oxide) | 248 ppm @ 10.8 m |
| $NO_2$ (nitrogen dioxide) | 14 ppm @ 26 m |
| $H_2CO$ (formaldehyde) | 4.2 ppm @ 10.0 m |
| $CH_3CHO$ (acetaldehyde) | 50 ppm @ 6.7 m |
| $CH_3OH$ (methanol) | 48 ppm @ 13 m |
| $C_7H_8$ (toluene) | 97 ppm @ 3.4 m |
| $C_6H_6$ (benzene) | 100 ppm @ 3.4 m |
| $C_8H_{10}$ (m-Xylene) | 305 ppm @ 1.0 m |
| $C_8H_{10}$ (o- Xylene) | 313 ppm @ 1.0 m |
| $C_8H_{10}$ (p- Xylene) | 286 ppm @ 1.0 m |
| $C_8H_9$ (ethyl benzene) | 17.7 ppm @ 3.6 m |
| $NH_3$ (ammonia) | 33 ppm @ 26 m |
| Interferents: | |
| $H_2O$ (Water) | 9.92% @ 57.0 m |
| $CO_2$ (Carbon Dioxide) | 4.0% @ 68.5 m |

m = meters, ppm = parts per million

## 5.3 FTIR Procedures

### *5.3.1 Laboratory Evaluation*

The objective of the laboratory evaluation was to document the FTIR measurement performance for formaldehyde and the BTEX compounds in a sample matrix similar to that of combustion turbine exhaust. An apparatus was set up to simulate the expected gas stream concentrations of the most prominent interferents, water and carbon dioxide. This was accomplished by generating a heated, humidified gas stream and blending it with nitrogen and carbon dioxide gas

standards. This gas stream was then monitored by the FTIR for several hours to determine any biases as well as to detection limits based on 3 times the standard deviation. A NIST traceable standard of the formaldehyde was injected, at known volumes, into this gas stream and subsequently reduced to a point where it was no longer possible to maintain a constant injection flow of the formaldehyde standard (1.7 ppm formaldehyde/13.4 ppm $SF_6$). Based on limitations of the mass flow controller, the minimum formaldehyde concentration spiked was approximately 20 ppb. This gas stream was also spiked with a NIST traceable BTEX standard and directed through a water and $CO_2$ scrubber. Again the biases were determined and MDLs were calculated. The MDL results are presented in Table 5-2.

### *5.3.2 Field Measurements*

Independent measurements of the inlet and exhaust gas streams of the combustion turbine were sampled for both formaldehyde and BTEX compounds. The effectiveness of the FTIR in monitoring low levels of BTEX compounds strongly depends on the ability to remove (scrub) CO2 from the sample. Therefore, a soda lime scrubber and Perma-Pure dryer were put inline as a scrubbing device for $CO_2$ and water respectively. The soda lime scrubber also removes all polar compounds (formaldehyde, HCl, $NH_3$, etc.). It was not possible to monitor for these components during times when the sample was conditioned.

The samples were extracted from two sampling locations available on the turbine. While the outlet location was ideal (no flow disturbances - 8 duct diameters down or 2 duct diameters up stream), the inlet sampling location did not meet these requirements. However, velocity measurements were made and the probe was positioned such that it was central to the mean of the flow with respect to velocity. Due to high temperatures at the inlet location, a glass-lined probe was used, whereas, at the cooler outlet location, a stainless probe was used to extract the gas sample. The outlet probe was positioned such that it drew sample from the central axis of the airflow of the stack. Heated extraction lines (150 feet long at the outlet and 100 feet at the inlet), containing polyfluoroalcohol (PFA) grade Teflon™ tubing, were used to deliver stack gas to the heated FTIR sample cell. All compounds were analyzed on a hot/wet basis to ensure that no analyte losses occurred due to condensation.

### *5.3.3 Analytical Method Characterization*

An analytical method was developed for monitoring the analytes expected in the turbine exhaust stream. The estimates of the MDLs for the target compounds displayed in Tables 5-2 were determined via the procedures described above.

**Table 5-2**
**FTIR MDL Evaluation**

| Compound | Laboratory Evaluation MDL (ppm) | Actual Field MDL (ppm) | Method 320 Quantitation Limit (ppm) |
|---|---|---|---|
| CO (carbon monoxide) | 0.010 | Not Available | 0.251 |
| $CH_4$ (methane) | 0.035 | 0.090 | 0.317 |
| $C_2H_4$ (ethylene) | Not Included | 0.027 | 0.268 |
| NO (nitric oxide) | 0.052 | 0.258 | 1.51 |
| $NO_2$ (nitrogen dioxide) | 0.050 | 0.360 | 0.327 |
| $H_2CO$ (formaldehyde) | 0.008 | 0.012 | 0.0135 |
| $CH_3CHO$ (acetaldehyde) | 0.009 | 0.169 | 0.816 |
| $CH_3OH$ (methanol) | Not Included | 0.033 | 0.097 |
| $C_7H_8$ (toluene)* | 0.028 | 0.428 | 0.131 |
| $C_6H_6$ (benzene)* | 0.016 | 0.260 | 0.128 |
| $C_8H_{10}$ (m- Xylene)* | 0.030 | 0.260 | 0.369 |
| $C_8H_{10}$ (o- Xylene)* | 0.022 | 0.501 | 0.126 |
| $C_8H_{10}$ (p-Xylene)* | 0.017 | 0.212 | 0.266 |
| $C_8H_9$ (ethyl benzene)* | 0.024 | 0.189 | 0.289 |
| $NH_3$ (ammonia) | 0.010 | 0.018 | 0.093 |

*Derived from scrubbed data

Although most of the laboratory-based MDLs were comparable to those observed in the field, significant differences were observed for some compounds. These different MDLs are related to the different $H_2O$ and $CO_2$ contents in the laboratory and field samples. The gas stream generated in the laboratory contained approximately half the moisture content that was observed in the field (5% in laboratory to 10% actual), and the laboratory study was conducted in a controlled and stable environment. These differences in moisture contents were contributing factors for the slight differences in MDLs for most compounds. However, for compounds such as BTEX the differences were greater and are related to the ability to remove $CO_2$ from the sample gas. During the laboratory study, the $CO_2$ was removed more effectively than was possible in the field due to the higher water concentrations.

### *5.3.4 Extractive FTIR System*

A description of the URS extractive FTIR system used for this project, as well as the steps followed in validating the FTIR spectrometer/analysis method, are included in the following subsections.

#### 5.3.4.1 System Description

A fully integrated system consisting of a Nicolet FTIR spectrometer and a 12.5-liter sample cell (with an infrared path length set to approximately 60 m) was used to perform the testing. The approximate cell mirror spacing was 0.8 meters, and the 0.13-meter ID cell chamber was a nickel-coated aluminum tube. Gold-coated glass mirrors were used to minimize degradation of the reflective surface from moisture or any reactive gases in the exhaust stream. The IR beam exiting the sample cell was detected by a liquid nitrogen-cooled Mercury/Cadmium/Telluride detector, a photoconductive device that produces an electrical voltage proportional to the amount of IR light that strikes it. The FTIR scans were recorded while sampling a dynamic flow (at ~8 liters per minute) of gas using a diaphragm pump through the probe assembly, the heated (185$^{o}$C) Teflon™ line, and the heated (185$^{o}$C) FTIR cell. The cell pressure was continuously monitored during measurement periods using an Omega pressure sensor calibrated over the 200 to ~800 torr range and incorporated in each spectral analysis. Instrumental resolutions were set at approximately 0.5 cm$^{-1}$ and signal averaging was performed over five-minute intervals.

The probe and extraction system diagrammed in Figure 5-1 was similar to the one used for sampling throughout data collection at the gas turbine. The only difference was that the sampling system used on-site had the heated extraction connected directly to the probe without any unheated sections. The field system accommodated delivery of both scrubbed and unscrubbed samples. This was done using a series of heated solenoid valves that, when turned on, redirected the sample through a Perma-Pure dryer and soda lime scrubber prior to entering the FTIR cell. A diaphragm pump at the outlet of the FTIR continuously drew the samples through the extractive system.

