July 1999

Environmental Technology Verification Report

ENERAC 3000E
PORTABLE EMISSION ANALYZER

Prepared by

Battelle Memorial Institute

Under a cooperative agreement with

U.S. Environmental Protection Agency

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Advanced Monitoring Systems

Enerac 3000E
Portable Emission Analyzer

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development (ORD) provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

The Environmental Technology Verification (ETV) Program has been established by the EPA, to verify the performance characteristics of innovative environmental technology across all media and to report this objective information to permitters, buyers, and users of the technology, thus substantially accelerating the entrance of new environmental technologies into the marketplace. Verification Organizations oversee and report verification activities based on testing and Quality Assurance protocols developed with input from major stakeholders and customer groups associated with the technology area. At present, there are twelve environmental technology areas covered by ETV. Information about each of the environmental technology areas covered by ETV can be found on the Internet at http://www.epa.gov/etv.htm.

Effective verifications of monitoring technologies are needed to assess environmental quality, and to supply cost and performance data to select the most appropriate technology for that assessment. In 1997, through a competitive cooperative agreement, Battelle Memorial Institute was awarded EPA funding and support to plan, coordinate, and conduct such verification tests, for "Advanced Monitoring Systems for Air, Water, and Soil" and report the results to the community at large. Information concerning this specific environmental technology area can be found on the Internet at http://www.epa.gov/etv/07/07_main.htm.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. In particular we recognize Joseph Tabor, Steve Speakman, and Joshua Finegold of Battelle, and Bob Gasser of Energy Efficiency Systems, Inc.

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List of Abbreviations

AC	alternating current
AMS	Advanced Monitoring Systems
ANSI	American National Standards Institute
Btu/hr	British thermal unit per hour
ccm	cubic centimeter per minute
CEMS	continuous emission monitoring system
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FID	flame ionization detector
ft^3	cubic feet
gpm	gallons per minute
kW	kilowatt
LOD	limit of detection
lpm	liters per minute
m^3	cubic meters
NH_3	anhydrous ammonia
NIST	National Institute of Standards and Technology
NO	nitric oxide
NO_x	nitrogen oxides
NO_2	nitrogen dioxide
O_2	oxygen
PE	performance evaluation
ppm	parts per million, volume
ppmC	parts per million carbon
QA	quality assurance
QC	quality control
QMP	Quality Management Plan
rms	root-mean-square
RPM	revolutions per minute
SAS	Statistical Analysis System

SCAQMD	SCAQMD Air Quality Management District
SCR	selective catalytic reduction
SO_2	sulfur dioxide
UHP	ultra-high purity

Chapter 1
Background

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification Program (ETV) to facilitate the deployment of innovative 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, permitting, purchase and use of environmental technologies.

ETV works in partnership with recognized testing organizations; with stakeholder groups consisting of regulators, buyers and vendor organizations; 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 EPA's National Exposure Research Laboratory and its verification organization partner, Battelle Memorial Institute, operate the Advanced Monitoring Systems (AMS) program under ETV. The AMS program has recently evaluated the performance of portable nitrogen oxides monitors used to determine emissions from combustion sources. This verification statement provides a summary of the test results for the Enerac 3000E Portable Emission Analyzer.

Chapter 2
Technology Description

The objective of the ETV Advanced Monitoring Systems (AMS) pilot is to verify the performance characteristics of environmental monitoring technologies for air, water, and soil. This report provides results for verification testing of the Enerac 3000E electrochemical NO and NO_2 analyzer, manufactured by the Enerac division of Energy Efficiency Systems, Inc., of Westbury, New York. The following is a description of the Enerac 3000E analyzers, based on information provided by the vendor.

The Enerac 3000E analyzer integrates advanced electrochemical sensor technology with automatic quality control features. Key features include

- Automatic NO Temperature Control: The Enerac 3000E's NO sensors are held at a temperature below 30°C to avoid erroneously overreporting actual NO emissions

- Automatic Sensor/Filter Check: The Enerac 3000E's autocalibration certification protocol checks and documents both sensor and interference rejection filter performance during each calibration

- Single Multi-Range Sensors: The Enerac 3000E measures NO concentrations from 10 ppm to over 3,000 ppm.

The Enerac 3000E system measures 18" x 13" x 6" and weighs 22 pounds. The advanced NO sensor is cooled to a constant temperature by means of a pair of thermoelectric coolers located below the aluminum plate on which the NO sensor is mounted. The temperature sensor (upper right hand side of the main sensor body) monitors and controls the temperature of the NO sensor. Enerac's proprietary precision control modules are placed on the sensor's body to control the sensor's true range and sensitivity. The same sensor can measure from 10 ppm of NO to 3,000 ppm. The standard nominal ranges of the 3000E are 0 to 1,000 ppm NO and 0 to 500 ppm NO_2. Alternative NO ranges provided by the 3000E are 0 to 3,000 ppm and 0 to 300 ppm.

Many low NO_x combustion systems can emit a large fraction of the NO_x as NO_2. Some systems have NO_2 fractions of over 80 percent, depending on operating conditions. Enerac's battery-operated permeation dryer can provide effective sample conditioning for such sources.

Figure 2-1. Enerac 3000SEM

The Enerac 3000E also has advanced two-way communications via a modem. All performance parameters can be remotely checked by the factory.

In the verification test conducted here, two identical 3000E analyzers were operated simultaneously in all testing. The two analyzers were designated as Unit A and Unit B. The performance of each unit was verified separately, and selected test results were compared to assess unit-to-unit repeatability.

Chapter 3
Test Design and Procedures

3.1 Introduction

The verification test described in this report was conducted in January 1999 on commercial portable nitrogen oxides analyzers. The tests were conducted at Battelle in Columbus, Ohio, according to procedures specified in the *Test/QA Plan for Verification of Portable NO/NO$_2$ Emission Analyzers*.(1) Verification testing of the analyzers involved the following tests:

1. A series of laboratory tests in which certified NO and NO$_2$ standards were used to challenge the analyzers over a wide concentration range under a variety of conditions.

2. Tests using three realistic combustion sources, in which data from the analyzers undergoing testing were compared to chemiluminescent NO and NO$_x$ measurements made following the guidelines of EPA Method 7E.(2)

These tests are listed in Table 3-1.

Table 3-1. Identity and Schedule of Verification Tests Conducted on Enerac 3000E Analyzers

Test Activity	Date Conducted
Laboratory Tests	
Linearity	January 25, 1999, p.m.
Interrupted Sampling	January 25, 1999, p.m. to January 26, 1999, a.m.
Interferences	January 26, a.m.
Pressure Sensitivity	January 26, p.m.
Ambient Temperature	January 26, p.m. and January 27, 1999 a.m.
Source Tests	
Gas Rangetop	January 27, 1999, p.m.
Gas Water Heater	January 27, 1999, p.m.
Diesel Generator High RPM	January 28, 1999, a.m.
Diesel Generator–Idle	January 28, 1999, a.m.

To assess inter-unit variability, two identical Enerac 3000E analyzers were tested simultaneously. These two analyzers were designated as Unit A and Unit B throughout all testing. The commercial analyzers were operated at all times by a representative of Enerac so that each analyzer's performance could be assessed without concern about the familiarity of Battelle staff with the analyzers. At all times, however, the Enerac representative was supervised by Battelle staff. Displayed NO and NO_2 readings from the analyzers (in ppm) were manually entered onto data sheets prepared before the test by Battelle. Battelle staff filled out corresponding data sheets, recording, for example, the challenge concentrations or reference analyzer readings, at the same time that the analyzer operator recorded data. This approach was taken because visual display of measured NO and NO_2 (or NO_x) concentrations was the "least common denominator" of data transfer among several NO/NO_2 analyzers tested. Copies of the blank data recording sheets used by Battelle and vendor staff are included as Appendix A of this report.

Verification testing began with Enerac staff setting up and checking out their two analyzers in the laboratory at Battelle. Once vendor staff were satisfied with the operation of the analyzers, the laboratory tests were begun. These tests were carried out in the order specified in the test/QA plan.(1) Upon completion of laboratory tests, the analyzers were moved to a nearby building where the combustion sources described below were set up, along with two chemiluminescent nitrogen oxides monitors which served as the reference analyzers. The combustion source tests were conducted indoors, with the combustion source exhausts vented through the roof of the test facility. This arrangement assured that testing was not interrupted and that no bias in testing was introduced as a result of the weather. Sampling of source emissions began with the combustion source emitting the lowest NO_x concentration and proceeded to sources emitting progressively more NO_x. In all source sampling, the analyzers being tested sampled the same exhaust gas as did the reference analyzers. This was accomplished by inserting the Enerac analyzers' gas sampling probes into the same location in the exhaust duct as the reference analyzers' probe.

3.2 Laboratory Tests

The laboratory tests were designed to challenge the analyzers over their full nominal response ranges, which for the Enerac 3000E analyzers were 0 to 1,000 ppm for NO and 0 to 500 ppm for NO_2. These nominal ranges greatly exceed the actual NO or NO_2 concentrations likely to be emitted from most combustion sources. Nevertheless, the lab tests were aimed at quantifying the full range of performance of the analyzers. Additional laboratory tests were also conducted to assess the multi-range NO capability of the analyzers using NO ranges of 0 to 3,000 ppm and 0 to 300 ppm.

Laboratory tests were conducted using certified standard gases for NO and NO_2, and a gas dilution system with flow calibrations traceable to the National Institute of Standards and Technology (NIST). The NO and NO_2 standards were diluted in high purity gases to produce a range of accurately known concentrations. The NO and NO_2 standards were EPA Protocol 1 gases, obtained from Scott Specialty Gases, of Troy, Michigan. As required by the EPA Protocol(3) the concentration of these gas standards was established by the manufacturer within 1 percent accuracy using two independent analytical methods. The concentration of the NO standard (Scott Cylinder Number ALM 057210) was 3,925 ppm, and that of the NO_2 standard (Scott Cylinder

Number ALM 019660) was 493.2 ppm. These concentrations were confirmed in a performance evaluation audit, conducted near the end of the verification tests, by comparison with independent standards obtained from other suppliers (see Section 4.5.1.2).

The gas dilution system used was an Environics Model 2020 mass flow controlled diluter (Serial Number 2108). This diluter incorporated four separate mass flow controllers, having ranges of 10, 10, 1, and 0.1 lpm, respectively. This set of flow controllers allowed accurate dilution of gas standards over a very wide range of dilution ratios, by selection of the appropriate flow controllers. The mass flow calibrations of the controllers were checked against a NIST standard by the manufacturer prior to the verification test, and were programmed into the memory of the diluter. In verification testing, the Protocol Gas concentration, inlet port, desired output concentration, and desired output flow rate were entered by means of the front panel keypad of the 2020 diluter, and the diluter then set the required standard and diluent flow rates to produce the desired mixture. The 2020 diluter indicated on its front panel display the actual concentration being produced, which in some cases differed very slightly from the nominal concentration requested. In all cases the actual concentration produced was recorded as the concentration provided to the analyzers undergoing testing. The 2020 diluter also provided warnings if a flow controller was being operated at less than 10 percent of its working range, i.e., in a flow region where flow control errors might be enhanced. Switching to another flow controller then minimized the uncertainties in the preparation of the standard dilutions.

Dilution gases used in the laboratory tests were Acid Rain CEM Zero Air and Zero Nitrogen from Scott Specialty Gases. These gases were certified to be of 99.9995 percent purity, and to have the following maximum content of specific impurities: $SO_2 < 0.1$ ppm, $NO_x < 0.1$ ppm, $CO < 0.5$ ppm, $CO_2 < 1$ ppm, total hydrocarbons < 0.1 ppm, and water < 5 ppm. In addition the nitrogen was certified to contain less than 0.5 ppm of oxygen, while the air was certified to contain 20 to 21 percent oxygen.

Laboratory testing was conducted primarily by supplying known gas mixtures to the analyzers from the Environics 2020, using a simple manifold that allowed the two analyzers to sample the same gas. The experimental setup is shown schematically in Figure 3-1. The manifold itself consisted of a 9.5-inch length of thin-walled 1-inch diameter 316 stainless steel tubing, with 1/4-inch tubing connections on each end. The manifold had three 1/4-inch diameter tubing side arms extending from it: two closely spaced tubes are the sampling points from which sample gas was withdrawn by the two analyzers, and the third provided a connection for a Magnehelic differential pressure gauge (±15 inches of water range) that indicated the manifold pressure relative to the atmospheric pressure in the laboratory. Gas supplied to the manifold from the Environics 2020 always exceeded by at least 0.5 lpm the total sample flow withdrawn by the two analyzers. The excess vented through a “T” connection on the exit of the manifold, and two coarse needle valves were connected to this “T”, as shown in Figure 3-1. One valve controlled the flow of gas out the normal exit of the manifold, and the other was connected to a small vacuum pump. Closing the former valve elevated the pressure in the manifold, and opening the latter valve reduced the pressure in the manifold. Adjustment of these two valves allowed close control of the manifold pressure within a target range of ±10 inches of water, while maintaining excess flow of the gas mixtures to the manifold. The arrangement shown in Figure 3-1 was used

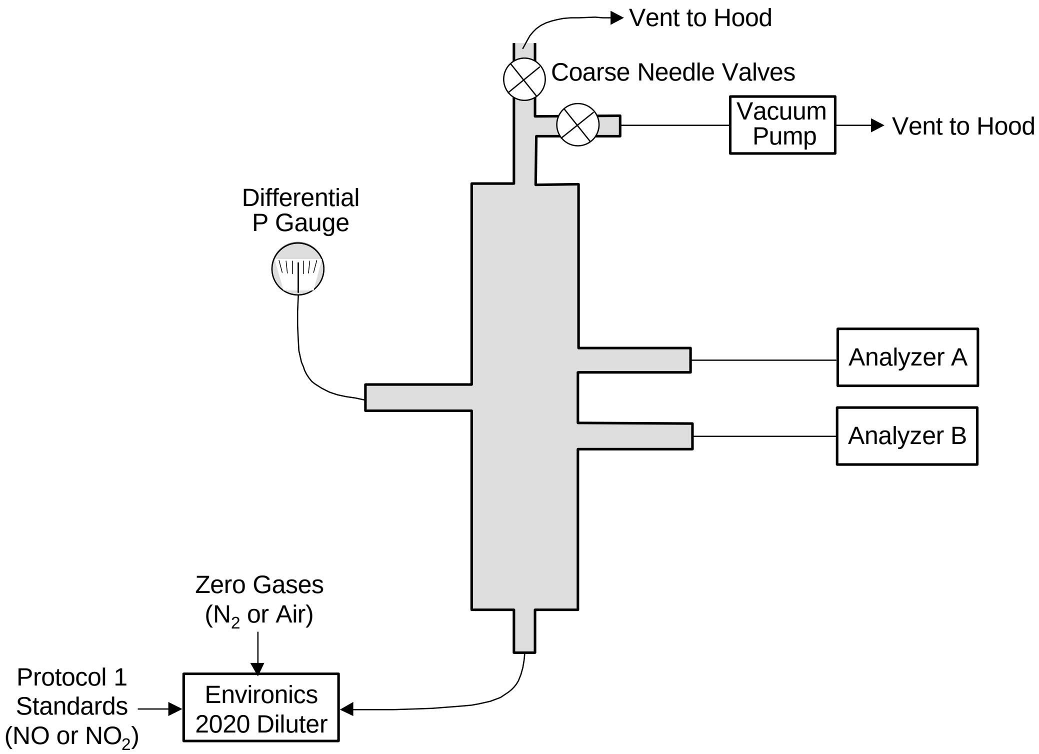

Figure 3-1. Manifold Test Setup

in all laboratory tests, with the exception of interference testing. For most interference testing, gas standards of the appropriate concentrations were supplied directly to the manifold, without use of the Environics 2020 diluter.

Laboratory testing consisted of a series of separate tests evaluating different aspects of analyzer behavior. The procedures for those tests are described below, in the order in which the tests were actually conducted. The statistical procedures that were applied to the data from each test are presented in Chapter 5 of this report.

3.2.1 Linearity

The linearity of analyzer response was tested by wide-range multipoint calibrations with NO and NO_2. Linearity testing consisted of a 21-point response check for NO, and for NO_2. Prior to this check, the Enerac analyzers were provided with the appropriate zero gas, and then with an NO or NO_2 span gas concentration near the respective nominal full scale of the analyzers (i.e., near 1,000 ppm NO or 500 ppm NO_2). The actual values of the span gases provided were 1,002 ppm NO and 493.2 ppm NO_2. However, both analyzers indicated an overrange condition for NO_2, even though the 493.2 ppm NO_2 span gas concentration was within the nominal NO_2 range of the analyzers. Since the 493.2 ppm span concentration is within 2 percent of the nominal range, this occurrence can be readily accounted for by a small difference between the verification standard and the factory span gas used to set the instrument's upper range. In any case, this overrange condition was alleviated when the NO_2 concentration was reduced to 400 ppm, and 400 ppm NO_2

was adopted as the span value for the NO_2 linearity test. After adjustments to the analyzers to accurately match that span value, the 21-point check proceeded without further adjustments. The 21 points consisted of three replicates each at 10, 20, 40, 70, and 100 percent of the nominal range, in randomized order, and interspersed with six replicates of zero gas.(1) Following completion of all 21 points, the zero and 100 percent spans were repeated, also without adjustment of the analyzers. This entire procedure was performed for NO and then for NO_2. Throughout the linearity test, the analyzer indications of both NO and NO_2 concentrations were recorded, even though only NO or NO_2 were supplied to the analyzers. This procedure provided data to assess the cross-sensitivity to NO and NO_2.

After the linearity tests over ranges of 0 to 1,000 ppm NO and 0 to 400 ppm NO_2, additional linearity tests were conducted for NO over ranges of 0 to 3,000 ppm and 0 to 300 ppm. These were accomplished by changing the control module which sets the sensitivity of the sensor, thereby changing its range. The additional NO linearity tests followed the same procedure described above.

It should be noted that a low-range NO control module was used in each Enerac analyzer during the 0 to 300 ppm NO and 0 to 400 ppm NO_2 linearity tests, whereas a mid-range NO control module was used in each analyzer for the 0 to 1,000 ppm and 0 to 3,000 ppm NO linearity tests, and for all other testing. One feature of the mid-range module is that the analyzers report all readings below 3 ppm NO as being zero. This feature is intended to prevent users from attempting to make ambient air NO_x measurements. Thus, for the higher NO linearity tests and for all other testing, the Enerac 3000E analyzers provided no NO response information below 3 ppm.

3.2.2 Detection Limit

Data from zero gas and from 10 percent of full-scale points in the linearity test were used to establish the NO and NO_2 detection limits of the analyzers, using a statistical procedure defined in the test/QA plan.(1)

3.2.3 Response Time

During the NO and NO_2 linearity tests, upon switching from zero gas to an NO or NO_2 concentration of 70 percent of the respective full scale (i.e., about 700 ppm NO or 350 ppm NO_2), the analyzers' responses were recorded at 10-second intervals until fully stabilized. These data were used to determine the response times for NO and for NO_2, defined as the time to reach 95 percent of final response after switching from zero gas to the calibration gas.

3.2.4 Interrupted Sampling

After the zero and span checks that completed the linearity test, the Enerac analyzers were shut down (i.e., their electrical power was turned off overnight), ending the first day of laboratory testing. The next morning the analyzers were powered up, and the same zero gas and span concentrations were run without adjustment of the analyzers. Comparison of the NO and NO_2 zero and span values before and after shutdown indicated the extent of zero and span drift resulting from the shutdown. Near full-scale NO and NO_2 levels (i.e., 1,000 ppm NO and 400 ppm NO_2) were used as the span values in this test.

3.2.5 Interferences

Following analyzer startup and completion of the interrupted sampling test, the second day of laboratory testing continued with interference testing. This test evaluated the response of the Enerac analyzers to species other than NO and NO_2. The potential interferants listed in Table 3-2 were supplied to the analyzers one at a time, and the NO and NO_2 readings of the analyzers were recorded. The potential interferants were single components, except for a mixture of SO_2 and NO, which was intended to assess whether SO_2 in combination with NO produced a bias in NO response.

