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Environmental Technology Verification Report

COSA INSTRUMENTS MODEL 7000 VARIO PLUS PORTABLE EMISSION ANALYZER

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ETV ETV ETV

September 2000

Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

COSA Instruments Model 7000 Vario Plus Portable Emission Analyzer

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Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development has financially supported and collaborated in the extramural program described here. This document has been peer reviewed by the Agency and recommended for public release. Mention of trade names or commercial products does not constitute endorsement or recommendation by the EPA for use.

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 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.

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List of Abbreviations

AMS	Advanced Monitoring Systems
ANSI	American National Standards Institute
Btu/hr	British thermal unit per hour
ccm	cubic centimeter per minute
CEM	continuous emission monitor
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FID	flame ionization detector
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
RPM	revolutions per minute
SAS	Statistical Analysis System
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, 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, operate the Advanced Monitoring Systems (AMS) Center under ETV. The AMS Center 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 COSA Instruments Model 7000 Vario Plus Portable Emission Analyzer.

Chapter 2
Technology Description

The objective of the ETV AMS Center is to verify the performance characteristics of environmental monitoring technologies for air, water, and soil. This verification report provides results for the verification testing of COSA Instruments 7000 Vario Plus analyzers. The following description of the 7000 Vario Plus analyzer is based on information provided by the vendor.

The COSA 7000 Vario Plus is specifically designed to measure O_2, CO, NO, NO_2, and SO_2 emissions from a variety of combustion sources, including boilers, incinerators, and internal combustion engines. The COSA 7000 Vario Plus uses electrochemical sensors, with a high range CO sensor and a hydrocarbon sensor also available for applications involving internal combustion engine emission testing. The unit also measures gas and ambient temperatures and stack draft. Calculated parameters include carbon dioxide, combustion efficiency, excess air, and flue gas losses. A customized hard copy of the measurements can be printed out, or up to 300 complete combustion tests can be stored to be downloaded to a PC.

The COSA 7000 Vario Plus also includes a complete sample conditioning system with a heated sample gas hose, sample gas cooler, and condensate removal system. The Vario Plus dimensions are 22" x 13" x 8.5" and it weighs 30 pounds. Options include flow measurement; soot measurement; automatic remote, unattended measurement with data logging; 4 to 20mA DC outputs; and remote handheld interface, printer, or keyboard.

The two COSA 7000 Vario Plus analyzers subjected to the ETV testing reported here were standard systems for measuring O_2, CO, SO_2, NO, and NO_2. The focus of this verification test was on the NO and NO_2 measurement capabilities.

Figure 2-1. COSA 7000 Vario Plus Analyzer

Chapter 3
Test Design and Procedures

3.1 Introduction

The verification test described in this report was conducted in May 2000. The test was 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)

The schedule of tests conducted on the COSA Instruments 7000 Vario Plus analyzers is shown in Table 3-1.

Table 3-1. Identity and Schedule of Tests Conducted on COSA Instruments 7000 Vario Plus Analyzers

Test Activity	Date Conducted
Laboratory Tests	
Linearity	May 15, 2000, p.m.
Interrupted Sampling	May 15, p.m. - May 16, a.m.
Interferences	May 16, a.m.
Pressure Sensitivity	May 16, a.m.
Ambient Temperature	May 16, p.m.
Combustion Source Tests	
Gas Rangetop	May 17, a.m.
Gas Water Heater	May 17, a.m.
Diesel Generator–High RPM	May 18, a.m.
Diesel Generator–Idle	May 18, a.m.

To assess inter-unit variability, two identical 7000 Vario Plus analyzers were tested simultaneously. These two analyzers were designated as Unit A and Unit B throughout all testing. The 7000 Vario Plus analyzers were operated at all times by a representative of COSA Instruments 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 COSA Instruments 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.

Verification testing began with COSA Instruments 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 gas combustion source exhausts vented through the roof of the test facility. The diesel engine was located immediately outside the wall of the test facility; sampling probes ran from the analyzers located indoors through the wall to the diesel exhaust duct. 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 7000 Vario Plus 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 7000 Vario Plus analyzers were 0 to 2,000 ppm for NO and 0 to 1,000 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 laboratory tests were aimed at quantifying the full range of performance of the analyzers.

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% 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 031907) was 512 ppm. These standards were identical to NO and NO_2 standard cylinders used in the combustion source tests, which were confirmed near the end of the verification test by comparison with independent standards obtained from other suppliers.

The gas dilution system used was an Environics Model 4040 mass flow controlled diluter (Serial Number 2469). 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 keypad of the personal computer used to operate the 4040 diluter, and the diluter then set the required standard and diluent flow rates to produce the desired mixture. The 4040 diluter indicated on the computer 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 4040 diluter also provided warnings if a flow controller was being operated at less than 10% 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% 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% oxygen.

Laboratory testing was conducted primarily by supplying known gas mixtures to the analyzers from the Environics 4040 diluter, 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 4040 diluter 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

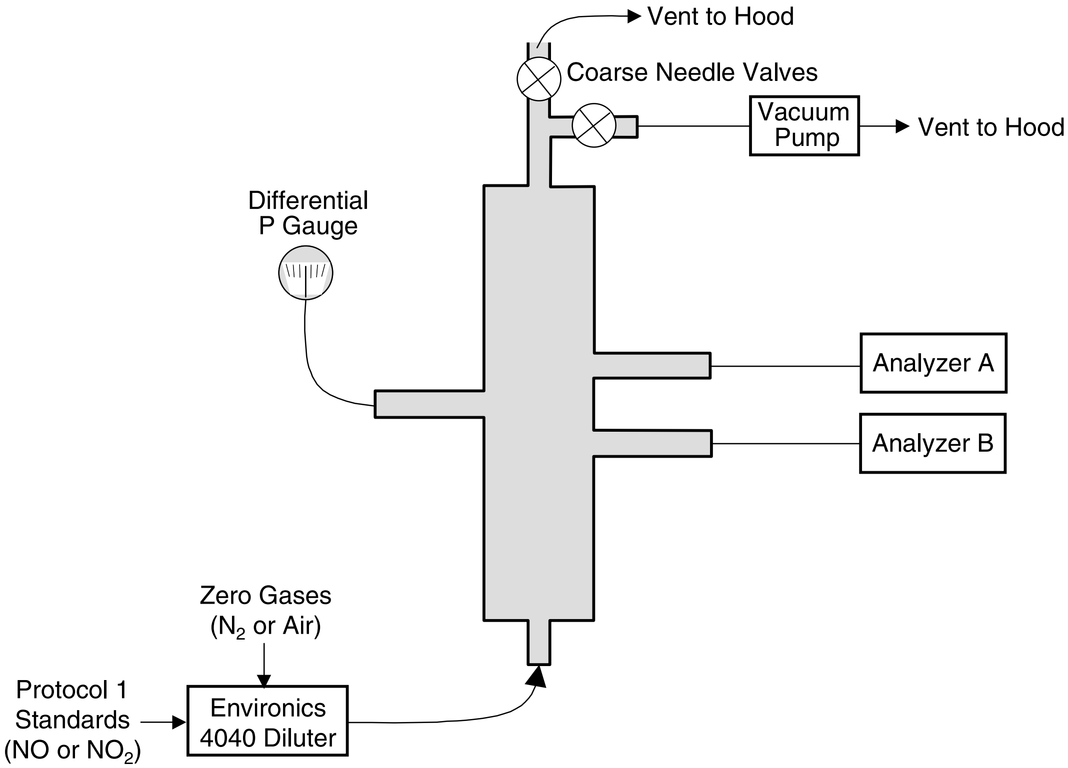

Figure 3-1. Manifold Test Setup

close control of the manifold pressure within a target range of ±10 inches of water, while main taining excess flow of the gas mixtures to the manifold. The arrangement shown in Figure 3-1 was used 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 4040 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. Before starting the series of laboratory tests, the 7000 Vario Plus analyzers were calibrated with 100 and 1,000 ppm NO, and with 250 and 500 ppm NO_2, prepared by diluting the EPA Protocol Gases using the Environics 4040 diluter.

