



5-2001

Data Analysis and Correlations for the Particulate Matter Continuous Emission Monitoring System Test Program at the TSCA Incinerator

James A. Calcagno, III
University of Tennessee - Knoxville

Follow this and additional works at: https://trace.tennessee.edu/utk_gradthes

 Part of the [Environmental Engineering Commons](#)

Recommended Citation

Calcagno, III, James A., "Data Analysis and Correlations for the Particulate Matter Continuous Emission Monitoring System Test Program at the TSCA Incinerator. " Master's Thesis, University of Tennessee, 2001.
https://trace.tennessee.edu/utk_gradthes/1961

This Thesis is brought to you for free and open access by the Graduate School at TRACE: Tennessee Research and Creative Exchange. It has been accepted for inclusion in Masters Theses by an authorized administrator of TRACE: Tennessee Research and Creative Exchange. For more information, please contact trace@utk.edu.

To the Graduate Council:

I am submitting herewith a thesis written by James A. Calcagno, III entitled "Data Analysis and Correlations for the Particulate Matter Continuous Emission Monitoring System Test Program at the TSCA Incinerator." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Dr. Wayne T. Davis, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Terry L. Miller, Dr. James L. Smoot

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by James A. Calcagno, III entitled "Data Analysis and Correlations for the Particulate Matter Continuous Emission Monitoring System Test Program at the TSCA Incinerator". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Dr. Wayne T. Davis, Major Professor

We have read this thesis and
recommend its acceptance:

Dr. Terry L. Miller

Dr. James L. Smoot

Accepted for the Council:

Dr. Anne Mayhew

Interim Vice Provost and
Dean of the Graduate School

(Original signatures are on file in the Graduate Student Services Office.)

**DATA ANALYSIS AND CORRELATIONS
FOR THE PARTICULATE MATTER
CONTINUOUS EMISIONS
MONITORING SYSTEM
TEST PROGRAM
AT THE TSCA INCINERATOR**

**A Thesis Presented for the Master of Science Degree
The University of Tennessee, Knoxville**

**James A. Calcagno, III
May 2001**

ACKNOWLEDGEMENTS

I express a sincere gratitude to my major professor, Wayne Davis, for his patience and steadfast guidance throughout the course of this project. I am also particularly grateful to the committee members, Terry Miller and James Smoot for their invaluable comments and kind assistance. A special thanks goes to the Project Manager at the TSCA Incinerator, Jim Dunn, who provided his time and efforts to make this project a reality. Another special thanks goes to Marshall Allen at the Hemispheric Center for Environmental Technology for funding the principal part of this research. Without the help of this group of people, I would not have been able to bring this project to fruition.

ABSTRACT

A field study was conducted to evaluate the performance of three commercially available particulate matter (PM) continuous emission monitoring systems (CEMS) during 1999-2000 at the U.S. Department of Energy (DOE) Toxic Substance Control Act (TSCA) Incinerator located near Oak Ridge, Tennessee. The incinerator is permitted to treat mixed-waste, Resource Conservation Recovery Act (RCRA) hazardous and non-hazardous waste, and wastes containing polychlorinated biphenyls (PCB). The mixed-waste treated at the incinerator contains both low-level radioactive and hazardous chemical constituents. The air pollution control system of the incinerator utilizes Maximum Achievable Control Technology (MACT), which is comprised of a rapid quench, venturi scrubber, packed bed scrubber, and two ionizing wet scrubbers in series. The CEMS chosen for the demonstration were two beta-gauge devices and a light-scattering device. The performance of the CEMS was evaluated using the requirements in the Environmental Protection Agency (EPA) draft (11-3-98) Performance Specification 11 (PS11) and draft (11-3-98) Procedure 2. The various possible combinations of treating liquid, aqueous, and solid wastes simultaneously presented a challenge in establishing a single, acceptable correlation relationship for the individual CEMS. The flue gas of the incinerator was also continually at or near saturated moisture conditions, yet offering an additional challenge to the CEMS. The results of the EPA reference Method 5i stack tests for establishing the calibration curves demonstrated that the beta-gauge monitors could meet PS11 criteria, and the light-scattering monitor could not meet PS11 criteria. Experience seemed to establish however, that more than one set of correlation tests might be necessary to determine the nature of the calibration curve.

TABLE OF CONTENTS

CHAPTER	Page
1 INTRODUCTION	1
1.1 Research Objective	1
1.2 General Description of PM and CEMS	3
1.3 Overview of Federal Regulations	4
2 LITERATURE REVIEW	6
2.1 Historical Development	6
2.2 Preliminary Field Demonstrations	9
2.3 Technical Approach	10
2.3.1 Reference Method 5i	11
2.3.2 Procedure 2	11
2.3.3 Performance Specification 11	13
2.4 Primary Field Demonstrations	14
2.4.1 DuPont Hazardous Waste Incinerator	15
2.4.2 Eli Lilly Hazardous Waste Incinerator	18
2.5 Summary	20
3 TSCA INCINERATOR AND FACILITY	21
3.1 General Description	21
3.2 Incinerator Process System	22
3.3 Air Pollution Control System	24
3.4 Process Data Collection	27

4	CONTINUOUS EMISSION MONITORING SYSTEMS	28
4.1	Durag F-904 K Beta Monitor.....	29
4.2	Environment SA Beta 5M Monitor.....	31
4.3	Sigrist CTNR Light-scattering Monitor.....	33
5	CALIBRATION TEST METHODOLOGY	36
5.1	Method 5i Stack Sampling Procedure.....	36
5.1.1	Sampling Location	36
5.1.2	Sampling Protocol.....	37
5.2	Particulate Monitoring Systems.....	38
5.2.1	Installation Locations.....	38
5.2.2	Process Data.....	39
5.3	Data Collection and Analysis.....	39
5.3.1	Reference Method 5i.....	39
5.3.2	CEMS Continuous Raw Data	42
5.3.3	Inter-instrument Comparisons	46
6	RESULTS/DISCUSSION.....	50
6.1	Quality Assurance Criteria of Procedure 2	51
6.1.1	Standardization of the Linear Portion of RSD.....	52
6.1.2	Slope Criterion	54
6.2	Pre-testing Activity	54
6.2.1	Phase 1 Correlation Test	54
6.2.2	Phase 2 Correlation Test	55
6.3	Final-testing Activity (M5i Phase 3 Data)	58

6.4	PM CEMS (Performance Specification 11).....	61
6.4.1	Durag-904 K Beta Monitor.....	62
6.4.2	Environment SA Beta 5M Monitor.....	64
6.4.3	Sigrist CTNR Light-scattering Monitor.....	67
6.5	Relative Correlation Audit.....	69
6.6	Inter-instrument Comparison Between CEMS	71
7	CONCLUSIONS/SUMMARY	74
	REFERENCES	80
	APPENDIX	84
	Appendix A Tables Discussed in Body of Report.....	85
	Appendix B Figures Discussed in Body of Report	100
	Appendix C Airtech Laboratory Report Phase 3 M5i Testing.....	132
	Appendix D Summary of M5i and CEMS Data for Phase 3 Testing.....	143
	Appendix E CEMS Sample Spreadsheet Calculations	145
	VITA	155

LIST OF TABLES

TABLE	Page
2.1 Summary of PM CEMS Performance Characteristics (without outliers) for the DuPont Waste Incinerator	86
2.2 Summary of PM CEMS Performance Characteristics (without outliers) for the Eli Lilly Waste Incinerator	86
3.1 Typical Flue Gas Conditions at the Sampling Location Under Normal Incinerator Operating Conditions	87
3.2 Incinerator Process Parameters Monitored During the PM CEMS Demonstration.....	88
4.1 Input/Output Signal Requirements for the Purpose of Data Logging.....	89
4.2 Summary of PM CEMS Sampling Characteristics	90
5.1 Summary of CEMS Measuring Ranges and Equations for Conversion Between Milliamp and Concentration	91
6.1 Estimation of Precision and Rejection of Statistical Outliers for Phase 2 M5i PM Concentration Data.....	92
6.2 Summary of Waste Feed Categories, Ash Content, and Feed Rates for Phase 3	93
6.3 Three Different Levels of PM Concentration Over the Incinerator Operations for Phase 3	93

(list of tables continued)

TABLE	Page
6.4 Estimation of Precision and Rejection of Statistical Outliers for Phase 3 M5i PM Concentration Data.....	94
6.5 CEMS and M5i Phase 3 Data Adapted for Use in the Correlation Tests	96
6.6 Summary of Durag Phase 3 PS11 Calibration Results	97
6.7 Summary of ESA Phase 3 PS11 Calibration Results.....	98
6.8 Summary of Sigrist Phase 3 PS11 Calibration Results.....	99

LIST OF FIGURES

FIGURE	Page
3.1 Aerial photograph of the TSCA Incinerator demonstration area.....	101
3.2 Overall schematic of the TSCA Incinerator process systems and the air pollution control equipment.....	102
4.1 Front view of Durag F-904 K beta-gauge monitor	103
4.2 General diagram of dilution probe for Durag monitor.....	104
4.3 Front view of ESA Beta 5M monitor.....	105
4.4 Presentation of ESA monitor and probe assemble.....	106
4.5 Diagram of side view of Sigrist CTNR light-scattering monitor.....	107
4.6 Schematic of Sigrist photometer cell and optical sampling configuration	108
5.1 Diagram of TSCA Incinerator stack sampling platforms and port elevations...	109
5.2 Detail of TSCA Incinerator stack sampling ports.....	110
5.3 Reference Method 5i sampling train and filter holder assembly	111
5.4 Layout of CEMS around incinerator stack	112
5.5 Schematic representing batch sampling cycle time of beta-gauge monitors	113
6.1 Phase 2 M5i Cross Correlation (7 Runs Meeting RSD Criteria).....	114
6.2 Phase 3 M5i Cross Correlation (19 Runs Meeting RSD Criteria).....	115
6.3 Durag Linear Calibration Curve for Phase 3	116
6.4 Durag Logarithmic Calibration Curve for Phase 3	117
6.5 Durag Polynomial Calibration Curve for Phase 3	118

(list of figures continued)

FIGURE	Page
6.6 ESA Linear Calibration Curve for Phase 3	119
6.7 ESA Logarithmic Calibration Curve for Phase 3	120
6.8 ESA Polynomial Calibration Curve for Phase 3	121
6.9 Sigrist Linear Calibration Curve for Phase 3	122
6.10 Sigrist Logarithmic Calibration Curve for Phase 3	123
6.11 Sigrist Polynomial Calibration Curve for Phase 3	124
6.12 ESA Phase 3 Linear Calibration Curve with Phase 2 Data Inserted for RCA	125
6.13 Sigrist Phase 3 Logarithmic Calibration Curve with Phase 2 Data Inserted for RCA	126
6.14 Durag vs. ESA (1-hour Averages for October 19-22 & 24)	127
6.15 Durag vs. Sigrist (1-hour Averages for October 19-22 & 24)	128
6.16 ESA vs. Sigrist (1-hour Averages for October 19-22 & 24)	129
6.17 Durag and ESA Responses vs. Waste Feeds During October 19	130
6.18 Sigrist Response vs. Waste Feeds During October 19	131

NOMENCLATURE

ACA	Absolute Correlation Audit
acfm	Actual cubic feet per minute
acm	Actual cubic meter
AES	Airtech Environmental Services
CAA	Clean Air Act
CEMS	Continuous Emission Monitoring System(s)
CFR	Code of Federal Regulations
CI	Confidence Interval
cm	Cubic meter
CNF	Central Neutralization Facility
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DOE	Department of Energy
dscm	Dry standard cubic meter
EERC	Energy and Environmental Research Corporation
EPA	Environmental Protection Agency
ESA	Environnement (Environment) SA or Emissions SA
ESC	Environmental Systems Corporation
ESP	Electrostatic Precipitator
ETTP	East Tennessee Technology Park
FRP	Fiber-reinforced Polyester

HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
Hg	Mercury
ISO	International Standards Organization
IWS	Ionizing Wet Scrubber
mA	Milliamp
M5i	Method 5i
MACT	Maximum Achievable Control Technology
mbar	Millibar
mg	Milligram
min	Minute
mm	Millimeter
N	Normal
N/A	Not Applicable
NAAQS	National Ambient Air Quality Standards
NaOH	Sodium Hydroxide
NG	Natural Gas
NESHAPS	National Emission Standards for Hazardous Air Pollutants
NSPS	New Source Performance Standards
nm	Nanometer
O ₂	Oxygen
P2	Procedure 2
PCB	Polychlorinated Biphenyls

PLA	Polystyrene Latex Aerosols
PLC	Programmable Logic Controller
PM	Particulate Matter
PS11	Performance Specification 11
QA	Quality Assurance
QC	Quality Control
R or (r)	Correlation Coefficient
RCA	Response Correlation Audit
RCRA	Resource Conservation and Recovery Act
ROM	Read Only Memory
RSD	Relative Standard Deviation
S ratio	Experimental value of deviation (Observed S ratio)
sec	Second
SVA	Sample Volume Audit
SCDAS	Supervisory Control and Data Acquisition System
SO ₂	Sulfur Dioxide
SSQATP	Site-Specific Quality Assurance Test Plan
TI	Tolerance Interval
TSCA	Toxic Substance Control Act
TÜV	(Technischer Überwachungsverein) or Technical Inspection Association.
UD	Upscale Drift
WFR	Waste Feed Rate
ZD	Zero Drift

CHAPTER 1

INTRODUCTION

1.1 Research Objective

This thesis summarizes the data analysis and correlation tests that were conducted to demonstrate and evaluate particulate matter (PM) continuous emission monitoring systems (CEMS) at the U.S. Department of Energy (DOE) Toxic Substance Control Act (TSCA) Incinerator located at the East Tennessee Technology Park (K-25) near Oak Ridge, Tennessee. During July 1999, three PM CEMS were installed on the incinerator: (1) a Durag F-904K beta monitor, (2) an Emissions SA Beta 5M monitor (ESA), and (3) a Sigrist CTNR light-scattering monitor. The primary goal of the study was to determine if PM CEMS operation could satisfy the Environmental Protection Agency (EPA) requirements in draft Performance Specification 11 (PS11) and the quality assurance (QA) criteria identified in draft Procedure 2 (P2). Both these guidance documents are works-in-progress that will eventually appear in CFR 40 Part 60, Appendix B and F, respectively.

On September 30, 1999, EPA proposed Maximum Achievable Control Technology (MACT) standards for hazardous waste combustors (i.e., all incinerators, cement kilns, and lightweight aggregate kilns that burn hazardous wastes). Emission standards were established in the ruling for several hazardous air pollutants or hazardous air pollutant surrogates, such as dioxin/furan, mercury, particulate matter, semi-volatile and low volatile metals, hydrochloric acid/chlorine gas, and hydrocarbons. To verify compliance with the standards, the EPA also discussed the use of CEMS. Although the

final rule did not require the use of CEMS for parameters other than carbon monoxide, hydrocarbon, oxygen (to provide a dilution correction) and particulate matter, the EPA is encouraging their use wherever feasible because of certain advantages, which are: (1) CEMS directly measure the air pollutants; (2) they lead to some degree of certainty regarding compliance to existing regulations; (3) they allow the public to be better informed about the emissions from the source at all times; and (4) from a facility standpoint, CEMS provide real time feedback on combustion processes and allow the operator to exert a greater degree of control over the operational procedures that might affect the emissions.

Even though the new MACT standards required the use of PM CEMS, the installation deadline was deferred because the Agency is still in the process of gathering additional data to develop source-specific performance requirements. Accordingly, EPA wished to have more time to resolve other outstanding technical issues that relate to the implementation of the PM CEMS requirement, such as: (1) the relation of the CEMS requirement to all other testing, monitoring, notification, and record keeping, (2) the relation of the CEMS requirement to the PM emission standard, and (3) the technical issues involving performance, maintenance and calibration of the instrument. Since these issues will be discussed in later rulemaking decisions, the EPA has deferred the effective date of the PM-CEMS requirement pending further testing. At present, EPA is also promoting the use of CEMS for other parameters, such as total mercury, multi-metals, hydrochloric acid, and chlorine gas.

1.2 General Description of PM and CEMS

Particulate matter is a term used to define solid and liquid particles, except uncombined water, that remain suspended in the atmosphere for extended periods of time and contain the chemicals or material from the original source. Particulate matter is known to damage human and animal health, and retard plant growth. Certain pollutant gases can also form particles through physical and chemical reactions. However, this type of PM is not the focus of the present study.

The general size range for airborne PM is between 0.001 and 500 μm , though primary concern is reserved for particles less than or equal to 10 μm because it is in this range that PM impacts the environment by affecting the transmission of light or visibility. Smaller particles (less than 0.1 μm) are also easily inhaled and trapped in the alveoli the lungs, causing various health problems (Wark, Warner, & Davis, 1998). Stationary sources of fuel combustion, transportation (i.e., mobile sources), and industrial processes are all major contributors to anthropogenic atmospheric PM. Examples of these sources of PM are the fossil fuel-burning electric power plants and industrial furnaces, trucks and automobiles, and the bulk handling of a dry material that can result in the creation of fine dust.

A continuous emission monitoring system (CEMS), as defined by EPA, is the total equipment necessary for the determination of a gas, PM concentration, or emission rate from a stack using pollutant analyzer measurements. Generally a conversion equation or graph is required to produce the results in units that are applicable to the emission limit or standard. Continuous monitoring of parameters can determine if a source is in compliance with the applicable air regulations. The analyzer sends signals to

programmable logic controller (PLC). A personal computer utilizing appropriate software connects with the PLC. Advances in computer technologies also enable the facility to collect, store, and manage large quantities of data. Collectively, these components are known as a Data Acquisition System.

1.3 Overview of Federal Regulations

The basic federal standards that regulate or control air pollutants in the United States are the National Ambient Air Quality Standards (NAAQS), the New Source Performance Standards (NSPS), and the National Emission Standards for Hazardous Air Pollutants (NESHAPS). The NAAQS deal with the concentration of pollutants that are considered permissible in the everyday outdoor atmosphere. Currently there are six NAAQS pollutants: carbon monoxide, lead, nitrogen dioxide, ozone, PM, and sulfur dioxide. Ambient-based sampling devices are used to monitor these pollutants.

The NSPS set limits on the amount or concentration of pollutants that may be emitted from a new stationary source (usually from a stack) into the atmosphere. The NSPS are further divided into industrial source categories. For example, the NSPS for new Municipal Waste Combustor established emission standards for cadmium, carbon monoxide, dioxins/furans, hydrogen chloride, lead, mercury, nitrogen oxides, opacity, PM, and sulfur dioxide. At this time, the monitoring requirements for certain gaseous pollutants (e.g., CO, NO_x, and SO₂) call for the use of CEMS. For the remainder of the NSPS pollutants (i.e., Cd, dioxins/furans, HCl, Hg, and PM), annual stack sampling is required using an accepted reference method. Opacity is the notable exception in this example. A trained and certified observer from ground level, following the provisions specified in EPA reference Method 9, can determine opacity from visual observations

made about the stack plume. Otherwise, the facility can install a monitor that continuously measures the opacity of the flue gas. Opacity is important because it provides a relative indication for the concentration of pollutants (e.g., acid gas or PM) exiting the stack, and as a result, it provides information on the operation and maintenance of the air pollution control equipment. Nevertheless, opacity is not a true measure of the mass emission of the pollutants, and furthermore, it has been shown that instrumental measurements of opacity correlated better with each other than with the observer measurements of opacity (Conner and White, 1980).

All hazardous air pollutants are essentially regulated under NESHAPS. However since little progress was actually seen in the reduction of certain air pollutants during the intervening years after the promulgation of the Clean Air Act (CAA) of 1970, fundamental modification were made to NESHAPS in the CAA Amendments of 1990, specifically under Title III. At this stage, each major source (new or existing) is now required to meet MACT standards, which are defined as not less than the average emission level achieved by controls on the best performing 12 percent of existing sources, by category for existing sources, and not less stringent than the emission control that is achieved in practice by the best controlled similar source for new sources. For hazardous waste combustors, these standards are being promulgated under joint authority of the CAA and the Resource Conservation and Recovery Act (RCRA), and as mentioned previously, the current MACT standards for hazardous waste combustors require the use of PM CEMS. Thus, there is a need to persist in efforts to develop and demonstrate instruments that have the ability to accurately measure PM emissions.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical Development

There has always been a necessity for better systems to monitor stack emissions than by conducting manual stack sampling because manual stack tests are time consuming and do not give daily results about stack emissions. Initially ambient air analyzers and/or industrial process analyzers were adapted to monitor gaseous pollutants and/or flue-gas opacity, however these first experimental efforts were not very successful (Jahnke, 1992). Continuous emission monitoring for PM started in Germany during the 1960s, and the first opacity requirements were promulgated in the United States in 1971. Throughout the early 1970s, the EPA also funded research to determine if a transmissometer could be used to estimate PM mass concentration, but the manufacture of transmissometers for use by in stationary sources did not develop until 1975 with the establishment of Performance Specification 1.

A transmissometer is an instrument that determines the extinction coefficient and the visual range or opacity of the atmosphere. It measures the fraction of light from a collimated light source that reaches a light detector between a fixed distance. A portion of the light does not reach the detector because it is absorbed or scattered by the medium. The equation that defines percent opacity is $\{(1 - T) \times 100\}$. The fraction of light transmitted, T is (I/I_0) , where I_0 is the original intensity of the light at the source, and I is the intensity of the light at the detector. It has been shown that $T = \exp(-\sigma d)$, where σ is the overall extinction coefficient with units of length^{-1} , and d is the path length distance

between the light source and the detector. For simplicity, the extinction coefficient used here included the effects of both light-scattering and adsorption by the gas molecules and the particulate matter.

Connor and Hodkins (1967) showed that the opacity of smoke from a stack containing fine particles was affected by the wavelength of light used in the transmissometer. Their results indicated that the opacity of the plume as measured by a blue light source was greater than the opacity of the plume as measured by a white light source (i.e., 40% vs. 25% opacity, respectively). A red light source had less opacity than the white light source (i.e., 18% vs. 25% opacity, respectively), and the opacity of the white light source was roughly five-times greater than the opacity of an infrared source (i.e., 25% vs. 5% opacity, respectively). Connor (1974) also demonstrated that particle size and light wavelength were functionally related. By means of a white light (average wavelength about 0.5 μm), the researcher discovered that particles much smaller than the light wavelength (i.e., particle diameters $< 0.05 \mu\text{m}$) contributed little to opacity. Particles much larger than the light wavelength (i.e., particle diameters $> 2 \mu\text{m}$) were not a function of the opacity, and for particles about the same size as the wavelength of white light, opacity showed a strong dependence on particle size.

Conner, Knapp and Nader (1979) correlated opacity and PM mass concentration measurement separately for three cement (rotary-kiln) plants and three oil-fired power plants with in-stack transmissometers. Two of the kilns were wet processes systems that used an ESP for the air pollution control equipment; the other kiln was a dry process system that used a bag-house for air pollution control. Two oil-fired boilers burned high-sulfur oil at high excess oxygen conditions, and the other boiler burned low-sulfur oil at

low excess oxygen conditions. No air pollution control equipment had been installed on any of the oil-fired boilers. The researchers discovered that the opacity attenuation coefficient and PM mass concentration were related, however the slopes of the curves (attenuation coefficient/mass concentration) were distinctly different at each facility. It was obvious that a useful correlation existed, but the response from the instrument was strongly dependent on the operating characteristics that were in effect at the kiln and/or the boiler.

Philosophies changed within the EPA during the 1980s in relation to particulate monitoring, and PM CEMS were not a priority again in the U.S. until new initiatives began in the mid 1990s. The early approach towards PM CEMS in Germany was similar to the United States. However, the eventual course followed by the Federal Environmental Agency in Germany lead to wide-range suitability testing and specifications for particulate continuous monitors. In addition, the European International Standards Organization (ISO) developed standards for the certification of PM CEMS that eventually would serve as the guidelines EPA used to draft Procedure 2 (P2) and Performance Specification 11 (PS11) to govern the design, performance, and installation of PM monitors in the U.S.

Initial tests of transmissometers by the TÜV-Rhineland (the German technical inspection agency similar to the Underwriters Laboratories in the U.S.) did not produce results to the satisfaction of the agency. Nevertheless, improvements were made on the transmissometer, and over 5000 instruments were eventually installed throughout the country to measure opacity. As emission regulations became more stringent over the years and air pollution control equipment improved, the PM concentrations decreased to

levels that were too low to be accurately measured with simple transmissometers. Subsequently the emphasis shifted toward optical devices that could measure the forward or back-scattering of light through a process involving the light beam striking the particles and detecting certain parts of the scattered light at a some angle between the light beam and the detector. In this configuration, the concentration of high or low PM is proportional to the intensity of the scattered light, as long as the particle properties, like size, shape, color or refractive index do not change appreciably. Consequently, light-scattering monitors represent about 80 percent of the new PM monitors that were installed during the 1990s in Germany (Clapsaddle and Trenholm, 2000).

2.2 Preliminary Field Demonstrations

The EPA recognized that the poor correlation between opacity and PM concentrations near the proposed emission limits was an inherent problem if an opacity monitor was going to be used to demonstrate compliance since the detection level of continuous opacity monitors was typically reached at PM concentrations of about 45 mg/dscm @ 7% O₂. In 1996 the EPA Office of Solid Waste proposed a rule (Federal Register; April 19, 1996) that would require the installation and operation of CEMS for PM and mercury in hazardous waste incinerators. To support the CEMS requirements, the EPA proposal included draft specifications, test procedures, and quality assurance requirements for the new monitoring systems. The EPA also had previously solicited proposal from vendors to participate in the Agency's ongoing field demonstration test program for PM CEMS (Federal Register; February 27, 1996).

Prior to this initiative, limited field pilot programs were conducted during 1995 at the Rollins Environmental Services hazardous waste incinerator, located in Bridgeport,

New Jersey, and the LaFarge Cement Company hazardous waste kiln, located in Fredonia, Kansas. Optical (light-scattering) and beta-gauge instruments (i.e. devices that measure beta radiation attenuation) were tested at both facilities to gain experience in designing future tests, and to support vendor claims that PM CEMS could be used for compliance of emission standards. A full calibration of the instruments was also attempted at the LaFarge plant according to European specifications ISO No. 10155. From these two preliminary field studies, EPA concluded that the statistical criteria of ISO 10155 could be used as the basis for Agency's proposed performance specification for PM CEMS, but the manual gravimetric reference Method 5 (M5) measurements used in the calibration of the PM CEMS responses exhibited significant variability when measuring low PM concentrations because of probe washing requirements and the difficulty in filter recovery (Roberson, 1997).

2.3 Technical Approach

The satisfactory outcome of the preliminary tests mentioned above encouraged EPA to conduct long-term data gathering field demonstrations of PM CEMS to determine what accomplishments could be achieved. Yet before discussing the results of the two most important long-term field studies conducted to date (i.e. by Eli Lilly and Dupont), it is necessary to review the EPA certification requirements and procedures for PM CEMS. These documents are either currently still in draft form (i.e. P2 and PS11) or have recently been included in the CFR 40, Part 60 Appendix (i.e., M5i). Nevertheless, these documents will eventually serve as the regulatory guidance for all future PM compliance monitoring for stationary sources located throughout the United States.

2.3.1 Reference Method 5i: The EPA determined that much of the variability in previous attempts to calibrate PM CEMS resulted from inaccuracies in performing the filter recovery procedure in reference Method 5 (M5). This error would occur when the PM mass of the total sampling train was very small. Accordingly, the EPA developed a modified procedure, called M5i and recommend that it be used to calibrate the CEMS when the PM of the total sampling train is expected to be 50 mg or less. Basically M5i differs from the traditional M5 through the use of a smaller, lightweight, integrated filter and filter assembly that can be tared as a single unit. This improves M5 by eliminating the filter recovery step, and its associated errors due to the loss or contamination of sample. However, one negative consequence of the smaller filter is that at higher emission levels, the filter can become plugged. Since it is important that accurate M5i measurements are obtained for the CEMS calibration, EPA requires that paired sampling trains be used simultaneously traversing across two 90° axes. If the measurements between the two samples do not agree, then there is ample evidence that something was not consistent during the sample collection.

2.3.2 Procedure 2: Since the quality of the calibration curve can be no better than the quality of the reference method data that is used to develop the curve, it is necessary to quantify the precision and accuracy of the reference method data based on pre-determined criteria. Procedure 2 (P2) contains the quality control (QC) and quality assurance (QA) requirements for the PM CEMS program. It includes a method for evaluating the M5i data for outliers. The requirements for routine response and absolute correlation audits, which must be performed on a periodic basis to verify the continued

reliability of the initial PM calibration curve are specified in P2, as well as daily instrument zero and span checks.

When EPA embarked on the CEMS field demonstration test program, they initially proposed screening the M5 data to remove statistical outliers. At the time, a statistical outlier was defined as paired-data points with a relative standard deviation (RSD) greater than 30%, where $RSD\% = (|Train\ A - Train\ B|) * 100 / (Train\ A + Train\ B)$. Analyzing the historical M5 data helped EPA develop this criterion, but eventually several persons, including a vendor with extensive experience with the European correlation programs, as well as TÜV -Rhineland, recommended that EPA tighten the RSD criteria (EPA July, 1999). After the Dupont and Eli Lilly field studies, EPA concurred and promulgated that a graduated precision criterion be utilized to remove M5i statistical outliers. The criterion was defined as a 10% RSD for PM emissions greater than or equal to 10 mg/dscm, increased linearly to 25% RSD for concentrations down to 1 mg/dscm with PM concentrations lower than 1 mg/dscm having no RSD limit. Further discussion clarifying these RSD criteria will be presented in another section of this report.

The critical analytical auditing requirements of Procedure 2 are: (1) the absolute correlation audit (ACA) which requires an evaluation of the PM CEMS to a series of reference standards; (2) the response correlation audit (RCA) which involves again collecting simultaneous CEMS responses and manual reference method data to determine whether the initial calibration curve of PS11 is still valid; and (3) the sample volume audit (SVA) which evaluates the accuracy of the PM analyzer to measure the sample gas volume.

2.3.3 Performance Specification 11: The calibration test procedure for PM CEMS is referred to as Performance Specification 11 (PS11). This procedure differs from the calibration of gaseous CEMS, which use calibration gases of known concentration to periodically calibrate the instrument. The PS11 calibration test is carried out by making simultaneous CEMS and M5i measurements at three different levels of PM mass concentrations over the full range of operations for the facility. The technique is called the "correlation". The essential consequence is the development of a statistical correlation equation between CEMS and M5i results. A minimum of 15 dual-train M5i runs are required and correlated. At least 20% of the minimum 15 measured data points should occur in each of the following levels:

- Level 1 (low): from no PM emissions concentration to 50% of the maximum PM concentration;
- Level 2 (medium): 25% to 75% of the maximum PM concentration; and
- Level 3 (high): 50% to 100% of the maximum PM concentration.

A correlation or regression analysis between M5i measurements and the PM CEMS responses is then used to develop an equation that will predict the PM concentration from CEMS response. The calculation method of least squares is applied to investigate the correlations using three different curve fits: linear, logarithmic, and quadratic (or a second degree polynomial). The fitness of the curve must meet each of the following criteria:

- Criterion A: The correlation coefficient "r" shall be greater than or equal to 0.85;

- Criterion B: The confidence interval (95%) at the emission limit shall be within 10% of the emission limit value specified in the regulations; and
- Criterion C: The tolerance interval at the emission limit shall have 95% confidence that 75% of all possible values are within 25% of the emission limit value specified in the regulations.