Table 3-2. Summary of Interference Tests Performed

Interferant	Interferant Concentration
CO	496 ppm
CO_2	5.03%
SO_2	501 ppm
NH_3	494 ppm
Hydrocarbon Mixture*	485 ppm C_1, 98 ppm C_2, 48 ppm $C_3 + C_4$
SO_2 and NO	451 ppm SO_2 + 385 ppm NO

*C_1 = methane; C_2 = ethane; and $C_3 + C_4$ = 24 ppm propane + 24 ppm n-butane.

The CO, CO_2, SO_2, and NH_3 mixtures used in the interference test were all obtained as Certified Master Class Calibration Standards from Scott Technical Gases, at the concentrations indicated in Table 3-2. The indicated concentrations were certified by the manufacturer to be accurate within ± 2 percent, based on analysis. The CO, CO_2, and NH_3 mixtures were all in Ultra-High Purity (UHP) air, and the SO_2 mixture was in UHP nitrogen. The SO_2/NO mix listed in Table 3-2 was prepared by diluting the SO_2 standard with the NO Protocol Gas using the Environics 2020.

The hydrocarbon mixture listed in Table 3-2 was prepared at Battelle in UHP hydrocarbon-free air, starting from the pure compounds. Small quantities of methane, ethane, propane, and n-butane were injected into a cylinder that was then pressurized with UHP air. The required hydrocarbon concentrations were approximated by the preparation process, and then quantified by comparison with a NIST standard containing 8.61 ppm carbon (ppmC) in the form of propane. Using a gas chromatograph with a flame ionization detector (FID) the NIST standard was first analyzed twice, producing peak areas of 18,627 and 18,791 area units per 8.61 ppmC of propane.

The average FID response factor (18,709 units (± 116 units)/8.61 ppmC) was then used to determine the concentrations of the components of the prepared hydrocarbon mixture. Two analyses of that mixture both gave a result of 485 ppm methane; the corresponding results for ethane were 97 and 98 ppm; for propane 23 and 24 ppm; and for n-butane 24 and 25 ppm.

In the interference test, each interferant in Table 3-2 was provided to the sampling manifold shown in Figure 3-1, at a flow in excess of that required by the two analyzers. Each period of sampling an interferant was preceded by a period of sampling the appropriate zero gas.

3.2.6 Pressure Sensitivity

The pressure sensitivity test was designed to quantify the dependence of analyzer response on the pressure in the sample gas source. By means of two valves at the downstream end of the sample manifold (Figure 3-1), the pressure in the manifold could be adjusted above or below the ambient room pressure, while supplying the manifold with a constant ppm level of NO or NO_2 from the Environics dilution system. This capability was used to determine the effect of the sample gas pressure on the sample gas flow rate drawn by the analyzers, and on the NO and NO_2 response.

The dependence of sample flow rate on pressure was determined using an electronically timed bubble flow meter (Ultra Flow Primary Gas Flow Calibrator, Model 709, Serial No. 010928; SKC, Inc.). This flow meter was connected in line (i.e., inserted) into the sample flow path from the manifold to one of the commercial analyzers. Zero gas was supplied to the manifold at ambient pressure, and the analyzer's sample flow rate was measured with the bubble meter. The manifold pressure was then adjusted to -10 inches of water relative to the room, and the analyzer's flow rate was measured again. The manifold pressure was adjusted to +10 inches of water relative to the room, and the flow rate was measured again. The bubble meter was then moved to the sample inlet of the other commercial analyzer, and the flow measurements were repeated.

The dependence of NO and NO_2 response on pressure was determined by sampling the appropriate zero gas, and an NO or NO_2 span gas of about 700 ppm and 350 ppm, respectively, at each of the same manifold pressures (room pressure, -10 inches, and +10 inches). This procedure was conducted simultaneously on both analyzers, first for NO at all three pressures, and then for NO_2 at all three pressures. The data at different pressures were used to assess zero and span drift resulting from the sample pressure differences.

3.2.7 Ambient Temperature

The purpose of the ambient temperature test was to quantify zero and span drift that may occur as the analyzers are subjected to different temperatures during operation. This test involved providing both analyzers with zero and span gases for NO and NO_2 (at the same ppm concentrations used in the pressure test) at room, elevated, and reduced temperatures. A temperature range of 45 to 105°C was targeted in this test. The elevated temperature condition was achieved using a 1.43 m^3 steel and glass laboratory chamber, thermostated at 105°F using external heat lamps. The reduced temperature condition was achieved using a conventional domestic refrigerator (Crosley Model CT19A5W) with a refrigerator volume of 13.1 ft^3.

The general procedure was to provide zero and span gas for NO, and then for NO_2, to both analyzers at room temperature, and then to place both analyzers and the sampling manifold into the heated chamber. Electrical and tubing connections were made through a small port in the lower wall of the chamber. A thermocouple readout was used to monitor the chamber temperature and room temperature, and the internal temperature indications of the analyzers themselves were monitored, when available. After 1 hour or more of stabilization in the heated chamber, the zero and span tests were repeated. The Enerac analyzers were then removed from the heated chamber and allowed to stabilize while operating at room temperature overnight. The next morning the zero and span tests were repeated at room temperature. The analyzers, manifold, and other connections were then transferred to the refrigerator. After a stabilization period of 1 hour or more, the zero and span checks were repeated at the reduced temperature.

3.3 Combustion Source Tests

3.3.1 Combustion Sources

Three combustion sources (a gas rangetop, a gas residential water heater, and a diesel engine) were used to generate NO_x emissions from less than 10 ppm to nearly 500 ppm. Emissions databases for two of these sources (rangetop and water heater) exist as a result of prior measurements, both of which have been published.(4,5)

3.3.1.1 Rangetop

The low-NO_x source was a residential natural gas fired rangetop (KitchenAid Model 1340), equipped with four cast-iron burners, each with its own onboard natural gas and combustion air control systems. The burner used (front-left) had a fixed maximum firing rate of about 8 KBtu/hr.

The rangetop generated NO in the range of about 4 to 8 ppm, and NO_2 in the range of about 1 to 3 ppm. The database on this particular appliance was generated in an international study in which 15 different laboratories, including Battelle, measured its NO and NO_2 emissions.(4)

Rangetop NO_x emissions were diluted prior to measurement using a stainless-steel collection dome, fabricated according to specifications of the American National Standards Institute (ANSI Z21.1).(6) For all tests, this dome was elevated to a fixed position 2 inches above the rangetop surface. Moreover, for each test, a standard “load” (pot) was positioned on the grate of the rangetop burner. This load was also designed according to ANSI Z21.1 specifications regarding size and material of construction (stainless steel). For each test, the load contained 5 pounds of room-temperature water.

The exit of the ANSI collection dome was modified to include seven horizontal sample-probe couplers. One of these couplers was 1/4-inch in size, three were 3/8-inch in size, and three were ½-inch in size. Their purpose was to accommodate various sizes of vendor probes and one reference probe simultaneously during combustion-source sampling.

This low-NO_x combustion source was fired using “standard” natural gas, obtained from Praxair, Inc., which was certified to contain 90 percent methane, 3 percent ethane, and the balance nitrogen. This gaseous fuel contained no sulfur.

3.3.1.2 Water Heater

The medium-NO_x source was a residential natural gas-fired water heater (Ruud Model P40-7) of 40-gallon capacity. This water heater was equipped with one stamped-aluminum burner with its own onboard natural gas and combustion air control systems, which were operated according to manufacturer’s specifications. The burner had a fixed maximum firing rate of about 40 KBtu/hr. Gas flow to the water heater was monitored using a calibrated dry-gas meter.

The water heater generated NO emissions in the range of 50 to 70 ppm, and NO_2 in the range of 5 to 10 ppm. NO_x emissions dropped as the water temperature rose after ignition, stabilizing at the levels noted above. To assure constant operation of the water heater, a continuous draw of 3 gpm was maintained during all verification testing. The database on this particular appliance was generated in a national study in which six different laboratories measured its emissions, including Battelle.(5)

Water heater NO_x emissions were not diluted prior to measurement. The draft hood, integral to the appliance, was replaced with a 3-inch diameter, 7-inch long stainless-steel collar. The exit of this collar was modified to include five horizontal sample-probe couplers. One coupler was 1/4-inch in size, whereas the two other pairs were either 3/8- or ½-inch in size. Their purpose was to accommodate various sizes of vendor probes and one reference probe simultaneously during sampling.

This medium-NO_x combustion source was fired on house natural gas, which contained odorant-level sulfur (4 ppm mercaptan). The composition of this natural gas is essentially constant, as monitored by a dedicated gas chromatograph in Battelle’s laboratories.

3.3.1.3 Diesel Engine

The high-NO_x source was an industrial diesel 8 kW electric generator (Miller Bobcat 225D Plus), which had a Deutz Type ND-151 two-cylinder engine generating 41 KBtu/hr (16 horsepower). This device generated NO_x emissions over a range of about 150 to 450 ppm, depending on the load on the super-charged engine. High load (3,500 RPM) resulted in the lowest NO_x; idle (2,000 RPM) resulted in the highest NO_x. At both conditions, about one-third of the NO_x was NO_2. The database on the diesel generator emissions was generated in tests conducted in the 2 weeks prior to the start of the verification tests.

NO_x emissions from this engine were not diluted prior to measurement. The 1-inch exhaust outlet of the engine, which is normally merely vented to the atmosphere, was fitted with a stack designed to meet the requirements of the U.S. EPA (Method 5).(9) The outlet was first expanded to 2 inches of 1.5-inch diameter copper tubing, then to 15 inches of 2-inch diameter copper tubing, and finally to 2 inches of 3-inch diameter copper tubing. The 3-inch diameter tubing was modified to include five horizontal sample-probe couplers. One of these couplers was 1/4-inch in size, two were 3/8-inch in size, and two were 1/2-inch in size. These couplers held the sample probes in place. The 3-inch tube was connected to a 3-inch stack extending through the roof of the test laboratory. This high-NO_x combustion source was fired on commercial diesel fuel, which, by specification, contains only 0.03 to 0.05 weight percent sulfur.

3.3.2 Test Procedures

The procedures followed during combustion source testing consisted of those involved with the sampling systems, reference method, calibration gas supply, and the sources, as follows.

3.3.2.1 Sampling Systems

Prior to sampling, the Enerac representative inserted two of its product’s probes into the exhaust duct of the rangetop, water heater, or diesel engine. The Enerac probes were fitted one above the other, sampling from a point within about 1/4 inch of the inlet of the reference analyzers’ probe. Each Enerac probe had a fritted Hastelloy® inlet filter that screwed into the probe tip.

The reference analyzer probe consisted of a 26-inch long, 1/4-inch diameter stainless-steel tube, the upstream 2 inches of which were bent at a right angle for passage into the center of the source exhaust duct. Each combustion source had a dedicated sampling probe, connected to the reference analyzers with 1/4-inch tubing. The lengths of sample-transfer tubing required to connect vendor instruments to the rangetop, water heater, and diesel engine were about 4 feet, 4 feet, and 8 feet, respectively. The lengths of sample-transfer tubing required to connect reference instruments to the rangetop, water heater, and diesel engine were about 7 feet, 9 feet, and 4 feet, respectively.

In source testing, the Enerac analyzers were operated with their integral heated sampling probes and sample conditioning systems. Neither the reference sampling probe nor the reference sample-transfer lines were heated. Visible condensation of combustion-generated water did not occur. The reference analyzer moisture-removal system consisted of a simple ice bath (0°C). The reference particulate-removal system consisted of a 47-millimeter in-line quartz fiber filter.

3.3.2.2 Reference Method

The reference method of NO determination against which the vendor analyzers were compared was the ozone chemiluminescence method for NO that forms the basis of EPA Method 7E.(2) The reference measurements were made using a Model 10 and a Model 14A source-level NO_x monitor (both from Thermo Environmental Instruments), located side-by-side near the combustion sources. These monitors sampled from a common intake line and operated on identical ranges of 100 ppm or 1,000 ppm full scale, depending on the source. Both instruments use stainless steel catalytic converters maintained at 650°C (1,200°F) for reduction of NO_2 to NO for detection. Digital electronic voltmeters were connected directly to the amplifier output of the monitors, to provide direct digital display of the data. The Model 10 and 14A monitors provide sequential, rather than simultaneous, measurement of NO and NO_x, so display of both readings required manual switching of sampling modes on both instruments. This requirement resulted in the NO and NO_x readings from the reference analyzers being separated in time by about 15 seconds, due to the stabilization needed after switching. This effect is believed to have negligible impact on the verification results due to the stability of source emissions.

The chemiluminescence analyzers were calibrated using the Environics Series 100 and the EPA Protocol 1 gases (see below). The calibration procedure was specified in the test/QA plan, and required calibration at zero, 30 percent, 60 percent, and 100 percent of the applicable range value (i.e., 100 or 1,000 ppm). Calibration results closest in time to the verification source test were used to establish scale factors applicable to the source test data. The conversion efficiency of the stainless steel converters was determined by calibrating with both NO and NO_2 on the applicable ranges, using the EPA Protocol 1 gases. The ratio of the linear regression slope of the NO_2 calibration to that of the NO calibration determined the NO_2 conversion efficiency. For the Enerac source tests, which took place on January 27 and 28, 1999, calibration data from January 26 were applied. Conversion efficiency values of 85.5 percent and 89.9 percent were found for the Model 14A and Model 10 monitors, respectively. All reference NO_2 data were corrected to account for these conversion efficiencies.

3.3.2.3 Calibration Gas Supply

Before and after sampling of each combustion source, both the analyzers undergoing testing and the reference analyzers were supplied with zero gas and with standard NO and NO_2 mixtures at levels comparable to those expected from the source. To prepare these mixtures, Protocol 1 gases identical to those used in the laboratory testing were diluted using an Environics Series 100 Computerized Multi-Gas Calibrator (Serial Number 2416). The same Acid Rain CEM zero gases were used for dilution and zeroing as were used in the laboratory tests. When low dilution ratios were required for some calibration points, Tylan FC-260 (3 lpm) and FC-280 (5 lpm) mass flow controllers were used instead of the Environics calibrator. The Tylan flow controllers were calibrated using the same SKC electronic bubble flow meter used in the laboratory tests, and were operated with a Tylan four-unit control and readout device. The pre- and post-test span values used with each combustion source are given in Table 3-3.

Table 3-3. Span Concentrations Provided Before and After Each Combustion Source

Source	NO Span Level (ppm)	NO_2 Span Level (ppm)
Gas Rangetop	20	10
Gas Water Heater	100	15
Diesel–High RPM	200	50
Diesel–Idle	400	100

The pre- and post-test zero and span values were used to assess the drift in zero and span response of the tested reference and analyzers caused by exposure to source emissions.

Before the start of source testing, the Enerac analyzers were first calibrated against 200 ppm NO and 100 ppm NO_2 span gases, prepared using the Environics Series 100, as described above. The span gases listed in Table 3-3 were then sampled before and after sampling the respective combustion sources.

3.3.2.4 Operation of Sources

Verification testing was conducted with the combustion sources at or near steady-state in terms of NO_x emission. For the rangetop, steady-state was achieved after about 15 minutes, when the water began to boil. For the water heater, steady-state was achieved in about 15 minutes, when its water was fully heated. Because the water heater tank had a thermostat, cycling would have occurred had about 3 gpm of hot water not been continuously drained out of the tank.

For the diesel engine, steady-state was achieved in about 10 minutes of operation. The diesel was operated first at full speed (3,500 RPM) to achieve its lowest NO_x emissions. Prior to sampling the NO_x emissions at idle, the diesel engine was operated at idle for about 20 minutes to effectively “detune” its performance.

The order of operation of the combustion sources was (1) rangetop, (2) water heater, (3) diesel engine (high RPM), and (4) diesel engine (idle). This allowed the analyzers to be exposed to continuously increasing NO and NO_2 levels, and avoided interference in low level measurements that might have resulted from prior exposure to high levels.

Sampling of each combustion source consisted of obtaining nine separate measurements of the source emissions. After sampling of pre-test zero and span gases provided from the calibration source, and with both the reference and vendor analyzers sampling the source emissions, the Enerac operator indicated when he was ready to take the first set of readings (a set of readings consisting of the NO and NO_2 response on both Units A and B). At that time the Battelle operator of the reference analyzers also took corresponding readings. The analyzers undergoing testing were then disconnected from the source, and allowed to sample room air until readings dropped well below the source emissions levels. The analyzers were then reconnected to the source, and after stabilizing another set of readings was taken. There was no requirement that analyzer readings drop fully to zero between source measurements. This process was repeated until a total of nine readings had been obtained with both the vendor and reference analyzers. The same zero and span gases were then sampled again before moving to the next combustion source.

One addition to this procedure was the extended sampling test, conducted as the last operation in the combustion source testing. This test involved continuous sampling of the diesel engine emissions for a full hour with no intervals of room air sampling. Data were recorded for both reference and vendor analyzers at 1-minute intervals throughout that hour of measurement. This test was conducted only after nine sequential sets of readings had been obtained from all the combustion sources by the procedure described above.

Chapter 4
Quality Assurance/Quality Control

Quality control (QC) procedures were performed in accordance with the quality management plan (QMP) for the AMS pilot(7) and the test/QA plan(1) for this verification test.

4.1 Data Review and Validation

Test data were reviewed and approved according to the AMS pilot QMP, the test/QA plan, and Battelle's one-over-one approval policy. The Verification Testing Leader reviewed the raw data and data sheets that were generated each day and approved them by adding his signature and date. Laboratory record notebooks were also reviewed, signed, and dated by the Verification Testing Leader.

Other data review focused upon the compliance of the chemiluminescent reference and analyzer data with the quality requirements of Method 7E. The purpose of validating reference Method 7E data was to ensure usability for the purposes of comparison with the Enerac analyzers. The results of the review of the reference analyzer data quality are shown in Table 4-1. The data generated by the reference analyzers were used as a baseline to assess the performance of the technologies for NO/NO_2 analysis.

4.2 Deviations from the Test/QA Plan

During the physical set up of the verification test, deviations from the test/QA plan were made to better accommodate differences in vendor equipment, availability of Battelle personnel and equipment, and other changes or improvements. Any deviation required the approval signature of Battelle's Verification Testing Leader and the pilot manager. A planned deviation form was used for documentation and approval of the following changes:

1. Dr. Agnes Kovacs did not participate in the statistical analysis of data from the verification test.
2. The order of testing was changed, and a span value of 70 percent of range (rather than 100 percent) was used in the pressure sensitivity test.
3. The order of the ambient temperature test was changed.
4. The exact concentrations used in the mixture of SO_2 and NO for the interference test were changed.
5. A different diesel generator was used than that originally planned.
6. An oxygen sensor was not used during source tests.
7. Thermo Environmental Models 14A/10 NO/NO_x analyzers were used for reference method.

8. Triplicate calibration points were not run on reference method analyzers.
9. Unheated sample line and tubing were used, based on Battelle's previous experience in sampling the combustion sources used in this test and other similar sources.

Table 4-1. Results of QC Procedures for Reference NOx Analyzers for Testing of Enerac 3000E Analyzers

NO_2 conversion efficiency	85.5% for Model 14A in 100 ppm and 1,000 ppm ranges				
NO_2 conversion efficiency	89.9% for Model 10 in 100 ppm and 1,000 ppm ranges				
Calibration of reference method using four points at 0, 30, 60, 100% for NO	Meets criteria (r^2 = 0.9998)				
Calibration of reference method using four points at 0, 30, 60, 100% for NO_2	Meets criteria (r^2 = 0.9998)				
Calibrations (100 ppm range)	Meet ± 2% requirement (relative to span)	Model 10		Model 14A	
		NO		NO	
		Error, % of Span	% of Scale	Error, % of Span	% of Scale
		0.6%	30%	0.2%	30%
		0.3%	60%	0.3%	60%
		NO_2		NO_2	
		Error, % of Span	% of Scale	Error, % of Span	% of Scale
		0.2%	30%	0.6%	30%
		0.5%	60%	0.2%	60%
Zero drift	Meets ± 3% requirement (relative to span) on all combustion sources				
Span drift	Meets ± 3% requirement (relative to span) on all combustion sources				
Interference check	< ± 7% (No interference response observed)				

There was one undocumented deviation. Due to a delay in the arrival of the protocol gases used in the verification test, Battelle was not able to run one instrument through the entire test sequence prior to verification testing. The impact of this deviation on the final data is described in the Performance System Audits section of this report.