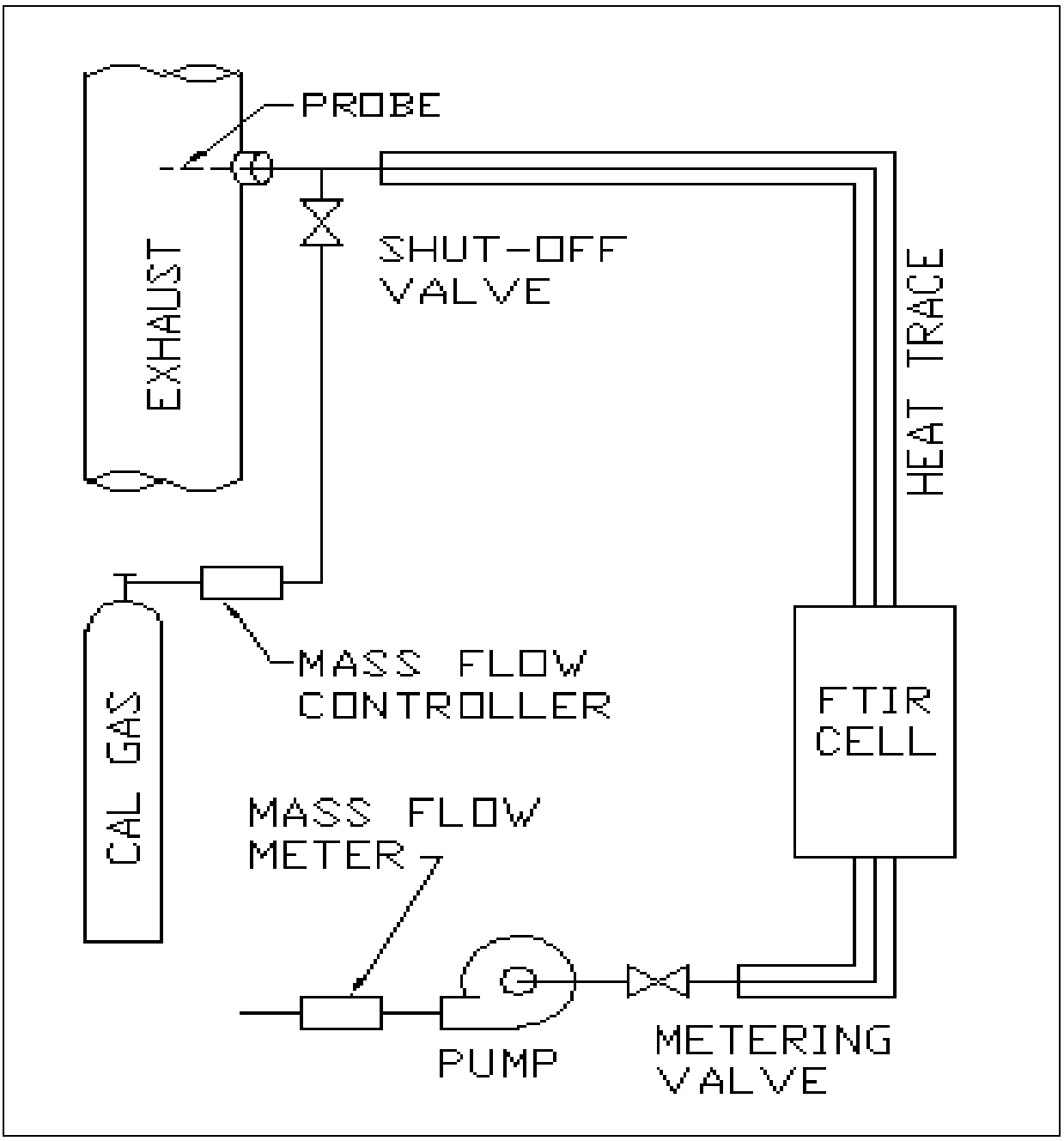



**Figure 5-1**
**FTIR Sampling System Schematic**

### 5.3.4.2 FTIR Calibration/Validation Procedures

A series of field calibrations was completed with the extractive FTIR system in order to ensure data of highest quality. A description of these calibrations/validations is given below.

#### *5.3.4.2.1 Field Validation*

As per EPA Method 320 and the URS Protocol, the following on-site procedures were performed to validate the analysis method before sampling began:

1. **Calibrated cell path length using a gas mixture containing R-22 in nitrogen with NIST certified concentrations**

   The NIST certified R-22 gas cylinder was attached directly to the FTIR's cell using a gas regulator and PFA Teflon™ tubing. After the sample cell was sufficiently flushed with the certified gas mixture, a 1.5-minute signal averaged spectrum (64 scans), at ~0.5 $cm^{-1}$ resolution was recorded. The integrated area of the main R-22 absorption band (centered at ~1120 $cm^{-1}$) was then measured and compared to a reference spectrum obtained from the URS spectral library. The ratio of the two areas, ($A_{cell}/A_{ref}$), was computed and the cell path length could then be calculated by invoking the relationship described in Equation 5-1:

   $$path = \frac{C_{ref} * L_{ref} * P_{ref} * T_{cell}}{C_{cell} * P_{cell} * T_{ref}} * \left( \frac{A_{cell}}{A_{ref}} \right)$$ **Equation 5-1**

   where $C_{ref} * L_{ref}$ is the concentration-path length product for the reference spectrum, $P_{ref}$ and $T_{ref}$ the absolute pressure and temperature at which the reference was measured, $P_{cell}$ and $T_{cell}$ the absolute pressure and temperature of the cell, and $C_{cell}$ is the R-22 concentration in the gas mixture used to perform the calibration. Inserting the values recorded on-site gave a path length of approximately 60 meters. This calibrated value was then used for all subsequent measurements.

2. **Checked for spectrometer resolution and frequency line shifts using ambient air.**

   According to the URS protocol, the FTIR spectrometer was verified to have met resolution specifications before testing commenced. After sufficiently purging the sample cell with ambient air, a 0.5 $cm^{-1}$ resolution, five-minute signal-averaged spectrum was recorded. The resolution was checked by measuring the line-width, at half-maximum, of two isolated water absorption bands centered at 1187.02 $cm^{-1}$ and 1149.46 $cm^{-1}$, respectively. The half-widths were then entered into Table 5-3 for comparison with the predicted line widths.

   The extractive FTIR spectrometer resolutions were deemed acceptable for turbine exhaust testing, since the observed line widths were found to be no larger than 1.1 times the predicted line widths for this type of FTIR.

**Table 5-3**
**Predicted vs. Measured Line Widths for 0.5 $cm^{-1}$ Resolution**

| Line Type Position ($cm^{-1}$) | Predicted Line Width ($cm^{-1}$) | Observed Line Width from FTIR ($cm^{-1}$) Inlet/Outlet |
|---|---|---|
| $H_2O$ @ 1187.02 | 0.513 | 0.535 |
| $H_2O$ @1149.46 | 0.510 | 0.542 |

The same ambient air spectra recorded for resolution verification were analyzed for the existence of spectrometer line shifts. The deuterated water (HDO) absorption lines in the 2776.0 $cm^{-1}$ to 2780.7 $cm^{-1}$ region were compared with the same bands present in the water reference spectrum used in the analysis method. No line shifts greater than 1/10 of the operating resolution were observed, so line shifting algorithms were not needed for the analysis method.

3. **Recorded periodic cell backgrounds consisting of dynamic fills with dry nitrogen.**

   The sample cell "blanks" (backgrounds) were recorded by purging the cell thoroughly with ultra-high purity nitrogen before testing commenced. Subsequent sample spectra were then ratioed against the new backgrounds prior to quantification. Backgrounds were collected on a daily basis at a minimum.

#### *5.3.4.2.2 System Validation*

Field validation of select target compounds, at various concentration levels, was conducted while on site. The validations were conducted using NIST traceable standards spiked on top of stack gas. The QA standard for all the formaldehyde Method 320 spikes was a 1.7 ppm formaldehyde/13.4 ppm $SF_6$ mix. The QA validations were necessary in both characterizing the extraction apparatus and cell interactions toward the primary compounds of interest, and verifying that the analysis method would return accurate concentrations. The validation results and pertinent discussions are presented below.

### *5.3.5 FTIR Data Handling*

FTIR raw and processed data were stored on computer hard disk, transferred to backup storage media, and kept in a secure location after the completion of the testing. All quantification routines used to process the data were backed up on compact disks and saved on the system hard drive.

## 5.4 Discussion of FTIR Results

### *5.4.1 Methodology*

In accordance with EPA Method 320, QA and Calibration Transfer Standard (CTS) tests were performed to ensure the FTIR system was operating correctly and producing data of the highest integrity. Deviations from this method were minor and are as follows:

- Pre-test calculations, with the exception of instrument operating calculations, were not necessary. A laboratory study was conducted and FTIR data had been collected on many occasions at similar sites, therefore expected concentration levels had been established and analytical quantification methods developed. The quantification methods were slightly improved after testing began to better account for spectral line shifts and interferences. All data collected prior to the final method improvements were reanalyzed with the finalized quantification method.
- The QA spike done on October 11 was done on top of stack gas as dictated by EPA Method 320 however, the turbine was not running as the QA spike was done.
- There was no inline filter used during sampling. The particulate loading was not expected to be high and the extraction line temperature was not sufficient to decompose most particulate. Therefore, the absence of an inline filter should not have any effect on the sample.
- The Teflon™ calibration line, which delivered the QA standards to the inlet spiking "T", was unheated. This line was virgin Teflon™ and had been purged with nitrogen to ensure that no water was present. These precautions ensured that the formaldehyde was delivered to the spiking tee dry and contaminant free.
- The tests were defined by the Avogadro Group's sampling team in conjunction with the plant and were based on the ability to coordinate data collection at the required operating conditions. Since the FTIR is automated, it ran while Avogadro staff collected data for multiple tests. Method 320 QA spikes and CTS tests were done within 24-hours of the sampling runs but not immediately prior to or after each individual test.
- The gas bottle regulator used on the formaldehyde QA standard was not a purgeable regulator. However the regulator used was corrosive resistant, heated, and solely used for formaldehyde.

### *5.4.2 QA Spiking*

As per EPA Method 320 QA spikes of formaldehyde were done at three different levels. In addition to the analyte of interest, each QA spiking gas standard contained a component to be used as a spectroscopic tracer. Common properties to all spectroscopic tracers are that they exhibit a broad absorption profile over a large concentration range and they are chemically inert. The linear behavior of the spectroscopic tracer allows a precise measurement of the dilution ratio of the spiked gas to native gas. For the Method 320 QA spike this dilution ratio was determined

using $SF_6$ and applied to calculate the theoretical formaldehyde concentration using the following equation:

$$H_2CO_{Theoretical} = \left(\frac{SF_{6sample}}{SF_{6cylinder}}\right)\left(H_2COc_{ylinder}\right) + \left[1 - \left(\frac{SF_{6sample}}{SF_{6cylinder}}\right)\right]\left(H_2CO_{stack}\right)$$

Where:

$H_2CO_{Theoretical}$ = Theoretical $H_2CO$ concentration (ppm)
$SF_{6sample}$ = $SF_6$ concentration (ppm) as seen by the FTIR during QA spiking
$SF_{6cylinder}$ = The concentration (ppm) of $SF_6$ in the NIST traceable gas standard
$H_2CO_{cylinder}$ = The concentration (ppm) of $H_2CO$ in the NIST traceable gas standard
$H_2CO_{stack}$ = The concentration (ppm) of $H_2CO$ in the stack during stable conditions

The criterion for a successful QA test is a measured concentration within 0.7-1.3 times the calculated theoretical concentration[1]. Spikes at three levels were conducted and each spike met the Method 320 criterion. The results of the QA spiking are present in Table 5-4.

