December 2000

Environmental Technology Verification Report

NO_x Control Technologies

Catalytica Combustion Systems, Inc. Xonon™ Flameless Combustion System

Prepared by

Midwest Research Institute

Research Triangle Institute

Under a Cooperative Agreement with

United States Environmental Protection Agency

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

Research Triangle Institute

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**NO_x AIR POLLUTION CONTROL TECHNOLOGY**
APPLICATION:	**A PROCESS-INHERENT NO_x EMISSION CONTROL SYSTEM FOR GAS TURBINE APPLICATIONS**
TECHNOLOGY NAME:	**XONON™ COOL COMBUSTION**
COMPANY:	**CATALYTICA ENERGY SYSTEMS, INC.***
ADDRESS:	**430 FERGUSON DRIVE MOUNTAIN VIEW, CA 94043-5272** — **PHONE: (650) 960-3000 FAX: (650) 960-0127**
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* Catalytica Energy Systems, Inc. is the former Catalytica Combustion Systems, Inc. (CCSI)

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; with stakeholder groups that consist of buyers, vendor organizations, permitters, and other interested parties; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology (APCT) program, one of 12 technology areas under ETV, is operated by the Research Triangle Institute (RTI) in cooperation with EPA's National Risk Management Research Laboratory. Midwest Research Institute, on behalf of the APCT program, has evaluated the performance of a nitrogen oxides (NO_x) control technology utilizing flameless catalytic combustion for stationary gas turbines, Xonon™ Cool Combustion (formally known as Xonon™ flameless combustion.)

VERIFICATION TEST DESCRIPTION

All tests were performed in accordance with general guidance given by the APCT program "Generic Verification Protocol for NO_x Control Technologies for Stationary Combustion Sources" and the specific technology test plan "Verification Test/QA Plan for Xonon™ flameless combustion system." These documents include requirements for quality management, quality assurance, auditing of the test laboratories, and test reporting format.

The Xonon™ Cool Combustion system was tested as installed and operating on a Kawasaki M1A-13A gas-turbine-generator set (1.5 MW) located in Santa Clara, California, on July 18 and 19, 2000. NO_x concentrations were measured using continuous emission monitors (CEMs) following EPA Reference Method 20 for gas turbines. Other gaseous emissions were monitored using the applicable EPA test method. Other process variables were monitored using calibrated plant instrumentation.

Tests were conducted to meet the data quality objective of a 95 percent confidence interval with a width of ±10 percent or less of the mean NO_x emission concentration for concentrations above 5 ppmvd, ±25 percent or less below 5 ppmvd and above 2 ppmvd, and ±50 percent or less below 2 ppmvd. In addition to outlet NO_x concentration and the primary process variables, carbon monoxide and unburned hydrocarbon emission concentrations were also measured using EPA reference methods, and the installation efforts, site modifications, staffing, maintenance requirements, and similar issues were noted qualitatively.

A single test run consisted of measuring outlet NO_x concentration and the other parameters over a 32-min steady-state process condition with the primary variable, ambient temperature, at either its low point or high point (i.e., early morning or late afternoon). The test design was a replicated 2 × 1 factorial using two levels of ambient temperature and greater than 97 percent of the rated full load. A total of 12 test runs were conducted over the 2-day field test period. Ambient temperature variation was small over the test period. Table 1 gives the operating performance envelope over which the Xonon™ Cool Combustion system was verified.

Verification Statement Table 1. Verification Test Performance Envelope[a]

	Ambient Temperature, °C
Low	15
High	25

[a]At >97 percent of full turbine load.

DESCRIPTION OF XONON™ TECHNOLOGY

This verification statement is applicable to the Xonon™ Cool Combustion system for gas turbine applications without the air management system. The Xonon™ Cool Combustion system is completely contained within the combustion chamber of the gas turbine. Xonon™ Cool Combustion completely combusts fuel to produce a high-temperature mixture, typically about 1300 °C (2400°F). Dilution air is added to shape the temperature profile required at the turbine inlet.

The Xonon™ Cool Combustion system consists of four sections:

- **Preburner.** The preburner is used to preheat the air before it enters the catalyst module and during startup for acceleration of the turbine. The preburner tested as part of this verification was a lean, premixed combustor.
- **Fuel injection and fuel/air mixing system.** This unit injects the fuel and mixes it with the main air flow to provide a very well mixed, uniform fuel/air mixture to the catalyst.
- **Xonon™ catalyst module.** In the catalyst module, a portion of the fuel is combusted without a flame to produce a high-temperature gas.
- **Homogeneous combustion region.** Located immediately downstream of the catalyst module, the homogeneous combustion region is where the remainder of the fuel is combusted, and carbon monoxide and unburned hydrocarbons are reduced to very low levels (also a flameless combustion process).

The overall combustion process in the Xonon™ system is a partial combustion of fuel in the catalyst module followed by complete combustion downstream of the catalyst in the burnout zone. Partial combustion within the catalyst produces no NO_x. Homogeneous combustion downstream of the catalyst usually produces no NO_x, because combustion occurs at a uniformly low temperature. A small amount of fuel is combusted in the preburner to raise the compressed air temperature to about 470°C (880°F). NO_x in the turbine exhaust is usually from the preburner.

The design of each Xonon™ combustor is customized to the particular turbine model and operating conditions of the application and would typically be defined through a collaborative effort with the manufacturer of the turbine to integrate the hardware into the design. Catalytica Energy Systems, Inc. expects that the Xonon™ Cool Combustion technology incorporated in a Xonon™ combustion system for a natural-gas-fueled Kawasaki M1A-13A gas turbine is capable of achieving emissions of NO_x of less than 2.5 ppmvd (corrected to 15 percent oxygen [O_2]) on a 1-hour rolling average basis, and less than 2.0 ppmvd (corrected to 15 percent O_2) on a 3-hour rolling average basis. Under the same conditions, the Xonon™ combustion system is expected to achieve carbon monoxide (CO) emissions of less than 6 ppmvd (corrected to 15 percent O_2). The footprint may vary depending on the implementation, although generically the Xonon™ combustion system would likely be somewhat larger than the combustor that is typically supplied as standard equipment by the turbine manufacturer. Each unit could have multiple fuel inputs from separate control valves, and additional instrumentation for control and monitoring would be integrated into the turbine control system.

This verification statement covers application of the Xonon™ Cool Combustion system to small gas turbines operated at full load when combusting natural gas within the stated operating condition envelope. This unit was operated at the test site by the vendor, Catalytica Energy Systems, Inc., for over 4,000 hours before the verification test. Data from this long-term operating period have been submitted to a number of regulatory authorities for their review and evaluation. While these data and the instruments used were not verified during this test, within the operating condition envelope the results are generally consistent with the verification test results. Catalytica Energy Systems, Inc. should be contacted for these data or other information.

VERIFICATION OF PERFORMANCE

The verified NO_x emission results are given in Table 2. The analysis of variance between NO_x and ambient temperature indicated that ambient temperature did not affect NO_x emissions over the narrow range encountered during this verification test.

Verification Statement Table 2. NO_x Control Performance

Ambient Temperature Range	Percent of Full Turbine Load Range	Mean Outlet NO_x Concentration ppmvd @ 15% O_2	Half-Width of 95% Confidence Interval on Mean Outlet NO_x ppmvd @ 15% O_2
15 to 25°C (59 to 77°F)	98-99%	1.13	0.026

ppmvd = parts per million by volume dry basis.

CO emissions averaged 1.36 ppmvd at 15 percent O_2. Unburned hydrocarbon (UHC) emissions averaged 0.16 ppmv (wet basis reported as propane).

The APCT quality assurance (QA) Officer has reviewed the test results and quality control data and has concluded that data quality objectives given in the NO_x Control Technology generic verification protocol and test/QA plan have been attained. During the verification tests, the EPA and APCT QA staffs conducted a performance evaluation and a technical system audit at the field test site, which confirm that the verification test was conducted in accordance with the EPA-approved test/QA plan.

This verification statement verifies the NO_x emissions characteristics of the Xonon™ Cool Combustion system within the range of application tested (see Table 2). Extrapolation outside that range should be done with an understanding of the scientific principles that control the performance of the Xonon™ Cool Combustion system. Gas turbine users with NO_x control requirements should also consider other performance parameters such as service life and cost when selecting a NO_x control system.

In accordance with the NO_x Control Technology generic verification protocol, this verification report is valid indefinitely for application of the Xonon™ Cool Combustion system within the range of applicability of the statement.

Original signed by Hugh W. McKinnon 12/15/00
Hugh W. McKinnon Date
Acting Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original signed by Jack R. Farmer 12/22/00
Jack R. Farmer Date
Program Manager
Air Pollution Control Technology Program
Research Triangle Institute

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Environmental Technology Verification Report

NO_x Control Technologies

Catalytica Combustion Systems, Inc. Xonon™ Flameless Combustion System

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Notice

This document was prepared by Midwest Research Institute (MRI) under a contract with Research Triangle Institute (RTI) with funding from Cooperative Agreement No. CR826152-01-2 with the U.S. Environmental Protection Agency (EPA). The document has been subjected to RTI/EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

Catalytica Combustion Systems, Inc. becomes Catalytica Energy Systems, Inc.

