August 2001

Environmental Technology Verification Report

RUPPRECHT & PATASHNICK, CO. SERIES 1400a TEOM® PARTICLE MONITOR

Prepared by

Battelle
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Under a cooperative agreement with

EPA U.S. Environmental Protection Agency

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

Battelle

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ETV Joint Verification Statement

TECHNOLOGY TYPE:	**Continuous Ambient Fine Particle Monitor**
APPLICATION:	**MEASURING FINE PARTICULATE MASS IN AMBIENT AIR**
TECHNOLOGY NAME:	**Series 1400a TEOM® Particle Monitor**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

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

The Advanced Monitoring Systems (AMS) Center, one of six technology centers under ETV, is operated by Battelle in cooperation with EPA's National Exposure Research Laboratory. The AMS Center has recently evaluated the performance of continuous monitors used to measure fine particulate mass and species in ambient air. This verification statement provides a summary of the test results for the Rupprecht & Patashnick, Co. Series 1400a TEOM particle monitor.

VERIFICATION TEST DESCRIPTION

The objective of this verification test is to provide quantitative performance data on continuous fine particle monitors under a range of realistic operating conditions. To meet this objective, field testing was conducted in two phases in geographically distinct regions of the United States during different seasons of the year. The first phase of field testing was conducted at the ambient air monitoring station on the Department of Energy's National Energy Technology Laboratory campus in Pittsburgh, PA, from August 1 to September 1, 2000. The second phase of testing was performed at the California Air Resources Board's ambient air monitoring station in Fresno, CA, from December 18, 2000, to January 17, 2001. Specific performance characteristics verified in this test include inter-unit precision, agreement with and correlation to time-integrated reference methods, effect of meteorological conditions, influence of precursor gases, and short-term monitoring capabilities. The Series 1400a TEOM monitor reports measurement results in terms of $PM_{2.5}$ mass and, therefore, was compared with the federal reference method (FRM) for $PM_{2.5}$ mass determination. Additionally, comparisons with a variety of supplemental measurements were made to establish specific performance characteristics.

Quality assurance (QA) oversight of verification testing was provided by Battelle and EPA. Battelle QA staff conducted a data quality audit of 10% of the test data, and performance evaluation audits were conducted on the FRM samplers used in the verification test. Battelle QA staff conducted an internal technical systems audit for Phase I and Phase II. EPA QA staff conducted an external technical systems audit during Phase II.

TECHNOLOGY DESCRIPTION

The Series 1400a TEOM monitor can be configured with appropriate separation devices to measure ambient particulate mass concentrations in real time of any of the following: PM_{10}, $PM_{2.5}$, PM_1, or TSP (total suspended particulates). In this verification test, the Series 1400a TEOM monitors were configured with PM_{10} heads and $PM_{2.5}$ sharp cut cyclones. A tapered element oscillating microbalance, which is a patented inertial mass measurement technique, directly measures particle mass collected on a filter. Mass concentration data are reported in micrograms per cubic meter. The Series 1400a TEOM monitor has exposed collection filters that can be analyzed for heavy metals using standard laboratory techniques. Active volumetric flow control maintains a constant volumetric flow rate by using density-adjusted mass flow control that incorporates ambient pressure and temperature sensors. The Series 1400a TEOM monitor is a gravimetric instrument that draws ambient air through a filter at a constant flow rate, continuously weighing the filter and calculating rolling 10-minute smoothed mass concentrations. The Series 1400a TEOM monitor computes the total mass accumulation on the collection filter, as well as 30-minute, one-hour, eight-hour, and 24-hour averages of the mass concentration. Hydrophobic filter material and sample collection at above-ambient temperature eliminates the necessity for humidity equilibration. Both analog and RS-232 outputs are available. Input/output capabilities include a menu-driven user interface, seven analog input channels for receiving external data with conversion to engineering units, vector-based averaging for wind speed and direction, internal data logging of system and external information, three user-defined analog output channels, two contact closure alarm circuits, and advanced RS-232 support for the retrieval of current and logged information. The Series 1400a TEOM monitor is 35.56 cm (14 in.) wide, approximately 99.36 cm (39.12 in.) high, and 27.94 cm (11 in.) deep.

VERIFICATION OF PERFORMANCE

Inter-Unit Precision: Regression analysis of the data from the duplicate Series 1400a TEOM monitors showed r^2 values of 0.851 and 0.949, respectively, for the hourly data and 24-hour average results during Phase I. The slopes of the regression lines were 0.879 (0.027) and 0.901 (0.080), respectively, for the hourly data and 24-hour averages, where the values in parentheses are 95% confidence intervals. An intercept of 1.22 (0.66) $\mu g/m^3$ was observed for the hourly data, and 0.87 (1.73) $\mu g/m^3$ for the 24-hour averages. The calculated coefficient of variation (CV) for the hourly data was 22.5%, and for the 24-hour averages, the CV was 9.0%. Regression analysis showed r^2 values of 0.998 and 0.9995, respectively, for the hourly data and 24-hour average results during Phase II. The slopes of the regression lines were 0.986 (0.004) and 0.992 (0.008), respectively, for the hourly data and

24-hour averages, and the intercepts were -0.50 (0.17) µg/m^3 and -0.73 (0.33) µg/m^3, respectively. The calculated CV for the hourly data was 12.1%; and, for the 24-hour average data, the CV was 3.2%.

Comparability/Predictability: During Phase I, comparisons of the 24-hour averages with $PM_{2.5}$ FRM results showed slopes of the regression lines for Monitor 1 and Monitor 2 of 0.964 (0.096) and 0.911 (0.099), respectively; these slopes were not significantly different from unity at the 95% confidence level. The regression results show r^2 values of 0.945 and 0.935 for Monitor 1 and Monitor 2, respectively. The intercepts of the regression lines were 2.21 (1.94) and 1.85 (2.01) µg/m^3, respectively, for Monitor 1 and Monitor 2. During Phase II, comparison of the 24-hour averages with $PM_{2.5}$ FRM results showed slopes of the regression lines for Monitor 1 and Monitor 2 of 0.463 (0.055) and 0.459 (0.054), respectively, indicating a negative bias relative to the FRM. The respective intercepts were -0.31 (4.6) and -1.1 (4.5) µg/m^3, and both TEOM 1400a monitors gave r^2 values of 0.915 relative to the FRM.

Meteorological Effects: Multivariable model analysis was used to determine if the meteorological conditions had an influence on the readings of the Series 1400a TEOM monitors relative to the FRM results. This model ascribed to total precipitation, wind speed, and the variability in wind direction a statistically significant influence on the Series 1400a TEOM monitors relative to the FRM in Phase I, at the 90% confidence level. The model ascribed to the variability in wind direction, relative humidity, and solar radiation a statistically significant influence on the readings of the two monitors relative to the FRM in Phase II, at 90% confidence. However, the apparent effects on the Series 1400a TEOM monitors were small under the average conditions of each phase (approximately 5 to 7% effect in Phase I, and approximately 1% in Phase II), relative to the linear regression against FRM results alone.

Influence of Precursor Gases: The measured precursor gases had no influence on the results of either monitor relative to the FRM at the 90% confidence level during Phase I. During Phase II, the model ascribed to the concentration of nitric oxide a significant effect on the two Series 1400a TEOM monitors relative to the FRM. Under typical conditions during Phase II, this effect was approximately 1%.

Short-Term Monitoring: In addition to 24-hour FRM samples, short-term monitoring was performed on a five-sample-per-day basis in Phase II. Considering all short-term results together, linear regression of these data showed slopes of 0.555 and 0.552, respectively, for Monitor 1 and Monitor 2. The intercepts of the regression lines were -6.2 and -6.9 µg/m^3, respectively; and the r^2 values were 0.798 and 0.806, respectively. The observed negative bias relative to the short-term reference samples is consistent with the negative bias relative to 24-hour FRM results in Phase II.

Other Parameters: No operating problems arose during testing, and no maintenance was performed on either monitor.

Gabor J. Kovacs Vice President Environmental Sector Battelle	Date	Gary J. Foley Director National Exposure Research Laboratory Office of Research and Development U.S. Environmental Protection Agency	Date

August 2001

Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

RUPPRECHT & PATASHNICK, CO.
Series 1400a TEOM® Particle Monitor

by

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Notice

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

Foreword

The U.S. 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 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/07/07_main.htm.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. In particular we would like to thank the staff at the Department of Energy's National Energy Technology Laboratory, including Richard Anderson, Don Martello, and Curt White, for their assistance in conducting Phase I of the verification test reported here. We would like to thank the California Air Resources Board for its assistance in conducting Phase II of verification testing. We would like to acknowledge the efforts of ETV stakeholders for their assistance in planning this verification test and for reviewing the test/QA plan and the verification reports. Specifically, we would like to acknowledge Judith Chow of Desert Research Institute, Jeff Cook of the California Air Resources Board, Tim Hanley of EPA, and Rudy Eden of the South Coast Air Quality Management District. We also would like to thank Tim Hanley of EPA for the loan of a BGI FRM sampler for Phase II.

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List of Abbreviations

ADQ	audit of data quality
AMS	Advanced Monitoring Systems
CARB	California Air Resources Board
cm	centimeter
CO	carbon monoxide
CV	coefficient of variation
DOE	U.S. Department of Energy
DPI	digital pressure indicator
DRI	Desert Research Institute
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FRM	federal reference method
H_2S	hydrogen sulfide
Hg	mercury
IMPROVE	Interagency Monitoring for Protection of Visual Environments
in.	inch
L/min	liters per minute
m	meters
mg	milligram
mm	millimeters
NETL	National Energy Technology Laboratory
N_2	nitrogen
NIST	National Institute of Standards and Technology
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_3	ozone
ppb	parts per billion
QA/QC	quality assurance/quality control
QMP	quality management plan
R&P	Rupprecht & Patashnick
SCC	Sharp Cut Cyclone
SLAMS	state and local air monitoring stations
SFS	sequential filter sampler
SO_2	sulfur dioxide
TOR	thermal optical reflectance
TEOM	tapered element oscillating microbalance
TSA	technical systems audit

List of Abbreviations (Cont'd)

µg	microgram
WINS	well impactor ninety six

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 designing, distributing, permitting, purchasing, and using environmental technologies.

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

The EPA's National Exposure Research Laboratory and its verification organization partner, Battelle, operate the Advanced Monitoring Systems (AMS) Center under ETV. The AMS Center recently evaluated the performance of fine particle monitors for use in continuous monitoring of fine particulate matter in ambient air. This verification report presents the procedures and results of the verification test for the Rupprecht and Patashnick (R&P) Series 1400a TEOM® particle monitor.

Chapter 2
Technology Description

The following description of the Series 1400a TEOM monitor is based on information provided by the vendor.

The Series 1400a TEOM monitor can be configured with appropriate separation devices to measure ambient particulate mass concentration in real time of any of the following: PM_{10}, $PM_{2.5}$, PM_1, or TSP (total suspended particulates) in real time. In this verification test, the Series 1400a TEOM monitors were configured with PM_{10} heads and $PM_{2.5}$ sharp cut cyclones. A tapered element oscillating microbalance (TEOM), which is a patented inertial mass measurement technique, directly measures particulate mass collected on a filter. Mass concentration data are reported in micrograms per cubic meter. The Series 1400a TEOM monitor has exposed collection filters that can be analyzed for heavy metals using standard laboratory techniques. Active volumetric flow control maintains a constant volumetric flow rate by using density-adjusted mass flow control that incorporates ambient pressure and temperature sensors.

The Series 1400a TEOM monitor is a gravimetric instrument that draws ambient air through a filter at a constant flow rate, continuously weighing the filter and calculating rolling 10-minute smoothed mass concentrations. The Series 1400a TEOM monitor computes the total mass accumulation on the collection filter, as well as 30-minute, one-hour, eight-hour, and 24-hour averages of the mass concentration. Hydrophobic filter material and sample collection at above-ambient temperature eliminates the necessity for humidity equilibration. Both analog and RS-232 outputs are available.


Figure 2-1. R&P Instruments Series 1400a TEOM Particle Monitor

Input/output capabilities include a menu-driven user interface, seven analog input channels for receiving external data with conversion to engineering units, vector-based averaging for wind speed and direction, internal data logging of system and external information, three user-defined analog output channels, two contact closure alarm circuits, and advanced RS-232 support for the retrieval of current and logged information. The Series 1400a TEOM monitor is 35.56 cm (14 in.) wide, approximately 99.36 cm (39.12 in.) high, and 27.94 cm (11 in.) deep.

Chapter 3
Test Design and Procedures

3.1 Introduction

The objective of this verification test is to provide quantitative performance data on continuous fine particle monitors under a range of realistic operating conditions. To meet this objective, field testing was conducted in two phases in geographically distinct regions of the United States during different seasons of the year. Performing the test in different locations and in different seasons allowed sampling of widely different particulate matter concentrations and chemical composition. At each site, testing was conducted for one month during the season in which local $PM_{2.5}$ levels were expected to be highest. The verification test was conducted according to the procedures specified in the *Test/QA Plan for Verification of Ambient Fine Particle Monitors.*(1)

The first phase of field testing was conducted at the ambient air monitoring station on the Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) campus in Pittsburgh, PA. Sampling during this phase of testing was conducted from August 1 to September 1, 2000. The second phase of testing was performed at the California Air Resources Board's (CARB's) Air Monitoring Station in Fresno, CA. This site is also host to one of the EPA's $PM_{2.5}$ Supersites being managed by Desert Research Institute (DRI). This phase of testing was conducted from December 18, 2000, to January 17, 2001.

3.2 Test Design

Specific performance characteristics verified in this test include

- Inter-unit precision
- Agreement with and correlation to time-integrated reference methods
- Effect of meteorological conditions
- Influence of precursor gases
- Short-term monitoring capabilities.

