

Environmental Technology Verification Report

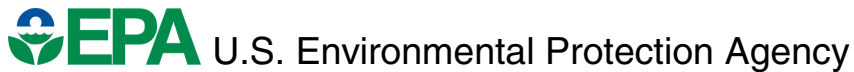
NIPPON INSTRUMENTS CORPORATION
MODEL AM-2 ELEMENTAL MERCURY
CONTINUOUS EMISSION MONITOR

Prepared by



Battelle

Under a cooperative agreement with



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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION
PROGRAM



ETV Joint Verification Statement

TECHNOLOGY TYPE: Continuous Emission Monitor

APPLICATION: MEASURING ELEMENTAL MERCURY

**TECHNOLOGY
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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 permittees; 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 emission monitors used to measure mercury in flue gases. This verification statement provides a summary of the test results for the Nippon Instruments Corporation Model AM-2 elemental mercury continuous emission monitor (CEM).

VERIFICATION TEST DESCRIPTION

The verification test was conducted over a three-week period in January 2001 at the Rotary Kiln Incinerator Simulator (RKIS) facility at EPA's Environmental Research Center, in Research Triangle Park, North Carolina. This mercury CEM verification test was conducted jointly by Battelle's AMS Center, EPA's Office of Research and Development, and the Massachusetts Department of Environmental Protection. A week of setup and trial runs was followed by two weeks of verification testing under different flue gas conditions. The daily test activities provided data for verification of the following performance parameters of the AM-2 monitor: relative accuracy in comparison to reference method results, correlation with the reference method, precision in sampling at stable flue gas conditions, calibration/zero drift from day to day, sampling system bias in transfer of mercury to the CEM's analyzer, interference effects of flue gas constituents on CEM response, response time to rising and falling mercury levels, response to low levels of mercury, data completeness over the course of the test, and setup and maintenance needs of the CEM. The Ontario Hydro (OH) draft American Society for Testing and Materials mercury speciation method was used as the reference method in this verification test. Paired OH trains were sampled at two locations in the RKIS duct to establish the precision of the OH method.

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, a series of performance evaluation audits on several measurements at the RKIS, and both an internal and an external technical systems audit of the procedures used in this verification. EPA QA staff also conducted an independent technical systems audit at the RKIS.

TECHNOLOGY DESCRIPTION

The AM-2 mercury CEM is a sampling, preconcentration, and detection system for elemental mercury. The unit draws a sample flow rate of 0.5 L/min through a distilled water scrubbing trap, for removal of any oxidized mercury species, and then through a dehumidifier, for removal of water vapor. The sample flow then passes through a gold amalgamation trap, which collects and concentrates the elemental mercury from the sample stream. Rapid heating of the gold trap drives the collected mercury into the absorption cell of the detector of the AM-2. Operating the unit with a fixed sample flow rate, collection time, and detection conditions allows the AM-2 response to be related to the $\mu\text{g}/\text{m}^3$ of mercury in the original sample stream. The sampling, desorption, and detection steps are conducted in a fully automated sequential fashion, so the AM-2 provides one measurement of elemental mercury with each complete cycle. In this verification test, the AM-2 operated with a 5-minute sample collection step, and a 13-minute overall cycle time. The AM-2 uses cold vapor atomic absorption to detect elemental mercury. The AM-2 requires no chemical reagents or gases other than a purified air supply, and operates on 100-110 V AC power. The unit is 44.5 cm wide x 28.7 cm deep x 28.5 cm high (17.5 in. W x 11.3 in. D x 11.2 in. H), and weighs 20 kg (44 lbs). A front panel keyboard allows programming of the AM-2 cycle parameters, and an LCD display provides a readout for mercury concentrations, date, time, self diagnostic functions, and error messages. A thermal dot matrix printer and RS-232C port for output of measurement data are built into the AM-2.

VERIFICATION OF PERFORMANCE

Relative accuracy: During the first week of verification testing, the Nippon AM-2 provided relative accuracy for elemental mercury of about 14% relative to OH results, at elemental mercury levels of approximately 6 to 7 $\mu\text{g}/\text{m}^3$. In the second week of verification, the AM-2 provided relative accuracy of about 23%, with elemental mercury levels ranging from about 5 to 25 $\mu\text{g}/\text{m}^3$. Excluding two of the nine OH runs in the second week, the AM-2 gave a relative accuracy of 12.3% in the second week of verification.

Correlation with the reference method: The coefficient of determination (r^2) of the AM-2 and OH results was 0.878, based on the combined data from both weeks of verification.

Precision at stable flue gas conditions: The precision (as percent relative standard deviation) of the AM-2 response was within 10% in 11 of the 15 OH periods and within 15% in 13 of the periods. This measured variability includes both variability in the test facility and in the AM-2 monitor.

Calibration/zero drift: Analysis of elemental mercury standard gases gave a 4.1% relative standard deviation (RSD) in AM-2 response during the first week of testing and a 3.4% RSD in AM-2 response during the second week.

Sampling system bias: The bias in transport of elemental mercury through the Nippon inlet system was approximately -7%.

Interference effects of flue gas constituents: When added to the duct along with mercury, chlorine (and to a lesser extent hydrogen chloride) sharply reduced the elemental mercury response of the AM-2. However, elevated levels of sulfur dioxide, nitrogen oxides, and carbon monoxide had a minimal effect on AM-2 response, and when these gases were all present along with chlorine and hydrogen chloride, no reduction in AM-2 response was observed, relative to that with mercury alone.

Response time to changing mercury levels: The AM-2 achieved 90 to 100% response to increases and decreases in mercury concentrations within one 13-minute measurement cycle. Thus, the 95% response time is essentially one measurement cycle.

Response to low levels of mercury: The AM-2 elemental mercury response increased with as little as 0.57 $\mu\text{g}/\text{m}^3$ of total mercury added to the flue gas. The actual elemental mercury concentrations were not determined independently for comparison to the AM-2 results. However, the AM-2 elemental mercury readings were highly correlated with the nominal total mercury level ($r^2 = 0.997$).

Data completeness: Data completeness for the AM-2 was 100%.

Setup and maintenance needs: The AM-2 was set up and ready to sample flue gas within about four hours after it was placed at the sampling port. The monitor required no gas supplies or other consumables and produced no waste. No scheduled maintenance was required over the two-week period of the verification test.

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NOTICE: ETV verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and Battelle make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of commercial product names does not imply endorsement.

August 2001

Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

Nippon Instruments Corporation Model AM-2 Elemental Mercury Continuous Emission Monitor

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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 permittees, 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.

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List of Abbreviations

AMS	Advanced Monitoring Systems
ANOVA	analysis of variance
APCS	air pollution control system
CEM	continuous emission monitor
Cl ₂	chlorine
CO	carbon monoxide
CO ₂	carbon dioxide
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
GFCIR	gas filter correlation infrared
H ₂ O ₂	hydrogen peroxide
H ₂ SO ₄	sulfuric acid
HCl	hydrogen chloride
Hg	mercury
Hg ⁰	elemental mercury
HgCl ₂	mercuric chloride
KCl	potassium chloride
KMnO ₄	potassium permanganate
L/min	liters per minute
m ³	cubic meters
MDEP	Massachusetts Department of Environmental Protection
mg/m ³	milligrams per cubic meter
mL	milliliter
NDIR	non-dispersive infrared
NIST	National Institute of Standards
NO	nitric oxide
NO _x	nitrogen oxides
O ₂	oxygen
OD	outside diameter
OH	Ontario Hydro
ORD	Office of Research and Development
PE	performance evaluation
ppb	parts per billion
ppm	parts per million
psig	pounds per square inch gauge
QA	quality assurance
QC	quality control
QMP	Quality Management Plan

RA	relative accuracy
RKIS	Rotary Kiln Incinerator Simulator
RSD	relative standard deviation
SO ₂	sulfur dioxide
TSA	technical systems audit

Chapter 1

Background

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, 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 permittees; 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 continuous emission monitors (CEMs) for mercury emissions in combustion flue gas. This verification report presents the procedures and results of the verification test for the Nippon Instruments Corporation Model AM-2 elemental mercury CEM.

Chapter 2

Technology Description

The objective of the ETV AMS Center is to verify the performance characteristics of environmental monitoring technologies for air, water, and soil. This verification report provides results for the verification testing of the Nippon Instruments Corporation Model AM-2 mercury CEM. The following description of the AM-2 is based on information provided by the vendor.

The AM-2 mercury CEM is a sampling, preconcentration, and detection system for elemental mercury. The unit draws a sample flow rate of 0.5 L/min through a distilled water scrubbing trap, for removal of any oxidized mercury species, and then through a dehumidifier, for removal of water vapor. The sample flow then passes through a gold amalgamation trap, which collects and concentrates the elemental mercury from the sample stream. Rapid heating of the gold trap drives the collected mercury into the absorption cell of the detector of the AM-2. Operating the unit with a fixed sample flow rate, collection time, and detection conditions allows the AM-2 response to be related to the $\mu\text{g}/\text{m}^3$ of mercury in the original sample stream. The sampling, desorption, and detection steps are conducted in a fully automated sequential fashion, so the AM-2 provides one measurement of elemental mercury with each complete cycle. In this verification test, the AM-2 operated with a 5-minute sample collection step, and a 13-minute overall cycle time.

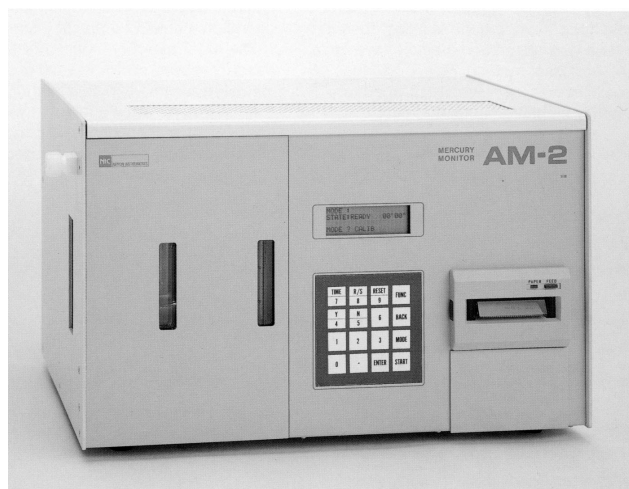


Figure 2-1. Nippon Instruments Corporation Model AM-2 Mercury Continuous Emission Monitor

The AM-2 uses cold vapor atomic absorption to detect elemental mercury. The detection limit of the AM-2 for environmental monitoring is $0.1 \text{ ng}/\text{m}^3$ or less. As modified for flue gas analysis in this verification test, the AM-2 had a detection limit of about $0.1 \mu\text{g}/\text{m}^3$ for emission monitoring. The AM-2 requires no chemical reagents or gases other than a purified air supply, and operates on 100-110 V AC power. The unit is 44.5 cm wide x 28.7 cm deep x 28.5 cm high (17.5 in. W x 11.3 in. D x 11.2 in H), and weighs 20 kg (44 lbs). A front panel keyboard allows programming of the AM-2 cycle parameters, and an LCD display provides a readout for mercury concentrations, date, time, self diagnostic functions, and error

messages. A thermal dot matrix printer and RS-232C port for output of measurement data are built into the AM-2.

Chapter 3

Test Design and Procedures

3.1 Introduction

This verification test was conducted according to procedures specified in the *Test/QA Plan for Pilot-Scale Verification of Continuous Emission Monitors for Mercury*.⁽¹⁾ The Nippon Instruments Model AM-2 CEM was verified for its measurement of elemental mercury by comparison to reference method measurements, by challenges with interferant species, and by repeated sampling of elemental mercury standard gases. The test activities provided data for verification of the following performance parameters of the AM-2 monitor:

- Relative accuracy in comparison to reference method results
- Correlation with the reference method
- Precision in sampling at stable flue gas conditions
- Calibration/zero drift from day to day
- Sampling system bias in transfer of mercury to the CEM's analyzer
- Interference effects of flue gas constituents on CEM response
- Response time to rising and falling mercury levels
- Response to low levels of mercury
- Data completeness over the course of the test
- Setup and maintenance needs of the CEM.

All but the last parameter listed were evaluated quantitatively, using data produced by the planned sequence of tests. The data used to verify these parameters are specified later in this section, and the statistical calculations used to quantify these parameters are presented in Section 5 of this report. The last parameter listed, setup and maintenance needs, was evaluated qualitatively by observing the operation and maintenance of the CEM by vendor staff during the test.

The verification test was conducted over a three-week period in January 2001 at the Rotary Kiln Incinerator Simulator (RKIS) facility at EPA's Environmental Research Center, in Research Triangle Park, North Carolina. The RKIS is a gas-fired, two-stage, pilot-scale incinerator that allows flue gas composition to be manipulated by injecting pollutant gases, particulate matter, and mercury at various points within and downstream of the combustion zone. The RKIS flue gases pass through an extended length of duct before entering an air pollution control system (APCS). When mercury is introduced into the facility flue gas, the facility must operate as a permitted hazardous waste facility, with limitations on hours of operation and personnel training.