Catalytica Combustion Systems, Inc. (abbreviated in this report as CCSI), a subsidiary of Catalytica, Inc., reorganized into stand-alone, publicly-traded Catalytica Energy Systems, Inc., on December 18, 2000. The Xonon™ Cool Combustion technology, referred to in this report as Xonon™ flameless combustion, remains the same, and all references to CCSI should be understood to refer to Catalytica Energy Systems, Inc. Contact information in the verification statement and report has been updated.

Availability of Verification Statement and Report

Copies of the public Verification Statement and Verification Report are available from

1. **Research Triangle Institute**
   P.O. Box 12194
   Research Triangle Park, NC 27709-2194

   Web site: http://etv.rti.org/apct/index.html
   or http://www.epa.gov/etv/ *(click on partners)*

2. **USEPA / APPCD**
   MD-4
   Research Triangle Park, NC 27711

   Web site: http://www.epa.gov/etv/library.htm *(electronic copy)*
   http://www.epa.gov/ncepihom/

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Abstract

Nitrogen oxides (NO_x) air pollution control technologies (APCTs) are among the technologies evaluated by the APCT Environmental Technology Verification (ETV) Program. The APCT program developed the *Generic Verification Protocol for NO_x Control Technologies for Stationary Combustion Sources* to provide guidance on the verification of specific technologies. The critical performance factor for this verification is the NO_x emission concentration within the performance envelope of the test. This protocol was developed by RTI and MRI, reviewed and discussed by a technical panel of experts, and approved by EPA. The protocol states the critical data quality objectives for a NO_x control technology verification, as well as noncritical but still important measurements of other performance parameters.

The Catalytica Combustion Systems, Inc., Xonon™ flameless combustion system was submitted to the APCT ETV program for verification. A test/quality assurance (QA) plan, prepared in accordance with the generic verification protocol, addressed the site specific issues associated with the verification test. The verification was conducted the week of July 17, 2000, at the Xonon™ installation on a 1.5-MW gas turbine in Santa Clara, CA. The mean outlet NO_x concentration during the verification was determined to be 1.13 ppmvd at 15% O_2. The measured NO_x concentration was well within the stated data quality objective for the NO_x measurement. Other important performance and operating parameters were also measured.

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Acronyms/Abbreviations

ADQ	Audit of data quality
ANSI	American National Standards Institute
APCT	Air Pollution Control Technology
ASME	American Society of Mechanical Engineers
CCSI	Catalytica Combustion Systems, Inc., renamed Catalytica Energy Systems, Inc.
cfm	Cubic feet per minute
CO	Carbon monoxide
CV	Coefficient of variance
DQO	Data quality objective
EED	MRI's Environmental Engineering Division
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
fpm	Feet per minute
GVP	Generic Verification Protocol
HMI	Human/machine interface
IR	Infrared
ISO	International Standards Organization
MFC	Mass flow controller
MRI	Midwest Research Institute
NESHAP	National Emission Standard for Hazardous Air Pollutants
NIST	National Institute of Standards and Technology
NO_x	Nitrogen oxides
OD	Outside diameter
PE	Performance evaluation
ppmv	Part per million by volume
ppmvd	Part per million by volume dry basis
ppmvw	Part per million by volume wet basis
QA	Quality assurance
QAO	Quality assurance officer
QC	Quality control
QMP	Quality management plan
QSM	Quality system manual
RH	Relative humidity
RTI	Research Triangle Institute
SOP	Standard operating procedure
SS	Stainless steel
TEI	Thermo Enviromental Instruments, Inc. (sometimes identified as TECO)
TSA	Technical systems audit
UHCs	Unburned hydrocarbons (same as total hydrocarbons)

Section 1.0

Introduction

The objective of the Air Pollution Control Technology (APTC) Environmental Technology Verification (ETV) Program is to verify, with high data quality, the performance of air pollution control technologies. A subset of air pollution control technologies is nitrogen oxides (NO_x) emission control technologies. One of these NO_x emission control technologies is the flameless combustion system known as Xonon™, developed by Catalytica Combustion Systems, Inc. (CCSI) of Mountain View, California. The Xonon™ flameless combustion system is an advanced combustion process designed for gas turbines that is capable of producing NO_x emissions below the current level of 9 to 25 parts per million by volume on a dry basis (ppmvd) at 15 percent oxygen (O_2) obtainable with dry, low-NO_x combustion techniques.

Control of NO_x emissions is of increasing interest, particularly related to the National Ambient Air Quality Standard for ozone. The Environmental Protection Agency (EPA) recently completed a rulemaking to reduce more than 1 million tons of NO_x each ozone season and offered to develop and administer a multistate NO_x trading program to assist the affected states. Additionally, many state and local permitting agencies are requiring unprecedentedly low NO_x emission levels.

To evaluate the performance of the Xonon™ flameless combustion system, a field test program was designed by Research Triangle Institute (RTI) and Midwest Research Institute (MRI) with assistance from CCSI. A site visit to the host facility was completed on April 17, 2000, and a test/QA plan was developed and approved by EPA on June 28, 2000. The verification field test was conducted on July 18 and 19, 2000.

The host facility was the Silicon Valley Power Gianera generating station located at 4948 Centennial Drive in Santa Clara, California. The Xonon™ flameless combustion system was installed on a 1,500-kW gas-turbine-generator set manufactured by Kawasaki (Model M1A-13A).

The verification statement for the Xonon™ flameless combustion system verification test is presented in the preceding section. A detailed description of the Xonon™ flameless combustion system is presented in Section 2. The procedures and methods used for the verification test are discussed in Section 3. The operating range over which the verification test was conducted is presented in Section 4. The results of the verification test are summarized and discussed in Section 5.

Appendices describing QA/QC activities and results (Appendix A), raw test data (Appendix B), and equipment calibration results (Appendix C) are attached.

Section 2.0

Description and Identification of Xonon™ Flameless Combustion System

The Xonon™ flameless combustion system is completely contained within the combustion chamber of the gas turbine. The Xonon™ system completely combusts fuel to produce a high-temperature gaseous mixture, typically over 1300 °C (2400°F). Dilution air is added to shape the temperature profile required at the turbine inlet.

The Xonon™ combustor consists of four sections:

5. **Preburner**. The preburner is used for startup preheat of air before it enters the catalyst module and acceleration of the turbine. The preburner could be a conventional, diffusion flame burner or could be a dry, low-NO_x type (lean, premixed) burner. For this Kawasaki turbine, the preburner was a lean premix burner.

6. **Fuel injection and fuel/air mixing system**. This system injects the fuel and mixes it with the main air flow to provide a very well-mixed, uniform fuel/air mixture to the catalyst.

7. **Xonon™ catalyst module**. In the catalyst module, a portion of the fuel is combusted without a flame to produce a high-temperature gas.

8. **Homogeneous combustion region**. Located immediately downstream of the catalyst module, the homogeneous combustion region is where the remainder of the fuel is combusted, and carbon monoxide and unburned hydrocarbons are reduced to very low levels (also a flameless combustion process).

The overall combustion process in the Xonon™ system is a partial combustion of fuel in the catalyst module followed by complete combustion downstream of the catalyst in the burnout zone. Partial combustion within the catalyst produces no NO_x. Homogeneous combustion downstream of the catalyst usually produces no NO_x, because combustion occurs at a uniformly low temperature. A small amount of fuel is combusted in the preburner to raise the compressed air temperature to about 470°C (880°F). NO_x in the turbine exhaust is usually from the preburner.

The design of each Xonon™ combustor is customized to the particular turbine model and operating conditions of the application and would typically be defined through a collaborative effort with the manufacturer of the turbine to integrate the hardware into the design. The footprint may vary depending on the implementation, although generically the Xonon™ combustion system would likely be somewhat larger than the combustor that is typically supplied as standard equipment by the turbine manufacturer. Each unit could have multiple fuel inputs from separate control valves, and additional instrumentation for control and monitoring would be integrated into the turbine control system.

When a Xonon™ combustion system is installed, initial startup and shakedown are supervised by CCSI personnel, and the requisite training to operate and service the equipment is provided at that time. Maintenance procedures and spare parts requirements are identified during design of the combustor for the specific turbine model, and this information is provided upon delivery of the equipment. CCSI indicates the elapsed time between installation and commissioning to be less than 1 month.

After initial commissioning, the Xonon™ combustion system is expected to require minimal ongoing service. CCSI expects the catalyst module to have a useful life of approximately 8,000 operating hours, requiring a replacement of the module at this interval.

This verification report covers application of the Xonon™ flameless combustion system to small gas turbines operated at full load when combusting natural gas within the stated operating condition envelope. The same pilot unit was operated at the test site by the vendor, CCSI, for over 4,000 hours before the verification test. Data from this long-term operating period have been submitted to a number of regulatory authorities for their review and evaluation. While these data and the instruments used were not verified during this test, within the operating condition envelope the results are generally consistent with the verification test results. CCSI should be contacted for these long-term data or other information.

CCSI Xonon™ Product Performance Expectations

CCSI expects that the Xonon™ flameless combustion technology incorporated in a Xonon™ combustion system for a natural-gas-fueled Kawasaki M1A-13A gas turbine is capable of achieving emissions of NO_x of less than 2.5 ppmvd (corrected to 15 percent oxygen [O_2]) on a 1-hour rolling average basis, and less than 2.0 ppmvd (corrected to 15 percent O_2) on a 3-hour rolling average basis. Under the same conditions, this Xonon™ combustion system is also expected to achieve carbon monoxide (CO) emissions of less than 6 ppmvd (corrected to 15 percent O_2).