The emission limit is defined here as the emission standard reported at the conditions of the CEMS (e.g., temperature, pressure, and moisture) experienced during the correlation test. Under PS11 guidelines, extrapolation of the correlation curve is limited to 125% of the highest measured PM CEMS concentration measured during the performance testing.

It is significant to note that the PS11 criteria have changed over the course of the field-testing demonstration programs. The original version of PS11 identified the correlation coefficient as greater than 0.90, the confidence interval percent within 20%, and the tolerance interval percent within 35%. Previous PS11 criteria also stated that the measured data points must lie within 0 to 30%, 30 to 60%, and 60 to 100% of the maximum PM concentration for the three levels, respectively that are listed above (Federal Register; December 30, 1997). The confidence interval (CI), and tolerance interval (TI) now proposed are at the same level as specified in the European ISO Method 101055.

2.4 Primary Field Demonstrations

Based on surveys done in Europe and preliminary testing done in the U.S., the EPA has determined that CEMS exist that can quantitatively measure PM mass

concentrations, rather than opacity. The two types of analytical instruments that currently dominate the market employ either light-scattering technology as the detection principle or carbon-14 beta attenuation technology. As previously stated, EPA's major field demonstration programs for PM CEMS began in 1996. The program included two phases: calibration testing to compare and evaluate results from each of the CEMS with the manual reference method and endurance testing over six months to critically examine CEMS performance relative to stability of the calibration and the reliability of continuous operation. The EPA also believed that hazardous waste incinerators represented the worst-case challenge to PM CEMS because they burn a wide variety of wastes to produce PM with a sufficient variation in characteristics (i.e., composition, size distribution, shape, and index of refraction). Many hazardous waste incinerators, in addition, utilize wet scrubber systems to control emissions, which result in flue gas with a saturated moisture content, yet another challenge for the CEMS. Lastly, hazardous waste incinerators have highly efficient air pollution control equipment, which requires CEMS testing at very low emission levels (Roberson, 1997).

2.4.1 DuPont Hazardous Waste Incinerator: The DuPont facility is located in Wilmington, Delaware. The incinerator can burn solid and liquid wastes. The air pollution control system was equipped with spray dryer, cyclone, reverse jet gas cooler/condenser, a variable-throat venturi scrubber, neutralizing spray absorber, chevron-type mist eliminator, electro-dynamic venturi, and centrifugal droplet separator (in that order). The flue gas is then passed through an induced draft fan and a series of steam heat coils before finally being exhausted from the stack. Preliminary measurements showed that PM emissions ranged between 10 to 100 mg/dscm at 7% O₂.

The estimated particle size distribution was approximately 90% < 1 μm . The average temperature and moisture conditions in the stack were about 320 °F and 25% moisture by volume.

For this field demonstration, six CEMS were tested representing three different measuring technologies: optical, beta-attenuation, and acoustic energy. Three of the CEMS were light-scattering monitors: Durag model DR-300-40, Environmental Systems Corp. (ESC) model P5A, and Sigrist model KTNR. Two of the CEMS were beta-gauge monitors: Verewa model F-904-KD and Emissions SA (ESA) model Beta 5M. The final monitor was a Jonas Inc. model Acoustic Energy PM. Both beta monitors and the Sigrist monitor employed an extractive, heated, and close-to-isokinetic probe sampling system that conveyed the sample to measuring sensors external from the stack. The remaining two optical systems and the acoustic monitor used an insitu sampling and measurement approach. The acoustic monitor did not produce acceptable results throughout the field-testing period and was not discussed further in the Dupont report.

Reference Method 5 (M5) calibration tests were performed over a 9-month period from September 1996 to April 1997. Response Correlation Audits (RCA) were also conducted during May 1997 to meet the requirements of Procedure 2. During the calibration tests, six different groups of fuel/wastes were fed into the combustion chamber: (1) fuel oil, (2) solids including shredded paper, animal bedding, and office/laboratory waste, (3) high-chlorinated solvents, (4) a mixture of low and/or non-chlorinated, (5) paint pigments containing water, resins, and solvents, and (6) jugs containing non-, low- or high-chlorinated solvents. The M5 data were compared to the output of the five CEMS according to draft PS11 criteria.

The tests from December 1996 through March 1997 established the initial calibration relationship. The total database contained 43-paired M5 and CEMS responses. Seven of the paired M5 runs were rejected because they were statistical outliers. A second round of calibration tests was conducted in April 1997. A total of 17-paired M5 runs and CEMS responses comprised this database, but two paired M5 runs were outliers and rejected from the database. The investigators decided that the September through November 1996 tests should only be used as a trial-and-error learning experience and not incorporated into the final cumulative database, but these results are included here to demonstrate the difficulty of obtaining valid PS11 calibrations before the operators have become thoroughly familiar with CEMS response and have fully characterized the PM emissions across the full range of incinerator operating conditions.

The PS11 acceptance criteria data are shown in [Table 2.1](#) only for the linear regression analysis that was conducted at the 34 mg/dscm @7% O₂ emission limit. (All tables and figures can be found/are located in the appendix). Based on this data and other information, the following conclusions were reached:

- None of the CEMS met any of the PS11 criteria during the September to November 1996 (pre-testing) period.
- For the first data set, each of the five CEMS, with one exception produced data meeting the PS11 criteria. The Sigrist did not achieve the tolerance interval measure at 25% for linear regression at the emission standard.
- For the second data set, all of five CEMS met the PS11 criteria. Then again, the Sigrist monitor was very close to not passing the tolerance interval criterion (i.e. 24.9% vs. 25%).

- When the slopes of the linear curves were compared between the first and second calibrations, the percent difference was within 4% for the beta monitors and within 7% for the Durag light-scattering monitor. However, the percent difference was 11% for the ESC and 22% for the Sigrist, both light-scattering monitors.
- The large percent difference between the first and second calibration curves for the ESC and Sigrist tended to imply that the linear regression equation was not a suitable fit for these monitors. When a logarithmic regression equation was used for the two monitors, agreement between the first and second calibration curve was within 2%. Although the logarithmic regression fit the data, only the ESC monitor passed PS11 criteria for both the first and second calibration data sets. The Sigrist yet again failed to pass the tolerance limit criteria on both the first and second calibration data.
- Except for the Verewa during the initial calibration period, each monitor produced data during the RCA tests (i.e., at least 75% falling within $\pm 25\%$ of the proposed emission limits). However, the RCA tests were not performed in strict accordance with P2.

2.4.2 Eli Lilly Hazardous Waste Incinerator: The Eli Lilly facility is located in Clinton, Indiana. The incinerator only burns liquid and aqueous wastes. The air pollution control system is equipped with a quench chamber, venturi scrubber, a demister tank, and scrubber tower in that order. Average temperature and moisture conditions in the stack were approximately 170 °F and 35% moisture by volume. The field demonstration program extended over an 11-month period. Two sets of calibration tests were

conducted. Phase I occurred from February 1998 to May 1998, and Phase II occurred from November 1998 to December 1998. Two CEMS were tested during both phases of the field demonstration: Sigrist model KTNR/SIGAR 4000 light-scattering monitor and Environmental SA (ESA) model Beta 5M beta-gauge monitor. Both monitors employed an extractive, heated probe system to deliver a sample to measuring sensors external from the stack. However, only the ESA monitor adjusted the gas-sampling rate to maintain isokinetic flow conditions at the probe nozzle. The same monitors were used during the second phase of the demonstration, but the ESA monitor had been mechanically modified to allow it to operate at higher moisture levels, and the Sigrist monitor was prevented from auto-ranging during the calibration test. A second beta-gauge monitor, a Durag model F-904, was added during Phase II, as a learning experience for the vendor, but the results were not reported in the final Eli Lilly report.

Various combinations of natural gas and waste types were burned in the incinerator during the M5i calibration test. Organic waste was always fed into the primary burner. Aqueous waste, a high salt concentrations waste, and waste spiked with tin chloride were fed into to the secondary injection ports. The water injected into the wet scrubbing system was also manipulated to control stack temperatures and thus produce different levels of moisture in the flue gas during the testing. During Phase I, a total of 74 paired M5i tests were completed. Five M5i paired tests did not meet the sampling criteria and were discarded from the Phase I data set. The particulate levels ranged from 17 to 45 mg/dscm @ 7% O₂. During Phase II, a total of 40 M5i tests were conducted, and five M5i paired tests were also discarded from data set. The particulate levels for Phase II ranged from 1 to 64 mg/dscm @ 7% O₂. The acceptance criteria data

are shown in [Table 2.2](#) for the PM CEMS for the Phase I and Phase II calibration tests.

The following conclusions were reached:

- Neither monitor met the draft PS11 criteria in the Phase I test for the correlation coefficient, but both monitors passed all the PS11 acceptance criteria during the Phase II test.
- Evaluation of the Phase II data showed that the best correlation relation was logarithmic for the Sigrist monitor and linear for the ESA monitor.
- No RCA tests were conducted to determine the long-term stability of the calibration curves thus established in Phase II.

2.5 Summary

The use of continuous PM monitors is feasible for regulatory compliance, however there are many factors that could significantly influence the ability to calibrate the monitor and for it to maintain a calibration relationship. While relatively uncomplicated, actual sample extraction and measurement have proven much more difficult in practice than in concept. Reliable operations of CEMS over prolonged periods of time have also not been sufficiently demonstrated. It has been hypothesized that changing the waste streams and the stack conditions in the incinerator will produce PM with different characteristics, and as a result, influence the reliability of the calibration curve developed with an optical CEMS. The EPA still feels that more time is needed to resolve the outstanding technical issues concerning PM CEMS. Since the technologies may not be adequate at this time, the EPA has not yet required implementation of the PM CEMS requirement for hazardous waste incinerators as of April 2001.

CHAPTER 3

TSCA INCINERATOR AND FACILITY

3.1 General Description

Wide ranges of waste categories are treated at the TSCA incinerator. These categories include oils, solvents and chemicals, aqueous liquids, solids, and liquid-free sludges. The TSCA facility holds federal and state permits to thermally treat mixed-waste, RCRA hazardous and non-hazardous wastes, and wastes containing polychlorinated biphenyls (PCB). Mixed-waste is a waste that contain both radioactive and hazardous chemical constituent. In the recent MACT ruling for hazardous waste incinerators, the EPA has decided that those standards were also compatible with the controls for mixed-waste incinerators.

The TSCA incinerator is a rotary-kiln furnace with a secondary combustion chamber. A wet scrubber air pollution control system is used for cleaning the effluent gases to comply with TSCA and RCRA regulations, as well as with the air emission standards for the state of Tennessee. The facility includes various support buildings for operator and maintenance personnel, the unloading and storage of waste in above ground tanks, an incinerator area, and concrete wastewater collection/holding ponds. An aerial photograph of the facility taken during 1995 is shown in [Figure 3.1](#). (All tables and figures can be found/are located in the appendix).

The high heat-of-combustion liquids are burned in the rotary kiln (the primary combustion chamber) and in the secondary combustion chamber with dual-fuel (natural gas/liquid waste) burners. However, aqueous wastes (i.e., liquid wastes containing at

least 60% water content) are injected through a lance only into the primary combustion chamber. Solid and sludge materials are received and stored in metal containers but are repackaged into combustible cardboard containers prior to incineration. The containerized solids and sludges are inserted into the rotary kiln by a hydraulic ram. The hazardous waste incinerator permit conditions allow for both solid and liquids to enter the rotary kiln, however only liquids may enter the secondary combustion chamber.

The off-gas from the secondary combustion chamber is passed through a multi-stage air pollution control system for cooling, removal/neutralization of acidic by-products, and removal of particulate matter (PM). The air pollution control system includes a quench chamber, a low-energy venturi scrubber, a packed bed scrubber, and two Ceilcote ionizing wet scrubbers (IWS®). Preceding the stack, an induced-draft fan is located downstream of the air pollution control system. The effluents from the wet scrubbers are pumped into holding ponds to allow settling of suspended solids. After a certain period of time and without disturbing the bottom sediment, the accumulated wastewaters in the holding ponds are transferred to the ETPP existing Central Neutralization Facility for final treatment. Solid-type wastes, such as scrubber sludge, residues from the incinerator wet ash removal system, and the sediment in the holding ponds are collected in steel drums for subsequent offsite disposal at a commercial landfill (EERC, 1999).

3.2 Incineration Process System

Auxiliary natural gas is used to maintain the minimum incineration temperatures inside the primary and secondary combustion chambers to ensure the stable destruction of wastes. A schematic of the incinerator process system is shown in [Figure 3.2](#). To

atomize the primary liquid waste, steam is fed through the burners with the liquid waste. The steam flow rate is controlled at a constant fixed ratio with respect to the waste flow rate. The normal operating temperature inside the kiln is maintained at approximately 1800 °F. The rotary kiln also receives and incinerates the boxes of solid and sludge wastes, which are fed by a hydraulic ram. A burner nozzle injects liquid wastes, and a lance injects aqueous wastes; both nozzle and lance are located at the kiln faceplate. The outer shell of the kiln is made of carbon steel; the inner shell is lined with refractory brick.

The next stage of the incineration process is the mixing chamber. It separates the primary combustion chamber (rotary kiln) and the secondary combustion chamber. The mixing chamber collects the hot gases and ash discharged from the rotary kiln. It is also constructed of carbon steel and is lined with refractory brick. The cross-sectional area of the mixing chamber is larger than the cross-sectional area of the rotary kiln, so the gas velocity is reduced, allowing larger PM to fall to the bottom of the chamber. The ash handling system conveys the residue from a water-filled trough beneath the mixing chamber to the ash hopper for disposal. Water in the ash trough provides a seal against air leakage. A circulation pump removes the suspended ash and solids from the water trough at the bottom of the mixing chamber and conveys the material to the purge water sumps.

The secondary combustion system receives the hot gases from the mixing chamber. The cross-sectional area at the entrance to the secondary combustion chamber is smaller so as to rapidly increase the gas velocity, providing turbulence and mixing of the kiln gas. Auxiliary natural gas and secondary liquid wastes are fired in the burners.

The secondary combustion chamber can receive liquid wastes pumped from the primary waste feed tanks or the fuel oil tanks, though it usually accepts secondary organic liquid wastes pumped from secondary waste feed tanks. The normal operating temperature in the secondary combustion chamber is maintained above 2200 °F. The off-gases from the secondary combustion chamber pass through a duct to the air pollution control system. All sections of the secondary combustion chamber are constructed of carbon steel and are refractory lined.

An induced-draft fan is provided within the system to draw gases from the kiln through the process equipment line and to discharge gases through the stack into the atmosphere. In the event of an induced-draft fan shutdown or an interruption of the water flowing to the quench chamber in the wet scrubber systems, a thermal relief vent at the outlet of the secondary combustion chamber can release combustion gases to the atmosphere. This prevents damage to the scrubber during an interruption of quenching and prevents backward flow from the incinerator during a shutdown of the induced-draft fan. When the thermal relief vent is activated, all waste material and fuel feeds to the incinerator are automatically discontinued except for natural gas to the secondary burner (EERC, 1999).

3.3 Air Pollution Control System

The air pollution control system is a wet scrubber process that reduces both acid gases and PM from being released into the atmosphere. A schematic of the air pollution control equipment is shown in [Figure 3.2](#). The hot flue gas received from the secondary combustion chamber is first cooled in a quench chamber. The system is supplied with fresh water and is equipped with a recycle water system and an emergency water backup

system. The quench chamber normally receives the hot flue gas at about 2200 °F (containing PM, SO₂, HF, and HCl) and saturates the flue gas to the adiabatic saturation temperature with a series of internal sprays of fresh and re-circulated water. The spray nozzle system has strainers installed on the supply lines to prevent clogging. The excess water from the fresh water spray header flows by gravity to the quench chamber recycle tanks, and pumps re-circulate this water back to the quench chamber. The pH of the recycled water is controlled with a 20% NaOH solution from the caustic storage tank. The quench chamber has an acid-resistant refractory lining, which is suitable to withstand the flue gas temperature and corrosive nature of the scrubbing water. The saturated gas stream from the quench chamber flows through a fire-retardant fiber-reinforced polyester (FRP) duct to the inlet of the venturi scrubber. With the exception of the venturi damper and the induced-draft fan, all of the air pollution control devices downstream of the quench chamber are manufactured of FRP materials.

The venturi scrubber receives the cooled water-saturated flue gas, removes some PM greater than 1-micron, and neutralizes a portion of the acid gases (HCl and HF). The venturi scrubber consists of converging and diverging cones with an automatic variable throat to maintain a pressure differential and an integral water collection sump. The re-circulating water system from the quench chamber supplies the scrubber solution upstream of the venturi throat through a nozzle, and the recycled water flows back to the quench sump. Again, the pH of the recycled water is controlled using a 20% caustic solution. A mist eliminator between the venturi scrubber and the packed-bed scrubber removes the entrained water from the saturated flue gas and minimizes the interference between the cross-flow liquid/gas flow in the packed-bed scrubber. In addition preceding

the mist eliminator, a dispersion plate distributes the gas flow more evenly before it reaches the mist eliminator. From the mist eliminator, the liquid effluents flow by gravity back into the quench chamber sump.

The packed-bed scrubber is a horizontal cross-flow unit that contains three feet of irrigated packing and has an entrainment separator following the packed bed. The scrubber functions to remove soluble and reactive gasses, such as HCl, HF, and SO₂. Re-circulated scrubber water irrigates the packing, however the water recycle system that serves the IWS units provides recycled water for the pack-bed scrubber. The pH of the recycled water is controlled with 20% caustic solution from the caustic solution storage tank. The packed-bed scrubber has an integral sump, and water flows from this sump towards the IWS sumps. The process gas from the packed-bed scrubber flows through an inlet transition duct to the IWS. This provides gradual changeover from the packed-bed to minimize turbulence before the gas enters the IWS.

Two identical IWS units are located in series. They remove PM of less than 1-micron from the flue gas stream with high efficiency. The key features of the IWS units are (1) an ionizing module for electrically charging particles, (2) a packed-bed section for removing charged particles, (3) a re-circulating water system, and (4) an integral sump. Both IWS units operate on a continuous basis, with the exception of the following: alternating every four hours, each IWS unit goes into a water flush cycle to remove the buildup of PM on the plates, Tellerettes, and other surfaces. During the flush cycle, the IWS operating voltage drops to zero, and the plates, etc. are flushed with recycled IWS scrubber water for about five minutes. The gas subsequently passes through a flow

control damper section, which is used to vary the stack gas velocity at the outlet of the IWS to the induced-draft fan.

The induced-draft fan maintains negative pressure throughout the incinerator system and discharges the water-saturated flue gas to the stack. The fan is constructed of Hastelloy. Instrumentation and controls measure gas pressure, temperature, fan drive motor power, and vibration. Loss of the fan operation shuts down all waste feed streams and the auxiliary fuel to the rotary kiln. A short FRP duct section carries the gas stream from the fan outlet to the stack inlet and then vents the gas stream to the atmosphere. The stack is constructed of FPP materials and is 100-feet high with a 54-inch inside diameter. The current amps and pressure drop across the induced-draft fan are used to provide an approximation for combustion gas velocity. The stack is equipped with several ports for sampling flue gas and continuous sampling systems for CO, O₂, and CO₂, and radionuclides. The typical flue gas conditions found inside the stack at the sampling locations under normal incinerator operations are shown in [Table 3.1](#) (EERC, 1999).

3.4 Process Data Collection

The entire combustion process and off-gas cleaning systems are monitored with process computers. Operational parameters are automatically recorded every 15-seconds by the incinerator Supervisory Control and Data Acquisition System (SCADA). The facility has conventional flue gas monitoring systems for O₂, CO, CO₂, stack gas temperature, stack pressure, and gas flow rate. [Table 3.2](#) lists key process data that are collected during the demonstration in order to interpret incinerator operations and convert the manual test data into the same units reported by the CEMS (EERC, 1999).

CHAPTER 4

CONTINUOUS EMISSION MONITORING SYSTEMS

Three PM CEMS were evaluated during this field demonstration: (1) a Durag F-904 K Beta Monitor, (2) an Emission SA Beta 5M Monitor, and (3) a Sigrist CTNR Light-scattering Monitor. All three instruments extract flue gas through heated sampling lines. The Durag and Sigrist monitors are programmable to deliver a slightly greater than isokinetic sample to the analyzer. Only the ESA monitor is designed to maintain true-isokinetic sampling conditions at the probe nozzle. However, isokinetic sampling is generally not critical for small particles less than about 3 μm in diameter because small mass minimizes the inertial effects of particles entering the nozzle (Lodge, 1988).

The Durag and ESA instruments are batch-sampling devices that collect PM on filter tape. The measurement principle is based on the absorption of beta radiation, which is emitted from a radioactive source (carbon-14) located in the sampling apparatus. Both beta-gauge monitors in their present configuration produce a signal on the order of every 10 to 15 minutes. The significant appeal of beta-gauge technology is that the instrument's response is independent of the PM characteristics, such as refractive index, particle size and density. The Sigrist monitor, on the other hand, is a true-continuous extractive sampler, and it employs light-scattering as the measurement principle. The primary advantages of this technology are (1) the response is almost instantaneous, and (2) because there are fewer moving parts, the instrument is very reliable. The primary drawback of the light-scattering technology is that the response from the instrument is very dependent on the PM characteristics, for example composition, density, particle size

distribution, and index of refraction. The CEMS are described in further detail in the following sections. The signal input/output requirements for the CEMS with the data logger (i.e., the SCADA system) are listed in [Table 4.1](#).

4.1 Durag F-904 K Beta Monitor

The Durag (formerly manufactured by Verewa) F-904-K beta PM monitor extracts a heated sample from the stack at slightly greater than isokinetic conditions. A programmable sampling flow rate is maintained with a vacuum pump, as isokinetic sampling is not actively controlled in response to changes in the gas velocity and temperature inside the stack. The sample gas is diluted with filtered recycled dry gas because the flue gas is in a wet saturated condition. The dilution gas is mixed with the extracted flue gas in the cyclonic mixing chamber of the nozzle. The total sample passes through heated sections consisting of the probe, sample line, and filter housing. The PM in the sample is then collected on filter tape. After passing through the filter tape, the sample gas is dried in a chiller, and the flow rate is measured. A portion of this clean dried sample gas is recycled and used for the dilution air. [Figure 4.1](#) shows a frontal view of the Durag monitor, and [Figure 4.2](#) shows the sampling probe and mixing nozzle.

The Durag monitor is commonly referred to as a continuous batch sampler. The filter tape mechanism has an emitter-detector location for analysis and a sampling location for gas extraction. In the direction of the tape movement, the sampling mechanism precedes the emitter-detector mechanism. The carbon-14 source emits beta radiation (electrons), and a Geiger-Muller counter is used to detect the pulse rate of these electrons as they penetrate the filter and PM collected on the filter. The PM measurement cycle first begins by analyzing a clean area (spot) on the filter tape for a fixed period of

time. This is called the zero-test; a clean filter area is transported into position (i.e., into the emitter-detector location), and the spot is exposed to the carbon-14 source, and beta attenuation is measured through the tape. The drive roll mechanism next positions this same section of filter tape into the sampling location, the vacuum pump is activated, and a gas sample is drawn through the filter tape. The filter tape is then transported to the measurement position (i.e., again to the emitter-detector location) and the filter spot is evaluated by exposure to the carbon-14 source, and the Geiger-Muller counter measures the pulse rate of beta radiation through the spot. Thus, the pulse rate through the same filter spot is measured before and after sampling. The difference between these two measurements is directly proportional to the PM mass collected on the filter tape.

A microprocessor calculates the PM concentration, given the mass collected and dry sample volume, and reports the concentrations on a dry standard basis via a 4-20 milliamp signal or in units (mg/Nm^3). The monitor is preprogrammed to report PM at European Normal (N) conditions, which are temperature at 0 °C and pressure at 1013 mbar. In addition, the Durag monitor allows for the conversion of the signal to several reporting conditions. For this field test demonstration, the monitor was programmed to report concentration at the U.S. standard conditions, which are temperature at 20 °C and pressure at 1013 mbar, via the 4-20 milliamp signal or in units (mg/dscm). Note that the concentration is not reported on a normalized oxygen basis (i.e., the units dscm contain the actual oxygen condition existing in the stack).

The gas sampling and analysis times can be programmed; therefore different reporting times can be obtained depending on the PM loading and filter cake porosity. A typical sample analysis requires two minutes to perform for both the blank (zero-test) and

the analysis of the dust loaded filter spot with about one minute of total time for the back and forward motions of the tape. For example, if the actual sampling time were set at five minutes, then a complete measuring cycle would occur approximately every ten minutes. The same spot on the filter tape can be used multiple times, however for the present demonstration, a clean section of filter tape was used during each measurement cycle.

The probe and sampling line can be purged with clean dry air to remove deposited PM. The initiation of the purge cycle is also programmable and is usually set at one purge per hour. The instrument does automatic zero drift (ZD) and upscale drift (UD) checks to meet quality control (QC) requirements and features several status signals for identifying operational modes error flags. The operational modes for calibration are “zero-signal” and “reference-signal”. The error flags are filter plug indication (vacuum-error), emissions higher than set point (measuring range-error), total volume higher than set point (volume-error), and broken filter tape (filter-tear). A summary of the important system parameters that were in effect during this field study is shown in [Table 4.2](#).

4.2 Environment SA Beta 5M Monitor

The Environment SA Beta 5M (ESA) extracts flue gas through a heated probe. A pitot-tube and thermocouple are used to determine the stack velocity and the required isokinetic sampling rate. A microprocessor tests for changes in gas velocity and temperature in the stack and automatically maintains isokinetic conditions at the probe nozzle by controlling compressed air through a pneumatic ejector to create a vacuum for sample collection. The sample gas passes through heated sections consisting of the probe, sample line, and filter holder housing. The dust sample is collected on filter tape.

The ESA monitor is also a continuous batch sampler like the Durag monitor. The filter tape mechanism has an emitter-detector location and a sampling location. In the direction of the tape movement, the emitter-detector mechanisms precede the sampling mechanism. This arrangement of analysis and sampling location was in reverse order for the Durag monitor, however the essential mechanics of tape movement are basically the same for both beta gauge monitors. The filter tape mechanism first positions a portion of clean filter tape in the emitter-detector location and a Geiger-Muller counter measures the pulse rate of beta radiation from a carbon-14 source through the section of filter tape. The mechanism then positions the filter area into the sampling location, and flue gas is drawn through the filter section. Finally the tape mechanism returns the filtered section back to the emitter-detector location, and the Geiger-Muller counter measures the pulse rate of beta radiation through the sampled filter spot. Likewise using the differential method (i.e., taking into account the clean and dirty filter), the final analysis is directly proportional to the PM mass that was collect during the sampling period.

The sampling duration is programmable and is measured along with the sample flow-rate. Sampling time is usually set at five to 10 minutes for typical applications. It can be set lower for higher PM concentration and filter cake porosity. The pre and post analyses (i.e., measurements of clean and dirty filter) each take about two minutes, and the total time during filter indexing is about one minute. Thus, a complete measurement cycle is made every ten to fifteen minutes. A microprocessor calculates the PM concentration, given the measured mass collected and the volume of gas sampled. The PM concentration data are reported on an actual basis either as a 4-20 milliamp signal or in units (mg/Nm^3). In this situation, actual conditions are only for the actual conditions

of oxygen and moisture in the stack. The ESA response is also internally corrected to the European Normal (N) conditions, which are temperature corrected to 0 °C and pressure corrected to 1013 mbar. At the end of each sampling period, the probe nozzle is momentarily closed, opened, and closed again under vacuum, in order to re-entrain any PM that may have been deposited in the probe and sampling line.

The instrument produces two status signals (flags) called “stand-by” and “general-alarm”. The former is for identifying suspect data or encountered problems during normal operation; the latter is for identifying operational modes for maintenance or calibration. The instrument makes continuous checks of its main components and signals any fault with a plain language message (e.g., paper tear fault), however the monitor must be assessed through the keyboard to display these plain language fault messages. The ESA unit features data sensors to report sample intake volume, stack gas temperature and velocity, and venturi tube temperature and static pressure. [Figures 4.3](#) and [4.4](#) are diagrams of the ESA monitor and probe assembly. [Table 4.2](#) contains a summary of the important system parameters that were in effect during the field study.

4.3 Sigrist CTNR Light-scattering Monitor

The Sigrist model CTNR is a light-scattering monitor. [Figure 4.5](#) is a diagram of the major components of the monitor. Using a fan (blower) to create a vacuum, the instrument extracts a heated gas sample from the stack at a constant flow rate. A smaller portion of this sample is passed through a light photometer cell. The entire gas sample is then returned to the stack. A purge system using pre-filtered air keeps the walls and windows of the photometer flow cell from being fouled by the extracted sample as it passes through the flow cell. [Figure 4.6a](#) is a schematic of the photometer. The Sigrist

monitor is programmed for the probe to sample at slightly greater than isokinetic conditions to reduce the relative error for changing gas flow velocities in the stack.

The illuminant light source is an incandescent bulb emitting between 360 and 2,800 nm. [Figure 4.6b](#) is a schematic of the optical sampling configuration. The photometer measures only a certain part of the forward scattered light under a 15° angle. The design incorporates the alternating-light dual beam method. The light is divided into two beams by a semitransparent mirror. One beam enters the sample where the dust particles scatter light in all directions. The 15° angle scattered light serves as the measurement signal. The second beam passes through a stable reference standard and serves as the reference signal. A chopper disk allows the measuring beam and reference beam to alternate through the photo-detector. The chopper disk also has a third position in which both beams are blocked. This serves as the zero value. Thus, the photo-detector receives three signals one after the other: (1) the measurement light with zero value (2) the reference light with zero value, and (3) the zero value alone. The zero value is subtracted from the two signal beams. The final value (i.e., the scattered light intensity) is established as the ratio of the measured beam to the reference beam. The intensity of the scattered light is linearly related to the concentration of the particles, as long as the properties of the particles (e.g., size, shape, color, or refractive index) do not change appreciably. This design along with the internal electronics is inherently self-compensating in its PM measurement, rendering it immune to fluctuations in aging, drift, humidity, temperature, voltage, and vibration.

The instrument was factory calibrated with polystyrene latex aerosols (PLA), uniform spherical particles with a diameter of 1 μm , to ensure the linearity of the

calibration over the complete measuring span. The monitor reports PM concentration on an actual basis either as a 4-20 milliamp signal or in units (mg/m^3 PLA). In this situation, actual conditions are for the actual conditions of oxygen and moisture in the stack and the actual temperature of the heated probe and sampling lines since the Sigrist monitor does not internally correct temperature to standard.

The Sigrist instrument as currently configured has two discrete measuring scales, and each measuring scale has four measuring ranges that reflect differences in sensitivity. The measuring scale is fixed and can only be changed by programming. On the other hand, the measuring range is usually allowed to operate on automatic mode to prevent the instrument from going off-scale. Additionally, the instrument can also be locked on a single measuring range. The monitor has five digital registers to display status flags. Three of the registers are necessary to identify the current measuring range, a single register is for calibration and/or maintenance, and one register is used to record error signals. The three measuring range registers will be discussed further in Section 5.3.2, which explains the data preparation. [Table 4.2](#) contains a summary of the important system parameters that were in effect during the field study.

