March 2003

Environmental Technology Verification Report

TESTO INC.
MODEL 350
PORTABLE MULTIGAS EMISSION ANALYZER

Prepared by
Battelle

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ETV ETV ETV

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Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

Testo Inc.
Model 350
Portable Multigas Emission Analyzer

by

Jeff Myers
Thomas Kelly
Zachary Willenberg
Karen Riggs

Battelle
Columbus, Ohio 43201

Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development 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. ETV consists of six environmental technology centers. Information about each of these centers can be found on the Internet at http://www.epa.gov/etv/.

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/centers/center1.html.

Acknowledgments

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List of Abbreviations

AC	alternating current
AMS	Advanced Monitoring Systems
ANSI	American National Standards Institute
Btu	British thermal unit
CARB	California Air Resources Board
CO	carbon monoxide
CE-CERT	College of Engineering Center for Environmental Research and Technology
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
H_2S	hydrogen sulfide
hr	hour
kW	kilowatt
LOD	limit of detection
NDIR	non-dispersive infrared
NIST	National Institute of Standards and Technology
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_2	oxygen
PC	personal computer
ppb	parts per billion
ppm	parts per million
PE	performance evaluation
QA	quality assurance
QC	quality control
QMP	Quality Management Plan
RA	relative accuracy
SCR	selective catalytic reactor
SO_2	sulfur dioxide
TSA	technical systems audit
UV	ultraviolet

Chapter 1
Background

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

ETV works in partnership with recognized testing organizations, with stakeholder groups (consisting of buyers, vendor organizations, and permitters), and with 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 (QA) 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 recently evaluated the performance of the Testo Inc. Model 350 M/XL portable multigas 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 the Testo Inc. Model 350 portable gaseous emission analyzer. Following is a description of the analyzer, based on information provided by the vendor. The information provided below was not verified in this test.

The Model 350 (Figure 2-1) is a self-contained emission analyzer system capable of measuring oxygen (O_2), carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), hydrogen sulphide (H_2S), and hydrocarbons in combustion emission sources, while capturing data on pressure, temperature, and flow. Low nitrogen oxides (NO_x) and low CO resolutions are 0.1 part per million (ppm) throughout the range. Figure 2-2 shows a schematic of the Model 350 as tested.

Figure 2-1. Testo Inc. Model 350

The Model 350 M/XL uses electrochemical sensors that are temperature-controlled to operate over an ambient temperature range of 20ºF to 115ºF and can be calibrated, exchanged, and upgraded in the field without hand tools. An optional CO dilution system permits sample range expansion to over 40:1.

The Model 350 weighs less than nine pounds and has an automatic sample conditioning system that includes a Peltier cooler, moisture removal pump, and patented non-heated sample line to provide representative samples from engines, turbines, boilers, burners, and other combustion sources. The entire system operates independently on nickel metal hydride batteries, or can be connected to AC power (90 to 260 volts, 50 to 60 Hertz).

A handheld control unit can operate the analyzer “docked” in the base unit or hundreds to thousands of feet from the base unit. The control unit provides the user with a simple interface and communications.

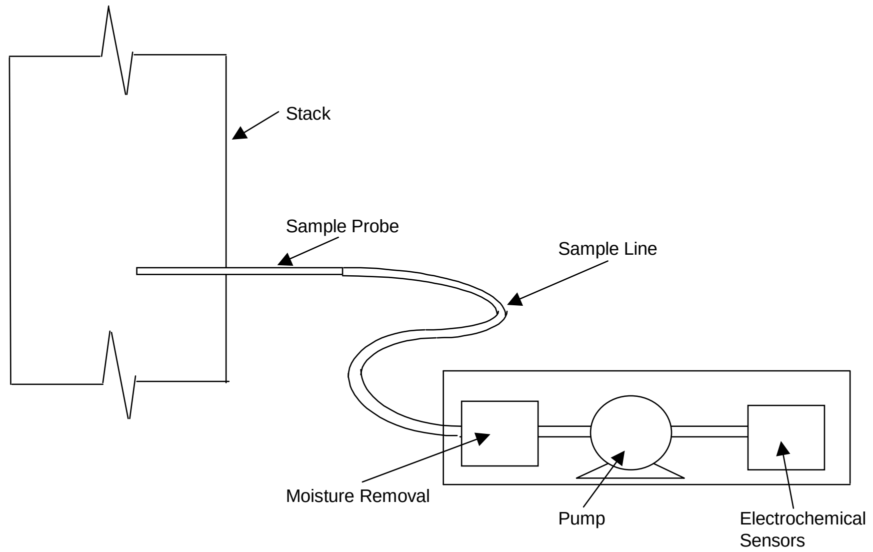

Figure 2-2. Testo Inc. Model 350 Sampling Schematic

Pulldown menu selections, user-defined function buttons, and/or a computer interface provide access to all operations of the system. Automatic programs for unattended operation facilitate remote, event-driven, and/or long-term (weeks) testing. An onboard printer provides documentation of test results, while internal data logging of up to 256,000 data points can be programmed. Data retrieval options include an onboard menu system and a computer download procedure; data points can be stored in files and converted to standard spreadsheets and charts.

Internal calculations are performed automatically. The unit provides onscreen information such as O_2 reference corrections (freely selectable), CO_2, combustion efficiency, excess air, flow, mass-emissions (pounds per hour, etc.), and flue gas loss. The system can be expanded to provide additional measurements for moisture, velocity, temperatures, 4- to 20-milliampere signals, and a variety of other inputs, including simultaneous multibox monitoring.

Four Model 350s were tested in this verification. Two analyzers were configured to measure O_2, CO, NO, and NO_2 with low range sensors for CO and NO. Two analyzers were configured to measure O_2, CO, SO_2, NO, and NO_2 with high range sensors for CO and NO. The low range analyzers did not have SO_2 sensors, and the O_2 and NO_2 sensors in all four analyzers were identical.

Chapter 3
Test Design and Procedures

3.1 Introduction

This verification test was conducted according to procedures specified in the *Test/QA Plan for Verification of Portable Gaseous Emission Analyzers*.[1] The verification was based on comparing results from the Model 350 to EPA protocol gas standards for SO_2, CO, O_2, NO, and NO_2, and to reference method results for those gases.

The high and low range Model 350 analyzers were verified in terms of performance on the following parameters:

- Linearity
- Response time
- Detection limit
- Performance after interrupted sampling
- Interferences
- Ambient temperature sensitivity
- Pressure sensitivity
- Accuracy
- Zero/span drift
- Measurement stability
- Inter-unit repeatability with duplicate analyzers.

3.2 Site Description

The verification test was conducted at the Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside.

3.3 Emission Sources

Emissions were sampled from a commercial gas-fired cooktop and a small diesel-fueled engine driving an electrical generator. Both combustion sources were installed and operated according to the manufacturer's instructions, with proper attention to safety requirements.

3.3.1 Commercial Cooktop

A commercial natural gas-fired cooktop with four range burners was used to generate CO, O_2, NO, and NO_2 emissions at the desired concentrations. This cooktop can be operated with any combination of one to four burners in operation. In addition, the firing rate of each burner can be adjusted from 0 to 8,500 British thermal units (Btu) per hour using its associated natural gas and combustion air control system. This cooktop has an overall maximum firing rate of 34,000 Btu per hour (34,000 Btu/hr). This appliance is capable of generating O_2 and NO_x (= NO + NO_2) emissions of various concentrations as a function of the number of burners operating and firing rates of each burner. Further, the CO concentration in the effluent can be varied by adjusting the combustion air flow rate on the individual burners. Emissions from this source were captured prior to measurement using a quartz collection dome designed according to the Z21.1 specifications of the American National Standards Institute (ANSI).(2)

3.3.2 Diesel-Fueled Engine

A portable diesel electrical generator was used to generate the SO_2, O_2, CO, and NO_x emissions for the combustion source tests. The 10-kilowatt (kW) generator is of a type used in portable residential backup power supplies. The engine load, and consequently emission concentrations, were varied over the desired load range by attaching electrical appliances to the generator.

The engine exhaust was ducted into a dilution tunnel. The dilution ratio can be adjusted from zero to 200:1 using a positive displacement (roots-type) blower with a variable frequency drive. By operating the generator at different loads and by adjusting the dilution ratio of exhaust gases, a wide range of emission concentrations could be generated. A high-sulfur diesel fuel was used in this generator to ensure the generation of substantial concentrations of SO_2.

3.4 Reference Methods

The outputs from all the reference method analyzers were collected and recorded electronically on a personal computer (PC) configured with LabView software. In addition, the data as read from the PC display were recorded manually on the hard copy forms.

The reference method sample conditioning system consisted of a 1/4-inch 316 stainless steel, single-point sample probe and a 3/8-inch insulated Teflon sample line, electrically heated to maintain a temperature of 247°F. A Universal Analyzers sample cooler (refrigerated condenser/ separator) was used to dry the sample gas. The dew point of the dry gas was maintained below 35°F. The sample pump was a Thomas Instrumentation, Inc. Model 607CA32 diaphragm pump. The diaphragm material was Viton A; other wetted parts of the pump were constructed of 316 stainless steel. The analyzers were provided with an unrestricted atmospheric sample vent.

NO, NO_2, NO_x—EPA Method 7E. The reference method for NO, NO_2, and NO_x determination was the chemiluminescence method that forms the basis of EPA Method 7E.(3) Measurements were made using a Thermo Environmental Instruments Model 10 source-level NO_x monitor. The monitor operates over ranges of 0 to 25 ppm to 0 to 2,500 ppm, and uses a stainless steel catalytic converter maintained at 650ºC for reduction of NO_2 to NO for detection. The monitor does not provide simultaneous measurements of NO and NO_x, thus manual switching of sampling modes is required to obtain readings of either compound. As a result, the NO and NO_x readings from the monitor are separated in time by at least 15 seconds as a result of the stabilization interval needed after switching. Because of this requirement, during the instrument stability tests, only the NO_x channel data were recorded. All NO_2 data were obtained by subtracting the NO channel response from the NO_x channel response.

O_2—EPA Method 3A. The reference method for O_2 determination was an instrumental, paramagnetic pressure sensor method that is consistent with EPA Method 3A.[4] The measurements were made using a Horiba Model CMA-331A Gas Emission Analyzer System. The O_2 component of this system utilizes the measurement principle of providing an uneven magnetic field in which the O_2 is attracted to the stronger field, raising the pressure in this section of the cell. The change in pressure is measured by a capacitor microphone detector and is converted to an electrical signal. This system was operated on the 0 to 10% and 0 to 25% O_2 ranges.

CO—EPA Method 10. The reference method for CO determination was the cross-modulation non-dispersive infrared (NDIR) method that forms the basis of California Air Resources Board (CARB) Method 10.[5] The measurements were made using a Horiba Model CMA-331A Gas Emission Analyzer System. The CO component of this system utilizes the measurement principle of absorption of infrared radiation passed through a measurement cell. The sample gas and zero air are alternately introduced to the measurement cell by means of a rotary valve, and an infrared detector equipped with a moving membrane measures the difference in radiation that is passed through the cell. The amplified signal from this detector is directly proportional to the CO concentration. This system was operated on the 0 to 200 ppm to the 0 to 5,000 ppm ranges.

SO_2—EPA Method 6C. The reference method for SO_2 determination was the ultraviolet fluorescence (UV) method that forms the basis of EPA Method 6C.[6] The measurements were made using an API Model 100AH analyzer.

3.5 Tests

Initial tests were performed in the laboratory with prepared gas mixtures. The standards of comparison in the laboratory tests were commercially obtained EPA protocol gas standards for SO_2, CO, O_2, NO, and NO_2. The laboratory tests performed, the objective of each test, and the number of measurements made in each test are summarized in Table 3-1. Combustion source tests were then conducted using a gas range burner and a diesel-powered electrical generator as the emission sources. The combustion source tests are described in Table 3-2. The standards of comparison in the combustion tests were the reference methods described in Section 3.4.

Table 3-1. Summary of Laboratory Tests

Laboratory Test	Objective	Total Number of Measurements[(a)]
Linearity	Determine linearity of response over the full measuring range	21
Response Time	Determine time needed for analyzer to respond to a change in target analyte concentration	up to 17
Detection Limit	Determine lowest concentration measurable above background signal	9
Interrupted Sampling	Determine effect on response of full analyzer shutdown	4
Interferences	Determine analyzer response to species other than target species	5
Ambient Temperature Effect	Determine effect of ambient temperature on analyzer zero and span	12
Pressure Sensitivity	Determine effect of duct pressure on analyzer sample flow and response	9

(a) Number of separate measurements made in the indicated test for each target analyte (SO_2, CO, O_2, NO, NO_2, or NO_x).

Table 3-2. Summary of Combustion Source Tests

Combustion Source Test	Objective	Comparison Based On	Total Number of Measurements[(a)]
Accuracy	Determine degree of agreement with reference method	Reference Method	45
Zero/Span Drift	Determine change in zero gas and span gas response due to exposure to combustion source emissions	Gas Standards	50[b]
Measurement Stability	Determine the analyzer's ability to sample combustion source emissions for an extended time	Reference Method	60[c]

(a) Number of separate measurements made in the indicated test for each analyzer for each analyte (SO_2, CO, O_2, NO, NO_2, or NO_x).
(b) Augmented with eight additional measurements from the linearity and ambient measurement tests.
(c) Data collected once per minute for one hour of measurement.

3.6 Test Schedule

The verification test was conducted at CE-CERT between June 11 and 21, 2002. The sequence of testing activities is shown in Table 3-3. Five test days were devoted to laboratory testing and three to source emission testing.

Table 3-3. Identity and Schedule of Tests Performed on Model 350 Analyzers

Test Type	Test Activity	Dates Performed
Laboratory	Linearity	June 11-13, 2002
	Response Time	June 11-13, 2002
	Detection Limit	June 11-13, 2002
	Interrupted Sampling	June 13-14, 2002
	Interferences	June 14, 2002
	Ambient Temperature Effect	June 14, 2002
	Pressure Sensitivity	June 16, 2002
Combustion Source Tests	Range Burner – Maximum Air	June 17, 2002
	Range Burner – Minimum Air	June 17, 2002
	Diesel Engine – Low Load	June 20, 2002
	Diesel Engine – Stability Test	June 20, 2002
	Diesel Engine – Medium Load	June 21, 2002
	Diesel Engine – High Load	June 20, 2002

3.7 Materials and Equipment

3.7.1 Gases

Table 3-4 identifies and shows the concentration of each compressed gas used in this test.

3.7.1.1 Standard Gases

EPA Protocol 1 Gases[7], obtained from a commercial supplier, were used to test and calibrate for SO_2, CO, O_2, NO, and NO_2. Span gases were obtained in concentrations that matched or exceeded the highest measuring ranges of the Model 350. These gas standards are listed first in Table 3-4.

3.7.1.2 Interference Gases

Interference gases were obtained from a commercial supplier, gravimetrically prepared, and certified with a preparation accuracy (relative to the nominal target concentration) within ±10% and an analytical accuracy (i.e., confirmation of the actual standard concentration by the supplier) within ±2%. Each interference gas was accompanied by a certificate indicating the analytical

Table 3-4. Compressed Gases Used in the Test

Cylinder No.	Certified Concentration	Balance	Certification Date	Expiration Date	Analytical Accuracy
[a]SA 9752	475 ppm NO_2	Nitrogen	10/02/01	10/01/03	±1%
[b]CC 74111	1,000 ppm NO_2	Nitrogen	02/06/01	02/05/01	±1%
[a]SA 11840	504 ppm CO	Nitrogen	09/18/01	09/18/04	±1%
[a]CC 139416	4,460 ppm CO	Nitrogen	02/26/02	02/26/05	±1%
[a]CC 109236	506 ppm SO_2	Air	09/30/01	09/27/03	±1%
[a]CC 139732	2,000 ppm SO_2	Air	02/25/02	02/21/05	±1%
[a]CC 81356	4,076 ppm NO, 4,080 ppm NO_x	Nitrogen	10/04/01	10/04/03	±1%
[b]CC 40132	49.3 ppm NO	Nitrogen	02/15/01	02/14/03	±1%
[b]CA 01633	9.88 ppm NO	Nitrogen	02/12/02	02/11/04	±1%
[b]CC 12342	201.7 ppm NO	Nitrogen	04/09/01	04/08/03	±1%
[a]CC 139843	98.3 ppm H_2	Nitrogen	02/22/02	02/21/05	±1%
[a]563628	2.24% CO_2	Nitrogen	05/21/01	05/21/04	±2%
[a]40777	9.24 ppm CH_4	Air	09/19/01	12/31/01	±1%
[a]SA 16671	5.01 % CO_2	Nitrogen	09/18/01	09/18/04	±1%
[b]CC 50070	2,999 ppm NH_3	Nitrogen	02/06/01	02/05/03	±10%
[a]SA 9072	50.8 ppm I-Butane 51.3 ppm Propane 100 ppm Ethane 503 ppm Methane	Nitrogen	10/04/01	10/03/04	±1%
[a]534060	<0.1 ppm NO_x <0.1 ppm THC <0.5 ppm CO <1 ppm CO_2 <1 ppm H_2O 20.0 ±1% O_2	Vehicle Emission Zero Air	04/23/01	N/A	N/A
[a]5243881	<0.1 ppm NO_x <0.1 ppm THC <0.5 ppm CO <1 ppm CO_2 <1 ppm H_2O 21.0 ±1% O_2	Vehicle Emission Zero Air	04/23/02	N/A	N/A

[a] Praxair
[b] Scott-Marrin

results and the uncertainty of the analytical procedures used to confirm the concentration. Each gas contained a single interferant in a matrix of high-purity air or nitrogen. Table 3-4 lists the interference gases for this test.

3.7.1.3 High-Purity Nitrogen/Air

The high-purity gas used for zeroing the reference methods and the commercial analyzers, and for diluting EPA protocol and interference gases, was Acid Rain CEM Zero Air, certified to be 99.9995% purity. A certificate of gas composition was obtained from the supplier confirming the quality of the gas. These zero gases are listed at the end of Table 3-4.

3.7.2 Reference Instruments

The reference method analyzers are described in Section 3.4.