Section 3.0

Procedures and Methods Used in Testing

A generic verification protocol (GVP) for testing NO_x control technologies was prepared and approved by the NO_x Control Technology Technical Panel (RTI, 2000a). The GVP established the guidelines for the verification test design, the data quality objective (DQO) for the primary verification parameter (for this verification test, NO_x concentration corrected to 15 percent O_2), and the test methods to be used. A test/QA Plan (RTI, 2000b) was written to apply the GVP to the Xonon™ verification. This section details the test design and the test methods used for the verification test of the Xonon™ flameless combustion system.

3.1 Test Design

The GVP for NO_x Control Technologies provides extended discussions on the experimental design approach for NO_x control technologies verification testing. The specific design for this test is described below.

The critical measurement for the Xonon™ flameless combustion system verification was the level of NO_x emitted in ppmvd at 15 percent O_2. This verification test was designed to measure the outlet NO_x emission concentration under targeted field test conditions with the Xonon™ flameless combustion system operating at a specified high load and the encountered low and high ambient temperature for the test days. Historical ambient temperature data suggested that its effect might be detectable by conducting sets of tests at dawn (cold) and in the afternoon (hot). Associated emissions concentrations were also measured using EPA reference methods, but the test was not designed around acquisition of these data. Ambient temperature was an important measurement for establishing the bounds of the verification test design.

Table 1. Verification Test Design (Target Values)[a]

Test Run	Ambient Temperature (time of day)
1	Low (dawn)
2	Low (dawn)
3	Low (dawn)
4	High (afternoon)
5	High (afternoon)
6	High (afternoon)
7	Low (dawn)
8	Low (dawn)
9	Low (dawn)
10	High (afternoon)
11	High (afternoon)
12	High (afternoon)

[a] Turbine load >95% maximum.

A 2 × 1 factorial experimental design was used with each of the parameters. Two replications of the factorial design (six test runs in each replication) was used for a total of 12 test runs. Table 1 gives the factorial design with the target values for each parameter. As required by the DQO, the product of this test design was the verified mean NO_x emission concentration(s) and the achieved 95 percent confidence interval of the mean for the specified operating range.

The factorial design allowed for statistical significance tests to determine whether the outlet NO_x concentration varied significantly with ambient temperature. Further, since two replicates were done, the significance of interactions between ambient temperature and outlet NO_x concentration could also be tested. If the outlet NO_x concentration did not change significantly with ambient temperature, the results are valid for the range of ambient temperature covered by the test. If the outlet NO_x concentration did vary significantly with ambient temperature, the results need to include information indicating the dependence of outlet NO_x concentration on ambient temperature. The results of the statistical significance tests are presented in Section 5.1.1.

Because the turbine was operated at constant full load (>97%) during the entire testing period, the process was assumed to be at equilibrium during all testing.

3.2 Sampling Methods

Table 2 lists all the measurement parameters for this verification test. They are categorized in the table as performance factors (e.g., direct emission measurements), associated impacts (e.g., CO and UHC emissions), and test conditions that were documented. Included in Table 2 are the factors to be verified, parameters to be measured for each factor, the measurement method for each parameter, and explanatory comments. The facility contact provided data for process condition parameters collected from the turbine human/machine interface (HMI) computer. Measurement methods and procedures are described in Sections 3.2.2 through 3.2.5.

3.2.1 Sampling Locations

Sample locations were chosen so that they met the minimum specified sample location criteria of the sample methods used or yielded a representative sample. The pollutant emission sampling location, process operating condition measurement locations, and ambient conditions measurement location are presented in Sections 3.2.1.1 through 3.2.1.3, respectively.

3.2.1.1 Pollutant Emission Sampling Location—

The NO_x, CO, UHC, O_2, and CO_2 concentrations were measured in the turbine exhaust stack (see Figure 1). Two sets of sampling ports were available, but neither met Method 20 criteria. As noted in the test/QA plan, the top set of sampling ports were judged as the most likely to yield a representative sample; therefore, the top sampling ports were used.

3.2.1.2 Process Conditions Measurement Locations—

Several parameters related to the operating conditions of the gas turbine during the verification test runs were recorded. These include electric power output, fuel flow rate, inlet temperature to the compressor, compressor discharge pressure, compressor discharge temperature, temperature into the catalyst, temperature out of the catalyst, and the exhaust gas temperature. The measurement locations for process and turbine parameters are identified in Figure 2 and are in relation to where the measurements are taken in the gas turbine.

Table 2. Summary of Measurements

Factors to be Verified	Parameter to be Measured	Measurement Method	Comments
Performance factors			
NO_x emissions	Outlet NO_x conc., ppmv	EPA Ref. Method 20 (40 CFR 60 App. A)	MRI provided and operated analyzer
Associated impacts			
CO emissions	Outlet CO conc., ppmv	EPA Ref. Method 10 (40 CFR 60 App. A)	MRI provided and operated analyzer
UHC emissions	Outlet THC conc., ppmvw	EPA Ref. Method 25A (40 CFR 60 App. A)	MRI provided and operated analyzer
O_2/CO_2 emissions	Outlet O_2/CO_2 conc.,%	EPA Ref. Method 20 (40 CFR 60 App. A)	MRI provided and operated analyzer
Test conditions documentation			
Percent of turbine's rated capacity	Electrical power ÷ turbine rating	Real power sensor	MRI collected data from facility contact
Fuel type	---	---	Natural gas
Fuel flow	Fuel flow rate	Coriolis-type flowmeter	Facility contact provided data from turbine HMI computer
Fuel sample results	Natural gas composition	Chromatographic analysis	From fuel sample results obtained from CCSI
Ambient conditions	Air temperature	Thermocouple or Thermohygrometer following EPA Quality Assurance Handbook for Air Pollution Measurement Systems, *Volume IV: Meteorological Measurements*	MRI conducted temperature, pressure, and humidity measurements concurrently
	Air pressure	ASTM D3631-95: aneroid barometer or equivalent	
	Air humidity	Thermohygrometer equivalent to ASTM E337-84(1996)e1	
Compressor parameters	Inlet temperature	Array of thermocouples on turbine	Facility contact provided data from turbine HMI computer
	Discharge temperature	Array of thermocouples on turbine	Facility contact provided data from turbine HMI computer
	Discharge pressure	Pressure gauge	Facility contact provided data from turbine HMI computer
Catalyst inlet condition	Temperature at catalyst inlet	Array of thermocouples on turbine	Facility contact provided data from turbine HMI computer
Catalyst outlet condition	Temperature out of the catalyst	Array of thermocouples on turbine	Facility contact provided data from turbine HMI computer
Catalyst hours of operation	Hours of operation since catalyst installed	Clock counter	Information provided by CCSI facility contact
Exhaust temperature	Exhaust gas temperature	Array of thermocouples on turbine	Facility contact provides data from turbine HMI computer
Compressor/turbine status	---	Pressure ratio compared to rated value	Information provided by CCSI facility contact

Figure 1. Turbine exhaust sampling location.

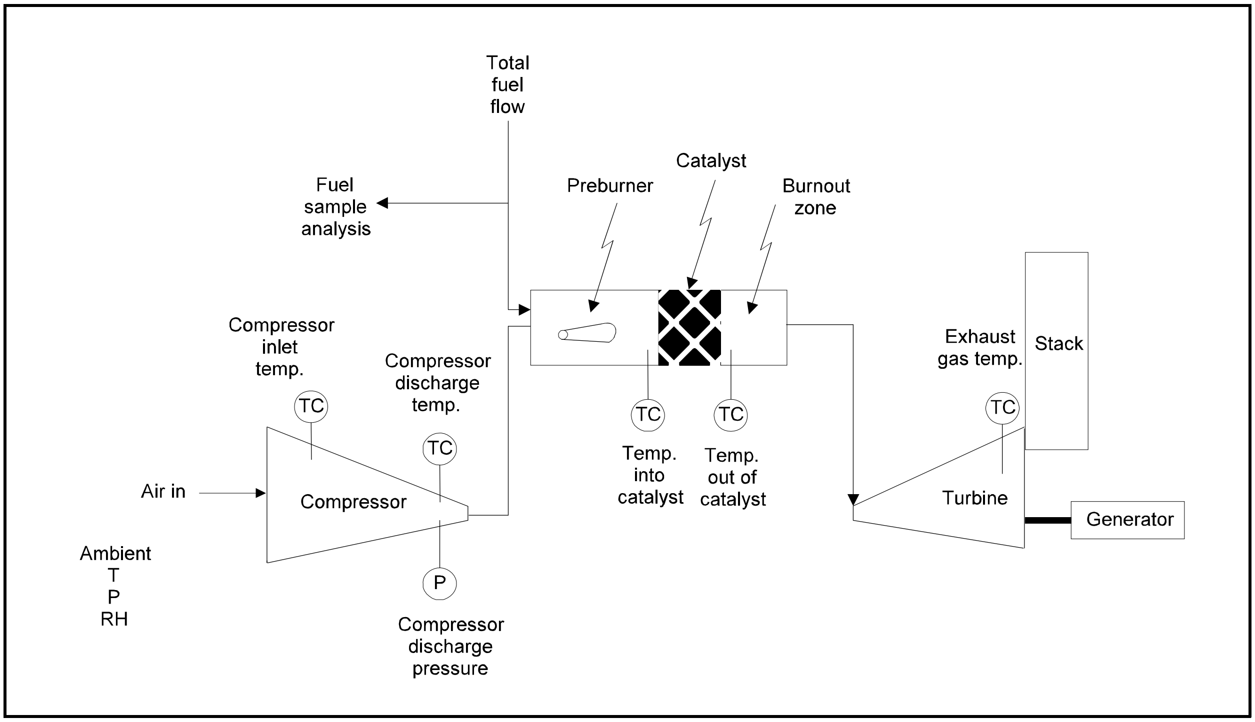

Figure 2. 1.5-MW gas turbine.