[1] "Test Method 320 – Vapor Phase Organic and Inorganic Emissions by Extractive FTIR".
[1] http://www.epa.gov/ttn/emc/Promgate.html

**Table 5-4**
**Method 320 CTS Results**

| Spike Level | QA Run | Date/Time | Calculated (ppm) | Actual (ppm) | Recovery | Comments |
|---|---|---|---|---|---|---|
| High | #1 Pre Test | 10/8/2002 16:54 | 0.361 | 0.430 | 119.2% | Pass |
| Mid | #1 Pre Test | 10/8/2002 17:03 | 0.094 | 0.113 | 119.4% | Pass |
| Low | #1 Pre Test | 10/8/2002 17:14 | 0.048 | 0.058 | 120.1% | Pass |
| | **TEST #1** | Start: 8/16:54 | | | | |
| High | #1 Post Test | 10/9/2002 19:01 | 0.735 | 0.870 | 118.4% | Pass |
| Mid | #1 Post Test | 10/9/2002 19:11 | 0.403 | 0.450 | 111.8% | Pass |
| Low | #1 Post Test | 10/9/2002 19:22 | 0.202 | 0.211 | 104.5% | Pass |
| | **TEST #2** | Start: 10/1749 | | | | |
| High | /#2 Pre Test | 10/11/2002 11:34 | 0.526 | 0.600 | 114.1% | Pass |
| Mid | #2 Pre Test | 10/11/2002 11:58 | 0.399 | 0.452 | 113.3% | Pass |
| Low | #2 Pre Test | 10/11/2002 11:46 | 0.270 | 0.338 | 124.9% | Pass |
| | **TEST #3** | Start: 11/1449 | | | | |
| High | #2 Post Test/#3 Pre Test | 10/12/2002 10:30 | 0.510 | 0.466 | 91.3% | Pass |
| Mid | #2 Post Test/#3 Pre Test | 10/12/2002 10:42 | 0.360 | 0.341 | 94.6% | Pass |
| Low | #2 Post Test/#3 Pre Test | 10/12/2002 10:54 | 0.194 | 0.202 | 103.8% | Pass |
| | **TEST #4** | Start: 12/1628 | | | | |
| High | #3 Post Test | 10/13/2002 16:06 | 0.568 | 0.410 | 72.2% | Pass |
| Mid | #3 Post Test | 10/13/2002 16:31 | 0.382 | 0.272 | 71.4% | Pass |
| Low | #3 Post Test | 10/13/2002 16:21 | 0.195 | 0.189 | 96.9% | Pass |

### *5.4.3 Calibration Transfer Standard (CTS) Results*

Calibration transfer standard (CTS) tests were conducted on a daily basis. The primary purpose of the CTS tests is to verify that the FTIR instrument conditions are stable throughout the testing period. Two parameters, the integrated area of a selected absorbance band and frequency position of a narrow absorbing band, were measured to insure that the FTIR did not change throughout the course of sampling. The criteria for a successful CTS run is a difference in the integrated area of no greater than 5% between pre- and post-test CTS standards and a frequency reproducibility of +/- 0.06 wave numbers ($cm^{-1}$). A NIST traceable standard containing 10.0 ppm R22 (integrated area) and 10.0 ppm CO (frequency position) was used as the CTS standard. Table 5-5 lists the results of the pre- and post- CTS runs.

**Table 5-5**
**Method 320 CTS Results**

| Date/Time | R22 Integrated Area | % Difference | CO Line Position | Comments |
|---|---|---|---|---|
| 10/9 12:12 | 30.789 | N/A Initial setting | 2094.836 | Pre Test # 1 |
| 10/10 16:58 | 30.672 | 0.4 | 2094.836 | Post Test #1 |
| 10/11 09:42 | 31.019 | -1.1 | 2094.836 | Pre Test #2 |
| 10/12 09:48 | 29.530 | 4.8 | 2094.836 | Post Test #2/ Pre Test #3 |
| 10/13 15:15 | 28.447 | 3.7 | 2094.836 | Post Test #3 |

### *5.4.4 FTIR Testing Results*

The results, as well as all other testing considerations, are presented chronologically in this section. Table 5-6 is a timeline for the FTIR monitoring that shows which test site (gas turbine exhaust or "inlet," HRSG stack or "outlet") was monitored and which gas stream (e.g., scrubbed/unscrubbed, turbine down) was flowing to the FTIR. A data point was collected every 5-minutes. Tables 5-7 and 5-8 present summaries of data collected throughout the testing:

- Unless otherwise stated, all concentrations are provided on a wet basis in units of ppmv. Those compounds having values less than their respective field MDL are listed as BDL - Below Detection Limit.
- For compounds that had periods where the FTIR concentration result was below the detection limit of the FTIR, ½ the reported field MDL was used for calculating the average concentrations. If this resulting average was below the MDL, then a less the MDL was reported for this compound.

**Table 5-6**
**Timeline of Collected FTIR Data**

| Date/Time | Turbine Operation | FTIR Sample | Comments |
|---|---|---|---|
| 10/8-10/9 1522 | Base Load | Inlet /Setup | Calibrations and Meth. 320 QA spike |
| 10/9 1522-1810 | Base Load | Inlet/Unscrubbed | |
| 10/9 1810-1953 | Base Load | Inlet/Unscrubbed | Meth. 320 QA spike |
| 10/9 1953-2339 | Base Load | Inlet/Unscrubbed | |
| 10/9 2349 – 10/10 0130 | Shut Down | Inlet/Unscrubbed | Initial Shut Down |
| 10/10 0130-1408 | Turbine Down | Inlet/Unscrubbed | Stagnant Turbine Exhaust |
| 10/10 1408-1825 | Turbine Down | No Sampling | |
| 10/10 1825 - 10/11 0253 | Turbine Down | Inlet/Unscrubbed | Stagnant Turbine Exhaust |
| 10/11 0258-0528 | 2 Cold Start Attempts | Inlet/Unscrubbed | Both Attempts Failed |
| 10/11 0258-0854 | Turbine Down | Inlet/Unscrubbed | Stagnant Turbine Exhaust |
| 10/11 0854-1206 | Turbine Down | Inlet/ Meth. 320 QA spike | Stagnant Turbine Exhaust |
| 10/11 1206-1449 | Turbine Down | No Sampling | |
| 10/11 1454-2053 | 3 Cold Start Attempts | Inlet/Unscrubbed | Turbine Up after 3rd Start |
| 10/11 2058 - 10/12 0901 | To 95 MW | Inlet/Unscrubbed | |
| 10/12 0905-1415 | Base Load | Inlet & Outlet Unscrubbed | Meth. 320 QA spike |
| 10/12 1415-1604 | Base Load | Outlet/Both* | 30-min. cycle time* |
| 10/12 1608-1725 | Base Load | Inlet/Both* | 30-min. cycle time* |
| 10/12 1731-2018 | Base Load | Outlet/Both* | 30-min. cycle time* |
| 10/12 2018-2353 | Base Load | Inlet/Both* | 30-min. cycle time* |
| 10/12 2353 - 10/13 1453 | Base Load | Outlet/Both* | 30-min. cycle time* |
| 10/13 1453-1651 | Base Load | Outlet | Meth. 320 QA spike |
| 10/13 1651-2139 | -- | -- | Generate Water Reference |
| 10/13 2139 - 10/14 1007 | Base Load | Outlet/Unscrubbed | Additional Data |