In particular, mercury injection into the RKIS flue gas could be performed only between the hours of 6:00 AM and 6:00 PM.

This mercury CEM verification test was conducted jointly by Battelle's AMS Center, EPA's Office of Research and Development (ORD), and the Massachusetts Department of Environmental Protection (MDEP). Specifically, ORD research programs on mercury chemistry and emissions made major contributions to this verification test in the form of planning and organization, facility operations, data acquisition, and leadership in conducting the tests at the RKIS. The MDEP provided financial support and comments on the test plan for this verification. In addition to these collaborations, important contributions to the study were made by the staff of ARCADIS Geraghty & Miller, Inc. Under subcontract with EPA/ORD, ARCADIS staff operated the test facility and associated monitoring equipment and conducted ancillary tasks, such as sampling, to confirm the concentrations of commercially prepared elemental mercury gas standards. Under subcontract with Battelle, ARCADIS staff performed reference flue gas mercury sampling, coordinated the analysis of those samples, and provided the resulting data for this report.

The schedule for the mercury CEM verification followed that stated in the test/QA plan,⁽¹⁾ in that a week of setup and trial runs was followed by two weeks of verification testing under different flue gas conditions. The overall schedule of the test is shown in Table 3-1.

Table 3-1. General Schedule of the ETV Mercury CEM Verification Test

Date	Verification Test Activities
January 8-12, 2001	Installation of vendor CEMs; shakedown of facility operations and mercury injection procedures; trial sampling of flue gas
January 15-19, 2001	Verification testing with flue gas composition approximating that of a coal-fired power plant
January 22-25, 2001	Verification testing with flue gas composition approximating that of a municipal waste incinerator
January 26, 2001	Packing of vendor CEMs; end of test

The first and second weeks of verification testing (January 15 to 19 and 22 to 25, respectively) were similar, in that largely the same daily sequence of tests was conducted in each of these weeks. However, as noted in Table 3-1, the flue gas composition differed between the two weeks.

It should be pointed out that, although facility shakedowns and trial sampling of flue gas were conducted during the week of January 8 to 12, relatively little time was available for the mercury CEMs to sample the full flue gas matrix. The variety of startup activities made it impossible to conduct full days of trial flue gas sampling. This situation contrasts with the normal installation procedures for such CEMs, in which one or two days are often allotted for extensive sampling of

the facility flue gas to tailor the CEM operation for the facility. The verification results reported here must be considered in light of this mode of operation.

The daily schedule of the verification test is illustrated in Table 3-2, which shows the testing activities conducted on each day and the CEM performance parameters addressed by each activity. The exact times when specific test procedures were done are noted when appropriate elsewhere in this report. On each day of the week, the AM-2 was challenged with a zero gas and a commercial compressed gas standard of elemental mercury. These gases were supplied to the analyzer one at a time as a test of day-to-day stability and speed of response. This test was done twice a day, except that on the last day of each week it was done only once. Monday through Wednesday of each week, the flue gas was sampled simultaneously by the AM-2 and the Ontario Hydro⁽²⁾ reference method. On Thursday and Friday of the first week, interference and low-level mercury response tests were done, respectively.

Throughout the verification test, the AM-2 was operated by representatives of Nippon Instruments Corporation. The intent of the testing was for the AM-2 to operate in a manner simulating operation at a combustion facility. Therefore, once the verification test began, no recalibration was performed other than the AM-2's built-in automated zeroing procedure. Nippon staff prepared reagents, maintained the monitor's inlet system, and handled recovery of data from the AM-2.

3.2 Test Conditions

The AM-2 was one of four mercury CEMs tested in this verification effort. All verification testing took place simultaneously, so that all CEMs were subjected to exactly the same test conditions.

3.2.1 RKIS Conditions

The natural gas combustor of the RKIS was operated continuously throughout the test period, to maintain elevated duct temperatures and thereby minimize the chance of retention and subsequent release of mercury by the refractory or other components of the system. The flue gas from the natural gas combustor was spiked with gases, mercury, and particulate matter to achieve different representative flue gas compositions. In all cases, once the required injection rates of mercury, gases, and particulate matter were established, at least 30 minutes of stabilization time was allowed before the start of any reference method sampling or verification data collection.

Mercury was injected into the RKIS flue gas using a peristaltic pump and aqueous solutions of mercury(II) or chloride (HgCl_2). Different injection locations and injection solutions were tried in trial runs to achieve stable total mercury levels and a reasonable split between elemental and oxidized mercury in the duct. The final selection was to use mercury(II) chloride solutions, with different injection locations (i.e., different injection temperatures) to achieve different elemental/oxidized splits in the two weeks of testing.

Table 3-2. Schedule of Daily Activities in the Mercury CEM Verification Test

Test Day	AM/PM	Activity (Performance Parameters)
Monday 1/15/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Tuesday 1/16/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Wednesday 1/17/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Thursday 1/18/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Spiking of flue gas with interferant gases (Interferences)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Friday 1/19/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time, Sampling System Bias)
	AM/PM	Preparation of low Hg levels in flue gas (Low-Level Response)
Monday 1/22/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Tuesday 1/23/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Wednesday 1/24/01	AM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
	AM/PM	Flue gas sampling (Relative Accuracy, Correlation, Precision)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time)
Thursday 1/25/01	AM/PM	Repeat of some interference tests (Interferences)
	PM	Zero/Hg° standard gas (Calibration/Zero Drift, Response Time, Sampling System Bias)

Potential interferant gases (sulfur dioxide, nitrogen oxides, carbon monoxide, hydrogen chloride, chlorine) were injected into the RKIS duct downstream of the combustion zone, using cylinders of the pure compressed gases as the source. Nitrogen oxides in the flue gas were prepared by injection of nitric oxide (NO). The target gas levels were established by monitoring the concentration in the duct using the RKIS facility CEMs (see Table 3-3), rather than by estimation based on dilution in the duct flow. The only exception was for chlorine, for which no CEM was available. The chlorine concentration was established by first injecting chlorine into the flame zone of the RKIS, where complete conversion of chlorine to hydrogen chloride is thermodynamically assured, and measuring the resulting hydrogen chloride using the hydrogen chloride CEM. The chlorine injection rate was then maintained, but moved to a lower temperature injection point and the concentration of HCl was measured again. The chlorine concentration was established from the difference in the two HCl readings.

Particulate matter was injected into the duct at the downstream end of the RKIS combustion zone, using a K-Tron Soder Model KCLKT20 screw feeder, which incorporated a strain gauge measurement of the mass of material injected. The fly ash used was a lignite coal fly ash, specially chosen for its low reactivity with mercury. The low target particulate loading (30 mg/m³) required operating the feeder at the extreme low end of its operating range, and resulted in substantial variation in the particulate loading in the duct (see below).

Figure 3-1 shows two views of the RKIS test facility and indicates the locations of the injection points for particulate matter, mercury, and interferant gases. Also shown are the port locations RM1 (Port 2) and RM2 (Port 8) where the reference Ontario Hydro (OH) method samples were collected. That sampling is presented in detail in Section 3.2.3. Between these two locations, at Ports 6 and 7, were the sampling locations of the mercury CEMs undergoing testing; the AM-2 was located at Port 7. The AM-2 test setup is described in more detail in Section 3.2.2. Figure 3-1 also shows the sampling location for the facility CEMs, downstream of all the sampling locations. The CEMs in place at the RKIS for this test are shown in Table 3-3.

The test conditions maintained throughout OH sampling in the two weeks of verification testing were intended to represent a coal-fired power plant flue gas and an incinerator flue gas, respectively. Table 3-4 summarizes the target and actual levels of mercury and of the other constituents in the flue gas in the two weeks of testing. In general, the actual constituent levels in the flue gas were close to the target levels. The mercury present during the first week of testing was predominantly in elemental form. During the second week of testing, to challenge the speciation capabilities of the CEMs, the injected mercury was predominantly in oxidized form. The flue gas water and oxygen contents were very consistent throughout both weeks of testing, at about 7% water and 14.6% oxygen, and the flue gas temperature at the CEM sampling ports was 400 to 430°F.

3.2.2 AM-2 Operation

The AM-2 was installed on a table within about three feet of the duct, at the port location identified as Port 7 in Figure 3-1. The AM-2 shared a sample probe and particle filter with another Nippon Instruments mercury CEM. The probe consisted of a glass tube of about 8-mm outside diameter (OD) enclosed in a stainless steel tube that extended to near the center of the

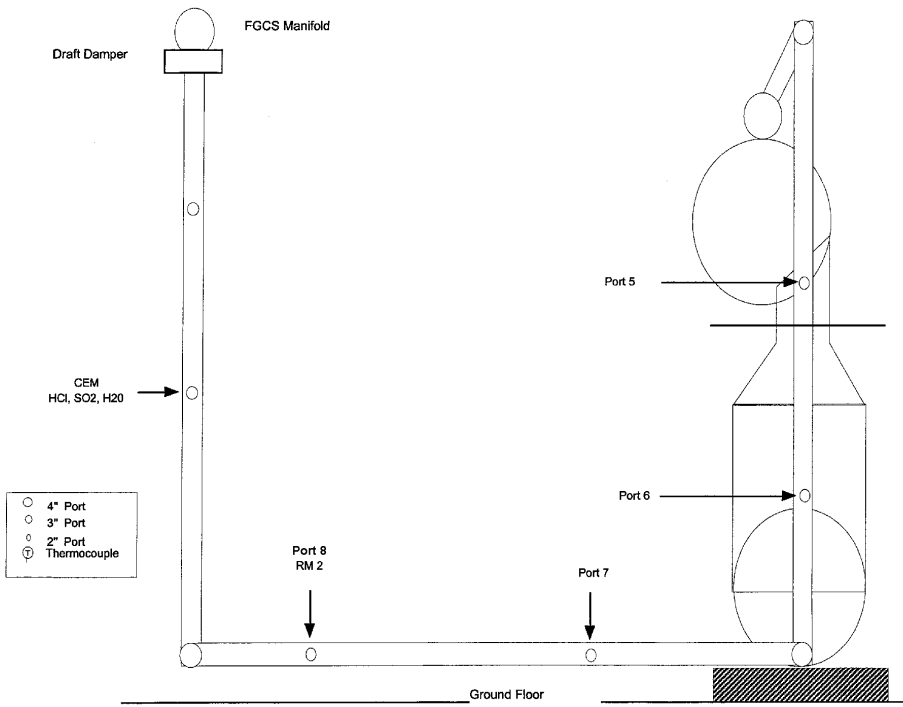
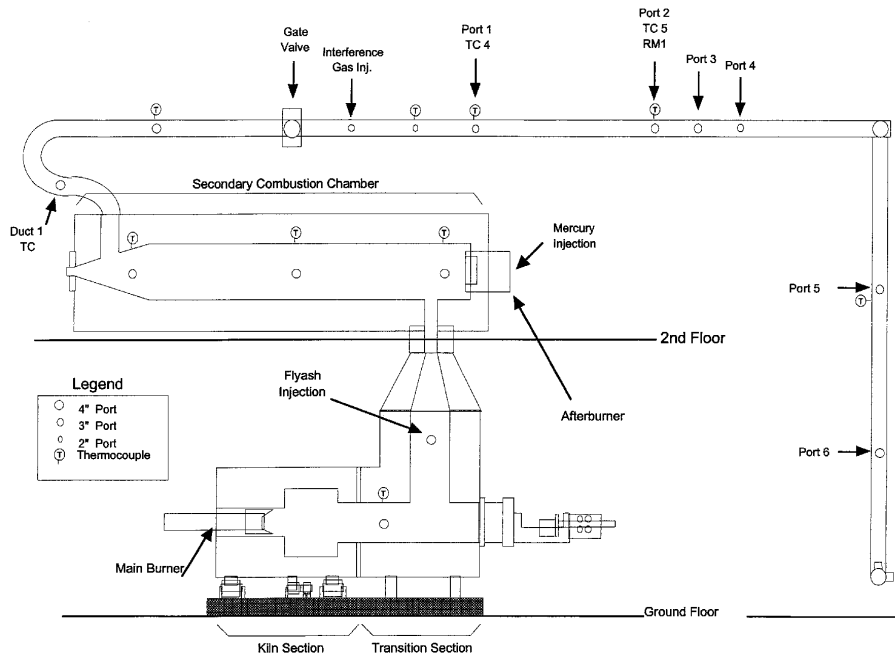


Figure 3-1. Side View (top) and End View (bottom) of the RKIS Test Facility

Table 3-3. Summary of RKIS CEMs

Analyte	CEM	Principle	Measurement Range(s)
O ₂	Rosemount Analytical Model 755R	Paramagnetic	0 - 25%
CO ₂	Fuji Electric ZRH-1 Gas Analyzer	NDIR	0 - 20%
CO	Horiba Model PIR 2000	NDIR	0 - 500 ppm
NO/NO _x	Thermo Environmental Model 10	Chemiluminescent	0 - 500 ppm
SO ₂	Bodenzeewerk Model MCS 100	GFCIR	0 - 250, 0 - 2,500 ppm
HCl	Bodenzeewerk Model MCS 100	GFCIR	0 - 100, 0 - 1,000 ppm

Table 3-4. Target Flue Gas Constituent Concentrations (and Actual Ranges) Used in Verification Test

Test Week	Total Hg (µg/m ³)	SO ₂ (ppm)	NO _x (ppm)	HCl (ppm)	Particles (mg/m ³)
One	8 ^a (7.3 - 7.8)	1,000 (952 - 978)	250 (226 - 245)	25 (21.5 - 24.3)	30 (0.2 - 71)
Two	80 ^b (72 - 119)	50 (51 - 63)	150 (137 - 159)	100 (77 - 92)	30 (2 - 54)

^a Predominantly elemental Hg.