3.2.1.3 Ambient Conditions Measurement Location—

Parameters related to the ambient conditions during the verification test runs include the ambient air temperature, ambient air pressure, and ambient relative humidity. The measurement location for the ambient conditions is shown in Figure 3. The temperature (T), pressure (P), and relative humidity (RH) measurement devices were placed on the platform just below the gas turbine air inlet filters. In this location, the measurements are representative of the inlet air conditions (as recommended in Section 4.3.4 of *EPA Quality Assurance Handbook for Air Pollution Measurement Systems*, *Volume IV: Meteorological Measurements*, Templeman, 1995). An aspirated radiation shield was used to prevent biases caused by direct sunlight exposure.

Figure 3. Ambient conditions sampling location.

3.2.2 NO_x, CO, UHC, and O_2/CO_2 Sampling Procedures

Turbine exhaust gas was sampled for NO_x, CO, UHC, and O_2/CO_2 using EPA reference methods. All sampling followed the requirements of the specific test method being used unless otherwise stated in this document or approved by RTI before the verification test. The analytical systems were calibrated before and after each 32-min test run following the procedures in each applicable EPA Reference Method (40 CFR 60 App. A).

3.2.2.1 Sampling System—

A diagram of the extractive gaseous measurement system used for the testing is shown in Figure 4. Two independent sampling systems were used, one for CO, O_2, CO_2, and NO_x and

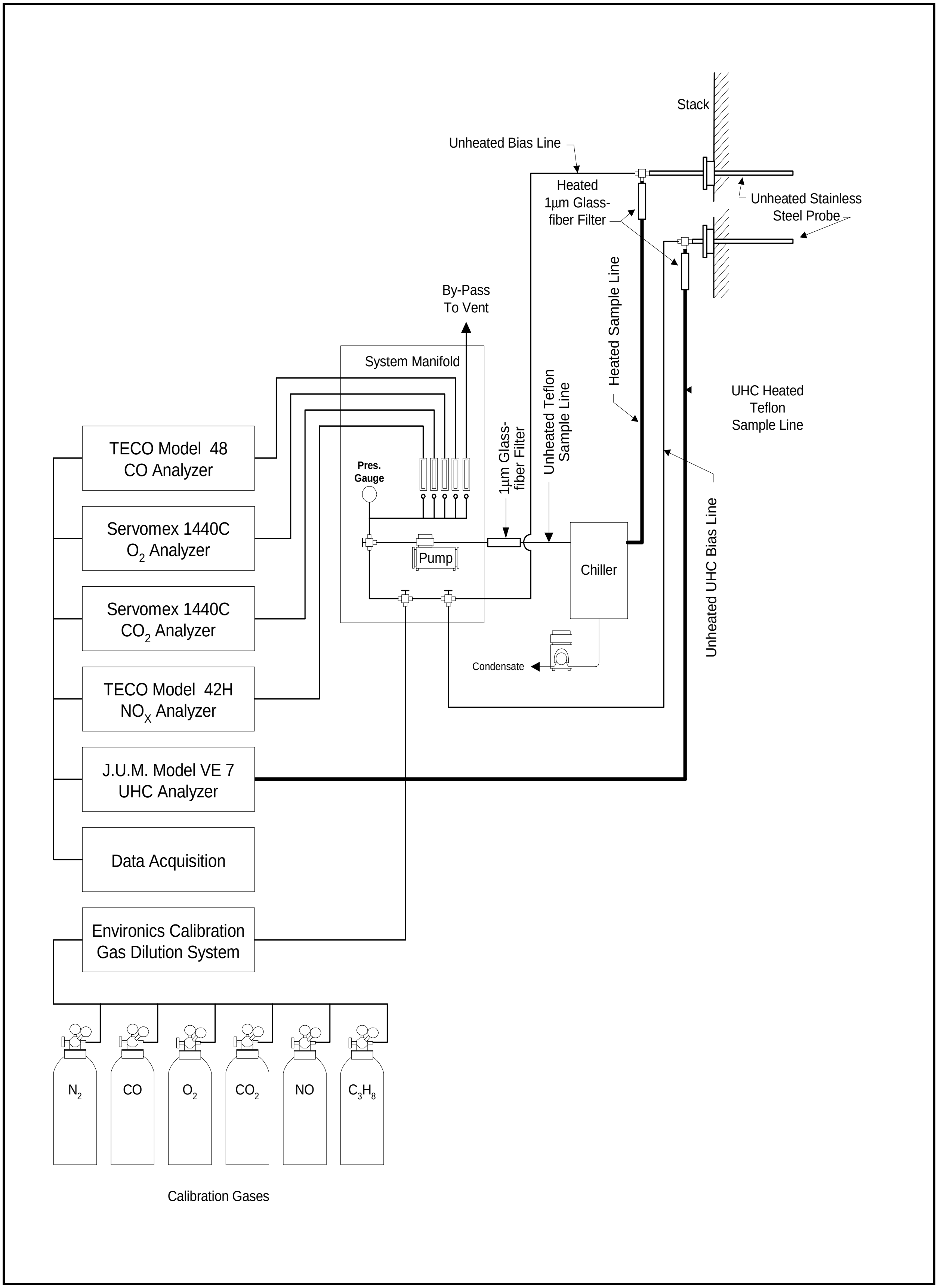

Figure 4. Extractive sampling system

another for UHC. All analyzers, calibration gases, and the sampling manifold were housed in an environmentally controlled trailer. The sampling system components were stainless steel (SS), Teflon, or glass. These materials have been proven to be inert for the gases of interest.

The sampling system for measurement of CO, O_2, CO_2, and NO_x consisted of

- Unheated stainless steel probe; 1.27 cm (0.5 in.) outside diameter (OD) (since the stack gas temperature was ~ 510°C [950°F], the probe was not heated);
- Heated (~121°C [250°F]) glass-fiber filter to remove particles with a diameter >1 μm;
- Heated (~121°C [250°F]) Teflon sample line (~3 m [10 ft] long and 0.95 cm [0.38 in.] OD) to transport the sample gas to the moisture removal condenser; temperature of the sample line was regulated with a thermostatic heat controller;
- Chiller condenser system submerged in an ice bath to condense and remove moisture in the sample gas; the condenser is a two-pass system to condense moisture while minimizing the liquid/air interface; a peristaltic pump was used to continually remove condensed water vapor; the water vapor dewpoint after the chiller was estimated to be ~ 3.5°C (38°F);
- Unheated Teflon sample line (~ 2.3 m [75 ft] long and 0.95 cm [0.38 in.] OD) to transport the sample gas from the chiller (located on the scaffold platform near the sample ports) to the sample manifold; just upstream of the sample extraction pump was a second glass-fiber filter;
- Teflon-lined sample pump to extract sample gas from the stack; sampling rate was ~ 10 L/min; and
- Individual rotameters regulated the sample flow to each analyzer and excess sample gas was dumped through the bypass.

The sampling system for measurement of UHCs consisted of

- Unheated SS probe; 1.27 cm (0.5 in.) OD;
- Heated (~121°C [250°F]) glass-fiber filter to remove particles with a diameter >1 μm;
- Heated (~121°C [250°F]) Teflon sample line (~23 m [75 ft] long and 0.63 cm [0.25 in.] OD) to transport the sample gas directly to the hydrocarbon analyzer; temperature of the sample line was regulated with a thermostatic heat controller; and
- Sample gas was extracted by a heated pump contained within the hydrocarbon analyzer.

The sampling system was calibrated by directing each calibration gas to the probe through an unheated Teflon tube. The probe was "flooded" with calibration gas, and the sample pump pulled as much of the calibration gas as needed to the system manifold. Excess calibration gas was dumped out the probe. This process of calibrating the system does not pressurize the sampling system and mask any leaks (see Section 3.2.3.5.2 for description of CO analyzer calibration).

Calibration gases were generated from a single, high-concentration EPA protocol gas with an Environics Model 2020 gas dilution system. The Environics system consists of four electronic mass flow controllers (MFCs). MFC 1 was used for the nitrogen dilution gas. MFC 2 (0 to 10 L/min) and MFC 3 (0 to 1 L/min) are used in combination with MFC 1 to generate the specified calibration gas concentration by diluting a high concentration standard gas. MFC 4 (0 to 0.1 L/min) was not used. The Environics system was calibrated at the factory on July 11, 2000. Also, the calibration of the combined MFCs that were used for this test (e.g., 1 + 2 and 1 + 3) was checked in accordance with EPA Method 205 the day before the field test began. The Method 205 data are summarized in Section 5.

3.2.2.2 Reference Analyzers—

The reference analyzers used for quantifying the gaseous concentrations are listed in Table 3. The table also includes a description of the analyzer and the measurement ranges used for this test. Measured pollutant concentrations were extremely low relative to the measurement ranges. Most notably, the UHC concentrations were about 0.1 to 0.2 part per million by volume on a wet basis (ppmvw) as measured on a 0- to 100-ppmvw range. Method 25A specifies a measurement range of 1.5 times the expected concentration, which is unfeasible at extremely low concentrations.