3.2.1 Linearity

Linearity testing consisted of a wide-range 21-point response check for NO, and for NO_2. At the start of this check, the 7000 Vario Plus analyzers sampled the appropriate zero gas and then an NO or NO_2 concentration near 2,000 ppm NO or 500 ppm NO_2. The actual concentrations were 2,000 ppm NO and 512 ppm NO_2. The 21-point check then proceeded without any adjustments to the analyzers. The 21 points consisted of three replicates each at 10, 20, 40, 70, and 100% of the concentrations stated above, in randomized order, and interspersed with six replicates of zero gas.(1) Following completion of all 21 points, the zero and 100% points 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 was supplied to the analyzers. This procedure provided data to assess the cross-sensitivity to NO and NO_2.

3.2.2 Detection Limit

Data from zero gas and from the 10% concentration 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% of the maximum level used (i.e., about 1,400 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% 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 7000 Vario Plus 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. Levels of 2,000 ppm NO and 512 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 7000 Vario Plus 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 used one at a time, 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.

The CO, CO_2, SO_2, and NH_3 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%, based on analysis. The CO, CO_2, and NH_3 were all in ultra-high purity (UHP) air, and the SO_2 was in UHP nitrogen. The SO_2/NO mixture listed in Table 3-2 was prepared by diluting the NO Protocol Gas with the SO_2 standard using the Environics 4040 diluter.

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[a]	465 ppm C_1, 94 ppm C_2, 46 ppm $C_3 + C_4$
SO_2 and NO	451 ppm SO_2 + 393 ppm NO

[a] C_1 = methane; C_2 = ethane; and $C_3 + C_4$ = 23 ppm propane + 23 ppm n-butane.

The hydrocarbon interferant 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-traceable standard containing 1,020 ppm carbon (ppmC) in the form of propane. Using a gas chromatograph with a flame ionization detector (FID) the NIST-traceable standard was first analyzed. The resulting FID response factor (2,438 area units/ppmC) was then used to determine the concentrations of the components of the prepared hydrocarbon mixture. Two analyses of that mixture gave results of 463 and 467 ppm methane; the corresponding results for ethane were 93 and 95 ppm; for propane 22 and 23 ppm; and for n-butane 23 and 23 ppm.

In the interference test, each interferant in Table 3-2 was provided individually to the sampling manifold shown in Figure 3-2, 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 4040 diluter. 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 (Buck Primary Flow Calibrator, Model M5, Serial No. 051238; 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, 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 concentrations used in the pressure sensitivity test) at room, elevated, and reduced temperatures. A temperature range of about 7 to 40°C (45 to 105°F) was targeted in this test. The elevated temperature condition was achieved using a 1.43 m^3 steel and glass laboratory chamber, heated using external heat lamps. The reduced temperature condition was achieved using a commercial laboratory refrigerated cabinet (Lab Research Products, Inc.).

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 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. The analyzers were returned to the laboratory bench; and, after a 1-hour stabilization period, the zero and span checks were repeated a final time.

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 over 300 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 5 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 1/2-inch in size. These were available 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% methane, 3% 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 approximately 50 to 80 ppm, and NO_2 in the range of 4 to 8 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 1/2-inch in size. Their purpose was to hold two 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 (approximately 4 ppm mercaptan).

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 generates NO_x emissions over a range of about 200 to 330 ppm, depending on the load on the super-charged engine. High load (3,500 RPM) resulted in the lowest NO_x; idle operation resulted in the highest NO_x. At both conditions, about one-third of the NO_x was NO_2. Data on diesel generator emissions were generated in tests conducted in the two weeks prior to the start of the verification test.

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 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% 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 COSA Instruments representative inserted two of his product's probes into the exhaust duct of the rangetop, water heater, or diesel engine. The 7000 Vario Plus analyzer probes were fitted close to each other, sampling from a point within about 1/4 inch of the inlet of the reference analyzers' probe.

The reference analyzer probe consisted of an 18-inch long, 1/4-inch diameter stainless-steel tube, the upstream 2 inches of which were bent at a right angle for connection to a stainless steel bulkhead union in the wall of the exhaust duct. The inner end of the bulkhead union connected to a short length of 1/4-inch diameter stainless steel tube that extended into the center of the source exhaust duct. The 7000 Vario Plus analyzers were each operated with their own sample probe and sample transfer lines, and with the optional sample conditioners to dry and filter the sample. Based on the results of trial runs conducted before the verification test, 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 condenser in an ice bath connected to the stainless steel probe by a 2-foot length of 1/4-inch diameter Teflon® tubing. The downstream end of the condenser was connected by a 3-foot length of 1/4-inch Teflon tubing to an inlet "tee" connected to both reference analyzers. The reference particulate-removal system consisted of a 47-millimeter in-line quartz fiber filter, which was used in sampling the diesel emissions.

3.3.2.2 Reference Method

The reference method 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 two Model 42-C source-level NO_x monitors (from Thermo Environmental Instruments), located on a wheeled cart positioned near the combustion sources. These monitors sampled from a common intake line, as described above. Both instruments use stainless steel converters maintained at 650ºC (1,202°F) for reduction of NO_2 to NO for detection. The two reference analyzers were designated as Unit No. 100643 and 100647, respectively.

The reference analyzers were calibrated before and after combustion source tests using an Environics Series 2020 diluter (Serial No. 2108) and EPA Protocol 1 gases for NO and NO_2 (3,925 ppm, Cylinder No. ALM 15489, and 511.5 ppm, Cylinder No. AAL 5289, respectively; Scott Specialty Gases). The calibration procedure was specified in the test/QA plan, and required calibration at zero, 30%, 60%, and 100% of the applicable range value (i.e., 50, 100, or 1,000 ppm, depending on the emission source). Calibration results closest in time to the combustion 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 COSA Instruments source tests, which took place on May 17 and 18, 2000, calibration data from May 15 were applied. Conversion efficiency values of 91.7 and 100% were found for the two reference analyzers, and all reference data were corrected for those 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 2020 Multi-Gas Calibrator (Serial Number 2108). The same Acid Rain CEM zero gases were used for dilution and zeroing as were used in the laboratory tests. 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 analyzers caused by exposure to source emissions.

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 engine 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 COSA Instruments 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.

The last operation in the combustion source testing 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 extended sampling was conducted only after nine sequential sets of readings had been obtained from all the combustion sources by the procedure described above. Results from this extended sampling were used to determine the measurement stability of the 7000 Vario Plus analyzers.

Chapter 4
Quality Assurance/Quality Control

Quality control (QC) procedures were performed in accordance with the quality management plan (QMP) for the AMS Center(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 Center 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. Laboratory record notebooks were also signed and dated by testing staff and reviewed by the Verification Testing Leader.

Other data review focused upon the compliance of the reference analyzer data with the quality requirements of Method 7E. The purpose of validating reference data was to ensure usability for the purposes of comparison with the demonstration technologies. 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 and other changes or improvements. Any deviation required the approval signature of Battelle's Verification Testing Leader and the Center manager. A planned deviation form was used for documentation and approval of the following changes:

1. The order of testing was changed in the pressure sensitivity test to require fewer plumbing changes in conducting the test.
2. The order of the ambient temperature test was changed to maximize the detection of any temperature effect.
3. The concentrations used in the mixture of SO_2 and NO for the interference test were changed slightly.
4. For better accuracy, the oxygen sensor used during combustion source tests was checked by comparison to an independent paramagnetic O_2 sensor, rather than to a wet chemical measurement.
5. Single points (rather than triplicate points) were run at each calibration level in calibrating the reference analyzers, in accord with Method 7E.