Finally, a comment is in order concerning the zero and span check procedure used before and after sampling of each source in the combustion source tests. Zero and span gases (Table 3-3) were supplied to the reference analyzers by connection to the fitting at the downstream end of the stainless steel sampling probe, i.e., the sampling probe itself was not used in the zero and span check. Enerac staff have pointed out that this procedure could allow a leak to go undetected at that fitting after the zero and span check has been completed and the probe has been reconnected. The absence of oxygen measurements, which might disclose a leak, adds to this concern. This issue is pertinent because of a possible leak of room air into the reference analyzer sampling line during one portion of the source testing, as described in Section 6.2.1.

4.3 Calibration of Laboratory Equipment

Equipment used in the verification test required calibration before use. Equipment types and calibration dates are listed in Table 4-2. Documentation for calibration of the following equipment was required before use in the verification test, and was maintained in the test file.

Table 4-2. Equipment Type and Calibration Date

Equipment Type	Calibration Date/ Temperature Check
Flow Controllers (Gas Dilution System) Environics Series 100	6/11/98
Flow Controllers (Gas Dilution System) Environics Model 2020	12/16/98
Digital Temperature Indicator Model 402A	1/7/99
Dwyer Magnahelic Pressure Gauge	1/11/99
Model R-275 In-line Dry Gas Meter	1/11/99
Doric Trendicator 400A Thermocouple Temperature Sensor	1/18/99
Model DTM-115 Reference Dry Gas Meter	9/22/98

4.4 Standard Certifications

Standard or certified gases were used in all verification tests, and certifications or analytical data were kept on file to document the traceability of the following standards:

EPA Protocol Gas Nitrogen Dioxide
EPA Protocol Gas Nitric Oxide
Certified Master Class Calibration Standard Sulfur Dioxide
Certified Master Class Calibration Standard Carbon Dioxide
Certified Master Class Calibration Standard Ammonia

Certified Master Class Calibration Standard Carbon Monoxide
Nitrogen Acid Rain CEM Zero
Acid Rain CEM Zero Air
Battelle-Prepared Organics Mixture.

All other QC documentation and raw data for the verification test are located in the test file at Battelle, to be retained for 7 years and made available for review if requested.

4.5 Performance System Audits

Internal and external performance system audits were conducted and the results are summarized in the following sections.

4.5.1 Internal Audits

Three internal audits were conducted during verification testing. A technical systems audit was conducted to assess the physical setup of the test, a performance evaluation audit was conducted to evaluate the accuracy of the measurement system, and an audit of data quality was conducted on 10 percent of all data generated during the verification test. A summary of the results of these audits is provided below.

4.5.1.1 Technical Systems Audit

A technical systems audit is a qualitative onsite audit of the physical setup of the test. The auditors determine the compliance of testing personnel with the test/QA plan. A self-assessment is required for each test as outlined in the AMS pilot QMP. The QA/QC Reviewer for the verification test conducted the internal technical systems audit on January 18, 1999. Observations and findings from this audit are listed in Table 4-3.

4.5.1.2 Performance Evaluation Audit

The performance evaluation audit was a quantitative audit in which measurement standards were independently obtained and compared with those used in the verification test to evaluate the accuracy of the measurement system. One such assessment was conducted by Battelle QA staff on February 4, 1999. No independent assessments of this type were conducted by EPA staff.

The performance evaluation (PE) samples were NO and NO_2 calibration gases independent of the test calibration standards containing certified concentrations of NO and NO_2. Accuracy of the reference analyzers was determined by comparing the measured NO/NO_2 concentrations using the verification test standards with those obtained using the certified PE values. Percent difference was used to quantify the accuracy of the results. The PE sample for NO was an EPA protocol gas having nearly the same concentration as the NO standard used in verification testing, but purchased from a different commercial supplier. The PE standard for NO_2 was a

Table 4-3. Observations and Findings From the Internal Technical Systems Audit

Observation/Finding	Corrective Action/Impact on Final Data
Method 7E calibration was not completed prior to verification testing. Analyzers gave unreliable results during first test, which prompted a calibration on 1/13/99. Full four-point calibration was not performed until 1/15/99 on the 0-100 range and 1/16/99 on the 0-1000 range for both Models 14A and 10. All criteria meet stated objectives in Method 7E for the calibration (linearity, calibration error) performed on the 15th and 16th.	Vendor source testing that was conducted prior to the first full four-point Method 7E calibration was repeated at a later date. Thus all vendor testing was conducted with fully calibrated reference analyzers. There is no impact on verification data because the first vendor test was repeated after Method 7E calibration was implemented.
From Pressure Sensitivity Test conducted 1/12/99 an explanation is needed of correction factor to be applied to data.	The O_2 sensors of the vendor's analyzers showed the presence of O_2 in the sample gas at a time when only NO in pure N_2 was being provided to the analyzers. This indicated a leakage of air into the sample manifold (which was at reduced pressure relative to the room). The amount of dilution caused by the leakage of air was calculated from the O_2 level observed, and exactly accounted for an apparently low NO response from the vendor's analyzers. That is, the O_2 data were used to correct the observed NO responses to what they would have been with no air leakage. The leak was corrected, and no impact exists on the Enerac testing.
Start and stop time for instruments to equilibrate at each temperature is not noted on data sheets.	Added start and stop time to data sheets as a method to document equilibration.
Calibration drift for all data reviewed is less than ± 3% relative to the span except Model 10 span post-test on 1/14/99 for diesel engine test which = 3.6%. Data for test should be flagged at minimum.	All source tests with the Enerac analyzers met the 3% requirement. No impact on final data.
Data and calculations for calibration drift test not found on test data sheets. Recommend a better system be implemented for assessing quality of the calibration drift for reference analyzers immediately following collection of test data so decision whether or not to proceed is clear to all participants.	Comparison of drift is easily made visually; written comments will be added if termination of a test is called for.
Zero/span values are documented on diesel engine test data sheets for all tests except on 01-13-98 post-test blank with no explanation.	This test was terminated. Notes were added as suggested and the test was later repeated in its entirety. No impact on Enerac testing.

commercial standard of 50.5 ppm NO_2 in air, whose concentration had been confirmed by comparison with a 50 ppm Standard Reference Material of NO in nitrogen, obtained from the National Institute of Standards and Technology. Table 4-4 summarizes the reference method performance evaluation results. Included in this table are the performance acceptance ranges and the certified gas concentration values. The acceptance ranges are guidelines established by the provider of the PE materials to gauge acceptable analytical results. As shown in Table 4-4, all of the observed concentrations were well within the acceptance ranges.

Table 4-4. Performance Evaluation Results

		Reading (V)	**Zero (V)**	**Zero Corrected**	**Apparent Concentration***	**Percent Difference****	**Limits**
Unit 14A	NO in N_2 (ppm)						
Test Std	3,925	9.92	0.01	9.91	3905.3	0.5%	± 2%
PE Std	3,988	10.13	0.01	10.12			
Unit 10	NO in N_2 (ppm)						
Test Std	3,925	1.01	-0.01	1.03	3895.7	0.7%	± 2%
PE Std	3,988	1.04	-0.01	1.05			
Unit 14A	NO_2 in Air (ppm)						
Test Std	50.0***	4.40	0.01	4.39	48.7	2.5%	± 5%
PE Std	50.5	4.56	0.02	4.54			
Unit 10	NO_2 in Air (ppm)						
Test Std	50.0***	0.44	-0.01	0.45	50.0	0.1%	± 5%
PE Std	50.5	0.44	-0.01	0.45			

*Concentration of Test Standard indicated by comparison to the Performance Evaluation Standard
**Percent difference of apparent concentration relative to Test Standard concentration.
***Prepared by dilution of 493.2 ppm NO_2 protocol gas.

4.5.1.3 Audit of Data Quality

The audit of data quality is a qualitative and quantitative audit in which data and data handling are reviewed and data quality and data usability are assessed. Audits of data quality are used to validate data at the frequency of 10 percent and are documented in the data audit report. The goal of an audit of data quality is to determine the usability of test results for reporting technology performance, as defined during the design process. Validated data are reported in the ETV verification reports and ETV verification statement along with any limitations on the data and recommendations for limitations on data usability.

The QA/QC Reviewer for the verification test audited 10 percent of the raw data. Test data sheets and laboratory record books were reviewed, and calculations and other algorithms were verified. Calibration drift test results were calculated and compared to the Method 7E criteria. Calculations that were used to assess the four-point calibration of the reference method were also verified to be correct.

4.5.2 External Audit

EPA conducted an on-site technical systems audit during the verification testing. This audit was conducted to observe and evaluate whether the verification team followed the test/QA plan. The external technical systems audit report is attached in Appendix B and the assessment is summarized below.

The auditors assessed the verification test procedures and personnel against the *Quality Management Plan for the ETV Advanced Monitoring Systems Pilot,*(7) the *Test/QA Plan for Verification of Portable NO/NO_2 Emission Analyzers,*(1) and *U.S. EPA Method 7E Determination of Nitrogen Oxides Emissions from Stationary Sources (Instrumental Analyzer Procedure)*.(2) The auditors were on site from January 20, 1999, through January 21, 1999. The technical systems audit was performed on the flow rate and ambient temperature laboratory tests and the relative accuracy tests with the gas rangetop, water heater, and a portion of the high RPM emissions of the diesel generator. No performance evaluations were conducted as a part of this audit.

This external technical systems audit showed that the verification test was well managed, particularly considering its complexity. All personnel appeared to be well trained for their particular duties. All involved showed enthusiasm and ingenuity during the verification testing. Personnel were very familiar with the test/QA plan. With one exception, differences for this verification test from the original test/QA plan were well documented by deviation reports on file at Battelle. The deviation report format includes a date, cites the deviation, provides an explanation of the deviation, and requires a Battelle approval signature. It was impressive that the deviation reports were present and were completed up front.

Two major findings resulted from this external technical systems audit. First, as a result of a delay in the arrival of the protocol gases used in the verification test, Battelle was not able to run one of the instruments through the test sequence prior to the first test. This undocumented deviation was from Section 5.6 of the test/QA plan, Test Schedule, and stated “To avoid bias in testing of the first analyzers through the sequence, Battelle’s personnel will first conduct the entire test sequence using an analyzer already on hand at Battelle. Testing will then continue with analyzers named in Section 2.4.” Second, the test/QA plan states that “The chemiluminescent monitors to be used for Method 7E reference measurements will be subjected to a four-point calibration with NO prior to the start of verification testing, on each measurement range to be used for verification.” The combustion source tests were started on January 13, 1999. No four-point calibration with NO was recorded in the combustion source testing laboratory notebook prior to January 13. This finding is also a finding in Battelle’s internal audit conducted during the first week of the verification test.

The impact of these two findings on the data presented in this report is as follows. Although Battelle did not run an instrument through the entire test sequence prior to initiating testing, each component of the test system was checked independently. Therefore, the absence of this pre-test check will not impact the final data. The lack of initial calibration of the reference analyzers does not affect the verification data since the calibration was completed before any combustion source testing used for verification.

Chapter 5
Statistical Methods

5.1 Laboratory Tests

The analyzer performance characteristics were quantified on the basis of statistical comparisons of the test data. This process began by converting the spreadsheet files that resulted from the data acquisition process into data files suitable for evaluation with Statistical Analysis System (SAS) software. The following statistical procedures were used to make those comparisons.

5.1.1 Linearity

Linearity was assessed by linear regression with the calibration concentration as the independent variable and the analyzer response as the dependent variable. Separate assessments were carried out for each Enerac analyzer. The calibration model used was

$$Y_c = h(c) + error_c \tag{1}$$

where Y_c is the analyzer's response to a challenge concentration *c*, *h(c)* is a linear calibration curve, and the error term was assumed to be normally distributed. (If the variability is not constant throughout the range of concentrations then weighting in the linear regression is appropriate. It is often the case that the variability increases as the true concentration increases.) The variability (σ_c) of the measured concentration values (c) was modeled by the following relationship,

$$\sigma_c^2 = \alpha + kc^{\beta} \tag{2}$$

where α, k, and β are constants to be estimated from the data. After determining the relationship between the mean and variability, appropriate weighting was determined as the reciprocal of the variance.

$$weight = w_c = \frac{1}{\sigma_c^2} \tag{3}$$

The form of the linear regression model fitted was $h(c) = \alpha_o + \alpha_1 c$. In the concentration subregion where the linear calibration model provides a valid representation of the concentration-response relation, concentration values were calculated from the estimated calibration curve using the relation

$$\hat{c} = \hat{h}^{-1}(Y_c) = \frac{Y_c - \hat{\alpha}_o}{\hat{\alpha}_1} \tag{4}$$

A test for departure from linearity was carried out by comparing the residual mean square

$$\frac{1}{4}\sum_{i=1}^{6}(\bar{Y}_{c_i} - \alpha_o - \alpha_1 c_i)^2 n_{c_i} w_{c_i} \tag{5}$$

to an F-distribution with 6 - 2 = 4 numerator degrees of freedom.

$\bar{Y}_{ci}$ is the average of the n_{ci} analyzer responses at the i^{th} calibration concentration, c_i. The regression relation was fitted to the individual responses; however, only the deviation about the sample mean analyzer responses at each calibration concentration provide information about goodness-of-fit.

$$\sum_{i=l}^{n}\sum_{j=l}^{n_{ci}}(Y_{cij} - \alpha_0 - \alpha_1 c_i)^2\, w_{ci} = \sum_{i=l}^{n}\sum_{j=l}^{n_{ci}}(Y_{ci} - \bar{Y}_{ci})^2\, w_{ci} + \sum_{i=1}^{n}(\bar{Y}_{cij} - \alpha_0 - \alpha_1 c_i)^2\, n_{ci} w_{ci}$$

The first summation on the right side of the equation provides information only about response variability. The second summation provides all the information about goodness-of-fit to the straight-line calibration model. This is the statistic that is used for the goodness-of-fit test.

5.1.2 Detection Limit

Limit of detection (LOD) is defined as the smallest true concentration at which an analyzer's expected response exceeds the calibration curve at zero concentration by three times the standard deviation of the analyzer's zero reading, i.e., $\alpha_o + 3\sigma_o$, if the linear relation is valid down to zero. The LOD may then be determined by

$$LOD = \frac{\left[(\alpha_o + 3\sigma_o) - \alpha_o\right]}{\alpha_1} = \frac{3\sigma_o}{\alpha_1} \tag{6}$$

where σ_o is the estimated standard deviation at zero concentration. The LOD is estimated as $LOD = 3\hat{\sigma}_0 / \hat{\alpha}_0$. The standard error of the estimated detection limit is approximately

$$\hat{SE}\ (\hat{LOD}) \cong \hat{LOD}\sqrt{\frac{1}{2(n-1)} + \left(\frac{SE\,(\hat{a}_1)}{\hat{a}_1}\right)^2}$$

Note that the validity of the detection limit estimate and its standard error depends on the validity of the assumption that the fitted linear calibration model accurately represents the response down to zero concentration.

5.1.3 Response Time

The response time of the analyzers to a step change in analyte concentration was calculated by determining the total change in response due to the step change in concentration, and then determining the point in time when 95 percent of that change was achieved. Using data taken every 10 seconds, the following calculation was carried out:

$$\text{Total Response} = R_c - R_z$$

where R_c is the final response of the analyzer to the calibration gas and R_z is the final response of the analyzer to the zero gas. The analyzer response that indicates the response time then is:

$$\text{Response}_{95\%} = 0.95(\text{Total Response}) + R_z.$$

The point in time at which this response occurs was determined by inspecting the response/time data, linearly interpolating between two observed time points, as necessary. The response time was calculated as:

$$RT = \text{Time}_{95\%} - \text{Time}_I,$$

where $\text{time}_{95\%}$ is the time at which Response_{RT} occurred and Time_I is the time at which the span gas was substituted for the zero gas. Since only one measurement was made, the precision of the response time was not determined.

5.1.4 Interrupted Sampling

The effect of interrupted sampling is the arithmetic difference between the zero data and between the span data obtained before and after the test. Differences are stated as ppm. No estimate was made of the precision of the observed differences.

5.1.5 Interferences

Interference is reported as both the absolute response (in ppm) to an interferant level, and as the sensitivity of the analyzer to the interferant species, relative to its sensitivity to NO or NO_2. The relative sensitivity is defined as the ratio of the observed NO/NO_2/NO_x response of the analyzer to the actual concentration of the interferant. For example, an analyzer that measures NO is challenged with 500 ppm of CO, resulting in an absolute difference in reading of 1 ppm (as NO). The relative sensitivity of the analyzer is thus 1 ppm/500 ppm = 0.2 percent. The precision of the interference results was not estimated from the data obtained, since only one measurement was made for each interferant.

5.1.6 *Pressure Sensitivity*

At each of ambient pressure, reduced pressure (-10 inches of water), and increased pressure (+10 inches of water), the analyzer flow rate, the response on zero gas, and the response on span gas were measured for each analyzer. Variability in zero and span responses for reduced and increased pressures was assumed to be the same as the variability at ambient pressure. The variability determined in the linearity test was used for this analysis. The duct pressure effects on analyzer flow rates and response were assessed by separate linear regression trend analyses for flow rate and for response. The precision of the pressure effects on zero concentration response and on span gas response was estimated based on the variability observed in the linearity test. Statistical significance of the trends across duct pressures was determined by comparing the estimated trends to their estimated standard errors, based on two-tailed t-tests:

$$t = \hat{b} / (0.040825\hat{s}(c)) \text{ for the zero concentration test}$$

$$t = \hat{b} / (0.070711\hat{s}(c)) \text{ for the span concentration test}$$

5.1.7 *Ambient Temperature*

The statistical analysis for evaluation of ambient temperature effects was similar to that used for assessing the pressure sensitivity. At room temperature, low temperature, and high temperature for each analyzer the response on zero gas and the response on span gas were observed. Variability for low and for high temperatures was assumed to be the same as variability at room temperature. The ambient temperature effects on zero and span readings were assessed by trend analysis for response with temperature, using separate linear regression analyses for the zero and for the span data. Precision of the ambient temperature effect was estimated based on the variability observed in the linearity test. Statistical significance of the trends across temperatures was determined by comparing the estimated trends to their estimated standard errors, based on two-tailed t-tests:

$$t = \hat{b} / (0.017231\hat{s}(c)) \text{ for the zero concentration test}$$

$$t = \hat{b} / (0.024363\hat{s}(c)) \text{ for the span concentration test}$$

5.2 Combustion Source Tests

5.2.1 Accuracy

The relative accuracy (RA) of the analyzers with respect to the reference method is expressed as:

$$RA = \frac{|\bar{d}| + t^{\alpha}_{n-1}\frac{S_d}{\sqrt{n}}}{\bar{x}} \times 100\% \qquad \textbf{(7)}$$

where *d* refers to the difference between the average of the two reference units and one of the tested units and *x* corresponds to the average of the two reference unit values. S_d denotes the sample standard deviation of the differences, based on n = 9 samples, while t^{α}_{n-1} is the t value for the 100(1 - α)th percentile of the distribution with n - 1 degrees of freedom. The relative accuracy was determined for an α value of 0.025 (i.e., 97.5 percent confidence level, one-tailed). The RA calculated in this way can be determined as an upper confidence bound for the relative bias of the analyzer $|\bar{d}|/\bar{x}$, where the bar indicates the average value of the differences or of the reference values.

Assuming that the reference method variation is due only to the variation in the output source and the true bias between the test and reference methods is close to zero, an approximate standard error for RA is

$$\hat{SE} \cong \frac{S_d}{\sqrt{n\,x}} \sqrt{0.3634 + \left(t^{a}_{n-1}\right)^2 \frac{1}{2(n-1)}} \times 100\% \qquad (8)$$

5.2.2 Zero/Span Drift

Statistical procedures for assessing zero and span drift were similar to those used to assess interrupted sampling. Zero (span) drift was calculated as the arithmetic difference between zero (span) values obtained before and after sampling of each combustion source. The same calculation was also made using zero and span values obtained before and after the linearity and ambient temperature tests. No estimate was made of the precision of the zero and span drift values.