3.7.3 Dilution System

The gas dilution system consisted of two Unit 7300 mass flow controllers, each with a range of 1 to 10 liters per minute, and a gas divider system. This set of flow controllers allowed accurate dilution of gas standards over a very wide range of dilution ratios by selecting the appropriate settings on the mass flow controllers. The flow rates of these mass flow controllers were certified on June 8, 2002, using a BIOS DryCal DC-Lite (serial number 5828). When the gas divider system was employed, the flow rates were calibrated with the BIOS at the time of use. The BIOS is a primary standard, traceable to NIST standards. During all tests involving this gas delivery system, the gas cylinder concentration and the mass flow controller settings were recorded for each data point taken. The actual gas concentrations produced were determined using an Excel spreadsheet and recorded as the concentrations provided to the analyzers undergoing testing. The spreadsheet was reviewed for accuracy. This delivery system was used to provide the test atmospheres for the analyzers under test as well as for the calibration of the reference method analyzers.

3.7.4 Temperature Sensors

The sensor used to monitor temperature in the exhaust stack or duct during experiments on combustion source emissions was a thermocouple equipped with a digital readout device. The thermometers used for measuring air temperature provided an accuracy within approximately ±1°F.

3.7.5 Gas Flow Meters

The natural gas flow to the gas burner and water heater was monitored during use with a dry gas meter and associated readout device. The dry gas meter readings were corrected for temperature and pressure.

Sierra Toptrack mass flow controllers were used in tests of the flow rate stability of the analyzers. Certification of flow rate precision was obtained from the supplier.

3.8 Test Procedures

Four Model 350 analyzers were tested, with two equipped with low range sensors for NO and CO, and two with high range sensors for those gases. The low range analyzers did not have SO_2 sensors, and the O_2 and NO_2 sensors in all four analyzers were the same. Table 3-5 describes the operational sensors and ranges over which the analyzers were tested. For O_2 and NO_2, only the high range analyzers were tested in all of the laboratory tests described below, with the exception of the interrupted sampling test.

Table 3-5. Model 350 Analyzer Ranges

Analyzer	Gas	Range
High Range	CO	0-5,000 ppm
	O_2	0-25%
	NO	0-3,000 ppm
	NO_2	0-500 ppm
	SO_2	0-2,000 ppm
Low Range	CO	0-500 ppm
	O_2	0-25%
	NO	0-300 ppm
	NO_2	0-500 ppm

The analyzer vendor indicated at the start of testing that the CO range for the high-range analyzers was 0 to 10,000 ppm, and a linearity test was initiated over that range. However, a substantially low response was observed in that test, and the test was stopped. After consultation among vendor staff, the nominal range for the CO linearity test was changed to 5,000 ppm. The SO_2 linearity test was conducted over a 0- to 2,000-ppm range, as stated in the test/QA plan, rather than over the 0 to 5,000 ppm range stated by the vendor at the time of testing. This difference was necessitated by the absence of an SO_2 gas standard higher than 2,000 ppm (see Section 4.2).

In all cases the two analyzers of each range were simultaneously tested, enabling assessments of inter-unit variability. Throughout this testing, the four Model 350s were designated as Low 1 (L1), Low 2 (L2), High 1 (H1), and High 2 (H2). A representative of Testo operated the Model 350s and manually recorded their responses (in ppm) on the data sheets. CE-CERT and Battelle personnel oversaw this process. In addition, CE-CERT operated and recorded the responses from the reference method analyzers, delivered the challenge concentrations, and provided the experimental conditions under which the analyzers were tested. Upon completion of testing, CE-CERT staff compiled and validated all the data for review by Battelle staff.

The testing began with the Testo representatives setting up and checking out the four Model 350s in the CE-CERT test facility. After the representatives were satisfied with the operation of the analyzers, the laboratory tests were performed in the order shown in Table 3-1.

Upon completion of laboratory tests, the combustion sources and reference analyzers were set up. The combustion source tests were performed at the same location as were the laboratory tests, with the source exhaust vented through the laboratory roof. This assured that testing was not interrupted and that bias was not introduced as a result of changes in weather conditions. In all source sampling, the analyzers being tested sampled at the same point in the exhaust stream as the reference analyzers. This was accomplished by placing the sample probes for the Model 350s at the same location in the combustion source exhaust duct as the inlet probe of the common sampling line for the reference analyzers.

3.8.1 Laboratory Tests

The laboratory tests were designed to challenge the analyzers over their full low and high ranges under a variety of conditions. These tests were performed using certified standard gases and a gas dilution system with flow rate calibrations traceable to the National Institute of Standards and Technology (NIST). The gas standards were diluted with high-purity gases to produce the desired range of concentrations with known accuracy.

Laboratory testing was conducted primarily by supplying known gas mixtures to the Model 350 analyzers from the gas delivery system, using a simple manifold that allowed two analyzers to sample the same test atmosphere. This manifold consisted of standard 1/4-inch-diameter Teflon tubing with a set of "Ts" and short tubes from which the test gases could be sampled from each analyzer at atmospheric pressure. The excess vented through a "T" connection on the exit of the manifold, and a rotameter with a needle valve was placed on this line to verify that the manifold provided an excess flow. This valve controlled the flow of gas out of the normal exit of the manifold. To perform the pressure sensitivity tests described in Section 3.8.1.7, an additional line, pressure gauge, and needle valve were connected to a small vacuum pump. Closing the former valve elevated the pressure in the manifold, and opening the latter valve reduced the pressure in the manifold. Adjustment of these two valves allowed close control of the manifold pressure within the target ranges, while maintaining excess flow of the gas mixtures to the manifold.

The procedures for the laboratory tests are described below, in the order in which the tests were performed. The statistical procedures that were applied to the data from each test are presented in Section 9.0 of the test/QA plan[1] and in Chapter 5 of this report.

3.8.1.1 Linearity

The linearity of response of each Model 350 analyzer was tested by 21-point calibrations of all the gases listed in Table 3-4, with the exceptions of low range O_2 and NO_2 (which were redundant with the high range analyzers for these gases). Prior to this check, the analyzers were provided with the appropriate zero gas, and then with a span gas concentration near the respective nominal full scale of the analyzers. After any necessary adjustments to the analyzers to match that span value, the 21-point check proceeded without further adjustments. The 21 points consisted of three replicates each at 10, 20, 40, 70, and 100% of the nominal range, in random order, and interspersed with six replicates of zero gas. Following completion of all 21 points, the zero and 100% spans were repeated, also without adjustment of the analyzers.

3.8.1.2 Response Time

The response times of the analyzers were established by monitoring the rise and fall of the Model 350 responses during the linearity tests. The Model 350 responses were recorded at 10-second intervals until equilibration. These data were used to determine the response times for all analytes, defined as the time to reach 95% of final response after switching from zero gas to the calibration gas, or to drop by 95% in switching to zero gas from calibration gas.

3.8.1.3 Detection Limit

Data from zero gas and from additional 5, 10, and 20% of full-scale points were used to establish the detection limits for CO, NO, NO_2, and SO_2, using the procedure described in Section 9.2.3 of the test/QA plan.[1] For O_2, the data from the linearity test (Section 3.8.1.1) were used to assess the detection limit.

3.8.1.4 Interrupted Sampling

After the zero and span checks at the end of the linearity tests, the electrical power to each Model 350 was turned off for a period of at least 12 hours. The Model 350 analyzers were then powered up, the same zero gas and span concentrations were introduced, and the analyzers' responses were recorded. No adjustment to the analyzers was made during the test. Comparison of the zero and span values before and after shutdown indicated the extent of zero and span drift resulting from the shutdown. Near full-scale levels were used as the span values in this test.

3.8.1.5 Interferences

The effect of potential interferences was tested by delivering test gases containing potential interferants at known concentrations to the Model 350s and monitoring their responses. The potential interferants listed in Table 3-6 were delivered one at a time to the analyzers, and the readings were recorded. Each period of sampling a potential interferant was preceded by a period of sampling zero air. The potential interferants were single components, except for a mixture of SO_2 and NO, which was designed to assess whether SO_2 in combination with NO produces a bias in the NO response.

3.8.1.6 Ambient Temperature Effect

The ambient temperature test quantifies the zero and span drift that may occur as the analyzers are subjected to different temperatures during operation. During this test, the analyzers were provided with zero and span gases at room, elevated, and reduced temperatures. To perform these tests, the Model 350s and the associated zero and span gas cylinders were moved into the temperature-controlled environmental chamber operated by test facility staff. The dimensions of this chamber are about 20 x 40 x 20 feet, thus enabling placement of the analyzers and gas cylinders inside the chamber. The target temperatures for this test were 70±5ºF, 105±5ºF, and 45±5ºF. Table 3-6 shows how the actual interference gas levels were generated.

Table 3-6. Summary of Interference Tests Performed

Interferant	Comments
5.01% CO_2	Generated by supplying undiluted gas from cylinder SA 16671 (5.01% CO_2).
98.3 ppm H_2	Generated by supplying undiluted gas from cylinder CC 139843 (98.3 ppm H_2).
500 ppm NH_3	Generated by dilution of cylinder CC 50070 (2,999 ppm NH_3), with dilution air at 25% of range, and span gas at 5% of range.
HC mix using SA 9072	Generated by supplying undiluted gas from cylinder SA 9072, 50.8 ppm I-butane, 51.3 ppm propane, 100 ppm ethane, and 503 ppm methane.
394 ppm NO and 400 ppm SO_2	Generated by diluting cylinders CC 139372 (2,000 ppm SO_2) and CC 81356 (4,076 ppm NO and 4 ppm NO_2) into one another, then diluting the product gas using the system flow divider. Used MFC #63 at 12.1% of range for SO_2 and MFC #64 at 2.9% of range for NO. Then the effluent was passed through the flow divider, which was set to nominal 40% span and 60% dilution. The resulting effluent (total flow rate) was measured with the BIOS meter and found to be 2.98 SLM.

The analyzers and cylinders were set up inside the chamber at ambient temperature. The analyzers were allowed to operate for at least one hour at a constant temperature. Then a zero, span, and a repeated zero check was performed on each analyzer, and their responses and the chamber temperature were recorded. No zero or span adjustments were conducted after this point. The same zero/span/zero checks were repeated each time after the chamber temperature was changed to 105±5ºF, 45±5ºF, and back to 70±5ºF. Before each zero/span/zero check, the analyzers and cylinders stabilized at each temperature for a period of at least one hour.

3.8.1.7 Pressure Sensitivity

The pressure sensitivity tests quantified the analyzer response and flow to changes in pressure in the sample gas source. The manifold described in Section 3.8.1 was used to determine the effect of the sample gas pressure on Model 350 sample flow rates and responses to known gas concentrations.

The sample flow rate check was performed by providing zero gas to the manifold at ambient pressure, and recording the indicated sample flow rate. The manifold pressure was adjusted to -10 inches of water relative to the room, and the flow rates were again recorded. Then the manifold pressure was adjusted to +10 inches of water relative to the room, and the flow rates were recorded.

The response to gas concentrations was determined by first sampling the appropriate zero gas. Then concentrations equivalent to 60% of full scale were delivered to each analyzer at room pressure, at -10 inches, and at +10 inches. These tests were performed on two Model 350s at a time. The resulting responses to the same concentrations at different pressures were used to assess changes in response as a result of differences in the sample pressure.

3.8.2 Combustion Source Tests

The two combustion sources used for these tests, a gas range burner cooktop and a diesel engine, are described in Section 3.3. Published emission databases were used to set up these sources for the nominal set of desired concentrations.

Prior to sampling, the Testo representative inserted two sample probes into the exhaust duct of the combustion source. The Testo probes were fitted together, sampling from a point within about 1/4 inch of the inlet of the sample line for the reference analyzers. The reference analyzer probe consisted of a 1/4-inch-diameter stainless-steel tube, the upstream 2 inches of which were bent at a right angle for passage into the center of the source exhaust duct. Each combustion source had a dedicated sampling probe, connected to the reference analyzers with 1/4-inch tubing.

The Testo analyzers were operated with their own sample probes and high-velocity non-heated sample transfer lines to condition, dry, and filter the sample. Neither the sampling probe for the reference analyzers nor the reference sample-transfer lines were heated. Visible condensation of combustion-generated water did not occur. The reference analyzer moisture-removal system consisted of a simple ice bath. The particulate-removal system for the reference analyzers consisted of a 47-millimeter in-line quartz filter.

The testing was performed with the combustion sources at or near steady state in terms of NO_x emission. For the range burner, steady state was achieved after about 15 minutes. For the diesel engine, steady state was achieved in about 10 minutes of operation. The engine was operated first at full speed to achieve its lowest NO_x emissions. The engine was operated at idle for about 20 minutes prior to sampling the NO_x emissions, to effectively “detune” its performance.

The order of operation of the combustion sources was as shown in Table 3-2, thus allowing the analyzers to be exposed to continuously increasing NO and NO_2 levels to avoid 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 the pre-test zero and span gases provided from the calibration system, and with both the reference and Testo analyzers sampling the source emissions, the Testo operator indicated when he was ready to take the first set of readings (a set of readings consisting of all responses on both analyzers). At that time, the CE-CERT operator also took corresponding reference 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 Model 350 and reference analyzers. The same zero and span gases were sampled again before moving to the next combustion source.

3.8.2.1 Accuracy

Accuracy relative to reference method results was verified by simultaneously monitoring the emissions from combustion sources with the reference method and with two units of the Model 350.

3.8.2.2 Zero/Span Drift

Zero and span drift were evaluated using data generated in the linearity, interrupted sampling, and ambient temperature tests in the laboratory and the accuracy test on combustion sources. In the combustion source tests, a zero and span check was performed for SO_2, CO, O_2, NO, and NO_2 on each analyzer before sampling the emissions from each source and then again after the source emissions measurements were completed. The zero and span drift were determined as the difference in response on zero and span gases in these two checks. This comparison was made for each analyzer, for all components, for both zero and span response, using data from all the combustion source test conditions. In the laboratory, zero and span values determined at the start and end of the linearity and ambient temperature tests were similarly compared, producing four more zero and four more span points for each species. The interrupted sampling test provided a distinct and independent measure of analyzer drift (zero and span before shutdown and after re-start).

3.8.2.3 Measurement Stability

Stability in source sampling was evaluated in conjunction with the accuracy test. At one load condition during sampling of the diesel engine, each analyzer sampled the emissions for a full hour continuously, with no intervals of room air sampling. Data were recorded for both reference and Model 350 analyzers at 1-minute intervals throughout the period. During this test, only the NO_x channel of the reference analyzer was recorded, because switching back and forth between the NO and NO_x channels involves a manual operation that causes a momentary pressure upset in the analyzer reaction chamber. Stability was assessed based on the uniformity over time of the analyzers' responses, with any instability of source output normalized by means of the reference method data.

Chapter 4
Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) procedures were performed in accordance with the quality management plan (QMP) for the AMS Center,[8] the test/QA plan for this verification test,[1] and the CE-CERT's "Quality Management Plan for the Environmental Technology Verification Program: Testing of Portable Gaseous Emission Analyzers, Revision 1.0," May 2002.

4.1 Instrument Calibration

4.1.1 Reference Method Monitors

The monitors used for O_2, NO/NO_2/NO_x, SO_2, and CO reference measurements were subjected to a four-point calibration with span gas prior to the first day of verification testing. One of the calibration points was zero gas; the other three calibration points were approximately 30, 60, and 100% of the full-scale measuring range. The NO_2 calibration was done using EPA Method EMC ALT-013,[9] i.e., the efficiency of a heated converter for reducing NO_2 to NO was determined. On each day of verification testing, each reference monitor underwent a zero and span check in the morning before the start of testing and again after all testing was completed for the day.

The initial multipoint calibrations of the reference analyzers were performed June 10 through 11, 2002. The results of these calibrations are summarized in Table 4-1. This table shows the range at which each analyzer was calibrated, the correlation coefficients from linear regression analysis, and whether or not each point of the calibration met the requirement of being within ±2% of the span value. As shown in the table, for cases where this ±2% requirement was not met at first, the multipoint calibration was repeated, with satisfactory results. In addition, the O_2 calibrations were repeated because the standard was improperly identified during the initial calibration. Further, the NO_2 converter efficiency of the TEI 10 analyzer was determined to be 94%. This table demonstrates that each reference method analyzer was in control at the time of testing the Model 350s.

In addition, the reference bias was calculated to be an additional 9% using a single-point calibration. This was determined by measuring the NO_2 at the probe tip and then measuring it directly into the reference analyzer. All data have been corrected for both the converter efficiency and the bias.

Table 4-1. Results of Pre-Test Calibrations on Reference Methods

Analyzer	Range	Calibration Date	Error at Each Conc. <2%?	r^2
SO_2	0-25 ppm	6/10/02	N	0.99993
SO_2	0-25 ppm	6/11/02	Y	0.99994
SO_2	0-500 ppm	6/10/02	Y	0.99995
SO_2	0-2,000 ppm	6/10/02	Y	0.999993
CO	0-200 ppm	6/10/02	N	0.99997
CO	0-200 ppm	6/11/02	Y	1.000000
CO	0-1,000 ppm	6/10/02	Y	0.9998
CO	0-5,000 ppm	6/10/02	Y	0.999995
O_2	0-25%	6/10/02	Y	0.99998
O_2	0-10%	6/10/02	Y	0.99995
O_2	0-25%	6/11/02	Y	0.99997
O_2	0-10%	6/11/02	Y	0.99996
CO_2	0-20%	6/10/02	Y	0.99994
CO_2	0-5%	6/10/02	Y	0.999992
NO_x	0-2,500 ppm	6/10/02	N	0.99991
NO_x	0-2,500 ppm	6/11/02	Y	0.9998
NO_x	0-1,000 ppm	6/10/02	Y	0.99997
NO_x	0-250 ppm	6/10/02	Y	0.99995
NO_x	0-25 ppm	6/10/02	Y	0.99993

Additional calibrations of the reference method analyzers were performed June 17 through 21, 2002, before and after each combustion source test. All of these calibrations met the requirements of an analyzer response within ±2% relative to the span value.

4.1.2 Gas Dilution System

The dilution system flow controllers were calibrated prior to the start of the verification test by means of a BIOS Dry Cal flowmeter, serial number H810. Corrections were applied as necessary for temperature, pressure, and water content.

4.1.3 Temperature Sensor/Thermometers

The thermocouple sensor used to determine source emission temperatures and the thermometers used to measure room or chamber temperatures were all calibrated against a certified temperature measurement standard within the six months preceding the verification test. Each source temperature measurement device was also checked once for accuracy, as specified in Section 4.2 of Method 2A, 40 CFR Part 60, Appendix A,[10] and agreement was within ±2%.