Table 4-1. Results of QC Procedures for Reference Analyzers for Testing COSA Instruments 7000 Vario Plus Analyzers

<table>
<tr><td>NO_2 conversion efficiency (Unit 100643)</td><td>91.7%</td><td></td></tr>
<tr><td>NO_2 conversion efficiency (Unit 100647)</td><td>100%</td><td></td></tr>
<tr><td>Calibration of reference method using four points at 0, 30, 60, 100% for NO</td><td>Meets criteria ($r^2 = 0.9999$)</td><td></td></tr>
<tr><td>Calibration of reference method using four points at 0, 30, 60, 100% for NO_2</td><td>Meets criteria ($r^2 = 0.9999$)</td><td></td></tr>
<tr><td>Calibrations (100 ppm range)</td><td>Meet ± 2% requirement (relative to span)</td><td>
<table>
<tr><th colspan="2">Unit 100643</th><th colspan="2">Unit 100647</th></tr>
<tr><th colspan="2">NO</th><th colspan="2">NO</th></tr>
<tr><th>Error, % of Span</th><th>at % of Scale</th><th>Error, % of Span</th><th>at % of Scale</th></tr>
<tr><td>0.8</td><td>30</td><td>0.9</td><td>30</td></tr>
<tr><td>0.2</td><td>60</td><td>0.3</td><td>60</td></tr>
<tr><th colspan="2">NO_2</th><th colspan="2">NO_2</th></tr>
<tr><th>Error, % of Span</th><th>at % of Scale</th><th>Error, % of Span</th><th>at % of Scale</th></tr>
<tr><td>0.4</td><td>30</td><td>0.6</td><td>30</td></tr>
<tr><td>0.1</td><td>60</td><td>0.2</td><td>60</td></tr>
</table>
</td></tr>
<tr><td>Zero drift</td><td>Meets ± 3% requirement (relative to span) on all combustion sources</td><td></td></tr>
<tr><td>Span drift</td><td>Meets ± 3% requirement (relative to span) on all combustion sources</td><td></td></tr>
<tr><td>Interference check</td><td>< ± 2% (no interference response observed)</td><td></td></tr>
</table>

6. A short, unheated sample inlet was used with the reference analyzers, based on pre-test trial runs, on Battelle's previous experience in sampling the combustion sources used in this test, and on other similar sources.
7. No performance evaluation audit was conducted on the natural gas flow rate measurement used with the gas water heater. This measurement was made with a newly calibrated dry gas meter.

4.3 Calibration of Laboratory Equipment

Equipment used in the verification test required calibration before use, or verification of the manufacturer's calibrations. Some auxiliary devices were obtained with calibrations from Battelle's Instrument Laboratory. Equipment types and calibration dates are listed in Table 4-2.

For key equipment items, the calibrations listed include performance evaluation audits (see Section 4.5.2). Documentation of calibration of the following equipment was maintained in the test file.

Table 4-2. Equipment Type and Calibration Date

Equipment Type	Use
Gas Dilution System Environics Model 4040 (Serial Number 2469)	Lab tests
Gas Dilution System Environics Model 2020 (Serial Number 2108)	Source tests
Fluke Digital Thermometer (LN-570068)	Ambient temperature test
Servomex 570A Analyzer (X-44058)	Flue gas O_2
Dwyer Magnahelic Pressure Gauge	Pressure sensitivity test
Doric Trendicator 410A Thermocouple Temperature Sensor (Serial Number 331513)	Flue gas temperature
American Meter DTM 115 Dry Gas Meter (Serial Number 89P124205)	Gas flow measurement

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

Three internal performance system 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% of all data generated during the verification test. A summary of the results of these audits is provided below.

4.5.1 Technical Systems Audit

A technical systems audit (TSA) was conducted on April 18, 2000, (laboratory testing) and May 17 and 18, 2000, (source testing) for the NO/NO_2 verification tests conducted in early 2000. The TSA was performed by the Battelle's Quality Manager as specified in the AMS Center Quality Management Plan (QMP). The TSA ensures that the verification tests are conducted according to the test/QA plan(1) and all activities associated with the tests are in compliance with the AMS Center QMP(7). All findings noted during the TSA on the above dates were documented and submitted to the Verification Testing Leader for correction. The corrections were documented by the Verification Testing Leader and reviewed by Battelle's Quality Manager and Center Manager. None of the findings adversely affected the quality or outcome of this verification test and all were resolved to the satisfaction of the Battelle Quality Manager. The records concerning the TSA are permanently stored with the Battelle Quality Manager.

4.5.2 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. That assessment was conducted by Battelle testing staff on May 26, 2000, and the results were reviewed by independent QA personnel.

The most important performance evaluation (PE) audit was of the standards used for the reference measurements in source testing. The PE standards were NO and NO_2 calibration gases independent of the test calibration standards that contained 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 standards. Percent difference was used to quantify the accuracy of the results. The PE sample for NO was an EPA Protocol Gas having a concentration (3,988 ppm) nearly the same as the NO standard used in verification testing, but purchased from a different commercial supplier (Matheson Gas Products). The PE standard for NO_2 was a similar commercial standard of 463 ppm NO_2 in air, also from Matheson. Table 4-3 summarizes the NO/NO_2 reference standard

Table 4-3. Performance Evaluation Results

Reference	Standard Analyzer	Reading on Diluted Standard	Apparent Concentration[a]	Percent Difference[b]	Acceptance Limits
Unit 100643	NO in N_2 (ppm)				
Test Std	3,925	98.8 ppm	3,917 ppm	0.2%	± 2%
PE Std	3,988	100.6 ppm			
Unit 100647	NO in N_2 (ppm)				
Test Std	3,925	99.6 ppm	3,917 ppm	0.2%	± 2%
PE Std	3,988	101.4 ppm			
Unit 100643	NO_2 in Air (ppm)				
Test Std	511.5	44.2 ppm	482 ppm	5.8%	± 5%
PE Std	463	42.5 ppm			
Unit 100647	NO_2 in Air (ppm)				
Test Std	511.5	49.6 ppm	471ppm	7.9%	± 5%
PE Std	463	48.8 ppm			

[a] Concentration of Test Standard indicated by comparison to the Performance Evaluation Standard; i.e., Apparent Concentration = (Test Std. Reading/PE Std. Reading) × PE Std. Conc.; e.g., Apparent Concentration = 98.8/100.6 × 3,988 ppm = 3,917 ppm.

[b] Percent difference of Apparent Concentration relative to Test Standard concentration; e.g., percent difference =

$$\frac{3{,}925\ \text{ppm} - 3{,}917\ \text{ppm}}{3{,}925\ \text{ppm}}\ \text{X}\ 100 = 0.2\%.$$

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.

Table 4-3 shows that the PE audit confirmed the concentration of the Scott 3,925 ppm NO test standard almost exactly: the apparent test standard concentration was within 0.2% of the test standard's nominal value. On the other hand, the PE audit results for the Scott 511.5 ppm NO_2 standard were not as close. The comparison to the Matheson PE standard indicated that the 511.5 ppm NO_2 Scott standard was only about 480 ppm, a difference of about 7% from its nominal value. This result suggests an error in the Scott test standard for NO_2. However, a separate line of evidence indicates that the Matheson PE standard is likely in error. Specifically, conversion efficiency checks on the reference analyzers (performed by comparing their responses to the Scott NO and NO_2 standards) consistently showed the efficiency of the converter in 42-C Unit 100647 to be very close to 100%. This finding could not occur if the concentration of the NO_2 standard were low. That is, a conversion efficiency of 100% indicates agreement between the NO standard and the NO_2 standard; and, as shown in Table 4-3, the NO standard is confirmed by the PE comparison. Thus, the likelihood is that the Matheson PE standard was in fact somewhat higher in concentration than its nominal 463 ppm value.

PE audits were also done on the O_2 sensor used for flue gas measurements, and on the temperature indicators used for ambient and flue gas measurements. The PE standard for O_2 was an independent paramagnetic sensor, and for temperature was a certified mercury-in-glass thermometer. The O_2 comparison was conducted during sampling of diesel exhaust; the temperature comparisons were conducted at room temperature. The results of those audits are shown in Table 4-4, and indicate close agreement of the test equipment with the PE standards.

4.5.3 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% 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 Battelle Quality Manager for the verification test audited 10% of the raw data. Test data sheets and laboratory record books were reviewed, and statistical calculations and other algorithms were verified. Calculations that were used to assess the four-point calibration of the reference method were also verified to be correct. In addition, data presented in the verification report and statement were audited to ensure accurate transcription.

Table 4-4. Performance Evaluation Results in O_2 and Temperature Measuring Equipment

Analyzer	Reading	Difference	Acceptance Limits
Servomex 570A O_2	18.9% O_2	0% O_2	–
PE Standard[a]	18.9% O_2		
Fluke Digital Thermometer	22.1°C	0.1°C	2% absolute T
PE Standard[b]	22°C		
Doric 410A Temp. Sensor	24.8°C	0.2°C	2% absolute T
PE Standard[b]	25.0°C	0.2°C	

[a] Independent paramagnetic O_2 analyzer.
[b] Certified mercury-in-glass thermometer.