**Table 5-7**
**Daily FTIR Results of Unscrubbed Data, Base Load (Wet Basis)**

| | | CH2O (ppm) | H2O (% vol) | CO2 (% vol) | CO (ppm) | CH4 (ppm) | NH3 (ppm) | NO2 (ppm) | NO (ppm) | NOx (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10-13 Outlet | *Min* | 0.024 | 8.87 | 3.63 | 1.58 | 0.55 | 7.82 | 2.88 | BDL | 3.12 |
| begin 10/13 2139 | *Max* | 0.047 | 11.35 | 3.78 | 1.88 | 0.75 | 11.18 | 3.67 | 1.36 | 5.03 |
| end 10/14 1007 | *Avg* | 0.031 | 9.99 | 3.72 | 1.68 | 0.62 | 9.22 | 3.41 | 0.73 | 4.14 |
| | | | | | | | | | | |
| 10-12 Inlet | *Min* | 0.040 | 9.23 | 3.56 | 2.26 | 0.94 | BDL | 5.34 | 23.46 | 28.80 |
| begin 10/12 1702 | *Max* | 0.052 | 11.13 | 3.95 | 3.49 | 1.34 | BDL | 6.72 | 34.99 | 41.71 |
| end 10/13 1133 | *Avg* | 0.048 | 10.16 | 3.81 | 3.17 | 1.09 | <0.018 | 6.09 | 27.14 | 33.23 |
| | | | | | | | | | | |
| 10-12 Outlet | *Min* | 0.031 | 10.22 | 3.17 | 0.70 | 0.68 | 7.88 | 3.15 | BDL | 3.38 |
| begin 10/12 1420 | *Max* | 0.065 | 11.89 | 3.76 | 1.68 | 1.10 | 12.41 | 3.82 | 1.23 | 5.05 |
| end 10/13 1429 | *Avg* | 0.050 | 10.59 | 3.63 | 1.19 | 0.90 | 10.57 | 3.51 | <0.26 | 3.93 |
| | | | | | | | | | | |
| 10-9 Inlet | *Min* | BDL | 10.14 | 3.67 | 1.90 | BDL | BDL | BDL | 32.85 | 33.03 |
| begin 10/9 1522 | *Max* | 0.098 | 12.47 | 3.97 | 2.31 | 0.17 | BDL | BDL | 34.34 | 34.52 |
| end 10/9 1800 | *Avg* | 0.064 | 11.30 | 3.87 | 2.10 | 0.06 | <0.018 | <0.012 | 33.63 | 33.81 |

| | | C7H8 (ppm) | C6H6 (ppm) | mXYLN (ppm) | oXYLN (ppm) | pXYLN (ppm) | ETHBZ (ppm) | C2H4 (ppm) | CH3OH (ppm) |
|---|---|---|---|---|---|---|---|---|---|
| 10-13 | *Min* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| Outlet | *Max* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| | *Avg* | <0.43 | <0.26 | <0.26 | <0.50 | <0.21 | <0.19 | <0.027 | <0.033 |
| | | | | | | | | | |
| 10-12 | *Min* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| Inlet | *Max* | BDL | BDL | BDL | BDL | BDL | 1.476 | BDL | 0.282 |
| | *Avg* | <0.43 | <0.26 | <0.26 | <0.50 | <0.21 | 0.21 | <0.027 | <0.033 |
| | | | | | | | | | |
| 10-12 | *Min* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| Outlet | *Max* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| | *Avg* | <0.26 | <0.26 | <0.26 | <0.50 | <0.21 | <0.19 | <0.027 | <0.033 |
| | | | | | | | | | |
| 10-9 | *Min* | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| Inlet | *Max* | 1.603 | BDL | BDL | BDL | BDL | BDL | 0.056 | BDL |
| | *Avg* | 0.469 | <0.26 | <0.26 | <0.50 | <0.21 | <0.19 | <0.027 | <0.033 |

BDL – below detection limit; see Table 5-2 for the field MDL values for each analyte.
CH2O (formaldehyde), CH4 (methane), NH3 (ammonia)
C7H8 (toluene), C6H6 (benzene), XYLN (xylenes), ETHBZ (ethylbenzene),
C2H4 (ethylene), CH3OH (methanol)

**Table 5-8**
**Daily FTIR Results of Scrubbed Data, Base Load (Wet Basis)**

| | | CO (ppm) | CH4 (ppm) | C7H8 (ppm) | C6H6 (ppm) | mXYLN (ppm) | oXYLN (ppm) | pXYLN (ppm) | ETHBZ (ppm) | CH3OH (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 10-12 | *Min* | 1.99 | 0.39 | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| Inlet | *Max* | 3.36 | 0.71 | BDL | BDL | BDL | BDL | BDL | BDL | BDL |
| | *Avg* | 2.97 | 0.45 | <0.23 | <0.26 | <0.26 | <0.50 | <0.021 | <0.19 | <0.033 |
| | | | | | | | | | | |
| 10-12 | *Min* | 0.46 | 0.36 | BDL | 0.47 | BDL | BDL | BDL | BDL | BDL |
| Outlet | *Max* | 3.69 | 1.19 | BDL | 0.52 | BDL | 1.30 | 1.34 | 0.32 | 2.68 |
| | *Avg* | 2.51 | 0.60 | <0.23 | <0.26 | <0.26 | <0.50 | <0.021 | <0.19 | 0.22 |

BDL – below detection limit; see Table 5-2 for the field MDL values for each analyte.
CH4 (methane), C7H8 (toluene), C6H6 (benzene), XYLN (xylenes), ETHBZ (ethylbenzene), CH3OH (methanol)

**Table 5-9**
**Summary of Average Results, Gas Turbine Exhaust, FTIR Analyzer, Various Loads**

| **Load, MW** | **0** | **5** | **29** | **95.1** | **158** |
|---|---|---|---|---|---|
| Fuel Flow, scf/hr | 511 | 595 | 850 | 1284 | 1937 |
| $O_2$, actual % vol dry | 18.4 | 18.3 | 17.2 | 14.7 | 13.7 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 380 | 110 | 77 | 45 | 32 |
| CO, ppm vol dry @ 15% $O_2$ | 3034 | 4360 | 3066 | 173 | 2 |
| Methane, ppm vol dry @ 15% $O_2$ | 5536 | 2797 | 1968 | 7 | 1 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 191604 | 227104 | 121753 | 407 | 47 |
| Benzene, ppb vol dry @ 15% $O_2$ | ND< 260 | ND< 260 | ND< 260 | ND< 260 | ND< 260 |

The $O_2$ results shown are from the conventional analyzer operated by Avogadro.
The results at 0, 5 and 29 MW were taken during unit startup and represent short periods of time during which the load was held steady.

**Table 5-10**
**Results Summary, FTIR, Emissions from HRSG Stack, Base Load**

| **Downstream from Catalyst – HRSG Stack** | **Run 2** | **Run 7** | **Run 8** | **Average** |
|---|---|---|---|---|
| Date / Time | N/A | 10-12-02 1457-1603 | 10-12-02 1817-2012 | |
| Load, MW | N/A | 160 | 160 | 160 |
| $O_2$, % vol dry | N/A | 13.8 | 13.6 | 13.7 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | N/A | 3.4 | 3.5 | 3.5 |
| CO, ppm vol dry @ 15% $O_2$ | N/A | 0.7 | 1.0 | 0.9 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | N/A | 50.5 | 33.0 | 41.8 |
| Note: See Table 5-2 for details on detection limits for the FTIR analyzer. The run times shown are the periods averaged for the FTIR. The $O_2$ concentrations shown are from conventional analyzer as in Table 6-5. | | | | |

**Table 5-11**
**Results Summary, FTIR, Emissions from Gas Turbine Exhaust, Base Load**

| **Upstream from Catalyst – Gas Turbine Exhaust** | **Run 1** | **Run 9** | **Run 10** | **Average** |
|---|---|---|---|---|
| Date / Time | 10-9-02 1522-1810 | 10-12-02 1702-1722 | 10-12-02 2102-2117 | |
| Load, MW | 155 | 160 | 160 | 158 |
| $O_2$, % vol dry | 13.4 | 13.8 | 13.6 | 13.6 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 30 | 34 | 32 | 32 |
| CO, ppm vol dry @ 15% $O_2$ | 1.7 | 1.9 | 2.4 | 2.0 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 56.7 | 39.3 | 44.3 | 46.8 |
| Note: See Table 5-2 for details on detection limits for the FTIR analyzer. The run times shown are the periods averaged for the FTIR. The $O_2$ concentrations shown are from conventional analyzer as in Table 6-3. | | | | |

# 6
# RESULTS, BASE LOAD TESTS

## Emissions

A summary of the average test results for each test site and method is provided in Tables 6-1 and 6-2. The results from individual test runs are presented in Tables 6-3 through 6-6.

The average results shown in Tables 6-1 and 6-2 represent the average of two or three test runs at base load. The $O_2$ concentration measured by the conventional method was used for correction of all the measured concentrations to 15% $O_2$.

The calculation of the percent reduction for CO measured by conventional methods is an estimate based on the practical detection limit (DL) for CO of 0.2 ppm volume dry. Lower concentrations of CO can be detected, but the uncertainty in the measurement remains at approximately 0.2 ppm. If the actual downstream (stack) concentration of CO were 0.2 ppm, then the upstream concentration (gas turbine exhaust) would need to be 4 ppm or higher in order to show at least 95% reduction of CO.

A summary of the results for the individual test runs is presented in Tables 6-3 through 6-6. The results of both the FTIR tests and the conventional tests are provided as average concentrations for each test run period. Note that the test run times shown for the conventional methods are those for the formaldehyde tests. The concurrent $NO_x$ and CO test runs were shorter in duration.

**Table 6-1**
**Summary of Average Results, Conventional Methods, Base Load**

| Sample Location | Upstream from Catalysts – Gas Turbine Exhaust | Downstream from Catalysts – HRSG Stack | Percent Reduction |
|---|---|---|---|
| Load, MW | 158 | 158 | -- |
| $O_2$, % vol dry | 13.6 | 13.6 | -- |
| $NO_x$, ppm vol dry @ 15% $O_2$ | 28 | 2.7 | 90 |
| CO, ppm vol dry @ 15% $O_2$ | 0.8 | <0.2 | >78 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 9.4 | 4.6 | 51 |

Note: The symbol "<" denotes results below the practical detection limit value shown. ½ of the detection limit was used for purposes of calculating an average. The results shown are for the average of 2 or 3 runs at base load.

* The practical detection limit for CO concentrations was approximately 0.2 ppm. The percent reduction shown is an estimate based on that detection limit.