To assess inter-unit precision, duplicate Series 1400a TEOM monitors were tested in side-by-side operation during each phase of testing. During Phase I, the monitors used were Serial Numbers 22086 and 23104. During Phase II, the monitors used were Serial Numbers 23326 and 23325. Collocation of the Series 1400a TEOM monitors with reference systems for time-integrated sampling of fine particulate mass and chemical speciation provided the basis for assessing the degree of agreement and/or correlation between the continuous and reference methods. Each test site was equipped with continuous monitors to record meteorological conditions and the concentration of key precursor gases (ozone, nitrogen oxides, sulfur dioxide, etc.). The data from the meteorological and gas monitors were used to assess whether these parameters affected the performance of the fine particle monitors relative to the FRM. Reference method sampling periods of 3, 5, and 8 hours were used in Phase II of this test to establish the short-term monitoring capabilities of the continuous monitors being tested. Statistical calculations, as described in Chapter 5, were used to establish each of these performance characteristics.

Additionally, other performance characteristics of the technologies being verified, such as reliability, maintenance requirements, and ease of use, were assessed. Instrumental features that may be of interest to potential users (e.g., power and shelter requirements and overall cost) are also reported.

3.3 Reference Method and Supplemental Measurements

Since no appropriate absolute standards for fine particulate matter exist, the reference methods for this test were well established, time-integrated methods for determining particulate matter mass or chemical composition. It is recognized that comparing real-time measurements with time-integrated measurements does not fully explore the capabilities of the real-time monitors. However, in the absence of accepted standards for real-time fine particulate matter measurements, the use of time-integrated standard methods that are widely accepted was necessary for performance verification purposes. It should be noted that there are necessary differences between continuous and time-integrated, filter-based techniques. For example, in time-integrated sampling, particulate matter collected on a filter may remain there for up to 24 hours, whereas continuous monitors generally retain the particulate sample for one hour or less. Thus, the potential for sampling artifacts differs. Also, in the case of particle mass measurements, the mass of particulate matter is determined after equilibration at constant temperature and humidity, conditions that are almost certain to differ from those during sampling by a continuous monitor.

The Series 1400a TEOM monitor reports measurement results in terms of $PM_{2.5}$ mass and therefore was compared with the federal reference method (FRM) for $PM_{2.5}$ mass determination.(2) Additionally, comparisons with a variety of supplemental measurements were made to establish specific performance characteristics. Descriptions of the reference method and supplemental measurements used during the verification test are given below.

3.3.1 $PM_{2.5}$ Mass

The FRM for $PM_{2.5}$ mass determination, i.e., the 24-hour time-averaged procedure detailed in 40 CFR Part 50,(2) involves manual sampling using any of a number of designated commercially available filter samplers, followed by gravimetric analysis of the collected sample. In this method, a size-selective inlet is used to sample only that fraction of aerosol of interest (i.e., ≤ 2.5 µm aerodynamic diameter). The air sample is drawn into the sampler at a fixed rate (16.7 L/min) over 24 hours, and the aerosol is collected on a Teflon filter for gravimetric analysis. After equilibration of the sample and filter in a temperature- and humidity-controlled environment, the sample is weighed on an appropriate microbalance. The particulate sample weight is determined by subtracting the weight of the filter alone, determined prior to sampling after similar equilibration. Protocols for sample collection, handling, and analysis are prescribed by EPA(2) and were followed for this verification test.

Filter samples for the $PM_{2.5}$ FRM were collected daily during each phase of the testing using a BGI FRM sampler (RFPS-0498-116), and the $PM_{2.5}$ mass was determined according to the procedures mentioned above. In Phase I, a single BGI FRM sampler (SN 311) was operated daily from noon to noon to collect the FRM samples. These samples followed all aspects of the FRM except for the adoption of a noon-to-noon schedule (rather than midnight-to-midnight) to facilitate field operations. During Phase II, two BGI FRM samplers (SN 287 and SN 311) were used and were operated on alternate days to facilitate a midnight-to-midnight sampling schedule.

Collocated samples were collected during each phase to establish the precision of the FRM. A discussion of the collocated sampling is presented in Section 4.4 of this report.

3.3.2 Supplemental Measurements

Various supplemental measurements were used to further establish the performance of the continuous monitors being tested. Meteorological conditions were monitored and recorded continuously throughout each phase of the verification test. These measurements included temperature, relative humidity, wind speed, direction, barometric pressure, and solar radiation. These data were provided to Battelle for Phase I by DOE/NETL and for Phase II by DRI. Likewise, the ambient concentrations of various precursor gases including ozone and nitrogen oxides also were measured continuously during the verification test and used to assess the influence of these parameters on the performance of the monitors tested. Continuous measurements of sulfur dioxide, hydrogen sulfide, nitric oxide, nitrogen dioxide, nitrogen oxides, and ozone were provided for Phase I by DOE/NETL; and continuous measurements of carbon monoxide, ozone, nitric oxide, nitrogen dioxide, and nitrogen oxides were provided for Phase II by DRI. These gases were of interest as potential chemical precursors to aerosol components, and as indicators of ambient pollutant levels.

During Phase I, samples for chemical speciation were collected using an Andersen RAAS speciation sampler configured with five sample trains (one channel at 16.7 L/min and four channels at approximately 8 L/min). The 16.7 L/min channel was operated with a Teflon filter for $PM_{2.5}$ mass determination. Samples for carbon analysis were collected at 8 L/min on quartz filters and analyzed by the IMPROVE thermal optical reflectance method at DRI. Nitrate and sulfate samples were collected on nylon filters downstream of a magnesium-oxide-coated compound annular denuder, and analyzed by ion chromatography at Consol.

To supplement the 24-hour samples, additional samples for $PM_{2.5}$ mass were collected at the Fresno site over shorter sampling periods (i.e., 3-, 5-, 8-hour) to assess the capabilities of the monitors being tested in indicating short-term $PM_{2.5}$ levels. A medium-volume sequential filter sampling system (SFS) sampling at a flow rate of 113 L/min was used to collect the short-term mass and speciation samples during Phase II. The SFS was configured to take two simultaneous samples (i.e., Teflon-membrane/drain disk/quartz-fiber and quartz-fiber/sodium-chloride-impregnated cellulose-fiber filter packs) at 20 L/min through each sampling port. Anodized aluminum nitric acid denuders were located between the inlets and the filters to remove gaseous nitric acid. The remaining 73 L/min required for the 113 L/min total inlet flow was drawn through a makeup air sampling port inside the plenum. The timer was set to take five sets of sequential samples every 24 hours. Solenoid valves, controlled by a timer, switched between one to five sets of filters at midnight each day. A vacuum pump drew air through the paired filter packs when the valves were open. The flow rate was controlled by maintaining a constant pressure across a valve with a differential pressure regulator.

The filters were loaded at the DRI's Reno, NV, laboratory into modified Nuclepore filter holders that were plugged into quick-disconnect fittings on the SFS. One filter pack contained a 47-mm-diameter Teflon-membrane filter with quartz-fiber backup filter. A drain disc was placed between the Teflon-membrane and quartz-fiber filters to ensure a homogeneous sample deposit on the front Teflon-membrane filter and to minimize fiber transfer from one filter to the other. The Teflon-membrane filter collected particles for mass and elemental analysis. The other filter pack contained a 47-mm-diameter quartz-fiber filter with a sodium-chloride-impregnated cellulose-fiber backup filter on a separate stage. The deposit on the quartz-fiber filter was analyzed for ions and carbon. The sodium-chloride-impregnated cellulose-fiber backup filter was analyzed for nitrate to estimate losses due to volatilization of ammonium nitrate from the front filter during sampling.

This sequential filter sampler was operated from midnight to 5:00 a.m. (0000-0500), from 5:00 a.m. to 10:00 a.m. (0500-1000), from 10:00 a.m. to 1:00 p.m. (1000-1300), from 1:00 p.m. to 4:00 p.m. (1300-1600), and from 4:00 p.m. to midnight (1600-2400). These short-term sampling measurements were appropriately summed over 24 hours for comparison with the corresponding 24-hour results of the FRM reference samplers to establish the relationship between the two sets of measurements.

3.4 Data Comparisons

The primary means used to verify the performance of the Series 1400a TEOM monitors was comparison with the 24-hour FRM results. Additional comparisons were made with the supplemental meteorological conditions and precursor gas concentrations to assess the effects of these parameters on the response of the monitors being tested relative to the FRM. The short-term monitoring results from Fresno in Phase II of the verification test also were used to assess the capabilities of the Series 1400a TEOM monitors to indicate short-term levels of ambient $PM_{2.5}$. The comparisons were based on statistical calculations as described in Section 5 of this report.

Comparisons were made independently for the data from each phase of field testing; and, with the exception of the inter-unit precision calculations, the results from the duplicate monitors were analyzed and reported separately. Inter-unit precision was determined from a statistical inter-comparison of the results from the duplicate monitors.

3.5 Site Layout/Instrument Installation

In each phase of testing, the two Series 1400a TEOM monitors were installed in Battelle's instrument trailer, which is a converted 40-foot refrigerator semi-trailer. The Series 1400a TEOM monitors were placed on a counter top, with each monitor directly below a 7.6-cm (3 in.) port through the roof of the trailer. Separate inlet tubes, approximately three meters (10 feet) in length, were installed vertically through the sampling ports and secured on the trailer roof using tripods. A PM_{10} head and $PM_{2.5}$ Sharp Cut Cyclone (SCC) were used with each Series 1400a TEOM monitor to provide particle size selection. Total flow through the size-selective inlet was 16.7 L/min. An isokinetic flow splitter placed immediately downstream of the size-selective inlet extracted a sample flow of 1.0 L/min through the sample filter. Using the 1.0 L/min flow setting for the TEOM monitors, the lifetime of the filter was greater than the period of testing during each phase, and no filter replacement was necessary. In each phase, the sampled aerosol was heated to 50°C in the inlet system, and the default calibration factors of 1.03 for the slope and $3 \mu g/m^3$ for the intercept were used for the Series 1400a TEOM monitors. Data generated by the Series 1400a TEOM monitors were recorded internally and downloaded daily onto an on-site laptop computer throughout each phase of testing as described in Section 4.6.2.

3.5.1 Phase I

Phase I verification testing was conducted at the DOE/NETL facility within the Bruceton Research Center. The facility is located in the South Park area of Pittsburgh, PA, approximately 7 miles from downtown. The air monitoring station where testing was conducted is located on the top of a relatively remote hill within the facility and is impacted little by road traffic. The layout of the testing facility is illustrated schematically in Figure 3-1.

For this test, Battelle provided temporary facilities to augment the permanent facilities in use by the DOE/NETL air monitoring staff. These temporary facilities included a temporary Battelle/ETV platform (16-foot by 14-foot scaffold construction) and a Battelle instrument trailer. The Battelle trailer was positioned parallel with, and approximately 25 feet from, the DOE/NETL instrument trailer. The Battelle/ETV platform was located between the two trailers, with the surface at a height of approximately 2 meters (6 feet).

Most of the DOE/NETL continuous monitoring equipment, including the continuous precursor gas monitors, were located inside the DOE/NETL instrument trailer. A DOE/NETL Rupprecht & Patashnick (R&P) Co. Partisol FRM sampler used to evaluate FRM precision data was located outside on a DOE/NETL platform. The Series 1400a TEOM monitors were installed inside the Battelle trailer, and the BGI FRM sampler was installed on the Battelle/ETV platform. A vertical separation of approximately 2 to 3 meters and a horizontal separation of approximately 3 meters existed between the inlets of the Series 1400a TEOM monitors and the BGI FRM sampler. A 10-meter (33-foot) meteorological tower was located approximately 25 meters (65 feet) to the north of the DOE/NETL instrument trailer.

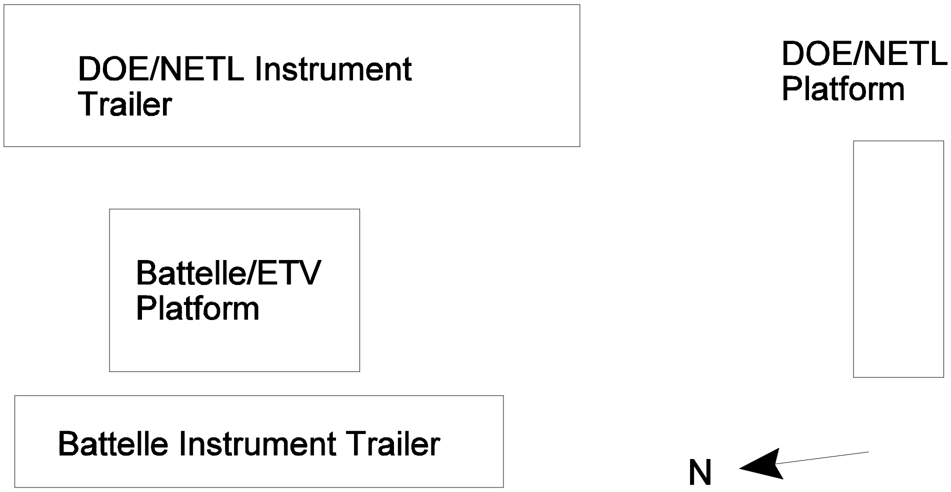

Figure 3-1. Site Layout During Phase I of Verification Testing (not drawn to scale)

3.5.2 Phase II

Phase II of verification testing was conducted at the CARB site on First Street in Fresno. This site is located in a residential/commercial neighborhood about 3 miles north of the center of Fresno. The two BGI FRM samplers and a 3-meter (10-foot) meteorological tower were located on the roof of the two-story building housing the CARB office. Continuous precursor gas monitors were located inside the CARB office space and sampled through a port in the roof of the building. The two BGI FRM samplers were located on the southernmost edge of the rooftop to be as close as possible to the instrument trailer. The Battelle trailer used during Phase I of this verification test also was used during Phase II. For Phase II, the Battelle trailer was located in the parking lot adjacent to the building in which the CARB site is located. The trailer was positioned approximately 25 meters (80 feet) to the south of the building, as shown in Figure 3-2. The Series 1400a TEOM monitors were located in the Battelle trailer and installed in the same fashion as in Phase I of the verification test. A difference in elevation of approximately 6 meters (20 feet) existed between the top of the trailer and the roof of the building housing the CARB site and between the inlet of the Series 1400a TEOM monitors and the BGI FRM samplers. In addition to the two BGI FRM samplers used to collect the reference samples, an R&P Partisol FRM sampler was operated on the rooftop by CARB. The R&P FRM sampler was positioned approximately 25 meters (65 feet) to the northeast of the BGI FRM samplers and was used to measure the precision of the FRM reference values. The sequential filter sampler used to collect the short-term samples was located near the R&P FRM sampler.