CHAPTER 5

CALIBRATION TEST METHODOGY

The correlation test or calibration procedure required collecting simultaneous CEMS and reference method measurements under a variety of incinerator operating conditions. This section provides an overview to the procedures that were used to calibrate the PM CEMS. The EPA guidance documents Performance Specification 11 (PS11) and Procedure 2 (P2) are currently available only in draft form (11-3-98). Eventually after EPA has finalizes the certification procedures for PM CEMS, both documents will appear in the CFR 40 Part 60, Appendix B and F, respectively. The reference Method 5i (M5i) can now be found in the July 1, 2000 CFR 40 Part 60, Appendix A – Test Methods.

5.1 Method 5i Stack Sampling Procedure

5.1.1 Sampling Location: The measurement of PM emissions in the stack utilized the procedures in M5i. The measurements were conducted from the upper platform on the stack using two sampling ports situated 90° apart. The floor grating of the upper sampling platform is located about 51 feet above ground level. The sampling ports are 4-inches in diameter, and are located 5 feet above the floor level of the upper platform. The ports had been installed specifically for performing compliance testing. The stack sampling location at the upper platform is more that 8-duct diameters downstream and 2-duct diameters upstream of the closest disturbance. Thus the location met the requirements for the minimum number of 12 traverse points. The facility had conducted velocity profile measurements of gas flow in the stack at the upper platform level, and

this data characterized the flow pattern in the stack as a relatively flat velocity profile. During the PM CEMS calibration, the port lengths and actual stack dimensions were confirmed on-site with the appropriate adjustments to traverse point locations according to the procedures in reference Method 1. The M5i measurements were made using duplicate trains simultaneously, and each M5i train was operated independently through a separate port. General schematics of the incinerator stack and sampling port locations are shown in [Figures 5.1](#) and [5.2](#).

5.1.2 Sampling Protocol: A schematic of the M5i sampling train and special filter holder assembly is shown in [Figure 5.3](#). A stainless steel sheathed thermocouple is used to measure stack temperature, while a stainless steel pitot-tube and an incline manometer are used to determine stack gas velocity. A flue gas sample is withdrawn isokinetically through a heated glass fiber filter from the stack during calibration tests. The filter collects any solid PM contained in the gas sample. The filter holder apparatus for M5i, mentioned previously in Section 2.3.1, is different from the standard M5 assembly. The M5i holder is fitted for a 47 mm filter. To minimize handling of the filter, the complete glass holder assembly including the filter is desiccated and weighed before and after sample collection.

During a sampling run, the water vapor in the gas sample passes through the impingers, downstream of the filter holder, where it is condensed or adsorbed and collected. The volumes of water condensed in the impingers and adsorbed on the silica gel are used to calculate the moisture content of the flue gas. After desiccating the filter and the associated probe rinse and weighing the results on an analytical balance, the mass of the particulate was determined. Stack gas samples were collected into Tedlar bags

from the back of each sample train for the duration of the run. Analysis was performed using an Orsat gas analyzer to determine carbon dioxide and oxygen content. The dry molecular weight of the stack gas was calculated using the measured gas from the analyzer, assuming the remainder of the stack gas composition was nitrogen. Dry gas meter readings during the test are used to determine the total dry gas volume sampled. Dividing the mass of the PM collected from the filter and probe rinse by the volume of gas sample drawn through the line provides the value for mass concentration.

Usually the M5i test is structured to be a nominal 60-minute test, excluding the time required for port changes midway into the run, and this was the procedure followed in the PM CEMS field demonstration. However, stack sampling was also conducted while burning only natural gas in the incinerator to produce very low PM emissions. Accordingly to improve the accuracy of detecting the PM weight gain on the filter paper during the incineration of natural gas only, these runs were extended to 120-minute tests, again excluding time required for port changes.

5.2 Particulate Monitoring Systems

5.2.1 Installation Locations: The floor grating of the lower sampling platform was located about 30 feet above ground level. Nevertheless, the sampling ports on the lower platform were only about 5 duct diameters downstream of the fan inlet duct. However, the facility had also taken velocity traverse data from these ports at the lower sampling platform, and profile data from these tests met the criteria in reference Method 1, demonstrating the absence of cyclonic flow and the acceptability of PM measurements at the location. The Durag and ESA monitors were installed on the lower sampling platform. It was necessary however that the Sigrist monitor be installed on an accessible

platform directly adjacent to the lower platform because the footprint of this monitor was appreciably greater than the available space on the lower platform.

The CEMS sampling probes were installed in the ports surrounding the stack. Each sampling port is 6-inches in diameter and was situated in the same plane. Thus, no CEMS measured downstream of another CEMS. Only the Sigrist monitor however had an inlet and outlet port connection. The two beta-gauge monitors did not return the gas sample to the stack. The placement of the probes was at a sufficient distance (approximately 20 feet) downstream from the manual M5i sampling location to minimize flow disturbances. As a further precaution, the PM CEMS nozzles were also positioned in the flatter velocity profile region of the stack, which was earlier discovered while verifying the absence of cyclonic flow at the lower platform level. The sampling probe placement for each CEMS around the stack is shown in [Figure 5.4](#).

5.2.2 Process Data: The entire combustion process and off-gas cleaning system was monitored with a process computer. The facility has flue gas monitoring systems for O₂, CO, CO₂, stack gas temperature, saturation gas temperature, and gas flow rate. [Table 3.2](#) in Section 3.3 is a list of the incinerator monitoring data that were collected in order to interpret process operations during the PM CEMS field demonstration. The operational parameters were automatically recorded every 15- seconds by the incinerator Supervisory Control and Data Acquisition System (SCDAS). TSCA personnel also maintained a logbook documenting incinerator operations.

5.3 Data Collection and Analysis

5.3.1 Reference Method 5i: Airtech Environmental Services (AES) of Bensenville, Illinois conducted the reference method measurements on the upper platform of the stack

in accordance with the procedures specified by the TSCA facility Site-Specific Quality Assurance Test Plan (SSQATP) and in accordance with EPA draft M5i procedures . Twelve single M5i tests were made over the course of 3 days (December 15 through December 17, 1999) and are referred to as Phase 1 data. Twelve paired M5i tests were conducted again over the course of 3 days (March 24 through March 26, 2000) and are referred to as the Phase 2 data. Finally, 20 paired M5i tests were made over the course of five days (October 19 through October 22 and October 24, 2000). These tests are called Phase 3 data. The M5i run identification scheme adopted by AES was to use consecutive numbers preceded by the letter R. For example, the first M5i run of Phase 2 is called run R13.

According to PS11, the M5i data must be converted into the same units of concentration that represent the reporting conditions of the CEMS. Thus as part of the AES final report, the PM concentration for each M5i test was also reported in the units of the measuring conditions of each CEMS. The following general equation was used to convert the dry-standard M5i runs at 7% oxygen into the appropriate reporting conditions of the PM CEMS:

$$C_{\text{CEMS}} = C_{\text{mg/dscm @ 7\% O}_2} \cdot \left(\frac{T_{\text{STD}}}{T_{\text{CEMS}}} \right) \cdot \left(\frac{P_{\text{CEMS}}}{P_{\text{STD}}} \right) \cdot (1 - B_{\text{WS}}) \cdot \left(\frac{20.9 - \% \text{O}_2}{20.9 - 7} \right) \quad (5.1)$$

where:

C_{CEMS} = concentration at reporting conditions of the CEMS (mg/acm)

$C_{\text{mg/dscm @ 7\% O}_2}$ = standard concentration reported by M5i test

T = absolute temperature

P = absolute pressure

B_{WS} = moisture fraction by volume, and

%O₂ = percent oxygen in the dry flue gas.

The subscripted letters T_{STD} and P_{STD} represent the standard conditions of temperature at 20 °C and pressure at 1013 mbar. The subscripted letters T_{CEMS} and P_{CEMS} represent the reporting conditions of temperature and pressure for the monitor, respectively. The following equations summarize the variables that are required to convert the M5i particulate result into the appropriate reporting conditions of each CEMS.

Since the Durag instrument already expressed concentration on a dry basis, at 20 °C and 1013 mbar, it only required the correction for percent oxygen.

For the Durag:

$$C_{\text{DURAG(mg/dscm)}} = C_{\text{(mg/dscm@7\%O)}} \cdot \left(\frac{20.9 - \%O_2}{20.9 - 7} \right) \quad (5.1a)$$

The ESA and Sigrist instruments require temperature, moisture, and percent oxygen corrections, although reporting conditions for temperature are different for both monitors.

For the ESA:

$$C_{\text{ESA(mg/Nm}^3\text{)}} = C_{\text{(mg/dscm@7\%O}_2\text{)}} \cdot \left(\frac{273 + 20}{273 + 0} \right) \cdot (1 - B_{\text{WS}}) \cdot \left(\frac{20.9 - \%O_2}{20.9 - 7} \right) \quad (5.1b)$$

For the Sigrist:

$$C_{\text{Sigrist(mg/m}^3 \text{ PLA)}} = C_{\text{(mg/dscm@7\%O}_2\text{)}} \cdot \left(\frac{273 + 20}{273 + 160} \right) \cdot (1 - B_{\text{WS}}) \cdot \left(\frac{20.9 - \%O_2}{20.9 - 7} \right) \quad (5.1c)$$

where B_{WS} is the moisture content of the flue gas and $\%O_2$ is the value of the percent oxygen in the dry flue gas, as determined from the M5i analysis for each run.

5.3.2 CEMS Continuous Raw Data: The SCDAS was programmed to select and record the instantaneous signals from the monitors at 15-second intervals. Typically the output from the PM analyzer is expressed in milliamps, which is then used as the preferred data, first by averaging the collection of 15-second milliamp signals corresponding with the M5i sampling period and then correlating the values according to PS11. However, the signal generation and sample measurement characteristics of the batch-sampling monitors (i.e., the ESA and Durag monitors) precluded the simple averaging of the 15-second signals recorded from the SCDAS. On the other hand, when the measuring range of the monitor is not constant, as in the case of the auto-range switching utility of the Sigrist instrument, this required that the 4-20 milliamp signal be converted to a common linear scale for the purpose of generating the calibration curve.

Throughout the testing period, certain inconsistencies were noticed between the direct output signals from the ESA monitor to the SCDAS and the concentration values represented on the digital display screen of the monitor. The measuring range of the ESA monitor was also exceeded once during the first day of testing. As a result of these

idiosyncrasies in the data collection, the raw signals from the CEMS required some initial preparation before the PS11 regression analysis could be performed. The following paragraphs will describe in detail the collection and treatment of the CEMS raw data.

The measuring range for the ESA monitor at the beginning of the M5i tests was fixed at 0 - 70 mg/Nm³. On the first day of testing however, the maximum range on the monitor was reached briefly during one of the M5i runs; consequently the measuring range on the ESA monitor was increased to 100 mg/Nm³ for the duration of the testing period. As in the case of the Sigrist unit, but for different reasons (i.e. because of inconsistencies transmitting the signal between monitor and SCADS), the direct milliamp output signal of the ESA monitor was not used to create the calibration curve.

The ESA monitor is a self-contained unit, and the internal memory has a total storage capacity of 2,800 measurements. For example using a 10-minute measurement cycle, the monitor will allow 20 days of measurements to be retained and retrieved. For that reason, the concentration values stored in the monitor memory were used to generate the calibration curve for the monitor. There are drawbacks nevertheless to using the ROM of the monitor for storing the emission measurements: (1) the values are not retained as milliamp responses, (i.e. the response signals are displayed at the units of the measuring conditions of the monitor, mg/Nm³); and (2) the PM measurements and time periods are not readily transferable electronically and must be physically scrolled, copied with pencil and paper, and hand typed into a computer database for analysis.

The ranges of operation for each monitor during the M5i testing period and the linear equations used to convert the milliamp signal to concentration are shown in [Table 5.1](#). In the interest of completeness, all the equations that might be necessary to convert

the different CEMS signals into units of concentration are represented in the [Table 5.1](#). Since the Durag monitor remained at the same range setting throughout the testing period, the milliamp signal of this monitor did not require conversion for the correlation analysis. On the other hand to maintain uniformity among the CEMS for the inter-instruments comparisons between the three CEMS, the signals of the monitors were converted into consistent units of concentration. The low-range PLA equations were in effect for the Sigrist monitor during the Phase 2 and 3 testing periods, and the high-range equations were in effect during Phase 1.

It was not possible to physically coordinate the start/stop time periods of the CEMS with the M5i runs, although this was recommended by PS-11. The present study was simultaneously evaluating three different CEMS, two of which were batch samplers on different cycles, and neither of which were designed to provide status signals that indicate the beginning or the end of the measuring cycle and/or the actual sampling period. In their present configurations, the beta-gauge monitors produced an emission signal on the order of every 12 minutes though the actual sampling or flue gas extraction period occurred in fact during the middle of the measuring cycle. Approximately 2.5 minutes are spent at the beginning of the measuring cycle to position the filter tape and take a zero measurement, and 2.5 minutes are spent at the end of the cycle to analyze the sample and move the filter tape into a fresh position. Since the monitor reports the sample analysis at the end of the measuring cycle, output and sampling time are not synchronized with respect to the true time.

To preserve the ESA and Durag responses that correspond in time with the sampling period of the M5i run and to reflect the time-out for M5i port changes, the

signals were converted into a time-weighted average. In general, the time-weighted average for PM concentration C_{WgtAve} is defined as:

$$C_{\text{WgtAve}} = \frac{\sum C_i t_i}{\sum t_i} \quad (5.2)$$

where C_i is the concentration for the beta-gauge sampling increment, and t_i is the time of sampling that corresponds to the time of the M5i test for the concentration C_i . Hence, the sum of all weighted concentrations divided by the total sampling period of the monitor during the M5i run establishes the 1-hour beta-gauge response for the PS-11 correlation test.

To further clarify the previous statements, a schematic of a beta-gauge output signal versus time is shown in [Figure 5.5](#). Concentration is represented as a step-function. Time is measured along the x-axis, except that time at zero minutes is arbitrary. In this example for simplicity, the measuring cycle for the monitor is 10 minutes and the sampling period is 5 minutes. The M5i run started inside of a measuring cycle, midway into a sampling period. The sampling interval is represented as the symbol t_1 , which in this case is only a fraction of the 5-minute sampling period. The concentration represented as C_o , on the other hand belongs to the previous measuring cycle, although it occurs spatially in an analogous position on the graph as the appearance of the time interval. Another fractional sampling period occurs at t_4 during the probe port change (i.e. where time t_4 is also not equal to 5 minutes, the maximum value of the sampling period). Thus, the 1-hour average concentration for the monitor is calculated as:

$$C_{\text{WgtAve}} = \frac{C_1 t_1 + C_2 t_2 + C_3 t_3 + C_4 t_4 + C_5 t_5 + C_6 t_6 + C_7 t_7}{t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7} \quad (5.3)$$

The Sigrist 15-second milliamp signals from the SCDAS as mentioned earlier were changed into (mg/m³ PLA) using the equations in [Table 5.1](#). The PLA data were then averaged to determine the average concentration, which occurred during the actual M5i test (i.e., the two 30 minute periods during which each traverse was conducted). converted into one-hour averages to correspond with the start and stop time periods of each M5i test. All the Sigrist data were adjusted to reflect the time break for M5i port changes.

5.3.3 Inter-instrument Comparisons: The final section of the report will examine how well the CEMS tracked against each other during the M5i testing period. A comparison will be made between the two beta-gauge monitors individually and then for each beta-gauge monitor with the light-scattering monitor. These inter-instrument comparisons are:

- Durag versus ESA (beta-gauge vs. beta-gauge),
- Durag versus Sigrist (beta-gauge vs. light-scattering), and
- ESA versus Sigrist (beta-gauge vs. light-scattering).

The product-moment correlation will be used to determine the strength of each comparison. The R-squared value can range from one (1) for a perfect association or tracking between the CEMS to a zero (0) for no association or tracking between the CEMS. Mathematically, the product-moment correlation analysis is almost identical to the regression correlation analysis in PS11, but the r-value described in PS11 is slightly

more robust than the R-squared value that will be use for these inter-instrument comparisons.

Note that the primary difference between general correlation analysis and regression correlation analysis is conceptual rather than procedural. The statistics is rightly called a correlation when the focus is whether or not two measured variables co-vary or vary together (e.g., in the comparison between two CEMS). Where as in PS-11, the main concern of the regression (correlation) is to describe the dependence of the Y variable (M5i measurement) on the independent X variable (CEMS response), or the strength of the relationship between M5i/CEMS responses that will be ultimately used to establish the calibration curve.

The three CEMS, as currently configured, express concentration at the same pressure (i.e., 1013 mbar) and the same oxygen content as in the flue gas but at different levels of temperature and moisture content. A convenient property of any correlation analysis is that the magnitude of (r) or (R^2) is unaffected by this disparity of units between the two data sets. Nevertheless, it is desirable to present the correlation between the CEMS in consistent units. Since it was necessary that the ESA be configured to report concentration in mg/Nm^3 (i.e., temperature at 0 °C and moisture content at the condition of the stack), it was also decided to convert the Durag and Sigrist measurements to the state of the ESA measurements. The general equation that is essential to make this conversion into equivalent units of concentration was shown in Section 5.3.

The Durag monitor required a correction for temperature (i.e. $T_{\text{Durag}}/T_{\text{ESA}} = (273 + 20)/(273 + 0) = 1.07$) and a correction to the stack moisture condition. On the other hand,

the Durag also reported concentration in milliamps. Thus, combining the Durag equation in [Table 5.1](#), which is required to convert milliamps into concentration, with the gas equation (5.1) in Section 5.3, the Durag response in concentration at the conditions of the ESA becomes:

$$C_{\text{Durag mg/Nm}^3} = [(C_{\text{Durag mA}} \cdot 6.25) - 25] \cdot [1.07 \cdot (1 - B_{\text{WS}})] \quad (5.4)$$

where $C_{\text{Durag mA}}$ is the Durag raw milliamp signal from the SCDAS, and B_{WS} is the average moisture fraction of the flue gas, in this situation, the average moisture concentration, as measured by Method 4 during the M5i testing, will be used.

The Sigrist concentration was already expressed in concentration units mg/m^3 PLA because it was allowed to auto-range, and it only required the correction for temperature (i.e., $T_{\text{Sigrist}}/T_{\text{ESA}} = (273 + 160)/(273 + 0) = 1.59$). Thus, using the gas equation (5.1) only for temperature, the Sigrist response in concentration at the conditions of the ESA becomes:

$$C_{\text{Sigrist mg/Nm}^3 \text{ PLA}} = (C_{\text{Sigrist mg/m}^3 \text{ PLA}}) \cdot 1.59 \quad (5.5)$$

where $C_{\text{Sigrist mg/m}^3 \text{ PLA}}$ is the concentration of the Sigrist that has already been converted from the raw milliamp signal collected by SCDAS into concentration mg/m^3 PLA.

All data conversions for the inter-instrument comparisons were conducted using the 15-second records from the data logger, including the responses for ESA monitor.

Remember only the hand-copied measurements from the ESA monitor RAM will be used to develop the calibration curves for the ESA. Block 1-hour averages were calculated for the entire five days during the Phase 3 testing period (October 19 through October 22, and October 24) for each monitor while the incinerator was operating. The 1-hour averages were also adjusted to correct for the lag time in responses for the Durag and ESA monitors. The reason for choosing 1-hour averaging times to compare the monitors was because it helps to prevent short-term spikes measured by one monitor, but not by the other monitor (due to shifts between the measurements times) from affecting the correlations. This is especially important for the batch samplers that only analyze the PM concentration in the flue gas approximately half of the time during the measuring cycle.

CHAPTER 6

RESULTS/DISCUSSION

Performance Specification 11 (PS11) is unique relative to the calibration of other types of CEMS because it is based on the technique of correlating monitor responses to emissions obtained by a reference method, rather than by calibrating the instrument with certifiable commercial standards. The essential component of this technique is that M5i measurements must be performed over three different levels of PM concentration (i.e., low, medium, and high) so that the full range of emissions from the source are entirely represented by the calibration curve. However, there is a certain degree of uncertainty associated with the approach of varying waste types and feed rates to provide adequate emission ranges for the correlation test. At least a 60-day shakedown period is recommended in PS11, in which the monitor is observed over routine process conditions for personnel to become familiar with the operation of the monitor and to establish relationships between process conditions and PM emissions before the actual correlation test is conducted.

In the present study, an abbreviated pre-correlation test was conducted after the shakedown effort was completed to allow the test team to gain additional experience at the facility, identify problems associated with any manual testing issues, and expose any other issues associated with managing the final correlation tests. The pre-correlation testing period was called Phase 1. Two additional rounds of correlation tests were also conducted and are identified correspondingly as Phase 2 and Phase 3. On the other hand,

the results from the Phase 1 and Phase 2 correlation tests will not be discussed with great detail in the present report because the broad range of emissions were not obtained and the minimum number of 15 valid M5i tests were not performed; both are requirements of PS11. Before going into a description of the results, it is necessary to further clarify the quality assurance criteria of EPA draft Procedure 2.

6.1 Quality Assurance Criteria of Procedure 2

The relative standard deviation (RSD) between paired runs is used to calculate the precision of the M5i data. Percent RSD is calculated according to the following formula:

$$\text{RSD}\% = \frac{|C_1 - C_2|}{(C_1 + C_2)} \cdot 100 \quad (6.1)$$

where C_1 and C_2 are the PM concentration values determined from Method 5i train-1 and train-2, respectively. In view of this, the quality assurance requirements for PM CEMS appearing in Procedure 2 asserts that:

"A minimum precision criteria for Reference Method PM data is that RSD (as defined in the above equation) for any data pair must be less than 10% as long as the mean PM concentration is greater than 10 mg/dscm. If the mean PM concentration is less than 10 mg/dscm, higher RSD values are acceptable. At mean PM concentration of 1 mg/dscm acceptable RSD for paired trains is 25%. Between 1 and 10 mg/dscm, acceptable RSD criteria must be linearly scaled from 25% to 10%. Pairs of manual method data exceeding these RSD criteria must be eliminated from the data set used to develop a PM CEMS correlation or to assess RCA."

Similar statements have appeared in the final rule "NESHAPS: Final Standards for Hazardous Air Pollutants for Hazardous Waste Combustors" (Federal Register, September 1999), in which EPA specifically addressed the RSD criteria for mean PM concentration below 1 mg/dscm. Since there was still confusion by stakeholders over interpretation of the test method specification and procedures in the final rule, EPA added the following remark to the above citation (Federal Register, July 2000):

"If the mean PM concentration is less than 1 mg/dscm, RSD does not apply and the mean result is acceptable."

Although this resolves the issue of the precision criteria for average PM concentrations of less than 1 mg/dscm, it was not clear whether negative mean PM concentrations are acceptable. It was also not entirely clear from the above citations, how one should handle mean PM concentrations that are equal to 10 mg/dscm. As a consequence of these concerns, it was felt that two additional guidelines were needed and were applied during the analysis of the results: (1) mean PM concentrations less than zero do not apply and will be rejected from the data set (i.e. negative mean PM concentrations are not applicable, N/A), and (2) at mean PM concentration equal to 10 mg/dscm, the acceptable RSD for paired trains is 10%. These two quality assurance criteria were also integrated into the data analysis, and a standardized quantification procedure for the acceptance of paired M5i data is put forward in the ensuing paragraphs.

6.1.1 Standardization of the Linear Portion of RSD: At the outset, a linear equation was developed to express the graduated RSD precision criteria between 1 and 10 mg/dscm. The x-y coordinates of the two boundary points that lie on the straight line are (10, 10)

and (1, 25). The slope (m) of the line is equal to the rise divided by the run $((10 - 25)/(10 - 1)) = -15/9$. Substituting (m) into the linear equation of the form $y = mx + b$, and evaluating the y-intercept (b) at one of the coordinate points (i.e., $x = 1$ and $y = 25$) conveys $b = (25 - (-15/9)) = 240/9$. Finally, the results are combined into a single expression, such that the percent acceptable relative standard deviation (ARSD) is defined as:

$$\text{ARSD}\% = \text{Round}\{(240/9) - (C_{\text{AVE}} \cdot (15/9))\} \quad (6.2)$$

where C_{AVE} is the average value of the paired trains between 1 and 10 mg/dscm. Round is a mathematical function to remind the user that appropriate significant figures are required relative to the C_{AVE} value because the slope and y-intercept are actually irrational numbers.

Finally, the percent minimum precision criterion (MPC) can be defined as:

$$\text{MPC}\% = \begin{pmatrix} \text{N/A} & \text{if } C_{\text{AVE}} < 0 \\ \text{No Limit} & \text{if } 0 \leq C_{\text{AVE}} < 1 \text{ mg/dscm} \\ 25\% & \text{if } C_{\text{AVE}} = 1 \text{ mg/dscm} \\ \text{ARSD}\% & \text{if } 1 \text{ mg/dscm} < C_{\text{AVE}} < 10 \text{ mg/dscm} \\ 10\% & \text{if } C_{\text{AVE}} \geq 10 \text{ mg/dscm} \end{pmatrix} \quad (6.3)$$

Accordingly from the above discussion, if the RSD% is greater than the MPC% for a data pair, then the manual M5i run is not acceptable, and the pair must be eliminated from the data set. For example, if C_{AVE} falls between 0 and 1 mg/dscm, the MPC% has no limit,

and all C_{AVE} values between 0 and 1 mg/dscm (including zero concentration) are acceptable.

6.1.2 Slope Criterion: The reference method data must also meet a second quality assurance requirement, which is used to identify the systematic errors. This condition fundamentally requires that paired M5i data passing the precision requirements discussed above be cross-plotted on an x-y coordinate graph. Linear regression analysis is then performed, and the slope of the best-fit line is determined. As a minimum condition according to Section 10.1.3 (Procedure 2), the slope calculated in the regression analysis must fall between 0.93 and 1.07. Defined as a double inequality, the minimum condition can be written as:

$$0.93 < m_{M5i} < 1.07 \quad (6.4)$$

where m_{M5i} is the best-fit slope of a linear equation with a floating y-intercept. The above test is referred to as the slope requirement (SR) in this study. For RSD calculations and the SR, the units of measurement may be arbitrary, as long as identical units (e.g. mg/dscm or mg/acm) are used consistently. In this report for the P2 analysis, all M5i particulate matter concentrations were standardized to 20 °C, 1013 mbar, dry basis (mg/dscm), and 7% oxygen.

6.2 Pre-testing Activity

6.2.1 Phase 1 Correlation Test: During December 15 through December 17, 1999, a series of 12 preliminary single-train M5i tests were conducted. Since this was an abbreviated pretest to simulate the actual correlation testing to be done later in the year,

the M5i test team performed only single-train sampling runs rather than the dual train sampling as recommended by PS11. Natural gas (only), a combination of solid wastes (containing discarded personal protection clothing, adsorbent material, and sweeping compounds) and an aqueous waste (containing waste treatment water, flammable solvents, and nitric acid) were incinerated for the correlation test.

The range of M5i data was 16.0 to 31.8 mg/dscm when corrected to 7% oxygen, which is approximately 47% to 94% of the MACT standard (34 mg/dscm @ 7% O₂). No attempt was made to exclude M5i outliers because only single-train runs were performed. As mentioned previously, the actual data is not included in this report, nevertheless the following observations are provided based on the results of the Phase 1 test. (1) During most of the pre-testing period the Durag behaved erratically. That is, throughout the M5i sampling runs, the monitor operated in error mode, and the output responses of the Durag were assumed invalid. (2) Prior to the incinerator shutdown in September 1999, the ESA had also not produced reliable data. Consequently, the monitor had been removed and returned to the manufacturer in France for maintenance, and it was not available for the Phase 1 test. (3) During the shakedown period a few minor difficulties were encountered with the Sigrist, but for the most part, the monitor performed flawlessly. However, a valid calibration relationship could not be established between M5i measurements and Sigrist responses (i.e., essentially the correlation coefficient r-value was approximately zero). This was primarily believed to be due to the inability to mix and vary the waste feed rates and to achieve the broad range of PM emissions.

6.2.1 Phase 2 Correlation Test: The second correlation test was conducted during the period of March 24 to March 26, 2000. A total of 12 paired-train M5i tests were

performed during which natural gas (only) and solid wastes (i.e., various solids and contaminated soil) were incinerated. The results for the RSD test are shown in [Table 6.1](#). The range for average PM concentrations was -1.05 to 14.8 mg/dscm at 7 % oxygen. The highest emission recorded during this correlation test was slightly less than 44% of the emission standard. However, only solid-type wastes were treated during this 3-day period. Liquid organic wastes were also scheduled for treatment in order to generate the higher PM emission levels needed for the correlation test, but the waste characterization data for the organic liquids were not available from the analytical laboratory at the time of the M5i testing, and the liquid waste streams could not be incinerated. Of the 12-paired M5i runs conducted during Phase 2, only seven runs passed the RSD criteria. Four M5i tests were rejected because they were statistical outliers (i.e., the RSD% was greater than the MPC% for the four out of the five test that failed). Average run R24 was negative because the magnitude of train-1 was negative and greater than the magnitude of the positive train-2. Thus, this negative average run was also rejected. Note: the reference method testing team used a chronological numbering sequence for the M5i sampling runs that included all three phases of correlation tests; the twelve and last M5i run conducted during Phase 2 was numbered R24.

Burning only natural gas was expected to produce the lowest PM emission with the intention of meeting the requirement of Level 1 in the testing protocol. Nevertheless, it is occasionally common for a slightly negative weight to occur during situations of very low mass gain on filter paper that is measured in a highly sensitive analytical balance. The modified filter holder assembly of M5i was developed to determine low-level PM and reduce the extent of direct handling of the filter paper and sample. Yet once the

filters are placed in the filter holder, the filters are never handled directly. A process disruption occurred during run R24, but this is unlikely to be the cause of the extremely high negative weight obtained from sample train-1. The source of the negative weight problems is unanswered.

The best-fit linear curve for the Phase 2 data passing the RSD criteria (i.e., train-1 versus train-2) is shown in [Figure 6.1](#). The R-squared value for the best-fit line was 0.9768; the slope of the line was 0.954. Thereby, these seven runs also met the slope requirement (i.e., $0.93 < 0.954 < 1.07$). Excluding the criteria for the minimum number of 15 paired M5i runs, which is a requirement of the correlation relation test, it was still not possible to meet the three level (i.e., low, medium, and high) conditions of PS-11. Of the seven-paired test, which did meet the RSD requirements, it was found that (7/7) or 100% met the Level 1 (low) requirement. One test (R22) was in the Level 2 (medium) category (i.e. 1/7 or 14%). Therefore, the Level 2 requirement was not met. No tests fell in Level 3 (high), thus the Level 3 requirement was also not met. Moreover, the full range of PM emissions from zero to no less than the emission standard was also not achieved. In spite of these predicaments, the correlation was still conducted at the level of the PM concentrations generated by the solid waste availability at the time of the test.