**Table 6-2**
**Summary of Average Results, FTIR Analyzer, Base Load**

| Sample Location | Upstream from Catalyst - Gas Turbine Exhaust | Downstream from Catalyst – HRSG Stack | Percent Reduction |
|---|---|---|---|
| Load, MW | 158 | 160 | -- |
| $O_2$, % vol dry | 13.6 | 13.7 | -- |
| $NO_x$, ppm vol dry @ 15% $O_2$ | 32 | 3.5 | 89 |
| CO, ppm vol dry @ 15% $O_2$ | 2.0 | 0.9 | 57 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 46.8 | 41.8 | 11 |

Note: The results shown are for the average of 2 or 3 runs at base load. The $O_2$ concentrations measured by Avogadro (by EPA Method 3A using a conventional CEM analyzer) were used for all the concentrations.

## Summary

The base load emission tests provide several important results. The two test methods provided similar results for $NO_X$ but different results for CO and formaldehyde. The results for the other compounds (BTEX, etc.) - although not summarized here - were below the detection limits for both FTIR and the conventional methods.

Both methods showed that the $NO_X$ emission reduction provided by the SCR was approximately 90 percent. The efficiency is dependent on the concentration of $NO_X$ at the turbine exhaust and on the amount of ammonia injected.

The CO results show very low concentrations at the turbine exhaust. These low concentrations at the catalyst inlet limited the measurable catalyst efficiency because the outlet concentrations were near the level of uncertainty for each test method. Proof of higher efficiency would require either higher inlet concentrations or lower detection limits for the outlet. Note that the actual differences between the methods may be overestimated here by the uncertainty of the measurements at such low concentrations.

One objective of the study was to determine the efficiency of the oxidation catalyst for reduction of formaldehyde emissions. The low concentrations at the catalyst inlet limited the measurable efficiency. The results indicate a relationship between the CO reduction and the formaldehyde reduction efficiencies, but more data would be necessary to provide statistical confidence in the calculation of a predictive factor.

The two test methods show different results, especially for formaldehyde, with the FTIR results significantly higher than those from the CARB Method 430 measurements. Previous studies have shown similar differences, so these results are not surprising. However, the magnitude of the differences is higher than anticipated from those studies.

The results from the conventional method were lower than the stated detection limit (12 ppb) of the FTIR method. The FTIR results were approximately 35 ppb higher than the results from Method 430. There may be biases in either method that were not determined within the scope of this study. The results do not by themselves indicate which measurement is closer to an actual quantification of the formaldehyde concentrations.

The previous studies have shown that elevated levels of $NO_2$ and/or NO in a sample matrix, relative to that of formaldehyde, result in depressed levels of formaldehyde as measured by CARB Method 430 (GRI 2001, API/GRI 1998). The $NO_2$ and NO interfere with the method's chemistry and cause the formaldehyde results to be biased low. One study was conducted on natural gas-fired internal combustion engines where much higher concentrations of formaldehyde, $NO_2$ and NO comprised the sample matrix as compared to those measured during this gas turbine testing. The second study was conducted on a GE LM2500 combustion turbine, and the concentrations of formaldehyde, $NO_2$ and NO measured after a CO catalyst were on the order of 300 ppbvd for formaldehyde (FTIR) and 43 ppmvd for $NO_X$. Note that the stack

location in the current test was downstream of an SCR, and the concentrations of NO and $NO_2$ were much lower, about 2-3 ppmvd for $NO_X$. These lower concentrations might be expected to have less influence on the CARB Method 430 measurements.

The GRI and API/GRI studies do not conclusively explain the discrepancies between the FTIR and CARB Method 430 results from this gas turbine testing. However, these two studies do confirm that the two methods have been shown to provide different results, and that there may be measurable technical reasons for the difference.

**Table 6-3**
**Results of Individual Test Runs, Conventional Methods, Emissions from Gas Turbine Exhaust, Base Load**

| **Upstream from Catalyst – Gas Turbine Exhaust** | **Run 1** | **Run 9** | **Run 10** | **Average** |
|---|---|---|---|---|
| Date / Time | 10-9-02<br>1505-1805 | 10-12-02<br>1445-1745 | 10-12-02<br>1811-2111 | |
| Load, MW | 155 | 160 | 160 | 158 |
| $O_2$, % vol dry | 13.4 | 13.8 | 13.6 | 13.6 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 27 | 29 | 27 | 27 |
| CO, ppm vol dry @ 15% $O_2$ | 0.6 | 0.9 | 0.8 | 0.8 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | <10.4 | 17.8 | 6.3 | 9.4 |
| Note: The symbol "<" denotes results below the practical detection limit value shown. ½ of the detection limit was used for purposes of calculating an average. The run times shown are for the formaldehyde test runs; the $O_2$, $NO_X$ and CO runs were shorter. | | | | |

**Table 6-4**
**Results of Individual Test Runs, FTIR, Emissions from Gas Turbine Exhaust, Base Load**

| **Upstream from Catalyst – Gas Turbine Exhaust** | **Run 1** | **Run 9** | **Run 10** | **Average** |
|---|---|---|---|---|
| Date / Time | 10-9-02<br>1522-1810 | 10-12-02<br>1702-1722 | 10-12-02<br>2102-2117 | |
| Load, MW | 155 | 160 | 160 | 158 |
| $O_2$, % vol dry | 13.4 | 13.8 | 13.6 | 13.6 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 30 | 34 | 32 | 32 |
| CO, ppm vol dry @ 15% $O_2$ | 1.7 | 1.9 | 2.4 | 2.0 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 56.7 | 39.3 | 44.3 | 46.8 |
| Note: See Table 5-2 for details on detection limits for the FTIR analyzer. The run times shown are the periods averaged for the FTIR. The $O_2$ concentrations shown are from conventional analyzer as in Table 6-3. | | | | |

**Table 6-5**
**Results of Individual Test Runs, Conventional Methods, Emissions from HRSG Stack, Base Load**

| **Downstream from Catalyst – HRSG Stack** | **Run 2** | **Run 7** | **Run 8** | **Average** |
|---|---|---|---|---|
| Date / Time | 10-9-02<br>1500-1800 | 10-12-02<br>1450-1750 | 10-12-02<br>1817-2117 | |
| Load, MW | 155 | 160 | 160 | 158 |
| $O_2$, % vol dry | 13.4 | 13.8 | 13.6 | 13.6 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 2.6 | 2.7 | 2.7 | 2.6 |
| CO, ppm vol dry @ 15% $O_2$ | <0.2 | <0.2 | <0.2 | <0.2 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 7.5 | 3.4 | <5.6 | 4.6 |
| Note: The symbol "<" denotes results below the practical detection limit value shown. ½ of the detection limit was used for purposes of calculating an average. The run times shown are for the Formaldehyde test runs; the $O_2$, $NO_X$ and CO runs were shorter. | | | | |

**Table 6-6**
**Results of Individual Test Runs, FTIR, Emissions from HRSG Stack, Base Load**

| **Downstream from Catalyst – HRSG Stack** | **Run 2** | **Run 7** | **Run 8** | **Average** |
|---|---|---|---|---|
| Date / Time | N/A | 10-12-02<br>1457-1603 | 10-12-02<br>1817-2012 | |
| Load, MW | N/A | 160 | 160 | 160 |
| $O_2$, % vol dry | N/A | 13.8 | 13.6 | 13.7 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | N/A | 3.4 | 3.5 | 3.5 |
| CO, ppm vol dry @ 15% $O_2$ | N/A | 0.7 | 1.0 | 0.9 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | N/A | 50.5 | 33.0 | 41.8 |
| Note: See Table 5-2 for details on detection limits for the FTIR analyzer. The run times shown are the periods averaged for the FTIR. The $O_2$ concentrations shown are from conventional analyzer as in Table 6-5. | | | | |

# 7
# RESULTS, LOW AND TRANSIENT LOAD TESTS

## Emissions

A summary of the average test results for the gas turbine exhaust location is provided in Tables 7-1 and 7-2. Table 7-3 presents the results of the conventional tests that were conducted at the turbine exhaust and the HRSG stack at 60% unit load (95 MW). The results of the continuous monitoring run during unit startup are provided in Table 7-4.

The average results shown in Tables 7-1 and 7-2 represent the average of one to three test runs at each load level. The $O_2$ concentration measured by the conventional method was used for correction of the measured concentrations from the conventional and the FTIR tests to ppm @ 15% $O_2$.

Figures 7-1 through 7-4 provide graphical representation of the formaldehyde, CO and hydrocarbon concentrations as measured across the range of unit loads. The results of the two test methods are compared in these figures. Note that Figure 7-2 has a linear scale to show detail, but the others have logarithmic scales to show the range of concentrations.

Most of the low-load tests were conducted during the startup of the unit. The "zero MW" level represents a brief time period (5 minutes) just after startup of the unit, before any generator load had been placed on the turbine. The 5 MW level represents an 8-minute time period when load was first applied (the load for the last minute of the period was 9 MW). The 29 MW level represents a 5-minute time period during which the unit "leveled off" as part of the normal startup procedure. The unit was taken up to base load (approximately 160 MW) and then brought down to 95 MW. The 95 MW level was maintained for 4 hours as part of the scheduled power production for the plant.