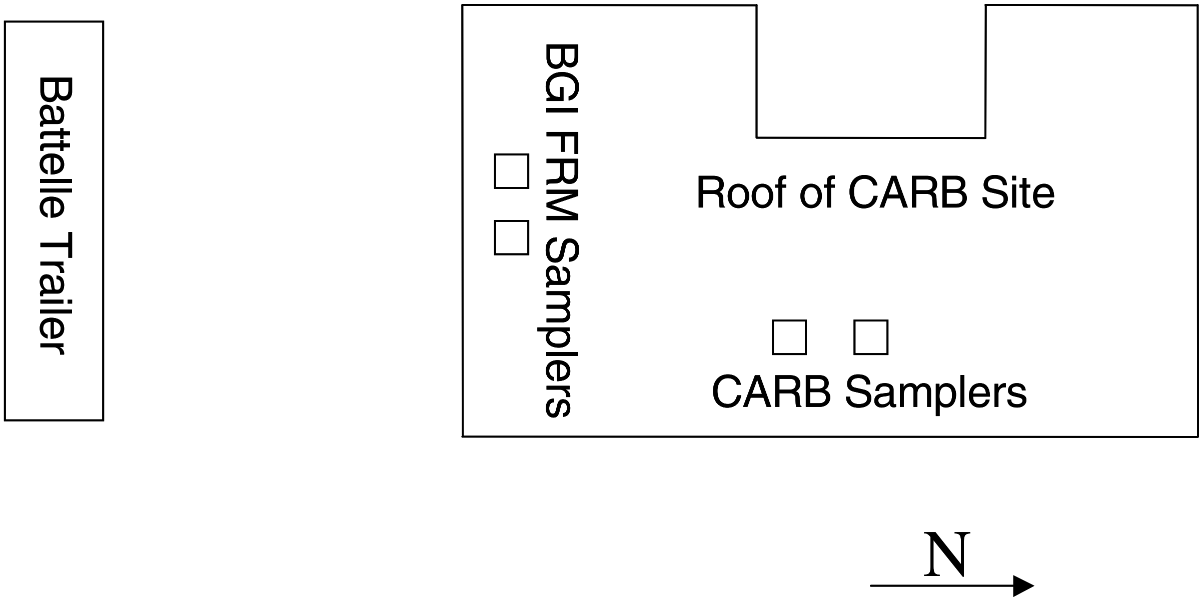

Figure 3-2. Site Layout During Phase II of Verification Testing (not drawn to scale)

Chapter 4
Quality Assurance/Quality Control

4.1 Data Review and Validation

Test data were reviewed and approved according to the AMS Center quality management plan (QMP),(3) the test/QA plan,(1) and Battelle's one-over-one policy. The Verification Test Coordinator or the Verification Testing Leader or designee reviewed the raw data, laboratory notebook entries, and data sheets that were generated each day and approved them by initialing and dating the records.

Data from the Series 1400a TEOM monitors were validated by a representative of R&P and reviewed by the Verification Test Coordinator before being used in statistical calculations. Data were checked for error flags and not used if flagged for power or instrument failure. Daily $PM_{2.5}$ concentration averages calculated from the continuous Series 1400a TEOM monitor data were considered valid if the percent data recovery for the 24-hour sampling period (i.e., noon to noon for Phase I, or midnight to midnight for Phase II) was 75% or greater.

4.2 Deviations from the Test/QA Plan

The following deviations from the test/QA plan were documented and approved by the AMS Center Manager. Neither of these deviations had any deleterious effect on the verification data.

- Calibration checks of the temperature and pressure sensors were not performed within one week of the start of Phase II. Subsequent checks of these sensors indicated proper calibration.

- The distance between the reference samplers and the monitors being tested was increased to approximately 25 meters to accommodate changes in the overall site layout for Phase II.

In addition, although not formally a deviation from the test/QA plan, we note that the relative humidity of the conditioning/weighing room used by Consol in Phase I occasionally deviated from the specified limits. The impact of this occurrence was minimal, as described in Section 4.4.1.

4.3 Calibration and Parameter Checks of Reference Sampler

The BGI FRM samplers provided by Battelle for this verification test were calibrated using National Institute of Standards and Technology (NIST)-traceable flow meters and temperature and pressure sensors. The calibration and verification of these samplers are described below.

4.3.1 Flow Rate Calibration and Verification

Prior to Phase I of the verification test, a three-point calibration of the BGI FRM flow rate was performed on June 22, 2000. Flows were measured at three set points (16.7 L/min, and approximately +10% and -10% of 16.7 L/min) using a dry gas meter (American Meter Company, Battelle asset number LN 275010, calibrated January 21, 2000). If necessary, the flows were adjusted manually until agreement with the dry gas meter fell within ±2% of the sampler's indicated flow reading.

The on-site operators checked the flow rate of the BGI FRM sampler both before and after Phase I of the verification test using an Andersen Instruments Inc. dry gas meter (identification number 103652, calibrated March 30, 2000). The flow rate was checked prior to testing on both July 19, 2000, and July 30, 2000. In both cases, the measured flow rate was verified to be within 4% of the flow rate indicated by the sampler. After testing, the flow rate was again checked on September 11, 2000, using the same Andersen dry gas meter. In this case, the flow rate did not fall within the 4% acceptance limit. This failure is probably linked to the failure of the ambient temperature thermocouple, on September 7, 2000, after completion of the Phase I sampling (see Section 4.3.2).

Prior to Phase II of the verification test, single point calibration checks of the duplicate BGI FRM samplers was performed at 16.7 L/min on December 15, 2000. These flow rate checks were performed using a BGI DeltaCal calibrator (BGI Inc., serial number 0027, calibrated October 24, 2000) and the measured flow rates were within 4% of the indicated flow on each sampler. Weekly flow rate checks also were performed throughout Phase II using the DeltaCal flow meter. In each case, the measured flow rates were within ±4% of the indicated reading of the BGI FRM and within ±5% of the nominal 16.7 L/min setpoint.

Calibration of the flow rate for the SFS sampler used during Phase II was maintained by DRI through daily flow checks with a calibrated rotameter, and through independent performance evaluation audits conducted by Parson's Engineering. No additional flow verification was performed for this test.

4.3.2 Temperature Sensor Calibration and Verification

Both the ambient temperature sensor and the filter temperature sensor of the BGI FRM sampler were checked at three temperatures (approximately 5, 22, and 45°C) on June 20, 2000. The sensor readings were compared with those from an NIST-traceable Fluke Model 52 thermocouple gauge (Battelle asset number LN 570068, calibrated October 15, 1999). Agreement between the sampler temperature sensors and the calibrated thermocouple was within ±2°C at each temperature.

The temperature sensors also were checked at the DOE/NETL site both before and after Phase I of the verification test by the on-site operators. Prior to testing, the sensors were checked on July 19, 2000, and July 30, 2000, against the readings from a mercury thermometer (Ever Ready, serial number 6419, calibrated October 29, 1999). For these checks, agreement between the sensors and the thermometer was within ±2°C. After the verification period, the ambient temperature sensor suffered a malfunction on September 7. The filter temperature sensor was checked on September 11, 2000, and showed agreement with the mercury thermometer within ±2°C. The sensor was replaced, after completing Phase I, with a new factory-calibrated sensor provided by BGI.

The temperature sensors for the two BGI FRM samplers were checked on January 16, 2001, against readings from a Fluke Model 52 thermocouple gauge (Battelle asset number LN 570077, calibrated October 26, 2000). For each BGI FRM, both the ambient and filter temperature sensor readings agreed with the thermocouple readings within ±2°C.

4.3.3 Pressure Sensor Calibration and Verification

Before Phase I, the barometric pressure sensor in the BGI FRM sampler was calibrated against an NIST-traceable Taylor Model 2250M barometer (Battelle asset number LN 163610, calibrated January 12, 2000) and an NIST-traceable convectron gauge (Granville-Phillips Co., Battelle asset number LN 298084, calibrated August 25, 1999) on June 17 and 18, 2000. The sensor was calibrated at ambient pressure and under a reduced pressure (approximately 100 mm mercury below ambient).

Checks of the pressure sensor were performed at the DOE/NETL site both before and after Phase I of the verification test. The pressure sensor was checked on July 19, 2000, and July 30, 2000, using an NIST-traceable Taylor Model 2250M barometer (Battelle asset number LN 163609, calibrated January 12, 2000). On September 11, 2000, the pressure sensor of the BGI FRM sampler was again checked against the same barometer, but did not agree within the acceptance criterion of 5 mm mercury. This failure is possibly associated with the failure of the ambient temperature sensor on September 7, 2000.

The ambient pressure sensor for both BGI FRM samplers used in Phase II was checked against the pressure readings of a BGI DeltaCal on January 16, 2001. Agreement between the BGI FRM pressure readings and those of the DeltaCal was within ±5 mm mercury for both samplers.

4.3.4 Leak Checks

Leak checks of the BGI FRM sampler were performed every fourth day during Phase I of the verification test. These leak checks were conducted immediately following the cleaning of the WINS impactor and were performed according to the procedures in the operator's manual for the BGI FRM sampler. All leak checks passed the acceptance criteria provided in the operator's manual.

Leak checks of the BGI FRM and SFS samplers were performed daily during Phase II of the verification test. These leak checks were conducted during set-up for each 24-hour sampling period. All leak checks passed before the sampler set-up was completed.

4.4 Collocated Sampling

4.4.1 Phase I—Pittsburgh

To establish the precision of the $PM_{2.5}$ FRM, the BGI FRM sampler was collocated with an R&P FRM sampler for Phase I, including a period of two weeks prior to and one week after Phase I of the verification test. During the sampling periods before and after Phase I, the BGI and R&P FRM samplers were located on the same platform and within 4 meters of one another. During the Phase I testing period, these samplers were separated by a horizontal distance of approximately 25 meters with a vertical separation of less than 2 meters. The samples from the BGI FRM sampler were collected and analyzed by Consol, and the samples from the R&P FRM sampler were collected and analyzed by on-site Mining Safety and Health Administration staff.

Figure 4-1 shows the results of the collocated FRM sampling conducted for Phase I. These data were analyzed by linear regression; and the calculated slope, intercept, and r^2 values are 0.939 (0.033), 1.28 (0.66) $\mu g/m^3$, and 0.957, respectively, where the values in parentheses are 95% confidence intervals (CIs). Despite completely independent operations (i.e., separate sampling staff and weighing facilities), these data show very good agreement between the BGI FRM and the R&P FRM samplers. The data also indicate that, although the humidity in the conditioning/weighing room at Consol was not always within the specified FRM limits, the influence of the elevated humidity was not severe.

4.4.2 Phase II—Fresno

During Phase II of testing, duplicate BGI FRM samplers (SN 287 and SN 311) were used to collect the 24-hour FRM reference samples. These samplers were operated one at a time on alternate days to facilitate midnight-to-midnight sampling. Likewise, an R&P Partisol sampler was used by CARB to collect 24-hour FRM samples. The R&P FRM sampler was located approximately 25 meters from the BGI FRM samplers, with no vertical separation. The same on-site operators performed the sampling for the FRM samplers; however, DRI performed the gravimetric analyses for the BGI FRM samplers and CARB performed the analyses for the R&P FRM sampler.

Figure 4-2 shows the results for the collocated FRM sampling conducted for Phase II. Only 12 days of collocated sampling were available from the Fresno site. The linear regression of these data shows a slope of 1.096 (0.106) an intercept of -1.04 (4.7) $\mu g/m^3$, and an r^2 value of 0.982, where the numbers in parentheses indicate the 95% CIs.