The Durag behaved erratically during the Phase 2 testing, as it had done for the duration of the Phase 1 period. Again the output responses of this monitor were assumed to be erroneous, and no attempt was made to develop a calibration curve from the data. The ESA and Sigrist however, did not encounter any operational problems throughout the Phase 2 correlation testing (i.e., there was 100% data available from these monitors). Thus, the development of the calibration curve for the ESA and Sigrist proceeded. The

procedure included calculation of the correlation coefficient, confidence interval and tolerance interval percents for the M5i/CEMS data sets and comparison of the results to the PS11 criteria.

The actual data from the Phase 2 calibration tests will not be presented here, but the following statements are offered to summarize the results of the PS11 linear regression analysis. (1) The correlation r-values for the ESA and Sigrist were 0.959 and 0.911, respectively; (2) The confidence interval and tolerance interval percent measured at the emission limit were 26.5% and 12.4%, respectively for the ESA, and 40.2% and 18.0%, respectively for the Sigrist. Despite the fact that the linear correlation r-values for the ESA and Sigrist were greater than 0.85, and thus both monitors passed the correlation coefficient test, neither monitor came very close to passing the confidence interval percent, and yet the monitors passed the tolerance interval percent test. The peculiar nature of this fact suggests that the confidence intervals are more sensitive to evaluation beyond the range of the sample data, and it demonstrates the erroneous consequence of making inferences beyond the observed data. Since no data existed to support the validity of the linear best-fit curve beyond the 125% limit, and the 125% limit fell substantially below the emission limit in the Phase 2 tests, it is questionable whether any analysis performed beyond the sample data can be considered realistic, and any conclusions reached about the confidence and tolerance criteria are immaterial in this context.

6.3 Final-testing Activity (M5i Phase 3 Data)

The final round of correlating testing was conducted during the period of October 19 through October 22 and October 24, 2000. A summary of the Airtech (AES)

laboratory report on the M5i testing for Phase 3 is included in Appendix C. Primary and secondary liquid waste, aqueous waste, and two types of solid waste were available for the Phase 3 test, and a total of 20-paired M5i tests were performed. [Table 6.2](#) is a summary of the waste feed categories, the percent ash content of the waste, and the feed-rate ranges that were in effect during Phase 3. The material ash content is sometimes utilized to predict PM emissions factors because combustion processes in the incinerator do not destroy the ash. Since the aqueous waste stream contained the highest ash content relative to the primary and secondary liquid waste streams and the solid wastes, it was thought that by manipulating the aqueous waste feed rate in conjunction with other waste types, the full range of PM emissions could be achieved during the final round of tests.

The results of the M5i tests and the evaluation of the RSD criteria are shown in [Table 6.4](#). This time, only a single M5i test failed the RSD criteria (i.e., run R45). The total sampling time for the 20 tests were 1,322 minutes excluding time-out for probe changes. The range for average PM concentrations was 1.81 to 78.3 mg/dscm at 7% oxygen. The highest average PM concentration measured was approximately 130% above the emission standard. Three times during the testing period, one of the sampling train operators was not able to maintain isokinetic sampling to within 10% of the true isokinetic sampling rate (see runs R27, R28, and R30). The percent isokinetics for the trains that failed were 89.1%, 85.2% and 85.3%, respectively. Percent isokinetics between 90% and 110% are considered acceptable according to reference M5i. Fortunately, it is not always necessary to have isokinetic sampling for small particles (i.e., under about 3 μm diameter) because their small mass minimizes the inertial effects for representative capture (Lodge, 1988). Supporting the small particle size effect,

analysis had been performed on three of nine separate flue gas samples collected during Phase 3. Using a scanning electron microscope to determine the particle size distribution, AES found that on average 96% of particles were below 1 μm diameter. Based on these observations, and the fact that the three runs not fully qualifying on the isokinetic condition actually did pass the RSD criteria, it was decided not to remove the runs from the Phase 3 data set.

Linear regression was performed for the 19-paired M5i tests meeting the RSD criteria. The paired data (i.e., train-1 versus train-2) are shown graphically in [Figure 6.3](#). The R-squared value was 0.9891, and the slope of the best-fit trendline was 0.934. Based on the slope requirement (i.e., $0.93 < 0.934 < 1.07$), it was concluded that all 19-paired M5i runs should be retained and used in preparing the calibration curves for the CEMS. It was necessary also to demonstrate that at least 20% of all the valid runs that will be used to generate the calibration curves did indeed fall within the Level 1, 2, and 3 range categories. These measurements of the different levels of PM concentration are shown in [Table 6.3](#). The values 19.6, 39.2, and 58.7 mg/dscm represent 25%, 50%, and 75% of the maximum PM concentration, respectively. Applying the range of paired runs to each level, for example in Level 1, five runs ranging between 1.8 to 22.6 mg/dscm fell within the 0 - 50% interval. Thus, 26.3% of the valid runs fell within Level 1. Continuing this line of reasoning, 52.6% and 21.1% of the remaining valid runs fell within Level 2 and 3, respectively, which demonstrated that at least 20% of the M5i measurements occurred in each distinct percent concentration range.

The oxygen and moisture percent are also required to convert the emission standard into the reporting condition of the CEMS, and when necessary to convert the CEMS concentrations into a consistent set of units for inter-instrument comparisons.

- The average oxygen content from the Method 3 testing conducted during Phase 3 was $10.1 \pm 0.4\%$. The minimum oxygen content was 9.6% and the maximum oxygen content was 10.9%.
- The average moisture content from Method 4 testing conducted during Phase 3 was $47.54 \pm 0.91\%$. The minimum moisture content was 45.74% and the maximum moisture content was 49.07%.

6.4 PM CEMS (Performance Specification 11)

The scope of this section focuses on the results of the correlation test on which a calibration curve was established for each CEMS according to the procedures specified in PS11. Three mathematical approaches (linear, logarithmic, and quadratic) are available for evaluation to determine which presents the best-fit curve for the data. In each approach, the correlation coefficient is calculated, followed by the 95% confidence interval, and the tolerance interval, which predicts the bounds of 75% of the data with 95% confidence.

The results for the Durag, ESA, and Sigrist and the corresponding M5i measurements for Phase 3 are presented in [Table 6.5](#). As explained in Section 5.3, these results were developed from averaging the 15-second CEMS records collected on the data logger for the corresponding M5i sampling times, excluding the times for port changes. Weighted averages were also used for the beta-gauge responses, and their data were offset to correspond with the response times. All CEMS underwent zero and drift

calibration tests prior to each day of testing. The data confirmed that the monitors were producing valid data before testing. Each CEMS also demonstrated 100% for data availability during the testing period. Then again, these two beta-gauge monitors were fundamentally batch-sampling devices that were configured to sample less than 60% of the time (i.e., 7 min/12 min) relative to the time that an entirely continuous monitor would be likely sampling. Summaries of the facility, M5i, and CEMS data are also included in the Appendix D of this report.

6.4.1 Durag-904K Beta Monitor: The average value of oxygen percent from the M5i runs was used to convert the emission standard of 34 mg/dscm at 7% oxygen to the emission standard reported at the conditions of the Durag. From equation 5.1a:

$$C_{\text{DURAG(mg/dscm)}} = 34 \frac{\text{mg}}{\text{dscm}} \cdot \left(\frac{20.9 - 10.1}{20.9 - 7} \right) = 26.42 \frac{\text{mg}}{\text{dscm}} \quad (6.5a)$$

thus, the emission limit for the Durag monitor was 26.4 mg/dscm at stack oxygen, 20 °C, 1013 mbar, and dry air condition. The total sampling time for the monitor during the 20 M5i tests was 765.3 minutes. Thus, the monitor was only sampling 57.9% of the time relative to the M5i testing period (i.e., 765.3 min/1322 min).

The PS11 calibration results for the Durag are presented in [Table 6.6](#). The correlation r-values were 0.964, 0.952, and 0.963, respectively for the linear, logarithmic, and polynomial regression analyses. The confidence and tolerance interval percents evaluated at the emission standard were (in the same order) 6.9% and 23.2% for linear regression, 8.0% and 26.9% for logarithmic regression, and 9.2% and 24.4% for

polynomial regression. As established from the acceptance criteria for PS11 (i.e., correlation coefficient greater than 0.85, confidence interval percent less than 10%, and tolerance interval percent less than 25%), both the linear and polynomial equations best characterized the calibration curve. However, the experimental value of deviation 0.31 (i.e., the observed S-ratio) was found to be less than the F_{1f} value 4.49 (i.e., from statistics tables). Therefore, the Durag responses values must be reported with the linear calibration curve. The spreadsheet calculations showing the important PS11 analysis variables are included in Appendix E.

Figures 6.3, 6.4, and 6.5 are the plots of the Durag responses versus the M5i runs for the linear, logarithmic and polynomial calibration curves, respectively. The boldface dashed line that passes through the data points represents the best-fit curve. The intersection of the horizontal and vertical dashed lines with the best-fit curve is the CEMS response at the emission limit. For example in Figure 6.3, this intersection point is approximately 6.6 mA along the x-axis and 26.4 mg/dscm along the y-axis. The x-axis for the logarithmic curve (see Figure 6.4) was converted to a base-10 scale, so the data and confidence and tolerance intervals could be viewed symmetrically. This conversion makes the logarithmic curve exist as a straight line.

Under PS-11 guidelines, extrapolation of the correlation curve is limited to 125% of the highest measured PM CEMS concentration. Referring again to Table 6.6, the maximum allowable predicted PM concentration for the linear curve was 66.9 mg/dscm (y-axis), which corresponded to about 10.8 mA (x-axis). In the figures, the 125% limit is represented with a box symbol. No data exists to support the validity of the best-fit curve beyond the 125% limit. Note that the 125% limit occurs substantially above the emission

limit for all three-regression conditions. The maximum allowable predicted concentration along the linear curve was almost 2.5 times the emission limit at the condition of the CEMS. Thus, the linear curve will also be able to predict PM emissions beyond the current emission standard.

The slope of the linear curve (b_1) was 9.55 (mg/dscm)/mA and the y-intercept (b_0) was -36.4 mg/dscm. Essentially, a 4 mA signal ought to represent zero concentration, but the linear equation predicts 1.77 mg/dscm at 4 mA. The curves for the upper and lower confidence intervals and tolerance intervals also intersect with the vertical dashed line at the CEMS response for the emission limit. These intersection points when projected back to the y-axis represent the upper and lower boundary values for the confidence and tolerance intervals evaluated at the emission limit. For example in [Figure 6.3](#), the lower and upper confidence limits are 24.6 mg/dscm and 28.2 mg/dscm, respectively, and the lower and upper tolerance limits are 20.3 mg/dscm and 32.6 mg/dscm, likewise in that order.

6.4.2 Environment SA Beta 5M Monitor: The average value of moisture and oxygen percent from the M5i runs, and the reporting temperature of the monitor were used to convert the emission standard of 34 mg/dscm at 7% oxygen to the emission standard reported at the conditions of the ESA. From equation 5.1b:

$$\begin{aligned}
 C_{\text{ESA(mg/Nm}^3\text{)}} &= 34 \frac{\text{mg}}{\text{dscm}} \cdot \left(\frac{273 + 20}{273 + 0} \right) \cdot (1 - 0.4754) \cdot \left(\frac{20.9 - 10.1}{20.9 - 7} \right) \\
 &= 14.87 \frac{\text{mg}}{\text{Nm}^3}
 \end{aligned}
 \tag{6.5b}$$

thus, the emission limit for the ESA monitor was 14.9 mg/Nm³ at stack moisture and oxygen content, 0 °C, and 1013 mbar. The total sampling time for the monitor during the 20 M5i tests was 748.2 minutes. Thus, the monitor was only sampling 56.6% of the time relative to the M5i testing period (i.e., 748.2 min/1322 min).

The PS11 calibration results for the ESA are presented in [Table 6.7](#). The correlation r-values were 0.985, 0.761, and 0.985, respectively for the linear, logarithmic, and polynomial regression analyses. The confidence and tolerance interval percents evaluated at the emission standard were (in the same order) 4.4% and 14.8% for linear regression, 16.8% and 55.9% for logarithmic regression, and 5.4% and 15.4% for polynomial regression. As established from the acceptance criteria for PS11 (i.e., correlation coefficient greater than 0.85, confidence interval percent less than 10%, and tolerance interval percent less than 25%), again both the linear and polynomial equations best characterized the calibration curve. On the other hand, the experimental value of deviation 0.41 (i.e., the observed S-ratio) was found to be less than the F_{1f} value 4.49 (i.e., from statistics tables). Therefore, the ESA responses values must be reported with the linear calibration curve. The spreadsheet calculations showing the important PS11 analysis variables are included in Appendix E.

[Figures 6.6](#), [6.7](#), and [6.8](#) are the plots of the ESA responses versus the M5i runs for the linear, logarithmic and polynomial calibration curves, respectively. The boldface dashed line that passes through the data points represents the best-fit curve. The intersection of the horizontal and vertical dashed lines with the best-fit curve is the CEMS response at the emission limit. For example in [Figure 6.6](#), this intersection point

is approximately 12.3 mg/Nm³ along the x-axis and 14.9 mg/Nm³ along the y-axis. The x-axis for the logarithmic curve (see [Figure 6.7](#)) was converted to a base-10 scale, so the data and confidence and tolerance intervals could be viewed symmetrically. This conversion makes the logarithmic curve appear as a straight line.

Under PS-11 guidelines, extrapolation of the correlation curve is limited to 125% of the highest measured PM CEMS concentration. Referring again to [Table 6.7](#), the maximum allowable predicted PM concentration for the linear curve was 41.6 mg/Nm³ (y-axis), which corresponded to about 36.5 mg/Nm³ (x-axis). In the figures, the 125% limit is represented with a box symbol. No data exists to support the validity of the best-fit curve beyond the 125% limit. Note that the 125% limit occurs substantially above the emission limit for all three-regression conditions. The maximum allowable predicted concentration along the linear curve was slightly greater than 2.75 times the emission limit at the condition of the CEMS. Thus, the linear curve will also be able to predict PM emissions beyond the current emission standard.

The slope of the linear curve (b_1) was 1.105 and the y-intercept (b_0) was 1.276 mg/Nm³. At zero response from the ESA, the linear equation predicted 1.28 mg/Nm³. The curves for the upper and lower confidence intervals and tolerance intervals also intersect with the vertical dashed line at the CEMS response for the emission limit. These intersection points when projected back to the y-axis represent the upper and lower boundary values for the confidence and tolerance intervals evaluated at the emission limit. For example in [Figure 6.6](#), the lower and upper confidence limits are 14.2 mg/Nm³ and 15.5 mg/Nm³ respectively, and the lower and upper tolerance limits are 12.7 mg/Nm³ and 17.1 mg/Nm³, likewise in that order.

6.4.3 Sigrist CTNR Light-scattering Monitor: The average value of moisture and oxygen percent from the M5i runs, and the reporting temperature of the monitor were used to convert the emission standard of 34 mg/dscm at 7% oxygen to the emission standard reported at the conditions of the Sigrist. From equation 5.1c:

$$\begin{aligned}
 C_{\text{Sigrist(mg/m}^3 \text{ PLA)}} &= 34 \frac{\text{mg}}{\text{dscm}} \cdot \left(\frac{273 + 20}{273 + 160} \right) \cdot (1 - 0.4754) \cdot \left(\frac{20.9 - 10.1}{20.9 - 7} \right) \\
 &= 9.379 \frac{\text{mg}}{\text{m}^3} \text{ PLA}
 \end{aligned} \tag{6.5c}$$

thus, the emission limit for the Sigrist monitor was 9.38 mg/m³ PLA at stack moisture and oxygen content, 160 °C, and 1013 mbar. The total sampling time for the monitor during the 20 M5i tests was 1,322 minutes. Thus, the monitor was sampling 100% of the time relative to the M5i testing period (i.e., 1322 min/1322 min).

The PS11 calibration results for the Sigrist are presented in [Table 6.8](#). The correlation r-values were 0.818, 0.908, and 0.895, respectively for the linear, logarithmic, and polynomial regression analyses. The confidence and tolerance interval percents evaluated at the emission standard were (in the same order) 14.8% and 49.5% for linear regression, 10.8% and 36.1% for logarithmic regression, and 13.4% and 39.4% for polynomial regression. As established from the acceptance criteria for PS11 (i.e., correlation coefficient greater than 0.85, confidence interval percent less than 10%, and tolerance interval percent less than 25%), no equation best characterized the calibration curve. Nevertheless, the experimental value of deviation 12.2 (i.e., the observed S-ratio) was found to be greater than the F_{lf} value 4.49 (i.e., from statistics tables). Therefore, the

polynomial regression gave a better fit than the linear equation. However, the logarithmic regression came closest to passing the confidence and tolerance interval criteria. The spreadsheet calculations showing the important PS11 analysis variables are included in Appendix E.

Figures 6.9, 6.10, and 6.11 are the plots of the Sigrist responses versus the M5i runs for the linear, logarithmic and polynomial calibration curves, respectively. The boldface dashed line that passes through the data points represents the best-fit curve. The intersection of the horizontal and vertical dashed lines with the best-fit curve is the CEMS response at the emission limit. For example in Figure 6.10, this intersection point is approximately 0.3243 mg/m³ PLA along the x-axis and 9.38 mg/m³ along the y-axis. The x-axis for the logarithmic curve was converted to a base-10 scale, so the data and confidence and tolerance intervals could be viewed symmetrically, and this conversion makes the logarithmic curve appear as a straight line.

Under PS-11 guidelines, extrapolation of the correlation curve is limited to 125% of the highest measured PM CEMS concentration. Referring again to Table 6.8, the maximum allowable predicted PM concentration for the logarithmic curve was 17.4 mg/m³ (y-axis), which corresponded to about 4.023 mg/m³ PLA (x-axis). In the figures, the 125% limit is represented with a box symbol. No data exists to support the validity of the best-fit curve beyond the 125% limit. Note that the 125% limit occurs significantly above the emission limit for all three-regression conditions. The maximum allowable predicted concentration along the logarithmic curve was about 1.85 times the emission limit at the condition of the CEMS. Thus, the logarithmic curve can predict PM

emissions beyond the current emission standard but recall no regression analysis passed all PS11 criteria.

The slope of the logarithmic curve (b_1) was $3.185 \text{ (mg/m}^3\text{)}/\text{mg/m}^3 \text{ PLA}$ and the y-intercept (b_0) was 12.97 mg/m^3 . A zero CEMS response is undefined on the logarithmic equation, however an x-intercept occurs at approximately $0.0171 \text{ mg/m}^3 \text{ PLA}$, and this point defines the baseline signal from the Sigrist that corresponds to zero concentration. The curves for the upper and lower confidence intervals and tolerance intervals also intersect with the vertical dashed line at the CEMS response for the emission limit. These intersection points when projected back to the y-axis represent the upper and lower boundary values for the confidence and tolerance intervals evaluated at the emission limit. For example in [Figure 6.10](#), the lower and upper confidence limits are 8.37 mg/m^3 and 10.4 mg/m^3 respectively, and the lower and upper tolerance limits are 6.0 mg/m^3 and 12.8 mg/m^3 , likewise in that order.

6.5 Relative Correlation Audit

A RCA is required to evaluate the stability of the monitor in terms of the initial correlation (i.e., to determine whether the calibration curve is still valid over time). It was expected that the Phase 2 tests would successfully produce correlations for the CEMS. The Phase 3 testing period had been reserved for the RCA test. However, this scenario did not occur, and a valid RCA test was not performed before the monitors were removed from the stack at the conclusion of the October 2000 tests. As a response to the RCA deficiency in the present field-testing program, it was decided to go backwards and use the incomplete Phase 2 data as the RCA test. Fully aware that this does not meet the intention or requirements of EPA draft Procedure 2 (P2), at least it could possibly

demonstrate the stability of the Phase 3 calibration curves between March and October 2000.

According to Procedure 2, the RCA measurements are regarded as consistent with the current calibration relation if at least 75% of a minimum number of 12 sets of CEMS/M5i measurements fall within the tolerance interval at $\pm 25\%$ of the emission limit established during the PS11 initial correlation test. Since the Durag did not generate valid data during Phase 2, it cannot take part in the current RCA illustration, but at least seven M5i/CEMS measurements were legitimate for the ESA and Sigrist monitors. Note: this RCA test was not completed in strict accordance with the P2 requirements, especially since 12 M5i/CEMS measurements are required at the three levels of PM concentration for the facility, and only seven measurements were used, which barely represented the Level 1 (low) range. Furthermore, the RCA data were collected in the time period occurring before the calibration curve data were collected; in other words, the audit test preceded the correlation test.

Figure 6.12 is a graph of the ESA Phase 2 data superimposed over the ESA Phase 3 linear calibration curve. Figure 6.13 is a graph of the Sigrist Phase 2 data superimposed over the Sigrist Phase 3 logarithmic calibration curve. In both figures, the Phase 3 data have been removed, but the confidence and tolerance intervals are retained. As is evident from the ESA figure, six out of seven or approximately 85% of the data points fell within the tolerance intervals. In the Sigrist figure, only four out of seven or approximately 60% of the data points fell within the tolerance intervals. Realize however, that the Sigrist Phase 3 logarithmic curve also did not pass the PS11 correlation criteria.

6.6 Inter-instrument Comparisons Between CEMS

To help understand the relationship between the beta-gauge technology and the light-scattering technology, three correlation analyses between the analyzers were conducted to discover how well they were responding to similar conditions in the stack. Precisely five days of 1-hour CEMS measurements or about 120 data points per monitor were correlated. [Figure 6.14](#) shows the Durag versus the ESA correlation for the linear trend line. The product-moment correlation R-squared value was 0.917, indicating a high correlation between the beta-gauge monitors. [Figures 6.15](#) and [6.16](#) show the Durag versus the Sigrist and the ESA versus the Sigrist, respectively. For these correlations the linear and logarithmic trend lines are both shown. The product-moment correlation R-squared values for linear trend lines were close to 0.707 and 0.645, and for the logarithmic trend lines, the R-squared values were 0.819 and 0.876, respectively. . The linear relationships were not very strong between the beta-gauge instruments and the Sigrist instrument. The fact that the logarithmic approach was somewhat better is no surprise since the PS11 regression analysis suggested that a logarithmic fit defined the relationship between Sigrist and the gravimetric M5i.

There is one additional area that can be used to illustrate the performance of the CEMS. Recall that the ionizing wet scrubbers (IWS) are the final air pollution control devices the flue gas enters before exiting the sack. To demonstrate the reliable operation and sensitivity between the monitors, a benefit can be taken from a relationship that exists between the electric field strength across the collecting plates of the IWS and the PM removal efficiency. As will be shown, particulate emissions increase during the flush cycle due to reduced collection efficiency of the IWS.

Remember that two identical IWS were located in series, and both devices operated on a continuous basis. However, alternating every 4 hours, each IWS goes into a water flush cycle to remove the build-up of PM on the plates and other IWS surfaces. During the flush cycle on one of the IWS, the voltage drops to zero, and the plates are flushed with re-circulated rinse water for about 5-minutes. It is possible that emissions might slightly increase during this time period because one IWS is offline, and also some of the captured particles can become re-entrained in the gas stream during the wash cycle.

Figures 6.17 and 6.18 show the PM concentration as measured by the Durag and ESA, and the Sigrist monitors, respectively, versus the waste feed rates and the IWS zero voltage conditions during October 16, 2000. On both graphs, the IWS zero voltage state is represented by large solid rectangles. The left hand y-axis represents the CEMS response; the right hand y-axis represents the waste feed rate and the zero IWS voltage condition. Time is represented along the x-axis. Notice in these figures that each monitor detected the increase in PM every time an IWS went into a wash cycle as represented by the voltage drop to zero and the ensuing increase in the response of the monitors. These spikes are especially evident between 8:00 and 12:00, than they are between 16:00 and 21:00 whereupon the waste feed rates had been increased. The response of the monitors matched the increase in the waste feed rates. Around 18:00 the waste feeds were briefly stopped. This event coincided with the wash cycle of IWS-2, and as reveal, the monitors responded appropriately.

Generally, the overall magnitude of the spike for each monitor should have been smaller for IWS-1, as compared with IWS-2. Since IWS-2 is down-stream of IWS-1, it captures a fraction of the increased particle emissions that escaped IWS-1 during its

cleaning cycle. On the other hand, any particles emitted during the IWS-2 cleaning cycle went directly into the stack and were measured by the CEMS. However, this observable fact was not represented in these two figures, and this was almost certainly related to the fact that the wastes feed rates were not constant during the time period when the IWS went into a wash cycle.

CHAPTER 7

CONCLUSIONS/SUMMARY

The uses of CEMS are increasingly being required by regulations to ensure that the source is meeting its permitted emission rates and for verifying that the mandated reduction of emissions are eventually being achieved. There is a critical need for the real-time quantification of emissions from the stack gas of waste incinerators. However, it is equally important that these CEMS provide accurate and reliable emission information. This study evaluated the results of three commercially available PM CEMS at a hazardous waste incinerator that routinely treats many different types of liquid, aqueous, and solid wastes. The ability to treat these various wastes simultaneously plus the fact that the flue gas of the incinerator was constantly near the saturated moisture condition presented a major challenge for the individual CEMS to establish a single, acceptable correlation relationship.

Three sets of reference method tests were conducted during a 10-month time period. The set of tests called Phase 1 and Phase 2 were not sufficient to achieve a suitable calibration curve according to U.S. EPA draft PS11 and P2 criteria. Phase 1 testing was conducted as a learning experience and was not really expected to produce reliable data; still, the Phase 2 testing was also unsuccessful because it was not possible to generate the full range of emissions necessary to produce the calibration curve at the current emission standard. However, the primary reason for the failure of Phase 2 to meet the EPA criteria cannot be attributed to the operation of the PM CEMS. Rather, it

was not possible for the facility to achieve the range of emissions needed due to the lack of a sufficient variation in the waste characteristics.

The Phase 3 correlation tests did meet the criteria of simultaneous M5i/CEMS measurements over the full range of operations for the facility. The CEMS also operated under reasonable normal facility operations, and there was 100% recovery of data from the three monitors. A total of 19 successful M5i/CEMS tests were used to generate the calibration curves. According to PS11 criteria, the Durag and ESA produced a valid linear calibration curve. For the Sigrist, a logarithmic calibration curve came closest to passing PS11 criteria, though acceptable values for the confidence and tolerance interval percent were not achieved. Therefore, Sigrist did not pass the correlation test requirements of PS11.

Extrapolation of the calibration curve is limited to 125% of the highest measured PM CEMS concentration. The upper and lower confidence intervals and tolerance intervals are depicted over the entire range of the calibration curve. The confidence intervals are always narrower than the tolerance intervals, and both are narrowest at the central region of the sample data, which actually specifies the mean value of the regression curve. As the CEMS values along the x-axis increase further outside the range of the actual data, the confidence and tolerance intervals also spread outwardly. The confidence intervals are evidently more sensitive to increasing values beyond the range of the sample data. It is possible that the confidence intervals could expand and intersect the boundaries of the tolerance intervals. Again, this demonstrates the erroneous result of making inference beyond the observed data.

A series of RCA tests must be performed at 6-month intervals to assure the continued validity over time of the initial calibration curve. In the project site-plan, the Phase 3 time period was reserved for these tests. Since the Phase 2 testing had basically turned out to be unproductive, the Phase 3 testing period that had been reserved for the RCA tests was used to generate the calibration relationships. Nonetheless to provide information on the long-term stability and accuracy of the calibration curves, the seven valid M5i/CEMS data points that had been collected from Phase 2 were used as a pseudo RCA test. About 6-months had intervened between Phase 2 and 3, and different wastes had been treated during each of the time periods. (The Durag monitor could not play a part in this trial because it did not produce reliable data during Phase 2.) From this examination though, it seems that at least the ESA Phase 2 data was consistent with the ESA Phase 3 calibration curve according to relaxed or pseudo RCA criteria. In contrast, the Sigrist Phase 2 data did not appear to be consistent with the Sigrist Phase 3 calibration curve. It should be recalled that one of the disadvantages of light-scattering as a detection principle is the possibility of a non-linear response to changing particle characteristics, like size distribution or refractive index. When very dissimilar wastes are incinerated, it is probable that the output response of a light-scattering monitor cannot be represented by a single calibration curve. Other test programs, where a consistent waste was incinerated have shown that the Sigrist passed the EPA PS11 requirements.

The proper functioning of air dilution/heating systems are vital in sampling moist flue gas to ensure that the dew point of the gas sample is not reached, consequently resulting in condensation before the sample actually passes through the analyzer. It was not possible to know precisely the moisture condition of the gas sample since none of

these monitors measured the dew point of the flue gas as it was analyzed. It is believed that the Durag did not produce reliable data during Phase 1 and 2 because the instrument could not handle the moisture conditions of the stack gas. The dilution-air chiller for the monitor was undersized during the system installation, and numerous malfunctions were also associated with the purge-air cycle trapping condensed water and wetting the filter tape. Typically, the light-scattering instrument by using a photocell design encounters fewer problems with condensation because the gas sample does not come into direct surface contact with the analyzer. Yet, there are no means to determine if water droplets are entrained in the gas sample. On the other hand for the beta-gauge instrument, the gas sample goes through the filter tape, which can undergo wetting if the gas sample is near the dew point and the filter mechanism not is adequately heated. In rating the instruments with respect to the sampling lines and peripherals like the ring pipe insulation, it was felt that the Sigrist had been much better designed than the two beta-gauge instruments. Moreover, the Sigrist had fewer moving part; therefore, it experienced fewer problems and required less maintenance than the beta-gauge monitors during the shakedown and operation periods.

The ESA monitor was considered superior to the Durag monitor during episodes of high particle mass loading of the filter paper. While sampling flue gas, both instruments could detect a vacuum error, but in doing so, the ESA could immediately terminate the measuring cycle and then analyze the sample; where as, the Durag could only generate an error flag to indicate that the sampling cycle value was a suspect measurement. Furthermore, the ESA monitor always maintained isokinetic sampling

conditions, which are the requirements of reference M5i testing. Alternatively, the Durag and Sigrist always analyzed the flue gas above the isokinetic sampling conditions.

Questions have been raised regarding the batch type beta-gauge devices, which have only one sampling head, such that they only measure a fraction of the time (e.g., sampling 5 minutes during each 10-minute cycle). This field study showed that the beta-gauge monitors still could satisfy the PS11 criteria at the TSCA incinerator, in spite of only sampling the flue gas less than about 60% of the time relative to the reference method. At the present, manufacturers of beta-gauge monitors are including a second sampling head to allow the batch samplers to meet the continuous monitoring requirements of the MACT standards. It is uncertain, whether EPA will approve the single sampling headed instruments used in this study, as meeting the requirement of continuous monitoring specified in PS11.

The primary advantage of the beta-gauge technology is that it is insensitive to changes in PM properties. Additionally, both beta-gauge monitors correlated highly between one another based on the comparison of hourly averages. While the beta-gauge samplers were shown to have met the PS11 criteria during the Phase 3 tests, the RCA tests have not yet been conducted to provide information on the long-term stability and accuracy of the initial calibration curve. Based on the tests conducted in this study, the most critical part of the certification procedure for the CEMS was that the correlation test be conducted over the full range of operation for the facility, especially at or near the emission standard. This may require the operators of the source to operate in a way that is exceeding the PM emission limit during the correlation test. Furthermore, the minimum number of 15 M5i paired tests may be insufficient to generate the calibration

curve for PS11. In reality, an average of 50 to 75 M5i tests may be required to be successful, especially in situations where very different types of hazardous and non-hazardous wastes are being incinerated.