**Table 7-1**
**Summary of Average Results, Gas Turbine Exhaust, Conventional Methods, Low Loads**

| **Load, MW** | **0** | **5** | **29** | **95.1** | **158** |
|---|---|---|---|---|---|
| Fuel Flow, Kscf/hr | 511 | 595 | 850 | 1284 | 1937 |
| $O_2$, actual % vol dry | 18.4 | 18.3 | 17.2 | 14.7 | 13.7 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 30 | 44 | 38 | 34 | 35 |
| CO, ppm vol dry @ 15% $O_2$ | 1763 | 1916 | 2505 | 61 | 0.9 |
| Total Hydrocarbons as $CH_4$, ppm vol dry @ 15% $O_2$ | 5080 | 5270 | 2677 | 6 | 1.6 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 125940 | -- | 76240 | 108 | 10 |
| Benzene, ppb vol dry @ 15% $O_2$ | -- | 53.6 | -- | -- | ND< 0.25 |
| The conventional methods included measurement of total hydrocarbons by direct FID analyzer. | | | | | |

**Table 7-2**
**Summary of Average Results, Gas Turbine Exhaust, FTIR Analyzer, Low Loads**

| **Load, MW** | **0** | **5** | **29** | **95.1** | **158** |
|---|---|---|---|---|---|
| Fuel Flow, scf/hr | 511 | 595 | 850 | 1284 | 1937 |
| $O_2$, actual % vol dry (from conventional method) | 18.4 | 18.3 | 17.2 | 14.7 | 13.7 |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 380 | 110 | 77 | 45 | 32 |
| CO, ppm vol dry @ 15% $O_2$ | 3034 | 4360 | 3066 | 173 | 2.2 |
| Methane, ppm vol dry @ 15% $O_2$ | 5536 | 2797 | 1968 | 7 | 0.1 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 191604 | 227104 | 121753 | 407 | 47 |
| Benzene, ppb vol dry @ 15% $O_2$ | ND< 260 | ND< 260 | ND< 260 | ND< 260 | ND< 260 |
| The FTIR method included measurement of Methane rather than total hydrocarbons. | | | | | |

**Table 7-3**
**Summary of Average Results, Conventional Methods, 60% Load**

| Sample Location | Upstream from Catalysts – Gas Turbine Exhaust | Downstream from Catalysts – HRSG Stack | Percent Reduction |
|---|---|---|---|
| Load, MW | 95 | 95 | -- |
| $O_2$, % vol dry | 14.6 | 14.7 | -- |
| $NO_X$, ppm vol dry @ 15% $O_2$ | 34 | 2.5 | 93 |
| CO, ppm vol dry @ 15% $O_2$ | 61 | 1.3 | 98 |
| Formaldehyde, ppb vol dry @ 15% $O_2$ | 107.9 | 10.5 | 90 |
| Note: These results are from a single test run at each location. | | | |