4.1.4 Gas Flow Meters

The dry gas meter was calibrated against a volumetric standard within the six months preceding the verification test. In addition, during the verification test, the meter calibration was checked against a reference meter according to the procedure described in Section 4.1 of Method 2A, 40 CFR Part 60, Appendix A.(10)

4.2 Amendments to the Test/QA Plan

During the setup and performance of the verification test, amendments to the test/QA plan were made to better accommodate the specific characteristics of the equipment being tested and to provide improvements to the operation since the plan was written. All amendments required the signature of the Battelle AMS Center Manager, the Battelle Verification Testing Leader, and the Battelle Quality Manager. A planned deviation form was used for documenting and approving the following changes:

1. At the start of the verification test, the analyzer vendor stated that the nominal SO_2 and CO ranges of the high range Model 350 analyzers were 0 to 5,000 ppm and 0 to 10,000 ppm, respectively. These values differed from the nominal ranges of 0 to 2,000 ppm for both gases specified when the test/QA plan was written. The 2,000 ppm SO_2 calibration gas standard obtained for the test was insufficient to cover the nominal 5,000 ppm SO_2 range. However, the Battelle Verification Testing Leader decided to proceed with the linearity test using that standard, and the linearity test for SO_2 was conducted over a 2,000 ppm range (Section 3.8). On the other hand, a high concentration certified standard for CO was available at the test site, and an attempt was made to conduct the CO linearity test over the nominal 10,000 ppm range. As described in Section 3.8, low response was observed in this test; and, after consideration, the vendor staff decided to reduce the range for the CO linearity test to 5,000 ppm.

2. Instead of using the data from the linearity test, a new procedure was developed to more accurately portray the detection limit of the Model 350. This procedure consisted of a set of three cycles between zero and a low concentration value (5% to 20% of range). The new procedure was implemented because the high gas concentrations used in the linearity test caused a residual effect, artificially biasing the detection limits upward.

3. During relative accuracy testing (RA), it was found that the diesel engine tested had very low CO emissions and could not challenge the high-range capability of the Model 350 high-range analyzer. To address this issue, the diesel exhaust stream was “spiked” (for one of the three operating conditions) with CO. The CO was metered into the exhaust stream to attain a sample concentration of approximately 2,000 ppm.

4.3 Standard Certifications

Standard or certified gases were used in all verification tests, and certifications or analytical data are on file documenting the traceability of all the gas standards identified in Table 3-4. All QC documentation and raw data for the verification test are in the test files at CE-CERT and Battelle, to be retained for at least seven years and made available for review if requested.

4.4 Audits

4.4.1 Pre-Test Laboratory Assessment

Battelle assessed CE-CERT's ability to perform the experimental work and verified that CE-CERT met the quality requirements of the test/QA plan prior to initiating the test. CE-CERT provided Battelle its laboratory QMP, related internal standard operating procedures, certification records, training records, calibration records, and other documents necessary to ensure that the CE-CERT had the appropriate operational procedures to ensure quality.

4.4.2 Performance Evaluation Audit

A performance evaluation (PE) audit was conducted on June 12, 2002, to assess the quality of the reference measurements made in this verification test. For the PE audit, an independent standard was used. Table 4-2 shows the results from the PE audit.

Table 4-2. Summary of Performance Audit Results[a]

Measurement to be Audited	Audit Procedure	Results (% difference)
Reference methods for SO_2	Analyze independent standards (i.e., obtained from a different vendor)	1.9
CO		2.9
O_2		1.4
NO		0.3
NO_2		0.3
Temperature	Compare to independent temperature measurement	0.3
Gas Flow Rate	Compare to independent flow measurement	0.4

[a] Each audit procedure was performed once during the test.

The PE audit for the reference methods consisted of analyzing a set of certified gas standards provided by Battelle for comparison to the corresponding standards used in the verification test. The standards provided by Battelle were obtained from a different supplier than those used in the verification and had nominal concentrations similar to the standards against which they were compared. The PE audit of the temperature and flow rate measurements consisted of a side-by-side comparison between the measurement devices used in the verification test and independent devices provided by Battelle. Flow measurements agreed within 5% and temperature readings agreed within 2% in absolute temperature, as specified by the test/QA plan.

4.4.3 Technical Systems Audit

The Battelle Quality Manager conducted a technical systems audit (TSA) June 11 through June 12, 2002, to ensure that the verification test was performed in accordance with the test/QA plan[1] and the AMS Center QMP.[8] As part of the audit, the Battelle Quality Manager reviewed the calibration sources, compared actual test procedures to those specified in the test/QA plan, and reviewed data acquisition and handling procedures. Observations and findings from this audit were documented and submitted to the Verification Test Coordinator for response. No findings were documented that required any corrective action. The records concerning the TSA are permanently stored with the Battelle Quality Manager.

4.4.4 Audit of Data Quality

At least 10% of the data acquired during the verification test was audited. Battelle's Quality Manager traced the data from the initial acquisition, through reduction and statistical analysis, to final reporting, to ensure the integrity of the reported results. All calculations performed on the data undergoing the audit were checked.

4.5 QA/QC Reporting

Each assessment and audit was documented in accordance with Sections 3.3.4 and 3.3.5 of the QMP for the ETV AMS Center.[8] The results of the TSA and the audit of data quality were sent to the EPA.

4.6 Data Review

Test data were reviewed and approved according to the requirements in the documents cited above. At the end of each day's test activities, the test facility QA Officer reviewed the completed data sheets and faxed them to Battelle for review. In addition, the digitized versions of these data sheets were checked against their original hard copies by the test facility QA Officer. Laboratory record notebooks were also reviewed, signed, and dated by the test facility manager.

Other data review focused on the compliance of the reference analyzer data with the quality requirements of each specific method to ensure their usability for comparison with the data from the Model 350 analyzers during the combustion source tests.

Records generated in the verification test received a one-over-one review within two weeks of generation before these records were used to calculate, evaluate, or report verification results. Table 4-3 summarizes the types of data recorded. The review was performed by a Battelle technical staff member involved in the verification test, but not the staff member who originally generated the record. The person performing the review added his/her initials and the date to a hard copy of the record being reviewed.

Table 4-3. Summary of Data Recording Process

Data to be Recorded	Responsible Party	Where Recorded	How Often Recorded	Disposition of Data [a]
Dates, times of test events	Test Facility	Laboratory record books.	Start/end of test, and at each change of a test parameter.	Used to check test results; manually incorporated in data spreadsheets as necessary.
Test parameters (temperature, pressure, analyte/ interferant identities and concentrations, gas flows, etc.)	Test Facility	Laboratory record books.	When set or changed, or as needed to document stability.	Used to check test results, manually incorporated in data spreadsheets as necessary.
Portable analyzer readings				
- digital display	Vendor	Data sheets provided by test facility.	At specified intervals during each test.	Manually entered into spreadsheets.
- printout	Vendor	Original to test facility, copy to vendor.	At specified intervals during each test.	Manually entered into spreadsheets.
- electronic output	Vendor/Test Facility	Data acquisition system (data logger, PC, laptop, etc.).	Continuously at specified acquisition rate throughout each test.	Electronically transferred to spreadsheets.
Reference monitor readings	Test Facility	Data sheets, or data acquisition system, as appropriate.	At specified intervals, or continuously at specified rate in each test.	Transferred to spreadsheets.

[a] All activities subsequent to data recording are carried out by Battelle.

Chapter 5
Statistical Methods

The statistical methods presented in this chapter were used to verify the performance factors listed in Section 3.1.

5.1 Laboratory Tests

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. A separate calibration was carried out for each analyzer unit. The calibration model is

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

where Y_c is the analyzer's response to a challenge concentration c, $h(c)$ is a linear calibration curve, and the error term is assumed to be normally distributed. Variability (σ) of the measured concentration values (c) was modeled by the following relationship:

$$\sigma_c^2 = a + k\,c^{\beta} \tag{2}$$

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

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

The form of the regression model to be fitted is $h(c) = \alpha_o + \alpha_1 c$. Concentration values were calculated from the estimated calibration curve using the formula

$$c = h^{-1}(Y_c) = (Y_c - \alpha_o)/\alpha_1 \tag{4}$$

A test for departure from linearity was carried out by comparing the residual sum of squares

$$\sum_{i=1}^{6} \left(\bar{Y}_{c_i} - a_0 - a_1 c_i\right)^2 n_{c_i} w_{c_i} \quad (5)$$

to a chi-square distribution with 6 - 2 = 4 degrees of freedom. (n_c is the number of replicates at concentration c).

5.1.2 Response Time

The response time of the analyzers to a step change in analyte concentration was calculated by determining the total change in response due to the step change (either increase or decrease) in concentration, and then determining the point in time when 95% of that change was achieved. Both rise and fall times were determined. Using data taken every 10 seconds, the following calculation was carried out:

$$\text{Total Response} = R_a - R_b \quad (6)$$

where R_a is the final response of the analyzer to the test gas after the step change, and R_b is the final response of the analyzer before the step change. The analyzer response that indicates the response time then is

$$\text{Response}_{RT} = 0.95(\text{Total Response}) \quad (7)$$

The point in time at which this response occurs was determined by inspecting the response/time data, and the response time was calculated as

$$RT = \text{Time}_{95\%} - \text{Time}_I, \quad (8)$$

where $\text{Time}_{95\%}$ is the time at which Response_{RT} occurs, and Time_I is the time at which the step change in concentration was imposed. Since only one determination was made, the precision of the rise and fall time results could not be estimated.

5.1.3 Detection Limit

The detection limit (LOD) was defined as the smallest true concentration at which the analyzer's expected response exceeded the calibration curve at zero concentration by three times the standard deviation of the analyzer's zero reading, i.e., $\alpha_o + 3\,\sigma_o$. The LOD may then be determined by

$$LOD = [(\alpha_o + 3\sigma_o) - \alpha_o]/\alpha_1 = 3\sigma_o/\alpha_1 \quad (9)$$

where σ_o is the estimated standard deviation at zero concentration. 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.

5.1.4 Interrupted Sampling

The effect of interrupted sampling was assessed by calculating the arithmetic difference between zero and span responses obtained before and after the analyzers were shut down overnight. No estimate could be made of the precision of the observed differences.

5.1.5 Interferences

The extent of interference was reported in terms of the absolute response of the analyzer to each interferant, and was also calculated in terms of the sensitivity of the analyzer to the interfering species, relative to its sensitivity to SO_2, CO, O_2, NO, or NO_2. The relative sensitivity was calculated as the ratio of the observed 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 a difference in NO reading of 1 ppm. The relative sensitivity of the NO analyzer to CO is thus 1 ppm/500 ppm = 0.2 %. The precision of the interference results was not estimated from the data obtained, since only two measurements were made for each interferant.

5.1.6 Ambient Temperature Effect

The response data obtained from a single point span check or a zero check at a given temperature and a given concentration (i.e., zero or span) are not statistically independent. Therefore, the average value in each sampling period was used as a single value in the comparison. Thus, at room temperature, low temperature, and high temperature, there were two data points for each analyzer, consisting of the average response on zero gas and the average response on span gas, for each target analyte. Variability for low and for high temperatures was assumed to be the same as the variability at room temperature, and the variability determined in the linearity test was used for this analysis. The presence of an ambient temperature effect on zero and span readings was assessed by trend analysis for response with temperature, using separate linear regression analyses for the zero and for the span data.

5.1.7 Pressure Sensitivity

At 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 for each target analyte. The analyzer response data at a given duct pressure and a given concentration (i.e., zero or span) are not statistically independent; therefore, the average value in each sampling period was used in the comparison. Thus, for ambient pressure, reduced pressure, and increased pressure, there were three total data points for each analyzer for each analyte, namely the analyzer flow rate, average response on zero gas, and average response on span gas. Variability for reduced and increased pressures was assumed to be the same as variability at ambient pressure, and the variability determined in the linearity test was used for this analysis. The presence of a duct pressure effect on analyzer flow rates and response was assessed by separate linear regression trend analyses for flow rate and for response. The trend analysis for response consisted of separate analyses for the zero and for the span data.

5.2 Combustion Source Tests

5.2.1 Accuracy

The percent RA of the analyzers with respect to the reference method was assessed by

$$RA = \frac{\left[\bar{d}\right] + t_{n-1}^{\alpha} \frac{S_d}{\sqrt{n}}}{\bar{x}} \times 100\% \qquad (10)$$

where $\bar{d}$ refers to the average difference between the reference and tested methods and $\bar{x}$ corresponds to the average reference method value. S_d denotes the sample standard deviation of the differences and was estimated 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 RA was determined for an α value of 0.025 (i.e., 97.5% confidence level, one-tailed). The RA calculated in this way was interpreted as an upper confidence bound for the relative bias of the analyzer. RA was calculated separately for each analyzer and for each target analyte.

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 source emissions. 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 the 60 minutes of data from this test. The existence of a trend in the data was assessed by fitting a linear regression line, with the difference between analyzer and corresponding reference readings as the dependent variable and time as the independent variable. The null hypothesis that the slope of the trend line was zero was tested using a one-sample two-tailed t-test with n-2 = 58 degrees of freedom.

5.2.4 Inter-Unit Repeatability

Inter-unit repeatability was assessed for the linearity, detection limit, accuracy, and measurement stability tests. A Student's t-test was used to compare where appropriate. For the measurement stability test, inter-unit repeatability was assessed by a linear regression of the inter-unit difference against time. The null hypothesis that the slope of the line is zero was tested using a matched-pairs t-test with n-2 = 58 degrees of freedom.

5.3 Data Completeness

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

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

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

Chapter 6
Test Results

The results of the verification test of the Model 350 analyzers are presented in this section. Throughout this section, the two low range analyzers are designated as units L1 and L2, and the two high range analyzers as units H1 and H2.

6.1 Linearity

Figures 6-1a and b show the linearity results, and Tables 6-1a through g list the data obtained from the linearity tests for the Model 350 high range analyzers (CO, NO, NO_2, O_2, SO_2) and low range analyzers (CO, NO), respectively. Table 6-2 shows the linear equations for each analyte developed from this data.

The results shown in Tables 6-1 and 6-2 confirm that the Model 350 provides linear response over wide operating ranges. The regression slopes shown in Table 6-2 range from 0.994 to 1.05, with all sensors except for the high range NO meeting the expected range of 0.98 to 1.02.[11] Similarly, the regression coefficient values (r^2) all exceed 0.9998. The positive intercepts in Tables 6-1b and e indicate that the NO and SO_2 responses at the zero concentration level were slightly positive for the high range analyzers.

Tables 6-1a, b, and e indicate that the analyzers' CO, NO, and SO_2 responses at the zero concentration level were slightly positive. This finding is believed to be caused by the wide range over which the Testo analyzers were calibrated in the linearity test. That is, exposure of the analyzers (and the entire sampling inlet) to NO levels of up to 3,000 ppm, CO to 5,000 ppm, and SO_2 to 2,000 ppm apparently caused a slight "memory" effect, in that analyzer response did not return completely to zero when provided with zero gas. The evidence for a memory effect, rather than a real offset, comes from the temporal increase in the zero readings. From Table 6-1b, for Testo Unit H1 the six zero readings from the NO linearity test were 0, 0, 4, 6, 9, and 1 ppm, whereas for Unit H2 they were 0, 0, 3, 7, 10, and 2 ppm. The upward trend in zero readings suggests a cumulative effect of exposure to high levels of NO. No comparable effect was seen for NO_2 (Table 6-1c), probably because the NO_2 linearity test used a much lower concentration range. Similarly, in combustion source tests described later in this section, a negligible change in NO readings on zero gas was seen after exposure to NO at levels up to 300 ppm. Thus, the slight upward trend in NO zero readings appears to be an artifact of the high NO levels used in the linearity test. The same magnitude was shown in the CO and SO_2 response and also appears to be an artifact of high concentrations.