^b Predominantly oxidized Hg.

duct. The probe connected to a heated glass container holding a glass fiber thimble filter. Each of the two Nippon Instruments CEMs drew sample gas through identical heated 6-mm OD Teflon lines, connected to a glass “T” fitting at the outlet of the filter housing. The sample gas flow of the AM-2 was 0.5 L/min. The total gas flow through the inlet probe and filter was about 1 L/min, and sampling was not isokinetic.

The nature of the inlet system is an important factor in verifying the performance of a mercury CEM, because the materials and temperature of the inlet may affect the chemical speciation and even the quantity of mercury that reaches the CEM. Since the CEMs were verified in this test partly by comparison to the OH method, each vendor was informed of the characteristics of the inlet system used with the OH trains. Vendors then made their own decisions about how best to sample the flue gas to assure consistent comparisons with the OH method. In the inlet system used with the AM-2, the filter was maintained at about 400°F, similar to the duct temperature; the heated line from the filter holder to the AM-2 was maintained at about 300°F. At the vendor’s discretion, due to the low particulate matter loading, the inlet filter was changed only after the first week of testing. The AM-2 determines vapor-phase elemental mercury only, so the particulate matter collected on the filter was not analyzed.

The AM-2 is a batch-wise, rather than truly continuous, mercury monitor. That is, the AM-2 automatically cycled through a sequence of sample collection, analysis, and zeroing that took about 13 minutes. Included in that sequence was a five-minute sampling interval. Thus the AM-2 provided a reading of elemental mercury in the flue gas every 13 minutes, based on a five-minute sample period. The output of the AM-2 was recorded both on a laptop computer and on the monitor's built-in printer.

3.2.3 Ontario Hydro Reference Method

The OH mercury speciation method⁽²⁾ was used as the reference method in this verification test, because of the need for a recognized approach to verify the elemental and oxidized mercury measurements made by the CEMs. Since the OH method is not officially designated as a reference method by EPA or the American Society for Testing and Materials, it was judged necessary to document the precision of the OH method itself during the verification test. As a result, in each OH sampling run, two OH trains were operated simultaneously at *each* of the two reference sampling points at the RKIS (Port 2, or RM1, and Port 8, or RM2 in Figure 3-1). At each location, two trains were placed at ports on opposite sides of the duct (designated 2A, 2C, 8A, and 8C, respectively), with their inlet probes positioned close together near the center of the duct. Thus, four OH trains were used for sampling at the same time in each OH run. Each OH train used a separate inlet probe and heated filter and sampled isokinetically near the duct center-line. An EPA Method 2 traverse was conducted at each OH sampling location, both before and after each OH run, to set the isokinetic sampling rate. The average of pre-and post-run traverses was used for final calculations.

The particulate filters in the OH trains were maintained at 250°F. No heating was applied to the sample probe, instead the sample temperature dropped naturally from the duct temperature to the filter temperature in passage from the probe to the filter. A sampling flow of about 1 m³/hr (about 16.7 L/min) was used in all OH runs.

None of the CEMs undergoing verification determined particulate mercury. As a result, the particulate filters from the OH trains were used for two purposes: to determine particulate mercury and to determine the particulate mass loading in the duct. For each OH run, one of the particulate filters from each sampling location (RM1 and RM2, Figure 3-1) was used for gravimetric determination of particle mass loading. The other was analyzed for particulate phase mercury. This approach provided a check on the particulate mercury level, while avoiding the expense of additional Method 5 runs to determine the particle loading. As detailed in Section 4.2.1, the particulate mercury determined by the OH sampling was negligible.

The meter boxes of the paired OH trains at each location were located side by side to allow monitoring by a single operator during sampling. During the runs, OH train data were recorded by hand on data sheets prepared for this test and also were entered immediately into an Excel spreadsheet running on a laptop computer at the sampling location. That spreadsheet automatically calculated run parameters, such as percent of isokinetic sampling rate, providing rapid and accurate control of the sampling process.

The OH trains were prepared by ARCADIS staff in a dedicated laboratory close to the RKIS high bay. Trains were brought to the RKIS for sampling and returned to the same laboratory for sample recovery immediately after sampling. Blank trains (one per day of OH sampling) were also brought to one of the sampling locations at the RKIS and returned along with the sampled trains for sample recovery. The glassware set used for the blank train was chosen at random each day from the several sets on hand. In addition, blank samples were taken of all reagents and rinse solutions used in the OH method. Samples were recovered into uniquely identified pre-labeled glass containers according to OH method procedures. Samples were delivered by ARCADIS staff within about 24 hours after sampling to Oxford Laboratories, in Wilmington, North Carolina, for analysis. Staff of Oxford Laboratories verified sample identities from chain-of-custody sheets before beginning sample analysis.

OH sampling was conducted under conditions of stable flue gas composition, on Monday, Tuesday, and Wednesday of each test week (i.e., on January 15 to 17 and 22 to 24, 2001). Two OH runs per day, of two hours each, were made during the first week. Three OH runs per day, of one hour each, were made during the second week. Typical sampled gas volumes were about 2 cubic meters and 1 cubic meter in the first and second weeks of testing, respectively. Table 3-5 shows the actual schedule of OH sampling in the verification test. The OH sampling proceeded smoothly, with the single exception of Run 9, which was interrupted by failure of the mercury solution injection pump. That run was resumed after repair of the pump, and no data were lost.

3.3 Verification Procedures

This section describes the specific procedures used to verify the CEM performance parameters that were listed in Section 3.1. The statistical procedures used to calculate the verification results are described in Section 5 of this report.

3.3.1 Relative Accuracy

Relative accuracy was assessed by the quantitative comparison of the mercury results from the OH method to those from the tested CEM. For the AM-2, this comparison was made only for elemental mercury. The AM-2 results during the period of each OH run were averaged for comparison to the OH result. In making this comparison, it must be noted that the cycle time of the AM-2 was 13 minutes, during which time gas was sampled for only five minutes. Thus, no more than five AM-2 data points were obtained for each hour of OH sampling, and the coverage of the sampling period by the AM-2 was $5/13 = 38\%$. This difference in sampling coverage was not important when flue gas mercury levels were constant, as in most OH runs. However, in a few cases, spikes in the indicated mercury level were observed simultaneously on more than one of the participating CEMs as a result of inadvertent brief changes in flue gas composition. The impact of such a spike on the AM-2 result could be different from the impact on the corresponding OH result. Consequently, the data were reviewed for the impact of such spikes on the accuracy calculation.

Table 3-5. Schedule of OH Sampling Runs During Mercury CEM Verification

Week	Run Number	Date	Start Time	End Time
One	1	1/15/01	12:07	14:08
	2	1/15/01	15:36	17:37
	3	1/16/01	12:12	14:13
	4	1/16/01	15:45	17:45
	5	1/17/01	10:58	12:59
	6	1/17/01	14:21	16:22
Two	7	1/22/01	11:32	12:33
	8	1/22/01	13:25	14:25
	9	1/22/01	16:15	16:51 ^a
			17:40	18:07 ^a
	10	1/23/01	10:47	11:47
	11	1/23/01	12:50	13:51
	12	1/23/01	16:00	17:01
	13	1/24/01	11:15	12:15
	14	1/24/01	14:30	15:31
15	1/24/01	16:15	17:16	

^a Run 9 was interrupted by a failure of the peristaltic pump used to inject mercury solution into the RKIS; the run was resumed after fixing the pump and allowing concentrations to stabilize.

The accuracy was calculated separately for the two different test conditions, i.e., the 24 OH results from the first week of testing and the 36 OH results from the second week were the basis for separate calculations of accuracy.

3.3.2 Correlation with Reference Method

The correlation of the AM-2 with the OH results was assessed using the same data used to assess accuracy. The average AM-2 elemental mercury results over each OH sampling run were calculated and compared to the corresponding OH results.

3.3.3 Precision

Precision of the AM-2 was determined based on the individual AM-2 results in each OH sampling run. The relative standard deviation of the successive AM-2 readings was calculated as

the measure of precision. This calculation was intended to assess CEM variability under conditions of stable mercury levels. Consequently, this calculation was limited to those time periods in which CEM data, facility data, and the observations of testing staff indicated that mercury addition and mercury flue gas levels were stable. Occasional spikes in mercury concentration were excluded from the calculation of precision, provided that the spikes were attributable to occurrences at the test facility, either by corroboration of multiple CEMs, or by observations of testing staff.

3.3.4 Calibration/Zero Drift

Day-to-day drift in AM-2 response to calibration and zero gases was assessed by sampling zero gas (nitrogen) and a commercial standard of elemental mercury in nitrogen with the monitor each day. The standard gases used for this procedure are described in Section 3.4.1. Those gases were not used as absolute mercury standards, but only as sources of stable mercury levels over the test period. The calibration/zero check was done twice on each day of testing, before and after all other test activities. However, on the last day of each week, this test was done once and was combined with a check of the sampling system bias (see Section 3.3.5). A low concentration mercury standard ($\sim 15 \mu\text{g}/\text{m}^3$) was used in the first week, and a higher concentration standard ($\sim 50 \mu\text{g}/\text{m}^3$) was used in the second week, to parallel the flue gas mercury levels used (see Table 3-4).

Drift was assessed in terms of the range and relative standard deviation of the repeated zero and calibration checks. Separate assessments of drift were made for the two weeks of testing.

3.3.5 Sampling System Bias

In nearly all cases, the drift checks described in Section 3.3.4 were conducted by supplying the zero and standard gases directly at the analyzer inlet of the CEM. However, on the last day of each week of testing, a drift check conducted in that manner was followed immediately by a similar check in which each gas was supplied at the inlet of the CEM's flue gas sampling system. The ratio of the CEM response at the analyzer to that through the entire sampling system determined the bias caused by the sampling system.

The AM-2 shared an inlet system with another Nippon Instruments CEM, as described in Section 3.2.2. That other CEM provided continuous real-time data, in contrast to the 13-minute cycle time of the AM-2. The two CEMs were connected to the inlet system in identical configurations. As a result, to facilitate the bias test procedure, the response of the other CEM was used to assess the sampling system bias.

The sampling system bias test was performed by withdrawing the Nippon sampling probe from the duct and connecting the tip of the inner glass probe to a Teflon line supplying the zero or calibration gas. A "T" fitting in the line allowed venting of a small excess flow of gas beyond that drawn by the Nippon CEMs. The gas supplied in this way passed through the probe, filter, and heated sampling lines before entering the analyzer inlets of the CEMs.

3.3.6 Interferences

On Thursday, January 18, the same low mercury level used on previous days (see Table 3-4) was established in the RKIS flue gas. The addition of mercury alone continued for approximately two hours, during which time the AM-2 sampled the flue gas to establish a baseline level of response. Then, with the mercury injection continuing as before, a series of potential interferant gases was injected into the flue gas, first one at a time, and then in combination. Finally, the gases were turned off, and the mercury injection alone was continued for about another half hour. The effect of the interferant gases was assessed by the changes in AM-2 response occurring during the introduction of the gases.

Table 3-6 summarizes the schedule of the interference test on January 18. Shown are the substances injected into the RKIS flue gas in successive time intervals during this test. The concentrations shown in Table 3-6 are the target concentrations; actual concentrations were maintained within $\pm 10\%$ of the target values.

Table 3-6. Schedule of January 18, 2001, Interference Test

Time	Hg ^a ($\mu\text{g}/\text{m}^3$)	Substances Injected in Flue Gas (Target Concentration, ppm)				
		NO	CO	SO ₂	HCl	Cl ₂
11:05 - 13:06	8					
13:06 - 13:39	8	500				
13:39 - 14:16	8		500			
14:16 - 15:05	8			2,000		
15:05 - 15:50	8				250	
15:50 - 16:30	8					10
16:30 - 17:06	8	500				10
17:06 - 17:36	8	500	500	2,000	250	10
17:36 - 18:02 ^b	8					

^aApproximate total Hg level.