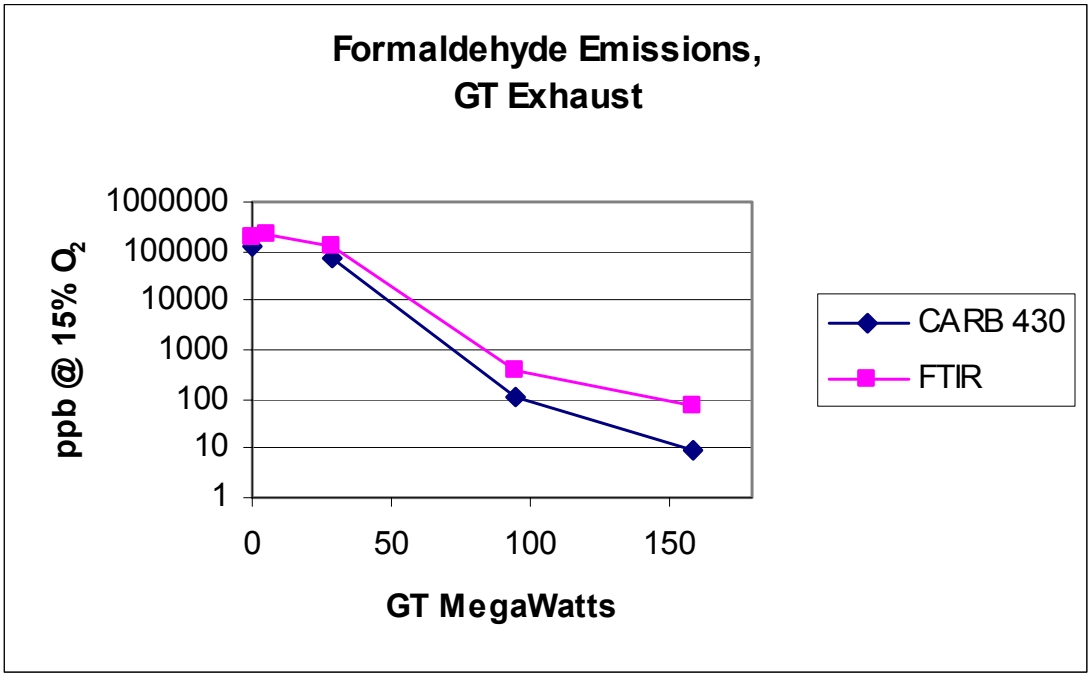



**Figure 7-1**
**Formaldehyde Emissions, Gas Turbine Exhaust**

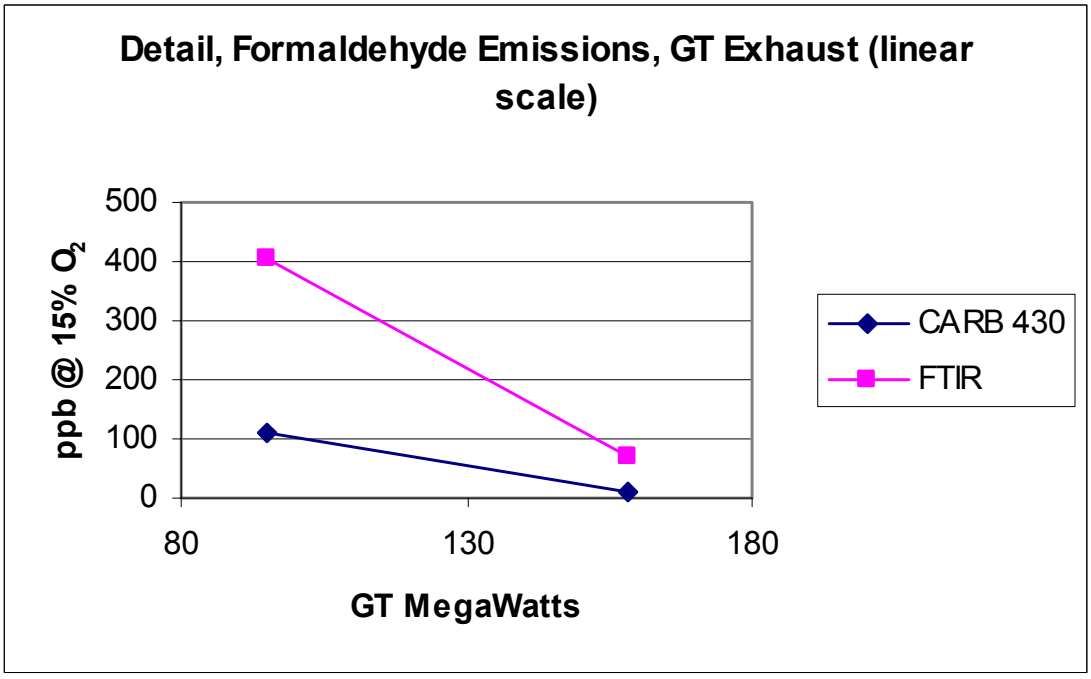



**Figure 7-2**
**Detail, Formaldehyde Emissions, Gas Turbine Exhaust**

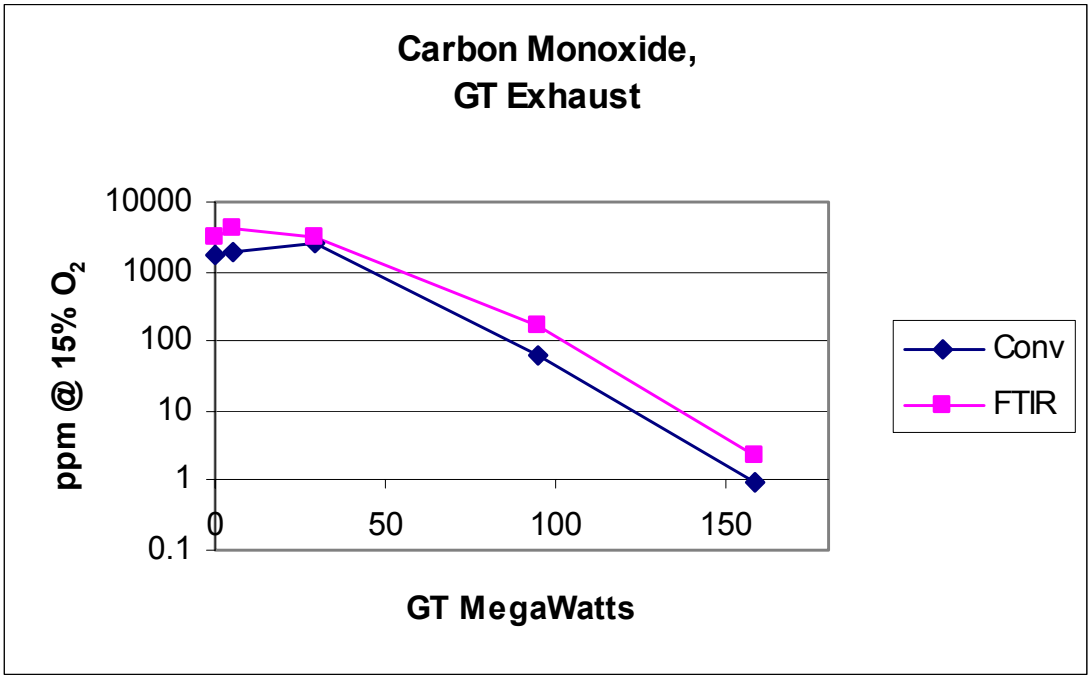



**Figure 7-3**
**Carbon Monoxide Emissions, Gas Turbine Exhaust**

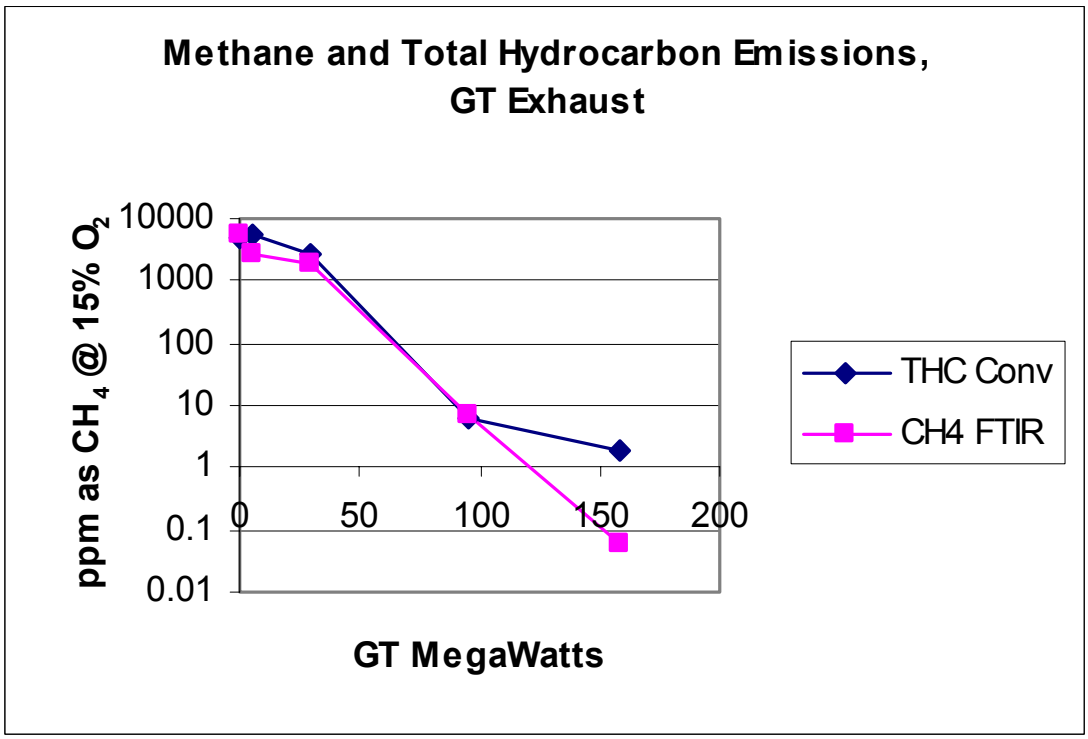



**Figure 7-4**
**Hydrocarbon Emissions, Gas Turbine Exhaust**

## Summary

Most of the measurements made at low loads and transient conditions were conducted at the turbine exhaust (or catalyst inlet). This was done to eliminate the variables imposed by the SCR and oxidation catalysts. The time at each condition was very limited, since most of the data were taken during unit startup. The exception was the test at 95 MW (approximately 60% of base load); the unit was operated at that load for approximately four hours, so there was time to conduct a conventional test run at the HRSG stack location as well.

The 95 MW tests provided some important results. The catalyst inlet concentrations of CO and formaldehyde were high enough to provide measurements at the outlet that were well above the method detection limits even at the 90+ percent emission reductions. Firm conclusions should not be drawn from these results, since they are based on a single test run. However, the data do indicate the type of results that could be expected from test runs conducted at lower unit loads.

The results provided by the FTIR were quite different from those provided by the conventional methods. Both techniques show that the pollutant concentrations increase as the unit load decreases. The best agreement was between the total hydrocarbon concentrations measured using a conventional FID analyzer and the methane concentrations measured using the FTIR. Otherwise the FTIR results were within an order of magnitude of the results of the conventional reference methods, but were not usually much closer.

The results for CO, methane, total hydrocarbons and formaldehyde were plotted on the charts presented as Figures 7-1 through 7-4. Most of these were plotted on a logarithmic scale, which shows that the method differences were mostly within an order of magnitude. The figures also show the utility of the test methods for measuring the trends in emissions at various unit loads.

**Table 7-4**
**Results Summary, Conventional Methods, Gas Turbine Exhaust, Unit Startup**

| Time, minutes | Raw Fuel Flow, Kscfm | Stack Flow, dscfm | CT Generator Megawatts | Total lb emitted each minute | | |
|---|---|---|---|---|---|---|
| | | | | CO | NOx as NO2 | THC as CH4 |
| 1 | 1.0 | 225,751 | 0.0 | 0.028 | 0.000 | 0.009 |
| 2 | 4.49 | 283,089 | 0.0 | 2.704 | 0.229 | 3.439 |
| 3 | 5.90 | 287,543 | 0.0 | 14.962 | 0.262 | 8.235 |
| 4 | 7.04 | 420,082 | 0.0 | 26.719 | 0.311 | 27.484 |
| 5 | 8.58 | 534,073 | 0.0 | 32.066 | 0.466 | 35.300 |
| 6 | 9.64 | 625,650 | 0.0 | 35.949 | 0.623 | 43.137 |
| 7 | 8.27 | 542,129 | 0.0 | 30.442 | 0.657 | 35.064 |
| 8 | 8.33 | 598,413 | 0.0 | 33.738 | 0.757 | 43.078 |
| 9 | 8.39 | 630,662 | 0.0 | 34.544 | 0.921 | 43.014 |
| 10 | 8.48 | 631,670 | 0.0 | 34.237 | 0.989 | 63.557 |
| 11 | 8.54 | 644,188 | 0.0 | 32.878 | 1.006 | 64.888 |
| 12 | 8.62 | 648,153 | 0.0 | 33.558 | 1.050 | 64.488 |
| 13 | 8.72 | 647,750 | 0.0 | 34.200 | 1.083 | 63.080 |
| 14 | 8.83 | 651,275 | 0.0 | 34.897 | 1.125 | 62.701 |
| 15 | 8.70 | 641,926 | 0.0 | 35.162 | 1.166 | 62.236 |
| 16 | 8.70 | 629,383 | 0.0 | 34.027 | 1.250 | 66.193 |
| 17 | 8.70 | 624,504 | 0.0 | 33.839 | 1.285 | 64.537 |
| 18 | 8.68 | 628,217 | 0.0 | 34.199 | 1.313 | 64.215 |
| 19 | 8.62 | 630,675 | 0.0 | 34.007 | 1.315 | 64.355 |
| 20 | 8.68 | 630,850 | 0.0 | 33.959 | 1.316 | 64.778 |
| 21 | 8.67 | 628,428 | 0.0 | 33.746 | 1.313 | 64.228 |
| 22 | 8.62 | 629,208 | 0.0 | 33.796 | 1.318 | 64.092 |
| 23 | 8.59 | 629,388 | 0.0 | 33.668 | 1.315 | 64.308 |
| 24 | 9.26 | 680,632 | 0.0 | 36.280 | 1.424 | 69.473 |
| 25 | 9.26 | 689,612 | 0.0 | 36.785 | 1.452 | 69.797 |
| 26 | 9.23 | 690,505 | 0.0 | 36.854 | 1.451 | 69.864 |
| 27 | 9.22 | 653,706 | 0.0 | 37.069 | 1.470 | 64.392 |
| 28 | 9.25 | 642,925 | 4.4 | 39.154 | 1.501 | 62.801 |
| 29 | 9.29 | 655,052 | 4.0 | 39.757 | 1.524 | 64.198 |
| 30 | 9.30 | 665,113 | 4.0 | 40.334 | 1.541 | 65.336 |
| 31 | 9.29 | 667,311 | 4.2 | 40.303 | 1.529 | 65.920 |
| 32 | 9.28 | 662,445 | 3.9 | 39.822 | 1.518 | 65.578 |
| 33 | 9.30 | 660,056 | 3.8 | 39.747 | 1.519 | 65.146 |
| 34 | 9.49 | 676,946 | 4.1 | 40.801 | 1.558 | 66.711 |
| 35 | 9.88 | 703,742 | 4.0 | 42.430 | 1.611 | 69.783 |
| 36 | 10.22 | 724,852 | 4.0 | 43.445 | 1.655 | 72.047 |
| 37 | 10.71 | 753,374 | 3.9 | 45.671 | 1.747 | 73.749 |
| 38 | 11.16 | 758,915 | 6.1 | 49.169 | 1.868 | 71.635 |
| 39 | 11.69 | 755,034 | 9.3 | 54.188 | 1.994 | 67.402 |
| 40 | 12.18 | 753,305 | 11.7 | 59.013 | 2.008 | 67.193 |