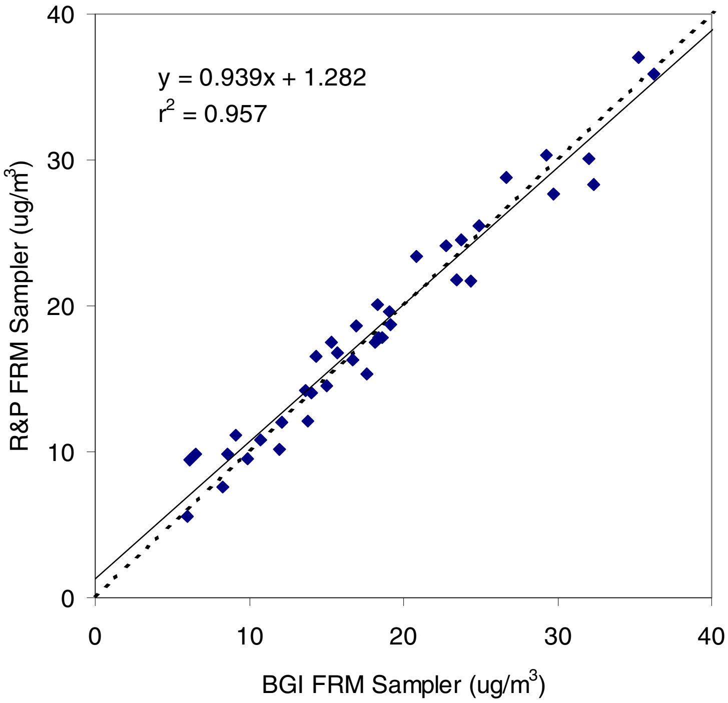

Figure 4-1. Comparison of Collocated $PM_{2.5}$ FRM Samplers for Phase I of Verification Testing

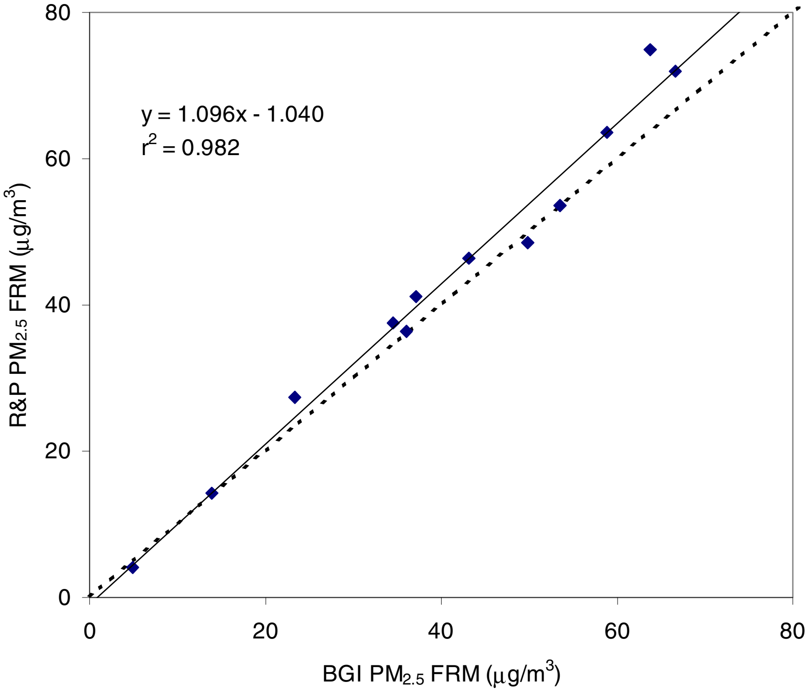

Figure 4-2. Comparison of Collocated $PM_{2.5}$ FRM Samplers for Phase II of Verification Testing

4.4.3 Summary

The results from the collocated FRMs in both Pittsburgh and Fresno show agreement that is consistent with the goals for measurement uncertainty of $PM_{2.5}$ methods run at state and local air monitoring stations (SLAMS). These goals are identified in Appendix A to 40 CFR Part 58, Section 3.5(4) which states: "The goal for acceptable measurement uncertainty has been defined as 10% coefficient of variation (CV) for total precision and ±10% for total bias." Since the collocated FRMs in both Pittsburgh and Fresno were operated by independent organizations, a comparison to the SLAMS data quality objectives for $PM_{2.5}$ is an appropriate way to assess whether the measurement systems were producing data of acceptable quality. In both Pittsburgh and Fresno, the results of the collocated sampling meet the data quality objectives for the total bias. In Fresno, the collocated sampling results show a CV of 6.3%, which meets the data quality objectives for precision. In Pittsburgh, the calculated CV was 10.5%. However, this value is driven largely by scatter in the low concentration range. When a single low data pair is removed, the CV becomes 9.1%, which meets the data quality objectives for total precision. (It should be noted, as well, that the Fresno collocated results consist of only 12 data points.) Thus, the collocated FRM results from Pittsburgh and Fresno show that the reference measurements were suitable for verifying the performance of continuous fine particle monitors.

4.5 Field Blanks

4.5.1 Phase I—Pittsburgh

During Phase I, at least 10% of the collected reference samples were field blanks. The observed filter mass difference of the field blanks ranged from -7 µg to 16 µg, and the corresponding $PM_{2.5}$ concentrations (which were determined using an assumed sample volume of 24 m^3) were all less than 0.7 $\mu g/m^3$, averaging 0.15 $\mu g/m^3$. FRM results for Phase I were not blank corrected.

4.5.2 Phase II—Fresno

During Phase II, at least 10% of the collected reference samples (for both the BGI FRM samplers and the DRI sequential filter sampler) were field blanks. The results were added to a database containing historical field blank data. On average, these blanks showed mass differences of 2 µg, with a standard deviation of 8 µg. Assuming a sample volume of 24 m^3 (i.e., FRM volume), these blanks account for ~ 0.1 $\mu g/m^3$. Assuming a sample volume of 3.6 m^3 (i.e., three-hour short-term sample from sequential filter sampler), these blanks account for ~ 0.6 $\mu g/m^3$. These blank values were negligible, even for the short-term sampling periods, in comparison with the $PM_{2.5}$ mass levels that were present during the Phase II testing (see Section 6.2). FRM results for Phase II were blank corrected using the data available from the historical database.

4.6 Data Collection

4.6.1 Reference Measurements

During Phase I, daily records of the sampling activities for the BGI FRM sampler were recorded on individual data sheets by the on-site operators, and summary data from the BGI FRM sampler were downloaded daily using portable data logging modules. Information recorded on the data sheets included identification of the sampling media (i.e., filter ID numbers) and the start and stop times for the sampling periods. Summary data from the sampler included the parameters listed above, in addition to the sampling duration, volume sampled, and average temperature and pressure readings.

During Phase II, summary data from the BGI FRM samplers were logged daily on sampling sheets by the on-site operators. These data included sample identification, start times for the sampling period, sampling duration, volume sampled, and average temperature and pressure readings.

4.6.2 Series 1400a TEOM Monitors

Several user-selectable parameters were recorded in an internal memory buffer, along with a date and time stamp, by each of the Series 1400a TEOM monitors throughout each phase of the verification test. During Phase 1, the user-selectable parameters recorded were mass concentration, 30-minute average mass concentration, one-hour average mass concentration, 24-hour average mass concentration, and total mass on the filter. During Phase II, the parameters recorded were 30-minute mass concentration, one-hour average mass concentration, eight-hour average mass concentration, 24-hour average mass concentration, total mass, instrument status, case temperature, and filter loading in percent. The recorded data were downloaded directly onto a laptop computer and saved as text files. These files were imported into a spreadsheet for analysis, and copies of the data were stored by the Verification Test Coordinator on a floppy disk as well as on a computer hard drive.

The data presented in this report are the one-hour average mass concentrations. Daily 24-hour averages were computed from these hourly data using midnight as the start hour and 11:00 p.m. as the end hour.

4.7 Assessments and Audits

4.7.1 Technical Systems Audit

Phase I—Pittsburgh

The technical systems audit (TSA) ensures that the verification tests are conducted according to the test/QA plan(1) and that all activities associated with the tests are in compliance with the ETV pilot QMP.(3) The Battelle Quality Manager conducted an internal TSA on August 3, 2000, at the Pittsburgh test site. All findings noted during this TSA were documented and submitted to the

Verification Test Coordinator for correction. The corrections were documented by the Verification Test Coordinator and reviewed by Battelle's Quality Manager, Verification Testing Leader, and AMS Center Manager. None of the findings adversely affected the quality or outcome of this phase of the verification test. All corrective actions were completed to the satisfaction of the Battelle Quality Manager. The records concerning this TSA are permanently stored with the Battelle Quality Manager.

Phase II—Fresno

An internal TSA was conducted by the Battelle Quality Manager on January 9, 2001, at the Fresno test site. An external TSA was also conducted concurrently by EPA quality staff, Ms. Elizabeth Betz and Ms. Elizabeth Hunike. All findings noted during these TSAs were documented and submitted to the Verification Test Coordinator for corrective action. None of the findings adversely affected the quality or outcome of this phase of the verification test for the Series 1400A TEOM. All corrective actions were completed to the satisfaction of the Battelle Quality Manager.

4.7.2 Performance Evaluation Audit

Phase I—Pittsburgh

The reference sampler provided by Battelle for this verification test was audited during Phase I to ensure that it was operating properly. During Phase I of the verification test, the flow rate of the BGI FRM sampler was audited on August 28, using a dry gas meter (American Meter Company, Battelle asset number LN 275010, calibrated April 17, 2000). The measured flow rate was within the ±4% acceptance criterion with respect to the internal flow meter and within the ±5% acceptance criterion with respect to the nominal flow rate.

Both temperature sensors in the BGI FRM sampler were checked on August 28, using a Fluke 52 thermocouple (Battelle asset number LN 570068, calibrated October 15, 1999). Agreement between each sensor and the thermocouple was within the ±2°C acceptance criterion.

Phase II—Fresno

A performance evaluation audit was conducted to ensure that the two BGI FRM samplers used during Phase II of testing were operating properly. The flow rates of the samplers were audited on January 16 and 17, 2001, using a dry gas meter (Schlumberger, SN 103620, calibrated July 6, 2000). For each sampler, the measured flow rate was within the ±4% acceptance criterion with respect to the internal flow meter and within the ±5% acceptance criterion with respect to the nominal flow rate.

The temperature readings for the two samplers were checked with a mercury thermometer (Fisher Scientific, SN 7116). Agreement between each sensor and the thermocouple was within the ±2°C acceptance criterion.

The pressure sensors for the two samplers were checked against a Druck digital pressure indicator (DPI) (SN 6016/00-2, calibrated June 28, 2000). Agreement between each sensor and the DPI was within the acceptance criterion of ±5 mm mercury.

4.7.3 Audit of Data Quality

Battelle's Quality Manager ensured that an audit of data quality (ADQ) of at least 10% of the verification data acquired during the verification test was completed. The ADQ traced the data from initial acquisition, through reduction and statistical comparisons, to final reporting. Reporting of findings followed the procedures described above for the Phase I TSA. All findings were corrected to the satisfaction of the Battelle Quality Manager, and none of the findings aversely affected the quality of the verification test for the Series 1400a TEOM monitors.

Chapter 5
Statistical Methods

Performance verification is based, in part, on statistical comparisons of continuous monitoring data with results from the reference methods. A summary of the statistical calculations that have been made is given below.

5.1 Inter-Unit Precision

The inter-unit precision of the Series 1400a TEOM monitors was determined based on procedures described in Section 5.5.2 of EPA 40 CFR 58, Appendix A, which contains guidance for precision assessments of collocated non-FRM samplers. Simultaneous measurements from the duplicate Series 1400a TEOM monitors were paired, and the behavior of their differences was used to assess precision. For both the hourly and the 24-hour $PM_{2.5}$ measurements, the coefficient of variation (CV) is reported. The CV is defined as the standard deviation of the differences divided by the mean of the measurements and expresses the variability in the differences as a percentage of the mean. As suggested by the EPA guidance, only measurements above the limit of detection were used in precision calculations. Inter-unit precision was assessed separately for each phase of the verification test.

5.2 Comparability/Predictability

The comparability between the Series 1400a TEOM monitors and the $PM_{2.5}$ FRM was assessed, since these monitors yield measurements with the same units of measure as the $PM_{2.5}$ FRM reference method. The relationship between the two was assessed from a linear regression of the data using the $PM_{2.5}$ FRM results as the independent variable and the Series 1400a TEOM monitor results as the dependent variable as follows:

$$C_i = \mu + \beta \times R_i + \varepsilon_i \qquad (1)$$

where R_i is the i^{th} 24-hour FRM $PM_{2.5}$ measurement; C_i is the average of the hourly Series 1400a TEOM monitor measurements over the same 24-hour time period as the i^{th} reference measurement;, μ and β are the intercept and slope parameters, respectively; and ε_i is error unexplained by the model. The average of the hourly Series 1400a TEOM monitor measurements is used because this is the quantity that is most comparable to the reference sampler measurements.

Comparability is expressed in terms of bias between the Series 1400a TEOM monitor and the $PM_{2.5}$ FRM reference method and the degree of correlation (i.e., r^2) between the two. Bias was assessed based on the slope and intercept of the linear regression of the data from the $PM_{2.5}$ FRM and the Series 1400a TEOM monitor. In the absence of bias, the regression equation would be $C_i = R_i + \varepsilon_i$ (slope = 1, intercept = 0), indicating that the 24-hour average of hourly Series 1400a TEOM monitor measurements is simply the $PM_{2.5}$ FRM measurement plus random error. A value of r^2 close to 1 implies that the amount of random error is small; that is, the variability in the hourly measurements is almost entirely explained by the variability in the $PM_{2.5}$ FRM measurements.

Quantities reported include r^2, intercept, and slope, with estimates of 95% CIs for the intercept and slope. Comparability to the FRM was determined independently for each of the two duplicate Series 1400a TEOM monitors being tested and was assessed separately for each phase of the verification test.

5.3 Meteorological Effects/Precursor Gas Influence

The influence of meteorological conditions on the relationship of the Series 1400a TEOM monitor readings to the $PM_{2.5}$ FRM reference results was evaluated, by using meteorological data as parameters in multivariable analyses of the reference/monitor comparison. The same evaluation was done with ambient precursor pollutant concentrations as the model parameters. The model used is as follows:

$$C_i = \mu + \beta \times R_i + \Sigma \gamma_j \times X_{ji} + \varepsilon_i \tag{2}$$

where X_{ji} is the meteorological or precursor gas measurement for the i^{th} 24-hour time period, γ_j is the associated slope parameters, and other notation is as in Equation 1. Comparability results are reported again after these variables are adjusted for in the model. Additionally, estimates of γ_j are provided. Meteorological effects and precursor gas interferences were assessed independently for each of the two duplicate Series 1400a TEOM monitors tested and were assessed separately for each phase of the verification test. In conducting these multivariable analyses, a significance level of 90% was used in the model selection. This significance level is less stringent than the 95% level used in other aspects of the verification, and was chosen so that even marginally important factors could be identified for consideration.

Note that the multivariable model ascribes variance unaccounted for by linear regression against the FRM to the meteorological or precursor gas parameters. The model treats all candidate parameters equally. The model discards the least significant parameter and is rerun until all remaining variables have the required significance (i.e., predictive power). The results of the model should not be taken to imply a cause-and-effect relationship. It is even possible that the parameters identified as significant for one unit of a monitoring technology may differ from those identified for the duplicate unit of that technology due to differences in the two data sets.

5.4 Short-Term Monitoring Capabilities

This assessment was based on linear regression analysis of results from the Series 1400a TEOM monitors and the short-term (3-, 5-, and 8-hour) sampling results from the two BGI FRM samplers generated in Phase II only. The analysis was conducted, and the results are reported in a fashion identical to that for the comparability results for the 24-hour samples described in Section 5.2.