^bBrief inadvertent injection of Cl₂ to the duct occurred near the start of this time period.

3.3.7 Response Time

Response time of the AM-2 was determined in both weeks of the test, as part of the calibration/zero drift test. The rise time and fall time were determined by recording successive AM-2 readings when the delivery of elemental mercury standard gas was started or stopped, respectively. The time to reach 95% of the final value was estimated from successive readings. The 13-minute cycle time of the AM-2 limited the resolution of the time response determination, i.e., the

response time is stated in terms of the number of 13-minute cycles needed to reach 95% of the final value.

3.3.8 Low-Level Response

The mercury levels shown in Table 3-4 were not intended to challenge the detection limit of the AM-2. Instead the ability of the AM-2 to detect low mercury levels was tested by a procedure conducted on January 19. On that day, the AM-2 initially sampled RKIS flue gas with no mercury present, but with sulfur dioxide, nitrogen oxide, and hydrogen chloride present at the concentrations used in the first week of testing (i.e., 1,000 ppm, 250 ppm, and 25 ppm, respectively; Table 3-4). Injection of mercury then began, starting with a low mercury concentration, and stepping upwards in concentration at time intervals of about one-half hour. After the highest mercury concentration, the mercury injection was shut off, and flue gas without added mercury was again sampled. The mercury solutions used for this test had aqueous concentrations of 0.304 to 2.45 µg/mL, sufficient to produce total flue gas mercury concentrations of nominally 0.57 to 4.54 µg/m³. The actual flue gas mercury concentrations were not determined; as a result, the nominal total mercury concentrations are used for comparison to the CEM results. The low-level response of the AM-2 was determined based on the lowest mercury concentration detected above the flue gas background. Note that since the AM-2 determines elemental rather than total mercury, a quantitative comparison of AM-2 response to nominal total mercury level was not appropriate. Table 3-7 summarizes the schedule for this test.

Table 3-7. Schedule of January 19, 2001, Low-Level Response Test

Time Period	Nominal Flue Gas Total Hg Concentration (µg/m³)
10:44 - 11:39	0
11:39 - 12:21	0.57
12:21 - 12:56	1.13
12:56 - 13:33	2.27
13:33 - 14:15	4.54
14:15 - 14:55	0

3.3.9 Data Completeness

Data completeness was determined by comparing the data recovered from the AM-2 to the amount of data expected upon completion of all portions of the verification test. Data completeness was evaluated in terms of the percentage of total data recovered.

3.3.10 Setup and Maintenance Needs

Setup and maintenance needs were documented qualitatively, through observation and communication with the vendor during the verification test. Factors noted included the frequency of

scheduled maintenance activities, the extent of any downtime, the number of staff operating or maintaining the CEM, and the quantity of consumables used and/or waste materials produced.

3.4 Equipment and Materials

3.4.1 Commercial Elemental Mercury Standards

Four commercial compressed gas standards of elemental mercury in nitrogen were used as stable sources of elemental mercury for verification of day-to-day instrument calibration drift and sampling system bias. These gases were purchased from Spectra Gases, Inc., Branchburg, New Jersey. Spectra Gases reported the nominal prepared mercury concentration of each standard and performed an initial analysis of each cylinder in November 2000, using a commercial CEM of a different design than those participating in the verification test. In addition, each of these standards was sampled before and after the verification test, using a miniature impinger train modeled after the OH method. Collected samples were then submitted for laboratory mercury analysis, along with the collected samples from OH flue gas sampling, to determine the cylinder gas mercury content. The protocol for conducting this miniature impinger sampling was subjected to review by ARCADIS and EPA staff and was approved by EPA prior to use in this study.⁽³⁾ Unfortunately, the pre-test analysis results showed evidence of excessive loss of mercury in sampling the gas with the mini-impinger train. This possibility was subsequently confirmed by conducting the sampling with a different pressure regulator on the mercury gas standard. The regulator originally used was shown to remove some mercury from the gas and to require extremely long equilibration times to achieve stable delivery of mercury. Consequently, the pre-test results are not valid. Post-test results from the mini-impinger train, and from an EPA-owned mercury CEM like the one used by the gas vendor, are shown in Table 3-8.

Table 3-8 lists the mercury standards used, along with the vendor's nominal prepared concentration and initial analysis result, provided by Spectra Gases. Also listed in Table 3-8 are the cylinder concentrations determined post verification in March 2001 by means of the mini-impinger sampling method and an EPA-owned mercury CEM.

Table 3-8 shows generally good consistency among the gas vendor's prepared mercury concentrations, the gas vendor's own pre-test analysis, and the post-test analyses. In particular, the agreement between the mini-impinger OH samples obtained post test and the vendor's prepared concentration is within 6.4%, 3.5%, 14.1%, and 6.0%, respectively, for cylinders CC19870, CC19931, CC20219, and CC20291. This agreement is good, considering the novel nature of these standards and the four-month time interval between their preparation and the post-test analysis.

Cylinders CC19931 and CC19870 were prepared at full cylinder pressure of 2,000 psig. However, because of vapor pressure limitations of elemental mercury, cylinders CC20291 and CC20219 were prepared with an initial pressure of only 900 psig. To assure consistent testing of day-to-day drift, each CEM undergoing verification was challenged repeatedly with just one gas standard in each week of testing. In addition, to assure sufficient gas to complete the testing in each week, the gas standards were assigned to participating CEMs in such a way as to balance

Table 3-8. Mercury Standard Gas Identification and Analysis Results

Cylinder Number	Prepared Hg° Conc. (µg/m³) ^a	Pre-Test	Post-Test	
		Gas Vendor Analysis (µg/m³)	OH Mini-Train Analysis (µg/m³)	EPA CEM Analysis (µg/m³)
CC19870	12.5	14	11.7	9.3
CC19931	14.1	16	13.6	13.0
CC20219	44.0	49	50.2	47.0
CC20291	49.8	55	46.8	50.6

^a Concentrations in µg/m³ converted from ppbv concentrations stated by Spectra Gases, using a conversion factor of 1 ppbv Hg° = 8.3 µg/m³ at 20°C and 1 atmosphere pressure.

the consumption of all standard gases. Thus, the AM-2 monitor was challenged in the first week of testing only with mercury standard cylinder number CC19870 and, in the second week, only with cylinder number CC20219. In both weeks of testing, the use of those cylinders was shared among the AM-2, another Nippon CEM, and another vendor’s CEM. The final gas pressures in the elemental mercury standards at the conclusion of testing were approximately 900 psig and 1,000 psig in cylinders CC19870 and CC19931, respectively, and approximately 300 psig and 550 psig in cylinders CC20219 and CC20291, respectively.

The mercury standard cylinders were used with miniature low-volume stainless steel regulators (Spectra Gases 04-1D3EATNN-018), which were flushed for about 30 minutes before use with a 0.5 L/min flow of the standard gas. The delivery plumbing from the regulators was originally made almost entirely of SilcoSteel® fittings, i.e., stainless steel internally coated with a layer of glass. However, long equilibration times were observed in first supplying the 12.5 and 14.1 µg/m³ standards to the CEMs in the first week of testing. Consequently, the delivery system was modified to consist of all Teflon, except for the regulator itself. This change notably improved the delivery of the mercury gas standards to the CEMs.

3.4.2 Performance Evaluation Equipment

Performance evaluation (PE) audits were conducted on several key measurements at the RKIS. Each of those audits was conducted using a reference standard or measurement system provided by Battelle that was independent of that used in the verification test. Table 3-9 lists the PE audit equipment used and, when appropriate, the date of the calibration of the audit equipment prior to the verification test. The PE audit of the OH mercury analysis was done by spiking two blank trains with a dilution of a commercial National Institute of Standards (NIST)-traceable mercury standard. The results of the PE audits are reported in Section 4.3.2.

Table 3-9. Performance Evaluation Audit Equipment Used for the Verification Test

Measurement Audited	PE Equipment	Date Calibrated	Source of Calibration
Flue gas O ₂ and CO ₂	LandTec GA-90 Gas Analyzer, Model GA1.1 (S. No. 693)	12/19/00	Vendor
Flue gas temperature	Fluke Model 52, (S. No. 73970010) with Type K Thermocouple	11/29/00	Battelle Instrument Lab
Barometric pressure	Taylor Model 2250M Aneroid Barometer (Inventory No. LN163610)	12/20/00	Battelle Instrument Lab
Flue gas pressure	Magnehelic Model 2005 (S. No. R51006LG64)	10/25/00	Battelle Instrument Lab
Impinger weighing	Cenco Class T Weight Set (200 g and 500 g weights)	1/3/01	Battelle Instrument Lab
Ontario Hydro mercury analysis	EM Science Atomic Absorption Standard MX0399-2, traceable to NIST SRM #1333.	NA	Vendor

Chapter 4 Data Quality

The quality of the verification data was assured by quality assurance and quality control (QA/QC) procedures, performed in accordance with the quality management plan (QMP) for the AMS Center⁽⁴⁾ and the test/QA plan⁽¹⁾ for this verification test. Minor deviations from the test/QA plan were documented in the verification records at the RKIS during testing. Deviations required the approval of Battelle's AMS Center Manager. A planned deviation form was used for documentation and approval of each of the following changes:

1. The elemental mercury gas standards were not analyzed by the University of North Dakota Energy and Environmental Research Center because the procedure to be used would have consumed a substantial fraction of each standard.
2. The performance evaluation for oxygen and carbon dioxide measurements at the RKIS used an electrochemical monitor for these gases rather than paramagnetic and infrared monitors, as stated in the plan.
3. The solution used for the injection of mercury into the RKIS duct was made with mercuric chloride instead of mercuric nitrate.
4. As a result of the use of mercuric chloride rather than mercuric nitrate for the injection solution, the stock solution was made up with hydrochloric acid instead of nitric acid, and no additional acid was added in making up dilutions of the stock solution.
5. Recovered OH samples were stored at room temperature before delivery to the analytical laboratory, consistent with OH method requirements, instead of under refrigeration.
6. To better test the capabilities of the mercury CEMs, the low-level response test was conducted with flue gas mercury levels of about 0.5, 1, 2, and 4 $\mu\text{g}/\text{m}^3$ instead of 1, 2, 4, and 8 $\mu\text{g}/\text{m}^3$.
7. The RKIS carbon dioxide CEM was changed before the verification test began. A Fuji Electric Model ZRH-1 was in place at the RKIS, instead of the Horiba VIA 510 stated in the test/QA plan.

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8. Calculation of interference effects in terms of “relative sensitivity” was not done, since this calculation was inappropriate in situations where chemical transformations of mercury species took place.

None of these deviations had any significant effect on the quality of the verification data.

4.1 Facility Calibrations

Continuous monitors for oxygen, carbon monoxide, carbon dioxide, nitrogen oxides, sulfur dioxide, and hydrogen chloride are installed at the RKIS and its associated APCS to monitor system performance and document flue gas composition. For this verification test, those monitors were calibrated according to standard facility practice on each test day. Calibration procedures consisted of a multipoint calibration check at the start of the day and a drift check at the end of the day. On days when OH sampling was conducted, the drift check was also conducted after each OH run. All calibration results were within the allowable tolerances for drift and linearity. All calibration results were documented for inclusion in the verification data files.

Flue gas water content was determined from impinger weights in the OH trains by means of an electronic balance located in the OH train preparation/recovery laboratory. Copies of the calibration records for that balance were included in the data file.

Key measurements that factored directly into the verification test results were also the subject of PE audits, as described in Section 4.3.2. Those measurements included the facility CEMs for oxygen and carbon dioxide and the balance used for determination of water.

4.2 Ontario Hydro Sampling and Analysis

The preparation, sampling, and recovery of samples from the OH trains followed all aspects of the QA/QC requirements in the OH method. A daily blank train was prepared, kept at either the upstream or downstream sampling location during sample runs, and recovered along with the sampled trains. The impinger glassware used for preparing the blank train was selected at random each day from among the several sets used, so that blank results reflect the actual state of the sampling equipment. All required reagent blanks were collected, and additional reagent blanks (beyond those required in the method) of the acetone rinse reagent and of the 5% w/v potassium permanganate called for in Section 13.2.8.3 of the OH method were collected. A sample numbering system was implemented that provided unique identification of each train and of each recovered sample from that train. This numbering system was implemented by means of pre-printed labels applied to sample containers arranged in order of sample recovery for each train. The recovered samples were delivered to the analytical laboratory within about 24 hours after collection. Oxford Laboratories, which conducted the OH analyses, similarly adhered to all requirements of the OH analytical process. Replicate analysis of samples was performed as required by the OH method, and all results met the 10% acceptance criterion. The analytical results for each set of analyses were accompanied by data quality documentation that reported the laboratory calibration procedures and results applicable to those analyses.

Because of the importance of the OH data in this verification, the following sections present key data quality results from the OH data.