The following statements summarize the lessons learned from this field study:

- Careful planning and selection of the appropriate waste feeds and incinerator operating conditions for generating a wide range of PM emissions are crucial to achieve a successful correlation test.
- The beta-gauge instrument that reported emissions on a dry basis was sufficiently challenged by moisture condensation from the saturated flue gas sample prior to the volume measurement. Numerous operational problems were encountered with both beta-gauge instruments, but these difficulties were eventually resolved through vendor intervention. The light-scattering device required only minor maintenance, and it operated trouble-free throughout the field demonstration.
- There were no apparent effects from trace levels of low-level radioactive emissions on the determination of PM concentration by the beta gauge monitors.
- Paired train data at concentrations less than 10 mg/dscm had difficulty meeting the relative standard deviation criteria for precision.
- The beta gauge monitors passed all three minimum specifications for the correlation test criteria.
- The light-scattering device failed two of the three minimum specifications for the correlation test. It may be necessary to generate more than one calibration curve depending on the waste feed type.

REFERENCES

LIST OF REFERENCES

Clap saddle, C and Trenholm, A. "Current Knowledge of Particulate Matter (PM) Continuous Emission Monitoring". Prepared by Midwest Research Institute for EPA Office of Air Quality Planning and Standards. Research Triangle Park, NC. EPA-454/R-00-039. September 8, 2000.

Conner, W.D. and Hodkins, J.R. "Optical Properties and Visual Effects of Smoke-Stack Plumes". Public Health Service/National Center for Air Pollution Control. Cincinnati, OH. NTIS Publication Number PB999AP30. 1967.

Conner, W. D. "Measurement of Opacity and Mass Concentration of Particulate Emissions by Transmissometry". National Environmental Research Center. Research Triangle Park, NC. EPA-650/2-74-128. 1974.

Conner, W.D., Knapp, K.T., and Nader, J.S. "Applicability of Transmissometers to Opacity Measurement of Emissions - Oil-fired Power Plants and Portland Cement Plants". Environmental Sciences Research Lab. Research Triangle Park, NC. EPA 600/2-79-188. 1979.

Conner, W.D. and White, N. "Comparative Study of Plume Opacity Measurement Methods". Environmental Sciences Research Lab. Research Triangle Park, NC. EPA600/2-80-001. 1980.

Durag Service Manual: (F-904 K-PLC). Durag Incorporated Elektronik Co. 105 Kollaustasse. Hamburg, Germany. 1999 (unpublished).

Energy and Environmental Research Corporation (EERC). "Particulate Matter Continuous Emission Monitoring Systems Field Study, Site-Specific Quality Assurance Test Plan". Prepared for the U.S. Department of Energy and Bechtel Jacobs Company. Revision 2. July 20, 1999 (unpublished).

EPA (U.S. Environmental Protection Agency), "CEMS Demonstration Announcement". Federal Register: Vol. 61, No. 39, February 27, 1996.

EPA (U.S. Environmental Protection Agency), "Hazardous Waste Combustors; Revised Standards; Proposed Rule: CEMS Demonstration Announcement". Federal Register: Vol. 61, No. 39, April 19, 1996.

EPA (U.S. Environmental Protection Agency), "Total Mercury and Particulate Continuous Emission Monitoring Systems; Measurement of Low Level Particulate Emissions; Implementation at Hazardous Waste Combustors; Proposed Rule". Federal Register: Vol. 62, No. 249, December 30, 1997.

EPA (U.S. Environmental Protection Agency), "Particulate Matter CEMS Demonstration: DuPont Experimental Station On-Site Incinerator", EPA 68-D2-0164. February 12, 1997.

EPA (U.S. Environmental Protection Agency), "Procedure 2: Quality Assurance Requirements for Particulate Matter Continuous Emission Monitoring Systems", Office of Solid Waste, Washington, DC: Work-in-Progress (11-3-98).

EPA (U.S. Environmental Protection Agency), "Performance Specification 11: Specifications and Test Procedures for Particulate Matter Continuous Emission Monitoring Systems in Stationary Sources", Office of Solid Waste, Washington, DC: Work-in-Progress (11-3-98).

EPA (U.S. Environmental Protection Agency), "Final Technical Support Document for HWC MACT Standards; Volume IV; Compliance with the HWC MACT Standards" EPA 68-D2-0164 and 68-W7-0029. July 1999.

EPA (U.S. Environmental Protection Agency), "NESHAPS: Final Standards for Hazardous Air Pollutants for Hazardous Waste Combustors, Final Rule", Federal Register: Vol. 64, No. 189, September 30, 1999.

EPA (U.S. Environmental Protection Agency), "Method 5i: Determination of Low Level Particulate Matter Emissions from Stationary Sources", CFR 40 Part 60, Appendix A. Washington DC: July 1, 2000.

EPA (U.S. Environmental Protection Agency), "NESHAPS: Final Standards for Hazardous Air Pollutants for Hazardous Waste Combustors", Federal Register: Vol. 65, No. 132, July 10, 2000.

ESA Service Manual: (Beta 5M Monitor). Environnement S.A. 111 Boulevard Robespierre. Poissy, France. 1998 (unpublished).

Jahnke, J.A. Continuous Emission Monitoring. Van Nostrand Reinhold. New York, NY. 1993.

Lilly Project Report: "Particulate Matter CEMS Test, Volume 1". Prepared by Focus Environmental Inc. for Eli Lilly and Co. Indianapolis, IN. September 1998.

Lilly Project Report: "Addendum to September 1998 PM CEMS; Phase II". Prepared by Focus Environmental Inc. for Eli Lilly and Co. Indianapolis, IN. April 30, 1999.

Lodge, James P. Jr. (Ed.). Methods of Air Sampling and Analysis (Third Edition). CRC Press. Boca Raton, FL. 1988.

Sigrist Service/Instruction Manuals: CTNR Light-scattering Monitor. Sigrist-Photometer AG. 1 Hofurlistrasse. Ennetburgen, Switzerland. 1998 (unpublished).

Roberson, R.L. "Status of EPA's Continuous Particulate Mass (PM) Monitor Demonstrations". Presented at the 1997 EPRI CEM User Group Meeting. Denver, CO. May 14-16, 1997.

Wark, K., Warner, C.F. and Davis W.T. Air Pollution: Its Origin and Control. Addison-Wesley Longman, Inc. Menlo Park, CA. 1998.

APPENDIX

Appendix A

Tables Discussed in Body of Report

Table 2.1
Summary of PM CEMS Performance Characteristics
(without outliers) for the DuPont Waste Incinerator*

CEMS	Detection Principal	M5i Testing Period	Correlation Coefficient > 0.90	Confidence Interval < 10%	Tolerance Interval < 25%
ESA	beta	Pre-test	0.554	26.2	38.3
		First	0.927	7.3	23.7
		Second	0.985	5.7	15.5
Verewa	beta	Pre-test	0.691	27.3	32.1
		First	0.968	5.1	20.0
		Second	0.961	8.0	21.7
Durag	optical	Pre-test	0.715	21.7	36.0
		First	0.952	7.2	17.2
		Second	0.972	6.9	18.8
ESC	optical	Pre-test	0.708	22.1	36.4
		First	0.966	5.2	21.2
		Second	0.978	6.2	16.9
Sigrist	optical	Pre-test	0.644	25.5	40.0
		First	0.936	7.1	28.7
		Second	0.951	9.2	24.9

* Analysis based on linear regression

Table 2.2
Summary of PM CEMS Performance Characteristics
(without outliers) for the Eli Lilly Waste Incinerator

CEMS	Detection Principal	M5i Testing Period	Correlation Coefficient > 0.90	Confidence Interval < 10%	Tolerance Interval < 25%
ESA	beta	Phase I*	0.31	3.1	5.5
		Phase II*	0.99	2.6	9.1
Sigrist	optical	Phase I*	0.73	1.7	2.4
		Phase II**	0.97	6.7	24.3

* Analysis based on linear regression; ** Analysis based on logarithmic regression

Table 3.1
Typical Flue Gas Conditions at the Sampling Location
Under Normal Incinerator Operating Conditions

Description	Condition	Units
Temperature	175 -185	°F
Static Pressure	- 0.25	inches H ₂ O
Flow Rate	8,000 – 9,000	dscf
	17,000 – 19,000	acfm
Velocity	18 – 20	fps
O ₂	9 – 11	%
CO ₂	5 – 8	%
Moisture	45 – 55	%
PM Loading (front-half)	0.005 – 0.030	gr/dscf @ 7% O ₂
	10 – 70	mg/dscm @ 7% O ₂

(Adapted from: EERC, 1999)

Table 3.2
Incinerator Process Parameters Monitored
During the PM CEMS Demonstration

Description	Range*	Units
Stack Barometric Pressure	400 – 800	mm Hg
Stack Temperature	0 – 400	°F
Combustion Gas Velocity	0 – 35	fps
O ₂ Monitor 1	0 – 25	% dry
O ₂ Monitor 2	0 – 25	% dry
IWS-1 Voltage	0 – 40,000	volts
IWS-2 Voltage	0 – 40,000	volts
Primary Feed Rate	0 – 1000	lbs/hr
Aqueous Feed Rate	0 – 500	lbs/hr
Secondary Feed Rate	0 – 1000	lbs/hr
Solids Feed Rate	0 – 1000	lbs/hr
Solids Scale Reading	0 – 100	lbs
NG to Secondary Burner	0 – 21,000	scfh
NG to Primary Burner	0 – 11,000	scfh
CO ₂ Monitor 1	0 – 20	% dry
CO ₂ Monitor 2	0 – 20	% dry

(Adapted from: EERC, 1999); *Min-max range of detector.

Table 4.1
Input/Output Signal Requirements for the Purpose of Data Logging*

Durag F-904K	Input	Analog	None
		Digital	Start calibration – unit is looking for a contact closure (no voltage) from the data logger for a minimum of 2 seconds duration. This will initiate the calibration routine.
	Output	Analog	Dust concentration (mg/N-m ³) – range is programmable.
			Dust concentration – isolated (4 –20 mA).
			Mass of dust on filter tape (mg) – range is fixed at 10 mg.
		Digital	Filter tape torn error
			Measuring range error – over range.
			Sample volume error – total volume deviates from set point.
			Vacuum error – probe or filter tape plugged.
			Zero – results from zero test of calibration.
			Span – results from upscale calibration.
ESA Beta 5M	Input	Anal/Digital	None
	Output	Analog	Dust concentration (mg/N-m ³) – range is programmable.
			Dust concentration – isolated (4-20 mA).
			Geiger counts (counts/sec).
			Intake volume (N-liters).
			Stack gas velocity (m/sec).
			Stack temperature (°C).
			Venturi static pressure (mbar).
			Venturi tube temperature (°C).
			Error alarm code number.
		Digital	General error alarm.
Sigrist CTNR	Input	Anal/Digital	None
	Output	Analog	Dust concentration - isolated (4 –20 mA).
			Relay 1, 2, and 3 are used to signal range information.
			Dust concentration low range response (mg/m ³ PLA).*
			Dust concentration high range response (mg/m ³ PLA).*
		Digital	Range 4 active; relays 1, 2 & 3 open.
			Range 3 active; relays 3 close; relays 1 & 2 open.
			Range 2 active; relays 2 close; relays 1 & 3 open.
			Range 1 active; relays 1 close; relays 2 & 3 open.
			Relay 4 close – instrument in service/calibration mode.
			Relay 5 close – instrument error or malfunction. See error code on monitor digital display.

(Adapted from: EERC, 1999); *Sigrist monitor operation only one set of ranges is active

Table 4.2
Summary of PM CEMS Sampling Characteristics

Description	Durag	ESA	Sigrist
Flow Rate Sampling Condition	Slightly above average stack velocity	Maintained isokinetic automatically	Slightly above average stack velocity
Sampling Protocol	Dry Dilution (air) & Heated Probe	Heated Probe (only)	Heated Probe (only)
Probe Temperature	120 °C	120 °C	160 °C
Gas Sampling Volume and/or Dilution Volume	400 L 135 L	~ 300 L	n/a
Reporting Conditions	Dry, 20 °C & 1013 mbar	Wet, 0 °C & 1013 mbar	Wet, 160 °C & 1013 mbar
Concentration Sampling Range (see also Table 5.1)	0 - 100 mg/dscm	0 – 100 mg/Nm ³	0 – 50 mg/m ³ PLA
Measuring Cycle	10 - 12 min	10 - 12 min	~ 1 sec
Sampling Cycle	5 – 7 min	5 - 7 min	Continuous

Table 5.1
Summary of CEMS Measuring Ranges and Equations
for Conversion between Milliamp and Concentration

Instrument	Concentration Range	Linear Equation
Durag (mg/dscm)	0 – 100	$Y = 6.25X - 25$
ESA (mg/Nm ³)	0 – 70	$Y = 4.375X - 17.5$
	0 – 100	$Y = 6.25X - 25$
Sigrist low-range* (mg/m ³ PLA)	0 – 0.05	$Y = 0.003125X - 0.0125$
	0 – 0.2	$Y = 0.0125X - 0.05$
	0 – 1	$Y = 0.0625X - 0.25$
	0 – 30	$Y = 1.875X - 7.5$
Sigrist high-range** (mg/m ³ PLA)	0 – 0.1	$Y = 0.00625X - 0.025$
	0 – 1	$Y = 0.0625X - 0.25$
	0 – 5	$Y = 0.3125X - 1.25$
	0 – 50	$Y = 3.125X - 12.5$

*Sampling range during Phase 1; **Sampling range during Phase 2 and 3.
Y = Concentration; X = milliamp signal.

Table 6.1
Estimation of Precision and Rejection of Statistical Outliers
for Phase 2 M5i PM Concentration Data

Date	Waste Types	Run No.*	PM Concentration (mg/dscm) @ 7% O ₂		Ave PM Conc	RSD (%)	MPC (%)	Result
			Train-1	Train-2				
24-Mar	Natural Gas	R13	1.25	2.96	2.11	40.6	23.2	Fail
	Natural Gas	R14	1.87	0.807	1.34	39.7	24.4	Fail
	Combination Solids	R15	10.9	8.46	9.68	12.6	10.5	Fail
	Combination Solids	R16	7.13	7.85	7.49	4.81	14.2	Pass
25-Mar	Natural Gas	R17	1.19	0.991	1.09	9.12	24.8	Pass
	Combination Solids & Soil Solids	R18	3.89	4.66	4.28	9.01	19.5	Pass
	Combination Solids & Soil Solids	R19	5.74	5.84	5.79	0.86	17.0	Pass
	Combination Solids & Soil Solids	R20	3.31	3.09	3.20	3.44	21.3	Pass
26-Mar	Natural Gas	R21	0.811	-0.677	0.07	1110	No-limit	Pass
	Combination Solids & Soil Solids	R22	15.0	14.5	14.75	1.69	10.0	Pass
	Soil Solids	R23	1.94	3.77	2.86	32.0	21.9	Fail
	Soil Solids	R24	-3.69	1.60	-1.05	-253	N/A	Fail

*The Phase 1 data was not included, in this paper; but to maintain consistency with the Method 5i laboratory report, the AES numbering scheme for the runs was maintained throughout this paper.
RSD = Relative Standard Deviation; MPC = Minimum Precision Criteria.

Table 6.2
Summary of Waste Feed Categories, Ash
Content, and Feed Rates for Phase 3

Waste	Description	lb/hr	
Primary	Waste oils and organics (ash content 0.1 % by weight)	Min	140
		Max	340
		Ave	260
Secondary		Min	110
		Max	310
		Ave	230
Aqueous	Nitric acid with depleted uranium and combination bulk liquids (ash content 6.9 % by weight)	Min	130
		Max	350
		Ave	270
Solid I	Repackaged solids with PCBs (ash content 5.7% by weight)	Min	115
		Max	160
		Ave	140
Solid II	Spent carbon (ash content 5.4% by weight)	Min	260
		Max	370
		Ave	330

Table 6.3
Three Different Levels of PM Concentration
Over Incinerator Operations for Phase 3

Level	Range	Interval* (mg/dscm)	No. Runs	Method 5i Runs	Range (mg/dscm)*		%
					MIN	MAX	
1 (low)	0-50%	$x < 39.2$	5	R26, R36, R37, R38, R44	1.8	22.6	26.3
2 (medium)	25-75%	$19.6 > x > 58.7$	10	R27, R28, R32, R33, R34, R35, R39, R41, R42, R43	25.3	38.4	52.6
3 (high)	50-100%	$x > 39.2$	4	R29, R30, R31, R40	39.3	78.3	21.1

* PM concentrations (mg/dscm) are also reported at 7% oxygen.

Table 6.4
Estimation of Precision and Rejection of Statistical Outliers
for Phase 3 M5i PM Concentration Data

Date	Waste Types	Run No.*	PM Concentration (mg/dscm) @ 7% O ₂		Ave PM Conc	RSD (%)	MPC (%)	Result
			Train-1	Train-2				
19-Oct	Primary/Secondary & Aqueous	R26	22.8	22.3	22.55	1.11	10.0	Pass
	Primary/Secondary & Aqueous	R27	32.4**	33.3	32.85	1.37	10.0	Pass
	Primary/Secondary & Aqueous	R28	23.5	27.1**	25.30	7.11	10.0	Pass
	Primary/Secondary & Aqueous	R29	51.7	50.9	51.30	0.78	10.0	Pass
	Primary/Secondary & Aqueous	R30	80.0	76.6**	78.30	2.17	10.0	Pass
20-Oct	Aqueous	R31	54.7	48.3	51.50	6.21	10.0	Pass
	Primary/Secondary, Aqueous & Solid I	R32	32.4	29.9	31.15	4.01	10.0	Pass
	Primary/Secondary, Aqueous & Solid I	R33	26.7	26.0	26.35	1.33	10.0	Pass
	Primary/Secondary, Aqueous & Solid I	R34	24.5	27.2	25.85	5.22	10.0	Pass
	Primary/Secondary, Aqueous & Solid I	R35	38.9	37.8	38.35	1.43	10.0	Pass
21-Oct	Primary/Secondary & Solid II	R36	5.55	5.21	5.38	3.16	17.7	Pass
	Primary & Solid II	R37	8.65	8.26	8.46	2.31	12.6	Pass
	Primary/Secondary & Solid II	R38	13.7	13.5	13.60	0.74	10.0	Pass

Table 6.4 (continued)

Date	Waste Types	Run No.*	PM Concentration (mg/dscm) @ 7% O ₂		Ave PM Conc	RSD (%)	MPC (%)	Result
			Train-1	Train-2				
22-Oct	Primary/Secondary, Aqueous & Solid II	R39	33.6	33.1	33.35	0.75	10.0	Pass
	Primary/Secondary, Aqueous & Solid II	R40	41.0	37.6	39.30	4.33	10.0	Pass
	Primary/Secondary, Aqueous & Solid II	R41	31.8	31.4	31.60	0.63	10.0	Pass
	Primary/Secondary, Aqueous & Solid II	R42	31.9	31.8	31.85	0.16	10.0	Pass
	Primary/Secondary & Aqueous	R43	34.9	33.5	34.20	2.05	10.0	Pass
24-Oct	Primary/Secondary	R44	1.85	1.77	1.81	2.21	23.7	Pass
	Primary/Secondary	R45	2.11	1.25	1.68	25.60	23.9	Fail

*Run 25 was not reported; it was discontinued during the Method 5i sampling test because condensed moisture in the train exceeded the capacity of the impinges and liquid water saturated the silica gel.

** The Method 5i train operator was unable to maintain an isokinetic sampling rate to within 10% of the true isokinetic rate.

RSD = Relative Standard Deviation; MPC = Minimum Precision Criteria.

Table 6.5
CEMS and M5i Phase 3 Data
Adapted for Use in the Correlation Tests

Run No.	Durag		ESA		Sigrist	
	CEMS (mA)	M5i (mg/dscm)	CEMS (mg/Nm ³)	M5i (mg/Nm ³)	CEMS (mg/m ³ PLA)	M5i (mg/m ³)
R26	5.581	16.38	8.67	9.151	0.253909	5.771
R27	6.583	23.61	10.30	13.41	0.511662	8.459
R28	5.891	19.44	9.21	10.61	0.239761	6.692
R29	8.654	39.48	19.69	21.70	1.425907	13.69
R30	9.457	61.42	29.21	33.59	3.218443	21.18
R31	8.433	41.26	20.95	23.63	0.529626	14.90
R32	6.579	25.10	12.50	14.15	0.343226	8.830
R33	5.834	21.00	10.55	12.25	0.228386	7.710
R34	5.848	20.89	10.31	12.00	0.367018	7.564
R35	6.894	30.35	10.86	17.29	0.544798	10.90
R36	4.305	3.945	0.55	2.256	0.011863	1.423
R37	4.525	6.708	3.13	3.786	0.054513	2.387
R38	4.415	10.78	4.52	6.152	0.031211	3.880
R39	6.616	27.11	12.58	15.25	0.383198	9.617
R40	6.373	31.21	12.99	17.36	0.599869	10.93
R41	6.353	25.07	10.75	13.93	0.286351	8.785
R42	6.659	25.37	11.36	14.05	0.320300	8.862
R43	6.916	27.04	11.96	15.16	0.305484	9.558
R44	4.475	1.325	0.08	0.7578	0.018696	0.4779
R45*	4.421	1.305	0.14	0.7336	0.017807	0.4626

* Run did not pass Procedure 2 RSD% criteria.

Table 6.6
Summary of Durag Phase 3
PS11 Calibration Results

Description		Linear	Logarithmic	Polynomial
		$y = b_1x + b_0$	$y = b_1\ln(x) + b_0$	$y = b_2x^2 + b_1x + b_0$
PS11 Correlation r-value =		0.964	0.952	0.963
Regression Coefficients	$b_2 =$	-	-	0.2000
	$b_1 =$	9.548	59.90	6.881
	$b_0 =$	-36.42	-85.10	-27.94
Maximum Predicted Concentration, y_{\max} 125% (mg/dscm) =		66.90	57.55	69.95
at x_{\max} 125% (mA) =	10.82			
CEMS Response Required to Report Emission Standard (mA) =		6.58	6.44	6.62
Emission Standard at Condition of CEMS (mg/dscm) =	26.42			
Confidence Interval (%) at Emission Standard =		6.9	8.0	9.2
Tolerance Interval (%) at Emission Standard =		23.2	26.9	24.4
Comparison between Linear and Polynomial Best-fit Curves		The linear equation is the best-fit curve.		
F_{1f} value =	4.49			
Observed (S) ratio =	0.31			

Table 6.7
Summary of ESA Phase 3
PS11 Calibration Results

Description		Linear	Logarithmic	Polynomial
		$y = b_1x + b_0$	$y = b_1\text{Ln}(x) + b_0$	$y = b_2x^2 + b_1x + b_0$
PS11 Correlation r-value =		0.985	0.761	0.985
Regression Coefficients	$b_2 =$	-	-	-0.0028
	$b_1 =$	1.1050	4.3592	1.1812
	$b_0 =$	1.2764	4.8684	0.9033
Maximum Predicted Concentration, y_{max} 125% (mg/Nm ³) =		41.62	20.55	40.29
at x_{max} 125% (mg/Nm ³) =	36.51			
CEMS Response Required to Report Emission Standard (mg/Nm ³) =		12.31	9.93	12.18
Emission Standard at Condition of CEMS (mg/Nm ³) =	14.87			
Confidence Interval (%) at Emission Standard =		4.4	16.8	5.4
Tolerance Interval (%) at Emission Standard =		14.8	55.9	15.4
Comparison between Linear and Polynomial Best-fit Curves		The linear equation is the best-fit curve.		
F_{If} value =	4.49			
Observed (S) ratio =	0.41			

Table 6.8
Summary of Sigrist Phase 3
PS11 Calibration Results

Description		Linear	Logarithmic	Polynomial
		$y = b_1x + b_0$	$y = b_1\ln(x) + b_0$	$y = b_2x^2 + b_1x + b_0$
PS11 Correlation r-value =		0.818	0.908	0.895
Regression Coefficients	$b_2 =$	-	-	-2.7715
	$b_1 =$	5.5636	3.1848	14.243
	$b_0 =$	5.6785	12.965	3.3666
Maximum Predicted Concentration, y_{\max} 125% (mg/m ³) =		28.06	17.40	15.81
at x_{\max} 125% (mg/m ³ PLA) =	4.023			
CEMS Response Required to Report Emission Standard (mg/m ³ PLA) =		0.6652	0.3243	0.4641
Emission Standard at Condition of CEMS (mg/m ³) =	9.38			
Confidence Interval (%) at Emission Standard =		14.8	10.8	13.4
Tolerance Interval (%) at Emission Standard =		49.5	36.1	39.4
Comparison between Linear and Polynomial Best-fit Curves		The logarithmic equation is the best-fit curve.		
F_{1f} value =	4.49			
Observed (S) ratio =	12.2			

Appendix B

Figures Discussed in Body of Report



Figure 3.1: Aerial photograph of the TSCA Incinerator demonstration area.
Note: the picture was taken during 1995; since that time, additional buildings
have been added to the facility grounds.

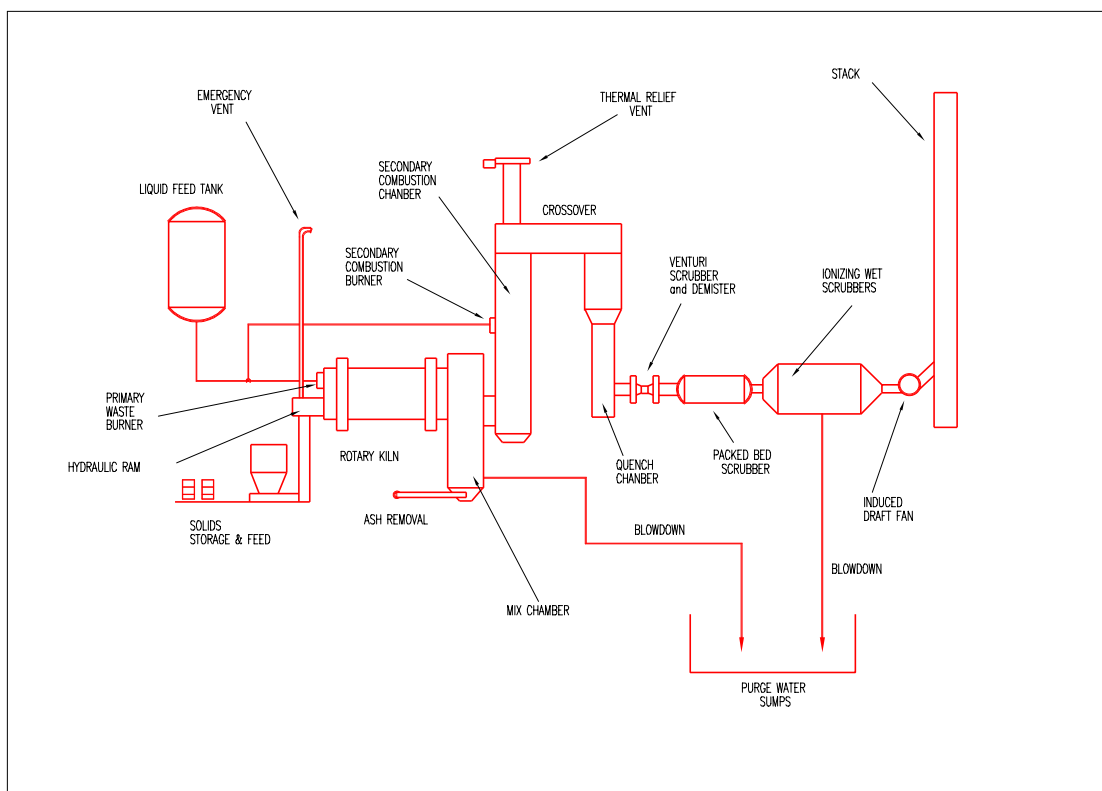


Figure 3.2: Overall schematic of the TSCA Incinerator process systems and air pollution control equipment. (Adapted from: EERC, 1999).

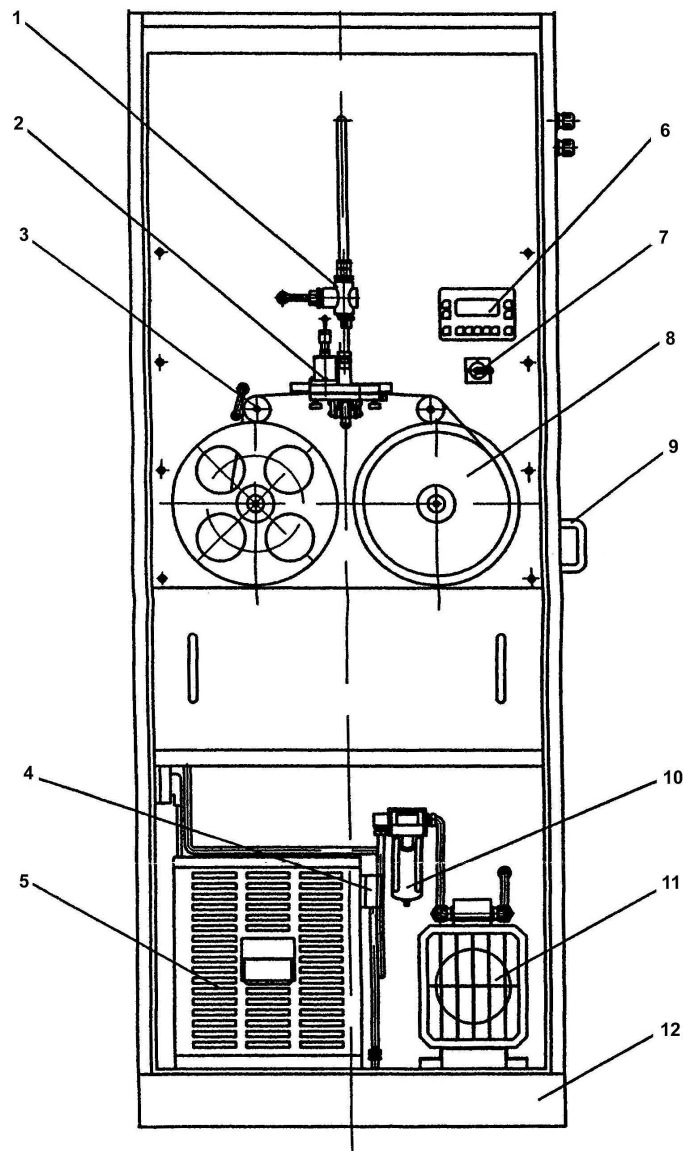


Figure 4.1: Front view of Durag F-904 K beta-gauge monitor. General description: The measurement and control assembly are enclosed in a sealed cabinet. The following components are located in the cabinet: (1) Three-way ball valve - entry for flue gas sample; (2) Filter adapter - contains beta source and Geiger- Müller detector; (3) Filter tape pad roll; (4) Peristaltic pump; (5) Sample gas chiller; (6) Keyboard and display; (7) Main switch; (8) Supply filter tape reel; (9) Grip; (10) Filter; (11) Sample gas pump; (12) Cabinet base.