These comparisons were made only after establishing the relationship between the short-term sampling results and the corresponding 24-hour results. The relationship between the two sets of reference measurements was made by linear regression using the weighted sum of the results from the short-term sampling as the dependent variable and the 24-hour FRM results as the independent variable in the regression analysis. Comparability was assessed using Equation 1, replacing the average of hourly measures with the average of short-term sampler measurements. The short-term sampling results also have been used to assess the effects of meteorological conditions and precursor gas concentrations on the response of the Series 1400a TEOM monitors. These short-term results were used in place of the 24-hour FRM measurements in the analysis described in Section 5.3 for Phase II only. Independent assessments were made for each of the duplicate Series 1400a TEOM monitors, and the data from each phase of testing were analyzed separately.

Chapter 6
Test Results

6.1 Phase I—Pittsburgh (August 1 - September 1, 2000)

Samples were collected daily between August 1 and September 1, 2000, using a $PM_{2.5}$ FRM sampler. During this period, the daily $PM_{2.5}$ concentration as measured by the BGI FRM sampler ranged from 6.1 $\mu g/m^3$ to 36.2 $\mu g/m^3$, with an average daily concentration of 18.4 $\mu g/m^3$. Typically, the $PM_{2.5}$ composition was dominated by sulfate and carbon species. On average, the measured sulfate concentration, determined by ion chromatography, accounted for approximately 47% of the daily $PM_{2.5}$ mass. Total carbon, as measured by the IMPROVE thermal optical reflectance (TOR) method, accounted for approximately 38% of the $PM_{2.5}$ mass, with elemental carbon contributing approximately 22% and organic carbon contributing approximately 77% of the total carbon. Additionally, nitrate contributed about 8.3% of the daily $PM_{2.5}$ concentration.

Table 6-1 summarizes the meteorological conditions during Phase I, and Table 6-2 summarizes the observed concentrations of the measured precursor gases during this period.

Table 6-1. Summary of Daily Values for the Measured Meteorological Parameters During Phase I of Verification Testing

	Wind Speed (mph)	Vertical Wind Speed (mph)	Wind Direction (degrees)	Air Temp. @ 10 m (C)	Air Temp. @ 2 m (C)	RH (%)	Solar Radiation (W/m^2)	Press. (mbar)	Total Precip. (in.)
Average	3.35	0.09	196	20.0	16.6	89.4	162.8	979.7	0.0014
Max	6.45	0.29	298	24.1	22.5	95.8	246.1	986.7	0.03
Min	1.88	-0.03	106	14.6	12.1	80.2	47.9	974.5	0.00

Table 6-2. Summary of Daily Values for the Measured Precursor Gas Concentrations During Phase I of Verification Testing

	SO_2 (ppb)	H_2S (ppb)	NO (ppb)	NO_2 (ppb)	NO_x (ppb)	O_3 (ppb)
Average	6.9	1.5	3.1	10.1	13.0	24
Max	12.8	2.9	10.4	17.4	27.4	51
Min	2.7	-0.6	0.14	5.3	5.3	5

6.1.1 Inter-Unit Precision

The hourly mass concentration readings from the two Series 1400a TEOM monitors for Phase I of the verification test are shown in Figure 6-1a. Breaks in the data indicate periods during which power outages occurred at the test site (August 6, 7, and 10-11). The two traces in Figure 6-1a appear barely distinguishable. In Figure 6-1b these same data are plotted against one another to illustrate the correlation between the two monitors.

For comparison with the $PM_{2.5}$ FRM reference measurements, the hourly data were averaged from noon to noon for each day to correspond with the 24-hour sampling periods used in Phase I of the verification test. In Figure 6-2a the noon-to-noon averages for Phase I of the verification test are presented for the two Series 1400a TEOM monitors. A correlation plot of these data is shown in Figure 6-2b.

These data were analyzed by linear regression, and the results of this analysis are presented in Table 6-3. The CV for these values was also determined according to Section 5.1, and the calculated CV is shown in Table 6-3. The regression analysis of the hourly data shows a coefficient of determination $r^2 = 0.851$ between the duplicate monitors. The results of the regression analysis indicate a bias between the two monitors, with Monitor 1 generally reading higher than Monitor 2 [slope = 0.879 (0.027)]. A Student's t-test indicates a statistically significant bias between the two monitors, with Monitor 1 reading 1.2 $\mu g/m^3$ higher than Monitor 2 on average. The calculated CV for the hourly data is 22.5%, most of which may be attributed to the observed bias between the monitors rather than random variations in the readings. The regression results for the hourly data show that the intercept of the correlation plot is 1.22 (0.63) $\mu g/m^3$, which is statistically significant at the 95% confidence level.

For the 24-hour average concentration results from the duplicate monitors, the regression results in Table 6-3 show an r^2 value of 0.949. The calculated CV for the 24-hour averages is 9.0%. As with the hourly data, a Student's t-test indicates a bias between the duplicate monitors. A bias between the two monitors is also indicated by the correlation plot, which has a slope of 0.901 (0.08) that is statistically different from unity at the 95% confidence level. These data show an intercept of 0.87 (1.73) $\mu g/m^3$, which is not statistically significant at the 95% confidence level.

Table 6-3. Linear Regression and Coefficient of Variation Results for Hourly and 24-Hour Average $PM_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase I

Parameter	Hourly Data	24-Hour Average Data
Slope (95% CI)	0.879 (0.027)	0.901 (0.080)
Intercept ($\mu g/m^3$) (95% CI)	1.22 (0.63)	0.87 (1.73)
r^2	0.851	0.949
CV	22.5%	9.0%

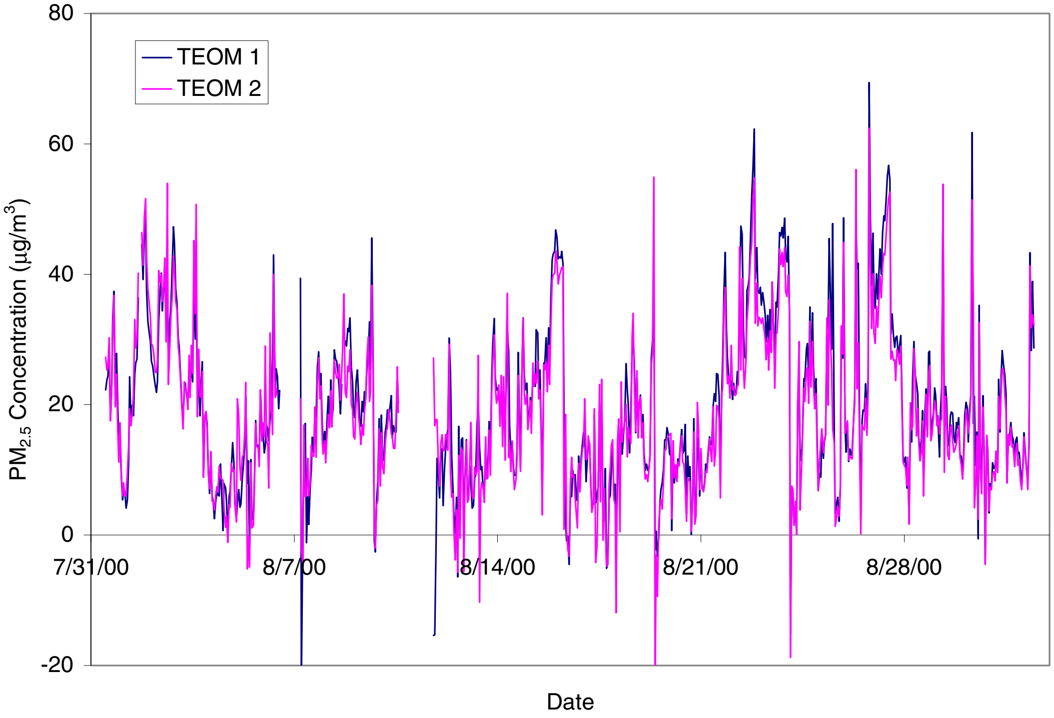

Figure 6-1a. Hourly $PM_{2.5}$ Mass Concentrations from Duplicate Series 1400a TEOM Monitors During Phase I of Verification Testing (original graph is in color)

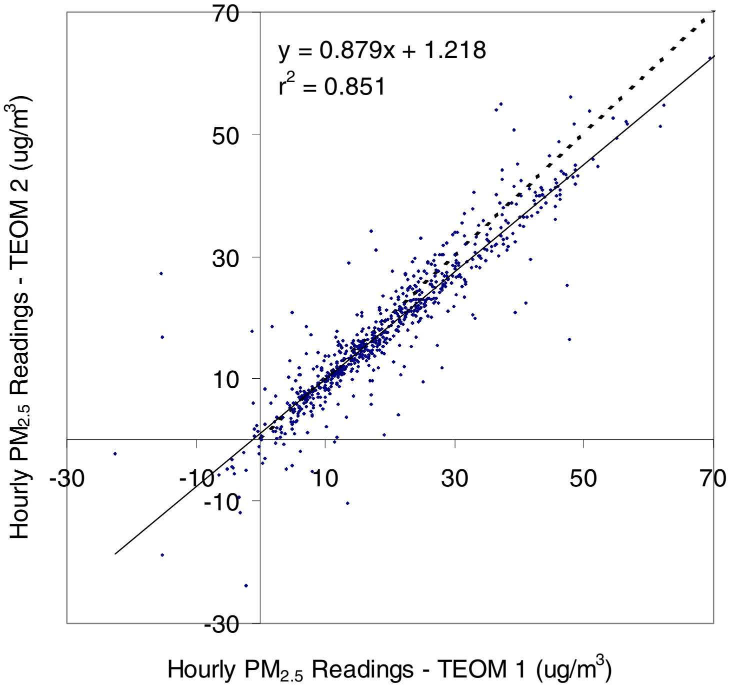

Figure 6-1b. Correlation Plot of the Hourly $PM_{2.5}$ Data from Duplicate Series 1400a TEOM Monitors During Phase I of Verification Testing

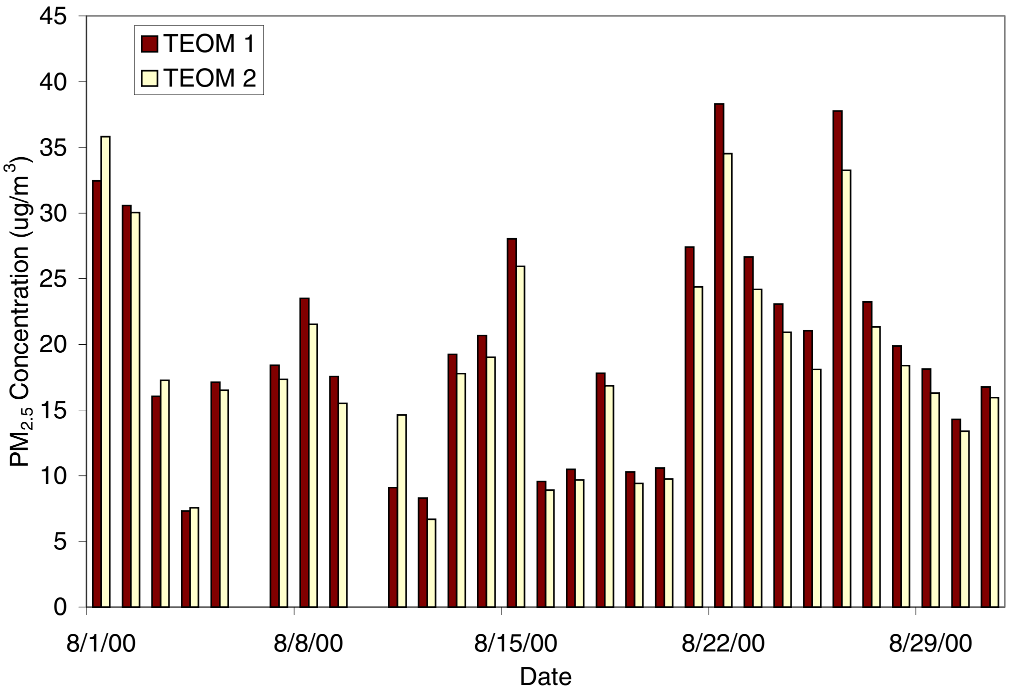

Figure 6-2a. 24-Hour Average $PM_{2.5}$ Mass Concentrations from Duplicate Series 1400a TEOM Monitors During Phase I of Verification Testing

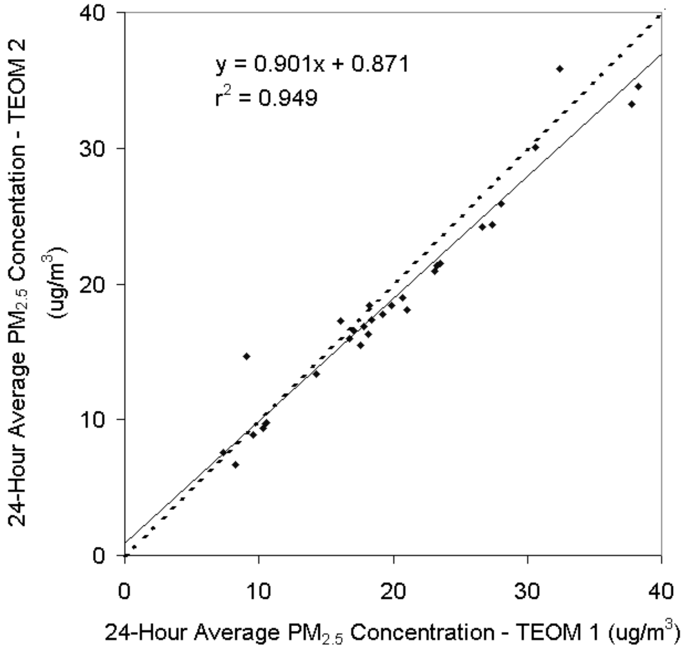

Figure 6-2b. Correlation Plot of 24-Hour $PM_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase I of Verification Testing

6.1.2 Comparability/Predictability

In Figure 6-3a, the noon-to-noon averages of the Series 1400a TEOM monitor measurements are shown, along with the $PM_{2.5}$ FRM type measurements for Phase I of the verification test. These $PM_{2.5}$ concentration values were analyzed by linear regression according to Section 5.2 to establish the comparability of each of the Series 1400a TEOM monitors with the $PM_{2.5}$ FRM sampler. The resulting comparisons are plotted in Figure 6-3b; and the calculated slope, intercept, and r^2 value of the regression analyses are presented in Table 6-4 for each monitor.