**Table 7-4 (continued)**
**Results Summary, Conventional Methods, Gas Turbine Exhaust, Unit Startup**

| Time, minutes | Raw Fuel Flow, Kscfm | Stack Flow, dscfm | CT Generator Megawatts | Total lb emitted each minute | | |
|---|---|---|---|---|---|---|
| | | | | CO | NOx as NO2 | THC as CH4 |
| 41 | 12.31 | 735,582 | 14.1 | 61.017 | 1.921 | 65.761 |
| 42 | 12.49 | 690,926 | 17.6 | 67.403 | 1.860 | 59.651 |
| 43 | 12.85 | 700,331 | 21.0 | 69.963 | 1.902 | 59.733 |
| 44 | 13.22 | 697,069 | 23.6 | 74.288 | 1.933 | 57.267 |
| 45 | 13.59 | 710,497 | 24.3 | 77.758 | 1.978 | 57.733 |
| 46 | 13.86 | 712,682 | 25.6 | 79.696 | 2.010 | 55.653 |
| 47 | 14.21 | 705,373 | 27.9 | 82.064 | 2.041 | 50.419 |
| 48 | 14.43 | 684,956 | 31.8 | 81.753 | 2.046 | 43.269 |
| 49 | 14.74 | 673,076 | 34.6 | 80.825 | 2.069 | 37.006 |
| 50 | 15.34 | 674,190 | 38.0 | 78.766 | 2.122 | 30.942 |
| 51 | 15.59 | 664,067 | 41.0 | 73.497 | 2.131 | 25.041 |
| 52 | 15.91 | 654,186 | 44.0 | 67.930 | 2.205 | 19.262 |
| 53 | 16.53 | 655,395 | 46.7 | 61.943 | 2.350 | 13.877 |
| 54 | 17.09 | 657,082 | 50.4 | 59.915 | 2.407 | 12.079 |
| 55 | 17.68 | 658,533 | 53.5 | 52.614 | 2.529 | 8.076 |
| 56 | 18.18 | 654,346 | 56.5 | 44.442 | 2.359 | 6.738 |
| 57 | 18.96 | 657,994 | 60.8 | 37.965 | 2.260 | 5.280 |
| 58 | 19.66 | 656,293 | 65.3 | 29.913 | 2.196 | 4.010 |
| 59 | 20.54 | 657,278 | 69.0 | 23.691 | 2.148 | 3.088 |
| 60 | 21.28 | 650,069 | 72.6 | 14.135 | 2.321 | 1.200 |
| 61 | 21.94 | 647,124 | 77.7 | 5.309 | 2.569 | 0.486 |
| 62 | 22.10 | 640,899 | 82.5 | 2.254 | 2.899 | 0.289 |
| 63 | 22.19 | 634,190 | 87.8 | 0.880 | 3.102 | 0.213 |
| 64 | 22.24 | 625,775 | 92.9 | 0.724 | 2.968 | 0.181 |
| 65 | 22.60 | 627,498 | 97.2 | 0.744 | 2.778 | 0.169 |
| 66 | 22.82 | 631,011 | 97.9 | 0.824 | 2.719 | 0.149 |
| 67 | 22.99 | 633,988 | 98.9 | 0.827 | 2.692 | 0.131 |
| 68 | 23.06 | 634,494 | 98.5 | 0.818 | 2.670 | 0.122 |
| 69 | 23.02 | 628,440 | 101.5 | 0.662 | 2.575 | 0.104 |
| 70 | 22.96 | 624,201 | 103.4 | 0.537 | 2.524 | 0.102 |
| 71 | 22.97 | 622,220 | 104.2 | 0.535 | 2.502 | 0.083 |
| 72 | 23.10 | 625,803 | 104.1 | 0.538 | 2.499 | 0.083 |
| 73 | 23.00 | 625,745 | 104.0 | 0.612 | 2.488 | 0.075 |
| 74 | 22.96 | 624,936 | 103.6 | 0.692 | 2.474 | 0.062 |
| 75 | 22.99 | 624,317 | 103.7 | 0.704 | 2.475 | 0.062 |
| 76 | 22.96 | 621,914 | 103.6 | 0.627 | 2.474 | 0.062 |
| 77 | 22.93 | 622,200 | 103.7 | 0.683 | 2.477 | 0.062 |
| 78 | 22.93 | 620,749 | 103.6 | 0.626 | 2.473 | 0.056 |
| 79 | 22.99 | 621,748 | 103.6 | 0.645 | 2.466 | 0.041 |
| 80 | 23.01 | 623,072 | 103.5 | 0.721 | 2.473 | 0.041 |

**Table 7-4 (continued)**
**Results Summary, Conventional Methods, Gas Turbine Exhaust, Unit Startup**

| Time, minutes | Raw Fuel Flow, Kscfm | Stack Flow, dscfm | CT Generator Megawatts | Total lb emitted each minute | | |
|---|---|---|---|---|---|---|
| | | | | CO | NOx as NO2 | THC as CH4 |
| 81 | 23.02 | 624,948 | 103.1 | 0.779 | 2.468 | 0.042 |
| 82 | 23.22 | 630,488 | 103.9 | 0.711 | 2.507 | 0.042 |
| 83 | 23.68 | 643,062 | 104.1 | 0.725 | 2.557 | 0.043 |
| 84 | 24.36 | 663,320 | 103.6 | 0.698 | 2.643 | 0.044 |
| 85 | 24.92 | 681,403 | 103.6 | 0.768 | 2.712 | 0.045 |
| 86 | 25.62 | 698,506 | 105.2 | 0.693 | 2.788 | 0.046 |
| 87 | 26.28 | 709,714 | 109.4 | 0.473 | 2.839 | 0.045 |
| 88 | 26.91 | 718,671 | 112.9 | 0.319 | 2.791 | 0.024 |
| 89 | 27.57 | 728,572 | 116.6 | 0.194 | 2.695 | 0.024 |
| 90 | 28.14 | 732,262 | 121.5 | 0.195 | 2.469 | 0.024 |
| 91 | 28.80 | 747,269 | 126.0 | 0.199 | 2.483 | 0.025 |
| 92 | 29.50 | 767,625 | 129.6 | 0.204 | 2.547 | 0.025 |
| 93 | 30.18 | 786,730 | 133.5 | 0.198 | 2.579 | 0.026 |
| 94 | 30.42 | 790,843 | 137.3 | 0.141 | 2.598 | 0.026 |
| 95 | 30.42 | 789,583 | 141.7 | 0.094 | 2.569 | 0.026 |
| 96 | 30.48 | 790,228 | 145.7 | 0.094 | 2.587 | 0.026 |
| 97 | 30.81 | 795,472 | 148.6 | 0.095 | 2.604 | 0.026 |
| 98 | 31.42 | 809,622 | 149.3 | 0.096 | 2.644 | 0.027 |
| | | | **Total lb emitted:** | **2654.36** | **190.60** | **2906.69** |

Note: Startup was deemed complete when the SCR Outlet NOx was in compliance with the permit limit for the unit.

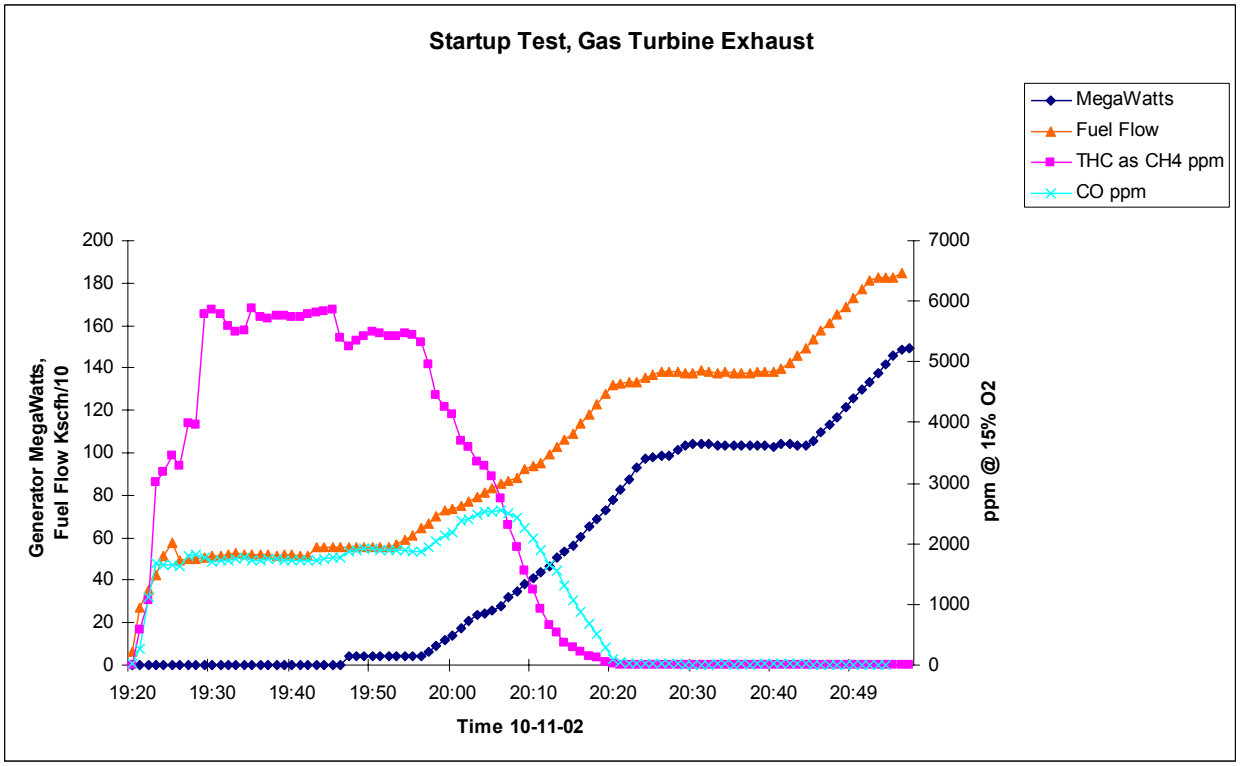



**Figure 7-5**
**Emissions and Unit Load During Startup, Gas Turbine Exhaust**

# 8
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