Table 3. Reference Analyzers and Measurement Ranges

Pollutant	Reference Analyzer	Measurement Range	Description
NO_x	Thermo Environmental Instruments (TEI) 42H	0-20 ppmv	Uses the principle of chemiluminescence to measure the concentration of NO_x in the sample stream. The instrument uses a heated can NO_2 converter.
CO	Thermo Environmental Instruments (TEI) 48	0-50 ppmv	Uses the principle of gas filter correlation and non-dispersive infrared (GFC-NDIR) to measure the concentration of CO in the sample stream.
UHC	J.U.M VE 7	0-100 ppmvw	Uses the principle of flame ionization detection (FID) to measure the concentration of hydrocarbons in the sample stream.
O_2/CO_2	Servomex 1440C	0-25% / 0-20%	The O_2 detector uses the principle of paramag-netics, and the CO_2 detector uses a single- beam, dual-wavelength IR technique.

3.2.3 Sampling Methods Requirements

Each of the sampling methods has different criteria to ensure the quality of the sample and the data collected. Each of these requirements is presented in the following sections.

3.2.3.1 Analyzer Interference Test—

An initial interference check was completed on the NO_x, CO, O_2, and CO_2 analyzers before their first use. For the interference test, the gases listed in Table 4 were injected into each analyzer. For acceptable analyzer performance, the sum of the interference responses to all of the interference gases must be $\leq$2 percent of the analyzer span value. The interference test results are presented in Section 5.

3.2.3.2 NO_2 Converter Efficiency Test—

The NO_2 converter efficiency is tested as part of routine analyzer QC Method 20. The test relies on the oxidation reaction of NO in the presence of oxygen. NO reacts to form NO_2 in equilibrium with NO. For the test, a clean, leak-free Tedlar bag was filled half full with the mid-level NO calibration gas. The bag was then filled with 20.9 percent O_2 gas. The bag was attached directly to the NO_x analyzer sample inlet. After approximately a 2-min stabilization period, 30 1-min average NO_x analyzer readings were recorded. For an acceptable converter, the 1-min average response at the end of 30 min is required to not decrease more than 2 percent of the highest peak 1-min value. That is, the analyzer should be capable of converting all the NO to NO_2. The results of the NO_2 converter efficiency check are presented in Section 5.

Table 4. Gas Analyzers Interference Test Gas Concentrations

CO	SO_2	CO_2	O_2
NO_x Analyzer Interference Gases			
498 ppmv	201 ppmv	9.98%	20.9%
CO Analyzer Interference Gases			
NA	NA	9.98%	NA
O_2 Analyzer Interference Gases			
498 ppmv	197 ppmv	9.98%	NA
CO_2 Analyzer Interference Gases			
498 ppmv	197 ppmv	NA	20.9%

NA = Not applicable.

3.2.3.3 Response Time Test—

3.2.3.3.1 Method 20 Response Time - NO_x and O_2/CO_2. To determine the response time according to Method 20 procedures, the zero gas (i.e., N_2) was injected into the sampling system at the probe. When the analyzer's readings were stable, the zero gas was turned off so the effluent could be sampled. When a stable reading was obtained, the upscale response time was determined as the time required for the computer readout to record a 95 percent step change from the zero reading to the stable effluent concentration. Then the high-level calibration gas for each analyzer was injected into the sampling system at the probe. When the analyzer's readings were stable, the high-level gas was turned off so that the effluent could be sampled. When a stable reading was obtained, the downscale response time was determined as the time required for the computer readout to record a 95 percent step change from the calibration gas reading to the stable effluent concentration. This procedure was repeated until three upscale and three downscale response times were completed. The longest of all the upscale and downscale response times was reported as the system response time for that analyzer. For Method 20, the response time must be 30 s or less. The response times are presented in Section 5, Table 13.

3.2.3.3.2 Method 25A Response Time - UHC. For EPA Method 25A, only an upscale response time test is required. To determine the upscale response time, the zero gas was injected into the sampling system at the probe. Then, the high-level calibration gas was injected into the sampling system. The upscale response time was determined as the time required for the computer readout to reach 95 percent of the high-level calibration gas reading. This procedure was repeated three times, and the average was reported as the response time. The response time is presented in Section 5, Table 13.

3.2.3.4 Preliminary O_2 Traverse—

Method 20 requires a preliminary O_2 traverse to be conducted at multiple sample points across the stack's cross-sectional area. The preliminary O_2 traverse determines the eight lowest O_2 concentration sampling points from an array of multiple points. These eight low O_2 points are used as the traverse points for the individual test runs. However, since this stack had a cross-sectional area of 0.66 m^2 (7.1 ft^2), only eight traverse points would be used for the preliminary O_2 traverse. Therefore, a preliminary O_2 traverse was not necessary and was not done, and eight traverse points for the test runs were selected in accordance with EPA Method 1.

3.2.3.5 Calibrations—

Table 5 lists the calibration gas concentrations used for the reference method testing. EPA protocol gas was used to calibrate the analyzers. Each of the reference methods has different calibration procedures. The individual method calibration procedures are described in Sections 3.2.3.5.1 through 3.2.3.5.3. The gaseous pollutant measurement system was calibrated before and after each test run. Also, no test run started more than 2 hours after a pretest calibration, and all post-test calibrations were completed within 1 hour of the end of a test run.

Table 5. Calibration Gas Concentrations

Calibration point	O_2	CO_2	NO_x	CO	UHC
Zero	Pure N_2	Pure N_2	Pure N_2	Pure N_2	Pure N_2
Low-level	NA	NA	5.02 ppmv	15.0 ppmv	29.9 ppmv
Mid-level	11.99%	3.01%	10.03 ppmv	29.9 ppmv	49.9 ppmv
High-level	20.9%	9.98%	17.04 ppmv	44.9 ppmv	84.9 ppmv

3.2.3.5.1 Method 20 Calibration Procedures. The NO_x calibration gas was 201.85 ppmv NO in a balance of N_2. The O_2 calibration gas was 38.4 percent O_2 in a balance of N_2. The CO_2 calibration gas was 40.05 percent CO_2 in a balance of N_2. Copies of the calibration gas certifications are attached in Appendix A. As noted earlier, a gas dilution system was used to make the targeted gas concentration levels shown in Table 5 from the single, high-concentration EPA protocol gas.

For calibration error checks of both the NO_x and diluent analyzers, the zero gas and mid-level gas were introduced separately into the sampling system at the probe. Each analyzer's response was adjusted to the appropriate level. Then the remainder of the calibration gases were introduced into the sampling system, one at a time. The acceptable response of the analyzer to each calibration gas must be within ±2 percent of span.

At the conclusion of a test run, the zero and mid-level calibration gases for each analyzer were introduced separately into the sampling system. Both the zero drift and calibration drift, calculated in accordance with Equation 1, must be within ±2 percent of span. If a drift was greater than 2 percent of span, the test run would have been considered invalid and the measurement system would have been repaired to satisfy drift tolerances before additional test runs were conducted. Method 20 calibration results are summarized in Section 5. Individual pre- and post-test run calibrations are presented in Appendix B.

$$\text{Percent drift} = (\text{Final response} - \text{Initial response}) / \text{Span value} \times 100 \qquad (1)$$

3.2.3.5.2 Method 10 Calibration Procedures. The CO calibration gas was 199.8 ppmv CO in a balance of N_2. The calibration gas certification is shown in Appendix A. The gas dilution system was used to make the targeted gas concentration levels from the single, high-concentration EPA protocol gas.

CO analyzer calibration error checks were conducted before the start of each day's testing. The calibration error check was conducted (after final calibration adjustments were made) by separately injecting each of the four calibration gases (zero, low-, mid-, and high-level) directly into the analyzer and recording the response. If the calibration error was greater than 2 percent, the analyzer would have been repaired or replaced and recalibrated to an acceptable calibration error limit before proceeding.

Zero and upscale sampling system calibration checks were performed both before and after each test run to quantify the reference measurement system calibration drift and the sampling system bias. Upscale calibration checks were performed using the mid-level gas. During these checks, the calibration gases were introduced into the sampling system at the probe so that they were sampled and analyzed in the same manner as the sample gas. Drift means the difference between the pre- and post-test run system calibration check responses. Sampling system bias means the difference between the system calibration check response and the initial calibration error response (direct analyzer calibration) at the zero and upscale calibration gas levels. Method 10 calibration results are summarized in Section 5. Individual pre- and post-test run calibrations are presented in Appendix B.

3.2.3.5.3 Method 25A Calibration Procedures. The UHC calibration gas was 190.6 ppmv propane in a balance of nitrogen. Copies of the calibration gas certification are located in Appendix B. The gas dilution system was used to make the targeted gas concentration levels shown in Table 5 from the single, high-concentration EPA protocol gas.

For calibration error checks, the zero gas and high-level gas were introduced separately into the sampling system at the probe. The UHC analyzer's response was adjusted to the appropriate level. Then the low- and mid-level calibration gases were introduced into the sampling system, one at a time. The acceptable response of the analyzer to each calibration gas must be within ±5 percent of the calibration gas value.

At the conclusion of a test run, the zero and mid-level calibration gases were introduced separately into the sampling system. Both the zero drift and calibration drift, calculated in accordance with Equation 1, must be within ±3 percent of span. If a drift was greater than 3 percent of span, the test run would have been considered invalid, and the measurement system would have been repaired before additional test runs were conducted. Method 25A calibration results are summarized in Section 5. Individual pre- and post-test run calibrations are presented in Appendix B.