4.2.1 Ontario Hydro Precision

The results of the OH flue gas sampling and analysis are shown in Tables 4-1a-c and 4-2a-c, for the first and second weeks of verification testing, respectively. Tables 4-1a and 4-2a show the elemental mercury results, Tables 4-1b and 4-2b the oxidized mercury results, and Tables 4-1c and 4-2c the total vapor-phase mercury results from the OH runs. Particulate mercury, determined on one OH particulate filter at each location in each OH run, was not detectable during the first week of verification testing. During the second week of testing, of the 18 filters analyzed for particulate mercury, 11 showed mercury of less than $0.5 \mu\text{g}/\text{m}^3$, five showed levels 0.5 to $1 \mu\text{g}/\text{m}^3$, and two showed levels of 1.0 to $1.5 \mu\text{g}/\text{m}^3$. Thus, particulate mercury was a negligible fraction of the total mercury present in RKIS flue gas.

Inspection of the data in these tables shows that, in nearly all cases, the agreement between duplicate OH results (i.e., the precision of the OH method) was good at both the upstream and downstream sampling locations. Furthermore, the mercury levels determined at the upstream location generally agreed closely with those at the downstream location. This observation indicates that little loss of mercury or change in mercury speciation occurred during the transit of flue gas from one location to the other. The variability in OH results was larger in the second week of sampling (Tables 4-2a-c) than in the first week (Tables 4-1a-c). This undoubtedly results in part from the greater proportion of oxidized mercury present in the second week. The oxidized mercury is more difficult to transport and sample, and the proportion of oxidized mercury may have varied due to small variations in RKIS conditions (e.g., temperature). Day-to-day variations in mercury results in the second week are also due in part to changes in delivery conditions. Most notably, the pump used to inject the mercury solution into the RKIS failed during OH Run 9 on January 22 and was replaced with a different pump. The higher total mercury levels measured on January 23 and 24, relative to those on January 22, are probably due to a slightly higher delivery rate on those days.

To quantify the characteristics of the OH reference data before using them for verification of the Nippon AM-2, the OH data were subjected to a statistical analysis, addressing three issues:

- The precision of the duplicate OH results at both the upstream and downstream sampling locations
- The agreement between the mercury levels determined by the OH method at the upstream and downstream sampling locations
- The identification of any outliers in the data.

These issues were addressed separately for the elemental, oxidized, and total mercury data.

Table 4-1a. Elemental Mercury Results from OH Sampling in the First Week of Verification Testing

Date	Port Location	Elemental Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/15/01	Run 1	6.78	6.49	6.28	6.29
1/15/01	Run 2	6.20	6.23	6.18	5.98
1/16/01	Run 3	6.51	6.52	6.09	6.12
1/16/01	Run 4	6.43	7.00	7.55	6.50
1/17/01	Run 5	6.31	6.53	6.03	5.95
1/17/01	Run 6	6.10	6.56	5.29	5.99

Table 4-1b. Oxidized Mercury Results from OH Sampling in the First Week of Verification Testing

Date	Port Location	Oxidized Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/15/01	Run 1	1.11	1.11	1.23	1.07
1/15/01	Run 2	0.93	1.11	1.20	1.36
1/16/01	Run 3	1.05	1.05	1.25	1.12
1/16/01	Run 4	1.09	0.99	1.40	1.26
1/17/01	Run 5	1.32	1.29	1.42	1.30
1/17/01	Run 6	1.70	1.42	1.64	1.68

Table 4-1c. Total Mercury Results from OH Sampling in the First Week of Verification Testing

Date	Port Location	Total Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/15/01	Run 1	7.89	7.60	7.51	7.36
1/15/01	Run 2	7.13	7.34	7.38	7.34
1/16/01	Run 3	7.56	7.57	7.34	7.24
1/16/01	Run 4	7.52	7.99	8.95 ^a	7.76
1/17/01	Run 5	7.63	7.82	7.45	7.25
1/17/01	Run 6	7.80	7.98	6.93	7.67

^a Shaded cells indicate data excluded as outliers.

Table 4-2a. Elemental Mercury Results from OH Sampling in the Second Week of Verification Testing

Date	Port Location	Elemental Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/22/01	Run 7	11.1	12.4	11.4	11.6
1/22/01	Run 8	14.3	15.1	13.6	11.5
1/22/01	Run 9	25.1	20.9	27.4	27.4
1/23/01	Run 10	3.5 ^a	7.0	6.0	6.9
1/23/01	Run 11	8.2	9.3	7.2	7.5
1/23/01	Run 12	8.0	8.1	6.7	3.7 ^a
1/24/01	Run 13	6.8	7.2	6.4	6.2
1/24/01	Run 14	4.9	5.4	6.3	5.7
1/24/01	Run 15	6.7	6.9	7.6	5.2

^a Shaded cells indicate data excluded as outliers.

Table 4-2b. Oxidized Mercury Results from OH Sampling in the Second Week of Verification Testing

Date	Port Location	Oxidized Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/22/01	Run 7	61.4	67.3	63.3	69.1
1/22/01	Run 8	71.2	75.2	67.2	67.4
1/22/01	Run 9	46.5	33.2 ^a	44.0	46.0
1/23/01	Run 10	60.5 ^a	97.0	96.3	97.7
1/23/01	Run 11	111.2	110.2	100.5	98.5
1/23/01	Run 12	113.8	114.3	105.5	70.5 ^a
1/24/01	Run 13	88.0	88.0	85.6	84.5
1/24/01	Run 14	77.7	87.7	81.6	67.5
1/24/01	Run 15	86.9	91.4	84.8	81.8

^a Shaded cells indicate data excluded as outliers.

Table 4-2c. Total Mercury Results from OH Sampling in the Second Week of Verification Testing

Date	Port Location	Total Hg ($\mu\text{g}/\text{m}^3$)			
		Upstream		Downstream	
		2A	2C	8A	8C
1/22/01	Run 7	72.5	79.7	74.7	80.7
1/22/01	Run 8	85.4	90.2	80.7	78.9
1/22/01	Run 9	71.5	54.1 ^a	71.4	73.4
1/23/01	Run 10	64.0 ^a	104.0	102.3	104.6
1/23/01	Run 11	119.4	119.5	107.7	106.1
1/23/01	Run 12	121.8	122.5	112.2	74.1 ^a
1/24/01	Run 13	94.9	95.2	92.0	90.7
1/24/01	Run 14	82.6	93.1	87.9	73.2
1/24/01	Run 15	93.6	98.3	92.4	87.0

^a Shaded cells indicate data excluded as outliers.

The precision of duplicate OH trains at both sampling locations was assessed by Student's t-tests. Nonparametric Wilcoxon Rank Sum tests were also used to compare the results from the t-tests. The outcome of this analysis was that, in the first week of verification testing, the average agreement of paired OH trains was within 2.7% for elemental mercury, within 4.4% for oxidized mercury, and within 1.7% for total mercury. In the second week of testing, agreement of paired trains was within 14.8% for elemental mercury, within 7.2% for oxidized mercury, and within 8.1% for total mercury. These results are very good considering the low concentrations of mercury species and the difficulty of preparing and sampling oxidized mercury in the flue gas. The statistical analysis found no significant differences between the paired OH results (i.e., Port A vs Port C) for elemental, oxidized, or total mercury at either the upstream or the downstream sampling location.

Evaluation of upstream/downstream differences in the OH results used an analysis of variance (ANOVA) approach. Student's t-tests and Nonparametric Wilcoxon Rank Sum tests were also used to compare the results of the ANOVA. The statistical analysis found no significant differences between the upstream and downstream levels of elemental or total mercury in either week of testing. The upstream and downstream elemental mercury levels agreed on average within 4.9% and within 7.0% in the first and second week of testing, respectively. Those of total mercury agreed within 2.0% and within 4.3%, respectively. Similarly, in the second week of testing, the upstream and downstream levels of oxidized mercury agreed within 4.2%. On the other hand, a significant upstream/downstream difference of 11.2% in oxidized mercury was found in the first week of testing. However, it must be noted that this resulted from an average absolute difference of only 0.15 $\mu\text{g}/\text{m}^3$ at oxidized mercury levels of 1.2 to 1.3 $\mu\text{g}/\text{m}^3$. This absolute difference is comparable to the detection limit of the OH method. Although a significant upstream/downstream difference may be indicated by the statistical tests, the agreement between upstream and downstream oxidized mercury levels is still very good considering the low mercury levels present.

The analysis for outliers in the OH data relied on a studentized residual approach as the primary criterion, with COVRATIO and DFFITS statistics⁽⁵⁾ as secondary criteria. A mercury measurement was considered an outlier if the primary criterion and at least one of the secondary criteria were met. The aim of this analysis was to identify OH results that were not accurate indications of the flue gas mercury content, rather than to eliminate data that resulted from facility or other variations. For example, the statistical analysis identified all the elemental mercury results from OH Run 9 (20.9 to 27.4 $\mu\text{g}/\text{m}^3$, Table 4-2a) as outliers relative to other data from the second week of testing. However, those values are thought to arise from the failure of the mercury solution delivery pump in that run and the interruption and resumption of mercury delivery to the RKIS. That is, the OH elemental mercury results from Run 9 are thought to reflect actual test facility variability. As a result, most of the OH results from Run 9 have been retained in the data set. On the other hand, the analysis did disclose a few outliers in the OH data, which are shown in Tables 4-1a-c and 4-2a-c in shaded cells. Those values were excluded from the calculations used to verify mercury CEM performance on the basis of the duplicate precision and upstream/downstream differences for individual results. In this analysis, the precision of paired results was compared to the average precision results stated above. Individual values showing differences greater than three times the average precision were excluded. As Tables 4-1 and 4-2 show, this

procedure excluded a few individual values differing sharply from the other simultaneous OH results.

As a result of these analyses of the OH data, it was concluded that each OH result, excluding outliers, could be taken as a separate and independent measurement of flue gas composition. The result of excluding the outlying values is that, for the first week of testing, 24 values for elemental and oxidized mercury were used in the verification and 23 values for total mercury. For the second week of testing, 34 values for elemental mercury and 33 values for oxidized and total mercury were used.

4.2.2 Ontario Hydro Blank Trains

Table 4-3 shows the analytical results from the six blank OH trains collected during the verification test. This table lists the flue gas concentrations (in $\mu\text{g}/\text{m}^3$) that would be inferred from the blank train results, assuming gas sample volumes of 2 m^3 in the first week of testing and 1 m^3 in the second week. Results are shown for oxidized mercury (from the potassium chloride impingers of the OH trains) and for elemental mercury (from both the peroxide and potassium permanganate impingers of the OH trains). The detection limit for mercury in these samples was $0.1 \mu\text{g}$. As Table 4-3 indicates, the great majority of blank train results were below the detection limit, and the few detectable mercury levels were negligible when compared to the levels actually found in the flue gas samples (Section 4.2.1). These results indicate that OH samples were not exposed to contamination sources during sample recovery, handling, and analysis.

Table 4-3. Equivalent Flue Gas Mercury Concentrations ($\mu\text{g}/\text{m}^3$) Found in Blank Ontario Hydro Trains

Date	Train ID	Oxidized Hg	Hg ^o (H ₂ O ₂)	Hg ^o (KMnO ₄)
1/15/01	I-GR-OHI-1 ^a	< 0.05	< 0.05	0.29
1/16/01	I-GR-OHA-2 ^a	<0.05	<0.05	<0.05
1/17/01	I-GR-OHB-3 ^a	<0.05	<0.05	<0.05
1/22/01	II-GR-OHI-4 ^b	<0.1	<0.1	0.31
1/23/01	II-GR-OHI-5 ^b	<0.1	<0.1	<0.1
1/24/01	II-GR-OHI-6 ^b	0.12	<0.1	<0.1

^a Equivalent flue gas concentrations calculated from blank train results using assumed sample volume of 2 m^3 .

^b Equivalent flue gas concentrations calculated from blank train results using assumed sample volume of 1 m^3 .

4.2.3 Ontario Hydro Reagent Blanks

A total of 39 samples of the various OH reagents were collected for analysis between January 15 and January 24, covering all impinger reagents and train rinse solutions. Mercury was found at detectable levels in only two of those 39 samples. The levels found in those two samples were

negligible in terms of their equivalent flue gas mercury concentration when compared to the concentrations found in the actual flue gas samples (Section 4.2.1).

4.3 Mercury Mass Balance

Because of the potential for loss of mercury from the flue gas, a valuable QA exercise is to calculate the mass balance of mercury in the RKIS facility. This was done by comparing the total mercury result from each OH train (Section 4.2.1) to the expected total mercury level in the RKIS flue gas, based on the duct flow rates and the concentrations and flow rates of the injection solutions. The ratio of the OH total mercury to the expected total mercury, expressed as a percentage, is defined as the percent recovery of the injected mercury. Table 4-4 summarizes this comparison, showing percent recovery values for both the upstream and downstream OH results for both weeks of the verification test. In each case, the mean and standard deviation, maximum, minimum, and median of the percent recovery values are shown. The outliers identified in Section 4.2.1 were excluded from this calculation.