5.2.3 Measurement Stability

The temporal stability of analyzer response in extended sampling from a combustion source was assessed by means of a trend analysis on 60 minutes of data obtained continuously using the diesel generator as the source. The existence of a difference in trend between the test unit and the average of the reference units was assessed by fitting a linear regression line with the difference between the measured concentration for a test unit and the average of the reference units as the dependent variable, and time as the independent variable. Subtracting the average reference unit values adjusts for variation in the source output. The slope and the standard error of the slope are reported. The null hypothesis that the slope of the trend line on the difference is zero was tested using a one-sample two-tailed t-test with n - 2 = 58 degrees of freedom.

5.2.4 Inter-Unit Repeatability

The purpose of this comparison was to determine if any significant differences in performance exist between two identical analyzers operating side by side. In tests in which analyzer performance was verified by comparison with data from the reference method, the two identical units of each type of analyzer were compared to one another using matched pairs t-test comparisons. In tests in which no reference method data were obtained (e.g., linearity test), the two units of each analyzer were compared using statistical tests of difference. For example, the slopes of the calibration lines determined in the linearity test, and the detection limits determined from those test data, were compared. Inter-unit repeatability was assessed for the linearity, detection limit, accuracy, and measurement stability tests.

For the linearity test, the intercepts and slopes of the two units were compared to one another by two-sample t-tests using the pooled standard error, with combined degrees of freedom the sum of the individual degrees of freedom.

For the detection limit test, the detection limits of the two units were compared to one another by two-sample t-tests using the pooled standard error with 10 degrees of freedom (the sum of the individual degrees of freedom).

For the relative accuracy test, repeatability was assessed with a matched-pairs two-tailed t-test with n - 1 = 8 degrees of freedom.

For the measurement stability test, the existence of differences in trends between the two units was assessed by fitting a linear regression to the paired differences between the units. The null hypothesis that the slope of the trend line on the paired differences is zero was tested using a matched-pairs t-test with n - 2 = 58 degrees of freedom.

5.2.5 Data Completeness

Data completeness was calculated as the percentage of possible data recovered from an analyzer in a test; the ratio of the actual to the possible number of data points, converted to a percentage, i.e.,

$$\text{Data Completeness} = (N_a)/(N_p) \times 100\%,$$

where N_a is the number of actual and N_p the number of possible data points.

Chapter 6
Statistical Results

6.1 Laboratory Tests

6.1.1 Linearity

Tables 6-1a through d list the data obtained in the linearity tests for NO and NO_2. The response of both the NO and NO_2 sensors in each analyzer is shown in Tables 6-1a through d. Table 6-1a shows the data obtained in the NO test over 0 to 1,000 ppm, and Table 6-1b shows the data from the NO_2 test over a 0 to 400 ppm range. Tables 6-1c and d list the data obtained in additional NO linearity tests over ranges of 0 to 3,000 ppm and 0 to 300 ppm, respectively. As noted in Section 3.2.1, the Enerac analyzers reported 0 ppm at all NO concentrations below 3 ppm, in the 0 to 1,000 ppm and 0 to 3,000 ppm NO tests (Tables 6-1a and c, respectively) because of the NO control modules used in the analyzers.

Tables 6-2a through c show the results of the linear calibration curve fits for each unit and each analyte, based on the data shown in Tables 6-1a through d. Tables 6-2a through c show that the linearity tests of the Enerac analyzers gave regression slopes for NO that range from 0.986 to 1.009, and for NO_2 that are both 0.992. These slopes are all in the range of 0.98 to 1.02, stated as acceptable in the SCAQMD tests protocol.(8) The R^2 values for NO range from 0.9997 to 0.9999, while the values for NO_2 are 0.9987 and 0.9980. These all exceed or are close to the value of 0.999 stated as acceptable in the SCAQMD protocol.(8)

The linearity test data in Tables 6-1a through b also indicate the extent of cross-sensitivity of the Enerac NO and NO_2 sensors. In NO tests to 1,000 ppm (Table 6-1a) and 300 ppm (Table 6-1d), no response to NO was seen on the NO_2 sensors of the Enerac analyzers. However, some response was seen in the linearity test to 3,000 ppm NO (Table 6-1c). Using those data, linear regression of the NO_2 responses of the analyzers against the NO levels provided (Table 6-1c) gives the following regression equations:

$$\text{Unit A } NO_2 \text{ Response} = 0.00216 \text{ (Actual NO) } -0.98 \text{ ppm}$$
$$\text{Unit B } NO_2 \text{ Response} = 0.00251 \text{ (Actual NO) } -1.01 \text{ ppm}$$

Table 6-1a. Data from NO Linearity Test Over 0-1,000 ppm Range on Enerac 3000E Analyzers

Reading	Actual NO (ppm)	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
1	0	0	0	0	0
2	1002	994	0	997	0
3	99.7	104	0	103	0
4	400.7	413	0	413	0
5	0	0	0	0	0
6	701.2	711	0	711	0
7	200.2	208	0	207	0
8	99.7	104	0	104	0
9	0	0	0	0	0
10	200.2	207	0	208	0
11	400.7	413	0	414	0
12	701.2	716	0	716	0
13	0	0	0	3	0
14	1002	995	0	1000	0
15	701.2	713	0	716	0
16	400.7	414	0	417	0
17	0	0	0	3	0
18	200.2	207	0	207	0
19	99.7	104	0	105	0
20	1002	994	0	999	0
21	0	0	0	3	0

Table 6-1b. Data from NO_2 Linearity Test Over 0-400 ppm Range on Enerac 3000E Analyzers

Number	Actual NO_2 (ppm)	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
1	0	0	0	0	0
2	400.9	0	403	0	404
3	48.2	1	47	1	46
4	197	0	195	0	194
5	0	1	3	1	3
6	345.7	0	342	0	342
7	97.2	0	97	0	95
8	48.2	0	45	0	44
9	0	1	0	1	0
10	97.2	0	93	0	90
11	197	0	195	0	193
12	345.7	0	348	0	349
13	0	1	4	1	4
14	400.9	0	403	0	406
15	345.7	0	352	0	354
16	197	0	202	0	201
17	0	1	4	1	4
18	97.2	0	95	0	92
19	48.2	0	45	1	43
20	400.9	0	404	0	406
21	0	1	4	1	4

Table 6-1c. Data from NO Linearity Test Over 0-3,000 ppm Range on Enerac 3000E Analyzers

Number	Actual NO (ppm)	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
1	0	15	0	18	0
2	3005	3020	12	2985	12
3	292.7	287	0	283	0
4	1198	1219	0	1194	0
5	0	17	0	19	0
6	2103	2114	0	2112	3
7	592.6	591	0	586	0
8	292.7	276	0	271	0
9	0	11	0	19	0
10	592.6	585	0	586	0
11	1198	1213	0	1194	0
12	2103	2119	0	2095	0
13	0	19	0	19	0
14	3005	2985	8	2991	8
15	2103	2129	0	2095	3
16	1198	1219	0	1208	0
17	0	17	0	19	0
18	592.6	585	0	586	0
19	292.7	276	0	276	0
20	3005	2994	6	2981	7
21	0	17	0	19	0

Table 6-1d. Data from NO Linearity Test Over 0-300 ppm Range on Enerac 3000E Analyzers

Number	Actual NO (ppm)	Unit A NO (ppm)	Unit A NO$_2$ (ppm)	Unit B NO (ppm)	Unit B NO$_2$ (ppm)
1	0	1	0	1	0
2	300.5	299	0	300	0
3	29.7	32	0	32	0
4	120	124	0	124	0
5	0	1	0	1	0
6	209.9	214	0	213	0
7	59.8	63	0	63	0
8	29.7	31	0	32	0
9	0	1	0	1	0
10	59.8	62	0	63	0
11	120	125	0	124	0
12	210.3	214	0	215	0
13	0	1	0	1	0
14	300.5	301	0	302	0
15	210.3	215	0	215	0
16	120	125	0	125	0
17	0	1	0	1	0
18	59.8	63	0	63	0
19	29.7	32	0	32	0
20	300.5	302	0	302	0
21	0	1	0	1	0

Table 6-2a. Statistical Results for First Test of Linearity (NO span = 1000 ppm, NO$_2$ span = 400 ppm)

	Unit A		Unit B	
Linear Regression	NO	NO$_2$	NO	NO$_2$
Intercept (ppm) (Std Err)	7.284 (2.093)	0.686 (0.844)	3.545 (1.264)	0.204 (1.026)
Slope (Std Err)	0.996 (0.005)	0.992 (0.008)	1.009 (0.004)	0.992 (0.010)
R^2	0.9997	0.9987	0.9997	0.9980

Table 6-2b. Statistical Results for Second Test of Linearity (NO span = 3000 ppm)

Linear Regression	Unit A NO	Unit B NO
Intercept (ppm) (Std Err)	10.043 (3.237)	18.759 (0.383)
Slope (Std Err)	0.996 (0.004)	0.986 (0.002)
R^2	0.9997	0.9999

Table 6-2c. Statistical Results for Third Test of Linearity (NO span = 300 ppm)

Linear Regression	Unit A NO	Unit B NO
Intercept (ppm) (Std Err)	2.820 (0.599)	2.392 (0.269)
Slope (Std Err)	0.999 (0.005)	1.005 (0.004)
R^2	0.9997	0.9998

with R^2 values of 0.52 and 0.67, respectively. These results indicate a slight sensitivity of the NO_2 sensors to NO, amounting to about 0.2 percent of the actual NO level. This degree of cross-sensitivity is negligible in any real-world application.

As seen in Table 6-1b, no response was observed from the Enerac NO sensors when sampling up to 400 ppm of NO_2, indicating no cross-sensitivity of the NO sensors to NO_2.

6.1.2 Detection Limit

Table 6-3 shows the estimated detection limits for each test unit and each analyte, calculated from the data obtained in each linearity test.

Table 6-3 displays the estimated detection limits, and their standard errors for NO and NO_2, separately for each Enerac analyzer. The determination of NO detection limits from the 1,000 ppm and 3,000 ppm NO linearity tests may have been affected by the operating mode used in those tests, in which the Enerac analyzers read zero at all NO concentrations below 3 ppm. In addition, in other tests the analyzers gave identically the same 1 ppm response on all zero gas samples. As a result, in some tests all readings on zero gas were the same, and there was no variation in zero readings with which to estimate the detection limit. The detection limit for NO on Unit A was 8.3 ppm in the 0 to 3,000 ppm test; detection limits for NO on Unit B were 4.9 ppm in the 0 to 1,000 ppm test and 1.2 ppm in the 0 to 3,000 ppm test. Detection limits for NO_2 were about 6 ppm in the 0 to 400 ppm test on both analyzers. Both NO units showed a constant 1 ppm response on zero air in the 0 to 300 ppm test (Table 6-1d), indicating excellent stability and suggesting a detection limit less than the 1 ppm measurement resolution.

Table 6-3. Estimated Detection Limits for Enerac 3000E Analyzers

	Unit A		Unit B	
	NO	**NO_2**	**NO**	**NO_2**
Estimated Detection Limit (ppm)* (Standard Error) (ppm)	0**** (0.000)	5.973 (1.890)	4.886 (1.545)	5.972 (1.889)
Estimated Detection Limit (ppm)** (Standard Error) (ppm)	8.300 (2.625)	---	1.242 (0.393)	---
Estimated Detection Limit (ppm)*** (Standard Error) (ppm)	0**** (0.000)	---	0**** (0.000)	---

*First test, Tables 6-1a and b.
**Second test, Table 6-1c.
***Third test, Table 6-1d.
****No variation in zero responses with which to assess detection limit.

6.1.3 Response Time

Table 6-4 lists the data obtained in the response time test of the Enerac 3000E analyzers. Table 6-5 shows the response times of the analyzers to a step change in analyte concentration, based on the data shown in Table 6-4.

Table 6-5 shows that the Enerac 3000E analyzers provide substantially faster responses for NO than for NO_2, and that the two analyzers were very similar in their response to both species. Time response for NO was about 60 seconds, and for NO_2 was about 100 seconds. These response times are well within the 4-minute time response criterion generally required of portable NO/NO_2 analyzers.(8)

6.1.4 Interrupted Sampling

Table 6-6 shows the zero and span data resulting from the interrupted sampling test, and Table 6-7 shows the differences (pre- minus post-) of the zero and span values. Span concentrations of 1,000 ppm NO and 400 ppm NO_2 were used for this test. Greater zero and span differences were seen for NO_2 than for NO on both analyzers. NO zero readings (Table 6-6) were all zero, and consequently so were the zero differences (Table 6-7). This lack of zero variation may be real, or the operating mode of the Enerac analyzers, which forced readings of 0 ppm at all NO levels below 3 ppm, may have affected the results. NO span differences were -4 to 2 ppm, equivalent to 0.4 percent or less of the 1,000 ppm span level. NO_2 zero drift was 4 ppm downward on both analyzers during the overnight shutdown. Span differences for NO_2 were equivalent to 2.5 to 2.8 percent of the 400 ppm span level.

Table 6-4. Response Time Data for Enerac 3000E Analyzers

Time (sec)	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
0	0	0	0	0
10	75	0	40	0
20	310	34	239	36
30	523	117	481	117
40	603	189	584	192
50	651	239	641	240
60	677	275	673	275
70	693	297	690	296
80	702	311	698	310
90	708	320	703	319
100	708	326	706	324
110	707	329	708	328
120	708	332	707	330
130	709	334	711	332
140	711	336	711	334
150	713	337	713	336
160	713	338	713	337
170	713	339	711	338
180	711	340	711	339
190		340		340
200		341		340
210		341		341
220		342		342

Table 6-5. Response Time Results for Enerac 3000E Analyzers

	Unit A		Unit B	
	NO	NO_2	NO	NO_2
Response Time (sec)*	59	98	61	102

* The analyzer’s responses were recorded at 10-second intervals; therefore the point in time when the 95 percent response was achieved was determined by interpolating between recorded times to the nearest second.

Table 6-6. Data from Interrupted Sampling Test with Enerac 3000E Analyzers

	Unit A NO	Unit A NO_2	Unit B NO	Unit B NO_2
Pre-Shutdown Date:	**1/25/99**	**Time:**	**22:30**	
Pre-Shutdown Zero (ppm):	0	4	0	4
Pre-Shutdown Span (ppm):	1000	404	1000	406
Post-Shutdown Date:	**1/26/99**	**Time:**	**10:00**	
Post-Shutdown Zero (ppm):	0	0	0	0
Post-Shutdown Span (ppm):	998	394	1004	395

Table 6-7. Pre- to Post-Test Differences as a Result of Interruption of Operation of Enerac 3000E Analyzers

	Unit A		Unit B	
Pre-Shutdown—Post-Shutdown	**NO**	**NO_2**	**NO**	**NO_2**
Zero Difference (ppm)	0	4	0	4
Span Difference (ppm)	2	10	-4	11

6.1.5 Interferences

Table 6-8 lists the data obtained in the interference tests. Table 6-9 summarizes the sensitivity of the analyzers to interferant species, based on the data from Table 6-8. Note that cross-sensitivity to NO and NO_2 has been addressed using the linearity data, in Section 6.1.1.

Table 6-9 indicates that none of the individual interferants produced a response from the NO or NO_2 sensors of the Enerac analyzers (i.e., both analyzers read 0 ppm throughout the sampling of those interferants). Even assuming that a 2 ppm response to one of the interferants was hidden (forced to zero) by the analyzers' operating mode for NO, the maximum relative sensitivity to any of the individual interferants would be less than 0.5 percent. The last row of entries in Table 6-9 indicates that, for the one mixed interferant, SO_2 + NO, the response to NO was higher for both Units A and B than the 385 ppm NO supplied. If the higher NO response is ascribed to a positive interference from the SO_2 present along with the NO, then the relative sensitivity to SO_2 is effectively 8 to 9 percent [e.g., (426-385)/451 x 100 = 9.1%].

Table 6-8. Data from Interference Tests on Enerac 3000E Analyzers

Interferant Gas	Interferant, Conc. (ppm)	Response (ppm equivalent) Unit A NO	Unit A NO_2	Unit B NO	Unit B NO_2
Zero		0	0	0	0
CO	496 ppm	0	0	0	0
Zero		0	0	0	0
CO_2	5.03%	0	0	0	0
Zero		0	0	0	0
NH_3	494 ppm	0	0	0	0
Zero		0	0	0	0
HCs	590 ppm	0	0	0	0
Zero		0	0	0	0
SO_2	501 ppm	0	0	0	0
Zero		0	0	0	0
SO_2 + NO	451+385 ppm	426	0	422	0

Table 6-9. Results of Interference Tests of Enerac 3000E Analyzers

Interferent	Unit A Response ppm (relative sensitivity, %) NO	NO_2	Unit B Response ppm (relative sensitivity, %) NO	NO_2
CO (496 ppm)	0	0	0	0
CO_2 (5.03 %)	0	0	0	0
NH_3 (494 ppm)	0	0	0	0
HCs (590 ppm)	0	0	0	0
SO_2 (501 ppm)	0	0	0	0
SO_2 (451ppm) + NO (385ppm)	41 (9.1%)	0	37 (8.2%)	0

6.1.6 Pressure Sensitivity

Table 6-10 lists the data obtained in the pressure sensitivity test. Table 6-11 summarizes the findings from those data in terms of the ppm differences in zero and span readings at the different duct gas pressures, and the ccm differences in analyzer flow rates at the different duct gas pressures. Table 6-11 also indicates whether zero and span differences are statistically significant at the 95 percent confidence level. No pressure effect on zero readings was seen with either analyzer for NO or NO_2. A significant pressure effect was seen on NO_2 span readings, but the results are due almost entirely to an elevation of the span readings at increased pressure. At reduced pressure, NO_2 span readings were essentially identical to those at ambient pressure. The 28 ppm increase in NO_2 span response at increased pressure is equivalent to 8.1 percent of the 345 ppm NO_2 span concentration used. This much larger difference in span response at increased pressure may be related to the much larger effect of increased pressure on analyzer flow rates, which is described below.

The pressure effect on NO span values was smaller and less consistent than that for NO_2. The span differences shown in Table 6-11 are equivalent to 0.6 to 1.7 percent of the 700 ppm NO span concentration used.

Tables 6-10 and 6-11 also indicate a surprisingly large dependence of the sample gas flow rate drawn by the two analyzers on the duct pressure. Sample flow rates at +10 inches of water exceeded those at ambient pressure by 99 to 163 percent; flow rates at -10 inches of water were reduced by 20 to 22 percent. The reason for this finding is unclear, but may relate to the internal plumbing of the Enerac analyzers; as noted above, these large differences in flow rates were associated with small differences in zero or span response.

6.1.7 Ambient Temperature

Table 6-12 lists the data obtained in the ambient temperature test with the Enerac 3000E analyzers.

Table 6-13 summarizes the sensitivity of the analyzers to changes in ambient temperature. This table is based on the data shown in Table 6-12, where the span values are 700 ppm for NO and 345 ppm for NO_2.

Table 6-13 indicates whether zero and span differences are statistically significant with temperature at the 95 percent confidence level. No dependence of NO_2 zero readings on temperature was found; however, a small but statistically significant dependence of NO zero readings was found, with the highest readings at elevated temperature. As with all assessments of NO zero readings on the Enerac analyzers, it is not clear whether the NO operating mode of the analyzers has obscured or exaggerated real variability by forcing readings below 3 ppm to zero. In any case, in light of the known potential for electrochemical NO sensors to drift with temperature, the small NO zero drifts observed (i.e., about 5 ppm or less, Table 6-13) must be considered of minimal practical importance.