Source: Durag Service Manual: (F-904 K-PLC). Durag Incorporated Elektronik Co. 105 Kollaustasse. Hamburg, Germany. 1999 (unpublished).

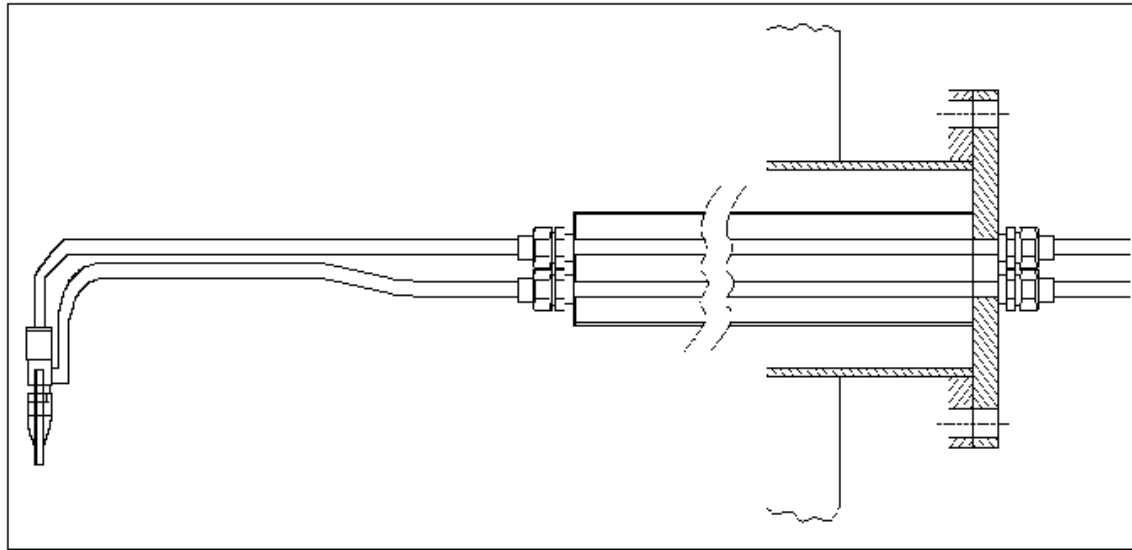


Figure 4.2: General diagram of the dilution probe for Durag monitor.
Note the probe is fixed to the port on the outside of the stack wall; insulating materials and heated sampling lines are not shown.
Source: Durag Service Manual: (F-904 K-PLC). Durag Incorporated
Elektronik Co. 105 Kollaustasse. Hamburg, Germany. 1999 (unpublished).

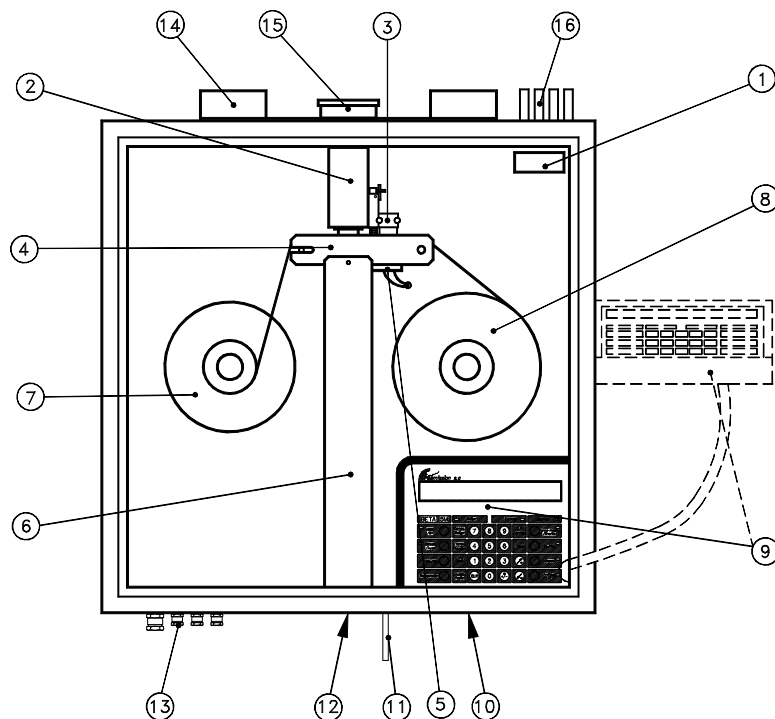


Figure 4.3: Front view of ESA Beta 5M monitor. General description: (1) Standard calibration foil; (2) Retractable upstream sample connection; (3) Radioactive-source; (4) Filter strip drive carriage; (5) Geiger-Müller detector; (6) Downstream sample connection contains a venturi tube; (7) Take-up spool; (8) Feed spool; (9) Programming keyboard and display unit; (10) Compressed-air inlet; (11) Condensate discharge tube; (12) Sample gas discharge line; (13) Four packing glands for electric signal and supply cables; (14) Cabinet sliding mounts; (15) Receptacle for sampling probe apparatus; (16) Four Staubli-type air connections for pitot-tube, thermocouple, and air pressure-valve control. Source: ESA Service Manual: (Beta 5M Monitor). Environnement S.A. 111 Boulevard Robespierre. Poissy, France. 1998 (unpublished).

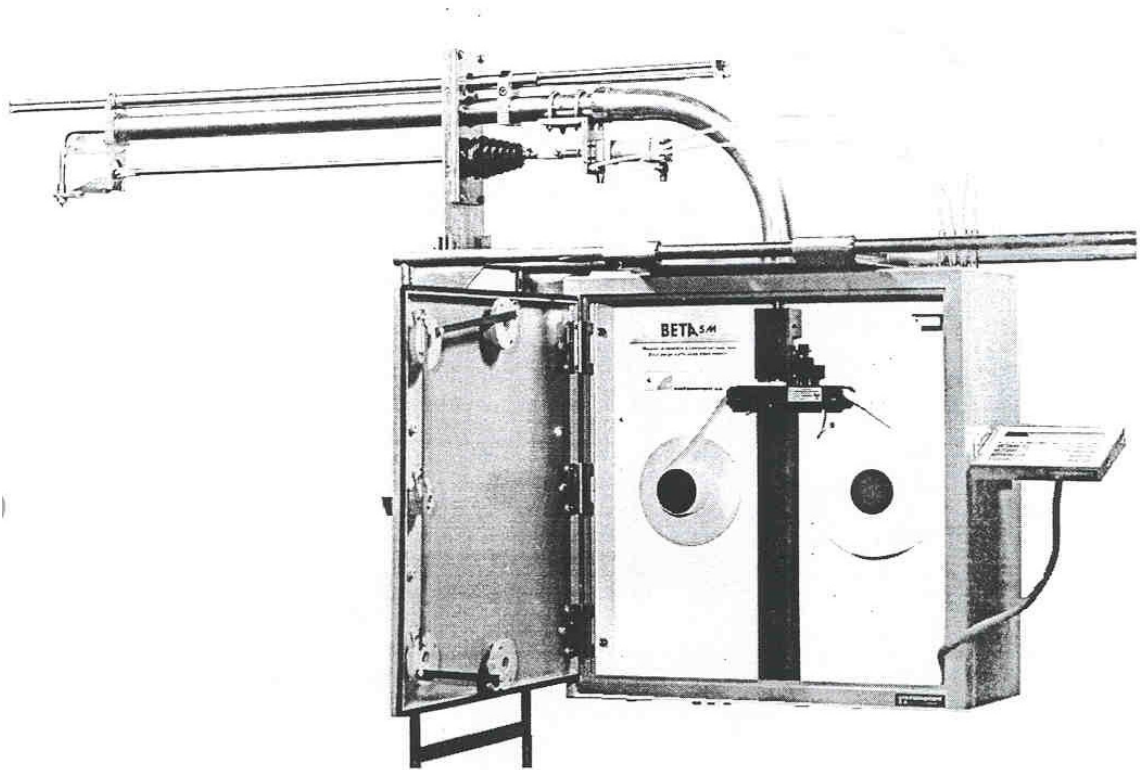


Figure 4.4: Presentation of ESA monitor and probe assemble.
Source: ESA Service Manual: (Beta 5M Monitor). Environnement S.A.
111 Boulevard Robespierre. Poissy, France. 1998 (unpublished).

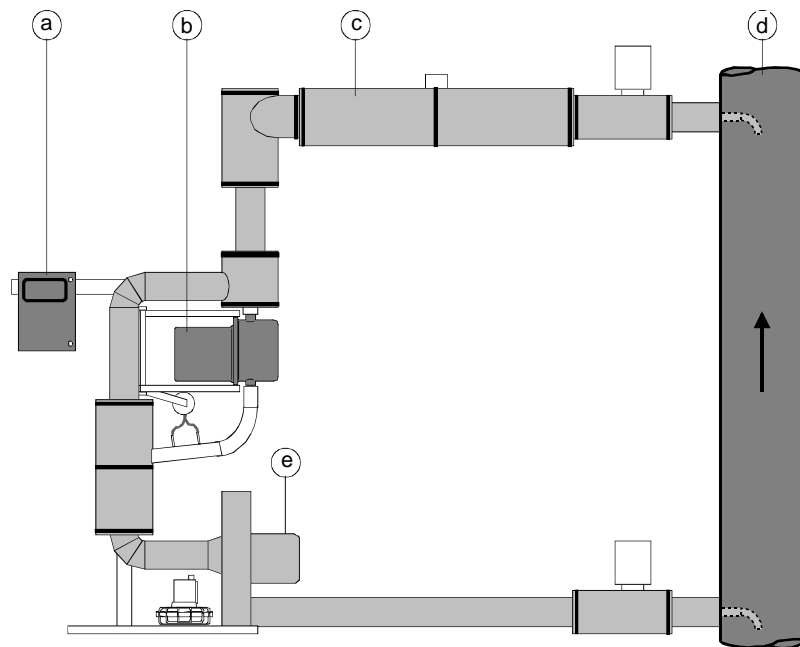
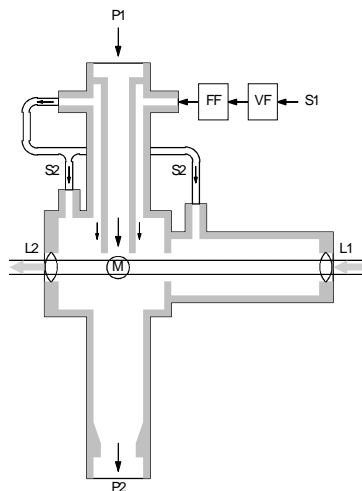


Figure 4.5: Diagram of side view of Sigris CTNR Light-scattering monitor. General description: (a) Control unit; (b) Photometer; (c) Ring pipe and heated sampling line; (d) Gas duct or stack; (e) Fan blower.

Source: Sigris Service/Instruction Manuals. CTNR Light-scattering Monitor. Sigris-Photometer AG. 1 Hofurlistrasse. Ennetburgen, Switzerland. 1998 (unpublished).

(a)



(b)

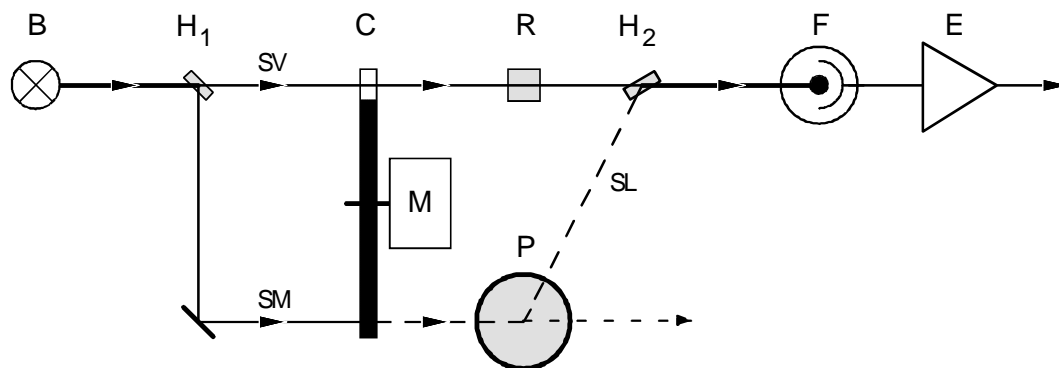


Figure 4.6: Schematics of Sigrist photometer cell and optical sampling configuration.

(a) Photometer cell: (P1) Sample entry point; (P2) Purge air and sample outlet; (S1) Purge air supply; (S2) Treated purge air; (L1) Light entry point; (L2) Light outlet at 15°; (M) Measurement point; (FF) Fine filter; (VF) Roughing Filter.

(b) Optical sampling configuration: (B) Light from incandescent bulb; (H_n) Semi-transparent mirrors; (SM) Measuring beam; (SV) Reference beam; (P) Sample cell; (SL) 15° Scattered light; (F) detector; (R) Optical attenuator; (C) Chopper wheel and (M) motor; (E) Milliamp signal.

Source: Sigrist Service/Instruction Manuals. CTNR Light-scattering Monitor. Sigrist-Photometer AG. 1 Hofurlistrasse. Ennetburgen, Switzerland. 1998 (unpublished).

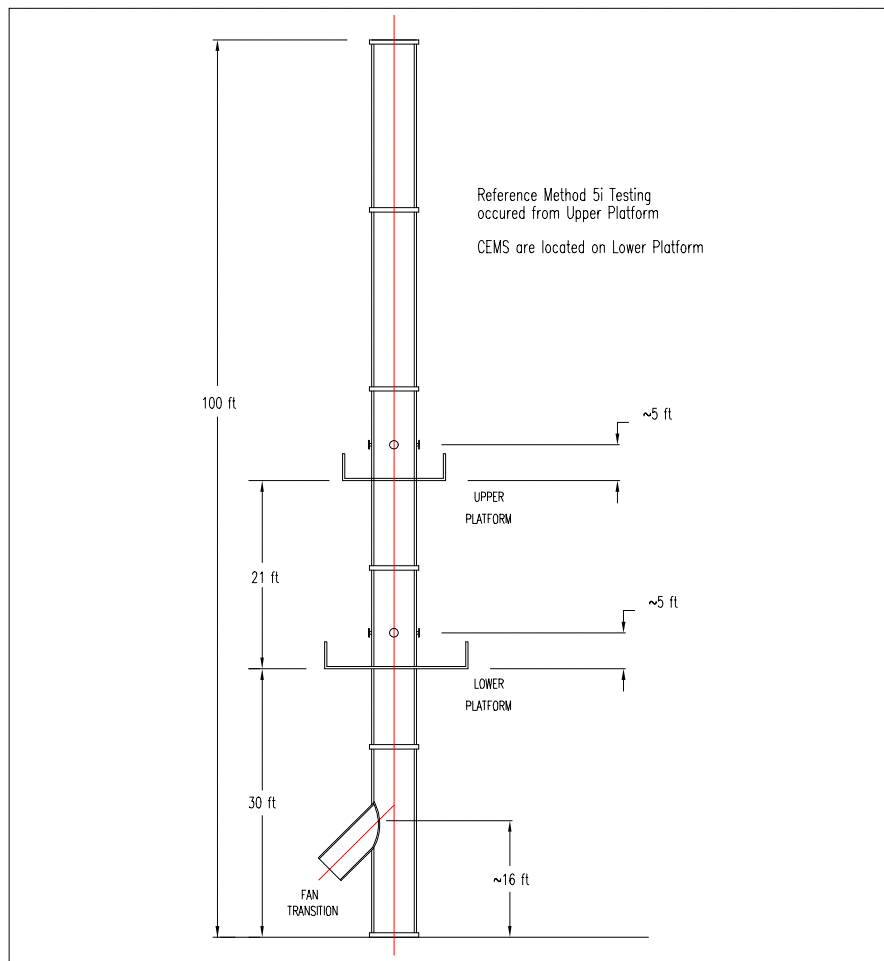


Figure 5.1: Diagram of TSCA Incinerator stack sampling platforms and port elevations. (Adapted from: EERC, 1999).

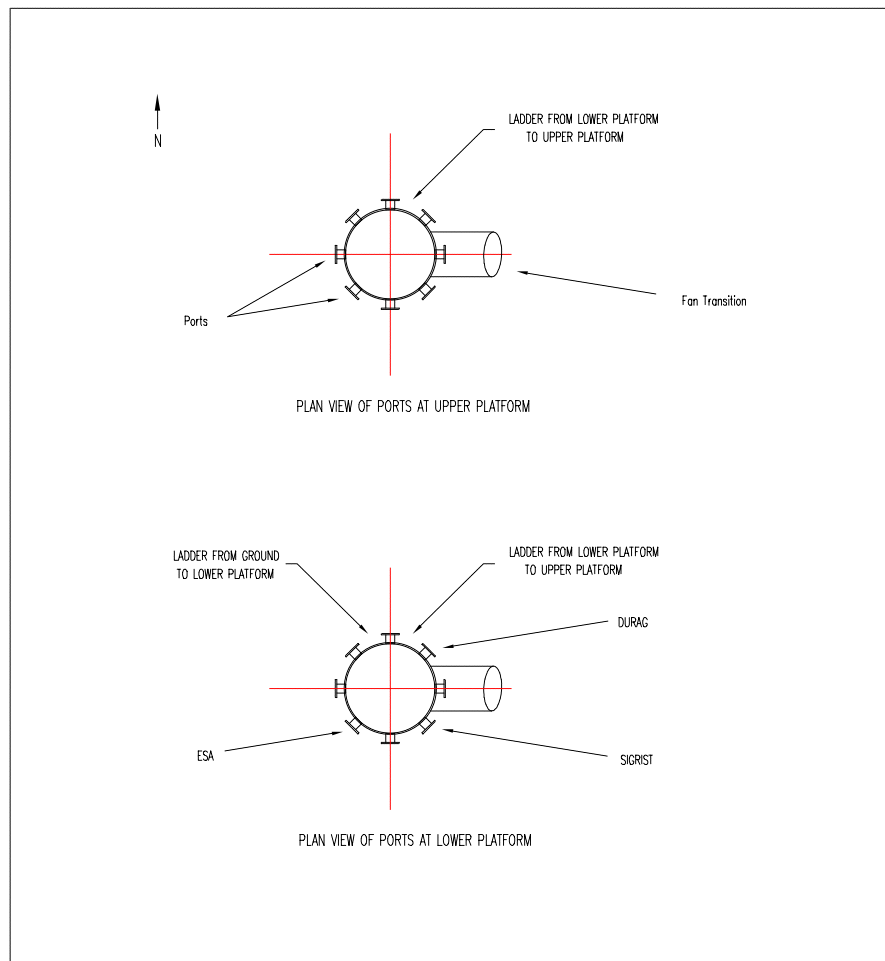


Figure 5.2: Detail of TSCA Incinerator stack sampling ports.
(Adapted from: EERC, 1999)

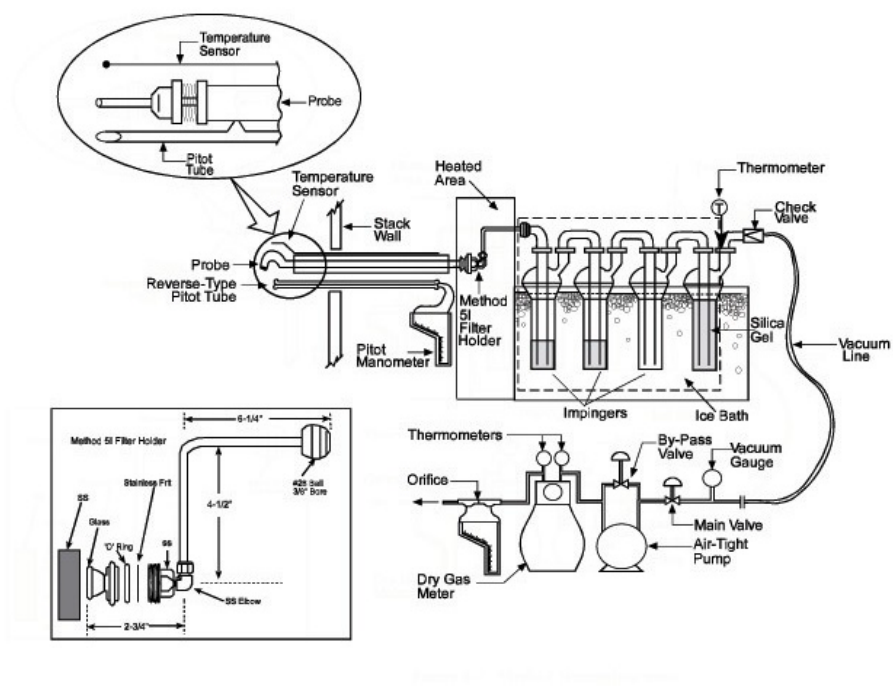


Figure 5.3: Reference Method 5i sampling train and filter holder assembly.

Source: EPA (U.S. Environmental Protection Agency), "Method 5i: Determination of Low Level Particulate Matter Emissions from Stationary Sources", CFR 40 Part 60, Appendix A. Washington DC: July 1, 2000.

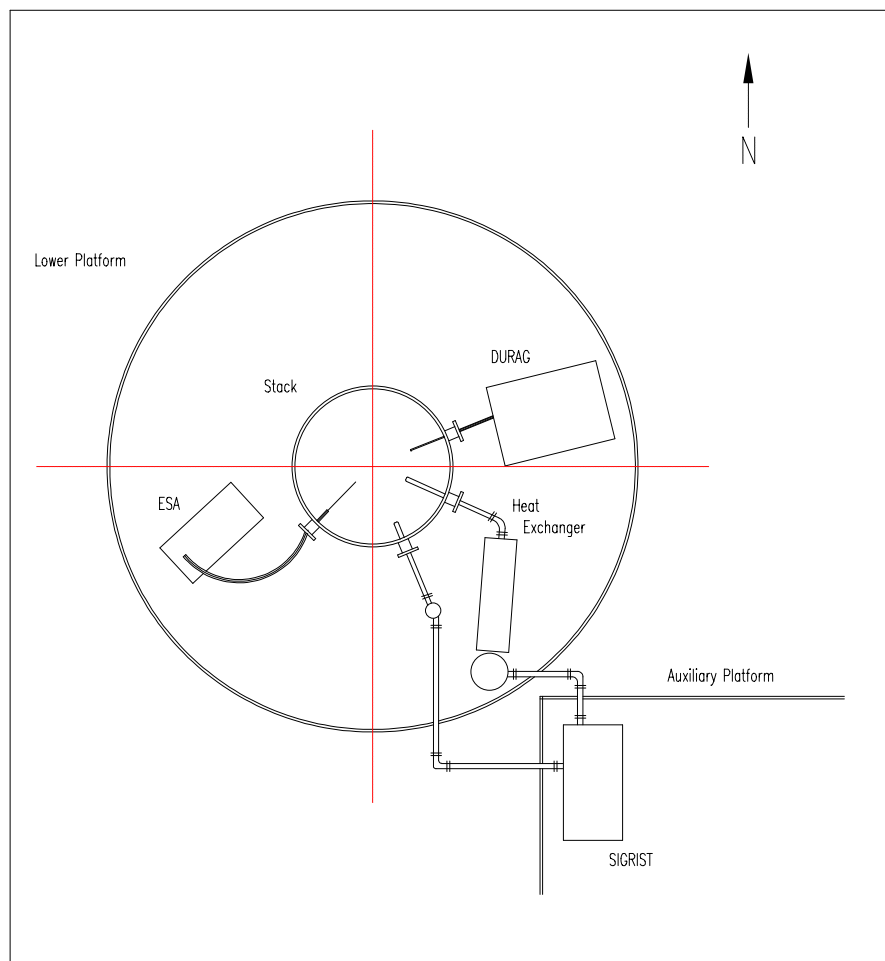


Figure 5.4: Layout of CEMS around incinerator stack.
(Adapted from: EERC, 1999)

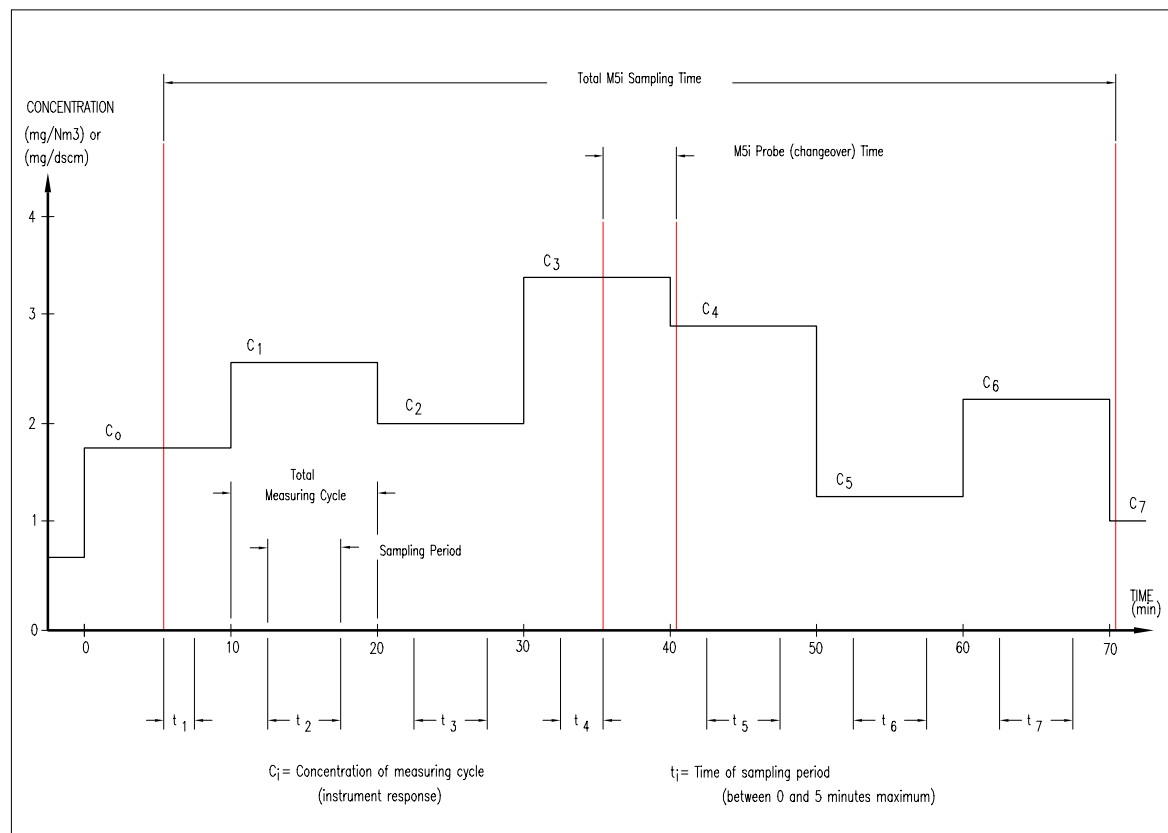


Figure 5.5: Schematic representing batch sampling cycle time of the beta-gauge monitors. Note: the total measuring cycle and actual sampling times are based upon a hypothetical reference method run.

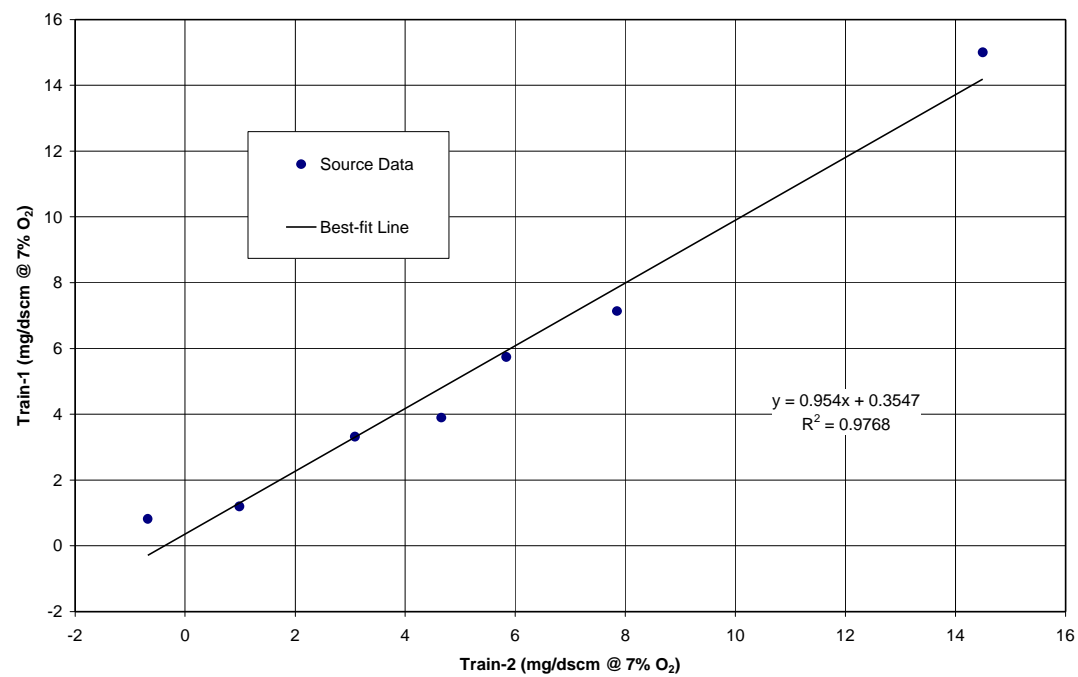


Figure 6.1: Phase 2 M5i Cross Correlation (7 Runs Meeting RSD Criteria).

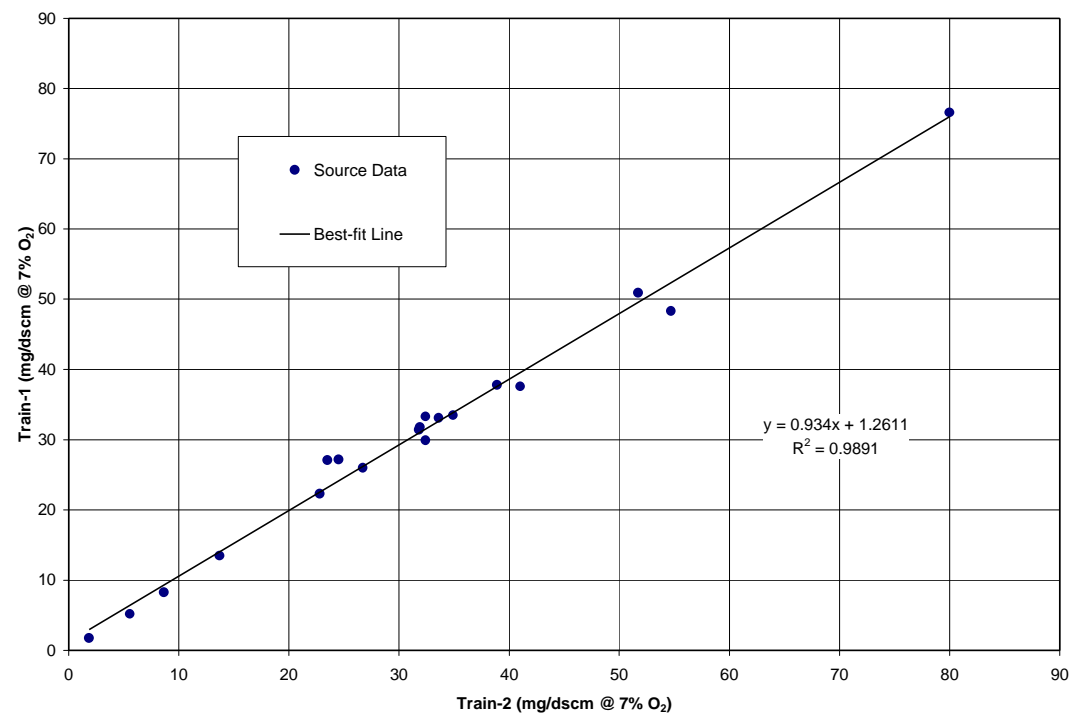


Figure 6.2: Phase 3 M5i Cross Correlation (19 Runs Meeting RSD Criteria).