Table 4-4. Percent Recovery of Total Mercury Injected into the RKIS

Period	Parameter	Upstream Recovery (%)	Downstream Recovery (%)
Week One			
	Mean (Std. Dev.)	112.2 (13.1)	111.3 (8.7)
	Maximum	137.7	122.2
	Minimum	100.8	99.5
	Median	105.0	113.0
Week Two			
	Mean (Std. Dev.)	110.7 (14.2)	112.1 (14.4)
	Maximum	134.4	136.2
	Minimum	91.2	87.3
	Median	108.4	110.8

Table 4-4 shows that the mass balance for mercury injected into the RKIS was good. Over the entire verification test, the minimum mass balance value was 87.3% and the maximum was 137.7%. For both sampling locations in both weeks of testing, the average mass balance was about 111 to 112%. These results confirm that mercury injected into the RKIS was not lost, and in particular confirm that there was no significant difference in mercury levels between the upstream and downstream sampling locations. Table 4-4 does indicate that the OH results were usually higher than the expected mercury level by about 10 to 12%, on average.

4.4 Audits

4.4.1 Technical Systems Audit

Battelle's Quality Manager performed an internal technical systems audit (TSA) of the verification test on January 16 and 17, 2001, during the first week of testing. The TSA ensures that the verification test is conducted according to the test/QA plan⁽¹⁾ and that all activities associated with the test are in compliance with the AMS Center QMP.⁽⁴⁾ On January 16 the Battelle Quality Manager visited the RKIS test site, where he toured the test area, observed the performance of OH method sampling, reviewed Battelle notebooks and calibration gas certificates, reviewed facility CEM calibration records, and met with the ARCADIS Quality Manager. On January 17, the Battelle Quality Manager visited Oxford Laboratories and reviewed the OH analysis procedures in use there. All the observations of the Battelle Quality Manager were documented in a TSA report. There were no findings of any issues that could adversely affect verification data quality. The records concerning the TSA are permanently stored with the Battelle Quality Manager.

In addition to the internal TSA performed by Battelle's Quality Manager, an external TSA was conducted by EPA on January 23, 2001. The EPA external TSA included all the components of the internal TSA, except that EPA QA staff did not visit Oxford Laboratories. The findings of this TSA were documented in a report submitted to the Battelle Quality Manager. No adverse findings were noted in this external TSA.

4.4.2 Performance Evaluation Audits

A series of PE audits was conducted on several different measurements at the RKIS to assess the quality of the measurements made in the verification test. These audits were performed by Battelle staff and were carried out with the cooperation of EPA and ARCADIS staff. These audits addressed only those measurements that factored into the data used for verification. Each PE audit was performed by analyzing a standard or comparing to a reference independent of standards used during the testing (see Section 3.4.2). Each PE audit procedure was performed once during the verification test, with the exception that OH trains were spiked once in each week of testing. Table 4-5 summarizes the PE audits on several measurement devices of the RKIS; Table 4-6 summarizes the PE audit results from spiking OH trains.

Table 4-5 shows that all the PE audit results on measurement devices were well within the required tolerances stated in the test/QA plan.⁽¹⁾ The PE audit for oxygen and carbon dioxide was conducted by sampling the same gas entering the facility oxygen and carbon dioxide CEMs, using a portable monitor for those gases. This was done using a "T" fitting at the inlet of each facility CEM, so that the readings from the portable audit monitor and the CEMs were obtained in simultaneous sampling of the flue gas. Duct temperature measurement was audited by inserting a calibrated thermocouple into the same location in the duct as the temperature probe used for Method 2 velocity measurements. The small temperature difference observed probably resulted from the inability to place the two probes at exactly the same location in the small duct.

Table 4-5. Summary of PE Audits on Mercury CEM Verifications

Measurement Audited	Date	Audit Method	Observed Agreement	Required Agreement
Flue gas O ₂	1/19/01	Comparison to independent O ₂ measurement	0.1% O ₂	1% O ₂
Flue gas CO ₂	1/19/01	Comparison to independent CO ₂ measurement	5% of CO ₂ reading	10% of CO ₂ reading
Flue gas temperature	1/18/01	Comparison to independent temperature measurement	1.0% absolute T	2% absolute T
Local barometric pressure	1/15/01	Comparison to independent barometric pressure measurement	0.43 " H ₂ O	0.5 " H ₂ O
Flue gas pressure	1/19/01	Comparison to independent pressure measurement	0.02 " H ₂ O	0.5 " H ₂ O
Impinger weights (electronic balance)	1/18/01	Weighing certified weights	0.03% (0.14 g at 500 g)	Larger of 1% or 0.5 g

Barometric pressure was audited using a calibrated aneroid barometer. Flue gas pressures were audited using a Magnehelic gauge installed in parallel with a set of similar gauges used for the Method 2 velocity determinations. Gauges with ranges of 0 to 0.25, 0 to 0.5, and 0 to 2 inches of water were audited. The PE audit of the electronic balance used certified weights of 200 and 500 grams; the observed agreement shown in Table 4-5 is for the 500-gram weight, which showed the greater percentage deviation.

The PE audit of the OH train mercury analysis was conducted once in each week of the test, and the results are summarized in Table 4-6. In the first week, impingers 1 (KCl), 4 (H₂O₂/HNO₃), and 5 (KMnO₄/H₂SO₄) of a blank OH train (I-LB-ST-1) were each spiked with 1 mL of a NIST-traceable solution containing 10 µg/mL of mercury. In the second week, the same impingers of a blank train (II-LB-ST-2) were each spiked with 3 mL of the same solution. As Table 4-6 shows, recovery of the spiked mercury was well within the 10% tolerance stated in the test/QA plan⁽¹⁾ for all spiked samples except the potassium permanganate impinger from the first spiked train. These results indicate that the OH analysis was accurate at spiked mercury levels comparable to those collected in the actual OH sampling. The high readings obtained in analysis of the potassium permanganate impinger from the first spiked train may have been caused by the need to spike that train twice. That is, train I-LB-ST-1 was originally spiked on January 18 and stored overnight for recovery.

However, inadvertent pressurization caused a spillover between impingers 4 and 5 overnight. As a result, the train was emptied, rinsed, refilled, and spiked on January 19, as indicated in Table 4-6. The higher-than-expected mercury level in impinger 5 may have resulted from contamination during this process.

Table 4-6 Results of PE Audit of OH Train Analysis

Date	Train	Impinger ^a Number	Spike ^b (µg)	Analyses			Observed Agreement ^c (%)	Required Agreement (%)
				1st (µg)	2nd (µg)	Average (µg)		
1/19/01	I-LB-ST-1	1	10	9.75	9.53	9.64	-3.6	10
		4	10	9.85	9.61	9.73	-2.7	10
		5	10	11.6	12.0	11.8	18	10
1/24/01	II-LB-ST-2	1	30	29.6	29.9	29.75	-0.8	10
		4	30	29.9	30.0	29.95	-0.2	10
		5	30	28.7	28.5	28.6	-4.7	10

^a Impinger 1 = KCl, 4 = H₂O₂, 5 = KMnO₄.

^b Amount of mercury injected based on dilution of NIST-traceable standard.

^c Observed Agreement = (Average analysis - Spike)/Spike × 100.

4.4.3 Data Quality Audit

Battelle's Quality Manager audited at least 10% of the verification data acquired in the verification test. The Quality Manager traced the data from initial acquisition, through reduction and statistical comparisons, to final reporting. All calculations performed on the data undergoing audit were checked.

Chapter 5 Statistical Methods

The following statistical methods were used to reduce and generate results for the performance factors.

5.1 Relative Accuracy

The relative accuracy (RA) of the AM-2 with respect to the elemental and total mercury results of the reference (OH) method was assessed by the following equation, which is incorporated in EPA performance specifications for continuous emission monitoring systems:

$$RA = \frac{|\bar{d}| + t_{n-1}^{\alpha} \frac{S_d}{\sqrt{n}}}{\bar{x}} \times 100\% \quad (1)$$

where d refers to the arithmetic difference between corresponding OH and AM-2 results, and x corresponds to the OH result. S_d denotes the sample standard deviation of the differences, while t_{n-1}^{α} is the t value for the $100(1 - \alpha)$ th percentile of the distribution with $n-1$ degrees of freedom. To calculate RA, the OH and corresponding AM-2 results were paired, and the differences between the paired results were calculated. Then, the absolute mean (\bar{d}) and standard deviation (S_d) of those differences were calculated. The mean of the OH results (\bar{x}) was calculated, and the value of t_{n-1}^{α} was taken from appropriate tables for the relevant values of n and α . The RA was determined for an α value of 0.025 (i.e., 97.5% confidence level, one-tailed). RA was calculated separately for the first and second week of testing. The OH results used for the RA calculation were as stated in Section 4.2.1.

5.2 Correlation with Reference Method

The degree of correlation of the AM-2 with the reference method results was assessed in terms of the coefficient of determination (r^2), which is the square of the correlation coefficient (r). This

calculation was made separately for the first and second week of testing, and also for the full data set from both weeks of testing.

5.3 Precision

Precision was calculated in terms of the percent relative standard deviation (RSD) of a series of CEM measurements made during stable operation of the RKIS, with mercury injected at a constant level into the combustion zone. During each OH sampling run, all readings from the AM-2 were recorded, and the mean and standard deviations of those readings were calculated. Precision (P) was determined as

$$P = \frac{S}{\bar{X}} \times 100 \quad (3)$$

where S is the standard deviation of the readings and \bar{X} is the mean of the readings.

5.4 Calibration/Zero Drift

Calibration and zero drift were determined in a relative sense, rather than as deviations from an absolute standard, using the elemental mercury gas standards and high-purity nitrogen as zero gas. In the first week, nine elemental mercury standard readings, and nine zero readings, were used for this calculation. In the second week, seven readings of each type were available for this calculation. Drift was calculated in terms of the RSD, as

$$RSD = \frac{S}{\bar{x}} \times 100 \quad (3)$$

where \bar{x} is the mean, and S the standard deviation, of the daily readings on standard or zero gas. This calculation, along with the range of the data, indicated the day-to-day variation in zero and standard readings.

5.5 Sampling System Bias

Sampling system bias was calculated as the difference in CEM response when sampling elemental mercury standard gas through the entire sample interface, compared to that when sampling the same gas directly at the analyzer, expressed as a percentage of the response at the analyzer. That is,

$$B = \frac{R_{si} - R_a}{R_a} \times 100 \quad (4)$$

where B is the percent bias, R_{si} is the reading when the standard gas is supplied at the sampling inlet, and R_a is the reading when the standard is supplied to the analyzer. As described in Section 3.3.5, this check was conducted using another Nippon CEM undergoing verification, which showed an identical inlet configuration with the AM-2, but which provided much faster time response. The results of this bias check are summarized in Section 6.5, and the bias check data are presented elsewhere.⁽⁶⁾

5.6 Interferences

Interferences were determined during sampling of combustion flue gas, in terms of the difference in response to a constant mercury level when potential interferant gases were added or removed. Interferences were assessed in terms of the effect of the interferant species (NO_x , CO , SO_2 , HCl , Cl_2) introduced alone or together into the flue gas. The interferant levels were established by means of the facility CEM responses for each interferant, as described in Section 3.2.1.

5.7 Response Time

The response time was determined as the time after a step change in mercury concentration when the AM-2 reading reached a level equal to 95% of that step change. Both rise time and fall time were determined. The AM-2 response times were determined in conjunction with a calibration/zero drift check, by starting or stopping delivery of the elemental mercury standard gas to the AM-2's sampling interface, recording readings until stable readings were obtained and then estimating the 95% response time.

5.8 Low-Level Response

The ability of the AM-2 to determine low mercury concentrations was assessed by comparing responses at successive nominal total mercury levels of 0, 0.57, 1.13, 2.27, and 4.54 $\mu\text{g}/\text{m}^3$ in the RKIS flue gas. This test was conducted in a flue gas matrix containing elevated levels of sulfur dioxide, nitrogen oxides, and hydrogen chloride, as described in Section 3.3.8. The lowest mercury level producing a response above that with no mercury added is of interest in this test. Since the AM-2 determines elemental mercury, and only the nominal total mercury concentrations were known, a quantitative comparison of AM-2 responses to the nominal concentrations was not conducted.

Chapter 6 Test Results

The results of the verification test of the Nippon AM-2 mercury CEM are presented in this section, based upon the statistical methods shown in Chapter 5.