A significant dependence of span values on ambient temperature was found for NO with both analyzers and for NO_2 with Unit A (Table 6-13). However, even the NO results present an inconsistent picture (see Table 6-12). For both units at elevated temperature, the NO span value was lower than that at room temperature, but by different amounts. At reduced temperature, for Unit A, the NO span value was almost the same as that at room temperature; whereas for Unit B the NO span value was greater than that at room temperature. These results suggest a reduction in NO span response as temperature increases, but do not accurately quantify that dependence. The Unit A NO_2 results suggest the opposite effect (i.e., an increase in response as temperature increases), but the Unit B results do not strongly support that trend. It must be noted that the first room temperature test and the elevated temperature test were done in the evening, and the

Table 6-10. Data from Pressure Sensitivity Test for Enerac 3000E Analyzers

Pressure		Unit A NO	Unit A NO_2	Unit B NO	Unit B NO_2
Ambient	Flow rate (ccm)	667	667	663	663
	Zero (ppm)	0	0	0	0
	NO span (ppm)	721	0	721	0
	Zero (ppm)	0	0	0	0
	NO_2 span (ppm)	7	342	0	336
	Zero (ppm)	0	0	0	0
+10 in. H_2O	Flow rate (ccm)	1755	1755	1318	1318
	Zero (ppm)	0	0	0	0
	NO span (ppm)	725	0	711	0
	Zero (ppm)	0	0	0	0
	NO_2 span (ppm)	6	370	0	364
	Zero (ppm)	0	0	0	0
-10 in. H_2O	Flow rate (ccm)	518	518	528	528
	Zero (ppm)	0	0	0	0
	NO span (ppm)	709	0	710	0
	Zero (ppm)	0	0	3	0
	NO_2 span (ppm)	7	342	0	337
	Zero (ppm)	0	0	0	0

Table 6-11. Pressure Sensitivity Results for Enerac 3000E Analyzers

		Unit A		Unit B	
		NO	NO_2	NO	NO_2
Zero	High–Ambient (ppm diff*)	0	0	0	0
	Low–Ambient (ppm diff)	0	0	1	0
	Significant Pressure Effect	N	N	N	N
Span	High–Ambient (ppm diff)	4	28	-10	28
	Low–Ambient (ppm diff)	-12	0	-11	1
	Significant Pressure Effect	Y	Y	Y	Y
Flow Rate	High–Ambient (ccm diff*)	1088		655	
	Low–Ambient (ccm diff)	-149		-135	

* ppm or ccm difference between high/low and ambient pressures. The differences were calculated based on the average of the zero values.

Table 6-12. Data from Ambient Temperature Test of Enerac 3000E Analyzers

Condition	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
(Room Temp.)				
Temp. 24.4°C (76°F)				
Zero	0	0	0	0
NO span	718	7	719	7
Zero	0	0	0	0
NO_2 span	7	349	0	346
(Heated)				
Temp. 41.7°C (107°F)				
Zero	3	0	3	0
NO span	709	5	717	4
Zero	6	0	8	0
NO_2 span	13	352	4	338
(Cooled)				
Temp. 10°C (50°F)				
Zero	0	0	0	0
NO span	733	4	740	3
Zero	0	0	0	0
NO_2 span	5	326	0	330
(Room Temp.)				
Temp. 24.4°C (76°F)				
Zero	0	0	0	0
NO span	734	7	721	6
Zero	0	0	0	0
NO_2 span	6	336	0	333

Table 6-13. Ambient Temperature Effects on Enerac 3000E Analyzers

		Unit A		Unit B	
		NO	NO_2	NO	NO_2
Zero*	Heat–Room (ppm diff*)	4.5	0	5.5	0
	Cool–Room (ppm diff)	0	0	0	0
	Significant Temp Effect**	Y	N	Y	N
Span	Heat–Room (ppm diff)	-17	9.5	-3	-1.5
	Cool–Room (ppm diff)	7	-16.5	20	-9.5
	Significant Temp. Effect	Y	Y	Y	N

* ppm difference between heated/cooled and room temperatures. The differences were calculated from the average of the recorded responses at room temperature.

second room temperature and reduced temperature tests were done the following morning. Thus, day-to-day drift may also contribute to the changes in zero and span readings that are attributed to temperature effects. Overall, the NO span differences amount to 2.9 percent or less of the 700 ppm NO span level, and those for NO_2 amount to 4.8 percent or less of the 345 ppm NO_2 span level. No consistent temperature dependence can be inferred from these results.

6.1.8 Zero and Span Drift

Zero and span drift were evaluated from data taken at the start and end of the linearity and ambient temperature tests. Those data are shown in Table 6-14, and the drift values observed are shown as pre- minus post-test differences in ppm in Table 6-15.

The results in Table 6-15 for the first linearity test show no zero drift for NO, but 4 ppm drift for NO_2. However, the NO zero drift may have been as large as ±2 ppm, and would still be read as zero because of the operating mode of the analyzers. Span drifts for NO and NO_2 equate to 0.1 percent, and up to 1.75 percent, of the respective span concentrations.

In the second linearity test (with up to 3,000 ppm NO), NO zero drift was 7 and 12 ppm on the two units, respectively. Span drift differed widely on the two units, but even for Unit A, the span drift was only 1.5 percent of the 3,000 ppm span concentration. The third linearity test (up to 300 ppm NO) showed that both zero and span drift of the NO sensors was within 1 ppm, or 0.3 percent of the span concentration.

The ambient temperature test showed no zero drift for either NO or NO_2 on either analyzer. That for NO could have been as large as ±2 ppm, because of the operating mode of the analyzers. The NO_2 span drift of 13 ppm found for both analyzers amounts to 3.8 percent of the NO_2 span concentration. The NO span drift values differed considerably between the two units (Table 6-15). The larger value, 16 ppm drift on Unit A, amounts to 2.3 percent of the NO span concentration.

Table 6-14. Data from Linearity and Ambient Temperature Tests Used to Assess Zero and Span Drift of the Enerac 3000E Analyzers.

Test		Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
First Linearity Test*	Pre-Test Zero*	0	0	0	0
	Pre-Test Span*	999	399	1001	399
	Post-Test Zero*	0	4	0	4
	Post-Test Span*	1000	404	1000	406
Second Linearity Test**	Pre-Test Zero**	5	–	12	–
	Pre-Test Span**	3039	–	2980	–
	Post-Test Zero**	17	–	19	–
	Post-Test Span**	2994	–	2981	–
Third Linearity Test***	Pre-Test Zero***	0	–	0	–
	Pre-Test Span***	301	–	301	–
	Post-Test Zero***	1	–	1	–
	Post-Test Span***	302	–	302	–
Ambient Temperature	Pre-Test Zero	0	0	0	0
	Pre-Test Span	718	349	719	346
	Post-Test Zero	0	0	0	0
	Post-Test Span	734	336	721	333

*NO 0 - 1,000 ppm and NO_2 0 - 400 ppm.
**NO 0 - 3,000 ppm.
***NO 0 - 300 ppm.

Table 6-15. Zero and Span Drift Results for the Enerac 3000E Analyzers

		Unit A		Unit B	
Pre- and Post-Differences		NO (ppm)	NO_2 (ppm)	NO (ppm)	NO_2 (ppm)
First Linearity Test	Zero	0	-4	0	-4
	Span	-1	-5	1	-7
Second Linearity Test	Zero	-12	–	-7	–
	Span	45	–	-1	–
Third Linearity Test	Zero	-1	–	-1	–
	Span	-1	–	-1	–
Ambient Temperature Test	Zero*	0	0	0	0
	Span	-16	13	-2	13

* Drift is the difference (pre-monitoring minus post-monitoring) between the first and last zero check response averages at room temperature.

Note that these span drift values were obtained over the course of two days, i.e., the two room temperature span checks were conducted on one evening and on the following morning, respectively (Section 6.1.7). Even so, nearly all the Enerac zero and span drift results meet the 3 percent requirements stated in the SCAQMD test protocol.(8)

6.2 Combustion Source Tests

6.2.1 Relative Accuracy

Tables 6-16a through d list the measured NO, NO_2, and NO_x data obtained in sampling of the four combustion sources. Note that the Enerac analyzers measure NO and NO_2, and the indicated NO_x totals are the sum of those data; in contrast, the reference monitors measure NO and NO_x, and NO_2 is determined by difference. Tables 6-16a through d show that a wide range of NO and NO_2 concentrations was emitted by the four sources. However, it should be noted that, even so, the NO and NO_2 emission levels covered only a small part of the measurement range of the Enerac 3000E analyzers.

Table 6-17 displays the relative accuracy (in percent) for NO, NO_2, and NO_x of Enerac Units A and B for each of the four sources. Estimated standard errors are shown with the relative accuracy estimates. These standard error estimates were calculated under the assumption of zero true bias between the reference and test methods. If the bias is in fact non-zero the standard errors underestimate the variability.

The relative accuracy results of the Enerac analyzers varied with different sources. With the gas rangetop (Table 6-16a), the NO responses of the Enerac units were generally within about 1 ppm of the reference analyzers (i.e., within the measurement resolution of the analyzers), resulting in relative accuracies of 16 and 27 percent for Units A and B at the low NO levels observed. On the other hand, both Enerac units indicated zero for NO_2 throughout the test, resulting in relative accuracies over 100 percent at the 2 ppm NO_2 levels observed. Note that this behavior is not due to an operating mode of the analyzer as described in Sections 3.2.1 and 6.1.1; that mode applies to NO measurements rather than to NO_2. As a consequence of the failure to detect NO_2, the NO_x totals from the Enerac analyzers with the gas rangetop were consistently low by 1 to 2 ppm, resulting in relative accuracies for NO_x of about 20 percent on both analyzers (Table 6-17).

With the gas water heater (Table 6-16b), similar performance was observed. In this case the Enerac units provided good relative accuracy for NO: 9 percent and 3.4 percent for Units A and B, respectively. However, no response was seen for NO_2 at levels of 4 to 6 ppm. Overall, NO_x relative accuracy with the water heater was about 16 percent and 11 percent, respectively, despite the failure to detect NO_2. This result is a consequence of the high proportion of NO to NO_2 in the water heater emissions.

The performance of the Enerac analyzers differed greatly between the diesel test at high RPM (Table 6-16c) and that at idle (Table 6-16d). In the high RPM test, both Enerac analyzers gave NO readings considerably higher than those of the reference analyzers, and NO_2 readings considerably lower (Table 6-16c). As a result, relative accuracy for both NO and NO_2 is poor for

Table 6-16a. Data from the Gas Rangetop in Verification Testing of Enerac 3000E Analyzers

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit A NO_x (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)	Unit B NO_x (ppm)	14A NO (ppm)	14A NO_2 (ppm)	14A NO_x (ppm)	10 NO (ppm)	10 NO_2 (ppm)	10 NO_x (ppm)
1	5	0	5	5	0	5	4.4	2.3	6.7	4.9	1.9	6.8
2	6	0	6	6	0	6	4.8	2.2	6.9	5.2	1.8	7.0
3	6	0	6	6	0	6	4.9	2.4	7.3	5.4	2.2	7.6
4	6	0	6	6	0	6	5.0	2.2	7.2	5.4	2.3	7.7
5	6	0	6	6	0	6	5.2	2.1	7.3	5.7	2.1	7.8
6	6	0	6	6	0	6	5.2	2.0	7.2	5.6	2.2	7.8
7	6	0	6	7	0	7	5.2	2.0	7.2	5.6	2.2	7.8
8	6	0	6	7	0	7	5.1	2.2	7.3	5.6	2.3	7.9
9	6	0	6	7	0	7	4.9	2.5	7.4	5.6	2.4	8.0

Table 6-16b. Data from Gas Water Heater in Verification Testing of Enerac 3000E Analyzers

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit A NO_x (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)	Unit B NO_x (ppm)	14A NO (ppm)	14A NO_2 (ppm)	14A NO_x (ppm)	10 NO (ppm)	10 NO_2 (ppm)	10 NO_x (ppm)
1	76	0	76	80	0	80	79.1	3.7	82.8	84.9	5.2	90.0
2	62	0	62	66	0	66	65.4	5.5	70.8	69.2	5.3	74.6
3	64	0	64	68	0	68	62.3	5.8	68.1	68.6	1.4	70.0
4	53	0	53	57	0	57	55.7	5.0	60.7	59.0	5.5	64.5
5	53	0	53	56	0	56	54.8	5.9	60.7	58.8	5.9	64.7
6	50	0	50	54	0	54	53.6	4.1	57.7	56.7	5.1	61.8
7	50	0	50	53	0	53	52.8	5.0	57.8	56.7	5.1	61.8
8	50	0	50	53	0	53	52.6	5.0	57.6	56.4	5.1	61.6
9	50	0	50	53	0	53	53.1	4.7	57.8	57.2	4.9	62.1

Table 6-16c. Data from the Diesel Generator at High RPM in Verification Testing of Enerac 3000E Analyzers

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit A NO_x (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)	Unit B NO_x (ppm)	14A NO (ppm)	14A NO_2 (ppm)	14A NO_x (ppm)	10 NO (ppm)	10 NO_2 (ppm)	10 NO_x (ppm)
1	169	12	181	170	15	185	108.3	54.1	162.4	108.1	49.0	157.1
2	152	17	169	159	13	172	97.4	58.5	155.9	96.9	55.2	152.2
3	146	13	159	164	7	171	96.4	53.7	150.1	96.9	51.1	148.0
4	155	11	166	167	5	172	96.5	54.4	150.9	96.9	51.1	148.0
5	156	12	168	166	6	172	96.2	55.0	151.3	96.9	51.1	148.0
6	156	12	168	166	6	172	94.3	55.1	149.4	95.1	52.1	147.2
7	154	12	166	163	6	169	91.0	56.4	147.4	92.3	52.1	144.4
8	152	13	165	162	7	169	90.4	56.3	146.7	91.3	52.1	143.5
9	152	12	164	162	6	168	88.8	55.9	144.7	90.4	51.1	141.5

Table 6-16d. Data from Diesel Generator at Idle in Verification Testing of Enerac 3000E Analyzers

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit A NO_x (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)	Unit B NO_x (ppm)	14A NO (ppm)	14A NO_2 (ppm)	14A NO_x (ppm)	10 NO (ppm)	10 NO_2 (ppm)	10 NO_x (ppm)
1	338	138	476	343	129	472	271.6	109.1	380.6	272.1	98.2	370.3
2	336	137	473	343	130	473	281.7	111.1	392.8	277.7	103.4	381.1
3	336	138	474	343	132	475	281.6	117.3	398.9	278.7	107.5	386.2
4	336	140	476	343	132	475	283.8	119.3	403.0	279.6	109.6	389.2
5	333	140	473	341	132	473	280.9	122.3	403.3	277.7	109.6	387.4
6	335	141	476	343	136	479	285.5	120.5	406.1	280.5	110.7	391.2
7	337	141	478	346	137	483	284.1	123.3	407.4	279.6	112.7	392.3
8	334	142	476	344	139	483	284.7	126.0	410.7	278.7	113.8	392.4
9	326	146	472	335	145	480	285.5	122.7	408.3	278.7	112.7	391.4

both analyzers in this test (Table 6-17). However, the excess in NO closely balances the deficit in NO_2 response, and consequently the relative accuracy for NO_x is good, i.e., about 14 percent for Unit A and 16 percent for Unit B (Table 6-17).

Table 6-17. Relative Accuracy of Enerac 3000E Analyzers

	Unit A			Unit B		
Source	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
Gas Rangetop	16.12*	105.04	22.68	27.41	105.04	20.68
(5 ppm NO, 2 ppm NO_2)***	(1.04)**	(1.82)	(0.86)	(2.81)	(1.82)	(1.77)
Gas Water Heater	9.02	110.13	16.23	3.35	110.13	11.04
(60 ppm NO, 5 ppm NO_2)	(0.60)	(3.67)	(0.71)	(0.65)	(3.67)	(0.78)
Diesel Generator–High RPM	64.91	77.85	13.91	74.82	90.56	16.40
(95 ppm NO, 50 ppm NO_2)	(1.25)	(0.54)	(0.68)	(1.18)	(1.91)	(0.40)
Diesel Generator–Idle (280 ppm NO, 115 ppm NO_2)	Not calculated—see text					

* Relative accuracy calculated using equation 7.
** Standard error of relative accuracy value, estimated using equation 8.
*** Approximate NO and NO2 levels from each source; see Tables 6-16a through d.

This behavior is believed to be related to the sampling probes used with the Enerac analyzers. Specifically, each analyzer had a fritted metal filter on the tip of its probe, and those filters were made of Hastelloy®, an alloy that contains about 6 percent molybdenum. Molybdenum is known to reduce NO_2 to NO, and, in fact, is used for that purpose in commercial chemiluminescent NO_x monitors. At the temperature of the diesel exhaust under high RPM conditions (400°C, 752°F, or more based on previous measurements), it is believed that the Enerac fritted filters reduced most of the NO_2 present to NO, artificially lowering the former while raising the latter. Additional NO_2 reduction may have come from reaction of NO_2 with carbon, trapped as soot in the fritted filter. This hypothesis accounts for the poor but offsetting accuracies seen for NO and NO_2, and the good accuracy seen for NO_x, in the high RPM diesel test (Tables 6-16c and 6-17). This hypothesis has been confirmed by Enerac staff in laboratory tests conducted with the fritted filters after the verification testing. It should be noted that stainless steel filters are also available for the Enerac probes, and are expected to be less subject to NO_2 reduction at the temperatures encountered. Also, it is unclear whether this reduction of NO_2 played a role in the failure of the Enerac analyzers to detect NO_2 from the two gas sources (see above).

In verification testing with the diesel at idle, exhaust gas temperatures were much lower, and no error from NO_2 reduction would be expected. This appears to be the case, as Table 6-16d indicates that both NO and NO_2 readings from the Enerac analyzers were higher than those from the reference analyzers. The reason for the consistently higher NO and NO_2 readings from the Enerac units in the diesel idle test is not entirely known. The NO and NO_x levels determined by the reference analyzers in this test were within the range of those in previous tests with this engine, as were those determined by the Enerac analyzers. Thus, there is no obvious reason to distrust either the reference or Enerac results. Furthermore, as will be shown in the next section, the Enerac analyzers gave good performance in analysis of the zero and span gases during source testing. However, several lines of argument raise concern about the reference measurements in the diesel idle test.

One line of argument is that the discrepancy between Enerac and reference results was very nearly the same (i.e., 20 to 25 percent) for both NO and NO_2, with both Enerac Units A and B. This discrepancy also persisted throughout the one-hour continuous sampling of diesel emissions (Section 6.2.3) that followed the nine-point accuracy test in Table 6-16d. These observations are suggestive of, and would be consistent with, the presence of a leak in the inlet line to the reference analyzers during the diesel idle testing, resulting in dilution of the sample with room air. Unfortunately, oxygen measurements (which could have indicated the presence of a leak) were not made in the verification test. Thus, direct confirmation of a leak during the diesel idle test does not exist. However, indirect evidence does suggest that the quality of the reference analyzer data was affected during the diesel idle test. One form of such evidence is the unit-to-unit agreement between the two Enerac analyzers, and between the two reference analyzers, in the source testing. For example, the average NO or NO_x values determined by Enerac Units A and B on the gas rangetop, gas water heater, and diesel engine at high RPM agreed within 5.45, 6.19, and 2.89 percent, respectively. The corresponding agreement between the two reference analyzers for NO_x was 6.09, 6.23, and 2.14 percent, respectively (i.e., very similar to the results from the Enerac analyzers). In contrast, in the 9-point diesel idle test, (Table 6-16d) the Enerac analyzers agreed within 0.44 percent, and the reference analyzers only within 3.65 percent. During the subsequent one-hour continuous test, the corresponding unit-to-unit agreement was 1.98 percent for the Enerac analyzers and 4.67 percent for the reference analyzers. Similarly, the correlation of data from the two reference analyzers was lower than was the case in other tests with the same diesel source. For example, in testing of three other vendors' analyzers for an hour continuously on the diesel source at idle, the reference analyzers showed inter-unit correlation coefficients of 0.98 to 0.99 for NO, and 0.89 to 0.94 for NO_x. In contrast, in testing of the Enerac analyzers on that source (Table 6-20) the reference NO and NO_x correlation coefficients were only 0.82 and 0.85, respectively. The data are not wholly conclusive; for example, inter-unit correlation of the two reference analyzers in the 9-point diesel idle test (Table 6-16d) was actually better for NO, NO_2, and especially NO_x than the corresponding inter-unit correlations from the Enerac analyzers. However, the data do suggest that the reference analyzer data in the diesel idle test were not of the same quality as in the other tests and, for this reason, no relative accuracy results are shown for this test in Table 6-17.

The unit-to-unit precision of the Enerac 3000E analyzers was very good and, in some cases, was better than that of the reference analyzers. The Enerac unit-to-unit precision for NO from the gas range and water heater was 5.45 percent and 6.19 percent, respectively (the Enerac analyzers failed to detect NO_2 from those sources). The Enerac unit-to-unit precision for NO_x from the diesel source at high RPM and at idle was 2.89 percent and 0.44 percent, respectively. These values compare favorably to the corresponding unit-to-unit precision values of the reference analyzers for NO_x of 6.09, 6.23, 2.14, and 3.65 percent, respectively. These results indicate a high degree of consistency in the behavior of the Enerac analyzers in source measurements. It should also be noted that this behavior was achieved with NO, NO_2, and NO_x emission levels in the low end of the Enerac 3000E's measurement range.