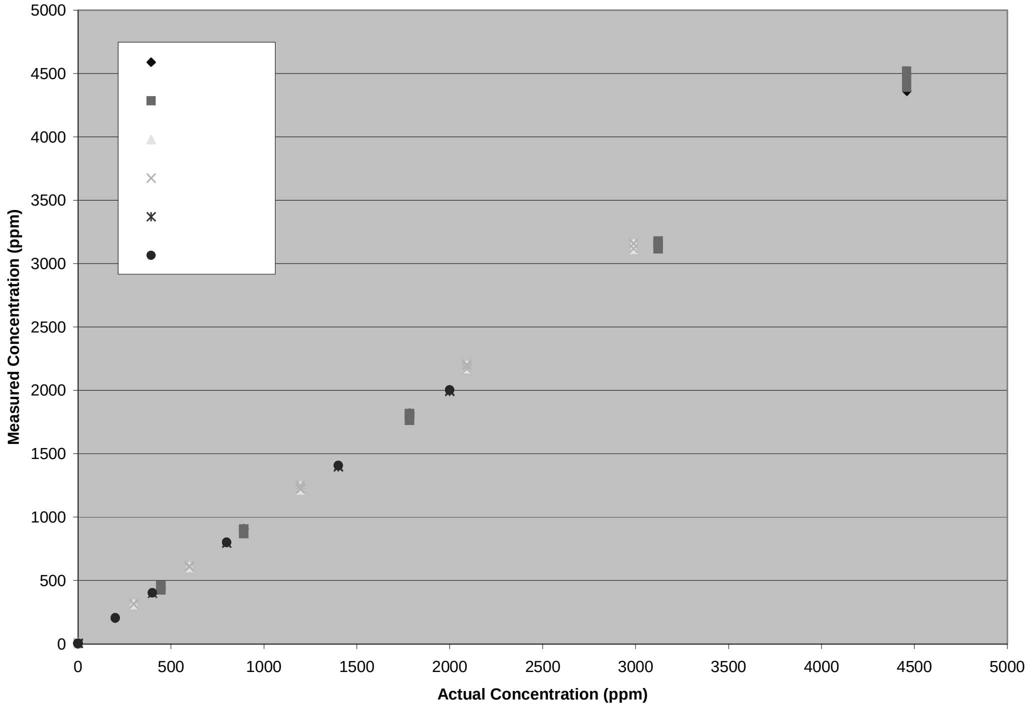

Figure 6-1a. Linearity Results for High Range Analyzers

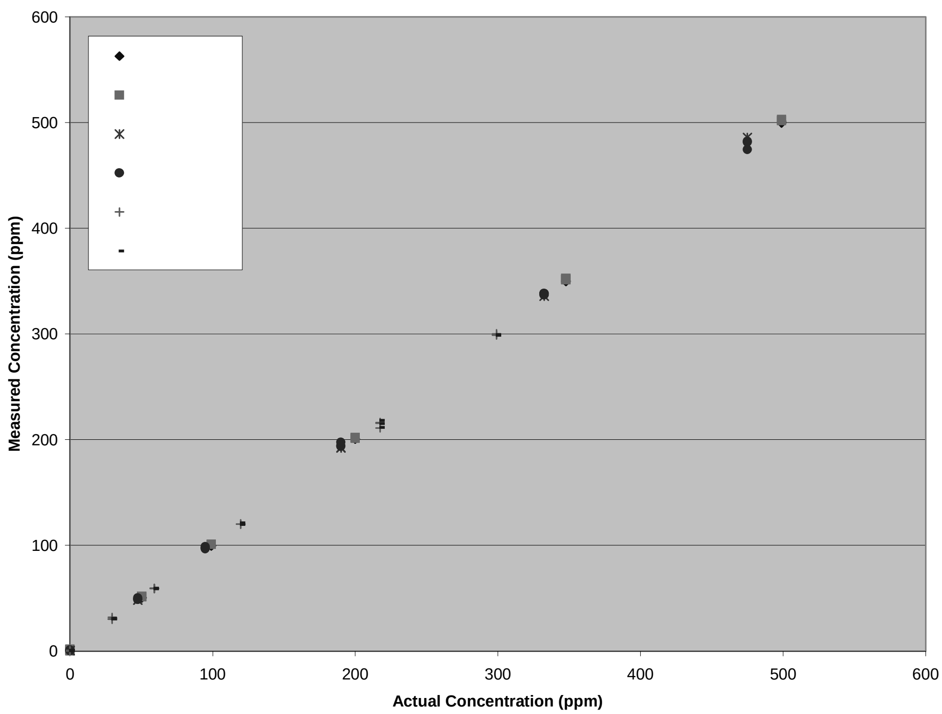

Figure 6-1b. Linearity Results for Low Range Analyzers

Table 6-1a. CO Data from Linearity Test of Model 350 High Range Analyzers

Reading	Actual CO (ppm)	Unit H1 CO (ppm)	Unit H2 CO (ppm)
1	0	0	0
2	4,460	4,510	4,516
3	446	462	461
4	1,784	1,818	1,817
5	0[a]	6	6
6	3,122[a]	3,177	3,178
7	892[a]	908	905
8	446	453	451
9	0	4	4
10	892	906	899
11	1,784	1,810	1,803
12	3,122	3,158	3,151
13	0	5	4
14	4,460	4,463	4,453
15	3,122	3,127	3,115
16	1,784	1,773	1,763
17	0	4	4
18	892	875	868
19	446	431	425
20	4,460	4,360	4,390
21	0	3	2

(a) Points used for response test times.

Table 6-1b. NO Data from Linearity Test of Model 350 High Range Analyzers

Reading	Actual NO (ppm)	Unit H1 NO (ppm)	Unit H2 NO (ppm)
1	0	0	0
2	2,989	3,112	3,118
3	299	312	314
4	1,196	1,216	1,220
5	0[a]	0	0
6	2,092[a]	2,170	2,170
7	598[a]	610	614
8	299	314	314
9	0	4	3
10	598	605	606
11	1,196	1,226	1,230
12	2,092	2,190	2,192
13	0	6	7
14	2,989	3,157	3,158
15	2,092	2,200	2,203
16	1,196	1,250	1,252
17	0	9	10
18	598	612	614
19	299	318	317
20	2,989	3,160	3,159
21	0	1	2

(a) Points used for response test times.

Table 6-1c. NO_2 Data from Linearity Test of Model 350 Analyzers

Reading	Actual NO_2 (ppm)	Unit H1 NO_2 (ppm)	Unit H2 NO_2 (ppm)
1	0	0.1	0.4
2	475	474.2	474.3
3	47.5	49.7	50.2
4	190	192.1	194.1
5	0[a]	0.2	0.5
6	333[a]	335.6	336.8
7	95.0[a]	97.7	98.6
8	47.5	48.3	49
9	0	0.2	0.9
10	95.0	96.7	96.7
11	190	192.4	193.6
12	333	338.1	338.4
13	0	0.5	0.8
14	475	482.1	481.2
15	333	337.2	337.8
16	190	197.1	197.4
17	0	0.8	1
18	95.0	96.8	97.1
19	47.5	48.2	48.8
20	475	486	482.3
21	0	0.5	0.8

(a) Points used for response test times.

Table 6-1d. O_2 Data from Linearity Test of Model 350 Analyzers

Reading	Actual O_2 (%)	Unit H1 O_2 (%)	Unit H2 O_2 (%)
1	0	0	0
2	20	20	20
3	2.1	1.9	1.9
4	8	7.9	7.9
5	0[a]	0[a]	0
6	14[a]	14[a]	14
7	4[a]	4[a]	4
8	2.1	2	2
9	0	0	0
10	4	4	4
11	8	7.9	7.9
12	14	14	14
13	0	0	0
14	20	20	20
15	14	14	14
16	8	7.9	8
17	0	0	0
18	4	4	4
19	2.1	2	2
20	20	20	20
21	0	0	0

(a) Points used for response test times.

Table 6-1e. SO_2 Data from Linearity Test of Model 350 Analyzers

Reading	Actual SO_2 (ppm)	Unit H1 SO_2 (ppm)	Unit H2 SO_2 (ppm)
1	0	0	1
2	2,000	1,993	2,001
3	200	206	206
4	800	796	799
5	0[a]	4	4
6	1,400[a]	1,398	1,405
7	400[a]	405	404
8	200	204	203
9	0	4	4
10	400	401	401
11	800	796	800
12	1,400	1,401	1,406
13	0	5	6
14	2,000	1,996	2,005
15	1,400	1,403	1,408
16	800	802	803
17	0	5	5
18	400	400	401
19	200	203	203
20	2,000	1,995	2,002
21	0	1	2

[(a)] Points used for response test times.

Table 6-1f. CO Data from Linearity Test of Model 350 Low Range Analyzers

Reading	Actual CO (ppm)	Unit L1 CO (ppm)	Unit L2 CO (ppm)
1	0	0.4	0
2	499	501.3	502
3	50.4	51.1	51.8
4	200	201.1	201
5	0[a]	0.1	0.4
6	348[a]	350.1	352.6
7	99.1[a]	100.2	101
8	50.4	50.7	51.2
9	0	0.5	1.2
10	99.1	99.3	100.8
11	200	200.4	201.5
12	348	349.5	351.6
13	0	0.4	1.1
14	499	499.5	502.6
15	348	350.1	351
16	200	200.6	202.1
17	0	1.1	1.8
18	99.1	99.7	101
19	50.4	50.2	51.1
20	499	499.5	501.5
21	0	1.1	1.5

(a) Points used for response test times.

Table 6-1g. NO Data from Linearity Test of Model 350 Low Range Analyzers

Reading	Actual NO (ppm)	Unit L1 NO (ppm)	Unit L2 NO (ppm)
1	0	0.3	0.1
2	299	300	299.2
3	29.6	31.8	31
4	120	120.1	119.5
5	0[a]	0.1	0.2
6	217[a]	215.6	215
7	59.2[a]	59.5	59.2
8	29.6	30.5	30.4
9	0	0.4	0.6
10	59.2	59.1	58.8
11	120	120	119.9
12	217	211	211.4
13	0	0.4	0.5
14	299	299.2	298.5
15	217	216.1	218.2
16	120	120.2	121.1
17	0	0.2	0.3
18	59.2	59.1	59.3
19	29.6	30.1	30.2
20	299	298.9	298.7
21	0	0.4	0.2

[(a)] Points used for response test times.

Table 6-2. Statistical Results for Linearity Test

		Intercept (ppm) (standard error)	Slope (standard error)	r^2
High Range Analyzers	CO (H1)	7.384 (9.663)	0.9996 (0.004)	0.9996
	CO (H2)	3.630 (8.545)	1.001 (0.004)	0.9997
	NO (H1)	-5.318 (5.055)	1.049 (0.003)	0.9998
	NO (H2)	-4.412 (4.707)	1.050 (0.003)	0.9998
	NO_2 (H1)	0.663 (0.596)	1.012 (0.003)	0.9999
	NO_2 (H2)	1.469 (0.593)	1.009 (0.003)	0.9999
	O_2 (H1)	-0.044 (0.018)	1.002 (0.002)	0.9999
	O_2 (H2)	-0.049 (0.017)	1.002 (0.002)	0.9999
	SO_2 (H1)	3.550 (0.801)	0.996 (0.001)	1
	SO_2 (H2)	3.176 (0.724)	1.000 (0.001)	1
Low Range Analyzers	CO (L1)	0.512 (0.196)	1.002 (0.001)	1
	CO (L2)	1.001 (0.233)	1.005 (0.001)	1
	NO (L1)	0.480 (0.477)	0.995 (0.003)	0.9998
	NO (L2)	0.466 (0.445)	0.994 (0.003)	0.9998

However, the effect observed might be important in real sampling, specifically in the instance where an analyzer was used to measure both low and high NO_x levels, e.g., upstream and downstream of a selective catalytic reactor (SCR) for NO_x removal. If a single calibration covering the entire range of concentrations to be encountered were prepared, measurements at the low concentrations (i.e., downstream of the SCR) might be compromised. In that instance, it would be preferable to conduct a low-level calibration and low-level measurements (downstream of the SCR), followed by a high-level calibration and upstream measurements. Alternatively, dilution of the high-level stream, or use of two different sensors for the low and high concentration regimes, would be preferable.

6.2 Response Time

Tables 6-3a through g list the data obtained for the response time tests of the Model 350 analyzers. Table 6-4 shows the response time results for each sensor based on a step change in analyte concentration. Response times for CO, NO, NO_2, O_2, and SO_2 were tested with the high range analyzers, and for CO and NO with the low range analyzers.

Table 6-4 shows that the Model 350 analyzers provided response times between 10 and 32 seconds for all analytes with both low and high range analyzers.

Table 6-3a. CO Response Time for Model 350 High Range Analyzers

Time (sec)	Analyzer H1 0% to 100% Analyzer Response (ppm)	Analyzer H1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer H2 0% to 100% Analyzer Response (ppm)	Analyzer H2 70% to 20% Analyzer Response (ppm)
0	5	3,177	0	4	3,178
10	33	3,017	10	77	2,020
20	2,020	2,020	20	2,030	1,920
30	2,990	1,280	30	3,010	1,144
40	3,120	972	40	3,170	966
50	3,160	940	50	3,162	936
60	3,171	927	60	3,172	923
70	3,173	923	70	3,176	918
80	3,177	919	80	3,179	916
90	3,179	915	90	3,178	911
100	3,181	913	100	3,182	911
110	3,180	912	110	3,177	907
120	3,178	912	120	3,176	907
130	3,177	909	130	3,178	905
140		909	140		905
150		908	150		905

Table 6-3b. NO Response Time for Model 350 High Range Analyzers

Time (sec)	Analyzer H1 0% to 100% Analyzer Response (ppm)	Analyzer H1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer H2 0% to 100% Analyzer Response (ppm)	Analyzer H2 70% to 20% Analyzer Response (ppm)
0	0	2,170	0	0	2,170
10	580	1,560	10	312	1,450
20	2,102	740	20	2,126	670
30	2,146	629	30	2,144	635
40	2,155	622	40	2,151	627
50	2,156	617	50	2,158	622
60	2,162	616	60	2,162	620
70	2,163	615	70	2,162	617
80	2,161	613	80	2,164	618
90	2,165	612	90	2,165	614
100	2,168	612	100	2,166	615
110	2,170	611	110	2,168	614
120	2,170	610	120	2,170	614
130		610	130	2,170	613
140		610	140		614
150		610	150		614

Table 6-3c. NO_2 Response Time for Model 350 High Range Analyzers

Time (sec)	Analyzer H1 0% to 100% Analyzer Response (ppm)	Analyzer H1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer H2 0% to 100% Analyzer Response (ppm)	Analyzer H2 70% to 20% Analyzer Response (ppm)
0	0.2	335.6	0	0.5	336.8
10	47.2	289.2	10	50.5	258.3
20	381.3	140.7	20	377.5	147.7
30	319.4	116.8	30	318.5	111.8
40	329.2	102.5	40	330.6	103.5
50	332.4	100.3	50	333.7	101.2
60	334.2	98.1	60	334.9	99.6
70	335.7	98.4	70	335.6	99.4
80	334.8	98.1	80	335.1	99.2
90	335.6	97.7	90	336.2	98.2
100	335.6	97.9	100	336.8	98.2
110		97.9	110		98.6
120		97.7	120		98.7

Table 6-3d. O_2 Response Time for Model 350 High Range Analyzers

Time (sec)	Analyzer H1 0% to 100% Analyzer Response (%)	Analyzer H1 70% to 20% Analyzer Response (%)	Time (sec)	Analyzer H2 0% to 100% Analyzer Response (%)	Analyzer H2 70% to 20% Analyzer Response (%)
0	0	14	0	0	14
10	1.5	9	10	2.5	9
20	13.6	4.2	20	13.6	4.2
30	13.9	4	30	13.9	4
40	14	4	40	14	4
50	14	4	50	14	4
60	14	4	60	14	4

Table 6-3e. SO_2 Response Time for Model 350 High Range Analyzers

Time (sec)	Analyzer H1 0% to 100% Analyzer Response (ppm)	Analyzer H1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer H2 0% to 100% Analyzer Response (ppm)	Analyzer H2 70% to 20% Analyzer Response (ppm)
0	4	1,398	0	4	1,405
10	391	978	10	420	933
20	1,244	468	20	1,264	465
30	1,347	425	30	1,360	423
40	1,366	417	40	1,382	417
50	1,379	416	50	1,391	413
60	1,384	411	60	1,394	412
70	1,386	407	70	1,395	408
80	1,390	405	80	1,398	407
90	1,392	406	90	1,400	407
100	1,394	405	100	1,402	405
110	1,397	405	110	1,402	405
120	1,395	402	120	1,403	405
130	1,397	403	130	1,404	405
140	1,398	405	140	1,404	404
150	1,398		150	1,405	
160	1,398		160	1,405	

Table 6-3f. CO Response Time for Model 350 Low Range Analyzers

Time (sec)	Analyzer L1 0% to 100% Analyzer Response (ppm)	Analyzer L1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer L2 0% to 100% Analyzer Response (ppm)	Analyzer L2 70% to 20% Analyzer Response (ppm)
0		349	0		350
10	203	346	10	203	348
20	311	247	20	336	212
30	340	154	30	342	139
40	345	110	40	349.7	109
50	347.5	104	50	349.8	106
60	348.5	102.6	60	351.5	102
70	349	101.4	70	352.5	103.2
80	349.2	101.1	80	352.6	103
90	350.1	100.6	90	353	102
100	350.1	100.6	100	353	102
110	350.1	100.4	110	352.6	101
120		100.2	120		101

Table 6-3g. NO Response Time for Model 350 Low Range Analyzers

Time (sec)	Analyzer L1 0% to 100% Analyzer Response (ppm)	Analyzer L1 70% to 20% Analyzer Response (ppm)	Time (sec)	Analyzer L2 0% to 100% Analyzer Response (ppm)	Analyzer L2 70% to 20% Analyzer Response (ppm)
0	0	215.6	0	0	215
10	205	102	10	210	135
20	213.3	61.9	20	213.4	60.9
30	214.5	60.2	30	214.2	60.1
40	214.3	60.1	40	214.1	60
50	214.7	59.8	50	214.5	59.5
60	214.8	59.5	60	214.9	59.2
70	215.3		70	214.8	
80	215.6		80	215.1	
90	215.6		90	215	

Table 6-4. Response Time Results for Model 350 Analyzers

		Response Time (Seconds)
High Range Analyzers	CO (H1)	32
	CO (H2)	30
	NO (H1)	20
	NO (H2)	20
	NO_2 (H1)	18
	NO_2 (H2)	18
	O_2 (H1)	20
	O_2 (H2)	19
	SO_2 (H1)	27
	SO_2 (H2)	27
Low Range Analyzers	CO (L1)	NA
	CO (L2)	NA
	NO (L1)	10
	NO (L2)	10

NA= Not Available

6.3 Detection Limit

Tables 6-5a through f show the detection limits for each Model 350 analyzer and each analyte, determined from the detection limit procedure described in Section 4.2. These detection limits apply to the calibrations over a 0 to 5% or 0 to 20% range for each sensor. The detection limit for O_2 was assessed based on the data from the linearity test (Table 6-1d). Calculated detection limits for high range analyzers were 1.22 ppm for CO, 1.57 and 1.66 ppm for NO, 0.41 and 0.26 ppm for NO_2, and 1.24 ppm for SO_2. The calculated NO detection limits for low range analyzers were 0.25 and 0.45 ppm; that for CO was 0.25 ppm.

In a few cases, including the high range CO measurement on analyzer H2 (Table 6-5a), the low range CO measurement on analyzer L1 (Table 6-5e), and the O_2 measurements on both high range analyzers (Table 6-1d), every reading from the Model 350 was exactly zero at a supplied concentration of zero. This resulted in a 0.0 standard deviation, and, therefore, an artificial 0.0 detection limit, according to the specified calculation.