3.2.3.6 CO_2 Trap—

Method 10 requires that CO_2 be removed from the sample gas that is sent to the CO analyzer. The CO_2 is removed because the commonly used, nondispersive infrared technology instrument for measurement of CO exhibits an interference from CO_2. However, the TEI Model 48 incorporates the technique of gas filter correlation to eliminate the CO_2 interference from the measurement of CO. Since the TEI Model 48 does not have a CO_2 interference (see the interference test results in Section 5), the CO_2 trap was not used.

3.2.3.7 Sample Location by Method 20 and Traverse Point Selection by Method 1—

Two sets of sampling ports were available on the turbine exhaust stack. One set was located immediately after a long 90° horizontal-to-vertical upward bend in the stack. The second set was located approximately 4.6 m (5 duct diameters) downstream of the 90° horizontal-to-vertical upward bend and 0.5 m (0.5 duct diameters) upstream of the stack exit. Neither of these port locations is ideal; however, the top ports were used (see Figure 1). Only one of the top ports was used for the Method 20 traverse because the scaffold was only set up on one side of the circular stack. Therefore, MRI did not have safe access to the second port for the Method 20 traverse. Because the gas concentration was not stratified across the one available diagonal traverse, all parties agreed that double traversing across the single port was acceptable. Table 6 shows the point locations.

Table 6. Method 20 Traverse Points

Point	Percent of Stack Diameter	Distance from Stack Wall (cm)
1	6.7	(0.9)
2	25.0	(3.5)
3	75.0	(10.6)
4	93.3	(13.2)

3.2.4 Process Data Collection

Process data were collected from the turbine control's HMI computer to document the test conditions. The CCSI facility contact provided the data from the HMI computer. Table 2 identifies the parameters that were measured and the party responsible. The test condition documentation parameters taken from the HMI computer were retrieved at 1-min intervals for each test run. Process data, at 1-min intervals for each test run, are presented in Appendix C. The process data measurements are summarized in Sections 3.2.4.1 through 3.2.4.6.

3.2.4.1 Electrical Power Generation by Turbine —

To determine the operating rate of the turbine during the verification test, the electrical power production from the electrical generator was recorded. This measurement was taken with a Real Power Sensor that determines the electrical power supplied at the generator terminals. At this writing, CCSI is not aware of any calibration of this device since commissioning of the site in October 1998. The output has been noted by CCSI to be consistent with the City of Santa Clara meter on several occasions.

3.2.4.2 Fuel Flow Rate—

The fuel flow rate into the combustion system was measured with a Coriolis-mass flowmeter. The flowmeter was calibrated for natural gas at the factory and was recalibrated on June 28, 2000. (The flowmeter is periodically compared to the City of Santa Clara's main turbine flowmeter.)

3.2.4.3 Compressor Inlet Temperature—

Compressor inlet temperature (also referred to as "ambient temperature" by the facility) was measured with two 1/8-in. diameter sheathed K-type thermocouples located in the inlet air duct. These devices are calibrated on a semiannual basis using a calibrated thermowell device.

3.2.4.4 Compressor Discharge Pressure—

Compressor discharge pressure was measured using two pressure taps and two absolute pressure transducers. The transducers were originally calibrated at the factory and are periodically re-calibrated by CCSI personnel using specially maintained and calibrated pressure-sensing devices. The absolute pressure transducers were last calibrated in March 2000.

3.2.4.5 Catalyst Inlet/Catalyst Outlet Temperatures—

The air temperature just upstream of the catalyst and the gas temperature just downstream of the catalyst were measured by separate thermocouple arrays. The catalyst outlet temperature was measured with a series of four to eight thermocouples installed at the exit from the catalyst bed. The thermocouples are calibrated by CCSI personnel whenever the thermocouple hardware is changed.

3.2.4.6 Turbine Exhaust Temperature—

The turbine outlet temperature was measured by four 1/8-in. diameter sheathed K-type thermocouples installed at the exit of the turbine, just upstream of the stack's silencer. These thermocouples were factory calibrated, were recalibrated by CCSI personnel upon receipt, and were recalibrated upon installation in the spring of 2000.

3.2.5 Ambient Conditions Sampling

Three ambient air conditions were measured three times during each test run: temperature, pressure, and relative humidity. Temperature and humidity were measured using an equivalent technique to ASTM E337-84(1996)e1. ASTM E337-84(1996)e1 uses an aspirated wet-bulb and dry-bulb device to determine relative humidity, but MRI used a thermohygrometer to obtain the relative humidity and ambient temperature. Pressure was measured using the ASTM D3631-95 method. Ambient pressure was measured with an aneroid barometer. The thermohygrometer and aneroid barometer were placed in a mechanically aspirated, grey steel box. The accuracy of the thermohygrometer measurements are ±3 percent for relative humidity and ±0.7°F for ambient temperature based on the manufacturer's performance specifications. The relative humidity is detected using the principle of changes in the capacitance of the sensor as its thin polymer film absorbs water molecules. Temperature is measured with a negative temperature coefficient thermistor. Results of the ambient conditions measurements are shown in Appendix C.

The equipment used to make the ambient conditions measurements is carefully maintained by MRI's Field Measurements section. The instrumentation was calibrated according to MRI standard operating procedures (SOPs): MRI-0721 - *Calibration of Thermocouple Probes, Thermocouple Indicators and Digital Thermometers*, MRI-0722 - *Calibration of Pressure Gauges*, and MRI-0729 - *Qualification and Calibration of Hygrometers* at MRI's laboratory before being transported to the field measurement site. Results of those calibrations are presented in Appendix C.

3.3 Data Acquisition and Data Management

Data to document the process operating conditions of the turbine and Xonon™ system were recorded by the turbine's HMI computer. These data were provided by the facility contact to MRI's Field Team Leader in electronic format after each three-run test series. Process data are shown in Appendix B. Data to document the ambient conditions were recorded manually on the sheets shown in Appendix B. A Labtech Notebook was used to record the concentration signals from the individual analyzers. The Labtech Notebook recorded the analyzer output at 1-s intervals and averaged those signals into 1-min averages. At the conclusion of a test run, the pre- and post-test calibration results were manually transcribed into a Microsoft Excel spreadsheet to calculate drift and system bias. After a series of test runs, the test run values were electronically transferred from the Labtech Notebook into a Microsoft Excel spreadsheet for data calculations and averaging. The calculations done by Microsoft Excel used the default rounding convention. The raw data printouts from the Labtech Notebook and the test run averages are shown in Appendix B.

For Method 20, the first 1-min average, after moving to a new traverse point, is typically disregarded as not representing the concentration at that traverse point. However, for this test program, since gaseous stratification was not present and test runs were 32 min in length, all data were used in the NO_x and O_2 concentration averages.

For this test program, the data measurement and collection activities for the Method 20 measurements shown in Figure 5 were used. This flow chart includes all data activities from the initial pretest QA steps to the passing of the data to the Task Leader. These steps were followed in the field. Data for other methods used during this verification test were collected and handled in the same manner as the Method 20 data.