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 7000 Vario Plus analyzer. The calibration model used was

$$Y_c = h(c) + error_c$$

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,

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

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.

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

The form of the linear regression model fitted was $h(c) = \alpha_o + \alpha_1 c$. In the concentration sub-region 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

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

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

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

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

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

where σ_o is the estimated standard deviation at zero concentration. The LOD is estimated as $\mathrm{LOD} = 3\hat{\sigma}_0 / \hat{\alpha}_1$. 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 7000 Vario Plus 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% 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%. 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:

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

$$t = \hat{\beta} / (0.07071\hat{\sigma}(c)) \text{ for the span concentration test}$$

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:

$$t = \hat{\beta} / (0.01723\hat{\sigma}(c)) \text{ for the zero concentration test}$$

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

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:

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

where *d* refers to the difference between the average of the two reference analyzers and one of the tested units and *x* corresponds to the average of the two reference analyzer 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% 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

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

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 7000 Vario Plus analyzer units 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 planned data points.

Chapter 6
Test Results

6.1 Laboratory Tests

6.1.1 Linearity

Tables 6-1a and b list the data obtained in the linearity tests for NO and NO_2, respectively. The response of both the NO and NO_2 sensors in each analyzer is shown in those tables.

Table 6-2 shows the results of the linear calibration curve fits for each unit and each analyte, based on the data shown in Tables 6-1a and b.

Table 6-1a. Data from NO Linearity Test of COSA Instruments 7000 Vario Plus 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	1	0	2
2	2000	1931	20	1945	19
3	200	205	7	205	7
4	800	806	7	809	7
5	0	2	3	2	3
6	1400	1386	3	1394	3
7	420	427	4	429	4
8	200	202	3	202	3
9	0	3	2	2	2
10	420	426	3	428	3
11	800	806	4	810	4
12	1400	1389	7	1397	7
13	0	3	2	2	2
14	2000	1934	9	1952	9
15	1400	1385	6	1396	7
16	800	807	5	812	5
17	0	3	2	3	3
18	420	428	3	429	3
19	200	202	2	203	3
20	2000	1935	7	1952	8
21	0	3	2	3	2

Table 6-1b. Data from NO_2 Linearity Test of COSA Instruments 7000 Vario Plus 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	512	2	511	2	508
3	50	0	53	0	53
4	200	0	201	0	200
5	0	0	2	0	2
6	350	0	353	0	350
7	105	0	108	0	108
8	50	0	52	0	52
9	0	0	2	0	2
10	105	0	106	0	106
11	200	0	201	0	200
12	350	1	353	1	350
13	0	0	2	0	3
14	512	2	516	2	512
15	350	1	356	1	353
16	200	0	205	0	204
17	0	0	2	0	3
18	105	0	107	0	106
19	50	0	52	0	52
20	512	2	516	3	512
21	0	0	2	0	3

Table 6-2. Statistical Results for Test of Linearity

	Unit A		Unit B	
Linear Regression	NO	NO_2	NO	NO_2
Intercept (ppm) (Std Err)	7.306 (3.128)	1.784 (0.268)	6.104 (2.598)	2.719 (0.759)
Slope (Std Err)	0.975 (0.004)	1.003 (0.002)	0.984 (0.004)	0.993 (0.002)
r^2	0.9997	0.9999	0.9997	0.9999

The results in Table 6-2 show that the NO_2 response of the 7000 Vario Plus analyzers was linear over the entire range tested of up to 512 ppm. The NO_2 slopes are 0.99 to 1.00, and the r^2 values are 0.9999.

The NO linearity results in Table 6-2 show that over the tested range of up to 2,000 ppm NO, the 7000 Vario Plus analyzers gave slopes of about 0.98. Inspection of the NO linearity data shows that the slope of the NO response is essentially 1.0 at all concentrations tested, except for a slightly low response at the 2,000 ppm point. For example, the regression slopes for the two 7000 Vario Plus units are 0.991 and 0.997 when only the lowest 18 calibration points in Table 6-1a (i.e., up to 1,400 ppm) are included. These results indicate that the linear range of NO response for the 7000 Vario Plus analyzers is at least 1,500 ppm, with possibly a slight downturn in response at levels approaching 2,000 ppm.

The data in Tables 6-1a and 6-1b also indicate the extent of cross-sensitivity of the COSA NO and NO_2 sensors. Regression of the 7000 Vario Plus NO_2 responses in the NO linearity test (Table 6-1a) gives the following results:

Unit A $NO_2 = 0.0042 \times(NO, ppm) + 2.0$ ppm, with $r^2 = 0.531$, and
Unit B $NO_2 = 0.0040 \times(NO, ppm) + 2.3$ ppm, with $r^2 = 0.566$.

These results indicate a very slight response of the COSA NO_2 sensors to NO, amounting to about 0.4% of the NO level present.

Similarly, regression of the 7000 Vario Plus NO responses in the NO_2 linearity test (Table 6-1b) gives the following results:

Unit A $NO = 0.0035 \times(NO_2, ppm) - 0.23$ ppm, with $r^2 = 0.762$, and
Unit B $NO = 0.0040 \times(NO_2, ppm) - 0.27$ ppm, with $r^2 = 0.718$.

These results also indicate a very small response of the COSA NO sensors to NO_2, amounting to about 0.4% of the NO_2 level present.

6.1.2 Detection Limit

Table 6-3 shows the estimated detection limits for each test unit and each analyte, determined from the data obtained in the linearity test. These detection limits apply to the calibrations conducted over a 0 to 2,000 ppm range for NO (Table 6-1a) and a 0 to 512 ppm range for NO_2 (Table 6-1b).

Table 6-3. Estimated Detection Limits for COSA Instruments 7000 Vario Plus Analyzers[a]

	Unit A		**Unit B**	
	NO	**NO_2**	**NO**	**NO_2**
Estimated Detection Limit (ppm)	3.7	2.4	3.3	3.5
(Standard Error) (ppm)	(1.2)	(0.8)	(1.1)	(1.1)

[a] Results are based on calibrations over 0 to 2,000 ppm range for NO and 0 to 512 ppm range for NO_2.

Table 6-3 displays the estimated detection limits, and their standard errors for NO and NO_2, separately for each 7000 Vario Plus analyzer. NO detection limits of 3 to 4 ppm, and NO_2 detection limits of 2 to 4 ppm, are indicated. It must be stressed that these detection limits are based on the zero gas responses, interspersed with sampling high levels of NO and NO_2 in the linearity tests.

6.1.3 Response Time

Table 6-4 lists the data obtained in the response time test of the 7000 Vario Plus 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. The observed response times were consistent, at 37 seconds for NO, and about 80 seconds for NO_2.

Table 6-5 shows that 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 2,000 ppm NO and 512 ppm NO_2 were used for this test.

Table 6-7 shows that changes in zero readings for both NO and NO_2 were only a few ppm. These small changes in zero reading indicate good stability of the analyzers, and probably result from the exposure to elevated NO and NO_2 levels in the linearity tests that immediately preceded the shutdown. That is, the small decreases in zero readings are probably the result of the analyzers returning to baseline readings after the linearity tests.

The 7000 Vario Plus analyzers showed no change in the NO_2 span response as a result of the shutdown (Table 6-7). The changes observed in the NO span response are negligible, amounting to, at most, 0.2% of the 2,000 ppm NO span value.

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. The results in Table 6-8 use the average of the zero readings before and after the interferant exposure to calculate the extent of the interference.