Table 6-5a. High CO Detection Limits for Model 350 Analyzers

CO Input Value (% of range)	CO Input Value (ppm)	Analyzer H1 CO Response (ppm)	Analyzer H2 CO Response (ppm)
0	0	0	1
5	504	504	504
0	0	1	1
5	504	507	507
0	0	0	1
5	504	507	507
0	0	0	1
5	504	504	503
0	0	0	1
5	504	505	505
0	0	0	1
5	504	504	504
Slope		1.00	1.00
Standard Deviation (ppm)		0.41	0.00
Detection Limit (ppm)		1.22	0.00

Table 6-5b. High NO Detection Limits for Model 350 Analyzers

NO Input Value (% of range)	NO Input Value (ppm)	Analyzer H1 NO Response (ppm)	Analyzer H2 NO Response (ppm)
0	0	0	0
5	160	159	158
0	0	1	1
5	160	159	159
0	0	0	1
5	160	159	158
0	0	1	1
5	160	159	159
0	0	1	1
5	160	160	160
0	0	0	0
5	160	159	159
Slope		0.99	0.99
Standard Deviation (ppm)		0.55	0.52
Detection Limit (ppm)		1.66	1.57

Table 6-5c. High NO_2 Detection Limits for Model 350 Analyzers

NO_2 Input Value (% of range)	NO_2 Input Value (ppm)	Analyzer H1 NO_2 Response (ppm)	Analyzer H2 NO_2 Response (ppm)
0	0	0.1	0.4
20	95	95.5	96.3
0	0	0.1	0.4
20	95	95.1	95.8
0	0	0.3	0.2
20	95	95.9	96.2
0	0	0.4	0.4
20	95	95.6	96
0	0	0.2	0.4
20	95	95.1	95.9
0	0	0.4	0.4
20	95	95.4	95.9
Slope		1.00	0.94
Standard Deviation (ppm)		0.14	0.08
Detection Limit (ppm)		0.41	0.26

Table 6-5d. High SO_2 Detection Limits for Model 350 Analyzers

SO_2 Input Value (% of range)	SO_2 Input Value (ppm)	Analyzer H1 SO_2 Response (ppm)	Analyzer H2 SO_2 Response (ppm)
0	0	0	0
5	101.2	101	101
0	0	1	1
5	101.2	101	101
0	0	1	1
5	101.2	101	100
0	0	1	1
5	101.2	100	100
0	0	1	1
5	101.2	101	101
0	0	1	1
5	101.2	101	101
Slope		0.99	0.99
Standard Deviation (ppm)		0.41	0.41
Detection Limit (ppm)		1.24	1.24

Table 6-5e. Low CO Detection Limits for Model 350 Analyzers

CO Input Value (% of range)	CO Input Value (ppm)	Analyzer L1 CO Response (ppm)	Analyzer L2 CO Response (ppm)
0	0	0	0
20	99.1	97.1	97.6
0	0	0	0
20	99.1	96.2	97.7
0	0	0	0.1
20	99.1	96.1	98.3
0	0	0	0
20	99.1	96.2	97.2
0	0	0	0
20	99.1	96.2	97.6
0	0	0	0.2
20	99.1	96.5	97.4
Slope		0.97	0.98
Standard Deviation (ppm)		0.00	0.08
Detection Limit (ppm)		0.00	0.25

Table 6-5f. Low NO Detection Limits for Model 350 Analyzers

NO Input Value (% of range)	NO Input Value (ppm)	Analyzer L1 NO Response (ppm)	Analyzer L2 NO Response (ppm)
0	0	0.3	0.1
20	60.5	61	61
0	0	0.5	0.5
20	60.5	61	61.1
0	0	0.5	0.4
20	60.5	61.4	60.7
0	0	0.4	0.4
20	60.5	61.6	61
0	0	0.5	0.2
20	60.5	61.3	60.9
0	0	0.5	0.4
20	60.5	61	60.6
Slope		1.00	1.00
Standard Deviation (ppm)		0.08	0.15
Detection Limit (ppm)		0.25	0.45

6.4 Interferences

Table 6-6 lists the response data obtained during the interference tests. Each interferant gas was run twice on each analyzer, so Table 6-6 shows two entries for all results. Table 6-7 shows the results of the interference tests in terms of the sensitivity to a specific interferant relative to that for each target analyte. Table 6-6 indicates that the single-blend test interferants and the hydrocarbon mix rarely produced any response from any of the sensors (i.e., sensors showed zero readings during sampling of those interferants). Thus, no interference is indicated from any of these species. Sampling of the NO/SO_2 mixture produced some departures from the expected responses (Table 6-6). For example, analyzer H1 read slightly higher, and analyzer H2 slightly lower, than the 400 ppm SO_2 concentration. These results are quantified as percentage differences in Table 6-7, but do not indicate any consistent interference in the SO_2 measurement from the NO present. On the other hand, the NO readings from both analyzers were consistently lower than the 394 ppm NO concentration, by 2.3 to 4.8% (Table 6-7). These data suggest a slight interference in the NO measurement from the co-present SO_2. NO_2 readings of 3 to 5 ppm were also found with this gas mixture (Table 6-6), equivalent to about 1% of the 394-ppm NO concentration. The NO_2 detected may have been present as an impurity in the NO standard; but, in any case, is not sufficient to account for the 2.3 to 4.8% deficit in NO readings with the NO/SO_2 mixture. These responses, however, were all less than 1% of the range for each sensor.

6.5 Ambient Temperature Effect

Tables 6-8a through g list the data obtained from the ambient temperature tests with the Model 350 analyzers. Table 6-9 shows the results of the temperature tests, with an indication of whether a significant dependence of zero or span response on temperature was observed. Statistically significant differences in zero readings were found in Unit H1 CO, Unit H1 and H2 O_2, and Unit L1 CO sensors. However, the differences amounted to only 1 ppm, 0.1%, 0.1%, and 0.15 ppm, respectively. Statistically significant differences in span readings were found only in the Unit H2 CO sensor. The difference in unit H2 CO readings between the highest and lowest temperatures was 16 ppm (i.e., 3.2% of the span gas concentration).

Table 6-6. Data from Interference Tests with Model 350 High Range Analyzers

Interference Gas Value	Analyzer H1 Response (ppm or % O_2)					Analyzer H2 Response (ppm or % O_2)				
	SO_2	NO	NO_2	CO	O_2	SO_2	NO	NO_2	CO	O_2
Zero, N_2	0[a]	0	0	0	0	0	0	0.2	0	0
	0[a]	0	0	0	0	0	0	0	0	0
5.01% CO_2	0	0	0	0	0	0	1	0.5	0	0
	0	0	0	0	0	0	0	0	0	0
98.3 ppm H_2	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
500 ppm NH_3	0	0	0	0	0	0	0	0	0	0
	0	1	0	0	0	0	0	0	0	0
HC Mix using	0	0	0	0	0	0	0	0	0	0
SA 9072	0	0	0	0	0	0	0	0	0	0
394 ppm NO and	405	375	4	0	0	402	385	5.0	0	0
400 ppm SO_2	388	384	3	0	0	383	383	3.6	0	0

[a] Dual entries indicate results from two trials with each interferant gas.

Table 6-7. Relative Sensitivity Results from Interference Tests with Model 350 High Range Analyzers

Interference Gas Value	Analyzer H1 Response (ppm) (relative sensitivity, %)[a]					Analyzer H2 Response (relative sensitivity, %)[a]				
	SO_2	NO	NO_2	CO	O_2	SO_2	NO	NO_2	CO	O_2
5.01% CO_2	[b]	0.002	0	0	0	0	0	0	0	0
	0[b]	0.002	0.001	0	0	0	0	0	0	0
0										
98.3 ppm H_2	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
500 ppm NH_3	0	0	0	0	0	0	0.2	0	0	0
	0	0	0	0	0	0	0	0	0	0
HC Mix using	0	0	0	0	0	0	0	0	0	0
SA 9072	0	0	0	0	0	0	0	0	0	0
394 ppm NO and	1.3[c]	-4.8[d]	1.0[d]	0	0	-1.5[c]	-2.5[d]	0.8[d]	0	0
400 ppm SO_2	0.5[c]	-2.3[d]	1.3[d]	0	0	-4.2[c]	-2.8[d]	0.9[d]	0	0

(a) Sensitivity to interferant species relative to sensitivity to indicated target analyte.
(b) Dual entries indicate results from the two trials with each interferant gas.
(c) Calculated relative to 400 ppm SO_2.
(d) Calculated relative to 394 ppm NO.

Table 6-8a. CO Data from Temperature Sensitivity Test with Model 350 High Range Analyzers

Temperature (°F)	Gas Component	CO Input Value (ppm)	Analyzer H1 CO Response (ppm)	Analyzer H2 CO Response (ppm)
67.7	Zero Gas	0	0	0
68.1	Span Gas	504	501	500
68.0	Zero Gas	0	0	0
105.7	Zero Gas	0	1	0
104.3	Span Gas	504	510	508
107.5	Zero Gas	0	1	0
47.3	Zero Gas	0	0	0
47.4	Span Gas	504	507	492
47.0	Zero Gas	0	0	0
67.8	Zero Gas	0	0	0
66.6	Span Gas	504	500	496
67.8	Zero Gas	0	0	0

Table 6-8b. NO Data from Temperature Sensitivity Test with Model 350 High Range Analyzers

Temperature (°F)	Gas Component	NO Input Value (ppm)	Analyzer H1 NO Response (ppm)	Analyzer H2 NO Response (ppm)
67.7	Zero Gas	0	0	0
67.9	Span Gas	201.7	201	201
68.0	Zero Gas	0	0	0
105.8	Zero Gas	0	0	0
105.3	Span Gas	201.7	203	204
108.1	Zero Gas	0	0	0
47.3	Zero Gas	0	0	1
46.8	Span Gas	201.7	202	203
47.0	Zero Gas	0	0	0
67.8	Zero Gas	0	0	0
67.8	Span Gas	201.7	202	204
67.8	Zero Gas	0	0	0

Table 6-8c. NO_2 Data from Temperature Sensitivity Test with Model 350 High Range Analyzers

Temperature (°F)	Gas Component	NO_2 Input Value (ppm)	Analyzer H1 NO_2 Response (ppm)	Analyzer H2 NO_2 Response (ppm)
67.7	Zero Gas	0	0	0
67.8	Span Gas	475	473.2	473
68.1	Zero Gas	0	0	0
105.9	Zero Gas	0	0	0
106.1	Span Gas	475	474.6	476.2
108.1	Zero Gas	0	0	0
47.3	Zero Gas	0	0	0
46.8	Span Gas	475	486.1	496.2
47.0	Zero Gas	0	0	0
67.8	Zero Gas	0	0	0.1
67.0	Span Gas	475	474.5	475.5
67.8	Zero Gas	0	0	0.2

Table 6-8d. O_2 Data from Temperature Sensitivity Test with Model 350 High Range Analyzers

Temperature (°F)	Gas Component	O_2 Input Value (%)	Analyzer H1 O_2 Response (%)	Analyzer H2 O_2 Response (%)
67.7	Zero Gas	0	0	0
68.0	Span Gas	20.9	20.9	20.9
68.0	Zero Gas	0	0	0
105.7	Zero Gas	0	0.1	0.1
105.1	Span Gas	20.9	20.9	20.9
107.5	Zero Gas	0	0.1	0.1
47.4	Zero Gas	0	0	0
47.2	Span Gas	20.9	20.9	20.9
47.0	Zero Gas	0	0	0
67.8	Zero Gas	0	0	0
67.3	Span Gas	20.9	20.9	20.9
67.8	Zero Gas	0	0	0

Table 6-8e. SO_2 Data from Temperature Sensitivity Test with Model 350 High Range Analyzers

Temperature (°F)	Gas Component	SO_2 Input Value (ppm)	Analyzer H1 SO_2 Response (ppm)	Analyzer H2 SO_2 Response (ppm)
67.7	Zero Gas	0	0	0
68.0	Span Gas	2,000	2,000	2,000
68.1	Zero Gas	0	1	1
105.7	Zero Gas	0	1	0
105.8	Span Gas	2,000	2,007	1,983
107.9	Zero Gas	0	1	0
47.3	Zero Gas	0	1	0
47.2	Span Gas	2,000	1,989	1,986
47.1	Zero Gas	0	1	1
67.8	Zero Gas	0	0	0
67.6	Span Gas	2,000	1,982	1,980
67.8	Zero Gas	0	2	0

Table 6-8f. CO Data from Temperature Sensitivity Test with Model 350 Low Range Analyzers

Temperature (°F)	Gas Component	CO Input Value (ppm)	Analyzer L1 CO Response (ppm)	Analyzer L2 CO Response (ppm)
67.6	Zero Gas	0	0	0
68.0	Span Gas	504	500.2	501.2
68.0	Zero Gas	0	0	0
105.8	Zero Gas	0	0.1	0
106.2	Span Gas	504	504.1	504.2
107.1	Zero Gas	0	0.2	0
46.9	Zero Gas	0	0	0
46.8	Span Gas	504	503.5	502.6
47.8	Zero Gas	0	0	0
67.5	Zero Gas	0	0	0
66.6	Span Gas	504	497.6	496.8
68.0	Zero Gas	0	0	0

Table 6-8g. NO Data from Temperature Sensitivity Test with Model 350 Low Range Analyzers

Temperature (°F)	Gas Component	NO Input Value (ppm)	Analyzer L1 NO Response (ppm)	Analyzer L2 NO Response (ppm)
67.8	Zero Gas	0	0	0
68.0	Span Gas	201.7	202.4	201.3
68.0	Zero Gas	0	0	0
105.7	Zero Gas	0	0	0
105.3	Span Gas	201.7	201.4	201.8
106.9	Zero Gas	0	0	0
46.3	Zero Gas	0	0	0
47.2	Span Gas	201.7	200.8	200.5
47.4	Zero Gas	0	0.1	0
67.5	Zero Gas	0	0	0
67.8	Span Gas	201.7	201.8	201.4
68.0	Zero Gas	0	0.3	0.1

Table 6-9. Ambient Temperature Effects with Model 350 Analyzers

Gas Component		CO		NO		NO_2		O_2		SO_2		Low CO		Low NO	
	Analyzer	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**L1**	**L2**	**L1**	**L2**
Zero Gas	High - Ambient (ppm diff[a])	1	0	0	0	0	-0.05	0.1	0.1	0.25	-0.25	0.15	0	-0.08	-0.03
	Low - Ambient (ppm diff)	0	0	0	0.5	0	-0.05	0	0	0.25	0.25	0	0	-0.03	-0.03
	Significant Temp. Effect (Y/N)	Y	N	N	N	N	N	Y	Y	N	N	Y	N	N	N
Span	High - Ambient (ppm diff[a])	9.5	10	1.5	1.5	0.75	1.95	0	0	16	-7	5.2	5.2	-0.7	0.45
	Low - Ambient (ppm diff)	6.5	-6	0.5	0.5	12.25	21.95	0	0	-2	-4	4.6	3.6	-1.3	-0.85
	Significant Temp. Effect (Y/N)	N	Y	N	N	N	N	N	N	N	N	N	N	N	N

[(a)] Zero gas results calculated as differences in averages of observations.

6.6 Interrupted Sampling

Table 6-10 shows the zero and span data from the interrupted sampling tests, and Table 6-11 shows the differences (pre- minus post-shutdown) of the zero and span values. For all components tested on all four analyzers, zero differences never exceeded 2 ppm (or 0.1% for O_2). Span differences following interruption were always less than 1.0% of the respective span concentrations. These results indicate no significant effect of the shutdown on analyzer zero or span readings.

Table 6-10. Data from Interrupted Sampling Test with Model 350 Analyzers

Pre-Shutdown Date: 06/13/02		**Time: 1720**				
Analyzer/Range		**O_2 (%)**	**CO (ppm)**	**NO (ppm)**	**NO_2 (ppm)**	**SO_2 (ppm)**
H1	Zero:	-0.1	0	0	2	1
	Span:	20.9	512	212	474.9	2000
H2	Zero:	-0.1	0	0	2	0
	Span:	20.9	512	208	474.5	2007
L1	Zero:	0	0.3	0	0.5	NA
	Span:	20.9	501.8	202.3	478.4	NA
L2	Zero:	0.1	0.7	0	0	NA
	Span:	20.9	503.1	203.6	485.2	NA
Post-Shutdown Date: 06/14/02		**Time: 0810**				
Analyzer/Range		**O_2 (%)**	**CO (ppm)**	**NO (ppm)**	**NO_2 (ppm)**	**SO_2 (ppm)**
H1	Zero:	0	0	0	0.2	0
	Span:	20.9	507	209	473.8	1982
H2	Zero:	0	0	0	0	0
	Span:	20.9	508	207	474.3	2002
L1	Zero:	0	0.2	0.1	0	NA
	Span:	20.9	502.3	203.1	480.2	NA
L2	Zero:	0	0.2	0	0	NA
	Span:	20.9	501.4	203.2	490.1	NA

NA = Not applicable.

Table 6-11. Pre- to Post-Test Differences as a Result of Interrupted Sampling with Model 350 Analyzers

Pre-Shutdown - Post-Shutdown Differences						
Analyzer/Range		**O_2 (%)**	**CO (ppm)**	**NO (ppm)**	**NO_2 (ppm)**	**SO_2 (ppm)**
H1	Zero:	-0.1	0	0	1.8	1
	Span:	0	5	3	1.1	18
H2	Zero:	-0.1	0	0	2	0
	Span:	0	4	1	0.2	5
L1	Zero:	0	0.1	-0.1	0.5	NA
	Span:	0	-0.5	-0.8	-1.8	NA
L2	Zero:	0.1	0.5	0	0	NA
	Span:	0	1.7	0.4	-4.9	NA

NA = Not applicable.

6.7 Pressure Sensitivity

Tables 6-12a through g list the data obtained from the pressure sensitivity tests. Table 6-13 shows the results in terms of the ppm differences in zero and span readings at the three different sample inlet gauge pressures, with an indication of whether a significant pressure effect was observed. No significant effect of gauge pressure was seen with any of the sensors. With the high range analyzers, the CO readings were about 50 ppm lower at reduced pressure compared with the readings at elevated pressure. However, this difference amounts to less than 2% of the span concentration used during the test.