6.2.2 Zero and Span Drift

Table 6-18 shows the data from the combustion source tests used to evaluate zero and span drift of the Enerac 3000E analyzers. Note that any NO zero readings below 3 ppm were forced to zero by the operating mode of the Enerac analyzers.

Table 6-18. Data Used to Assess Zero and Span Drift for Enerac 3000E Analyzers on Combustion Sources

Source		Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
Gas Rangetop*	Pre-Test Zero	0	0	0	0
	Pre-Test Span	20	9	20	8
	Post-Test Zero	0	0	0	0
	Post-Test Span	19	9	18	8
Gas Water Heater**	Pre-Test Zero	0	0	0	0
	Pre-Test Span	103	14	102	13
	Post-Test Zero	0	0	0	0
	Post-Test Span	109	13	107	12
Diesel–High RPM***	Pre-Test Zero	0	0	0	0
	Pre-Test Span	199	49	199	49
	Post-Test Zero	0	0	3	0
	Post-Test Span	204	49	204	49
Diesel–Idle****	Pre-Test Zero	0	0	0	0
	Pre-Test Span	405	104	404	106
	Post-Test Zero	3	0	6	0
	Post-Test Span	402	97	400	101

*Span values 20 ppm NO and 10 ppm NO_2.
**Span values 100 ppm NO and 15 ppm NO_2.
***Span values 200 ppm NO and 50 ppm NO_2.
****Span values 400 ppm NO and 100 ppm NO_2.

Table 6-19 summarizes the zero and span drift observed over each combustion test, in terms of the pre-test minus post-test differences in zero and span responses. Zero drift for NO_2 was zero in all combustion tests with both Enerac units. Zero drift for NO was zero on the gas combustion sources, but increased to as much as 6 ppm on Unit B with the diesel at idle. Small zero drifts may be somewhat obscured for NO because of the operating mode, which forces readings below 3 ppm to be reported as zero.

Table 6-19. Results of Zero and Span Drift Evaluation for Enerac 3000E Analyzers

		Unit A		Unit B	
Pre-Test—Post-Test		**NO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**NO_2 (ppm)**
Gas Rangetop	Zero	0	0	0	0
	Span	1	0	2	0
Gas Water Heater	Zero	0	0	0	0
	Span	-6	1	-5	1
Diesel Generator–High RPM	Zero	0	0	-3	0
	Span	-5	0	-5	0
Diesel Generator–Idle	Zero	-3	0	-6	0
	Span	3	7	4	5

Span drift for NO_2 with both analyzers was within 1 ppm on all sources except the diesel at idle. The 1 ppm span drift on the water heater amounts to 6.7 percent of the 15 ppm NO_2 span concentration. The NO_2 span drifts in the diesel idle test are 5 and 7 percent of the 100 ppm NO_2 span. For NO, the span drift values in Table 6-19 are equivalent to 5 to 10 percent of the NO span value in the gas rangetop test, 5 to 6 percent of the NO span in the water heater test, 2.5 percent of span in the diesel high RPM test, and 1 percent or less of the NO span in the diesel idle test.

6.2.3 Measurement Stability

Table 6-20 shows the data obtained in the extended sampling test, in which the Enerac 3000E and reference analyzers sampled diesel emissions at engine idle for a full hour without interruption or sampling of ambient air. The Enerac data were compared to the average of the reference analyzer data to assess whether a different trend in the emission data was observed for the Enerac analyzers relative to the reference analyzers. Table 6-21 shows the results of this evaluation, in terms of the slopes and standard errors of the NO, NO_2, and NO_x data with time. Also shown in Table 6-21 is an indication of whether the slopes indicated by the Enerac analyzers differed from those observed by the reference analyzers.

Table 6-20. Data from Extended Sampling Test with Diesel Generator at Idle, Using Enerac 3000E Analyzers

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit A NO_x (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)	Unit B NO_x (ppm)	14A NO (ppm)	14A NO_2 (ppm)	14A NO_x (ppm)	10 NO (ppm)	10 NO_2 (ppm)	10 NO_x (ppm)
1	336	144	480	346	141	487	286.3	122.5	408.8	279.6	112.7	392.3
2	335	144	479	346	142	488	285.5	123.4	409.0	279.6	111.7	391.3
3	333	145	478	343	143	486	285.8	123.1	408.9	279.6	111.7	391.3
4	335	145	480	344	143	487	281.7	125.7	407.4	277.7	112.7	390.5
5	335	145	480	348	143	491	287.0	124.0	410.9	280.5	112.7	393.3
6	333	146	479	343	143	486	284.3	127.1	411.4	277.7	115.8	393.6
7	329	145	474	338	143	481	279.8	124.5	404.4	274.0	113.8	387.8
8	333	145	478	343	143	486	285.1	122.8	407.9	279.6	109.6	389.2
9	329	145	474	340	143	483	282.6	124.6	407.2	275.9	110.7	386.5
10	326	146	472	335	144	479	277.3	124.1	401.3	272.1	111.7	383.8
11	324	146	470	335	144	479	281.8	123.5	405.3	274.0	110.6	384.7
12	326	146	472	336	145	481	280.4	121.8	402.2	274.9	110.6	385.6
13	325	145	470	335	145	480	277.0	121.9	398.9	270.3	112.7	383.0
14	322	145	467	333	144	477	279.0	120.0	398.9	271.2	111.7	382.9
15	326	146	472	338	145	483	277.9	120.8	398.8	274.0	110.6	384.7
16	327	146	473	338	145	483	280.1	119.9	400.0	274.0	110.6	384.7
17	328	146	474	340	145	485	280.9	123.3	404.2	275.9	111.7	387.6
18	329	146	475	341	145	486	281.1	124.9	406.0	274.0	111.7	385.7
19	329	146	475	338	146	484	279.9	123.9	403.8	274.9	111.7	386.6
20	332	147	479	341	146	487	282.1	123.0	405.1	274.9	112.7	387.7
21	329	146	475	341	145	486	283.5	122.5	406.0	275.9	112.7	388.6
22	333	146	479	341	145	486	284.5	122.4	406.9	275.9	114.8	390.7
23	329	146	475	340	145	485	281.1	124.1	405.3	274.9	114.8	389.7
24	326	146	472	336	145	481	279.6	125.9	405.5	273.1	115.8	388.9
25	325	146	471	336	145	481	278.3	124.2	402.5	271.2	114.8	386.0
26	326	147	473	338	145	483	278.9	119.0	397.9	272.1	114.8	386.9
27	327	147	474	338	145	483	279.9	118.4	398.3	272.1	112.7	384.9
28	328	146	474	336	145	481	281.6	123.6	405.2	274.0	113.8	387.8
29	329	146	475	340	145	485	282.1	123.8	405.9	274.0	113.8	387.8
30	332	147	479	343	145	488	282.7	124.5	407.2	274.9	112.7	387.7

Table 6-20. Data from Extended Sampling Test with Diesel Generator at Idle, Using Enerac 3000E Analyzers (continued)

	Enerac Analyzer Data						Reference Analyzer Data					
	Unit A NO (ppm)	Unit A NO$_2$ (ppm)	Unit A NO$_x$ (ppm)	Unit B NO (ppm)	Unit B NO$_2$ (ppm)	Unit B NO$_x$ (ppm)	14A NO (ppm)	14A NO$_2$ (ppm)	14A NO$_x$ (ppm)	10 NO (ppm)	10 NO$_2$ (ppm)	10 NO$_x$ (ppm)
31	334	147	481	343	145	488	283.6	127.9	411.5	274.9	117.9	392.9
32	330	146	476	341	145	486	281.7	126.8	408.5	274.9	116.9	391.8
33	333	146	479	343	145	488	283.0	126.4	409.4	274.0	116.9	390.9
34	334	147	481	346	146	492	284.5	123.5	408.0	274.9	115.8	390.8
35	335	149	484	346	147	493	288.0	125.0	413.0	278.7	115.8	394.5
36	338	149	487	348	147	495	290.2	123.5	413.7	279.6	114.8	394.4
37	337	148	485	348	147	495	289.0	127.1	416.2	280.5	115.9	396.4
38	333	148	481	346	147	493	288.3	125.8	414.1	277.7	116.9	394.6
39	335	148	483	346	148	494	286.9	126.3	413.2	277.7	115.8	393.6
40	334	149	483	343	147	490	289.3	124.6	413.9	277.7	116.9	394.6
41	333	149	482	346	147	493	287.9	126.2	414.1	276.8	116.9	393.7
42	333	148	481	343	147	490	284.0	129.7	413.7	275.9	116.9	392.8
43	332	149	481	343	148	491	282.4	130.5	412.8	276.8	115.8	392.7
44	332	149	481	343	148	491	283.6	127.9	411.5	275.9	115.8	391.7
45	331	149	480	341	148	489	288.9	123.9	412.8	276.8	115.8	392.7
46	329	148	477	338	147	485	282.4	129.4	411.7	274.9	114.8	389.7
47	324	147	471	336	147	483	279.8	129.0	408.8	273.1	114.8	387.9
48	329	147	476	340	147	487	279.8	129.0	408.8	271.2	116.9	388.1
49	326	148	474	336	147	483	282.0	127.6	409.6	272.1	116.9	389.0
50	325	148	473	336	147	483	282.8	126.6	409.4	272.1	116.9	389.0
51	324	147	471	335	147	482	280.8	126.8	407.5	271.2	115.8	387.0
52	326	147	473	336	147	483	281.8	125.6	407.4	271.2	115.8	387.0
53	324	147	471	335	147	482	279.6	127.0	406.6	271.2	114.8	386.0
54	324	147	471	336	147	483	278.9	127.9	406.8	269.3	115.8	385.2
55	326	147	473	338	146	484	279.5	129.3	408.9	271.2	115.8	387.0
56	327	147	474	338	146	484	282.6	127.9	410.6	272.1	117.9	390.1
57	324	146	470	333	145	478	278.5	129.4	407.9	270.3	116.9	387.2
58	322	145	467	332	145	477	279.2	126.3	405.5	269.3	114.8	384.1
59	324	145	469	336	145	481	280.0	127.7	407.7	270.3	114.8	385.1
60	326	146	472	335	145	480	279.8	129.0	408.8	270.3	115.8	386.1

Table 6-21 indicates that both the Enerac analyzers and the reference analyzers showed a gradual decrease in NO and an increase in NO_2 during the 1-hour sampling period. For NO, there was no difference statistically between the trend shown by the two Enerac analyzers and that shown by the reference analyzers. However, for NO_2, both Enerac analyzers showed a lower rate of increase (i.e., a smaller positive slope) than did the reference analyzers, and the small differences were statistically significant. As a result, a statistically significant difference was also found in the slopes for NO_x. Overall, the reference analyzers showed a slight increase in NO_x emissions from the diesel engine during the extended sampling, whereas the Enerac analyzers showed a slight decrease or essentially no change. However, though statistically significant differences are shown in Table 6-21, their practical significance is negligible. For example, the reference analyzers indicate an upward trend in NO_x of 0.052 ppm/min, or 3.1 ppm per hour, whereas the two Enerac analyzers indicate NO_x trends of -0.029 ppm/min (-1.7 ppm/hr) and 0.003 ppm/min (0.2 ppm/hr) respectively. Considering that the diesel engine emitted approximately 400 ppm of NO_x, these slight differences in slope are negligible, amounting to a difference of less than 5 ppm, or about 1 percent of the source output, over 1 hour of sampling.

Table 6-21. Results of Evaluation of Measurement Stability for Enerac 3000E Analyzer

	Unit A			**Unit B**			**Reference Units**		
	NO	**NO_2**	**NO_x**	**NO**	**NO_2**	**NO_x**	**NO**	**NO_2**	**NO_x**
Slope	-0.073	0.044	-0.029	-0.066	0.069	0.003	-0.047	0.099	0.052
(Std Err)	(0.030)	(0.008)	(0.035)	(0.031)	(0.008)	(0.034)	(0.022)	(0.011)	(0.027)
Difference in Slopes (ppm/min)	-0.026	-0.056	-0.081	-0.019	-0.030	-0.049	—	—	—
(Std Err)	(0.015)	(0.013) *	(0.017) *	(0.015)	(0.014) *	(0.019) *			

* Statistically significant difference in slope among test unit and the averages of the reference units at the 5 percent significance level.

6.2.4 *Inter-Unit Repeatability*

The repeatability of test results between the two Enerac analyzers was assessed in those cases where the data lent themselves to application of a t-test. The resulting t-statistics and associated p-values are listed in Table 6-22. Highlighted in bold are those p-values less than 0.05, which indicate a statistically significant difference between the two Enerac 3000E units at the 95 percent confidence level. As Table 6-22 shows, statistically significant differences between Units A and B were found in the regression intercept, detection limits, relative accuracy, and measurement stability, primarily for NO and NO_x. The differences found indicate the variability that may be expected from one analyzer to the next. However, although some statistically significant differences were found between the two analyzers, the practical importance of those differences is negligible. Overall, the test results do not show any significant difference in performance between Enerac Units A and B.

Table 6-22. Summary of Repeatability

Unit A vs. Unit B			NO	NO_2	NO_x
Linear Regression (Test 1)	Intercept	t-statistic	1.529	0.363	---
		p-value*	0.157	0.724	---
	Slope	t-statistic	-1.926	-0.018	---
		p-value	0.083	0.986	---
Linear Regression (Test 2)	Intercept	t-statistic	-2.674	---	---
		p-value*	**0.023**	---	---
	Slope	t-statistic	2.032	---	---
		p-value	0.070	---	---
Linear Regression (Test 3)	Intercept	t-statistic	0.652	---	---
		p-value*	0.529	---	---
	Slope	t-statistic	-1.105	---	---
		p-value	0.295	---	---
Detection Limit (a)		t-statistic	-3.162	0.001	---
		p-value	**0.004**	1.000	---
Detection Limit (b)		t-statistic	2.659	---	---
		p-value	**0.013**	---	---
Detection Limit (c)		t-statistic	***	---	---
		p-value	***	---	---
Relative Accuracy	Gas Rangetop	t-statistic	2.000	***	2.000
		p-value	0.081	---	0.081
	Gas Water Heater	t-statistic	20.239	***	20.239
		p-value	**<0.001**	---	**<0.001**
	Generator-High ppm	t-statistic	6.526	4.793	5.231
		p-value	**<0.001**	**0.001**	**<0.001**
	Generator-Idle	t-statistic	15.751	6.425	1.603
		p-value	**<0.001**	**<0.001**	0.148
Measurement Stability	Slope	t-statistic	-0.783	-5.478	-3.142
		p-value	0.437	**<0.001**	**0.003**

* p-value < 0.05 indicates that two test units are statistically different at the 5% significance level.

** Unit A and Unit B had all responses of 0 ppm at c=0. The estimated standard deviations were 0. The two-sample t-statistic could not be calculated.

*** Unit A and Unit B had exactly the same NO_2 readings on the gas burner and water heater emissions. The matched-pairs t-statistic could not be calculated.

6.3 Other Factors

In addition to the performance characteristics evaluated in the laboratory and source tests, three additional factors were recorded: analyzer cost, data completeness, and maintenance/operational factors.

6.3.1 Cost

The cost of each Enerac 3000E analyzer as used in this verification was about $12,000. This is for the complete analyzer, including sampling probe and lines, and with the capability for multiple measurement ranges.

6.3.2 Data Completeness

The data completeness in the verification tests was 100 percent for both units of the Enerac 3000E.

6.3.3 Maintenance/Operational Factors

The duration of the verification tests was not sufficient to determine the long-term reliability or maintenance costs of the Enerac analyzers. No maintenance problems or delays resulted at any time, and switching control modules to change the NO range was a simple and rapid operation. The operational mode of the analyzers in most of the verification tests, in which NO readings below 3 ppm were forced to zero, will not be appropriate in applications where very low NO readings are of interest.

It was found that the Hastelloy® fritted inlet filters reduced NO_2 to NO when sample gas temperatures were high enough (i.e., a few hundred degrees centigrade). The stainless steel fritted filters should be used instead, whenever possible. Although the Hastelloy® filters do not appear to affect the total NO_x content of the sample, they can radically alter the proportions of NO and NO_2 in the sample.

Chapter 7
Performance Summary

The two Enerac 3000E analyzers provided linear response for NO over their full operating ranges, including the basic 0 to 1,000 ppm range, and extended (0 to 3,000 ppm) and reduced (0 to 300 ppm) ranges. For NO_2, response was linear over a tested range of 0 to 400 ppm. The detection limit for NO_2 was about 6 ppm on both analyzers. Determination of detection limits for NO was complicated by an operational mode of the analyzers that forced readings below 3 ppm to be reported as zero. In different linearity tests, NO detection limits of 4.9 ppm and 1.2 ppm were found for Unit B, and a detection limit of about 8 ppm was found for Unit A. The response times of both analyzers for NO were about 60 seconds, and for NO_2 were about 100 seconds.

Drift in zero readings was usually 4 ppm or less over the course of a variety of laboratory and combustion source tests, on both the NO and NO_2 sensors of both analyzers. The only exceptions were zero drift values of 7 ppm and 12 ppm for NO, as a result of an NO linearity test up to 3,000 ppm. Within a single day, span drift was less than 2 percent of the span concentration for NO, using span concentrations of 700 to 1,000 ppm NO. Similarly, span drift for NO_2 was less than 2 percent of the span concentration, using span concentrations of 350 to 400 ppm. Shutting the analyzers off overnight did not increase either zero or span drift. No interference was found from any of the following: 496 ppm CO, 5.03 percent CO_2, 494 ppm NH_3, 590 ppm of total hydrocarbons, and 501 ppm SO_2. When sampling a mixture of 451 ppm SO_2 and 385 ppm NO, the NO sensors of the Enerac analyzers indicated 426 ppm and 422 ppm, respectively, suggesting a positive interference from the SO_2 equivalent to 8 to 9 percent of the SO_2 concentration.

Over the range of –10 to +10 inches of water (relative to the ambient pressure), the sample gas pressure had no significant effect on the zero or span readings of the analyzers. Ambient temperature over the range of 45 to 105°F (7 to 41°C) also had no consistent effect on the zero or span readings.

Relative accuracy of the Enerac analyzers differed in tests on three combustion sources. On two gas combustion sources having NO_2 emissions of 2 to 7 ppm, the Enerac analyzers detected no NO_2. Relative accuracy for NO on those sources (at NO levels of 5 to 60 ppm) ranged from 3 to 27 percent. On a diesel source at high RPM, the Enerac analyzers read high on NO and low by an equal amount on NO_2, apparently because of metal filters on the analyzers' sampling probes, which reduced NO_2 to NO. Relative accuracy values for NO and NO_2 with that source were 65 to 90 percent, but relative accuracy for NO_x was about 14 and 16 percent on the two analyzers, respectively. In sampling of a diesel source at idle, the Enerac analyzers performed well, but uncertainty about the quality of the reference data prevented calculation of relative accuracy.

Overall, the relative accuracy found for NO_x measurements with the two analyzers ranged from 11 to about 20 percent for all sources.

The two Enerac analyzers provided essentially identical performance in all aspects of the verification test. The unit-to-unit precision of the two Enerac analyzers ranged from 0.4 to 6.2 percent on the four combustion sources and, in some cases, was better than that of the reference analyzers.

Chapter 8
References

1. *Test/QA Plan for Verification of Portable NO/NO_2 Emission Analyzers*, Battelle, Columbus, Ohio, December 1998.

2. *U.S. EPA Method 7E, Determination of Nitrogen Oxides Emissions from Stationary Sources (Instrumental Analyzer Procedure)* Code of Federal Regulations, 40 CFR, Ch. 1, Part 60, Appendix A (1991).

3. *Traceability Protocol for Establishing True Concentrations of Gases Used for Calibrations and Audits of Continuous Source Emission Monitors: Protocol Number 1*, Research Triangle Park, NC: U.S. Environmental Protection Agency, Quality Assurance Division, June 1978.