The slopes of the regression lines for Monitor 1 and Monitor 2 are 0.964 (0.096) and 0.911 (0.099), respectively. In each case, the uncertainty in the slope of this plot includes unity at the 95% confidence interval and therefore indicates no statistical bias. The regression analysis shows an intercept of 2.21 (1.94) µg/m^3 for Monitor 1 and 1.85 (2.01) for Monitor 2. The analysis shows r^2 values of 0.945 and 0.935 respectively for Monitor 1 and Monitor 2.

Table 6-4. Comparability of the Series 1400a TEOM Monitors with the $PM_{2.5}$ FRM During Phase I

Regression Parameter	Monitor 1	Monitor 2
Slope (95% CI)	0.964 (0.096)	0.911 (0.099)
Intercept (µg/m^3) (95% CI)	2.21 (1.94)	1.85 (2.01)
r^2	0.945	0.935

6.1.3 Meteorological Effects

A multivariable model, as described in Section 5.3, was used to determine if the readings of the Series 1400a TEOM monitors were affected by the meteorological conditions. This analysis involved a backward elimination process to remove from the analysis model those parameters showing no statistically significant influence on the results. This model ascribed to total precipitation, wind speed, and the standard deviation of wind direction a statistically significant influence on the 24-hour Series 1400a TEOM readings relative to the FRM in Phase I, at the 90% confidence level. The analysis shows the following relationships:

$$\text{Monitor 1} = 0.978*\text{FRM} - 1.46*\text{WS} + 5.57*\text{TP} - 0.014*\text{WDSTD} + 8.19\ \mu g/m^3$$

and

$$\text{Monitor 2} = 0.947*\text{FRM} -1.12*\text{WS} + 4.40*\text{TP} - 0.020*\text{WDSTD} + 7.01\ \mu g/m^3$$

where FRM represents the measured $PM_{2.5}$ FRM values in µg/m^3, WS is the wind speed in mph, TP is the average precipitation in inches, and WDSTD is the standard deviation of the wind

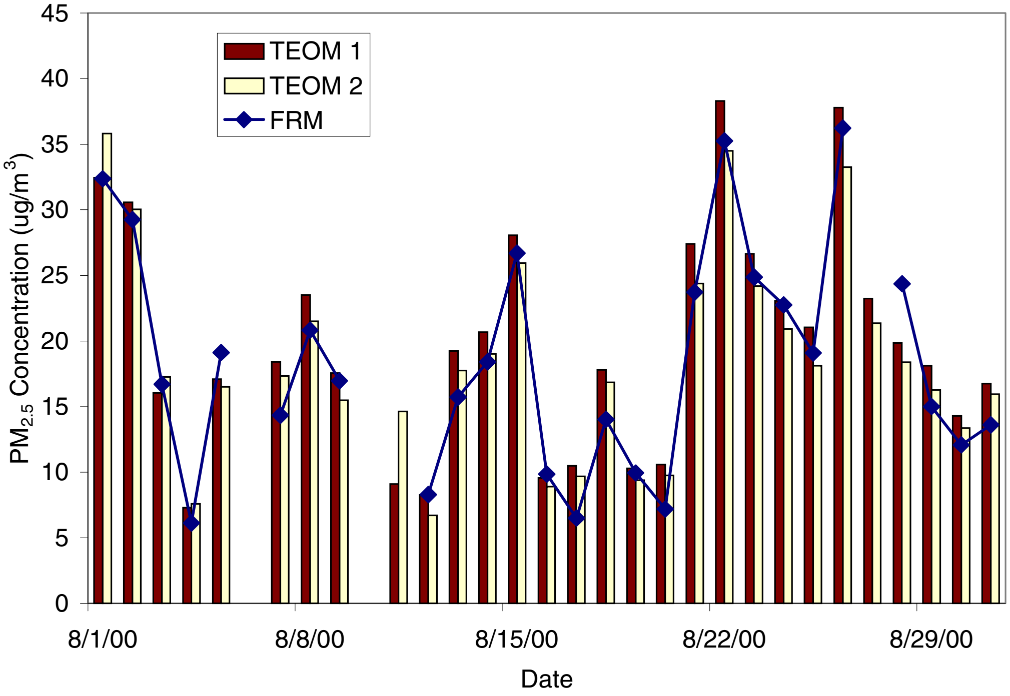

Figure 6-3a. Daily Average $PM_{2.5}$ FRM Concentrations and the 24-Hour Average $PM_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase I of Verification Testing

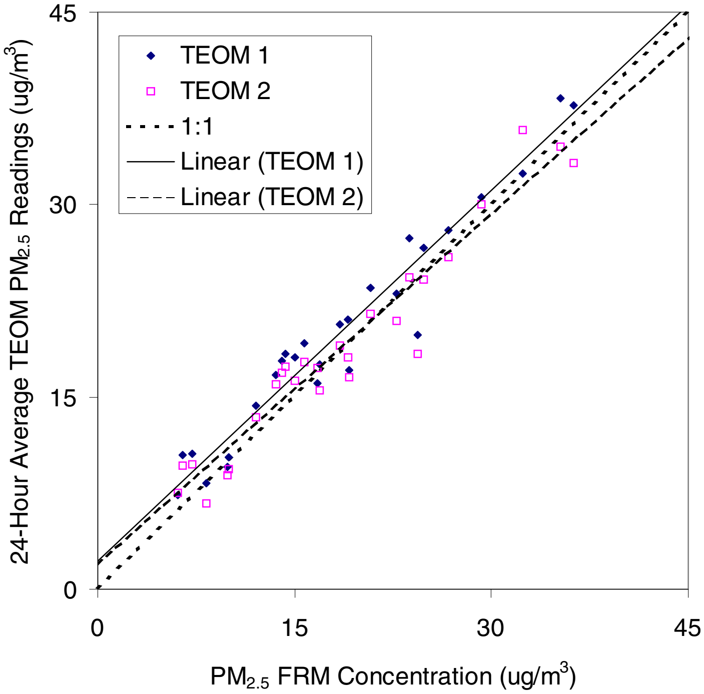

Figure 6-3b. Correlation Plot of the 24-Hour $PM_{2.5}$ Averages from Duplicate Series 1400a TEOM Monitors and the $PM_{2.5}$ FRM Results During Phase I of Verification Testing

speed in degrees. Phase I values for these meteorological parameters are summarized in Section 6.1, except for WDSTD, for which the Phase I average, maximum, and minimum were 34.2, 48.8, and 21.3 degrees, respectively.

The magnitude of the implied effects can be estimated by comparison of predicted Series 1400a TEOM readings to those based on the simple linear regression against FRM results. For example, using the average values for $PM_{2.5}$ and the various meteorological parameters during Phase I, the equation above would predict an average $PM_{2.5}$ reading of 20.8 µg/m^3 for Monitor 1:

$$\text{Monitor 1} = 0.978*18.4 - 1.46*3.35 + 5.57*0.0014$$

$$- 0.014*34.2 + 8.19\ \mu g/m^3$$

$$= 20.8\ \mu g/m^3.$$

Based on the linear regression results (Table 6-4) and the average $PM_{2.5}$ concentration during Phase I, Monitor 1 would read,

$$\text{Monitor 1} = 0.964*18.4 + 2.21$$

$$= 19.9\ \mu g/m^{3.}$$

The multivariable results show a difference of approximately 4.5% relative to the linear regression results.

For Monitor 2, the multivariable model would predict a $PM_{2.5}$ reading of 20.0 µg/m^3.

$$\text{Monitor 2} = 0.947*18.4 - 1.12*3.35 - 4.40*0.0014$$

$$- 0.020*34.2 + 7.01$$

$$= 20.0\ \mu g/m^3$$

whereas the linear equation would predict

$$\text{Monitor 2} = 0.911*18.4 + 1.85$$

$$= 18.6\ \mu g/m^3$$

i.e., a difference of approximately 7.5%.

In both cases, the combined effects of the meteorological parameters are small under average conditions.

6.1.4 Influence of Precursor Gases

As with the meteorological data, a multivariable analysis of the 24-hour average data was performed to determine if the presence of precursor gases influenced the readings of the Series 1400a TEOM monitors relative to the FRM results. This analysis involved a backward elimination process to remove from the analysis model those parameters showing no statistically significant influence on the results. This analysis indicates that none of the measured gases influenced the results of the 24-hour Series 1400a TEOM readings relative to the FRM at the 90% confidence level.

6.2 Phase II—Fresno (December 18, 2000 - January 17, 2001)

During Phase II, daily 24-hour $PM_{2.5}$ concentrations averaged 74 µg/m^3 and ranged from 4.9 µg/m^3 to 146 µg/m^3. A strong diurnal pattern was observed in the $PM_{2.5}$ concentration, with the peak levels occurring near midnight. Particle composition was dominated by nitrate and carbon. On average, the overall $PM_{2.5}$ concentration comprised 22% nitrate and 40% total carbon. Sulfate accounted for only about 2% of the daily $PM_{2.5}$ mass. Both nitrate and sulfate were determined by ion chromatography, and carbon was determined by the IMPROVE TOR method.

Table 6-5 summarizes the meteorological conditions during Phase II and Table 6-6 summarizes the observed concentrations of the measured precursor gases during this period.

Table 6-5. Summary of Daily Values for the Measured Meteorological Parameters During Phase II of Verification Testing.

	Wind Speed (mps)	Wind Direction (Degrees)	Air Temp. (C)	RH (%)	Solar Radiation (W/m^2)	Press. (mmHg)
Average	1.43	186	8.3	75.4	88.2	756.2
Max	4.18	260	12.8	92.0	123.5	761.7
Min	0.91	116	4.6	51.6	17.1	747.3

Table 6-6. Summary of Daily Values for the Measured Precursor Gas Concentrations During Phase II of Verification Testing

	CO (ppm)	O_3 (ppb)	NO (ppb)	NO_2 (ppb)	NO_x (ppb)
Average	1.9	13	61.8	32.6	94.4
Max	3.3	28	119.9	50.3	170.2
Min	0.4	6	4.1	14.8	18.9

6.2.1 Inter-Unit Precision

The hourly mass concentration readings from the two Series 1400a TEOM monitors for Phase II of the verification test are shown in Figure 6-4a. In Figure 6-4b, these data are plotted against one another to illustrate the correlation between the two monitors. As was the case in Phase I, the two Series 1400a TEOM monitors gave nearly indistinguishable readings of $PM_{2.5}$ mass.

For comparison with the $PM_{2.5}$ FRM reference measurements, the hourly data were averaged from midnight to midnight for each day to correspond with the 24-hour sampling periods used in Phase II of the verification test. In Figure 6-5a, the midnight-to-midnight averages for Phase II of the verification test are presented for the two Series 1400a TEOM monitors. A correlation plot of these data is shown in Figure 6-5b.

The results of a linear regression analysis of these data are presented in Table 6-7. The CV for the hourly and the midnight-to-midnight average values were also calculated and are shown in Table 6-7.

Table 6-7. Linear Regression and Coefficient of Variation Results for Hourly and 24-Hour Average $PM_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase II

Parameter	Hourly Data	24-Hour Average Data
Slope (95% CI)	0.986 (0.004)	0.992 (0.008)
Intercept (µg/m^3) (95% CI)	-0.50 (0.17)	-0.73 (0.33)
r^2	0.998	0.9995
CV	12.1 %	3.2 %

The regression results show r^2 values of 0.998 and 0.995, respectively, for the hourly data and the 24-hour averages. The results show a slope of 0.98 (0.004), and an intercept of -0.50 (0.17) µg/m^3 for the hourly data; and a slope of 0.992 (0.008), and an intercept of -0.73 (0.33) µg/m^3 for the 24-hour data.