Table 6-12a. CO Data from Pressure Sensitivity Test with Model 350 High Range Analyzers

Pressure	Gas Component	CO Input Value (ppm)	Analyzer H1 CO Response (ppm)	Analyzer H2 CO Response (ppm)
ambient	Zero Gas	0	4	4
	Span Gas	2,997	3,008	3,000
	Zero Gas	0	4	4
+ 10" H_2O	Zero Gas	0	4	4
	Span Gas	2,997	2,994	2,990
	Zero Gas	0	4	4
- 10" H_2O	Zero Gas	0	4	4
	Span Gas	2,997	2,942	2,939
	Zero Gas	0	4	4

Table 6-12b. NO Data from Pressure Sensitivity Test with Model 350 High Range Analyzers

Pressure	Gas Component	NO Input Value (ppm)	Analyzer H1 NO Response (ppm)	Analyzer H2 NO Response (ppm)
ambient	Zero Gas	0	1	2
	Span Gas	1,793	1,807	1,819
	Zero Gas	0	3	4
+ 10" H_2O	Zero Gas	0	3	4
	Span Gas	1,793	1,809	1,812
	Zero Gas	0	3	4
- 10" H_2O	Zero Gas	0	3	4
	Span Gas	1,793	1,806	1,810
	Zero Gas	0	4	4

Table 6-12c. NO_2 Data from Pressure Sensitivity Test with Model 350 High Range Analyzers

Pressure	Gas Component	NO_2 Input Value (ppm)	Analyzer H1 NO_2 Response (ppm)	Analyzer H2 NO_2 Response (ppm)
ambient	Zero Gas	0	0	0
	Span Gas	300	300.8	301.5
	Zero Gas	0	0.4	0.2
+ 10" H_2O	Zero Gas	0	0.4	0.2
	Span Gas	300	302	303.1
	Zero Gas	0	0.5	0.4
- 10" H_2O	Zero Gas	0	0.4	0.3
	Span Gas	300	302.5	303.4
	Zero Gas	0	0.4	0.5

Table 6-12d. O_2 Data from Pressure Sensitivity Test with Model 350 High Range Analyzers

Pressure	Gas Component	O_2 Input Value (%)	Analyzer H1 O_2 Response (%)	Analyzer H2 O_2 Response (%)
ambient	Zero Gas	0	0.1	0
	Span Gas	15.05	14.9	15
	Zero Gas	0	0	0.1
+ 10" H_2O	Zero Gas	0	0	0.1
	Span Gas	15.05	14.9	15
	Zero Gas	0	0	0.1
- 10" H_2O	Zero Gas	0	0	0.1
	Span Gas	15.05	14.9	15
	Zero Gas	0	0	0.1

Table 6-12e. SO_2 Data from Pressure Sensitivity Test with Model 350 High Range Analyzers

Pressure	Gas Component	SO_2 Input Value (ppm)	Analyzer H1 SO_2 Response (ppm)	Analyzer H2 SO_2 Response (ppm)
ambient	Zero Gas	0	0	0
	Span Gas	1200	1201	1200
	Zero Gas	0	0	0
+ 10" H_2O	Zero Gas	0	0	0
	Span Gas	1200	1203	1198
	Zero Gas	0	0	0
- 10" H_2O	Zero Gas	0	0	0
	Span Gas	1200	1204	1202
	Zero Gas	0	1	0

Table 6-12f. CO Data from Pressure Sensitivity Test with Model 350 Low Range Analyzers

Pressure	Gas Component	CO Input Value (ppm)	Analyzer L1 CO Response (ppm)	Analyzer L2 CO Response (ppm)
ambient	Zero Gas	0	0.2	0.5
	Span Gas	300.4	300.6	299.4
	Zero Gas	0	0.6	0.2
+ 10" H_2O	Zero Gas	0	0.6	0.3
	Span Gas	300.4	300.1	300.2
	Zero Gas	0	0.5	0.6
- 10" H_2O	Zero Gas	0	0.4	0.3
	Span Gas	300.4	299.5	300.3
	Zero Gas	0	0.6	0.3

Table 6-12g. NO Data from Pressure Sensitivity Test with Model 350 Low Range Analyzers

Pressure	Gas Component	NO Input Value (ppm)	Analyzer L1 NO Response (ppm)	Analyzer L2 NO Response (ppm)
ambient	Zero Gas	0	0	0
	Span Gas	179.7	179.3	179.1
	Zero Gas	0	0.2	0.4
+ 10" H_2O	Zero Gas	0	0.2	0.3
	Span Gas	179.7	179.2	179
	Zero Gas	0	0.3	0.4
- 10" H_2O	Zero Gas	0	0.4	0.3
	Span Gas	179.7	179	178.8
	Zero Gas	0	0.4	0.2

Table 6-13. Pressure Sensitivity Results for Model 350 Analyzers

	Gas Component	CO		NO		NO_2		O_2		SO_2		Low CO		Low NO	
	Analyzer	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**H1**	**H2**	**L1**	**L2**	**L1**	**L2**
Zero Gas	High - Ambient (ppm diff[a])	0	0	1	1	0.25	0.2	-0.05	0.05	0	0	0.15	0.1	0.15	0.15
	Low - Ambient (ppm diff)	0	0	1.5	1	0.2	0.3	-0.05	0.05	0.5	0	0.1	-0.05	0.3	0.05
	Significant Pressure Effect (Y/N)	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Span	High - Ambient (ppm diff[a])	-14	-10	2	-7	1.2	1.6	0	0	2	-2	-0.5	0.8	-0.1	-0.1
	Low - Ambient (ppm diff)	-66	-61	-1	-9	1.7	1.9	0	0	3	2	-1.1	0.9	-0.3	-0.3
	Significant Pressure Effect (Y/N)	N	N	N	N	N	N	N	N	N	N	N	N	N	N

[a] Zero gas results calculated as differences in averages of observations.

6.8 Accuracy

The RA of the Model 350 analyzers was assessed in a series of combustion source tests. Figure 6-2 shows the relative accuracy results. Tables 6-14a through g show the measured emissions data obtained during sampling of five separate combustion sources. The Model 350 high range analyzers (H1, H2) were used for all combustion sources (Tables 6-14a through e). The Model 350 low range analyzers (L1, L2) were used only for the range burner tests (Tables 6-14f and g). Note that the Model 350 analyzers measure NO and NO_2 separately, and the indicated NO_x readings are the sum of these two measurements. In contrast, the reference monitor measures NO and total NO_x concentrations, with NO_2 concentrations determined by difference.

Table 6-15a shows the RA (in percent) of the Model 350 high range analyzers (H1, H2) for all measured emissions for each of the five combustion sources tested. Table 6-15b shows the RA (in percent) of the Model 350 low range analyzers (L1, L2) for all measured emissions for each of the two range burner sources tested.

Table 6-15a shows that the RA results for the high range analyzers were within 10% for many of the target analytes in all combustion source tests. Oxygen measurements in particular showed RA values within 1.5% in all tests. The RA values for SO_2 with unit H1 were higher than those for unit H2, suggesting problems with the SO_2 sensor in unit H1; that sensor, in fact, failed during one of the diesel test runs (Table 6-14d). Almost all the RA values above 10% in Table 6-15a are for the NO_2 measurements. In part, this is due to the low NO_2 levels in the gas range tests (i.e., 4 ppm or less). An RA of 20% in that case indicates agreement within about 1 ppm. In addition, uncertainty in the determination of NO_2 by difference with the reference method may also play a role in the NO_2 RA values. For example, in the diesel condition #3 (Table 6-14e), the large variability in reference method NO_2 data may result from the determination of about 20 ppm NO_2 by difference from a total of nearly 500 ppm NO_x. The Testo unit measuring NO_2 directly showed less variability than the reference.

Table 6-15b shows that all RA results for the low range analyzers were between 0 and 27%. The RA value of 23% indicates average agreement within about 0.1 ppm at the observed NO_2 levels of about 4 ppm.

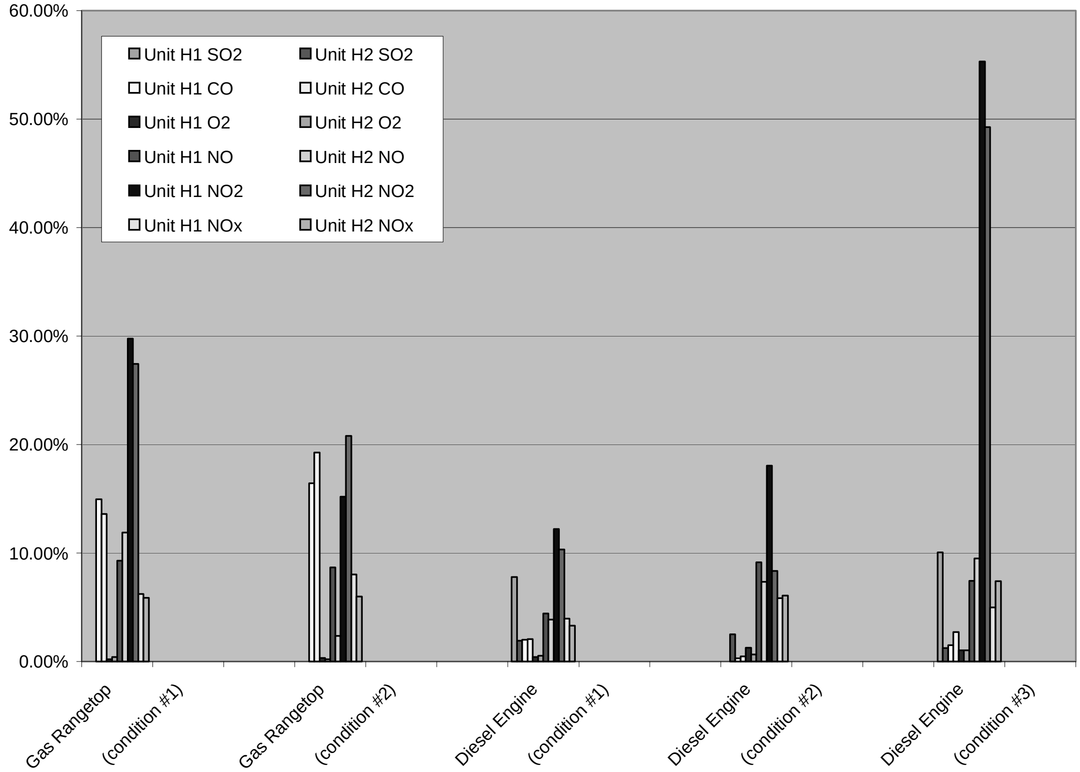

Figure 6-2. Relative Accuracy Results for Model 350 Analyzers

Table 6-14a. Data from the Relative Accuracy Test Using the Model 350 High Range Analyzers (Range Burner Condition #1, 10" H_2O manifold pressure, minimum primary air)

Sample Point	Model 350 Portable Analyzer Data												Reference Analyzer					
	SO_2[a] (ppm)		CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		SO_2[a] (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2						
1	-	-	6	6	16.5	16.5	15	16	4.2	5.0	19.2	21	-	5.3	16.4	16	4.4	20.4
2	-	-	7	6	16.5	16.5	17	16	3.5	5.3	20.5	21.3	-	5.8	16.5	16.8	4.7	21.5
3	-	-	6	6	16.5	16.5	18	16	4.5	5.5	22.5	21.5	-	5.9	16.5	17.1	4.3	21.4
4	-	-	6	6	16.5	16.6	17	16	4.5	4.7	21.5	20.7	-	5.8	16.5	18.1	4.2	22.3
5	-	-	7	6	16.6	16.6	17	16	4.5	5.7	21.5	21.7	-	5.7	16.6	19.7	4.7	24.4
6	-	-	6	7	16.7	16.7	19	16	2.8	5.1	21.8	21.1	-	5.8	16.7	17.2	4.6	21.8
7	-	-	6	6	16.6	16.6	19	16	3.0	4.6	22.0	20.6	-	5.6	16.6	16.8	3.9	20.7
8	-	-	5	5	16.7	16.7	18	17	2.8	4.8	20.8	21.8	-	5.3	16.7	16.4	4.2	20.6
9	-	-	5	6	16.6	16.7	18	16	3.0	5.1	21.0	21.1	-	5.1	16.6	16.8	4.3	21.1

[a] No SO_2 emission from this source.

Table 6-14b. Data from the Relative Accuracy Test Using the Model 350 High Range Analyzers (Range Burner Condition #2, 8" H_2O manifold pressure, maximum primary air)

Sample Point	Model 350 Portable Analyzer Data												Reference Analyzer					
	SO_2[a] (ppm)		CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		SO_2[a] (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2						
1	-	-	6	5	17.1	17.1	15	14	3.5	4.9	18.5	18.9	-	5.7	17.1	13.6	3.6	17.2
2	-	-	5	6	17.1	17.1	14	14	4.9	4.5	18.9	18.5	-	5.7	17.1	13.8	3.7	17.5
3	-	-	5	5	17.2	17.2	15	14	3.9	4.1	18.9	18.1	-	5.6	17.2	13.9	3.7	17.6
4	-	-	5	5	17.2	17.1	14	14	3.9	3.2	17.9	17.2	-	6.1	17.1	13.8	3.9	17.7
5	-	-	6	6	17.1	17.1	13	14	4.3	3.8	17.3	17.8	-	6.1	17.1	13.9	3.7	17.6
6	-	-	6	5	17.2	17.2	15	14	4.0	4.0	19.0	18.0	-	6.5	17.2	13.5	3.9	17.4
7	-	-	5	5	17.2	17.1	14	14	3.5	4.4	17.5	18.4	-	6.3	17.1	13.8	3.3	17.1
8	-	-	6	6	17.2	17.2	14	13	4.3	4.1	18.3	17.1	-	6.5	17.2	13.2	4.3	17.5
9	-	-	5	5	17.1	17.2	14	13	3.1	4.3	17.1	17.3	-	6.0	17.1	13.1	4.3	17.4

[a] No SO_2 emission from this source.

Table 6-14c. Data from the Relative Accuracy Test Using the Model 350 High Range Analyzers (Diesel Engine Condition #1, idle, no load)

Sample Point	Model 350 Portable Analyzer Data												Reference Analyzer					
	SO_2 (ppm)		CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2						
1	19	20	46	47	19.8	19.8	88	89	21.0	22.0	109.0	111.2	20	47	19.8	88	23.4	111.4
2	19	20	47	48	19.8	19.8	87	87	20.2	20.0	107.2	107.0	20	48	19.8	86	22.2	108.2
3	18	19	48	47	19.9	19.9	86	86	20.8	21.2	106.8	107.2	20	49	19.8	88	23.4	111.4
4	18	20	48	48	19.9	19.8	87	86	20.1	21.5	107.1	107.5	20	48	19.8	89	22.2	111.2
5	19	20	49	49	19.8	19.9	86	87	21.2	21.3	107.2	108.3	20	50	19.8	89	22.2	111.2
6	20	21	49	48	19.8	19.9	85	86	21.5	23.0	106.5	109.0	20	49	19.8	91	19.9	110.9
7	19	20	46	47	19.8	19.9	86	87	23.5	23.0	109.5	110.0	20	47	19.8	91	21.1	112.1
8	20	21	47	48	19.8	19.8	91	91	22.5	22.8	113.5	113.5	21	47	19.7	92	25.7	117.7
9	20	21	47	47	19.8	19.8	86	86	21.5	22.2	107.5	108.2	21	47	19.7	88	23.4	111.4

Table 6-14d. Data from the Relative Accuracy Test Using the Model 350 High Range Analyzers (Diesel Engine Condition #2, full speed, medium load, CO exhaust spiking)

Sample Point	Model 350 Portable Analyzer Data												Reference Analyzer					
	SO_2 (ppm)		CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2						
1	-[a]	168	1944	1938	17.4	17.4	240	241	37.9	43.5	277.9	284.5	172	1933	17.3	228	43.3	271.3
2	-	169	1983	1972	17.4	17.4	241	242	38.9	42.0	279.9	284.0	174	1978	17.3	229	39.8	268.8
3	-	165	2010	2026	17.4	17.4	241	236	38.9	43.9	279.9	279.9	169	2017	17.3	220	45.6	265.6
4	-	168	1985	1990	17.4	17.4	244	238	39.5	41.5	283.5	279.5	171	1987	17.4	224	44.5	268.5
5	-	167	2017	2010	17.4	17.4	244	239	39.9	44.5	283.9	283.5	170	2024	17.3	226	38.6	264.6
6	-	167	2038	2041	17.4	17.4	238	235	39.1	44.1	277.1	279.1	171	2046	17.3	227	36.3	263.3
7	-	167	2071	2066	17.4	17.4	236	232	39.9	43.9	275.9	275.9	171	2077	17.3	215	51.5	266.5
8	-	168	2020	2010	17.4	17.4	240	237	39.9	43.9	279.9	280.9	171	2016	17.4	219	46.8	265.8
9	-	167	2032	2017	17.4	17.4	235	232	39.9	44.1	274.9	276.1	171	2027	17.3	217	46.8	263.8

[a] SO_2 sensor malfunction

Table 6-14e. Data from the Relative Accuracy Test Using the Model 350 High Range Analyzers (Diesel Engine Condition #3, full speed, full load)

Sample Point	Model 350 Portable Analyzer Data												Reference Analyzer					
	SO_2 (ppm)		CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2						
1	550	616	74	75	11.3	11.3	478	475	10.2	14.1	488.2	489.1	609	74	11.2	460	17.6	477.6
2	548	605	79	80	11.3	11.3	488	491	15.1	16.1	503.1	507.1	610	79	11.2	452	32.8	484.8
3	545	602	72	73	11.3	11.3	488	495	15.6	16.5	503.6	511.5	606	71	11.2	462	22.2	484.2
4	545	599	75	76	11.2	11.2	486	492	15.5	17.1	501.5	509.1	604	74	11.2	450	35.1	485.1
5	548	600	75	76	11.2	11.2	487	494	16.0	17.1	503.0	511.1	607	74	11.1	456	24.6	480.6
6	545	602	72	73	11.3	11.3	487	500	16.0	17.1	503.0	517.1	605	73	11.2	457	23.4	480.4
7	546	599	77	78	11.2	11.2	485	500	15.8	17.9	500.8	517.9	607	76	11.1	458	23.4	481.4
8	546	600	71	72	11.2	11.2	490	497	15.6	17.9	505.6	514.9	606	70	11.1	464	19.9	473.9
9	549	599	71	71	11.2	11.2	488	500	16.0	17.7	504.0	517.7	605	70	11.1	466	22.2	488.2

Table 6-14f. Data from the Relative Accuracy Test Using the Model 350 Low Range Analyzers (Range Burner Condition #1, 10" H_2O manifold pressure, minimum primary air)

Sample Point	Model 350 Portable Analyzer Data										Reference Analyzer				
	CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2					
1	5.8	5.8	16.6	16.6	17.0	17.9	4.6	3.8	21.6	21.7	5.3	16.4	16	4.4	20.4
2	5.7	5.9	16.6	16.6	18.0	18.5	4.1	3.0	22.1	21.5	5.8	16.5	16.8	4.7	21.5
3	5.8	6.0	16.6	16.5	18.9	19.2	4.8	4.1	23.7	23.3	5.9	16.5	17.1	4.3	21.4
4	5.5	6.1	16.6	16.5	17.5	18.5	4.5	3.4	22.0	21.9	5.8	16.5	18.1	4.2	22.3
5	5.8	6.2	16.6	16.6	17.9	18.5	4.6	3.5	22.5	22.0	5.7	16.6	19.7	4.7	24.4
6	5.9	6.1	16.6	16.7	18.1	18.6	3.9	3.6	22.0	22.2	5.8	16.7	17.2	4.6	21.8
7	5.5	5.4	16.6	16.6	18.6	17.8	2.8	3.5	21.4	21.3	5.6	16.6	16.8	3.9	20.7
8	5.4	5.1	16.7	16.7	18.2	18.5	4.1	3.0	22.3	21.5	5.3	16.7	16.4	4.2	20.6
9	5.5	5.1	16.6	16.6	18.2	18.7	4.4	3.9	22.6	22.6	5.1	16.6	16.8	4.3	21.1