Table 6-4. Response Time Data for COSA Instruments 7000 Vario Plus Analyzers

Time (sec)	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
0	2	2	2	2
10	3	4	2	4
20	389	97	397	79
30	1233	226	1212	209
40	1360	283	1372	272
50	1375	310	1387	300
60	1379	324	1390	316
70	1381	331	1392	325
80	1382	336	1393	329
90	1383	339	1394	333
100	1384	341	1393	335
110	1385	342	1394	337
120	1384	343	1394	339
130	1386	344	1394	340
140	1385	345	1394	341
150	1385	346	1395	341
160	1386	346	1395	342
170	1386	347	1395	343
180	1385	347	1394	343
190	1386	348	1394	344
200		348		344
210		348		345
220		349		345
230		349		345
240		349		345
250		349		346
260		350		346
270		350		346
280		350		347
290		350		347
300		351		347

Table 6-5. Response Time Results for COSA Instruments 7000 Vario Plus Analyzers

	Unit A		Unit B	
	NO	NO_2	NO	NO_2
Response Time (sec)[a]	37	75	37	82

[a] The analyzer's responses were recorded at 10-second intervals; therefore the point in time when the 95% response was achieved was determined by interpolating between recorded times to the nearest second.

Table 6-6. Data from Interrupted Sampling Test with COSA Instruments 7000 Vario Plus Analyzers

	Unit A NO	Unit A NO_2	Unit B NO	Unit B NO_2
Pre-Shutdown Date:	05/15/2000	**Time:**	17:15	
Pre-Shutdown Zero (ppm):	3	2	3	3
Pre-Shutdown Span (ppm):	1934	516	1950	512
Post-Shutdown Date:	05/16/2000	**Time:**	8:15	
Post-Shutdown Zero (ppm):	0	0	0	0
Post-Shutdown Span (ppm):	1935	516	1946	512

Table 6-7. Pre- to Post-Test Differences as a Result of Interruption of Operation of COSA Instruments 7000 Vario Plus Analyzers

	Unit A		Unit B	
Pre-Shutdown—Post-Shutdown	NO	NO_2	NO	NO_2
Zero Difference (ppm)	3	2	3	3
Span Difference (ppm)	-1	0	4	0

Table 6-8. Data from Interference Tests on COSA Instruments 7000 Vario Plus Analyzers

Interferant Gas	Interferant, Conc. (ppm)	Unit A NO	Response (ppm equivalent) Unit A NO_2	Unit B NO	Unit B NO_2
Zero		0	2	0	2
CO	496	0	2	0	2
Zero		0	1	0	1
CO_2	5.03%	0	1	0	1
Zero		0	1	0	1
NH_3	494	0	0	0	0
Zero		0	0	0	0
HCs	605	0	0	0	1
Zero		0	0	0	0
SO_2	501	0	0	0	0
Zero		0	0	0	0
SO_2 + NO	451 + 393	399	0	399	0

Table 6-9. Results of Interference Tests of COSA Instruments 7000 Vario Plus Analyzers

	Unit A Response ppm (relative sensitivity, %)		Unit B Response ppm (relative sensitivity, %)	
Interferant	NO	NO_2	NO	NO_2
CO (496 ppm)	0	0.1%	0	0.1%
CO_2 (5.03%)	0	0	0	0
NH_3 (494 ppm)	0	-0.1%	0	-0.1%
HCs (605 ppm)	0	0	0	0.2%
SO_2 (501 ppm)	0	0	0	0
SO_2 (451 ppm) + NO (393 ppm)	1.33%	0	1.33%	0

Table 6-9 indicates that there were no significant interference effects from CO, CO_2, NH_3, HCs, and SO_2 or from SO_2 in the presence of NO. The response to 393 ppm NO was barely increased by the presence of 451 ppm SO_2.

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.

Tables 6-10 and 6-11 show that only very small changes in 7000 Vario Plus zero and span readings resulted from the changes in duct pressure, for both NO and NO_2. Average zero readings changed by less than 1 ppm, and span readings changed by no more than 8 ppm for NO (0.4 % of the 2,000 ppm span level) and 10 ppm for NO_2 (2% of the 512 ppm span level). The changes observed do not indicate any statistically significant effect of pressure on zero or span readings.

Tables 6-10 and 6-11 do show a small effect of pressure on the sample flow rates of the 7000 Vario Plus analyzers. The reduced pressure condition reduced the flow rates by 4 to 6%, and the increased pressure condition increased the flow rates by 8 to 15%, relative to the flows at ambient pressure.

Table 6-10. Data from Pressure Sensitivity Test for COSA Instruments 7000 Vario Plus Analyzers

Pressure		Unit A NO	Unit A NO_2	Unit B NO	Unit B NO_2
Ambient	Flow rate (ccm)	1664	1664	1555	1555
	Zero (ppm)	0	0	0	0
	NO span (ppm)	1944	5	1955	5
	Zero (ppm)	1	1	0	1
	NO_2 span (ppm)	8	505	8	510
	Zero (ppm)	0	3	0	3
+10 in. H_2O	Flow rate (ccm)	1807	1807	1787	1787
	Zero (ppm)	0	0	0	0
	NO span (ppm)	1948	4	1963	5
	Zero (ppm)	1	1	0	1
	NO_2 span (ppm)	8	514	7	513
	Zero (ppm)	0	2	0	3
-10 in. H_2O	Flow rate (ccm)	1560	1560	1489	1489
	Zero (ppm)	1	0	0	1
	NO span (ppm)	1946	4	1961	4
	Zero (ppm)	1	1	0	1
	NO_2 span (ppm)	8	515	8	512
	Zero (ppm)	0	2	0	3

Table 6-11. Pressure Sensitivity Results for COSA Instruments 7000 Vario Plus Analyzers

		Unit A		Unit B	
		NO	NO_2	NO	NO_2
Zero	High–Ambient (ppm diff[a])	0	-0.333	0	0
	Low–Ambient (ppm diff)	0.334	-0.333	0	0.334
	Significant Pressure Effect	N	N	N	N
Span	High–Ambient (ppm diff)	4	9	8	3
	Low–Ambient (ppm diff)	2	10	6	2
	Significant Pressure Effect	N	N	N	N
Flow Rate	High–Ambient (ccm diff*)	143		232	
	Low–Ambient (ccm diff)	-104		-66	

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

6.1.7 Ambient Temperature

Table 6-12 lists the data obtained in the ambient temperature test with the 7000 Vario Plus analyzers. Table 6-13 summarizes the sensitivity of the analyzers to changes in ambient temperature.

Tables 6-12 and 6-13 show that the temperature variations in this test had no significant effect on the NO_2 zero readings of either 7000 Vario Plus analyzer. However, a significant temperature effect was indicated for the NO zero readings. This result is almost entirely due to the slightly elevated NO zero readings observed when the analyzers were placed in the heated chamber (Table 6-12).

Temperature did have a significant effect on the NO and NO_2 span responses of both 7000 Vario Plus analyzers, but the consistency of the effects is different for NO and NO_2. A small but significant effect was seen for NO, with warmer environments giving higher span values. The total difference in span readings between cool and heated environments was about 2.5% of the 2,000 ppm NO span value. In contrast, the effect was not consistent for NO_2. Unit A showed a lower NO_2 span response in the heated environment, and a higher response in the cooled environment, than at room temperature. The Unit A NO_2 response was markedly high in the cooled environment (Table 6-12). Unit B showed slightly lower response at the heated condition, relative to room temperature. These results do not strongly show a consistent temperature effect for NO_2.

Table 6-12. Data from Ambient Temperature Test of COSA Instruments 7000 Vario Plus Analyzers

Condition	Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
(Room Temp.)				
Temp. 25.6°C (78°F)				
Zero	0	2	0	2
NO span	1948	16	1959	16
Zero	0	2	0	2
NO_2 span	8	515	8	511
(Heated)				
Temp. 39.4°C (103°F)				
Zero	5	1	6	0
NO span	1976	8	1988	8
Zero	8	1	8	1
NO_2 span	20	506	24	495
(Cooled)				
Temp. 7.2°C (45°F)				
Zero	0	3	0	3
NO span	1930	27	1935	26
Zero	0	0	0	0
NO_2 span	7	554	8	509
(Room Temp.)				
Temp. 22.8°C (73°F)				
Zero	0	1	0	1
NO span	1932	12	1951	12
Zero	1	1	1	1
NO_2 span	12	514	12	509

Table 6-13. Ambient Temperature Effects on COSA Instruments 7000 Vario Plus Analyzers

		Unit A		Unit B	
		NO	NO_2	NO	NO_2
Zero[a]	Heat–Room (ppm diff[a])	6.25	-0.5	6.75	-1
	Cool–Room (ppm diff)	-0.25	0	-0.25	0
	Significant Temp Effect	Y	N	Y	N
Span[a]	Heat–Room (ppm diff)	36	-8.5	33	-15
	Cool–Room (ppm diff)	-10	39.5	-20	-1
	Significant Temp. Effect	Y	Y	Y	Y

[a] ppm difference between heated/cooled and room temperatures. The differences were calculated using the average of two recorded responses at room temperature (Table 6-12).