6.1 Relative Accuracy

Table 6-1 shows the average elemental mercury results obtained from the AM-2 during the period of each OH sampling run. These averages were calculated from eight or nine AM-2 readings obtained during each two-hour OH run in the first week of testing, and from four or five AM-2 readings in each one-hour OH run, in the second week. The AM-2 averages were calculated by subtracting from each data point the daily average zero gas reading of the AM-2 (from the calibration/zero drift results in Section 6.4), and then weighting each five-minute sampling result by the fraction of its sampling period that overlapped the OH run. For example, an AM-2 sampling interval that overlapped the start of the OH run by only three minutes was given 3/5 the weight of an interval that was completely within the OH sampling period. The zero-corrected and averaged results are shown in Table 6-1 and may be compared to the OH elemental mercury results shown in Tables 4-1a and 4-2a.

The results of the calculation of relative accuracy for the AM-2 are shown in Table 6-2, which provides separate relative accuracy results for the two weeks of testing. In the great majority of cases, the AM-2 readings were slightly lower than the corresponding OH results, in both weeks of testing. A relative accuracy of about 14% was found for the AM-2 CEM in the first week of testing, with elemental mercury levels of approximately 6 to 7 $\mu\text{g}/\text{m}^3$ (as indicated by OH results, Table 4-1a). In other words, agreement between the AM-2 and the OH results was within about 1 $\mu\text{g}/\text{m}^3$ throughout the first week of testing. A relative accuracy of about 23% was found in the second week, with OH elemental mercury levels ranging from about 5 to 25 $\mu\text{g}/\text{m}^3$ (Table 4-2a). The relative accuracy in the second week was greatly affected by relatively poor agreement of the AM-2 with the OH results for Runs 7 and 8. If those two runs were excluded from the calculation, the relative accuracy value for the second week would be 12.3%. The reason for the poorer accuracy in those two runs, relative to all others, is not known.

In considering these results, it should be noted that the bias in transfer of elemental mercury through the AM-2 inlet was found to be about -7% (see Section 6.5). This negative bias due to the inlet system is likely a substantial contributor to the observed relative accuracy results.

Table 6-1. Average Elemental Mercury Results from Nippon AM-2 During OH Sampling Runs

Date	OH Run Number	AM-2 Hg^o (µg/m³)
January 15	1	6.09
	2	5.57
January 16	3	5.81
	4	5.68
January 17	5	5.54
	6	4.98
January 22	7	8.19
	8	7.8
	9	24.8
January 23	10	6.25
	11	5.96
	12	6.63
January 24	13	6.00
	14	5.78
	15	6.55

Table 6-2. Relative Accuracy Results for the Nippon AM-2^a

Testing Period	Relative Accuracy (%)
Week One	14.2
Week Two	22.7 ^b

^a Elemental mercury only.

^b When OH Runs 7 and 8 are excluded, relative accuracy for Week Two = 12.3%.

6.2 Correlation

The correlation of the AM-2 monitor with the OH reference method also was calculated using the elemental mercury results shown in Table 6-1. A correlation plot of the AM-2 and OH results from each week of testing is shown in Figure 6-1. This figure also shows the linear regression results and the correlation coefficients (r) for elemental mercury in each week, and in both weeks combined. The resulting coefficient of determination (r^2) for data from the first week was 0.155, reflecting the limited range of elemental mercury concentrations in the first week. The r^2 value for data from the second week was 0.869. The data set from both weeks combined is the largest and has the widest range of data values, and consequently is the most appropriate for calculation of correlation. When all data from both weeks were combined (58 total measurements of elemental mercury), an r^2 value of 0.878 was found.

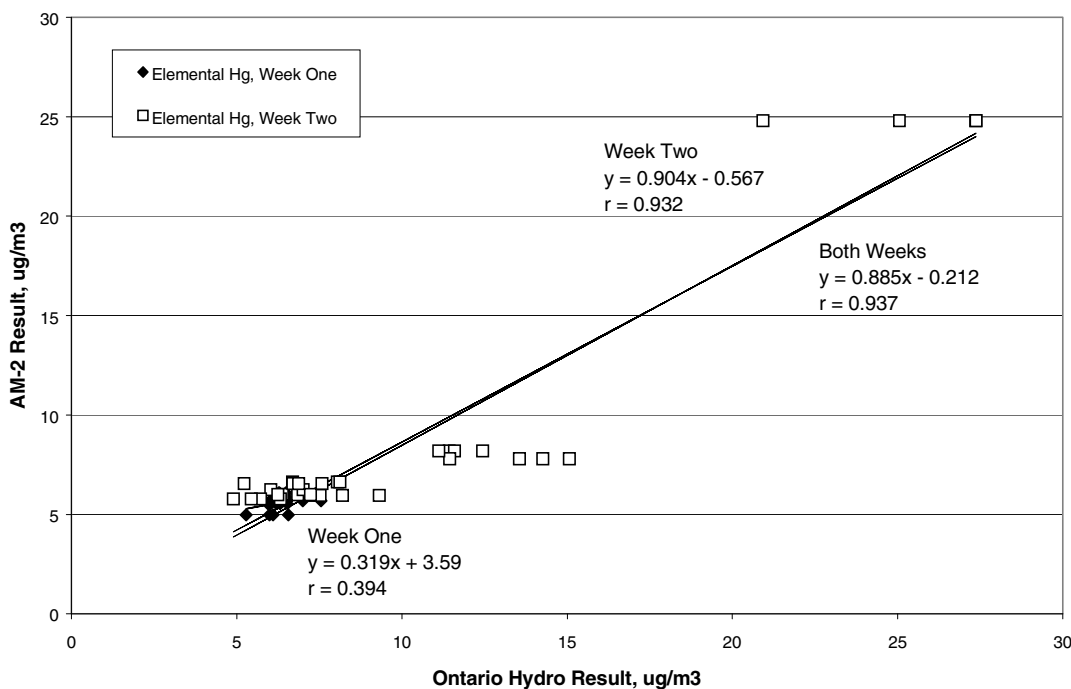


Figure 6-1. Correlation Plot of AM-2 and OH Results for Each Week of Testing

6.3 Precision

The precision of AM-2 response for elemental mercury was calculated from the repeated analyses of flue gas under nominally constant conditions during the 15 OH sampling runs. Table 6-3 shows the calculated precision results, in terms of the percent relative standard deviation (% RSD) of the readings in each run. The mean and standard deviations of the readings are also shown. These values were calculated using zero-corrected data, as was done in the calculation of relative accuracy; however, in this case, the AM-2 sampling periods were not weighted when they partially overlapped the start or end of the OH run. That is, all five-minute AM-2 sampling intervals over the time period of the OH run were treated equally, whether they

were completely within the OH sampling run or not. As a result, the average values shown in Table 6-3 may differ slightly from the AM-2 results shown in Table 6-1. The results shown for the AM-2 in Table 6-3 are each calculated from eight or nine readings in the first week of testing and from four or five readings in the second week.

The aim of this test was to assess the precision of the AM-2 under constant flue gas conditions. Unfortunately, occasional spikes in mercury concentration did occur during testing. When these spikes were corroborated by the response of multiple mercury CEMs as having been caused by the facility, or were clearly associated with occurrences at the facility, the spikes were removed from the data before precision was calculated. On the other hand, excursions of a single CEM that were not coincident with similar excursions of other CEMs, or not attributable to any occurrence at the RKIS, were not removed from the data.

Table 6-3 shows that the precision of the AM-2 results was within 15% RSD in 13 of the 15 OH sampling periods and was within 10% RSD in 11 of the 15 periods. These results indicate the combined variability of the AM-2 and the flue gas mercury levels and show that, in most cases, the RKIS facility maintained highly stable mercury levels. The precision results for OH Run 9 in Table 6-3 exclude a large spike in mercury level that was caused by the failure of the mercury solution delivery pump. The results for that run may still include some increased variability caused by the impending failure of that pump. The AM-2 showed a sharp decrease in reported elemental mercury from the start to the end of OH Run 10 that resulted in a relatively large percent RSD, and that could not be traced to any occurrence in the test facility. In Runs 11 and 13, simultaneous spikes in mercury were observed with the AM-2 and other CEMs, so those data were removed from the calculation.

6.4 Calibration/Zero Drift

The daily AM-2 readings on zero gas and elemental mercury standard gas are listed in Table 6-4. The data from the two weeks of testing are listed separately, because of the different standard gases used. Table 6-5 summarizes the calibration/zero drift results, in terms of the mean, standard deviation, percent RSD, maximum, and minimum of the zero and standard gas responses in each week. The first analysis of the mercury standard gas in the first week was excluded from the drift calculation because, as described in Section 3.4.1, the materials and procedure for delivering that standard did not allow proper equilibration in that first run.

Tables 6-4 and 6-5 show that the AM-2 gave a stable response to both zero and standard gases in the test. In particular, variation in response to both of the elemental mercury standard gases showed a 4% RSD or less. This observation shows the stability of the AM-2 and also supports the utility of the elemental mercury standards for confirmation of CEM stability. The mercury concentrations in the gas standards are not known absolutely, but the average mercury concentrations reported by the AM-2 for the two standard gases (15.5 and 55.3 $\mu\text{g}/\text{m}^3$, respectively) are within 11 and 13%, respectively, of the concentrations of 14 and 49 $\mu\text{g}/\text{m}^3$, based on analysis by the gas vendor (Table 3-8, Section 3.4.1).

Table 6-3. Precision Results for the Nippon AM-2

Date	OH Run Number	Mean Hg ^o (µg/m ³)	Std. Devn. (µg/m ³)	RSD (%)
January 15	1	5.94	0.75	12.6
	2	5.60	0.82	14.7
January 16	3	5.81	0.30	5.1
	4	5.68	0.21	3.8
January 17	5	5.54	0.34	6.1
	6	4.98	0.18	3.7
January 22	7	8.26	0.51	6.2
	8	7.90	0.33	4.2
	9	10.13	2.66	26.3 ^a
January 23	10	6.11	2.46	40.3
	11	4.45	0.10	2.3 ^a
	12	6.40	0.50	7.8
January 24	13	5.42	0.26	4.9 ^a
	14	5.68	0.18	3.2
	15	6.49	0.19	3.0

^a Brief spikes in data removed prior to calculation of precision.

6.5 Sampling System Bias

Because of the slow cycle time of the AM-2, it was not used to determine the bias of the sampling system shared by the AM-2 and another Nippon mercury CEM. Instead, since all aspects of the two inlet paths were identical, the other Nippon CEM was used for this purpose, and the bias data are presented in the verification report for that CEM.⁽⁶⁾ The observed bias in the transport of elemental mercury through the entire inlet to the Nippon CEMs was found to be -7.4%, using the low level standard on January 19, and -6.8%, using the high level standard on January 25.

Table 6-4. Zero and Standard Gas Responses of the Nippon AM-2

Week One			Week Two		
Date	Zero Gas ($\mu\text{g}/\text{m}^3$)	Standard Gas ($\mu\text{g}/\text{m}^3$)	Date	Zero Gas ($\mu\text{g}/\text{m}^3$)	Standard Gas ($\mu\text{g}/\text{m}^3$)
January 15	0.19	11.3 ^a	January 22	1.38	57.6
	0.32	14.7		1.97	54.8
January 16	0.33	15.0	January 23	2.93	54.1
	0.69	15.9		2.69	53.0
January 17	0.67	15.9	January 24	2.22	53.5
	0.96	15.2		2.75	57.2
January 18	0.67	16.7	January 25	0.88	56.7
	0.63	15.4			
January 19	0.62	15.2			

^a This value excluded from calculation of drift; delivery procedure for elemental mercury standard gas not properly equilibrated.