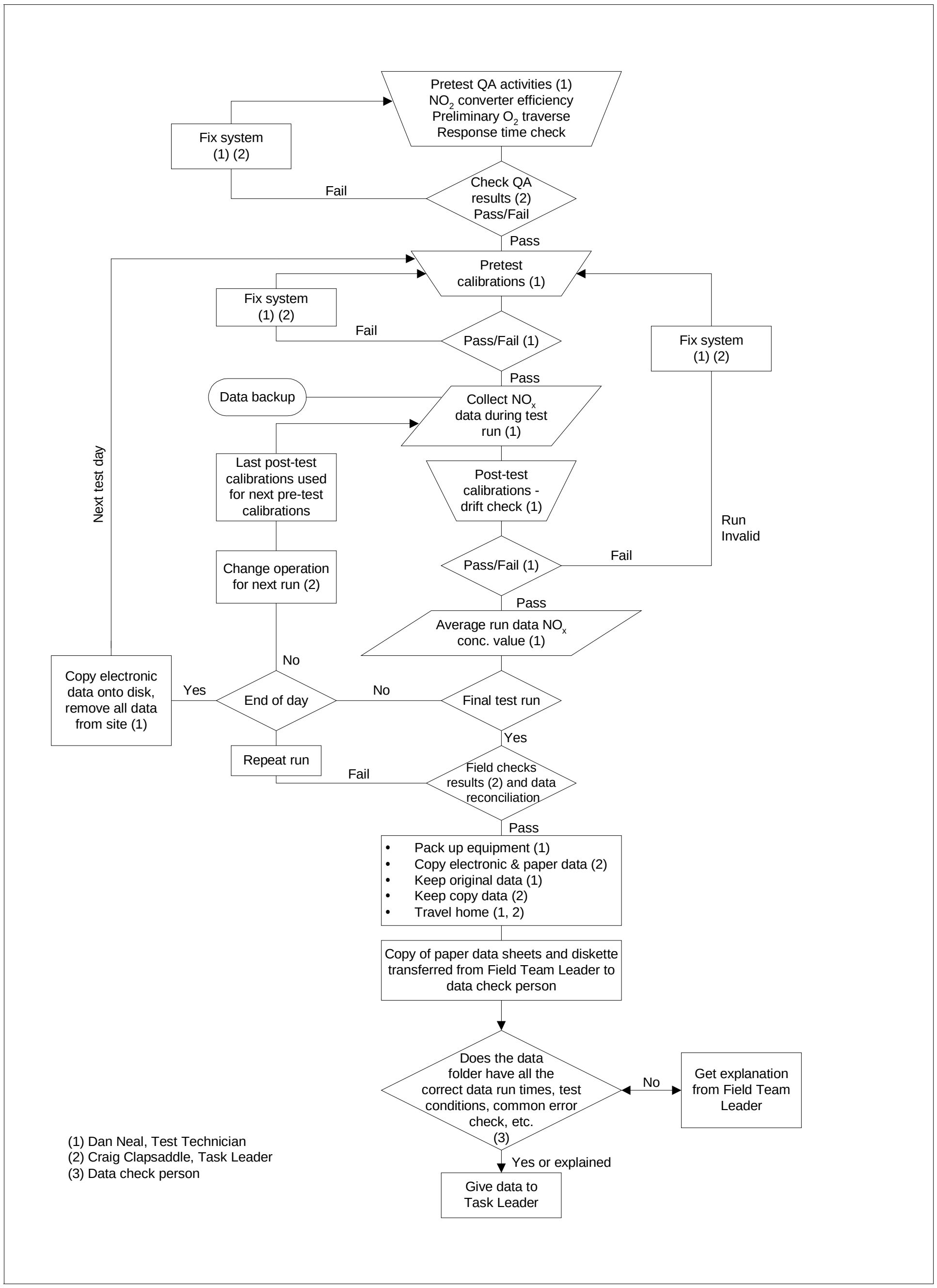

Figure 5. Method 20 NO_x/O_2 gas turbine emissions measurement flowchart.

Section 4.0

Statement of Operating Range of Test

For this verification test of the Xonon™ flameless combustion system, the CCSI representative indicated that the emissions performance of the technology was guaranteed to be less than 2.5 ppmvd NO_x at 15 percent O_2 and to be less than 6 ppmvd CO at 15 percent O_2. Without the air management system, this emission guarantee was valid only at full turbine load conditions. Therefore, the verification test was done at full turbine load.

During consultation with the CCSI representative, the only parameter identified that could possibly have an effect on emissions was ambient temperature. In general, lower ambient temperatures result in slightly higher NO_x emissions for Xonon™ -equipped turbines because slightly more fuel must be used in the pre-burner to achieve the desired inlet temperature to the catalyst. To evaluate the effect of ambient temperature on NO_x emissions, the verification test was conducted during and after sunrise (to achieve the lowest ambient temperature of the day) and during the afternoon (to achieve the highest ambient temperature of the day). The ambient temperature range experienced during the 12 test runs was from 15.1 to 25.3°C (58.8 to 77.2°F).

Data to document the process operating conditions of the turbine and Xonon™ flameless combustion system were recorded by the turbine's HMI computer. The operating conditions during the 12 test runs are presented in Table 7. The bottom two rows of Table 7 show the minimum and maximum values for each parameter. These minimum and maximum values form the operating range over which this verification test was conducted.

The natural gas collected during the test showed that the fuel had a dry gas higher heating value of 3.778×10^7 gross J/m^3 (1012.9 Btu/ft^3). The gas analysis is attached in Appendix B.

Table 7. Operating Parameter Ranges

Run	Ambient Temp.		Turbine Load		Fuel Flow Rate		Compressor Inlet Temp.		Compressor Discharge Pressure		Compressor Discharge Temp.		Temp. at Catalyst Inlet		Temp. Out of Catalyst		Exhaust Gas Temp.	
	°C	°F	(MW)	(%)[a]	kg/h	lb/h	°C	°F	kPa	psig	°C	°F	°C	°F	°C	°F	°C	°F
1	15.2	59	1.39	97.9	428	944	17	62	910	132	356	672	480	895	847	1557	524	980
2	16.3	61	1.38	98.1	425	937	17	63	903	131	356	673	480	895	847	1557	527	981
3	17.4	63	1.37	97.9	423	932	19	65	896	130	357	675	480	896	848	1558	529	983
4	25.2	77	1.25	98.9	406	894	26	78	869	126	364	686	484	903	850	1562	535	994
5	24.1	75	1.27	98.6	405	893	25	77	869	126	364	686	484	903	851	1564	534	993
6	21.3	70	1.29	98.4	411	907	22	72	876	127	361	682	481	898	849	1560	532	989
7	14.6	58	1.36	98.2	428	944	16	60	910	132	355	670	480	896	846	1555	526	979
8	16.3	61	1.35	98.3	425	938	17	63	910	132	356	673	480	896	847	1556	527	981
9	17.4	63	1.33	98.2	423	932	19	65	896	130	357	674	480	896	847	1556	529	983
10	20.7	69	1.29	98.4	412	908	22	72	882	128	361	681	481	898	846	1555	531	988
11	21.9	71	1.25	99.0	408	899	25	76	876	127	362	684	481	898	847	1556	533	991
12	23.5	74	1.23	98.4	407	898	25	76	869	126	362	684	482	900	849	1559	533	991
Minimum	15.2	59	1.23	97.9	405	893	16	60	869	126	355	670	480	895	846	1555	526	979
Maximum	25.2	77	1.39	99.0	425	944	26	78	910	132	364	686	484	903	851	1564	535	994

[a]Note: Turbine load (%) is the percent of turbine capability at the prevailing ambient conditions.

Section 5.0

Summary and Discussion of Results

A verification test of the Xonon™ flameless combustion system was conducted on July 18 and 19, 2000, in Santa Clara, California. The purpose of the verification test was to evaluate the NO_x emission performance for the Xonon™ flameless combustion system as claimed by CCSI. The test was conducted according to a test/QA plan that was approved by EPA on June 28, 2000.

The results of the verification test are summarized in Section 5.1. An important part of the verification test was the extensive QA applied to this field test. The results of all the QA and quality control (QC) checks performed during this verification test are summarized in Section 5.2. A few minor deviations from the test plan were encountered, and those are discussed in Section 5.3.

5.1 Results Supporting Verification Statement

The pollutant emission concentrations measured for the 12 test runs are presented in Table 8. As can be seen, the NO_x emission concentration was below the 2.5 ppmvd at 15 percent O_2 performance claim offered by CCSI. Also, the CO emission concentration is well below 6 ppmvd at 15 percent O_2. In addition, the unburned hydrocarbons concentrations were very low and virtually undetectable during the 12 test runs.

Table 8. Pollutant Emission Concentrations for Xonon™ Verification Test

Run	Ambient Temp. (°F)	NO_x (ppmvd @ 15% O_2)	CO (ppmvd @ 15% O_2)	UHC (as propane) (ppmvw)
1	59	1.15	1.19	0.17
2	61	1.14	1.71	0.16
3	63	1.08	1.50	0.17
4	77	1.06	1.10	0.15
5	75	1.11	1.03	0.17
6	70	1.13	1.22	0.15
7	58	1.22	1.10	0.18
8	61	1.17	1.02	0.13
9	63	1.13	1.19	0.20
10	69	1.14	1.91	0.12
11	71	1.12	1.88	0.18
12	74	1.13	1.46	0.19

5.1.1 Statistical Analysis of Variance

This section describes the statistical analysis of the verification test data. As discussed in Section 3.1, detection of ambient temperature effects required wide swings in daily temperature, which did not occur during the test period. The measured values from the verification test are compared to the performance capability range specified by CCSI. The first step in the statistical analysis was to perform the analysis of variance of NO_x concentration on ambient temperature. This step determines if ambient temperature has a significant effect on NO_x emissions at the 95 percent confidence level.

The analysis of variance produced a P-value of 0.1647. Only when the P-value is less than 0.05 would the ambient temperature have a significant effect on NO_x at the 95 percent confidence level. Therefore, the turbine's NO_x emissions were not affected by ambient temperature over the range of 58°F to 77°F.

5.1.2 Variability of NO_x Emissions

Because NO_x emissions were not a function of ambient temperature, the 95 percent confidence interval was calculated for the entire 12-run data set. The 95 percent confidence interval was found to be ±0.026 ppmvd at 15 percent O_2. Therefore, the NO_x emission concentration for this verification test can be stated as follows:

1.13 ± 0.026 ppmvd at 15 percent O_2 at the 95 percent confidence level.

5.2 Discussion of QA/QC and QA Statement

Extensive QA/QC was applied to this verification test, much more than is typically applied to an emissions test. The following QA and QC activities were part of this test:

- A DQO for the NO_x concentration measurement,
- Reference method QC checks,
- A technical system audit to evaluate all components of the data gathering and data management system,
- A performance evaluation sample to check the operation of the NO_x measurement system, and
- A data audit of 30 percent of the critical measurement (NOx concentration) and 10 percent of the noncritical measurement.

The results of each of these QA and QC checks are presented in Sections 5.2.1 through 5.2.3.

5.2.1 NO_x Measurement DQO

The DQO for the NO_x emission concentration measurement was stated in the test/QA plan as follows:

> For the NO_x emission concentration measurements, the overall NO_x emission must be within ±10 percent of the mean emission concentration above 5 ppmvd, ±25 percent below 5 and above 2 ppmvd, and ±50 percent below 2 ppmvd.

The DQO was computed as the half-width of the 95 percent confidence interval of the mean divided by the mean. Since ambient temperature was not significant, all 12 test runs were included in the DQO assessment.