Table 6-14g. Data from the Relative Accuracy Test Using the Model 350 Low Range Analyzers (Range Burner Condition #2, 8" H_2O manifold pressure, maximum primary air)

Sample Point	Model 350 Portable Analyzer Data										Reference Analyzer				
	CO (ppm)		O_2 (%)		NO (ppm)		NO_2 (ppm)		NO_x (ppm)		CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2					
1	5.3	5.3	17.1	17.1	15.2	15.1	3.5	3.0	18.7	18.1	5.7	17.1	13.6	3.6	17.2
2	5.8	5.7	17.1	17.1	14.7	14.3	3.1	3.4	17.8	17.7	5.7	17.1	13.8	3.7	17.5
3	5.4	5.8	17.2	17.2	15.1	15.2	3.7	2.7	18.8	17.9	5.6	17.2	13.9	3.7	17.6
4	6.1	4.9	17.1	17.1	14.7	14.6	3.2	3.9	17.9	18.5	6.1	17.1	13.8	3.9	17.7
5	6.0	6.3	17.1	17.1	14.5	14.6	3.7	2.7	18.2	17.3	6.1	17.1	13.9	3.7	17.6
6	6.1	6.3	17.2	17.2	14.8	15.0	3.2	3.1	18.0	18.1	6.5	17.2	13.5	3.9	17.4
7	6.2	6.5	17.2	17.1	14.9	14.3	2.8	3.4	17.7	17.7	6.3	17.1	13.8	3.3	17.1
8	6.5	6.3	17.2	17.2	14.6	14.1	3.1	3.9	17.7	18.0	6.5	17.2	13.2	4.3	17.5
9	6.1	5.3	17.1	17.1	14.5	13.8	3.3	3.2	17.8	17.0	6.0	17.1	13.1	4.3	17.4

Table 6-15a. Relative Accuracy of Model 350 High Range Analyzers

Source		Unit H1 SO_2 (%)	Unit H2 SO_2 (%)	Unit H1 CO (%)	Unit H2 CO (%)	Unit H1 O_2 (%)	Unit H2 O_2 (%)	Unit H1 NO (%)	Unit H2 NO (%)	Unit H1 NO_2 (%)	Unit H2 NO_2 (%)	Unit H1 NO_x (%)	Unit H2 NO_x (%)
Gas Rangetop (condition #1)	Rel. Acc.	-	-	14.97	13.60	0.22	0.43	9.30	11.89	29.77	27.43	6.22	5.88
Gas Rangetop (condition #2)	Rel. Acc.	-	-	16.42	19.24	0.33	0.21	8.66	2.38	15.19	20.80	8.02	5.99
Diesel Engine (condition #1)	Rel. Acc.	7.78	1.90	2.00	2.08	0.43	0.53	4.41	3.87	12.22	10.32	3.94	3.30
Diesel Engine (condition #2)	Rel. Acc.	-[a]	2.51	0.29	0.49	1.28	0.64	9.15	7.35	18.05	8.36	5.84	6.06
Diesel Engine (condition #3)	Rel. Acc.	10.06	1.24	1.52	2.73	1.03	1.03	7.45	9.49	55.30	49.26	5.00	7.41

[a] SO_2 sensor malfunction

Table 6-15b. Relative Accuracy of Model 350 Low Range Analyzers

Source		Unit L1 CO (%)	Unit L2 CO (%)	Unit L1 O2 (%)	Unit L2 O2 (%)	Unit L1 NO (%)	Unit L2 NO (%)	Unit L1 NO2 (%)	Unit L2 NO2 (%)	Unit L1 NO_x (%)	Unit L2 NO_x (%)
Gas Rangetop (condition #1)	Rel. Acc.	4.70	6.43	0.67	0.53	10.38	12.11	12.66	27.43	7.47	6.46
Gas Rangetop (condition #2)	Rel. Acc.	4.25	9.87	0.21	0.00	10.15	9.11	22.70	24.42	5.43	4.16

6.9 Zero/Span Drift

Zero and span data taken at the start and end of the linearity and temperature tests are shown in Table 6-16, and the drift values observed are shown in Table 6-17 as differences between the pre- and post-test concentration measurements in ppm. Table 6-17 also presents the zero and span drifts as a percent of span gas concentrations. For all components, results were consistent between the collocated analyzers. Zero drifts for all component sensors tested were either zero or slightly negative, but all zero drifts were less than 0.15% of the respective span gas concentrations. For the linearity tests, span drifts for the high concentration CO sensors averaged 138 ppm (+3.1% of span). Span drifts for the high concentration NO sensors averaged –44.5 ppm (–1.5% of span). Span drifts for the NO_2 sensors averaged –8.9 ppm (–1.9% of span). For all other sensors, the average span drifts were less than 0.4% of the respective span concentrations. Span drifts observed during the temperature tests were less than 1% for all components tested.

Zero and span data taken at the start and end of the diesel engine combustion tests are shown in Table 6-18, and the resulting drift values observed are shown in Table 6-19 as differences between the pre- and post-test concentration measurements in ppm. Table 6-19 also presents the zero and span drifts as a percent of span gas concentrations. For all components, results were consistent between the collocated analyzers. Zero drifts for all component sensors tested were negligible over the course of all three diesel engine combustion tests. Span drifts for the high concentration CO sensors ranged from –1 ppm to +12 ppm, with all span drifts less than 0.3% of span. Span drifts for the NO_2 sensors ranged from –4 ppm to +3 ppm, with all span drifts less than 1% of span. For all other sensors, the average span drifts were less than 0.6% of the respective span concentrations.

Table 6-16. Data from Linearity and Temperature Tests Used to Assess Zero and Span Drift of the Model 350 Analyzers

Linearity Test

Unit/Component	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)	L1 CO (ppm)	L2 CO (ppm)	L1 NO (ppm)	L2 NO (ppm)
Pre-Test Zero	0	0	0	0	0.1	0.4	0	0	0	1	0.4	0	0.3	0.1
Pre-Test Span	4,510	4,516	3,112	3,118	474.2	474.9	20	20	1,993	2,001	501.3	502	300	299.2
Post-Test Zero	3	2	1	2	0.5	0.8	0	0	1	2	1.1	1.5	0.4	0.2
Post-Test Span	4,360	4,390	3,160	3,159	481.0	482.3	20	20	1,995	2,002	499.5	501.5	298.9	298.7

Temperature Test

Unit/Component	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)	L1 CO (ppm)	L2 CO (ppm)	L1 NO (ppm)	L2 NO (ppm)
Pre-Test Zero	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pre-Test Span	501	500	201	201	473.2	473	20.9	20.9	2,000	2,000	500.2	501.2	202.4	201.3
Post-Test Zero	0	0	0	0	0	0.2	0	0	2	0	0	0	0.3	0.1
Post-Test Span	500	496	202	204	474.5	475.5	20.9	20.9	1,982	1,980	497.6	496.8	201.8	201.4

Table 6-17. Laboratory Test Zero and Span Drift Results for the Model 350 Analyzers

Linearity Test

Pre- and Post-Test Differences	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)	L1 CO (ppm)	L2 CO (ppm)	L1 NO (ppm)	L2 NO (ppm)
Zero	-3	-2	-1	-2	-0.4	-0.4	0	0	-1	-1	-0.7	-1.5	-0.1	-0.1
Span	150	126	-48	-41	-6.8	-7.4	0	0	-2	-1	1.8	0.5	1.1	0.5
Drift as % of Span														
Zero	-0.07	-0.04	-0.03	-0.07	-0.08	-0.08	0.00	0.00	-0.05	-0.05	-0.14	-0.30	-0.03	-0.03
Span	3.36	2.83	-1.61	-1.37	-1.43	-1.68	0.00	0.00	-0.10	-0.05	0.36	0.10	0.37	0.17

Temperature Test

Pre- and Post-Test Differences	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)	L1 CO (ppm)	L2 CO (ppm)	L1 NO (ppm)	L2 NO (ppm)
Zero	0	0	0	0	0	-0.2	0	0	-2	0	0	0	-0.3	-0.1
Span	1	4	-1	-3	-1.3	-2.5	0	0	18	20	2.6	4.4	0.6	-0.1
Drift as % of Span														
Zero	0.00	0.00	0.00	0.00	0.00	-0.04	0.00	0.00	-0.10	0.00	0.00	0.00	-0.10	-0.03
Span	0.02	0.09	-0.03	-0.10	-0.27	-0.53	0.00	0.00	0.90	1.00	0.52	0.88	0.20	-0.03

Table 6-18. Data from Diesel Engine Combustion Tests Used to Assess Zero and Span Drift of the Model 350 Analyzers

Diesel Engine Condition #1 (low)

Unit/Component	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Pre-Test Zero	0	0	0	0	0	0	0	0	0	0
Pre-Test Span	504	503	201	202	477.1	475.2	20.9	20.9	509	506
Post-Test Zero	0	0	1	0	0	0	0	0.1	0	1
Post-Test Span	504	504	204	203	478.8	479.5	20.9	20.9	517	515

Diesel Engine Condition #2 (medium)

Unit/Component	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Pre-Test Zero	0	0	0	0	0	0	0	0	0	0
Pre-Test Span	504	505	202	202	475.5	475.6	20.9	20.9	2,000	2,001
Post-Test Zero	0	0	0	0	0	0	0	0	0	0
Post-Test Span	502	502	203	204	473.3	476.4	20.9	20.9	1,989	1,992

Diesel Engine Condition #3 (high)

Unit/Component	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Pre-Test Zero	0	0	0	0	0	0.2	0.0	0.0	0	0
Pre-Test Span	2,230	2,230	815	815	476.6	476.2	20.9	20.9	2,007	2,003
Post-Test Zero	0	0	0	0	0.1	0.1	0.0	0.0	0	0
Post-Test Span	2,220	2,218	814	819	473.8	474.3	20.9	20.9	1,998	1,992

Table 6-19. Combustion Test Zero and Span Drift Results for the Model 350 Analyzers

Diesel Engine Condition #1 (low)

Pre- and Post-Test Differences	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Zero	0	0	-1	0	0	0	0	-0.1	0	-1
Span	0	-1	-3	-1	-1.7	-4.3	0	0	-8	-9
Drift as % of Span										
Zero	0.00	0.00	-0.033	0.00	0.00	0.00	0.00	0.00	0.00	-0.05
Span	0.00	-0.02	-0.10	-0.03	-0.36	-0.91	0.00	0.00	-0.40	-0.45

Diesel Engine Condition #2 (medium)

Pre- and Post-Test Differences	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Zero	0	0	0	0	0	0	0	0	0	0
Span	2	3	-1	-2	2.2	-0.8	0	0	11	9
Drift as % of Span										
Zero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Span	0.04	0.07	-0.03	-0.07	0.46	-0.17	0.00	0.00	0.55	0.45

Diesel Engine Condition #3 (high)

Pre- and Post-Test Differences	H1 CO (ppm)	H2 CO (ppm)	H1 NO (ppm)	H2 NO (ppm)	H1 NO_2 (ppm)	H2 NO_2 (ppm)	H1 O_2 (%)	H2 O_2 (%)	H1 SO_2 (ppm)	H2 SO_2 (ppm)
Zero	0	0	0	0	-0.1	0.1	0	0	0	0
Span	10	12	1	-4	2.8	1.9	0	0	9	11
Drift as % of Span										
Zero	0.00	0.00	0.00	0.00	-0.02	0.02	0.00	0.00	0.00	0.00
Span	0.22	0.27	0.03	-0.13	0.59	0.40	0.00	0.00	0.45	0.55

6.10 Measurement Stability

Tables 6-20a through e show the data obtained during the extended sampling test, in which the Model 350s (high range and low range) and reference analyzers sampled diesel emissions at engine idle for a full hour without interruption. The reference nitrogen oxides analyzer measured only NO_x throughout this test. The Model 350 data were compared to the reference analyzer data to assess any differences in emission concentration trends. Tables 6-21a and b show the results of this evaluation, in terms of the slopes and standard errors of the SO_2, CO, O_2, and total NO_x concentration data over time. Also shown in Tables 6-21a and b are any significant differences in slope indicated by the Model 350 analyzers versus the reference analyzers.

Table 6-21a indicates that both high range Model 350 analyzers (H1 and H2) show a statistically significant decrease in SO_2 concentrations over time compared with the reference analyzer. Unit H1 shows an increase in O_2 concentration, and Unit H2 shows an increase in NO_x relative to the respective reference analyzers. For SO_2, the average downward trend of 1.3 ppm/hr represents a decrease of 6% of the mean measured concentration over one hour of sampling. An upward trend of the O_2 measurement in Unit H1 of 0.06%/hr, while statistically significant, represents an increase of only 0.31% of the mean measured concentration. The upward trend of the NO_x measurement in Unit H2 of 3 ppm/hr, represents an increase of 3% of the mean measured concentration over one hour of sampling.

Table 6-21b indicates that both Model 350 low range analyzers (L1 and L2) show a statistically significant increase in NO_x concentrations over time compared with the reference analyzer. Unit L1 shows a increase in O_2 concentration relative to the reference analyzer. For NO_x, the average upward trend of 2.34 ppm/hr represents an increase of 2% of the mean measured concentration over one hour of sampling. The upward trend of the O_2 measurement in Unit L1 of 0.06%/hr, while statistically significant, represents an increase of only 0.31% of the mean measured concentration.

Table 6-20a. Reference Analyzer Data from Extended Sampling Test with Diesel Engine at Idle

Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO_x (ppm)	Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO_x (ppm)
1	22.1	45	19.7	98	31	22.7	46	19.6	97
2	21.2	45	19.7	96	32	22.8	45	19.6	97
3	21.4	46	19.6	98	33	22.7	45	19.6	98
4	21.5	45	19.7	98	34	22.9	46	19.7	98
5	21.6	46	19.7	97	35	22.9	46	19.7	99
6	21.8	45	19.7	97	36	22.7	45	19.7	98
7	22.3	46	19.7	96	37	22.8	45	19.7	97
8	22.7	46	19.7	97	38	22.7	46	19.7	96
9	22.8	45	19.7	97	39	22.7	46	19.7	98
10	22.9	44	19.7	99	40	22.8	45	19.7	97
11	22.7	46	19.7	97	41	22.8	44	19.6	98
12	22.8	46	19.7	98	42	22.9	45	19.7	99
13	23	45	19.7	97	43	22.9	46	19.7	97
14	22.8	45	19.7	97	44	22.8	45	19.7	97
15	23	45	19.7	97	45	22.9	45	19.6	99
16	22.9	45	19.7	97	46	23	45	19.7	98
17	22.8	46	19.7	96	47	22.9	46	19.7	97
18	22.7	45	19.6	97	48	23.1	45	19.6	96
19	22.8	46	19.7	96	49	22.8	45	19.8	98
20	22.9	46	19.7	97	50	23.1	45	19.7	96
21	22.8	45	19.7	99	51	23	45	19.6	98
22	22.8	45	19.6	100	52	23.1	45	19.6	99
23	22.9	45	19.6	97	53	23	45	19.7	99
24	22.7	46	19.6	98	54	22.8	46	19.6	98
25	22.8	46	19.7	99	55	22.8	46	19.7	97
26	22.7	46	19.6	97	56	22.8	45	19.7	97
27	22.8	46	19.7	95	57	23	45	19.6	98
28	22.7	45	19.6	98	58	22.7	46	19.7	97
29	22.6	45	19.6	98	59	22.8	45	19.6	97
30	22.8	45	19.6	96	60	22.9	45	19.7	98

Table 6-20b. Model 350 High Range (Unit H1) Analyzer Data from Extended Sampling Test with Diesel Engine at Idle

Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	17	45	19.8	85	20.5	106	31	16	45	19.9	89	20.9	110
2	17	44	19.8	86	20.7	107	32	16	44	19.8	91	21.5	113
3	17	45	19.8	86	21.3	107	33	16	44	19.9	81	20.7	102
4	17	45	19.8	88	21.4	109	34	17	46	19.9	89	21.1	110
5	19	45	19.8	87	21	108	35	15	46	19.8	91	21.7	113
6	17	43	19.8	88	21	109	36	14	44	19.9	88	21.1	109
7	16	43	19.8	89	21.5	111	37	15	42	19.9	88	21.3	109
8	15	42	19.8	87	21.3	108	38	16	45	19.8	89	21.1	110
9	16	45	19.8	88	21.3	109	39	16	44	19.9	91	20.7	112
10	16	44	19.9	87	21.5	109	40	16	45	19.9	92	20.5	113
11	15	45	19.9	88	21.3	109	41	15	43	19.8	92	21.3	113
12	16	45	19.9	88	21.5	110	42	15	45	19.9	90	21.3	111
13	14	43	19.8	87	21.5	109	43	15	45	19.9	92	21.7	114
14	16	45	19.9	89	21.5	111	44	15	45	19.9	89	21.1	110
15	15	45	19.9	87	21.7	109	45	16	45	19.9	86	21.3	107
16	15	44	19.9	89	20.9	110	46	17	45	19.8	89	21.3	110
17	16	45	19.9	90	20.9	111	47	15	45	19.9	89	21.1	110
18	15	45	19.8	87	21.7	109	48	16	45	19.8	89	20.5	110
19	16	44	19.9	88	21.7	110	49	17	45	19.8	91	20.7	112
20	15	44	19.8	89	21.1	110	50	17	46	19.8	90	20.3	110
21	16	46	19.9	89	21.7	111	51	15	44	19.9	91	20.3	111
22	15	43	19.8	88	21.1	109	52	15	45	19.8	92	21.3	113
23	15	44	19.8	89	22.1	111	53	16	44	19.9	89	21.1	110
24	15	44	19.8	89	21.5	111	54	15	45	19.8	89	20.3	109
25	16	44	19.8	89	21.7	111	55	16	44	19.9	91	20.5	112
26	14	44	19.9	89	21.7	111	56	16	45	19.9	89	21.1	110
27	16	44	19.8	88	20.9	109	57	16	44	19.9	89	20.7	110
28	14	44	19.8	84	21.5	106	58	17	44	19.9	85	20.3	105
29	16	46	19.8	88	21.1	109	59	16	44	19.9	86	19.3	105
30	15	45	19.9	89	21.9	111	60	16	43	19.9	85	19.9	105