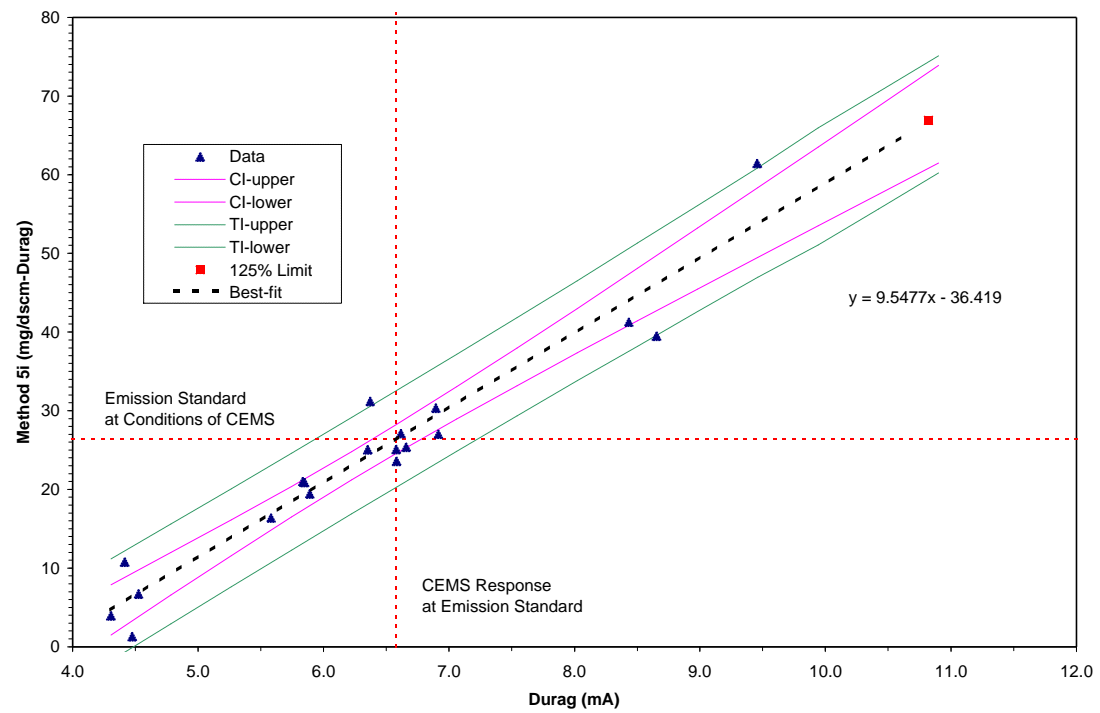


Figure 6.3: Durag Linear Calibration Curve for Phase 3.

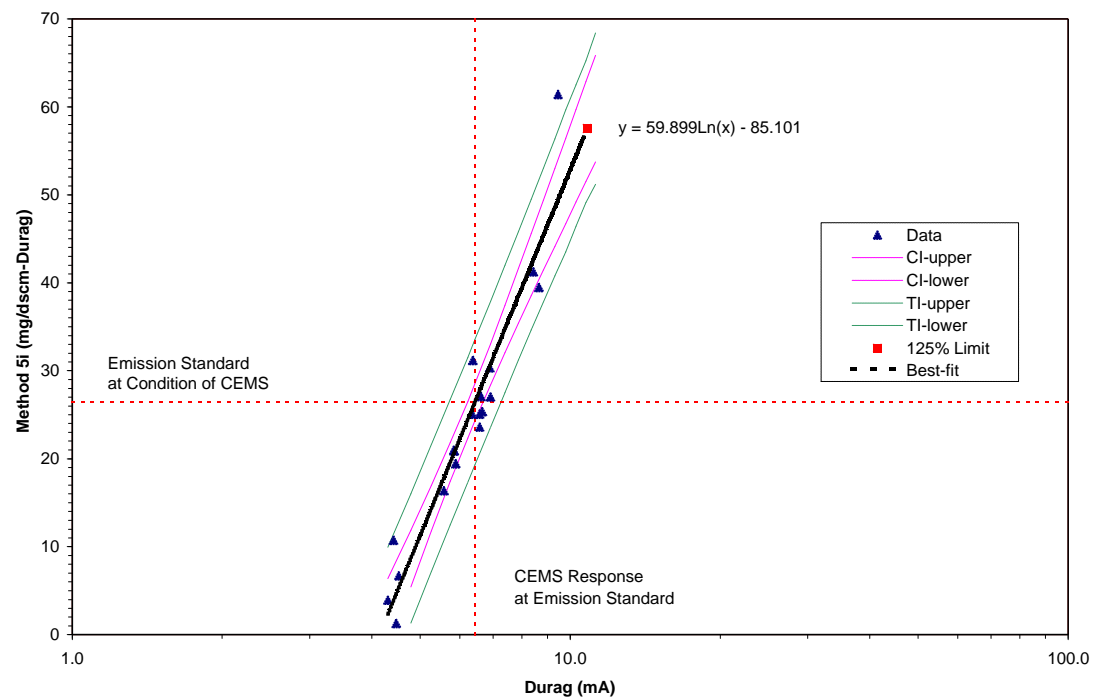


Figure 6.4: Durag Logarithmic Calibration Curve for Phase 3.

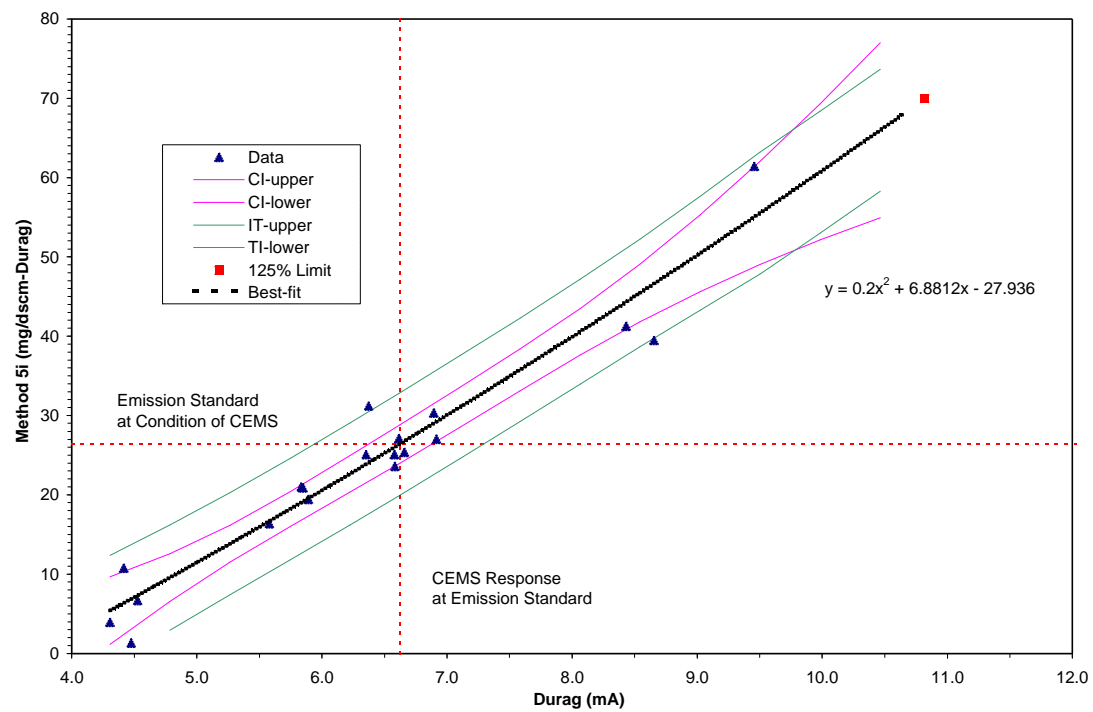


Figure 6.5: Durag Polynomial Calibration Curve for Phase 3.

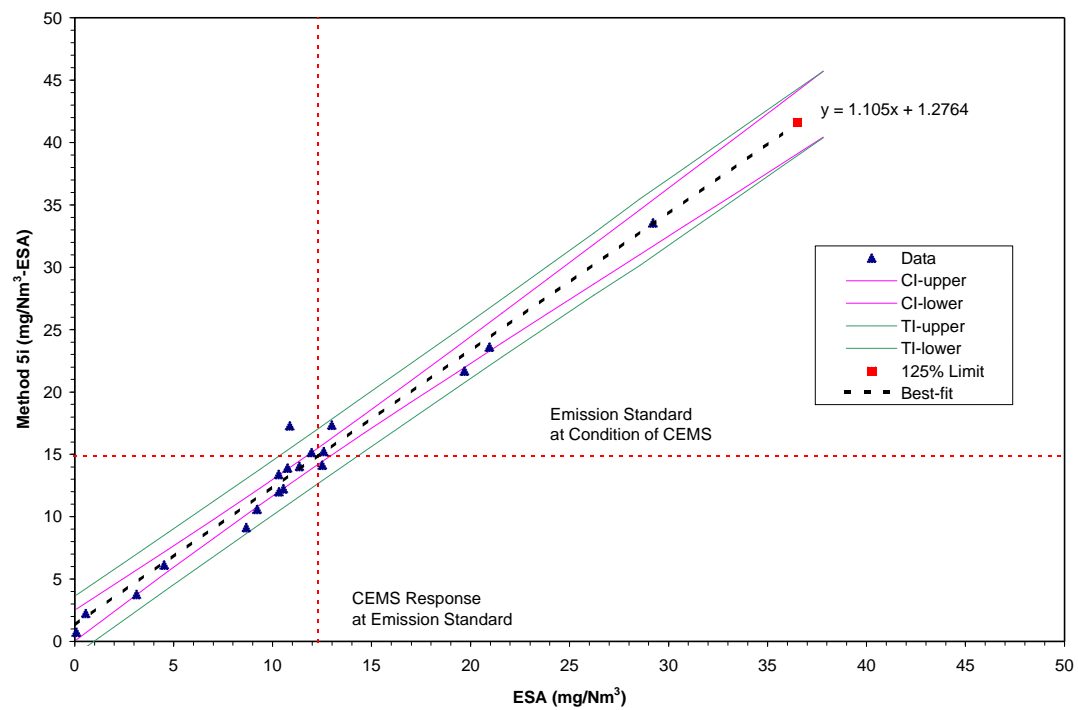


Figure 6.6: ESA Linear Calibration Curve for Phase 3.

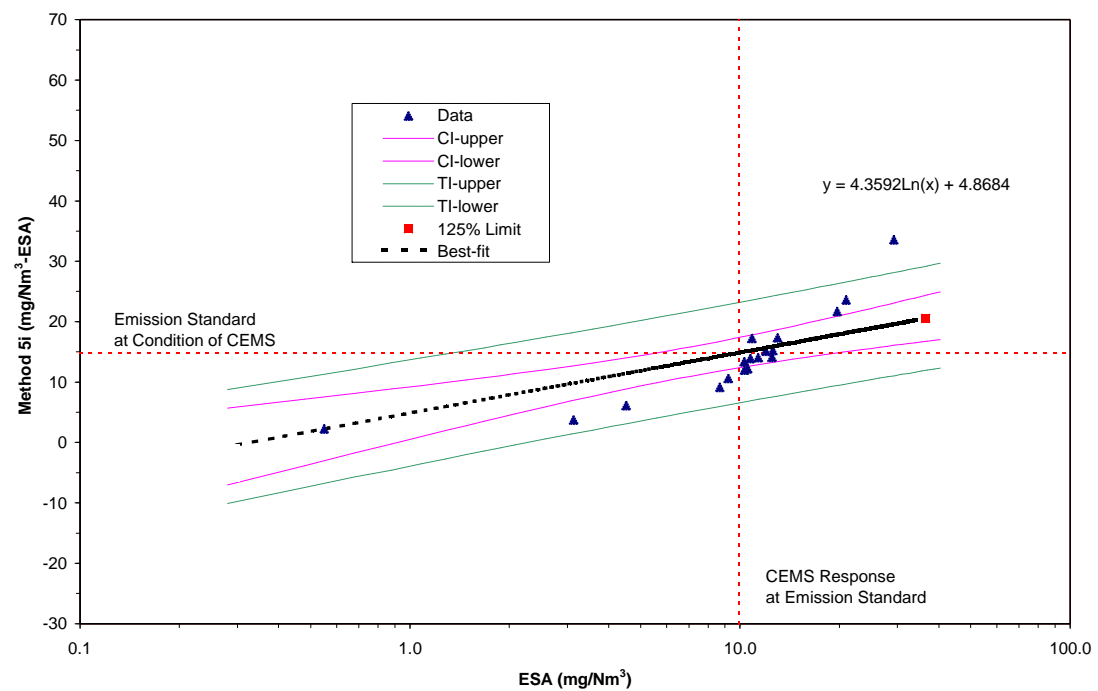


Figure 6.7: ESA Logarithmic Calibration Curve for Phase 3.

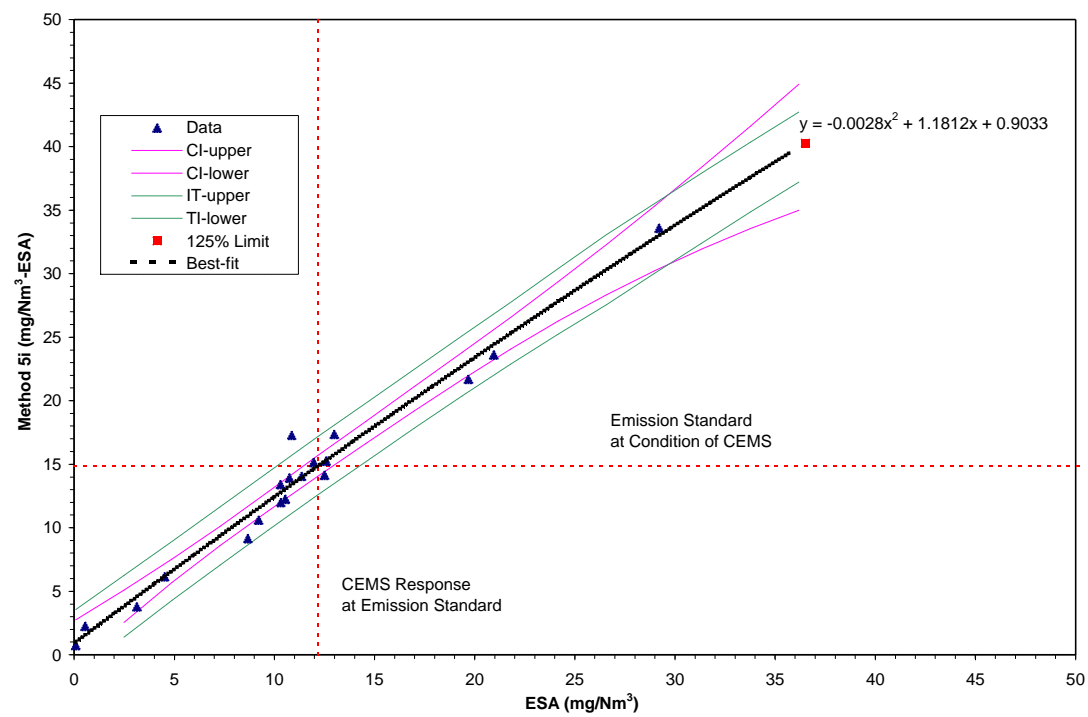


Figure 6.8: ESA Polynomial Calibration Curve for Phase 3.

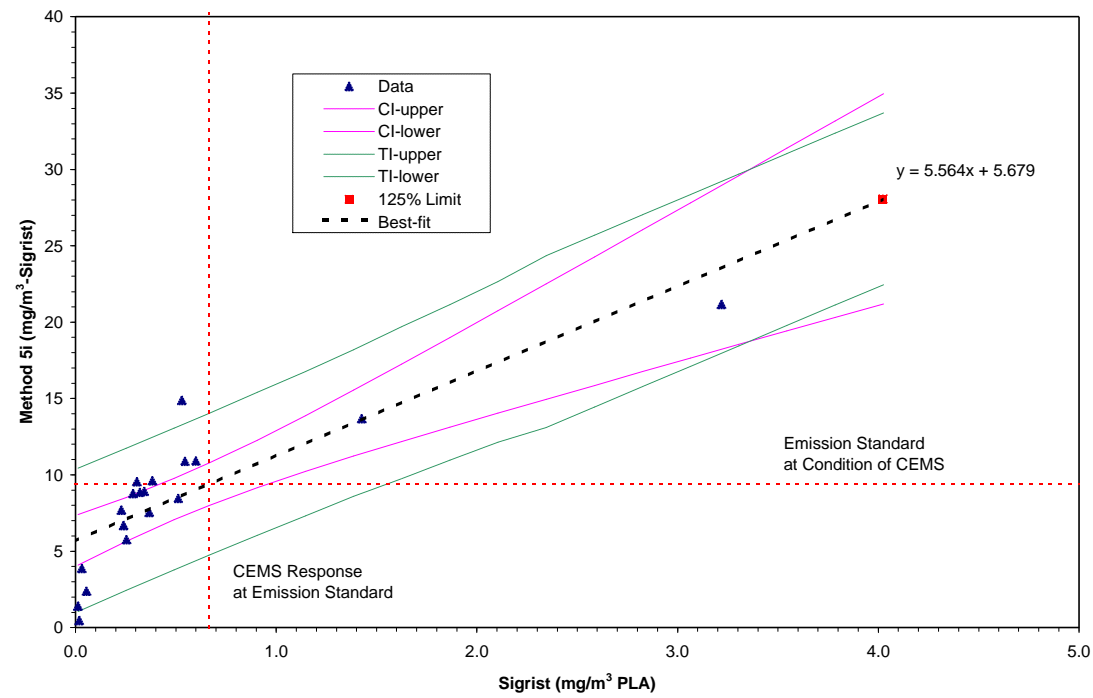


Figure 6.9: Sigrist Linear Calibration Curve for Phase 3.

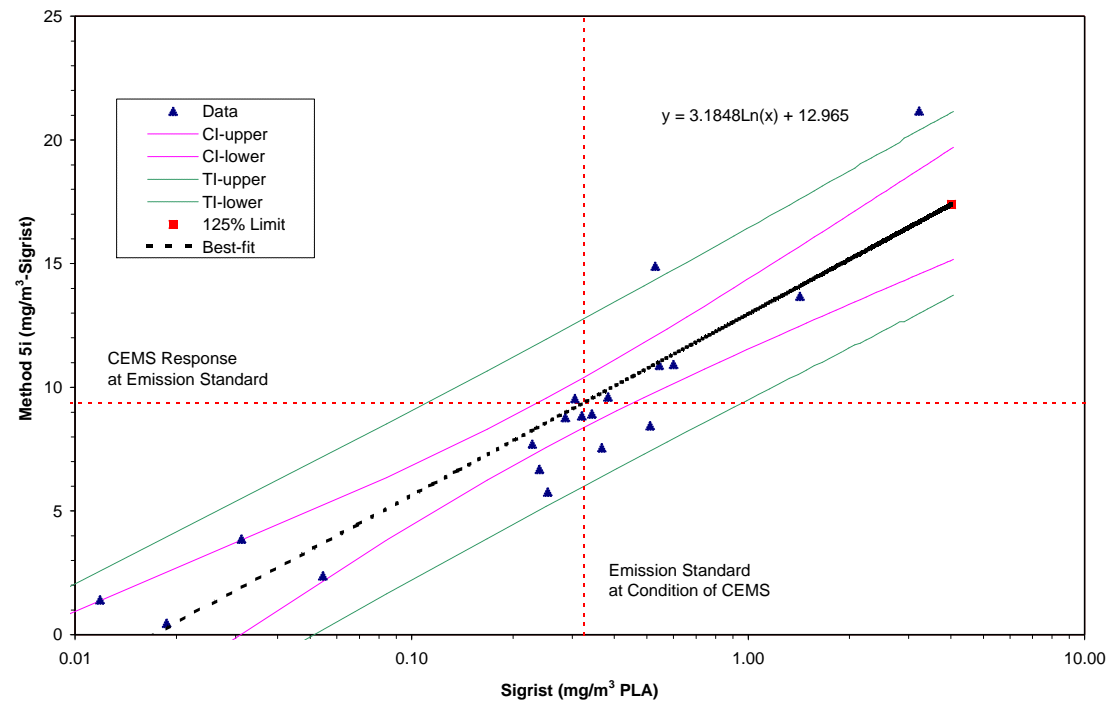


Figure 6.10: Sigrist Logarithmic Calibration Curve for Phase 3.

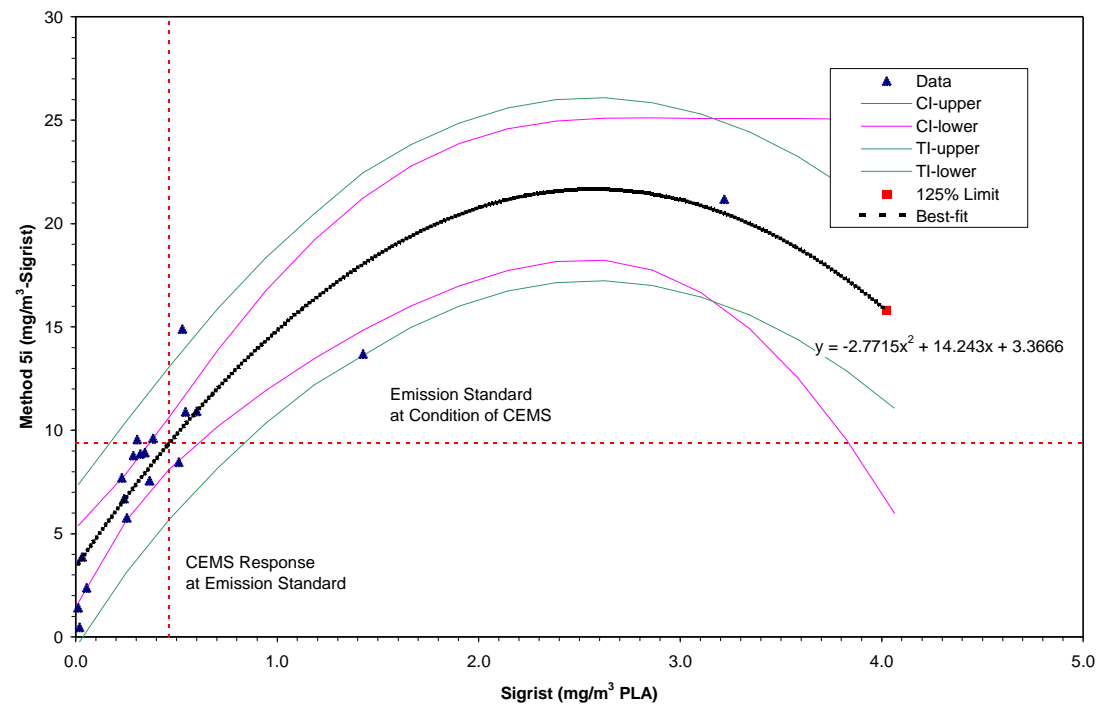


Figure 6.11: Sigrist Polynomial Calibration Curve for Phase 3.

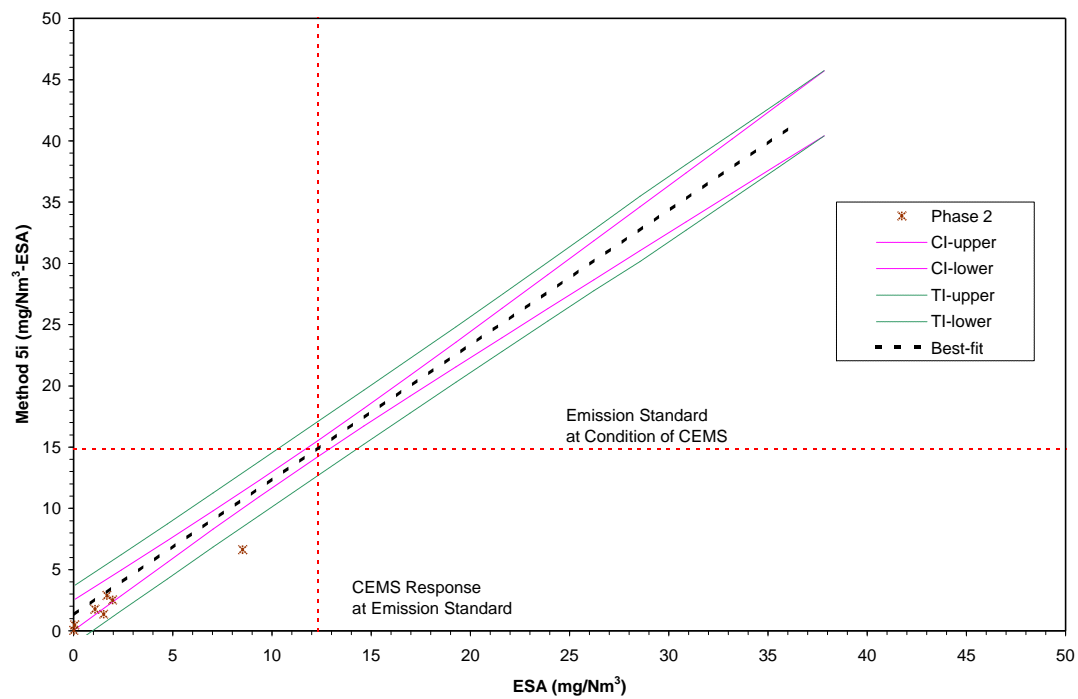


Figure 6.12: ESA Phase 3 Linear Calibration Curve with Phase 2 Data Inserted for RCA.

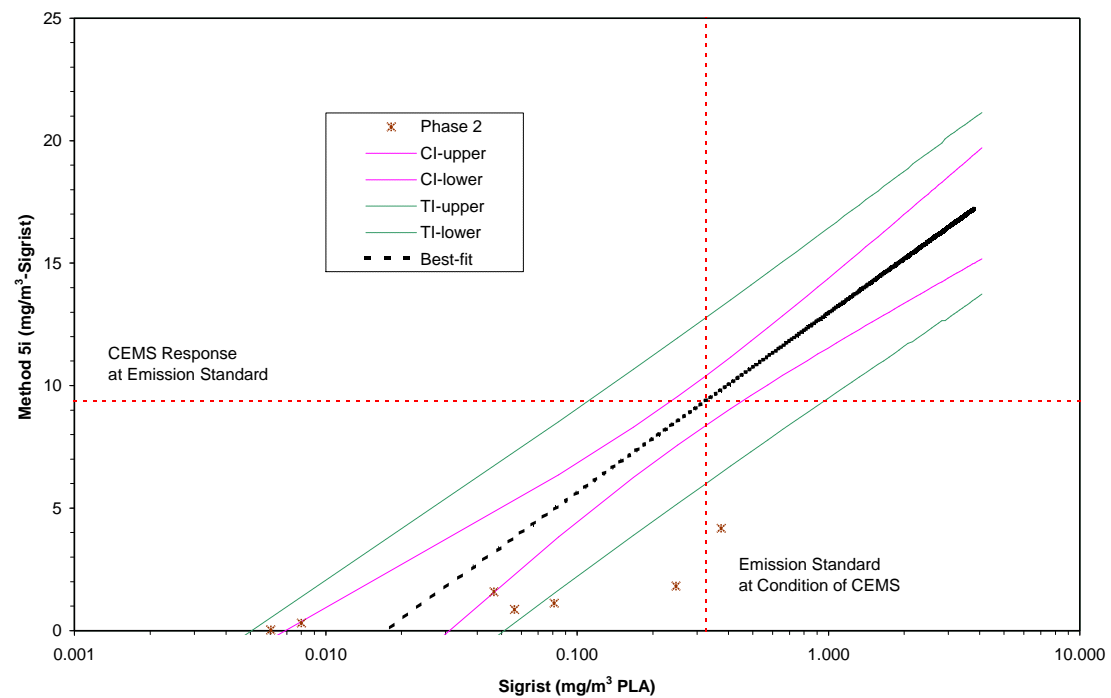


Figure 6.13: Sigrist Phase 3 Logarithmic Calibration Curve with Phase 2 Data Inserted for RCA

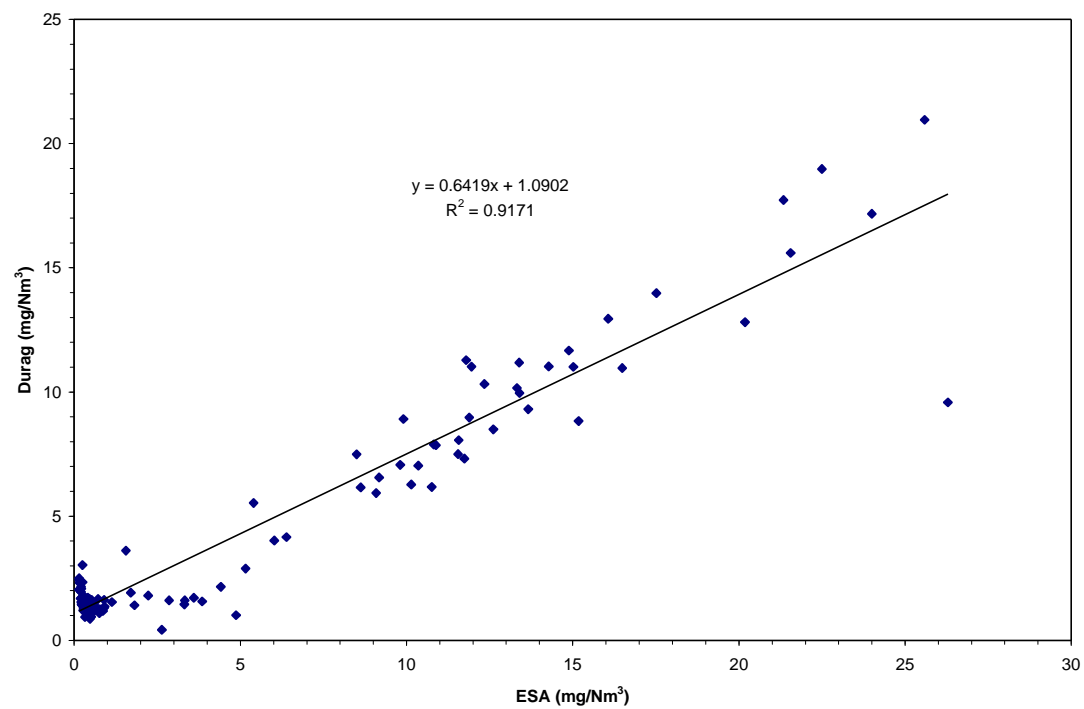


Figure 6.14: Durag vs. ESA (1-hour Averages for October 19-22 & 24).