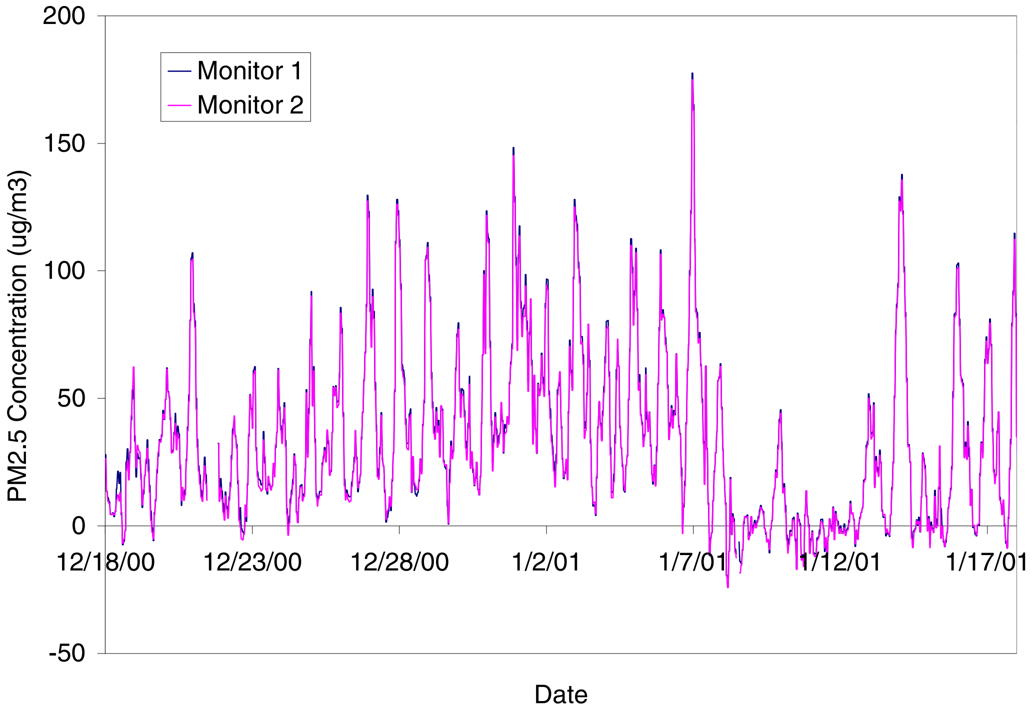

Figure 6-4a. Hourly $PM_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase II of Verification Testing

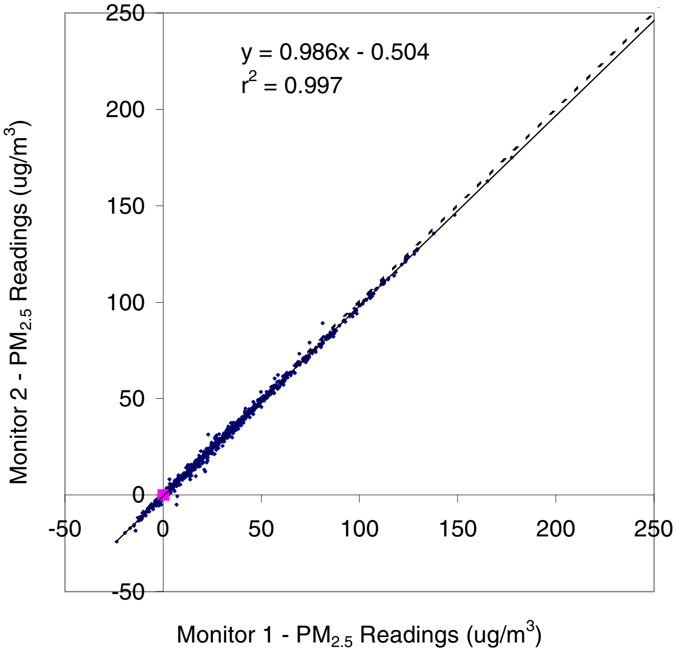

Figure 6-4b. Correlation Plot of Hourly $PM_{2.5}$ Measurements from Duplicate Series 1400a TEOM Monitors During Phase II of Verification Testing

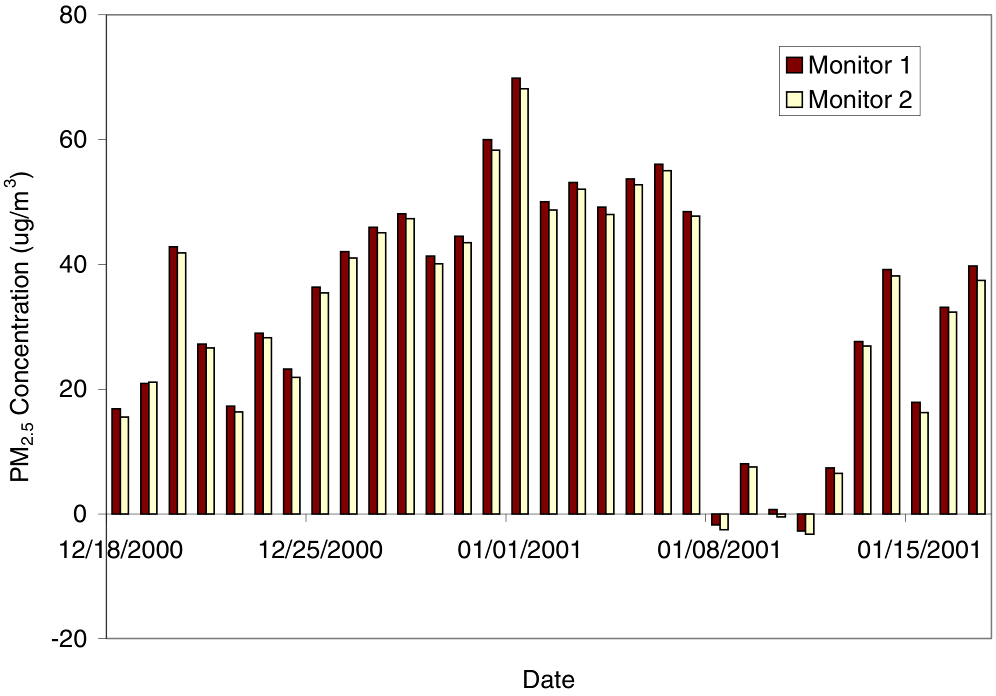

Figure 6-5a. Midnight-to-Midnight Average PM$_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase II of Verification Testing

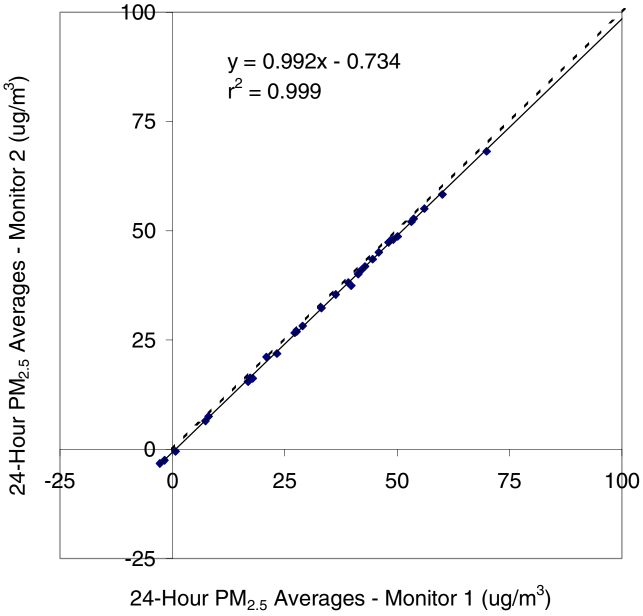

Figure 6-5b. Correlation Plot of the 24-Hour Average PM$_{2.5}$ Concentrations from Duplicate Series 1400a TEOM Monitors During Phase II of Verification Testing

6.2.2 *Comparability/Predictability*

In Figure 6-6a, the midnight-to-midnight averages of the Series 1400a TEOM monitor measurements are shown, along with the $PM_{2.5}$ FRM measurements for Phase II of the verification test. Figure 6-6b is a correlation plot of the 24-hour average TEOM readings against the corresponding FRM results. These $PM_{2.5}$ concentration values were analyzed by linear regression according to Section 5.2 to establish the comparability of each of the Series 1400a TEOM monitors with the $PM_{2.5}$ FRM sampler. The calculated slope, intercept, and r^2 value of the regression analyses are presented in Table 6-8 for each monitor.

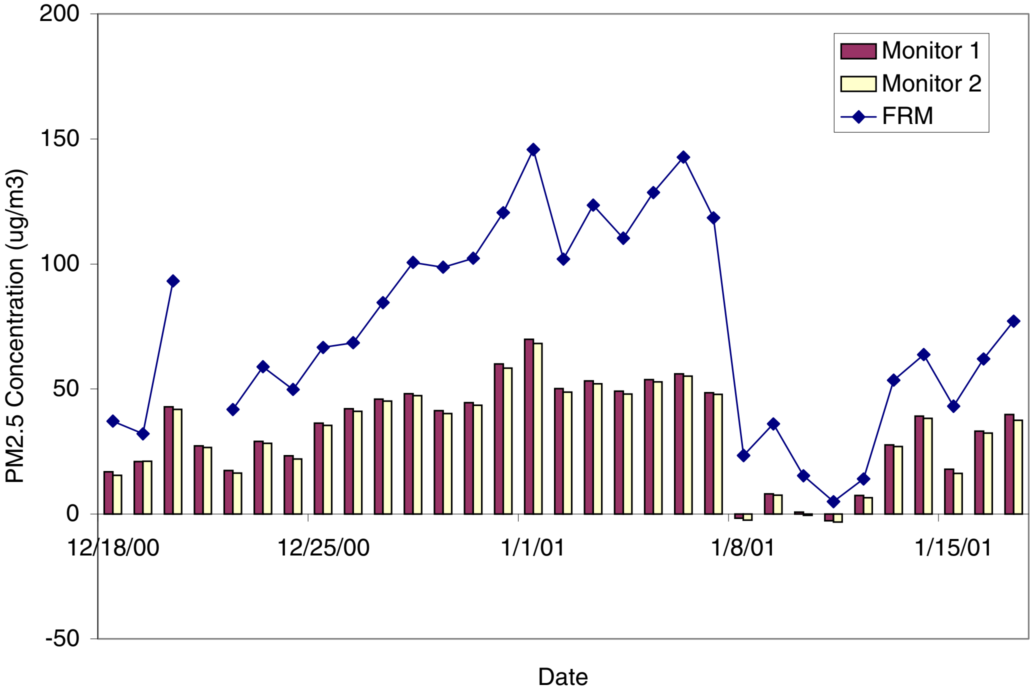

Figure 6-6a. Midnight-to-Midnight Average Concentrations from Duplicate Series 1400a TEOM Monitors and the $PM_{2.5}$ FRM Results During Phase II of Verification Testing

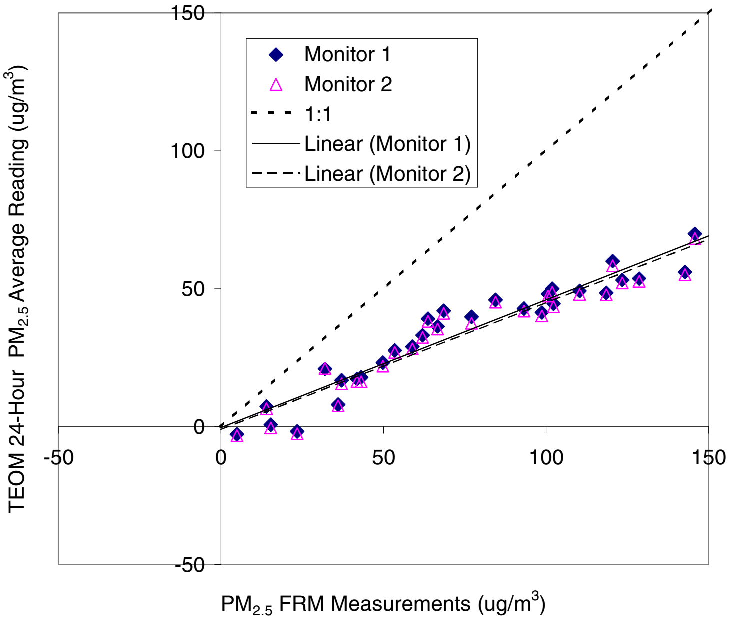

Figure 6-6b. Correlation Plot of 24-Hour Average Concentrations from Duplicate Series 1400a TEOM Monitors and the $PM_{2.5}$ FRM During Phase II of Verification Testing

Table 6-8. Comparability of the Series 1400a TEOM Monitors with the $PM_{2.5}$ FRM During Phase II

Regression Parameter	Monitor 1	Monitor 2
Slope (95% CI)	0.463 (0.055)	0.459 (0.054)
Intercept (µg/m^3) (95% CI)	-0.31 (4.6)	-1.1 (4.5)
r^2	0.915	0.915

The r^2 values of the regression analyses were 0.915 for both Monitor 1 and Monitor 2. However, Figures 6-6a and b show that both monitors gave 24-hour $PM_{2.5}$ readings that were roughly half of those from the FRM throughout Phase II. In fact, for Monitors 1 and 2, the slopes of the regression lines were 0.463 (0.055) and 0.459 (0.054), respectively. In each case, the slope was significantly different from unity, indicating a negative bias relative to the FRM of about 50%. The intercepts of the regression lines were -0.31 (4.6) for Monitor 1 and -1.1 (4.5) for Monitor 2 and were not statistically different from zero at the 95% confidence level. The observed bias between the Series 1400a TEOM monitors and the FRM may be due to differences in particle equilibration in the thermal conditions of the sampling and conditioning environments of the TEOM 1400a monitors and the FRM.

6.2.3 *Meteorological Effects*

Multivariable analysis was performed to determine if the meteorological conditions in Phase II had an influence on the readings of the Series 1400a TEOM monitors relative to the FRM results. This analysis involved a backward elimination process to remove from the analysis model those parameters showing no statistically significant influence on the results. The multivariable model ascribed to the standard deviation of wind direction, relative humidity, and solar radiation a statistically significant influence on the 24-hour Series 1400a TEOM readings relative to the FRM in Phase II, at the 90% confidence level. The analysis shows the following relationships:

$$\text{Monitor 1} = 0.446*\text{FRM} - 0.488*\text{WDSTD} + 0.616*\text{RH} + 0.196*\text{RAD} - 54.1\ \mu\text{g/m}^3$$

and

$$\text{Monitor 2} = 0.439*\text{FRM} - 0.499*\text{WDSTD} + 0.592*\text{RH} + 0.200*\text{RAD} - 52.7\ \mu\text{g/m}^3$$

where FRM represents the measured $PM_{2.5}$ FRM values in $\mu g/m^3$, WDSTD is the standard deviation of the wind direction in degrees, RH is the relative humidity in percent, and RAD is the daily average solar radiation in W/m^2. Phase II values for these meteorological parameters are summarized in Section 6.2, except for WDSTD, for which the Phase II average, maximum, and minimum were 18.7, 26.1, and 14.5 degrees, respectively.

The magnitude of these implied effects can again be assessed, relative to the linear regression against FRM results alone. Substituting the average values for each of these parameters from Phase II (Section 6.2) into these equations, the predicted values would be:

$$\begin{aligned}\text{Monitor 1} &= 0.446*74.0 - 0.488*18.7 + 0.616*75.4 \\ &\quad + 0.196*88.2 - 54.1 \\ &= 33.5\ \mu\text{g/m}^3\end{aligned}$$

and

$$\begin{aligned}\text{Monitor 2} &= 0.439*74.0 - 0.499*18.7 + 0.592*75.4 \\ &\quad + 0.200*88.2 - 52.7 \\ &= 32.7\ \mu\text{g/m}^3.\end{aligned}$$

The linear regression equations (Table 6-8) predict average values of

$$\begin{aligned}\text{Monitor 1} &= 0.463*74.0 - 0.31 \\ &= 33.9\ \mu\text{g/m}^3\end{aligned}$$

and,

$$\text{Monitor 2} = 0.459*74.0 - 1.1$$

$$= 32.9\ \mu g/m^3.$$

Thus, the combined effects of the meteorological parameters under typical conditions during Phase II were approximately 1.2% for Monitor 1, and 0.6% for Monitor 2, relative to the simple linear regression results.