6.1.8 Zero/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. Table 6-15 shows that zero drifts in these tests were 3 ppm or less for both NO and NO_2 on both 7000 Vario Plus analyzers. Zero drifts were less than 1 ppm in the temperature test, but were slightly larger in the linearity test, probably because of the elevated zero readings caused by the exposures to high NO and NO_2 levels. Span drift for NO_2 amounted to 5 ppm or less (about 1% of the 512 ppm span value). Span drift for NO amounted to 16 ppm or less (less than 1% of the 2,000 ppm NO span value).

Table 6-14. Data from Linearity and Ambient Temperature Tests Used to Assess Zero and Span Drift of the COSA Instruments 7000 Vario Plus Analyzers

Test		Unit A NO (ppm)	Unit A NO_2 (ppm)	Unit B NO (ppm)	Unit B NO_2 (ppm)
Linearity	Pre-Test Zero	0	0	0	0
	Pre-Test Span	1931	511	1945	508
	Post-Test Zero	3	2	3	3
	Post-Test Span	1934	516	1950	512
Ambient Temperature	Pre-Test Zero	0	2	0	2
	Pre-Test Span	1948	515	1959	511
	Post-Test Zero	0	1	0	1
	Post-Test Span	1932	514	1951	509

Table 6-15. Zero and Span Drift Results for the COSA Instruments 7000 Vario Plus Analyzers

		Unit A		Unit B	
Pre- and Post-Differences		**NO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**NO_2 (ppm)**
Linearity Test	Zero	-3	-2	-3	-3
	Span	-3	-5	-5	-4
Ambient Temperature Test	Zero	-0.5	1	-0.5	1
	Span	16	1	8	2

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 the four combustion sources. Note that the 7000 Vario Plus analyzers measure NO and NO_2, and the indicated NOx readings are the sum of those data. On the other hand, the reference analyzers measure NO and NO_x, with NO_2 determined by difference.

Table 6-17 displays the relative accuracy (in percent) for NO, NO_2, and NO_x of 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.

Table 6-17 shows that relative accuracy for NO_x ranged from 2.8 to 10.7% over both analyzers and all combustion sources. Relative accuracy for NO ranged from 2.2 to 18.9%, and the relative accuracy for NO_2 ranged from 7.6 to 17.4%. Interestingly, relative accuracy was generally better at lower concentrations. This finding appears to result primarily because the 7000 Vario Plus analyzers report NO values 10 to 20% higher than do the reference analyzers with the diesel source, but not with the gas combustion sources. The unit-to-unit repeatability of the COSA analyzers was often better than that of the two reference analyzers, indicating highly consistent performance.

The unit-to-unit agreement of the two 7000 Vario Plus analyzers in source sampling was also good. For example, the differences between the average NO_x values obtained by Units A and B in the four combustion sources ranged from 0.0 to 1.9%, relative to the average NO_x values. In comparison, the corresponding agreement for the two reference analyzers ranged from 1.2 to 5.9%, and the agreement of the two COSA analyzers was better in all combustion tests than that of the reference analyzers. These results indicate a high degree of consistency in the performance of the 7000 Vario Plus analyzers on combustion sources.

Table 6-16a. Data from Gas Rangetop in Verification Testing of COSA Instruments 7000 Vario Plus Analyzers

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	7	2	9	7	2	9	7.06	1.91	8.97	6.60	2.04	8.64
2	7	2	9	7	2	9	7.41	1.83	9.24	6.86	1.94	8.79
3	7	2	9	7	2	9	7.43	2.05	9.48	6.87	2.24	9.10
4	7	2	9	7	2	9	7.22	1.97	9.19	6.71	2.20	8.91
5	7	2	9	7	2	9	7.43	1.76	9.19	6.74	2.10	8.83
6	7	2	9	7	2	9	7.49	1.86	9.35	6.87	2.20	9.07
7	7	2	9	7	2	9	7.39	1.95	9.34	6.76	2.30	9.06
8	7	2	9	7	2	9	7.51	2.05	9.56	6.90	2.35	9.25
9	7	2	9	7	2	9	7.26	2.03	9.28	6.55	2.40	8.94

Table 6-16b. Data from Gas Water Heater in Verification Testing of COSA Instruments 7000 Vario Plus Analyzers

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	80	4	84	80	4	84	78.3	3.0	81.3	77.4	2.7	80.0
2	79	4	83	79	4	83	76.7	3.7	80.4	75.4	4.1	79.5
3	79	4	83	79	4	83	77.4	4.1	81.5	76.1	4.2	80.3
4	80	4	84	80	4	84	77.9	3.8	81.7	76.3	4.5	80.8
5	81	4	85	81	4	85	78.2	3.8	82.0	76.5	4.8	81.4
6	81	4	85	81	4	85	77.5	4.4	81.9	76.2	4.5	80.7
7	80	4	84	80	4	84	76.9	4.2	81.1	75.5	5.0	80.5
8	80	4	84	80	4	84	76.8	4.4	81.3	75.5	4.8	80.3
9	81	4	85	81	4	85	78.9	4.2	83.1	77.2	4.7	81.9

Table 6-16c. Data from Diesel Generator at High RPM in Verification Testing of COSA Instruments 7000 Vario Plus Analyzers

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	145	51	196	152	62	214	130.2	66.0	196.3	130.3	72.0	202.3
2	148	60	208	149	61	210	129.9	63.6	193.5	132.3	72.0	204.3
3	158	58	216	159	60	219	135.6	61.6	197.2	138.3	67.9	206.2
4	150	59	209	152	60	212	131.6	63.7	195.3	136.3	68.9	205.2
5	145	57	202	146	58	204	128.9	61.9	190.8	132.0	68.8	200.8
6	148	56	204	147	58	205	125.1	61.8	186.9	130.7	67.3	197.9
7	144	57	201	146	57	203	121.5	61.7	183.1	126.1	68.0	194.1
8	146	57	203	148	57	205	124.0	59.5	183.5	127.9	67.8	195.7
9	140	56	196	142	57	199	123.6	57.4	181.1	127.4	66.0	193.4

Table 6-16d. Data from Diesel Generator at Idle in Verification Testing of COSA Instruments 7000 Vario Plus Analyzers

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	200	85	285	198	82	280	166.4	82.8	249.2	172.3	82.3	254.6
2	198	81	279	197	80	277	167.3	86.0	253.3	175.4	93.6	269.0
3	199	85	284	198	83	281	168.2	87.1	255.3	174.3	96.7	271.1
4	198	86	284	197	85	282	163.5	89.2	252.7	170.3	97.7	268.1
5	194	86	280	195	83	278	160.7	88.1	248.8	168.3	96.7	265.0
6	195	86	281	195	84	279	159.7	86.0	245.7	167.3	95.7	263.0
7	175	86	261	176	83	259	145.6	84.9	230.5	151.3	94.7	246.0
8	170	84	254	171	82	253	142.7	86.0	228.7	149.3	94.7	243.9
9	162	86	248	163	84	247	132.3	84.9	217.3	138.3	94.7	232.9

Table 6-17. Relative Accuracy of COSA Instruments 7000 Vario Plus Analyzers

Source	Unit A NO (%)	Unit A NO_2 (%)	Unit A NO_x (%)	Unit B NO (%)	Unit B NO_2 (%)	Unit B NO_x (%)
Gas Rangetop (7 ppm NO, 2 ppm NO_2)[c]	2.226[a] (0.514)[b]	7.556 (1.589)	2.834 (0.541)	2.226 (0.514)	7.556 (1.589)	2.834 (0.541)
Gas Water Heater (75 ppm NO, 5 ppm NO_2)	4.833 (0.255)	14.061 (3.720)	4.178 (0.165)	4.833 (0.255)	14.061 (3.720)	4.178 (0.165)
Diesel Generator–High RPM (130 ppm NO, 65 ppm NO_2)	15.216 (0.592)	17.410 (1.558)	6.724 (0.756)	16.590 (0.562)	11.127 (0.455)	7.759 (0.388)
Diesel Generator–Idle (160 ppm NO, 90 ppm NO_2)	18.927 (0.443)	8.462 (1.012)	10.711 (0.520)	18.698 (0.385)	10.415 (0.871)	9.574 (0.431)

[a] Relative accuracy, percent relative to mean of two reference analyzers.
[b] Standard error of the relative accuracy value.
[c] Approximate NO and NO_2 levels from each source are shown; see Tables 6-16a through d.