Table 6-20c. Model 350 High Range (Unit H2) Analyzer data from Extended Sampling Test with Diesel Engine at Idle

Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	Point	SO_2 (ppm)	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	19	44	19.8	85	20	105	31	18	45	19.9	90	21.5	112
2	18	44	19.8	86	21.5	108	32	20	45	19.9	88	21.5	110
3	19	45	19.8	86	21.7	108	33	18	44	19.9	88	21.3	109
4	19	45	19.8	86	20.7	107	34	18	44	19.9	86	20.7	107
5	20	46	19.8	86	21.5	108	35	19	45	19.9	87	22.3	109
6	20	46	19.8	88	21.2	109	36	19	46	19.8	87	21.1	108
7	19	45	19.8	88	21.3	109	37	20	45	19.9	88	21.1	109
8	19	45	19.8	86	21.1	107	38	19	46	19.8	86	21.9	108
9	18	45	19.9	88	21.1	109	39	17	45	19.9	89	21.9	111
10	18	46	19.9	85	20.9	106	40	18	45	19.9	90	21.5	112
11	18	44	19.9	86	21.1	107	41	18	44	19.9	89	21.5	111
12	19	45	19.9	86	20.3	106	42	19.	45	19.9	88	20.7	109
13	19	46	19.9	86	21.5	108	43	19	45	19.9	87	20.3	107
14	19	45	19.9	87	21.7	109	44	19	45	19.8	88	21.5	110
15	19	46	19.9	88	20.7	109	45	19	45	19.9	88	21.1	109
16	21	45	19.9	88	20.9	109	46	19	46	19.8	86	21.7	108
17	20	44	19.9	85	21.1	106	47	19	46	19.9	86	21.1	107
18	19	45	19.9	88	21.3	109	48	18	45	19.9	91	21.9	113
19	19	44	19.9	89	21.3	110	49	18	45	19.9	86	21.1	107
20	20	47	19.9	90	21.5	112	50	19	44	19.9	87	21.5	109
21	18	45	19.9	88	21.7	110	51	19	45	19.9	92	20.9	113
22	21	44	19.9	88	21.1	109	52	19	44	19.9	91	20.7	112
23	19	44	19.9	85	21.5	107	53	20	46	19.9	90	21.5	112
24	20	46	19.9	88	20.7	109	54	19	46	19.9	89	21.1	110
25	20	45	19.9	87	21.7	109	55	19	45	19.8	90	21.1	111
26	19	45	19.9	86	21.3	107	56	18	44	19.9	89	20.7	110
27	19	43	19.9	89	21.1	110	57	18	46	19.9	89	20.9	110
28	19	45	19.9	88	21.3	109	58	19	43	19.8	89	21.9	111
29	19	45	19.8	86	21.3	107	59	19	45	19.8	90	22.1	112
30	18	46	19.9	88	21.5	110	60	17	45	19.8	91	21.5	113

Table 6-20d. Model 350 Low Range (Unit L1) Analyzer data from Extended Sampling Test with Diesel Engine at Idle

Point	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	Point	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	46.4	19.8	80.4	20.8	101	31	46.2	19.8	84.1	22.1	106
2	45.4	19.8	84	19.9	104	32	44.9	19.8	85.9	20.1	106
3	45.2	19.8	83.2	19.6	103	33	45.1	19.9	86.4	19.9	106
4	45.6	19.8	83	19	102	34	45.2	19.9	83.4	19.2	103
5	45.9	19.8	83.2	19.4	103	35	46.1	19.9	85.2	19	104
6	46.2	19.8	81.2	19.2	100	36	45	19.9	84.5	19.5	104
7	45.3	19.9	85.1	19.6	105	37	45	19.9	84.4	20.1	105
8	44.3	19.9	83.7	19.9	104	38	46.5	19.9	83.9	19.6	104
9	45.5	19.9	83.6	19.5	103	39	45.8	19.9	85	19.1	104
10	45.3	19.9	84.6	20.1	105	40	45	19.9	88.2	19.4	108
11	45.4	19.9	82.9	19.9	103	41	44.6	19.9	87.2	19.4	107
12	45.9	19.9	83.6	20.3	104	42	46	19.9	85	19.2	104
13	45.4	19.9	82.9	19.6	103	43	45	19.9	85	19.6	105
14	44.7	19.9	83.8	19.9	104	44	45.6	19.9	85.2	19.8	105
15	44.9	19.9	83.2	20.1	103	45	45.5	19.9	83	20.5	104
16	45.6	19.9	82.9	19.4	102	46	45.6	19.9	84.5	19.5	104
17	45.1	19.9	83.2	20.1	103	47	46.8	19.9	84.6	19.5	104
18	45.8	19.9	85.2	20	105	48	45.1	19.9	85.7	19	105
19	45.9	19.9	85.1	19.4	105	49	45	19.9	87.1	19.6	107
20	45.9	19.9	85.1	19.4	105	50	45.8	19.9	85.2	19.2	104
21	45.6	19.9	84.3	19.2	104	51	44.8	19.9	87.6	19.8	107
22	46.7	19.9	84.1	19.2	103	52	45.1	19.9	86.3	19.6	106
23	45	19.9	84	19.6	104	53	45.4	19.9	84.8	19.6	104
24	46.4	19.9	86	20.1	106	54	45.1	19.9	84.3	19.6	104
25	44.7	19.9	85	19.4	104	55	45.5	19.9	85.3	19.2	105
26	45.1	19.9	84	20.1	104	56	44.6	19.9	85	19.4	104
27	46.6	19.9	84.5	20.1	105	57	44.7	19.9	83.3	19.8	103
28	46	19.8	84.5	19.6	104	58	44.6	19.9	83.1	20.3	103
29	45.5	19.8	84.9	19.8	105	59	43	19.9	86.8	19.8	107
30	46	19.8	84.8	20.5	105	60	45.4	19.9	87.4	19.2	107

Table 6-20e. Model 350 Low Range (Unit L2) Analyzer data from Extended Sampling Test with Diesel Engine at Idle

Point	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)	Point	CO (ppm)	O_2 (%)	NO (ppm)	NO_2 (ppm)	NO_x (ppm)
1	47.3	19.9	81	24.1	105	31	45.2	19.8	86.2	22.8	109
2	46.4	19.8	85	22	107	32	44.9	19.9	86.2	23.5	110
3	44.5	19.8	83	23	106	33	43.6	19.9	87.8	23.5	110
4	45.7	19.9	84	23.2	107	34	44.1	19.9	83.6	23.5	111
5	44.9	19.9	83	22.2	105	35	44.2	19.9	84.8	23.5	108
6	44.5	19.9	83	23.2	106	36	44.2	19.9	84.1	23	107
7	42.8	19.9	85	22.6	107	37	43.5	19.9	83.2	23.5	107
8	45.2	19.9	83	22.6	106	38	42.5	19.9	84.5	23.1	108
9	44.7	19.9	86.8	22	107	39	46.1	19.9	87.3	23.3	111
10	42.1	19.9	85	22.6	108	40	44	19.9	87	22.4	109
11	43.6	19.9	84	23	107	41	42	19.9	85.6	23.9	110
12	45	19.9	85	22.6	108	42	45.6	19.9	84.6	22.3	107
13	43.7	19.9	84	23.5	107	43	44	19.9	86	23.3	109
14	43.8	19.9	83	23.5	106	44	45.8	19.9	86.2	23.3	110
15	45.2	19.9	84	23	107	45	45.1	19.9	83.8	23.5	107
16	45.7	19.9	84	23.2	108	46	45.2	19.9	84.5	23.5	108
17	42.9	19.9	82	22.8	105	47	43.2	19.9	84.5	22.5	107
18	46.3	19.9	85	22.8	108	48	43.7	19.9	85.4	23.5	109
19	46.3	19.9	87	23	110	49	44.8	19.9	84.7	22.8	108
20	46.2	19.9	87	23	110	50	44	19.9	85.5	23.6	108
21	44.1	19.9	83	23	106	51	44.5	19.9	87.8	23	111
22	41.3	19.9	85	23.7	109	52	43.8	19.9	86.5	23.6	110
23	43.3	19.9	85	23.5	109	53	45	19.9	85.1	23.8	109
24	44.2	19.9	86	23	109	54	44.6	19.8	86.4	23.6	110
25	45	19.9	86	23.5	110	55	44.8	19.9	84.4	23.2	108
26	44.8	19.9	84	22.6	107	56	43.9	19.9	87.5	23.2	111
27	42.9	19.9	85	23.6	109	57	44.6	19.9	84.9	22.1	107
28	44.2	19.8	84	22.8	107	58	43.8	19.9	85.2	22.8	108
29	44.3	19.8	83	23	106	59	46	19.9	87.1	24	111
30	44.9	19.8	85	23.5	109	60	43.9	19.9	87.4	23.7	111

Table 6-21a. Measurement Stability Results for Model 350 High Range Analyzers

	Unit H1				Unit H2			
	SO_2	CO	O_2	NO_x [(a)]	SO_2	CO	O_2	NO_x [(a)]
Difference in Slopes (ppm or %/min)	-0.02	0.007	0.001	0.011	-0.024	0.002	0.001	0.05
(ppm or %/hr)[(b)]	-1.2		0.06		-1.44			3
(Standard Error)	0.009	0.008	0.001	0.018	0.006	0.007	0.001	0.014
p-Value	0.0256	0.3303	0.0057	0.5337	0.0003	0.841	0.2406	0.0009

[(a)] Reference NO_x compared to NO + NO_2.
[(b)] Values presented in this row for significant slopes only.

Table 6-21b. Measurement Stability Results for Model 350 Low Range Analyzers

	Unit L1				Unit L2			
	SO_2	CO	O_2	NO_x [(a)]	SO_2	CO	O_2	NO_x [(a)]
Difference in Slopes (ppm or %/min)	NA	-0.007	0.001	0.035	NA	-0	0.001	0.043
(ppm or %/hr)[(b)]			0.06	2.1				2.58
(Standard Error)		0.006	0.0004	0.012		0.009	0.0004	0.012
p-Value		0.194	0.001	0.0063		0.681	0.0765	0.001

[(a)] Reference NO_x compared to NO + NO_2.
[(b)] Values presented in this row for significant slopes only.

6.11 Inter-Unit Repeatability

The repeatability of test results between the two sets of duplicate Model 350 analyzers was assessed in those cases where the data lent itself to application of a t-test. The resulting t-statistics and associated p-values are listed in Tables 6-22a and b. Highlighted in bold are those p-values less than 0.05, which indicate a statistically significant difference between duplicate Model 350 analyzers at a 95% confidence level. As Table 6-22a shows, significant differences between duplicate analyzers during the laboratory tests were found in the high range SO_2 measurement and low range CO measurements. While these results are statistically significant, they represent very small differences in the slopes and intercepts of the respective linearity equations (Table 6-2). As Table 6-22b shows, statistically significant differences between duplicate analyzers during the RA tests using the combustion sources were found in the SO_2, NO, NO_2, and NO_x measurements on individual sources. The considerable differences in SO_2 readings with the diesel engine high source was probably a symptom of the impending failure of the H1 SO_2 sensor in the final (Diesel Engine Medium) test (see Section 6.12.3). In most of these few

Table 6-22a. Summary of Repeatability—Laboratory Tests

Linearity Data Unit 1 vs. Unit 2		High CO	High NO	High NO_2	High O_2	High SO_2	Low CO	Low NO
Intercept	t-statistic	0.3820	-0.1793	-1.3524	-0.2260	0.4623	-2.4980	0.0283
	p-value[a]	0.355	0.431	0.103	0.413	0.325	**0.011**	0.489
Slope	F-statistic	0.0002	0.0853	0.2574	0.3040	23.5160	24.3483	0.0065
	p-value[a]	0.999	0.999	0.999	0.412	< **0.001**	< **0.001**	0.999

[a] Values highlighted in bold indicate significant differences between duplicate analyzers.

Table 6-22b. Summary of Repeatability—Combustion Tests

Relative Accuracy Data Unit 1 vs. Unit 2		SO_2	CO	O_2	NO	NO_2	NO_x
Diesel Engine Low	t-statistic	-10	0.8	1	1.414	-2.072	-2.742
	p-value[a]	**<.0001**	0.4468	0.3466	0.195	0.072	**0.0254**
	Mean Diff.	-1.111					-0.822
	%	5.49%					0.75%
Diesel Engine Medium	t-statistic	NA	1.036	2	0	-17.736	-1.61
	p-value[a]	NA	0.3307	0.0805	1	**<.0001**	0.1462
	Mean Diff.					-4.389	
	%					10.04%	
Diesel Engine High	t-statistic	-36.131	-8	0	-4.076	-5.516	NA
	p-value[a]	**<.0001**	<.0001	1	0.0036	**0.0006**	NA
	Mean Diff.	-55.556	-0.889		-7.444	-1.744	
	%	9.22%				10.36%	
Gas Range, 10" H_2O,	t-statistic	NA	0	-1.512	3.506	0.449	0.644
Minimum Primary Air	p-value[a]	NA	1	0.169	**0.008**	0.6653	0.5377
	Mean Diff.				1.444		
	%				8.23%		
Gas Range, 8" H_2O,	t-statistic	NA	0.555	0.555	1.835	-0.819	1.654
Maximum Primary Air	p-value[a]	NA	0.5943	0.5943	0.1038	0.4367	0.1367
	Mean Diff.						
	%						

[a] Values highlighted in bold indicate significant differences between duplicate analyzers.

cases, the unit-to-unit differences found are small, i.e., mean differences of about 1 ppm. Thus, the primary conclusion is that the duplicate Model 350 analyzers generally agree closely with one another.

6.12 Other Factors

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

6.12.1 Costs

The cost of each analyzer as tested in the verification program was approximately $8,000. This represents the purchase cost of the entire system, including the Model 350 analyzer, sample conditioner, sample line, probe, remote control unit, and accessories.

6.12.2 Data Completeness

The data completeness was 100% for the Model 350 Units H2, L1, and L2. The data completeness was 95% for Model 350 Unit H1, which experienced an SO_2 sensor failure prior to completing the final diesel engine RA test.

6.12.3 Maintenance/Operational Factors

The short duration of the verification tests prevented assessing long-term maintenance, durability, etc. The high range CO sensors were replaced after an attempt to assess linearity up to 10,000 ppm of CO (see Sections 3.8 and 4.2). The test plan was subsequently modified to reflect a high range of 0 to 5,000 ppm CO (see Section 4.2). Also, the SO_2 sensor in Model 350 unit H1 failed before the last combustion test (Diesel Engine Condition #2, Table 6-14d). Because no replacement sensor was available, that test was completed with only one of the two units measuring SO_2.

The Model 350 is rugged and readily portable, and setup time was minimal. The rapid sensor response times and measurement stability allowed verification testing to proceed smoothly. The Model 350 design incorporates a sample probe and sample conditioning system, making it adaptable to a wide range of measurement applications.

Chapter 7
Performance Summary

The Model 350 analyzers provided a linear response for all the target gases over their full measurement ranges. Response times ranged from 10 to 20 seconds for NO, and 30 to 32 seconds for CO, but were consistently 18 seconds for NO_2, 20 seconds for O_2, and 27 seconds for SO_2. Detection limits estimated from the laboratory testing for the high range analyzers (based on the upper end of the 3-sigma, 95% confidence level) were 1.22 ppm for CO, 1.57 to 1.66 ppm for NO, 0.26 to 0.41 ppm for NO_2, and 1.24 ppm for SO_2. Detection limits estimated from the laboratory testing for the low range analyzers were 0.25 ppm for CO and 0.25 to 0.45 ppm for NO. No detection limit could be calculated for O_2, since the analyzers always read 0.0% when provided with zero gas. A variety of selected interferants generally produced no response on the Model 350 analyzers, and no interferant produced a response as much as 1% of that from an equal concentration of target analyte. Responses to 394 ppm NO were 2.3 to 4.8% low when 400 ppm SO_2 also was present.

Ambient temperature over the range of 47°F to 105°F had a minimal (< 2% of span concentration) effect on the zero and span readings of the Model 350 analyzers. Zero and span differences caused by interruption of operation were less than 1.0% of the respective span concentrations. Over the tested range of –10 to +10 inches of water (relative to ambient pressure), the sample gas pressure had no significant effect on the zero or span readings of the Model 350 analyzers.

The RA of the Model 350 analyzers was usually within 10% for CO, NO, NO_x, and SO_2, and within 1% for O_2, with the sources tested (two range burner sources, three diesel engine sources). The only exceptions were those conditions where CO and NO_2 concentrations were below 6 ppm, and in NO_2 measurements from the diesel engine exhaust when NO_2 was less than 7% of total NO_x. For the low concentration conditions, the CO and NO_2 analyzers were accurate to within their 1-ppm resolution. For the NO_2 measurements from diesel exhaust, RAs ranged from 8% to 55%, and the direct mesurement of NO_2 by the Model 350 analyzers produced more consistent readings than did the determination of NO_2 by difference with the chemiluminescent reference method. Total NO_x RAs for the diesel engine tests were all within 7%.

Zero/span drift ranged between –1.68% and 3.36% of the span concentration, considering data from all the tests. When sampling diesel exhaust for an hour continuously, both high range Model 350 analyzers showed a statistically significant decrease in SO_2 concentrations over time compared with the reference analyzer. The average downward trend of 1.3 ppm/hr represented a decrease of 6% of the mean measured concentration over one hour of sampling. An upward trend of 3 ppm/hr in the NO_x measurement in one of the units represented an increase of 3% of the mean measured concentration over one hour of sampling. Both Model 350 low range analyzers showed a statistically significant increase in NO_x concentrations over time compared with the reference analyzer. The average upward trend of 2.34 ppm/hr represented an increase of 2% of the mean measured concentration over one hour of sampling. During the verification tests, duplicate Model 350 analyzers showed close unit-to-unit agreement, i.e., within 1% for almost all cases.

The Model 350 is rugged and readily portable, and setup time was minimal. The rapid sensor response times and measurement stability allowed verification testing to proceed smoothly. The Model 350 design incorporates a sample probe and sample conditioning system, making it adaptable to a wide range of measurement applications. The cost of a Model 350 analyzer system, as tested, is $8,000.

Chapter 8
References

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

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