6.2.4 Influence of Precursor Gases

As with the meteorological data, a multivariable analysis of the 24-hour average data was performed to determine if the concentrations of precursor gases influence the readings of the Series 1400a TEOM monitors relative to the FRM results. This analysis involved a backward elimination process to remove from the analysis model those parameters showing no statistically significant influence on the results. The multivariable model ascribed to nitric oxide a significant effect on both Series 1400a TEOM monitors relative to the FRM at the 90% confidence level. This analysis gives the following relationships:

$$\text{Monitor 1} = 0.415*\text{FRM} + 0.0853*\text{NO} - 2.43\ \mu g/m^3$$

and,

$$\text{Monitor 2} = 0.409*\text{FRM} +0.0880*\text{NO} - 3.11\ \mu g/m^3$$

where the concentration of nitric oxide is reported in ppb.

Using the average values for the FRM and NO during Phase II (Section 6.2), these equations predict average $PM_{2.5}$ values of:

$$\text{Monitor 1} = 0.415*74.0\ \mu g/m^3 + 0.0853*61.8\ \mu g/m^3 - 2.43\ \mu g/m^3$$

$$= 33.6\ \mu g/m^3$$

and,

$$\text{Monitor 2} = 0.409*74.0\ \mu g/m^3 + 0.0880*61.8\ \mu g/m^3 - 3.11\ \mu g/m^3$$

$$= 32.6\ \mu g/m^3.$$

These multivariable results each show a difference of about 1% from the respective values (33.9 $\mu g/m^3$ for Monitor 1, and 32.9 $\mu g/m^3$ for Monitor 2) predicted by the linear regression results, presented in Table 6-8.

6.2.5 Short-Term Monitoring

During Phase II of the verification test, short-term monitoring was conducted on a five-sample-per-day basis throughout the test period. Table 6-9 presents the averages and the ranges of $PM_{2.5}$ concentrations for these sampling periods during Phase II. Figure 6-7 shows the correlation between the time-weighted sum of the short-term measurements from the sequential filter sampler and the 24-hour FRM measurements. The slope and intercept of the regression line are 0.930 (0.077), and 2.2 µg/m^3 (6.6), respectively, with an r^2 value of 0.960, where the numbers in parentheses are 95% CIs.

Table 6-9. Summary of $PM_{2.5}$ Levels During Phase II of Verification Testing

$PM_{2.5}$ Concentration (µg/m^3)	Sampling Period				
	0000-0500	0500-1000	1000-1300	1300-1600	1600-2400
Average	81.0	52.2	56.8	46.7	87.7
Maximum	163.2	131.4	140.9	136.6	180.7
Minimum	3.4	7.7	4.8	2.2	7.2

In Figure 6-8, the averages of the Series 1400a TEOM monitor readings for all the short-term monitoring periods are plotted versus the corresponding $PM_{2.5}$ concentration values from the sequential filter sampler. Linear regression analysis of these data was performed separately for each Series 1400a TEOM monitor, and the results are presented in Table 6-10. Regression analyses were also performed separately for each of the five time periods during which the short-term samples were collected (i.e., 0000-0500, 0500-1000, 1000-1300, 1300-1600, and 1600-2400). These regression results are also presented in Table 6-10.

For all but one of the five sampling periods, the short-term monitoring results show r^2 values of 0.79 or greater. Both monitors show considerably lower correlation for the sampling period 1300-1600 ($r^2 < 0.5$). The overall regression slope for each monitor is about 0.55. The slopes of the regression lines for separate short-term sampling periods range from 0.29 to 0.72 for Monitor 1 and 0.29 to 0.70 for Monitor 2. Again, the 1300-1600 time period shows especially low slopes. (It should be noted that the reference $PM_{2.5}$ measurements have not been corrected to account for the observed difference between the time-weighted average of the short-term samples and the FRM.)

Table 6-10. Regression Analysis Results for Short-Term Monitoring

Short-Term Sampling Period	Monitor 1 Slope	Monitor 1 Intercept (μg/m^3)	Monitor 1 r^2	Monitor 2 Slope	Monitor 2 Intercept (μg/m^3)	Monitor 2 r^2
All	0.555	-6.2	0.798	0.552	-6.9	0.806
0000-0500	0.715	-7.7	0.922	0.703	-8.4	0.919
0500-1000	0.565	-2.7	0.829	0.550	-3.6	0.817
1000-1300	0.529	-7.1	0.883	0.544	-8.3	0.890
1300-1600	0.287	-3.5	0.497	0.290	-3.6	0.491
1600-2400	0.427	2.2	0.881	0.425	1.5	0.870

6.3 Instrument Reliability/Ease of Use

With the exception of three brief power outages between August 6 and 7, and an extended outage on August 10 and 11, 100% data recovery was achieved by each of the Series 1400a TEOM monitors from the time of installation (August 1, 16:00) to the end of Phase I sampling (September 1, 12:00). No operating problems arose during Phase I of testing, and no maintenance was performed on either monitor during this phase.

During Phase II of the verification test, with the exception of a period of several hours on December 21 when a representative of R&P took the two monitors off-line, 100% data recovery was achieved by each Series 1400a TEOM monitor. No operating problems arose, and no maintenance was performed on either monitor during Phase II of testing.

6.4 Shelter/Power Requirements

The Series 1400a TEOM monitors were installed and operated inside an instrument trailer during each phase of testing. The monitors and pumps were run on a single 15 A circuit. Vendor literature indicates a range of operating temperatures from 10 to 30°C; however, these limits were not verified in this test.

6.5 Instrument Cost

Because the cost of the Series 1400a TEOM, as tested, is subject to change and may be different for domestic and international markets, no pricing data were provided by the vendor for this report.

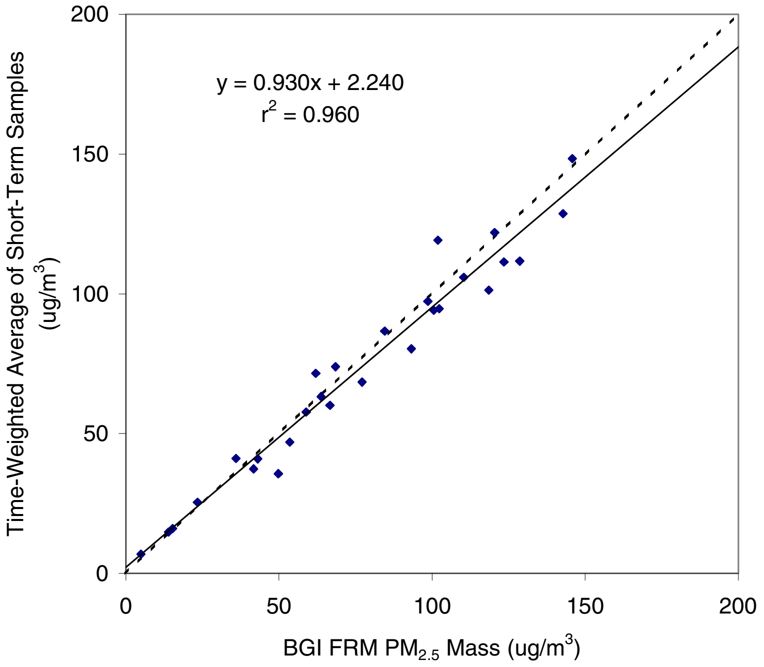

Figure 6-7. Correlation Plot of the Time-Weighted Averages for the Short-Term Samples and the PM$_{2.5}$ FRM

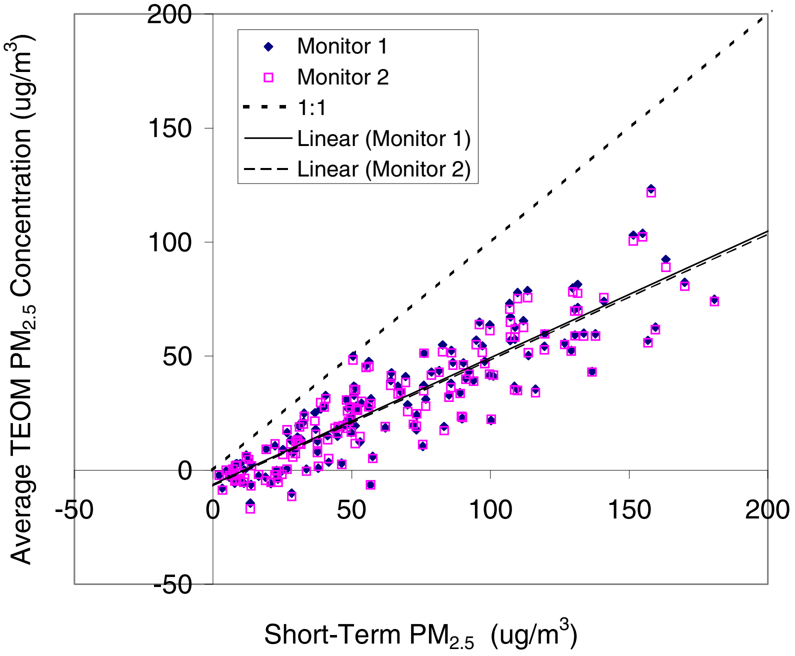

Figure 6-8. Correlation Plot of Short-Term Monitoring Results and the Corresponding Averages from Duplicate Series 1400a TEOM Monitors During Phase II of Verification Testing

Chapter 7
Performance Summary

The Series 1400a TEOM monitor is a continuous particle monitor designed to provide indications of the ambient particulate matter concentration with a time resolution down to 10 minutes. Duplicate Series 1400a TEOM monitors were evaluated under field test conditions in two separate phases of this verification test. The duplicate monitors were operated side by side and were installed with a PM_{10} head and a $PM_{2.5}$ SCC to provide size selection of the aerosol. The results from each phase of this verification test are summarized below.

7.1 Phase I—Pittsburgh (August 1 - September 1, 2000)

Inter-unit precision was assessed using both hourly and 24-hour data from Phase I. Regression analysis showed r^2 values of 0.851 and 0.949, respectively, for the hourly data and the 24-hour averages. The slopes of the regression lines were 0.879 (0.027) and 0.901 (0.080), respectively, for the hourly data and 24-hour averages, indicating that Monitor 2 was consistently lower in its readings than Monitor 1. An intercept of 1.22 (0.66) $\mu g/m^3$ was observed for the hourly data, and an intercept of 0.87 (1.73) for the 24-hour data. The calculated CV for the hourly data was 22.5%; and, for the 24-hour data, the CV was 9.0%.

Comparisons of the 24-hour averages with $PM_{2.5}$ FRM results showed slopes of the regression lines for Monitor 1 and Monitor 2 of 0.964 (0.096) and 0.911 (0.099), respectively. These slopes were not significantly different from unity at the 95% confidence level. The regression results show r^2 values of 0.945 and 0.935 for Monitor 1 and Monitor 2, respectively. The intercepts of the regression lines were 2.21 (1.94) and 1.85 (2.01) $\mu g/m^3$, respectively, for Monitor 1 and Monitor 2.

Multivariable analysis was performed to determine if the meteorological conditions had an influence on the readings of the Series 1400a TEOM monitors relative to the FRM results. This analysis indicated that during Phase I, total precipitation, wind speed, and the standard deviation of wind direction all had a statistically significant influence on the Series 1400a TEOM monitors relative to the FRM at the 90% confidence level. However, these effects were small (about 5 to 7%) under typical conditions during Phase I. A similar multivariable analysis was conducted to determine the effect of precursor gases. None of the measured gases influenced the Series 1400a TEOM monitor performance relative to the FRM at the 90% confidence level.

7.2 Phase II—Fresno (December 18, 2000 - January 17, 2001)

Regression analysis showed r^2 values of 0.998 and 0.9995, respectively, for the hourly and 24-hour data from the duplicate Series 1400a TEOM monitors in Phase II. The slopes of the regression lines were 0.986 (0.004) and 0.992 (0.008), respectively, for the hourly data and 24-hour averages; and the intercepts were -0.50 (0.17) µg/m^3 and -0.73 (0.33) µg/m^3, respectively. The calculated CV for the hourly data was 12.1%; and, for the 24-hour data, the CV was 3.2%.

Comparison of the 24-hour TEOM monitor averages with $PM_{2.5}$ FRM results showed slopes of the regression lines for Monitor 1 and Monitor 2 of 0.463 (0.055) and 0.459 (0.054), respectively. The regression results for Phase II show r^2 values of 0.915 for both Monitor 1 and Monitor 2. The respective intercepts were -0.31 (4.6) µg/m^3 and -1.1 (4.5) µg/m^3.

Multivariable analysis of the 24-hour average data showed that the standard deviation of wind direction, relative humidity, and solar radiation had a statistically significant influence on the readings of the two Series 1400A TEOM monitors relative to the FRM values at 90% confidence. In both cases, the combined effect of these parameters was about 1%. Also, the model ascribed to nitric oxide an influence on the readings of the two Series 1400a TEOM monitors relative to the FRM at the 90% confidence level. For both monitors, this effect was also about 1%.

In addition to 24-hour FRM samples, short-term monitoring was performed on a five-sample-per-day basis. The Series 1400a TEOM monitor results were averaged for each of the sampling periods and compared with the gravimetric results. Considering all short-term results together, linear regression of these data showed slopes of 0.555 and 0.552, respectively, for Monitor 1 and Monitor 2. The intercepts of the regression lines were -6.2 and -6.9 µg/m^3, respectively; and the r^2 values were 0.798 and 0.806, respectively. These results are consistent with those of the comparison to 24-hour FRM data in Phase II noted above. The 1300-1600 time period showed a different degree of agreement relative to the other short-term time periods, including low slope (< 0.3) and r^2 (< 0.5) values.

Chapter 8
References

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