6.2.2 Zero/Span Drift

Table 6-18 shows the data from the combustion source tests used to evaluate zero and span drift of the 7000 Vario Plus analyzers. Table 6-19 summarizes the zero and span drift results, showing that zero and span drift was never more than a few ppm in any of the combustion source tests, for either NO or NO_2, with either analyzer. The zero drift values exceeded ± 1 ppm only for the NO response of both 7000 Vario Plus analyzers with the diesel generator at idle. Those NO zero drift values with the diesel source are less than 1% of the 400 ppm NO span value.

The span drift values in Table 6-19 are similarly very small. Relative to the respective span values, the NO span drift was at most 1% of span (relative to the 200 ppm span value used with the diesel at high RPM), and the NO_2 span drift was at most 4% (relative to the 100 ppm span value used with the diesel at idle).

Table 6-18. Data Used to Assess Zero and Span Drift for COSA Instruments 7000 Vario Plus 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	9
	Post-Test Zero	0	0	0	0
	Post-Test Span	20	9	20	9
Gas Water Heater	Pre-Test Zero	0	0	0	0
	Pre-Test Span	104	14	104	14
	Post-Test Zero	0	0	0	0
	Post-Test Span	104	14	104	14
Diesel–High RPM	Pre-Test Zero	0	0	0	0
	Pre-Test Span	209	45	209	45
	Post-Test Zero	1	0	1	0
	Post-Test Span	211	43	211	43
Diesel–Idle	Pre-Test Zero	1	0	1	0
	Pre-Test Span	425	86	425	86
	Post-Test Zero	4	0	4	0
	Post-Test Span	427	82	427	84

Table 6-19. Results of Zero and Span Drift Evaluation for COSA Instruments 7000 Vario Plus 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	0	0	0	0
Gas Water Heater	Zero	0	0	0	0
	Span	0	0	0	0
Diesel Generator–High RPM	Zero	-1	0	-1	0
	Span	-2	2	-2	2
Diesel Generator–Idle	Zero	-3	0	-3	0
	Span	-2	4	-2	2

6.2.3 Measurement Stability

Table 6-20 shows the data obtained in the extended sampling test, in which the 7000 Vario Plus and reference analyzers sampled diesel emissions for a full hour without interruption or sampling of ambient air. 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 observed by the 7000 Vario Plus analyzers differed from those observed by the reference analyzers.

Table 6-21 shows that both the 7000 Vario Plus analyzers and the reference analyzers determined increasing trends in NO and NO_x, and a decreasing trend in NO_2, during the extended sampling of the diesel source. Most of the trends indicated by the 7000 Vario Plus analyzers were significantly different from those indicated by the reference analyzers. However, the actual difference in the measured trends was very small. For example the NO_x slopes determined by 7000 Vario Plus Units A and B were 0.151 ppm/min (9.1 ppm/hr) and 0.115 ppm/min (6.9 ppm/hr), respectively, compared to the reference analyzer trend of 0.023 ppm/min (1.4 ppm/hr). Thus, over a one-hour period the different trends resulted in a 7.7 ppm or less deviation from the trend of the reference analyzers, or about 3% of the NO_x level in the diesel exhaust.

Table 6-20. Data from Extended Sampling Test with Diesel Generator at Idle, Using COSA Instruments 7000 Vario Plus Analyzers

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	181	87	268	180	85	265	146.5	87.1	233.6	154.3	94.7	249.0
2	180	86	266	180	83	263	150.3	86.0	236.3	151.3	95.7	247.0
3	179	88	267	180	84	264	149.3	84.9	234.3	156.3	94.7	251.0
4	177	88	265	177	84	261	147.4	86.0	233.5	155.3	95.7	251.0
5	176	87	263	177	82	259	145.6	84.9	230.5	152.3	94.7	247.0
6	176	87	263	177	85	262	146.5	84.9	231.5	153.3	94.7	248.0
7	175	89	264	175	85	260	144.6	86.0	230.6	151.3	95.7	247.0
8	173	87	260	174	85	259	142.7	86.0	228.7	149.3	95.7	245.0
9	176	88	264	176	85	261	143.7	84.9	228.6	151.3	93.6	244.9
10	177	88	265	177	86	263	143.7	86.0	229.7	150.3	95.7	246.0
11	188	83	271	188	80	268	145.6	86.0	231.6	153.3	94.7	248.0
12	187	79	266	187	78	265	153.1	78.6	231.7	161.3	86.4	247.7
13	187	80	267	186	78	264	156.0	78.6	234.5	162.3	87.4	249.8
14	189	79	268	188	78	266	153.1	77.5	230.6	160.3	87.4	247.8
15	188	80	268	190	79	269	153.1	77.5	230.6	161.3	86.4	247.7
16	190	80	270	189	79	268	155.0	77.5	232.5	162.3	86.4	248.7
17	194	80	274	193	79	272	156.0	78.6	234.5	163.3	87.4	250.8
18	188	80	268	189	79	268	155.0	78.6	233.6	163.3	87.4	250.8
19	199	79	278	200	78	278	154.1	78.6	232.6	162.3	86.4	248.7
20	194	76	270	195	74	269	158.8	76.5	235.2	165.3	85.4	250.7
21	199	77	276	199	75	274	161.6	75.4	237.0	169.3	84.4	253.7
22	195	76	271	196	74	270	162.6	75.4	238.0	171.3	84.4	255.7
23	198	76	274	197	74	271	161.6	75.4	237.0	169.3	84.4	253.7
24	197	76	273	197	75	272	158.8	74.3	233.1	168.3	83.3	251.7
25	192	77	269	192	75	267	161.6	74.3	236.0	169.3	83.3	252.7
26	197	78	275	196	76	272	159.7	74.3	234.1	168.3	84.4	252.7
27	198	77	275	198	75	273	158.8	75.4	234.2	166.3	84.4	250.7
28	195	78	273	195	76	271	161.6	74.3	236.0	169.3	84.4	253.7
29	198	78	276	198	75	273	160.7	75.4	236.1	168.3	84.4	252.7
30	197	77	274	196	75	271	161.6	75.4	237.0	170.3	84.4	254.7

Table 6-20. Data from Extended Sampling Test with Diesel Generator at Idle, Using COSA Instruments 7000 Vario Plus Analyzers (continued)