As presented in Section 5.1.2, the half-width of the 95 percent confidence interval was 0.026 ppmvd at 15 percent O_2 and the mean NO_x concentration was 1.13 ppmvd at 15 percent O_2. Therefore, the DQO for NO_x equates to 2.3 percent, well within the DQO limit of 50 percent below 2 ppmvd.

5.2.2 Reference Method QC

The reference methods used to measure emission concentrations of NO_x, O_2/CO_2, CO, and UHCs have specific QC criteria that must be met. The QC criteria ensure the accuracy and stability of the measurement system and are summarized in Table 9. The results of the reference method QC checks are summarized in Sections 5.2.2.1 through 5.2.2.7. The raw data for the QC checks are in Appendix A.

Table 9. Reference Method QC Criteria

Method	Check	Criteria
Method 205	Dilution error	± 2% of reference value
Method 20	Interference	≤ 2% of span
	NO_2 converter efficiency	98%
	Response time	< 30 s
	Calibration error	± 2% of span
	Drift	± 2% of span
Method 10	Calibration error	± 2% of span
	System bias	± 5% of span
	Drift	± 3% of span
Method 25A	Calibration error	± 5% of gas value
	Drift	± 3% of span
Method 1	Traverse point	± 1 inch

5.2.2.1 Method 205 Dilution System Verification—

A gas dilution system was used to generate the targeted calibration gas concentrations from single, high-concentration EPA protocol gases specific to each analyzer. This dilution system must be verified in the field before each test program according to EPA Method 205 procedures. The dilution system verification was done with the NO_x analyzer on a 0- to 50-ppmv measurement range. The results of the verification of MFCs 1 and 2 and 1 and 3 are presented in Tables 10 and 11, respectively. For acceptable performance, the three-injection average at the low and high dilution points and

Table 10. Method 205 Summary Data Verification of Mass Flow Controllers 1 and 2

Standard Calibration Points	Reference Value Concentration (ppmv)	Average Analyzer Reading (ppmv)	Error (%)
Low dilution	24.90	24.64	1.03
Mid-level supply	25.59	25.46	0.52
Upper dilution	44.90	45.08	-0.40

the mid-level supply gas must be within ±2 percent of the reference value. As indicated in Tables 10 and 11, all dilution points were within the required ±2 percent.

Table 11. Method 205 Summary Data Verification of Mass Flow Controllers 1 and 3

Standard Calibration Points	Reference Value Concentration (ppmv)	Average Analyzer Reading (ppmv)	Error (%)
Low dilution	25.07	24.64	1.73
Mid-level supply	25.59	25.29	1.18
Upper dilution	45.10	44.87	0.51

5.2.2.2 Interference Test—

Before an analyzer is used, it must be demonstrated that other gases in the effluent do not interfere with the measurement technique. This test was done for the NO_x, CO, O_2, and CO_2 analyzers as required by the reference method. For acceptable performance the total interference from all the gases injected must be ±2 percent or less. The interference results are presented in Table 12. Those results show that none of the analyzers exhibited unacceptable interference.

Table 12. Analyzer Interference Results

Analyzer	Interference (% span)
NO_x	-0.25
CO	-1.80
O_2	0.80
CO_2	1.50

5.2.2.3 NO_2 Converter Efficiency Test—

Before each test program, the NO_x analyzer must demonstrate that the NO_2 converter is at least 98 percent efficient. The performance criteria state that, during the 30-min NO_2 converter efficiency test, the last NO_x analyzer reading must not decrease by more than 2 percent from the highest reading. The NO_2 converter showed a 0.2 percent decrease (5.02 ppmv was the highest reading and 5.01 ppmv was the last reading), well within the criteria for an acceptable converter. During the entire NO_2 converter efficiency test, the readings ranged from 4.97 to 5.02 ppmv.

5.2.2.4 Response Time Test—

A response time test was done for NO_x, O_2, CO_2, and UHCs. Method 20 requires a response time of 30 s or less. The results of the response time tests are summarized in Table 13.

Table 13. Response Times (seconds)

NO_x	O_2	CO_2	UHCs
27	25	24	19

5.2.2.5 Method 20 Calibrations—

For Method 20, the two calibration criteria are calibration error (±2 percent of span) and drift (±2 percent of span). The largest calibration error and drift for the NO_x, O_2, and CO_2 analyzers are presented in Table 14. See Appendix A, Pre- and Post-test Calibration Results. As shown in Table 14, all calibration criteria were met.

5.2.2.6 Method 10 Calibrations—

For Method 10 as performed for this test, the three calibration criteria are calibration error (±2 percent of span), system bias (±5 percent of span), and drift (±3 percent of span). The largest absolute calibration error was 0.46 percent, the largest system bias was -1.28 percent, and the largest drift was -0.44 percent. See Appendix A, Pre- and Post-Test Calibration Results. All calibration criteria were met.

Table 14. Method 20 Calibration Error and Drift Results

	Largest Absolute Calibration Error (%)	Largest Drift (%)
NO_x	-0.55	1.15
O_2	0.46	0.32
CO_2	0.43	1.20

5.2.2.7 Method 25A Calibrations—

For Method 25A, the two calibration criteria are calibration error (±5 percent of the gas value) and drift (±3 percent of span). The largest calibration error was -0.39 percent and the largest drift was -0.42 percent. See Appendix A, Pre- and Post-test Calibration Results. All calibration criteria were met.

5.2.3 Audits

Independent systematic checks to determine the quality of the data were performed throughout this project. These checks consisted of a technical system audit, a performance evaluation audit, and a data audit as described in Sections 5.2.3.1 through 5.2.3.3. The combination of these three audits and the evaluation of the method's QC data allowed the assessment of the overall quality of the data for this project. MRI's Task Leader managed the collection of and reviewed the field data as detailed in Sections B10.1, C1.1, and C1.2 of the test/QA plan.

5.2.3.1 Technical System Audit—

The technical system audit (TSA) was conducted by Robert Wright, RTI Quality Manager, and Michael Tufts of ARCADIS Geraghty and Miller, an EPA contractor. This audit evaluated all components of the data gathering and management system to determine if these systems had been properly designed to meet the QA objectives for this study. The TSA included a careful review of the experimental design, the test plan, and procedures. This review included personnel qualifications, adequacy and safety of the facilities and equipment, standard operating procedures (SOPs), and the data management system.

The TSA began with the review of study requirements, procedures, and experimental design to ensure that they met the data quality objectives for the study. During the system audit, the Task QA Officer inspected the analytical activities and determined their adherence to the SOPs and the test/QA plan.

The draft summary of Wright's TSA is provided in Appendix A. In general, the TSA found that the test program, as conducted, met all the data quality objectives for the study.

5.2.3.2 Performance Evaluation Audit—

A performance evaluation (PE) audit was conducted by Mike Tufts for EPA. For the PE audit, a performance evaluation sample (PES) was supplied to check the operation of the NO_x analytical system. The PES was measured for 6 continuous minutes on two occasions for a total of 12 measurements. The NO_x measurement systems read the 1.00 ppmv NO_x PES as 0.991 ± 0.012 ppmv at the 95 percent confidence level. A summary of the performance evaluation audit is presented in Table 15.

Table 15. NO_x Analyzer Performance Evaluation Audit

Time	NO_x System Readings (ppmv)
10:27	1.02
10:28	1.02
10:29	0.99
10:30	0.99
10:31	0.98
10:32	0.98
16:29	1.01
16:30	1.00
16:31	0.99
16:32	0.98
16:33	0.97
16:34	0.96
Mean	0.9908
Confidence Interval (95 percent)	0.0119

The method performance also was assessed using the method QC samples described in Sections 5.2.2.1 through 5.2.2.7.

5.2.3.3 Data Audit—

The data audit, an important component of a total system audit, was completed to determine if systematic errors were introduced. The data audit was performed by Jack Balsinger, the MRI task QA officer, by randomly selecting approximately 30 percent of the NO_x data and 10 percent of the remaining data and following them through the calculations. The scope of the data audit was to verify that the data-handling system was correct and to assess the quality of the data generated. The data review and data audit were conducted in accordance with MRI standard procedures.

In addition to the data audit, a data check was performed by James Surman of MRI. The data check was conducted to find errors in transposing data from the raw data printouts to the calculation sheets in the Microsoft Excel spreadsheets. Data were reviewed for completeness, and the method QC results were checked for acceptability. The Microsoft Excel spreadsheets were checked for accuracy relative to the reference method requirements, and simulated data were used to check the accuracy of the computations. Three minor errors were found and corrected. Two errors were typographical, and one error was a spreadsheet format error.

5.3 Deviations from Test Plan

One deviation from the test plan was experienced during the field test, and one corrective action was taken.

The test/QA plan indicated that an eight-point traverse—four points on one diagonal traverse and four points on another diagonal traverse—was to be done during the Method 20 sampling.

However, because of the arrangement of the scaffolding, only one of the sampling ports could be reached safely. Therefore, only four traverse points on the one diagonal traverse were used. Each point was sampled for 4 minutes during two passes to maintain the 32-min test duration.

While attempting to perform the Method 205 validation test on the dilution system, the NO_x analyzer's output was nonlinear. This issue was resolved by making an adjustment to the analyzer's photomultiplier tube in accordance with the operator's manual. Once the adjustment was made, the analyzer response was linear across the measurement range.

In addition, the auditors noted that the test/QA plan (RTI, 2000b) incorrectly stated that the CO_2 calibration gas consisted of CO_2 in air. It was actually CO_2 in nitrogen.

Section 6.0

References

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