Table 6-5. Summary of Calibration/Zero Drift Results for the Nippon AM-2

Testing Period	Mean ($\mu\text{g}/\text{m}^3$)	Std. Devn. ($\mu\text{g}/\text{m}^3$)	Relative Std. Devn. (%)	Maximum ($\mu\text{g}/\text{m}^3$)	Minimum ($\mu\text{g}/\text{m}^3$)
Week One					
Zero Gas	0.56	0.24	42.6	0.96	0.19
Standard Gas	15.5	0.64	4.1	16.7	14.7
Week Two					
Zero Gas	2.12	0.76	36.0	2.93	0.88
Standard Gas	55.3	1.87	3.4	57.6	53.0

6.6 Interference Effects

The effect of interferences was tested by injecting a constant level of mercury into the RKIS and altering the levels of several interferants, as described in Section 3.3.6. Figure 6-2 illustrates the response of the AM-2 during this test on January 18. The dashed vertical lines indicate the time periods in which each of the interferants or combination of interferants was introduced. The cycle

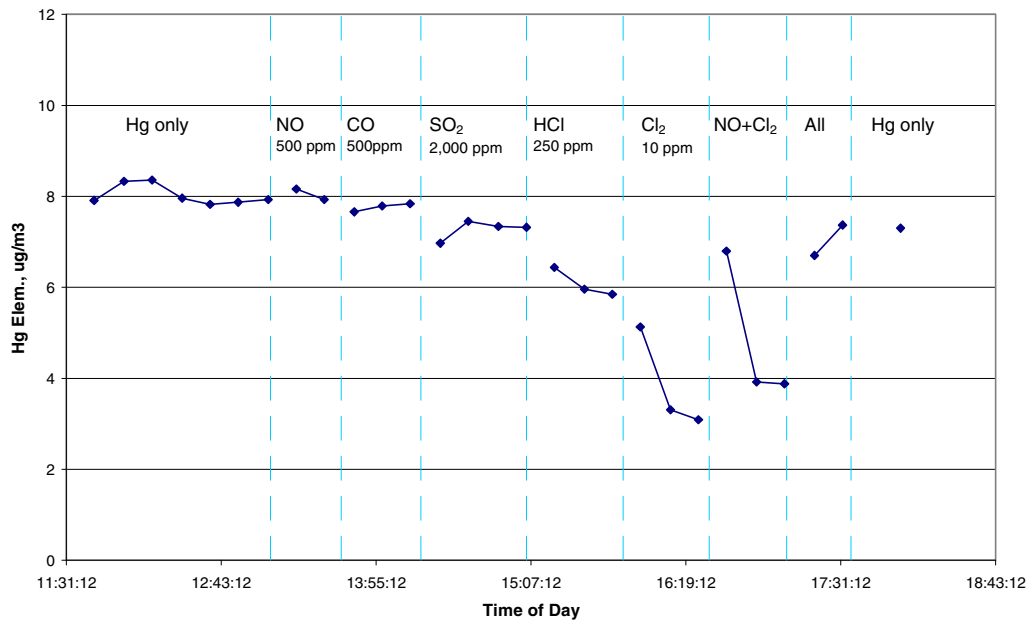


Figure 6-2. Nippon AM-2 Response in Interference Test, January 18, 2001

time of the AM-2 limits the number of data points obtained at each test condition, but the behavior with high levels of the several interferant gases is apparent.

It must be stressed that the AM-2 responds only to elemental mercury. Although the total mercury injection rate to the RKIS was constant in this test, no independent measurement was made of the elemental/oxidized speciation of the mercury in the flue gas. Also note that changes in injected interferants occasionally produced spikes or transients at the transition points from one interferant to the next.

Figure 6-2 shows that neither 500 ppm nitrogen oxide nor 500 ppm carbon monoxide had a significant effect on the elemental mercury response of the AM-2. The response decreased only slightly with the presence of 2,000 ppm of sulfur dioxide. Addition of 250 ppm hydrogen chloride to the duct caused a decrease in elemental mercury response of about 25%. Stabilization of the hydrogen chloride concentration at the target level took several minutes, and this is reflected in the AM-2 response in this period, which stabilized as the hydrogen chloride level rose and became constant. Injection of 10 ppm of chlorine sharply reduced the elemental mercury response. Addition of nitric oxide along with the chlorine initially produced a sharp increase in elemental mercury response on the AM-2, but this is probably the result of an inadvertent drop in the chlorine injection rate that occurred at this time, and not to any chemical effect of the added nitric oxide. Once injection rates were stable, the AM-2 responses were similar to those with chlorine alone, and thus any effect of added nitric oxide on the effect of the chlorine was small.

Figure 6-2 also shows that when all of the interferants were injected together at the indicated target levels, the AM-2 response increased, and showed good agreement with the response to mercury in the absence of interferants. The AM-2 responses with all interferants present show

that the AM-2 is not subject to serious interferences from high levels of several key pollutants in combustion emissions.

6.7 Response Time

The rise and fall times of the AM-2 response were tested as part of the zero and standard gas checks done to assess calibration and zero drift. This determination was somewhat limited by the 13-minute cycle time (including a five-minute sampling time) of the AM-2 and by the need to proceed rapidly with other test activities. Both rise and fall time were assessed for the AM-2 using the low-level mercury standard on January 17, and the rise time was assessed using the high-concentration standard on January 23, 24, and 25. Because of the long cycle time, response was assessed in terms of the percentage of final reading that the AM-2 achieved in a single 13-minute cycle. For this calculation, standard gas readings were first corrected for zero gas response before calculating the percentage change. Table 6-6 shows the data from these tests, listing the AM-2 responses as the zero and standard gases were introduced to and removed from the AM-2 inlet. Table 6-7 shows the results of these tests, in terms of the percentage change in response that occurred within one AM-2 cycle.

Table 6-7 shows that for both rise and fall time, the AM-2 achieved 90 to 100% response to a step change in concentration within one sampling/analysis cycle. Thus the 95% response time of the AM-2 is essentially one sampling/analysis cycle.

6.8 Low-Level Response

Figure 6-3 illustrates the response of the AM-2 to low levels of mercury injected into the duct, as described in Section 3.3.8. The dashed vertical lines indicate the time periods during which each nominal total mercury level was introduced. Each data point represents the elemental mercury reading of the AM-2 from one 13-minute measurement cycle. The cycle time of the AM-2 limits the number of data points obtained at each test condition.

Figure 6-3 shows that the AM-2 responded to all mercury concentrations injected, producing an increase above the flue gas background even with the injection of as little as $0.57 \mu\text{g}/\text{m}^3$ of total mercury. Thus, the primary observation from these data is that the AM-2 is sensitive enough to detect mercury at levels below $1 \mu\text{g}/\text{m}^3$. Since the actual flue gas mercury concentrations and speciation were not determined, no quantitative evaluation of the AM-2 elemental mercury response can be made. However, under the constant flue gas composition existing in this test, it is expected that elemental mercury would be a constant fraction of the total mercury present and, thus, that elemental and total mercury would be highly correlated. This was, in fact, observed. When the AM-2 elemental mercury readings at each nominal total mercury level are averaged, the coefficient of determination (r^2) between the AM-2 elemental mercury readings and the nominal total mercury was 0.997.

Table 6-6. Data from Response Time Tests on the Nippon AM-2

Date	Time	Z/S ^a	AM-2 Reading ($\mu\text{g}/\text{m}^3$)
Rise Time			
January 17	17:22	Z	0.96
	17:35	S	14.4
	17:49	S	15.2
January 23	18:28	Z	2.69
	18:41	S	53.2
	18:54	S	53.0
January 24	19:24	Z	2.75
	19:37	S	52.6
	19:51	S	57.2
January 25	15:30	Z	0.88
	15:43	S	52.2
	15:57	S	56.7
Fall time			
January 17	08:54	Z	0.67
	09:07	S	15.9
	09:21	Z	1.69
	09:34	Z	1.07

^a Z/S = zero or standard gas reading

Table 6-7. Results of Response Time Tests: Percentage Response to Concentration Change Within One AM-2 Cycle

Date	Rise/Fall	Percent Response in One Cycle
January 17	Rise	94.4
January 23	Rise	100
January 24	Rise	91.6
January 25	Rise	91.9
January 17	Fall	95.8

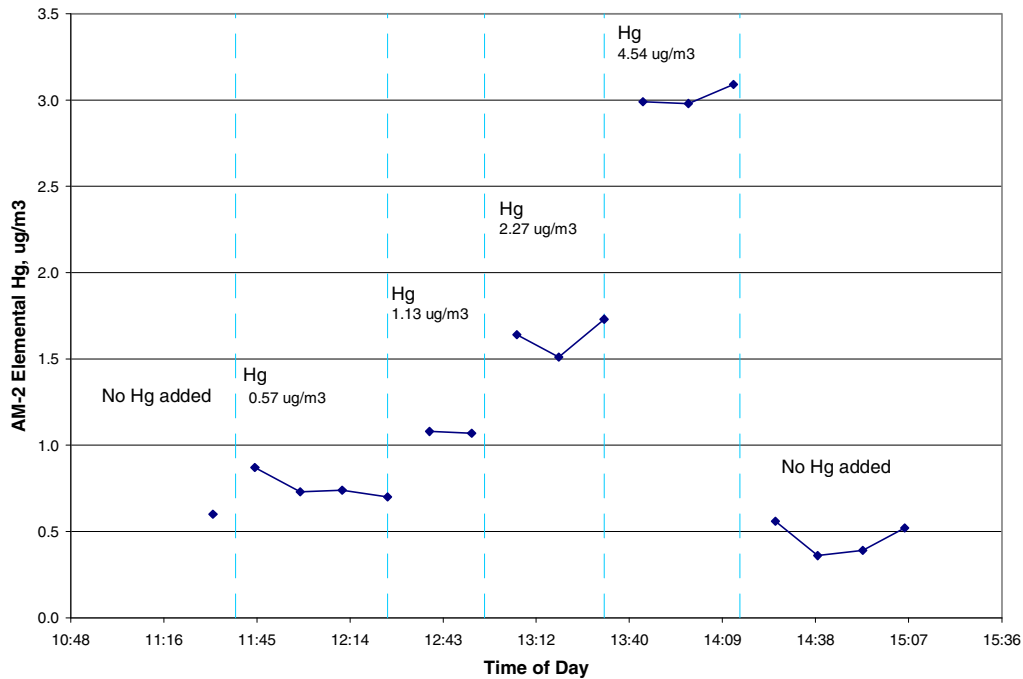


Figure 6-3. Nippon AM-2 Elemental Mercury Response in Low-Level Sensitivity Test, January 19, 2001

6.9 Data Completeness

The AM-2 monitor operated reliably throughout all of the verification test procedures, and no test data were lost as a result of any malfunction or down time. Consequently, the data completeness was 100%.

6.10 Setup and Maintenance

The AM-2 and a second Nippon CEM were set up by two Nippon representatives. Both those representatives were on site for the first week of testing, and one remained for the second week. The AM-2 setup proceeded smoothly, and operation of the monitor was trouble-free throughout the test. The AM-2 was set up and ready to sample flue gas within about four hours after it was placed at the sampling port. The monitor required no gas supplies or other consumables and produced no waste. No scheduled maintenance was required over the two-week period of the verification test.

6.11 Cost

As tested, the approximate purchase price of the AM-2 monitor is about \$30,000.

Chapter 7

Performance Summary

During the first week of verification testing, the Nippon AM-2 provided accuracy for elemental mercury of about 14% relative to OH results, at elemental mercury levels of approximately 6 to 7 $\mu\text{g}/\text{m}^3$. In the second week of verification, the AM-2 provided relative accuracy of about 23%, with elemental mercury levels ranging from about 5 to 25 $\mu\text{g}/\text{m}^3$. In two of the nine OH runs in the second week, the agreement of AM-2 and OH results was unusually poor. Excluding those two runs the AM-2 gave a relative accuracy of 12.3% in the second week of verification. The coefficient of determination (r^2) of the AM-2 and OH results was 0.878, based on the data from both weeks of verification.

Precision of the AM-2 response was assessed in periods of stable mercury levels in the flue gas, during the 15 OH sampling runs. The precision (as percent RSD) of the AM-2 response was within 10% in 11 of the 15 runs and within 15% in 13 of the runs. This measured variability includes both variability in the test facility and in the AM-2 monitor.

Calibration and zero drift were determined by repeated AM-2 analysis of zero gas and elemental mercury standard gases. Nine such analyses in the first week of verification gave 0.56 (± 0.24) $\mu\text{g}/\text{m}^3$ and 15.5 (± 0.64) $\mu\text{g}/\text{m}^3$ for zero and standard gas, respectively. The standard gas results equate to a 4.1% RSD in AM-2 response. Seven such analyses in the second week of verification gave 2.12 (± 0.76) $\mu\text{g}/\text{m}^3$ and 55.3 (± 1.87) $\mu\text{g}/\text{m}^3$, for zero and standard gas, respectively. The standard gas results equate to a 3.4% RSD in AM-2 response. The AM-2 achieved 90 to 100% response to increases and decreases in mercury concentrations within one 13-minute measurement cycle. Thus, the 95% response time is essentially one measurement cycle.

Sampling system bias of the inlet system used with the AM-2 was determined with another Nippon CEM that shared the common inlet system. The bias in transport of elemental mercury through the inlet system was approximately -7%.

When added to the duct along with mercury, chlorine (and to a lesser extent hydrogen chloride) sharply reduced the elemental mercury response of the AM-2. However, elevated levels of sulfur dioxide, nitrogen oxides, and carbon monoxide had a minimal effect on AM-2 response, and when these gases were present along with chlorine and hydrogen chloride, no significant reduction in AM-2 response was observed relative to that with mercury alone.

The AM-2 elemental mercury response increased above background with as little as 0.57 $\mu\text{g}/\text{m}^3$ of total mercury added to the flue gas. This result shows the capability of the AM-2 to detect mercury at levels below 1 $\mu\text{g}/\text{m}^3$. No independent measurement of the actual elemental mercury concentration was made for comparison to the AM-2 readings, but the AM-2 elemental mercury readings were highly correlated with the nominal total mercury level ($r^2 = 0.997$).

Data completeness for the AM-2 was 100%, and no repair or maintenance was needed. The unit uses no reagents or gases other than purified air, and produces no waste.

Chapter 8

References

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