	COSA Instruments Analyzer Data						Reference Analyzer Data					
	Unit A			Unit B			Unit 100643			Unit 100647		
	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
31	193	79	272	193	77	270	159.7	74.3	234.1	167.3	83.3	250.7
32	202	79	281	201	77	278	158.8	75.4	234.2	167.3	84.4	251.7
33	195	78	273	194	77	271	161.6	74.3	236.0	170.3	83.3	253.7
34	198	79	277	197	77	274	158.8	75.4	234.2	168.3	83.3	251.7
35	202	79	281	203	79	282	162.6	75.4	238.0	171.3	83.3	254.7
36	199	79	278	197	78	275	165.4	75.4	240.8	173.3	74.1	247.4
37	190	80	270	191	79	270	160.7	76.5	237.1	168.3	85.4	253.7
38	193	80	273	194	77	271	157.8	75.4	233.2	166.3	84.4	250.7
39	194	82	276	194	80	274	158.8	75.4	234.2	166.3	84.4	250.7
40	197	81	278	197	80	277	159.7	76.5	236.2	167.3	85.4	252.7
41	195	79	274	195	77	272	159.7	76.5	236.2	167.3	85.4	252.7
42	198	80	278	199	77	276	159.7	77.5	237.2	168.3	85.4	253.7
43	190	81	271	189	79	268	158.8	77.5	236.3	165.3	86.4	251.8
44	194	81	275	193	79	272	155.0	77.5	232.5	163.3	85.4	248.7
45	192	81	273	190	79	269	156.0	77.5	233.5	163.3	86.4	249.7
46	191	79	270	189	77	266	154.1	77.5	231.6	161.3	85.4	246.7
47	192	80	272	192	78	270	156.0	76.5	232.4	164.3	85.4	249.7
48	187	80	267	186	77	263	156.0	77.5	233.5	163.3	87.4	250.8
49	193	80	273	191	77	268	154.1	77.5	231.6	162.3	85.4	247.7
50	195	80	275	194	77	271	156.0	76.5	232.4	163.3	85.4	248.7
51	187	80	267	186	76	262	157.8	77.5	235.4	164.3	86.4	250.7
52	193	79	272	192	77	269	156.0	76.5	232.4	164.3	86.4	249.7
53	194	81	275	192	79	271	156.9	76.5	233.4	165.3	85.4	250.7
54	189	82	271	188	77	265	156.9	77.5	234.4	164.3	85.4	249.7
55	192	82	274	193	78	271	155.0	77.5	232.5	163.3	85.4	248.7
56	192	82	274	192	77	269	156.0	76.5	232.4	163.3	85.4	248.7
57	194	82	276	193	79	272	155.0	76.5	231.5	163.3	85.4	247.7
58	195	79	274	194	76	270	157.8	76.5	234.3	166.3	84.4	250.7
59	199	78	277	199	75	274	156.9	76.5	233.4	164.3	85.4	249.7
60	193	78	271	191	74	265	156.0	75.4	231.3	163.3	84.4	247.7

Table 6-21. Results of Evaluation of Measurement Stability for COSA Instruments 7000 Vario Plus Analyzer

	Unit A			Unit B			Reference Units		
	NO	**NO_2**	**NO_x**	**NO**	**NO_2**	**NO_x**	**NO**	**NO_2**	**NO_x**
Slope	0.239	-0.089	0.151	0.216	-0.101	0.115	0.172	-0.149	0.023
(Std Err)	(0.045)	(0.023)	(0.029)	(0.046)	(0.020)	(0.034)	(0.036)	(0.023)	(0.017
Difference in Slopes (ppm/min)	0.068	0.060	0.128	0.045	0.047	0.092	---	---	---
(Std Err)	(0.025)[a]	(0.011)[a]	(0.024)[a]	(0.025)	(0.014)[a]	(0.028)[a]			

[a] Statistically significant difference in slope among test unit and the averages of the reference units at the 5% significance level.

6.2.4 Inter-Unit Repeatability

The repeatability of test results between the two 7000 Vario Plus 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 7000 Vario Plus units at the 95% confidence level. As Table 6-22 shows, statistically significant differences were found primarily in the areas of relative accuracy and measurement stability.

The differences shown in Table 6-22 indicate the variability that may be expected from one analyzer to the next. Although some statistically significant differences were found, nevertheless the practical importance of these differences is often small. Considering the relative accuracy results, for example (Table 6-17), it is apparent that statistically significant differences may exist even when the two analyzers are equally applicable to the measurement at hand. For example, the relative accuracy result for NO_x for Unit A on the diesel at idle is 10.7%, whereas that for Unit B is 9.6%. These results may differ significantly in the statistical sense, but either unit would be more than adequate for determining NO_x emissions from that source. The fine degree of discrimination provided by the statistical tests should not obscure the fact that the two 7000 Vario Plus analyzers essentially worked equally well throughout the verification tests.

Table 6-22. Summary of Repeatability

Unit A vs. Unit B			NO	NO_2	NO_x
Linear Regression	Intercept	t-statistic	0.296	-1.162	---
		p-value [a]	0.774	0.272	---
	Slope	t-statistic	-1.716	3.162	---
		p-value	0.117	**0.010**	---
Detection Limit		t-statistic	0.246	-0.803	---
		p-value	0.808	0.428	---
Relative Accuracy	Gas Rangetop	t-statistic	[b]	[b]	[b]
		p-value	-	-	-
	Gas Water Heater	t-statistic	[b]	[b]	[b]
		p-value	-	-	-
	Generator–High RPM	t-statistic	2.639	1.859	2.268
		p-value	**0.030**	0.100	0.053
	Generator–Idle	t-statistic	0.286	8.102	5.547
		p-value	0.782	**<0.001**	**<0.001**
Measurement Stability	Slope	t-statistic	3.480	1.540	3.500
		p-value	**0.001**	0.130	**<0.001**

[a] p-value <0.05 indicates that two test units are statistically different at the 5% significance level (in bold text).
[b] Unit A and Unit B indicated exactly the same readings. No matched-pairs t-statistic was calculated.

6.3 Other Factors

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

6.3.1 Cost

The cost of each analyzer as tested in this verification test was about $12,000.

6.3.2 Data Completeness

The data completeness in the verification test was 100% for both units of the COSA Instruments 7000 Vario Plus.

6.3.3 Maintenance/Operational Factors

The short duration of the verification test prevented assessment of long-term maintenance costs, durability, etc., but no maintenance was required and no problems were encountered with the 7000 Vario Plus analyzers in this test. The analyzers appeared to be rugged, and the stability of the analyzers allowed verification testing to proceed smoothly.

Chapter 7
Performance Summary

The COSA Instruments 7000 Vario Plus analyzers provided linear response for NO_2 over the tested range of 0 to 512 ppm. Response for NO was linear over the range of 0 to at least 1,500 ppm, but showed a slightly low response at the maximum tested level of 2,000 ppm. Over the full tested range of 0 to 2,000 ppm NO, the regression slope of NO response was approximately 0.98. Detection limits estimated from these wide-range linearity tests were 3 to 4 ppm for NO and 2 to 4 ppm for NO_2. Response times were 37 seconds for NO and about 80 seconds for NO_2.

Drift in 7000 Vario Plus zero readings before and after source combustion and laboratory tests was within ±2 ppm in nearly all circumstances. In laboratory tests, span drift for NO and NO_2 was always less than 1% of the respective 2,000 ppm NO and 512 ppm NO_2 span levels. In sampling of gas combustion and diesel sources, NO span drift was always less than 1%, and NO_2 span drift always less than 4%, of the respective span levels. No interference was found from any of the following: 496 ppm CO; 5.03% CO_2; 494 ppm NH_3; 605 ppm of total hydrocarbons; 501 ppm of SO_2; or 451 ppm SO_2 in the presence of 393 ppm NO.

Over the tested range of +10 to -10 in. H_2O, sample gas pressure had no significant effect on 7000 Vario Plus zero or span readings. Reduced pressure lowered the analyzers' sample flow rates by about 5%, and positive pressure increased the flow rates by up to 15%. Variations in ambient temperature over the range of 7 to 39°C (45 to 103°F) had no consistent effect on the 7000 Vario Plus zero or span readings for NO_2. For NO, this temperature range caused a change in zero readings of about 6 ppm and a difference in span response of at most 2.5% relative to the 2,000 ppm span gas concentration provided. Both NO zero readings and span response increased with increasing temperature.

The relative accuracy of the COSA 7000 Vario Plus analyzers for NO_x ranged from 2.8 to 10.7% over both analyzers and all combustion sources. Relative accuracy for NO ranged from 2.2 to 18.9%, and the relative accuracy for NO_2 ranged from 7.6 to 17.4%. Relative accuracy was generally better at lower concentrations. This finding appears to result primarily because the NO values were 10 to 20% higher than the reference analyzers with the diesel source, but not with the gas combustion sources. At concentrations below 10 ppm, the 7000 Vario Plus analyzers were accurate within their 1 ppm measurement resolution. Unit-to-unit agreement of the two 7000 Vario Plus analyzers for NO_x ranged from 0.0 to 1.9% and was better than that of the two reference analyzers. Comparison of verification results from the two 7000 Vario Plus analyzers showed only slight differences, primarily in relative accuracy. Overall, the performance of the two analyzers was essentially identical.

Chapter 8
References

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