4. *Interlaboratory Program to Validate a Protocol for the Measurement of NO_2 Emissions from Rangetop Burners,* GRI-94/0458, Gas Research Institute, Chicago, Illinois, December 1994.

5. *Interlaboratory Study to Determine the Precision of an Emission Measurement Protocol for Residential Gas Water Heaters,* GRI-96-0021, Gas Research Institute, Chicago, Illinois, March 1996.

6. American National Standard (ANSI Z21.1) "Household Cooking Gas Appliances," American National Standards Institute, 24th Edition, American Gas Association, 1990.

7. *Quality Management Plan (QMP) for the ETV Advanced Monitoring Systems Pilot*, U.S. EPA Environmental Technology Verification Program, Battelle, Columbus, Ohio, September 1998.

8. *Portable NO_x Analyzer Evaluation for Alternative Nitrogen Oxide Emission Rate Determination at Process Units*, Source Testing and Engineering Branch, South Coast Air Quality Management District, Los Angeles, CA, September 21, 1994.

9. *U.S. EPA Method 5, Determination of Particulate Emissions from Stationary Sources*, Code of Federal Regulations, 40 CFR, Ch. 1, Part 60, Appendix A (1991).

Appendix A
Data Recording Sheets

Linearity Test Data Sheet

Date: Vendor/Analyzer:

Form Filled Out By:

Pre-Test Z/Span: Unit A: Zero (NO/NO$_2$) / Span (NO/NO$_2$) /

Unit B: Zero (NO/NO$_2$) / Span (NO/NO$_2$) /

		NO Test			NO$_2$ Test	
		Unit A (NO/NO$_2$)	Unit B (NO/NO$_2$)		Unit A (NO/NO$_2$)	Unit B (NO/NO$_2$)
	1.	/	/	1.	/	/
	2.	/	/	2.	/	/
	3.	/	/	3.	/	/
	4.	/	/	4.	/	/
	5.	/	/	5.	/	/
Time Response	6.	/	/	6.	/	/
	7.	/	/	7.	/	/
	8.	/	/	8.	/	/
	9.	/	/	9.	/	/
	10.	/	/	10.	/	/
	11.	/	/	11.	/	/
	12.	/	/	12.	/	/
	13.	/	/	13.	/	/
	14.	/	/	14.	/	/
	15.	/	/	15.	/	/
	16.	/	/	16.	/	/
	17.	/	/	17.	/	/
	18.	/	/	18.	/	/
	19.	/	/	19.	/	/
	20.	/	/	20.	/	/
	21.	/	/	21.	/	/

Post-Test Z/Span: Unit A: Zero (NO/NO$_2$) / Span (NO/NO$_2$) /

Unit B: Zero (NO/NO$_2$) / Span (NO/NO$_2$) /

Interrupted Sampling Data Sheet

Date: ____________________ Vendor/Analyzer: ___________________________

Form Filled Out By: ____

Pre-Shut Down Z/Span:
Date: ___________________________ Time: ___________________________

Unit A (NO/NO_2) Zero ____/____ Span ______/_______

Unit B (NO/NO_2) Zero ____/____ Span ______/_______

Post-Shut Down Z/Span:
Date: ___________________________ Time: ___________________________

Unit A (NO/NO_2) Zero ____/____ Span ______/_______

Unit B (NO/NO_2) Zero ____/____ Span ______/_______

Interference Test Data Sheet

Date: ____________ Vendor/Analyzer: ________________

Form Filled Out By: ______________________________

Interference Gas	Concentration	Response (NO/NO_2) Unit A	Response (NO/NO_2) Unit B
Zero	--	__/__	__/__
CO	496 ppm	__/__	__/__
Zero	--	__/__	__/__
CO_2	5.03%	__/__	__/__
Zero	--	__/__	__/__
NH_3	494 ppm	__/__	__/__
Zero	--	__/__	__/__
Hydrocarbons	590 ppm	__/__	__/__
Zero	--	__/__	__/__
SO_2	501 ppm	__/__	__/__
Zero	--	__/__	__/__
SO_2 + NO	451 ppm + 393 ppm	__/__	__/__

Flow Rate Sensitivity Data Sheet

Date: ____________ Vendor/Analyzer: ________________

Form Filled Out By: ________________________________

Flow Rate Data:

	Unit A (ccm)	Unit B (ccm)
Ambient P	____	____
+10 in H_2O	____	____
-10 in H_2O	____	____

Response Data:

		Unit A (NO/NO_2)	Unit B (NO/NO_2)
Ambient P	Zero	/	/
	NO Span	/	/
	Zero	/	/
	NO_2 Span	/	/
	Zero	/	/
+10 in H_2O	Zero	/	/
	NO Span	/	/
	Zero	/	/
	NO_2 Span	/	/
	Zero	/	/
-10 in H_2O	Zero	/	/
	NO Span	/	/
	Zero	/	/
	NO_2 Span	/	/
	Zero	/	/

Ambient Temperature Test Data Sheet

Date: ____________________ Vendor/Analyzer: ___________________________

Form Filled Out By: ____

	Response (NO/NO$_2$)	
	Unit A	Unit B
Room Temperature: _____________		
Zero	/	/
NO Span	/	/
NO$_2$ Span	/	/
Zero	/	/
Cold Chamber Temperature: _____________		
Zero	/	/
NO Span	/	/
NO$_2$ Span	/	/
Zero	/	/
Heated Chamber Temperature: _____________		
Zero	/	/
NO Span	/	/
NO$_2$ Span	/	/
Zero	/	/
Room Temperature: _____________		
Zero	/	/
NO Span	/	/
NO$_2$ Span	/	/
Zero	/	/

Accuracy Test Data Sheet: Rangetop Combustion

Date____________________ Vendor Analyzer: _________________________

Form Filled Out By:____

Pre-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit 14A: Zero ($NO/NO_2/NOx$) ____/____/_____ Span ($NO/NO_2/NOx$) ____/____/_____

Unit 10: Zero ($NO/NO_2/NOx$) ____/____/_____ Span ($NO/NO_2/NOx$) ____/____/_____

	Unit 14A ($NO/NO_2/NOx$)	Unit 10 ($NO/NO_2/NOx$)
1.	____/____/____	____/____/____
2.	____/____/____	____/____/____
3.	____/____/____	____/____/____
4.	____/____/____	____/____/____
5.	____/____/____	____/____/____
6.	____/____/____	____/____/____
7.	____/____/____	____/____/____
8.	____/____/____	____/____/____
9.	____/____/____	____/____/____

Post-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit 14A: Zero ($NO/NO_2/NOx$) ____/____/_____ Span ($NO/NO_2/NOx$) ____/____/_____

Unit 10: Zero ($NO/NO_2/NOx$) ____/____/_____ Span ($NO/NO_2/NOx$) ____/____/_____

Accuracy Test Data Sheet: Water Heater Combustion

Date____________________ Vendor Analyzer: _________________________

Form Filled Out By:____

Pre-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit A: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Unit B: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

	Unit A (NO/NO_2/NOx)	Unit B (NO/NO_2/NOx)
1.	____/____/____	____/____/____
2.	____/____/____	____/____/____
3.	____/____/____	____/____/____
4.	____/____/____	____/____/____
5.	____/____/____	____/____/____
6.	____/____/____	____/____/____
7.	____/____/____	____/____/____
8.	____/____/____	____/____/____
9.	____/____/____	____/____/____

Post-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit A: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Unit B: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Mod-1: 01/17/99

Accuracy Test Data Sheet: Diesel-Engine Combustion

Date____________________ Vendor Analyzer: ________________________

Form Filled Out By:____

Pre-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit 14A: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Unit 10: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

	Unit 14A (NO/NO_2/NOx)	Unit 10 (NO/NO_2/NOx)
1.	____/____/____	____/____/____
2.	____/____/____	____/____/____
3.	____/____/____	____/____/____
4.	____/____/____	____/____/____
5.	____/____/____	____/____/____
6.	____/____/____	____/____/____
7.	____/____/____	____/____/____
8.	____/____/____	____/____/____
9.	____/____/____	____/____/____

Post-Test Zero/Span

Calibration Gas & Concentration:____________ Instrument Range:____________

Calibration Gas & Concentration:____________ Instrument Range:____________

Unit 14A: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Unit 10: Zero (NO/NO_2/NOx) ____/____/_____ Span (NO/NO_2/NOx) ____/____/_____

Mo-1: 01/17/99

Measurement-Stability Test Data Sheet: Diesel-Engine Combustion

Date____________________ Vendor Analyzer: _________________________

Form Filled Out By:____

Diesel-Engine Load:_______________________

Time (t+min#)	Unit A (NO/NO_2/NOx)	Unit B (NO/NO_2/NOx)
1.	____/____/____	____/____/____
2.	____/____/____	____/____/____
3.	____/____/____	____/____/____
4.	____/____/____	____/____/____
5.	____/____/____	____/____/____
6.	____/____/____	____/____/____
7.	____/____/____	____/____/____
8.	____/____/____	____/____/____
9.	____/____/____	____/____/____
10.	____/____/____	____/____/____
11.	____/____/____	____/____/____
12.	____/____/____	____/____/____
13.	____/____/____	____/____/____
14.	____/____/____	____/____/____
15.	____/____/____	____/____/____
16.	____/____/____	____/____/____
17.	____/____/____	____/____/____
18.	____/____/____	____/____/____
19.	____/____/____	____/____/____
20.	____/____/____	____/____/____
21.	____/____/____	____/____/____
22	____/____/____	____/____/____
23.	____/____/____	____/____/____
24.	____/____/____	____/____/____
25.	____/____/____	____/____/____
26.	____/____/____	____/____/____
27.	____/____/____	____/____/____
28.	____/____/____	____/____/____
29.	____/____/____	____/____/____
30.	____/____/____	____/____/____

Measurement-Stability Test Data Sheet: Diesel-Engine Combustion

Date____________________ Vendor Analyzer: __________________________

Form Filled Out By:____

Diesel-Engine Load:______________________

Time (t + min#)	Unit A (NO/NO_2/NOx)	Unit B (NO/NO_2/NOx)
31.	____/____/____	____/____/____
32.	____/____/____	____/____/____
33.	____/____/____	____/____/____
34.	____/____/____	____/____/____
35.	____/____/____	____/____/____
36.	____/____/____	____/____/____
37.	____/____/____	____/____/____
38.	____/____/____	____/____/____
39.	____/____/____	____/____/____
40.	____/____/____	____/____/____
41.	____/____/____	____/____/____
42.	____/____/____	____/____/____
43.	____/____/____	____/____/____
44.	____/____/____	____/____/____
45.	____/____/____	____/____/____
46.	____/____/____	____/____/____
47.	____/____/____	____/____/____
48.	____/____/____	____/____/____
49.	____/____/____	____/____/____
50.	____/____/____	____/____/____
51.	____/____/____	____/____/____
52	____/____/____	____/____/____
53.	____/____/____	____/____/____
54.	____/____/____	____/____/____
55.	____/____/____	____/____/____
56.	____/____/____	____/____/____
57.	____/____/____	____/____/____
58.	____/____/____	____/____/____
59.	____/____/____	____/____/____
60.	____/____/____	____/____/____

Appendix B
External Technical Systems Audit Report

Environmental Technology Verification Program

Advanced Monitoring Systems Pilot

Air Monitoring Systems

NO/NO_2 Monitors Verification Test
January 20-21, 1999 Audit

Audit Report: ETVAMS001
Revision 1

Elizabeth A. Betz
Elizabeth A. Betz

Elizabeth T. Hunike
Elizabeth T. Hunike

1.0 Audit Information

1.1 Auditors:

Elizabeth A. Betz
Human Exposure & Atmospheric Sciences Division
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1.2 Dates of Audit: January 20-21, 1999

1.3 Location of Audit: Battelle Memorial Institute, Columbus, Ohio

1.4 Battelle Staff Interviewed and/or Observed:

Karen Riggs	ETV AMS Pilot Manager
Susan Abbgy	QA/QC Reviewer
Sandy Anderson	QA Manager
Verification Test Team:	
Tom Kelly	Verification Test Leader
Joe Tabor	Laboratory Verification Testing
Jim Reuther	Emission Source Verification Testing
Steve Speakman	Operator, Emission Sources/Reference Method

2.0 Background

Throughout its history, the U.S. EPA has evaluated technologies to determine their effectiveness in preventing, controlling, and cleaning up pollution. EPA has expanded these efforts by instituting the Environmental Technology Verification Program (ETV) to verify the performance of a larger number of innovative technical solutions to problems that threaten human health or the environment. The goal of ETV is to verify the environmental performance characteristics of commercial-ready technology through the evaluation of objective and quality assured data, so that potential purchasers and permitters are provided with an independent and credible assessment of what they are buying and permitting. The ETV Program Verification Strategy outlines the goals, operating principles, pilot selection criteria, and implementation activities. ETV includes twelve pilot projects. In these pilots, EPA is using the expertise of partner verification organizations to design efficient processes for conducting performance tests of innovative technologies. The implementation activities involve forming stakeholder groups who identify technologies needing verification, designing a generic verification protocol and then Test/QA

Plans for the specific technology to be verified. The verification tests are run on the identified technologies wishing to participate and verification statements based on the test results are generated.

One pilot, entitled Advanced Monitoring Systems (AMS), is to verify the performance of commercially available technologies used to monitor for environmental quality in air, water and soil. This pilot is managed by EPA's National Exposure Research Laboratory in Research Triangle Park, North Carolina and their verification partner for the AMS pilot project is Battelle Memorial Institute, Columbus, Ohio. This pilot has been divided into three sub-pilots, each looking at monitoring systems for a specific media, air, water and, eventually, soil. The Air AMS portion has evolved to the point of actually running verification tests on available air monitoring instrumentation.

3.0 Scope of Audit

3.1 Audit Preparation. The auditors reviewed the following documents pertinent to the ETV AMS Pilot:

a. *Environmental Technology Verification Program Quality and Management Plan for the Pilot Period (1995-2000), May 1998*
b. *Environmental Technology Verification Program Quality Management Plan for the ETV Advanced Monitoring Systems Pilot, September 1998*
c. *Test/QA Plan for Verification of Portable NO/NO_2 Emission Analyzers, December 4, 1998*
d. *U. S. EPA Method 6C, Determination of Sulfur Dioxide Emissions from Stationary Sources (Instrumental Analyzer Procedure)*
e. *U. S. EPA Method 7E, Determination of Nitrogen Oxides Emissions from Stationary Sources (Instrumental Analyzer Procedure)*

Based on the above material, a checklist was prepared. The U. S. EPA ETV AMS Pilot Manager, Robert G. Fuerst, was provided the checklist prior to the audit. The completed checklist for this audit is attached.

3.2 Audit Scope.

The audit encompassed a technical systems audit of a verification test (VT) on nitrogen oxides monitors at Battelle. A technical systems audit is a qualitative onsite audit of the physical setup of the test. The auditors determine the compliance of testing personnel with the test/QA plan. The auditors were on site from Wednesday afternoon through Thursday afternoon. The technical systems audit was performed on the flow rate and ambient temperature of the laboratory portion of the VT and the relative accuracy tests with the gas cooktop, water heater and a portion of the lower range emissions of a diesel generator. No performance evaluations were conducted as a part of this audit.

4.0 Executive Summary

4.1 The VT is well-managed, particularly considering its complexity. All personnel appeared to be well-trained for their particular duties. All involved showed enthusiasm and ingenuity during the VT.

4.2 The significant findings of this audit, cited in paragraph 5.0 below, had also been found by Battelle's QA staff during their audit earlier in the VT.

4.3 The technical systems audit showed that the VT personnel were very familiar with the Test/QA Plan. With one exception, differences for this VT from the original Test/QA Plan were well documented by deviation reports on file at Battelle. The deviation report format includes a date, cites the deviation, provides an explanation of the deviation and requires an approving Battelle signature. It was impressive that the deviation reports were present and were completed up front. The one difference from the VT that was not cited in a deviation report was that Battelle had intended to run an analyzer already on hand completely through the VT before the first vendor's analyzer. This was not done nor was a deviation report generated. The remaining differences were cited in the deviation reports.

5.0 Major Findings

5.1 Undocumented Deviation from the Test/QA Plan. The undocumented deviation was from section 5.6, Test Schedule, and stated "to avoid bias in testing of the first analyzers through the sequence, Battelle's personnel will first conduct the entire test sequence using an analyzer already on hand at Battelle. Testing will then continue with analyzers named in section 2.4." Due to a delay in the arrival of the protocol gases used in the VT, Battelle did not run one of their instruments through the test sequence. As a result a leak in the gas supply system in the laboratory test portion was not detected before the first vendor started the VT sequence.

5.2 Initial Calibration of Instruments for Emission Source Testing. The Test/QA Plan states that "the chemiluminescent monitors to be used for Method 7E reference measurements will be subjected to a 4-point calibration with NO prior to the start of verification testing, on each measurement range to be used for verification." The initial Emission's portion of the VT was started on January 13, 1999. There was no 4-point calibration with NO recorded in the Emission's VT laboratory notebook prior to the January 13th testing. This finding is also a finding in Battelle's Internal Audit conducted during the first week of the VT.

6.0 Results of Technical Systems Audit

6.1 Organization. The Battelle ETV AMS VT team consisted of four members. All team members were very knowledgeable of the procedures and helpful to the auditors. There are also two Battelle Quality Assurance staff members that are members of the ETV AMS team. Both were available and very helpful to the auditors. These Battelle QA staff members are responsible for running the internal audits required by the ETV related QMPs. One such audit was conducted the week prior to this EPA audit.

6.1.1 The Test/QA Plan stated that a Dr. Agnes Kovacs would be providing statistics and data analysis for this VT. One of the documented deviations was that Dr. Kovacs would not be participating in the VT as she has left Battelle. Although the deviation report stated that someone in the Statistics and Data Analysis Department would be taking her place, there was no indication in the deviation report as to who it would be.

6.2 Gas Cylinder Certifications. A review of the gas cylinder certifications uncovered some minor discrepancies. The expiration date on two of the cylinder certifications did not match the expiration date on the cylinders. The discrepancy was corrected by the gas manufacturer on the day of inspection. Battelle did not initially have certifications for the gas cylinders used in the source test. The gas manufacturer was contacted by phone and faxed in certifications for 3 of the 4 cylinders. The original certificates were later located on one of the team member's desk. The gas cylinder for one of the certificates reviewed was not found among the ETV VT equipment.

6.3 Temperature Sensor Certification. The certificate in the notebook maintained for the Laboratory Test Portion was for Model 402A, Serial # 40215 Temperature Indicator. This indicator was not seen by the Auditors. The Temperature Indicator used in the Laboratory Test portion to read the temperature of the monitors during the Ambient Test was Model 400A, decal # LN-560558. The certificate was not in the notebook, however, the indicator did have a label on it that stated that it was certified 1-7-99. Discussion with Susan Abbgy, after the audit, clarified that LN-560558 was an internal Battelle laboratory number and that the manufacturer's serial number on LN-560558 was 40215. However, the certificate did reflect an incorrect model number for Temperature Indicator Serial # 40215.

6.4 Deviation Reports. The dated reports cited the deviation, provided an explanation/justification of the deviation and required an approving Battelle signature. It was impressive that the deviations reports were present and were completed up front.

6.4.1 The Flow Rate Sensitivity Test procedure had three deviation reports. The Test/QA Plan called for the use of 60% span value during the test. A deviation report cited that this was changed to 70% span value to correlate to the Linearity Test. The two other reports related to the Flow Rate Sensitivity Test were very similar and called for a change in the order of the procedure to reduce the amount of plumbing changes required.

6.4.2 The Ambient Temperature Test had one deviation report. The order of the test was changed. The procedure called for doing a cooled chamber test first and then hot. The deviation report stated that all VTs will be done in the reverse order. The reason for the deviation was based on discussions with the vendors that indicated the rise in temperature after exposure to NO may cause more drift. The order was reversed to more clearly observe any drift.

6.4.2.1 During the Ambient Temperature Test observed, slight changes were made to accommodate the mass of the monitors. The vendor's monitors were larger than previous monitors and generated and held heat longer. The door to the heated chamber, once the monitors reached its temperature, had to remain slightly ajar to hold the chamber temperature at a constant value. The heated monitors were then placed in the cold chamber (a standard household refrigerator). The heat given off by the monitors raised the temperature in the refrigerator over 100°F. To obtain a cooled chamber reading the team members relocated the monitors to the outdoors which produced a cooled ambient temperature within the 45°F ±5°F for the one hour required for temperature equilibration and the additional time required to perform the zero and span check. This was a fine example of the ingenuity the VT team members showed to accommodate differences in monitors.

6.4.3 Interference Test. The mixture of SO_2 and NO for the Interference Test was changed from interferant levels of 250 ppm each of SO_2 and NO to interferant levels of 451 ppm SO_2 and 393 ppm NO. According to the deviation report, this change was made because the NO standard available wasn't at the anticipated concentration when the Test/QA Plan was written.

6.4.4 Source Testing.

6.4.4.1 The Test/QA Plan cited the use of two diesel generators for the Source Test. The selection of these generators was made based on studies that Battelle had used in the past that provided a database of emission levels generated by these sources. However, these generators were property of the Air Force and were unavailable at the time of the VT due to military activities in the Middle East. Battelle substituted one generator they had on site and collected emission data at two speeds to provide two higher emission levels than previously provided by the cooktop or water heater. This substituted generator produced two levels of emissions; however, neither level was over 500 ppm of NO. The database that Battelle had on the originally planned generators showed that one model would produce ranges between 100-1000 ppm NO_x and the second model would produce ranges between 600-2300 ppm NO_x. The impact of this change is that there will be no verification for higher ranges.

6.4.4.2 The oxygen sensor was not used during the source test. This VT's focus was the verification of NO/NO_2 levels and not to compare oxygen data. Source stability will be documented by NO_x measurements instead of oxygen measurements. The source stability for the water heater and the cooktop is also documented in two Battelle reports on data from these specific sources used in interlaboratory comparisons from 1994 through 1998. The initial generators planned for the VT also had similar data bases. The source stability of the generator actually used was verified by data collected in December and January prior to the VT. The actual data collected by the reference monitors during the VT also verified the source stability.

6.4.4.3 ThermoEnvironmental Models 14A and 10 NO/NO_2 analyzers were used for the reference method. The Test/QA Plan called for identical Beckman Model 955 monitors. The reason stated in the deviation report for the substitution was that the Thermo Instruments are newer and are in more current use.

6.4.4.4 Triplicate readings of calibration points were not run in the calibration of the reference method analyzers. Method 7E does not require triplicate readings of calibration points.

6.4.4.5 One deviation report addressed the use of unheated sample lines and poly tubing. The Test/QA Plan is based on EPA Method 7E but based on Battelle's own experience with the sources in the laboratory environment an unheated inlet was used. Additionally it should be noted that the VT is conducted inside in a laboratory setting with controlled temperature and humidity and Method 7E is for stack sampling. The only comment on this deviation report is that the originator of the deviation signed the report instead of obtaining an independent approval signature.

6.5 Leak Detected in the System in the Laboratory Test Portion. During the first vendors's laboratory test portion, a leak was detected in the system. The data sheets for the laboratory test portion of the first vendor's VT showed a note that a leak was detected and the vendor recorded oxygen levels. Also noted on the data sheet was a correction factor that would be used on the vendor's data that was made based on the vendor's oxygen readings. The correction factor notes were brought to the auditor's attention by Battelle's QA staff. Because the VT did no verification of oxygen levels, the correction factor may be inaccurate. As part of the documentation for that VT, the accuracy of the oxygen readings by the vendor needs to be addressed.

6.6 Initial Calibrations and Tests in the Source Laboratory. As stated under major findings, paragraph 5.2 above, the initial calibrations of the chemiluminescent monitors used as the Method 7E references were not done before the first VT. In addition no interference test was conducted prior to 1-18-99 which was after the second VT. However, all subsequent VTs had the required initial calibration and interference tests. This was also a finding in Battelle's internal audit conducted a week earlier. Battelle will need to address this in the VT report.

6.7 Corrections of Data Sheets. In most instances, corrections made on the data sheets followed Good Laboratory Practices; however, some did not (i.e., one line was not drawn through the incorrect entry and the correction was not dated and initialed).

6.8 Source Laboratory Notebook Entries. The initial entries were difficult to follow because the writing was almost illegible and there were missing entries. However, with the exception of the first VT, the four-point initial calibrations are recorded and the time and dates of the VTs are also shown. The actual source test data are recorded on data sheets. The notebook is only used to record the calibration and interference test data on the reference monitors and to record the times, dates and comments on the VTs.

Checklist for Verification Test (VT) of Portable NO/NO_2 Emission Analyzers

Date(s): January 20-21, 1999 **Location:** Battelle, Columbus, Ohio

Personnel Involved in the Audit:

	Titles	Names
EPA Auditor(s):		Elizabeth Betz
		Elizabeth Hunike
Battelle QA Rep present:	QA/QC Reviewer	Susan Abbgy
	QA Manager	Sandy Anderson
Battelle Auditees:	ETV AMS Pilot Manager	Karen Riggs
	Verification Test Leader	Tom Kelly
	Laboratory Verification Testing	Joe Tabor
	Emission Source Verification Testing	Jim Reuther
	Operator, Emission Sources/Reference Method	Steve Speakman
Vendor(s) Present:	Horiba	J. David Vojtko

General		Comments
Are the Testers familiar with:	ETV QMP	All staff seem familiar with the documents and there are copies of each in the ETV reference notebooks maintained in the Laboratory and Source Testing areas
	Verification Protocol	
	Test/QA Plan	
	QA Manager	
Generic Verification Protocol:	Finalized?	The Protocol has been finalized and is in the process of being placed on the web.
Test Plan:	Approved and Signed?	The test plan has been reviewed by the vendors. Approval signatures have been received as vendors have arrived to participate in the verification test

Technologies:

-Electrochemical (EC) sensors

Testo's Model 350 electrochemical NO and NO_2 analyzer
Also by direct measurement: O_2, CO, SO_2, Stack Temperature, Stack Pressure
By calculation: CO_2

Energy Efficiency System's ENERAC 3000SEM electrochemical NO & NO_2 analyzer
Also by direct measurement: O_2, CO, SO_2, CO_2, Stack Temperature

TSI's COMBUCHECK electrochemical NO or NO_2 analyzer

ECOM's A-Plus electrochemical NO and NO_2 analyzer
Also by direct measurement: O_2, CO, SO_2, Stack Temperature, Stack Pressure
By calculation: CO_2

-Chemiluminescence emitted from the reaction of NO with O_3 produced within the analyzer

Horiba's Model PG-250 portable gas analyzer
Also by direct measurement: O_2, CO, SO_2, CO_2

The audit was run during the second week of the Test Plan and the 4th vendor was being verified. The vendor was Horiba.

Pre-Test Requirements:

Dry Gas Meter: Initial Calibration Date: See Below

Accurate within 1% and measured in ft^3
Calibrated against a volumetric standard within 6 months preceding VT
During VT, checked at least once, against reference meter

In-Line Meter, Serial # 1036707, Rockwell R-275, certified 1/18/99
Reference Meter model DTM 115 certified 9/22/98

Temperature Sensor/Thermometers: Initial Calibration Date: See Below

Calibrated against a certified temp. measurement standard within 6 months preceding VT
During VT, checked at least once, against an ASTM mercury-in-glass reference thermometer at ambient temperature and be within 2%.

Temperature Indicator, Serial #40215, Model 402A, certified 1/7/99, certificate available but didn't locate this indicator. Temp indicator in Lab, LN-560558, Model 400A, certified 1/7/99.

Oxygen Monitor: Initial Calibration Date:________________

Calibrated within the last six months
During VT, checked once every test day by sampling of ambient air
During operation of one combustion source, assessed for accuracy

Did not use as cited in a documented deviation report.

Chemiluminescent Monitors to be used for Method 7E

Initial Interference Response conducted prior to VT Date: See Below
Measurement System Preparation prior to VT Date: See Below
Analyzer Calibration Error prior to VT Date: See Below
Sampling System Bias Check prior to VT Date: See Below
NO_2 to NO Conversion Efficiency Date: See Below

Calibrations Initial Calibration Date: See Below
4-point calibration with NO & NO_2 prior to VT, on each measurement range

For Horiba's VT both were run 1/20/99, however neither were done before first VT. Interference response was conducted prior to Horiba's VT but not prior to the first VT.

Each point shall be prepared in triplicate - cited in a documented deviation report

Calibration error requirement: <±2% of span for the zero, midrange and high-range calibration gases.

Zero and Span checks done daily AM and PM during the VT

Observed AM checks before source test, not present for PM.

Gas Dilution System Initial Calibration Date: 12/16/98
Flow measurement/control devices calibrated prior to VT by soap bubble flow meter.

Calibration Standards:
EPA Protocol 1 Gases (Calibration paperwork available):
NO in N_2, High Range: 80-100% of span
Mid-Range: 40-60% of span
Zero: Concentration $\leq$0.25 % of span, ambient air

Protocol Cylinder # ALM057210 expiration date on certificate and cylinder tag did not match.
Cylinder # ALM017108 expiration date on certificate and cylinder tag did not match.
Certificate available for Cylinder # ALM036273 but could not locate cylinder.
Certificates for Source Lab cylinders (AAL14789, ALM014050, AAL17452, ALM015489) could not be initially located.

Sample Location:
Minimum of 8 duct diameters downstream and 2 duct diameters upstream of flow disturbances and center point of the flue vent

The minimal distances from flow disturbances cited in the Reference Method relate to particulate and are not critical for gases and were not used. Vendor's instrument sampling tubes were placed beside those for the reference instruments.

Day One - Laboratory Tests:

Linearity: (response over the full measuring range) - Not Observed

21 measurements for each analyte (NO, NO_2 or NO_x)

Zero six times, each other three times

Calibration points used: 0, 10, 20, 40, 70 and 100% of the analyzer's measuring range

Horiba: 0-25, 0-50, 0-100, 0-250, 0-500, 0-1000, 0-2500

0, 250, 500, 1000, 1750 for 0-2500

Initial Zero and Span check?

After every three points, pure dilution gas provided and the analyzers' readings recorded?

Is the order of concentration points followed?

Final Zero and Span Check?

Linearity test was not observed; however, data sheets were examined. The 100% span used for the Horiba was 500 ppm. The laboratory log sheets verified that 21 measurements were made, the order of concentration points cited was used, and that initial and final Zero and Span checks were done.

Response Time Determinations - Not Observed

Analyzer's response recorded at 10 second intervals during Response Time check (estimated to be 30 readings)

Detection Limit - Not Observed

Detection limit is based on data from zero and 10% readings during Linearity test (9 readings)

Interrupted Sampling (four readings total) - Not Observed
Zero and Span recorded at end of Linearity Test on Day One

Day Two - Laboratory Tests

Interrupted Sampling continued - Not Observed
Zero and Span are recorded after analyzer has been powered up before any adjustments

Same Span from previous day is used

Interference Tests: - Not Observed

Actual concentrations were obtained from the data sheets. A documented deviation cited the change in the SO_2 and NO interferant concentrations.

Interferant	Interferant Concentration	Target Analyte
CO	500 ppm - Actual concentration used - 496 ppm	NO, NO_2, NO_x
CO_2	5% - Actual percentage used - 5.03%	NO, NO_2, NO_x
SO_2	500 ppm - Actual concentration used - 501 ppm	NO, NO_2, NO_x
NH_3	500 ppm - Actual concentration used - 494 ppm	NO, NO_2, NO_x
Hydrocarbon Mixture	~ 500 ppm C_1, ~ 100 ppm C_2, ~ 50 ppm C_3 and C_4 Hydrocarbon concentration used - 590 ppm	NO, NO_2, NO_x
SO_2 and NO	250 ppm each - Actual concentration used - 451 ppm SO_2 & 393 ppm NO	NO, NO_2, NO_x

Analyzer zeroed first and recorded
Interferant gas supplied, analyzer stabilized and analyte concentrations recorded (6 readings)

Flow Rate Sensitivity (9 readings) - Not Observed

Type of flow measuring device: automated bubble flowmeter, rotameter, or other
Ambient atmosphere and ambient flow rate recorded
Zero gas provided and recorded, span gas provided and recorded, zero provided again and recorded
Adjust pressure in system to +10" of water, record flow rate, repeat zero, span and zero
Adjust pressure in system to -10" of water, record, flow rate, repeat zero, span and zero

A leak was detected during the running of the flow rate test for the first vendor. The data sheets reflect this and also indicate a correction factor would be used in the calculations. The correction factor was based on the O_2 value recorded on the vendor’s monitors.

Ambient Temperature (12 readings)

Room Temperature recorded (assumed to be above 45°F and below 105°F)
Zero and Span and Zero done at each temperature
Instrument allowed to equilibrate to chamber temperature for 1 hour

The ambient temperature test was observed. Room temperature readings were done first. Then the monitors were placed in a heated chamber at 105°F at 13:24 and first readings were at 14:45. The chamber door had to remain slightly ajar to keep the temperature constant. Next the monitors were placed in the cooling chamber which was a household refrigerator. The heated monitors kept overheating the refrigerator. After the initial hour to equilibrate the monitors, the refrigerator temperature was at 110° F. To obtain the cooled ambient temperature needed for the test, the monitors were placed out the laboratory window onto the adjacent roof for an hour and were brought to 47°F. The cooling chamber test readings were taken from 6:38 pm to 6:43 pm.
This showed great ingenuity of the laboratory test staff to obtain the required ambient conditions for the test.

Day Three and Four - Source Tests

Method 7E

Measurement System Performance - Chemiluminescent Monitors
Thermo Environmental Instruments Model 10 and Model 14A. Data were recorded off a voltage meter attached to each instrument and voltage readings were then converted to concentrations. The Fluke voltage meter attached to Model 14A was calibrated 11/2/98 and the one attached to Model 10 was calibrated 11/3/98.

Zero Drift: ≤± 3% of the span over the period of each run
Calibration Drift: ≤± 3% of the span over the period of each run
Interference Check: ≤±7%

Measurement System Specifications:
A documented deviation cited changes to the sample probe and lines initially indicated to be allowed by EPA Method CTM-022 but later revised per July 16, 1999 letter from Battelle indicating the changed was based on Battelle's own experience with the sources used in the laboratory environment.

Sample Probe - Glass, stainless steel, or equivalent
Sample Line - Heated stainless steel or Teflon tubing
Sample Transport Lines - Stainless Steel or Teflon tubing
Calibration Valve Assembly - 3-way valve assembly or equivalent
Moisture Removal System - refrigerator-type condenser or similar device(?) - Ice Chest was used.
Particulate Filter - borosilicate or quartz glass wool or glass fiber mat, non-reactive with NO_x, in-stack or heated out-of-stack
Sample Pump - Leak free pump of any non-reactive material
Sample Flow Rate Control - control valve and rotameter or equivalent
Sample Gas Manifold - any non-reactive material
Data Recorder - strip chart recorder, analog computer or digital recorder; resolution shall be 0.5% of span

A data recorder was not used. The test data was recorded on log sheets, one filled out by the vendor on his monitors and one filled out by source laboratory operator for the reference monitors. Calibrations prior to VT are recorded in a bound notebook. Entries are also made to indicate the date and times the VTs in the source laboratory were run.

Sampling:
Measurements obtained only after twice the response time has elapsed
Zero and Calibration Drift tests performed immediately preceding and following every run
Adding zero gas & calibration gas (closely approximates the source) at calibration valve
Sampling continues only when zero and calibration drift are within specifications

Emission Calculations: - No calculations were observed
Concentrations are: avg readings (initial & final sampling system bias checks are averaged) adjusted for the zero and upscale sampling system bias checks

Relative Accuracy Tests

Low NO_x Sources

Gas Cooktop: NO and NO_2 ranges 1-9 ppm
Must operate continuously during test (can't cycle off)
Must operate at steady-state (See Page 8 or 9)

Condition/Specification	**Comments**
Analyzers (two each) zeroed and span checked initially only	✓- Span was 20 ppm NO and 10 ppm NO_2
Sampling probes of analyzers placed beside reference method probe	✓- Lines to instruments are then connected into a metal tube to top of stove top.
Analyzers are allowed to stabilize	✓
After initial readings, probes are switched to ambient air and stabilized	✓
Sample Probes are returned to source for a total of nine samplings	✓
Final zero and span check conducted on analyzer after each source, using the same span as initial check	✓

The cooktop used in the VT has been used by Battelle in a previous study. The data on the source levels generated by the cooktop are documented in a Battelle report entitled "An Interlaboratory Program to Validate a Protocol for the Measurement of NO_2 Emissions from Rangetop Burners." The data covers 1994 through 1998.

The gas supply for the cooktop is from a certified cylinder without sulfur.

Water Heater: NO and NO$_2$ ranges 10-80 ppm
Must operate continuously during test (can't cycle off)
Must operate at steady-state (See Page 8 or 9)

Condition/Specification	**Comments**
Analyzers (two each) zeroed and span checked initially only	✓ - Span was 100 ppm NO and 15 ppm NO$_2$
Sampling probes of analyzers placed beside reference method probe	✓ - connect in a "T" together
Analyzers are allowed to stabilize	✓
After initial readings, probes are switched to ambient air and stabilized	✓
Sample Probes are returned to source for a total of nine samplings	✓
Final zero and span check conducted on analyzer after each source, using the same span as initial check	✓

The water heater used in the VT has been used by Battelle in a previous study. The data on the source levels generated by the water heater is documented in a Battelle report entitled "An Interlaboratory Study to Determine the Precision of an Emission Measurement Protocol for Residential Gas Water Heaters." The data covers 1994 through 1998.

The gas supply for the water heater was from the city gas supply. However, Battelle has a gas chromatograph monitoring the concentration of the gas daily.

Medium NO_x Source

First Diesel Generator: NO and NO_2 ranges 100-1000 ppm NO_x
Must operate at steady-state

Condition/Specification	**Comments**
Analyzers (two each) zeroed and span checked initially only	✓ - Generator was run at high RPM Span was 200 ppm NO and 50 ppm NO_2
Sampling probes of analyzers placed beside reference method probe	✓
Analyzers are allowed to stabilize	✓
After initial readings, probes are switched to ambient air and stabilized	✓
Sample Probes are returned to source for a total of nine samplings	✓- initial sampling observed only, auditors departed
Analyzers are evaluated at three separate load conditions per generator	
Extended sampling interval (one hour) is conducted during one load condition	See Note Below
Final zero and span check conducted on analyzer after each source, using the same span as initial check	

Note: The Test/QA Plan called for two specific generators from the Air Force that were unavailable at the time of the VT. A generator on-site was modified to be both the medium and high source. This generator was run at a high RPM for the medium source and at idle for the high source. Because of the noise level at the high RPM, most of the extended sampling interval (one hour) was done during the high source test and not the medium source. One vendor chose to not submit its monitors to the high source so its extended sampling interval was done during the medium source (high RPM).

Steady-State:

Temperature changes in the center position of the exhaust of not more than ±l0°F;

NO_x changes at the center of the exhaust duct of $\leq \pm 5\%$ relative to the mean over the 15 minute interval as determined using the EPA reference method

O_2 changes, at the center of the exhaust duct of $\leq \pm 0.50\%$ absolute (±5000 ppm) from the mean sampled over the 15 minute interval.

High NO_x Source - Not Observed

Second Diesel Generator: NO and NO_2 ranges 600-2300 ppm NO_x
Must operate at steady-state

Condition/Specification	**Comments**
Analyzers (two each) zeroed and span checked initially only	
Sampling probes of analyzers placed beside reference method probe	
Analyzers are allowed to stabilize	
After initial readings, probes are switched to ambient air and stabilized	
Sample Probes are returned to source for a total of nine samplings	
Analyzers are evaluated at three separate load conditions per generator	
Extended sampling interval (one hour) is conducted during one load condition	
Final zero and span check conducted on analyzer after each source, using the same span as initial check	

Note: Instead of a second generator, the generator was run at idle to produce a span of 400 ppm NO and 100 ppm NO_2.

Steady-State:

Temperature changes in the center position of the exhaust of not more than ±l0°F;

NO_x changes at the center of the exhaust duct of $\leq \pm 5\%$ relative to the mean over the 15 minute interval as determined using the EPA reference method

O_2 changes, at the center of the exhaust duct of $\leq \pm 0.50\%$ absolute (±5000 ppm) from the mean sampled over the 15 minute interval.