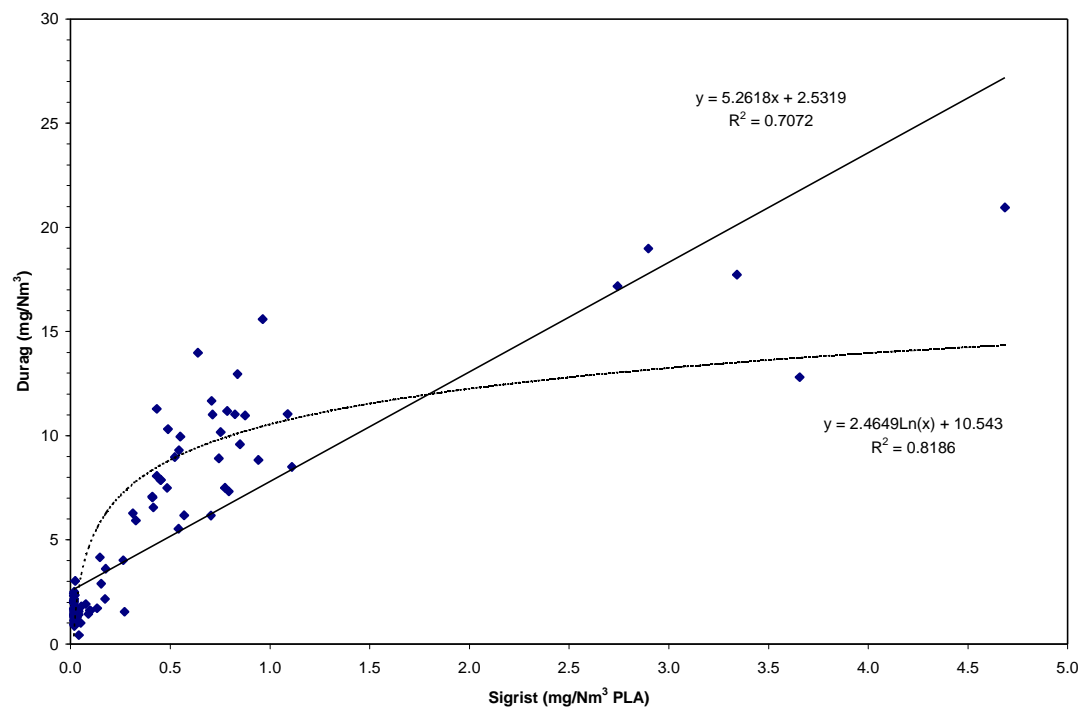


Figure 6.15: Durag vs. Sigrist (1-hour Averages for October 19-22 & 24).

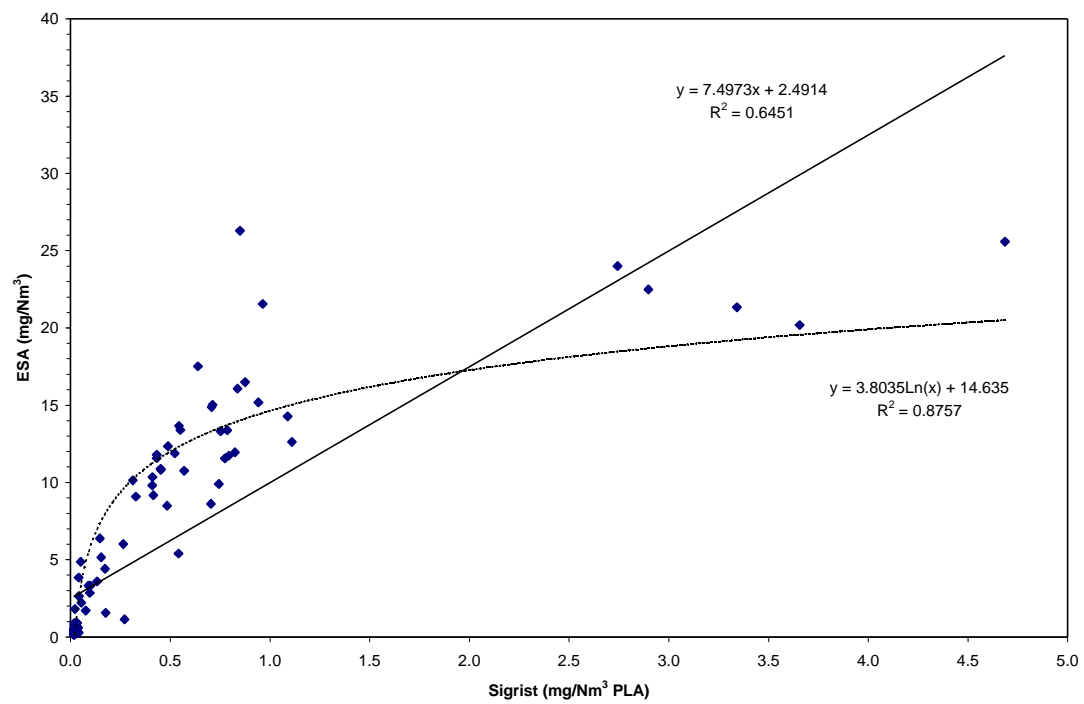


Figure 6.16: ESA vs. Sigrist (1-hour Averages for October 19-22 & 24).

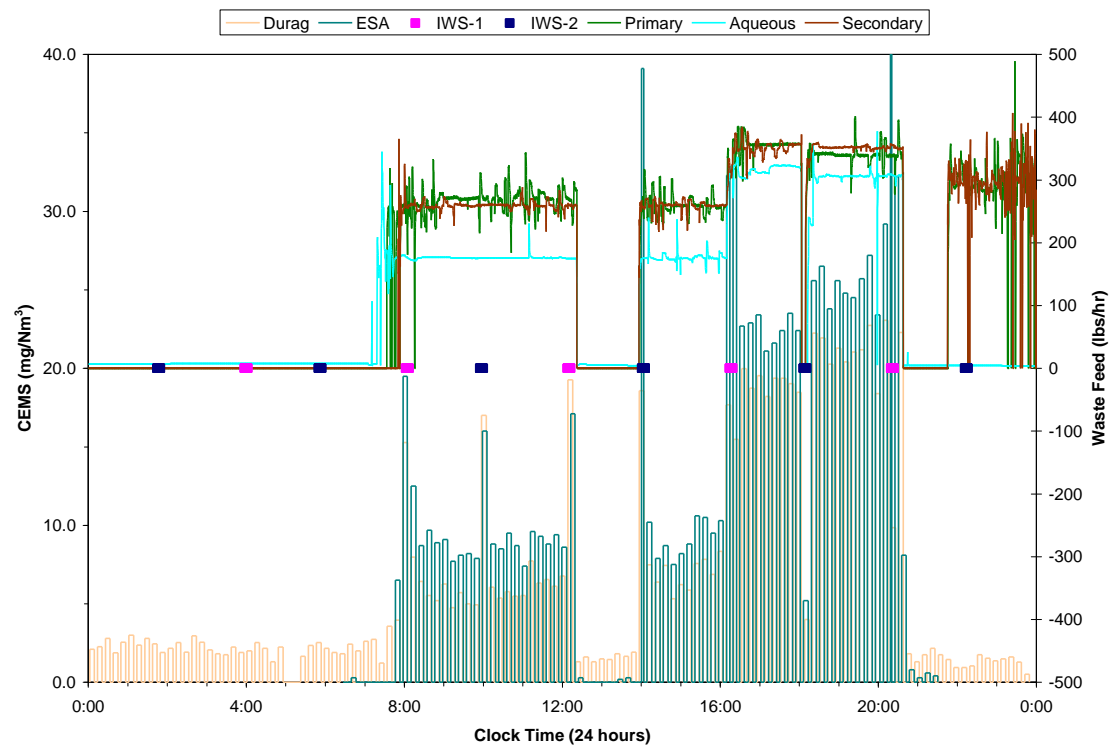


Figure 6.17: Durag and ESA Responses vs. Waste Feeds During October 19.

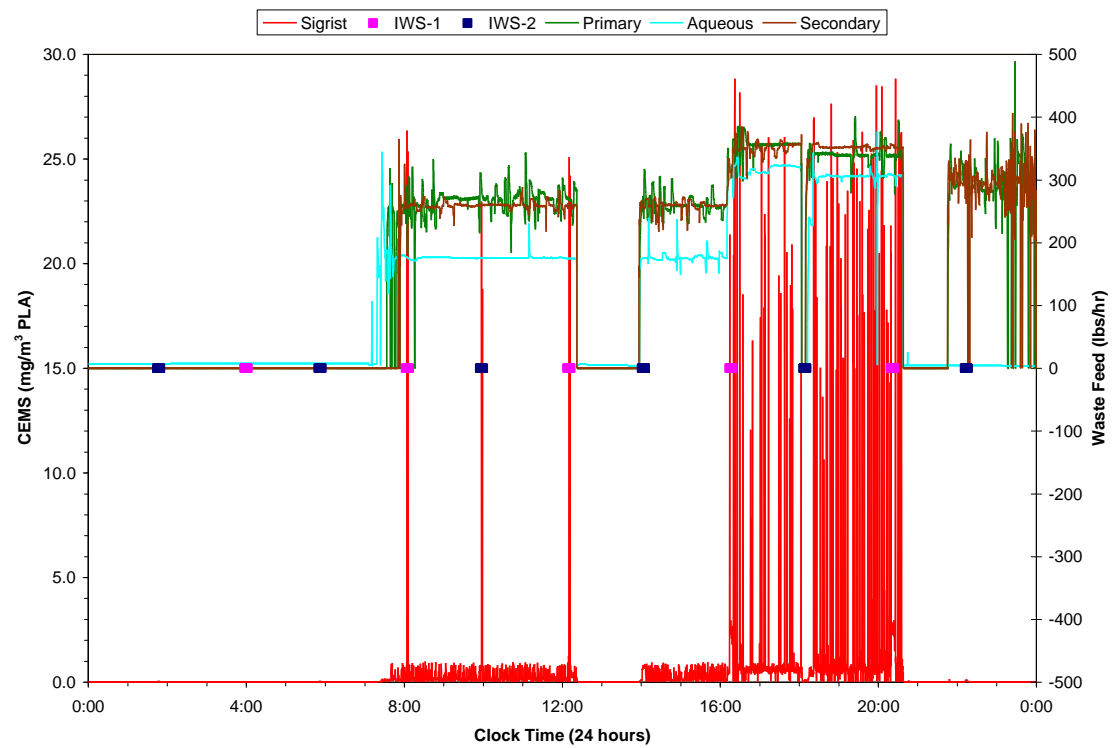


Figure 6.18: Sigrist Response vs. Waste Feeds During October 19.

Appendix C

Airtech Laboratory Report Phase 3 M5i Testing

Appendix C: Runs R26-R27

Phase 3: Modified from Airtech Final Laboratory Report December 15, 2000

<u>Test Parameters</u>	R26-T1	R26-T2	R27-T1	R27-T2
Date	10/19/2000	10/19/2000	10/19/2000	10/19/2000
First Port Start Time	8:19	8:19	10:59	10:59
First Port Stop Time	8:49	8:49	11:29	11:29
Second Port Start Time	9:01	9:01	11:49	11:49
Second Port Stop Time	9:42	9:42	12:20	12:20
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	Delay ⁵	Delay ⁵	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	180	176	179
Volumetric Flow Rate (acfm)	19,100	19,800	18,500	18,900
Volumetric Flow Rate (scfm)	15,600	16,100	15,100	15,300
Volumetric Flow Rate (dscfm)	8,390	8,090	8,000	8,130
Carbon Dioxide (%)	6.8	6.6	6.4	6.6
Oxygen (%)	10.80	10.80	11.00	10.80
Moisture (%)	46.21	49.73	47.17	46.96
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.00998	0.00972	0.0141	0.0145
Particulate Concentration (mg/dscm @ 7% O ₂)	22.8	22.3	32.4	33.3
Particulate Concentration (mg/acm)	7.28	6.60	9.95	10.4
Particulate Concentration (mg/dNcm-Durag) ¹	16.59	16.17	23.05	24.17
Particulate Concentration (mg/Ncm-ESA) ²	9.580	8.722	13.07	13.76
Particulate Concentration (mg/cm-Sigrist) ³	6.041	5.500	8.242	8.676
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	12.8	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	8.10	NA
Particulate Emission Rate (lb/hr)	0.521	0.490	0.690	0.736
Particulate Emission Rate (lb/day)	12.5	11.8	16.6	17.7

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

5 - Run 26: Stop at 9:14, Re-start 9:24. Change sample train component.

Averages	R26 (T1&T2)	R27 (T1&T2)
Durag	16.38	23.61
ESA	9.151	13.41
Sigrist	5.771	8.459
Oxygen	10.80	10.90
Moisture	47.97	47.07
Stack Temperature	178.4	177.5

Particulate Concentration (mg/dscm @ 7% O₂) 22.8 22.3 32.4 33.3

Appendix C: Runs R28-R29

Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R28-T1	R28-T2	R29-T1	R29-T2
Date	10/19/2000	10/19/2000	10/19/2000	10/19/2000
First Port Start Time	14:43	14:43	16:34	16:34
First Port Stop Time	15:13	15:13	17:33	17:33
Second Port Start Time	15:21	15:21	17:44	17:44
Second Port Stop Time	15:51	15:51	18:23	18:23
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	None	None	Filter ⁶	Filter ⁶
<u>Gas Conditions</u>				
Temperature (°F)	176	179	177	178
Volumetric Flow Rate (acfm)	18,600	19,800	17,500	18,800
Volumetric Flow Rate (scfm)	15,200	16,100	14,300	15,300
Volumetric Flow Rate (dscfm)	7,990	7,940	7,370	7,810
Carbon Dioxide (%)	6.6	6.4	6.6	6.8
Oxygen (%)	10.00	10.40	10.20	10.20
Moisture (%)	47.51	50.63	48.42	49.15
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0103	0.0118	0.0226	0.0222
Particulate Concentration (mg/dscm @ 7% O ₂)	23.5	27.1	51.7	50.9
Particulate Concentration (mg/acm)	7.90	8.21	16.8	16.2
Particulate Concentration (mg/dNcm-Durag) ¹	18.44	20.45	39.82	39.14
Particulate Concentration (mg/Ncm-ESA) ²	10.38	10.84	22.04	21.36
Particulate Concentration (mg/cm-Sigrist) ³	6.548	6.835	13.90	13.47
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	22.0	20.8
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	13.9	13.1
Particulate Emission Rate (lb/hr)	0.552	0.608	1.10	1.14
Particulate Emission Rate (lb/day)	13.2	14.6	26.4	27.5

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

6 - Run 29: Stop in first port at 16:58. Re-start 17:28. Stop in second port at 17:52. Re-start 18:00. Both stops to change out filter.

Averages	R28 (T1&T2)	R29 (T1&T2)
Durag	19.44	39.48
ESA	10.61	21.70
Sigrist	6.692	13.69
Oxygen	10.20	10.20
Moisture	49.07	48.79
Stack Temperature	177.7	177.2

Particulate Concentration (mg/dscm @ 7% O ₂)	23.5	27.1	51.7	50.9
--	------	------	------	------

Appendix C: Runs R30-R31
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R30-T1	R30-T2	R31-T1	R31-T2
Date	10/19/2000	10/19/2000	10/20/2000	10/20/2000
First Port Start Time	19:04	19:04	8:55	8:55
First Port Stop Time	19:34	19:34	9:25	9:25
Second Port Start Time	19:41	19:41	9:30	9:30
Second Port Stop Time	20:36	20:36	10:00	10:00
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	Filter ⁷	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	179	177	180
Volumetric Flow Rate (acfm)	18,500	18,700	18,600	18,500
Volumetric Flow Rate (scfm)	15,100	15,200	15,100	15,000
Volumetric Flow Rate (dscfm)	7,820	7,600	8,320	7,720
Carbon Dioxide (%)	6.8	6.8	6.4	6.8
Oxygen (%)	10.00	10.00	9.90	9.60
Moisture (%)	48.09	50.03	45.00	48.44
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0350	0.0335	0.02391	0.02109
Particulate Concentration (mg/dscm @ 7% O ₂)	80.0	76.6	54.7	48.3
Particulate Concentration (mg/acm)	26.6	24.4	19.4	16.4
Particulate Concentration (mg/dNcm-Durag) ¹	62.75	60.08	43.30	39.22
Particulate Concentration (mg/Ncm-ESA) ²	34.96	32.22	25.56	21.71
Particulate Concentration (mg/cm-Sigrist) ³	22.05	20.32	16.12	13.69
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	1.84	1.71	1.35	1.14
Particulate Emission Rate (lb/day)	44.1	41.1	32.4	27.2

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

5 - Filters in both sample trains were changed between ports.

7 - Run 30 T 1: Filter changed during port change. Stop Run 19:52, Restart 20:17

Averages	R30 (T1&T2)	R31 (T1&T2)
Durag	61.42	41.26
ESA	33.59	23.63
Sigrist	21.18	14.90
Oxygen	10.00	9.75
Moisture	49.06	46.72
Stack Temperature	178.1	178.5

Particulate Concentration (mg/dscm @ 7% O₂) 80.0 76.6 54.7 48.3

Appendix C: Runs R32-R33
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R32-T1	R32-T2	R33-T1	R33-T2
Date	10/20/2000	10/20/2000	10/20/2000	10/20/2000
First Port Start Time	10:47	10:47	14:13	14:13
First Port Stop Time	11:17	11:17	14:43	14:43
Second Port Start Time	11:36	11:36	14:50	14:50
Second Port Stop Time	12:06	12:06	15:20	15:20
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	Filter ⁵	Filter ⁵	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	179	177	177
Volumetric Flow Rate (acfm)	18,900	19,700	18,500	18,700
Volumetric Flow Rate (scfm)	15,400	16,000	15,100	15,200
Volumetric Flow Rate (dscfm)	8,260	8,220	8,250	8,200
Carbon Dioxide (%)	6.8	6.8	6.6	6.6
Oxygen (%)	9.80	9.60	9.80	9.80
Moisture (%)	46.36	48.57	45.25	46.23
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0142	0.0131	0.0116	0.0113
Particulate Concentration (mg/dscm @ 7% O ₂)	32.4	29.9	26.7	26.0
Particulate Concentration (mg/acm)	11.3	10.2	9.50	9.09
Particulate Concentration (mg/dNcm-Durag) ¹	25.90	24.30	21.30	20.70
Particulate Concentration (mg/Ncm-ESA) ²	14.90	13.40	12.50	12.00
Particulate Concentration (mg/cm-Sigrist) ³	9.400	8.460	7.880	7.540
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.801	0.749	0.658	0.637
Particulate Emission Rate (lb/day)	19.2	18.0	15.8	15.3

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R32 (T1&T2)	R33 (T1&T2)
Durag	25.10	21.00
ESA	14.15	12.25
Sigrist	8.930	7.710
Oxygen	9.70	9.80
Moisture	47.46	45.74
Stack Temperature	177.9	177.3

Particulate Concentration (mg/dscm @ 7% O₂) 32.4 29.9 26.7 26.0

Appendix C: Runs R34-R35
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R34-T1	R34-T2	R35-T1	R35-T2
Date	10/20/2000	10/20/2000	10/20/2000	10/20/2000
First Port Start Time	15:56	15:56	17:33	17:33
First Port Stop Time	16:26	16:26	18:03	18:03
Second Port Start Time	16:32	16:32	18:16	18:16
Second Port Stop Time	17:02	17:02	18:46	18:46
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	178	178	178
Volumetric Flow Rate (acfm)	19,200	18,700	19,600	19,400
Volumetric Flow Rate (scfm)	15,700	15,300	16,000	15,800
Volumetric Flow Rate (dscfm)	8,410	8,180	8,360	8,490
Carbon Dioxide (%)	6.8	6.8	6.8	6.6
Oxygen (%)	9.60	9.70	9.80	10.00
Moisture (%)	46.40	46.58	47.65	46.15
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0107	0.0119	0.0170	0.0165
Particulate Concentration (mg/dscm @ 7% O ₂)	24.5	27.2	38.9	37.8
Particulate Concentration (mg/acm)	8.69	9.53	13.3	13.0
Particulate Concentration (mg/dNcm-Durag) ¹	19.88	21.90	31.07	29.64
Particulate Concentration (mg/Ncm-ESA) ²	11.44	12.55	17.45	17.13
Particulate Concentration (mg/cm-Sigrist) ³	7.213	7.916	11.01	10.80
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.627	0.671	0.973	0.943
Particulate Emission Rate (lb/day)	15.0	16.0	23.3	22.6

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R34 (T1&T2)	R35 (T1&T2)
Durag	20.89	30.35
ESA	12.00	17.29
Sigrist	7.564	10.90
Oxygen	9.65	9.90
Moisture	46.49	46.90
Stack Temperature	177.5	177.6

Particulate Concentration (mg/dscm @ 7% O ₂)	24.5	27.2	38.9	37.8
--	------	------	------	------

Appendix C: Runs R36-R37
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R36-T1	R36-T2	R37-T1	R37-T2
Date	10/21/2000	10/21/2000	10/21/2000	10/21/2000
First Port Start Time	9:00	9:00	10:40	10:40
First Port Stop Time	9:30	9:30	11:10	11:10
Second Port Start Time	9:37	9:37	11:16	11:16
Second Port Stop Time	10:07	10:07	11:46	11:46
Filter Observations	No Change	No Change	Black	Black
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	180	178	180
Volumetric Flow Rate (acfm)	18,100	18,300	18,200	18,000
Volumetric Flow Rate (scfm)	14,700	14,800	14,800	14,600
Volumetric Flow Rate (dscfm)	7,790	7,990	7,760	7,740
Carbon Dioxide (%)	5.8	6.0	6.8	6.8
Oxygen (%)	10.80	10.60	9.80	9.95
Moisture (%)	47.22	46.19	47.74	47.06
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.00242	0.00228	0.00378	0.00361
Particulate Concentration (mg/dscm @ 7% O ₂)	5.55	5.21	8.65	8.26
Particulate Concentration (mg/acm)	1.74	1.69	2.95	2.80
Particulate Concentration (mg/dNcm-Durag) ¹	4.030	3.860	6.905	6.510
Particulate Concentration (mg/Ncm-ESA) ²	2.282	2.229	3.873	3.699
Particulate Concentration (mg/cm-Sigrist) ³	1.439	1.406	2.442	2.332
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.118	0.115	0.201	0.189
Particulate Emission Rate (lb/day)	2.82	2.77	4.82	4.53

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R36 (T1&T2)	R37 (T1&T2)
Durag	3.945	6.708
ESA	2.256	3.786
Sigrist	1.423	2.387
Oxygen	10.70	9.88
Moisture	46.71	47.40
Stack Temperature	178.6	179.0

Particulate Concentration (mg/dscm @ 7% O ₂)	5.55	5.21	8.65	8.26
--	------	------	------	------

Appendix C: Runs R38-R39
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R38-T1	R38-T2	R39-T1	R39-T2
Date	10/21/2000	10/21/2000	10/22/2000	10/22/2000
First Port Start Time	12:14	12:14	8:04	8:04
First Port Stop Time	12:44	12:44	8:34	8:34
Second Port Start Time	12:51	12:51	8:55	8:55
Second Port Stop Time	13:21	13:21	9:25	9:25
Filter Observations	light yellow/greight yellow/green		No Change	No Change
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	179	180	178	179
Volumetric Flow Rate (acfm)	17,800	18,700	17,800	18,100
Volumetric Flow Rate (scfm)	14,500	15,200	14,500	14,700
Volumetric Flow Rate (dscfm)	7,690	8,150	7,560	7,790
Carbon Dioxide (%)	6.7	6.8	7.0	7.0
Oxygen (%)	9.95	9.80	9.60	9.60
Moisture (%)	47.14	46.48	47.99	47.18
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.00597	0.00590	0.0147	0.0144
Particulate Concentration (mg/dscm @ 7% O ₂)	13.7	13.5	33.6	33.1
Particulate Concentration (mg/acm)	4.64	4.70	11.6	11.6
Particulate Concentration (mg/dNcm-Durag) ¹	10.77	10.79	27.35	26.87
Particulate Concentration (mg/Ncm-ESA) ²	6.109	6.195	15.27	15.23
Particulate Concentration (mg/cm-Sigrist) ³	3.853	3.907	9.627	9.606
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.310	0.329	0.774	0.784
Particulate Emission Rate (lb/day)	7.44	7.90	18.6	18.8

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R38 (T1&T2)	R39 (T1&T2)
Durag	10.78	27.11
ESA	6.152	15.25
Sigrist	3.880	9.617
Oxygen	9.88	9.60
Moisture	46.81	47.59
Stack Temperature	179.1	178.7

Particulate Concentration (mg/dscm @ 7% O ₂)	13.7	13.5	33.6	33.1
--	------	------	------	------

Appendix C: Runs R40-R41

Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R40-T1	R40-T2	R41-T1	R41-T2
Date	10/22/2000	10/22/2000	10/22/2000	10/22/2000
First Port Start Time	10:30	10:30	12:08	12:08
First Port Stop Time	11:00	11:00	12:38	12:38
Second Port Start Time	11:10	11:10	12:43	12:43
Second Port Stop Time	11:40	11:40	13:13	13:13
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	177	180	178	180
Volumetric Flow Rate (acfm)	17,700	18,100	18,000	18,200
Volumetric Flow Rate (scfm)	14,400	14,800	14,700	14,800
Volumetric Flow Rate (dscfm)	7,480	7,640	7,570	7,720
Carbon Dioxide (%)	6.9	7.0	6.9	7.0
Oxygen (%)	9.90	9.80	9.95	9.80
Moisture (%)	48.22	48.27	48.54	47.92
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0179	0.0164	0.0139	0.0137
Particulate Concentration (mg/dscm @ 7% O ₂)	41.0	37.6	31.8	31.4
Particulate Concentration (mg/acm)	13.7	12.7	10.5	10.6
Particulate Concentration (mg/dNcm-Durag) ¹	32.42	30.00	25.07	25.07
Particulate Concentration (mg/Ncm-ESA) ²	18.02	16.70	13.85	14.01
Particulate Concentration (mg/cm-Sigrist) ³	11.36	10.50	8.732	8.837
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.909	0.858	0.711	0.725
Particulate Emission Rate (lb/day)	21.8	20.6	17.1	17.4

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R40 (T1&T2)	R41 (T1&T2)
Durag	31.21	25.07
ESA	17.36	13.93
Sigrist	10.93	8.785
Oxygen	9.85	9.88
Moisture	48.24	48.23
Stack Temperature	178.5	179.2

Particulate Concentration (mg/dscm @ 7% O ₂)	41.0	37.6	31.8	31.4
--	------	------	------	------

Appendix C: Runs R42-R43

Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R42-T1	R42-T2	R43-T1	R43-T2
Date	10/22/2000	10/22/2000	10/22/2000	10/22/2000
First Port Start Time	14:28	14:28	16:00	16:00
First Port Stop Time	14:58	14:58	16:30	16:30
Second Port Start Time	15:03	15:03	16:34	16:34
Second Port Stop Time	15:33	15:33	17:04	17:04
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	179	180	179	180
Volumetric Flow Rate (acfm)	17,900	18,900	18,800	18,700
Volumetric Flow Rate (scfm)	14,600	15,400	15,300	15,200
Volumetric Flow Rate (dscfm)	7,520	7,970	8,020	7,940
Carbon Dioxide (%)	7.0	7.0	6.2	6.0
Oxygen (%)	9.8	9.9	9.8	10.0
Moisture (%)	48.6	48.2	47.6	47.9
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.0139	0.0139	0.0152	0.0146
Particulate Concentration (mg/dscm @ 7% O ₂)	31.9	31.8	34.9	33.5
Particulate Concentration (mg/acm)	10.7	10.6	11.9	11.1
Particulate Concentration (mg/dNcm-Durag) ¹	25.56	25.19	27.83	26.24
Particulate Concentration (mg/Ncm-ESA) ²	14.10	14.01	15.64	14.68
Particulate Concentration (mg/cm-Sigrist) ³	8.892	8.832	9.861	9.255
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.720	0.752	0.836	0.781
Particulate Emission Rate (lb/day)	17.3	18.1	20.1	18.7

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R42 (T1&T2)	R43 (T1&T2)
Durag	25.37	27.04
ESA	14.05	15.16
Sigrist	8.862	9.558
Oxygen	9.83	9.90
Moisture	48.39	47.77
Stack Temperature	179.3	179.2

Particulate Concentration (mg/dscm @ 7% O ₂)	31.9	31.8	34.9	33.5
--	------	------	------	------

Appendix C: Runs R44-R45
Phase 3: continued AES Report December 15, 2000

<u>Test Parameters</u>	R44-T1	R44-T2	R45-T1	R45-T2
Date	10/24/2000	10/24/2000	10/24/2000	10/24/2000
First Port Start Time	8:24	8:24	11:07	11:07
First Port Stop Time	9:24	9:24	12:07	12:07
Second Port Start Time	9:34	9:34	12:15	12:15
Second Port Stop Time	10:34	10:34	13:15	13:15
Filter Observations	No Change	No Change	No Change	No Change
Testing Anomalies Noted	None	None	None	None
<u>Gas Conditions</u>				
Temperature (°F)	178	180	177	179
Volumetric Flow Rate (acfm)	17,800	17,500	17,700	18,000
Volumetric Flow Rate (scfm)	14,600	14,300	14,600	14,800
Volumetric Flow Rate (dscfm)	7,750	7,660	7,640	7,690
Carbon Dioxide (%)	6.0	6.5	6.4	6.4
Oxygen (%)	10.80	10.70	10.00	10.20
Moisture (%)	46.86	46.52	47.50	47.95
<u>Particulate Results</u>				
Particulate Concentration (grains/dscf @ 7% O ₂)	0.000810	0.000775	0.000920	0.000545
Particulate Concentration (mg/dscm @ 7% O ₂)	1.85	1.77	2.11	1.25
Particulate Concentration (mg/acm)	0.588	0.570	0.714	0.410
Particulate Concentration (mg/dNcm-Durag) ¹	1.347	1.302	1.650	0.9599
Particulate Concentration (mg/Ncm-ESA) ²	0.7682	0.7473	0.9310	0.5363
Particulate Concentration (mg/cm-Sigrist) ³	0.4845	0.4713	0.5870	0.3382
Particulate Concentration (mg/Ncm-ESA) act moist ^{2,4}	NA	NA	NA	NA
Particulate Concentration (mg/cm-Sigrist) act moist ^{3,4}	NA	NA	NA	NA
Particulate Emission Rate (lb/hr)	0.0391	0.0374	0.0474	0.0277
Particulate Emission Rate (lb/day)	0.939	0.897	1.14	0.664

1 - Units expressed as mg/dNcm-Durag are reported dry and are corrected to 20°C and 1013 mbar.

2 - Units expressed as mg/Ncm-ESA are reported wet and are corrected to 0°C and 1013 mbar.

3 - Units expressed as mg/cm-Sigrist are reported wet and are corrected to 160°C and 1013 mbar.

4 - Units reported as "act moist" disregard the moisture saturation point. Measured moisture values were used for all calcs. NA indicates that the measured value did not exceed saturation.

Averages	R44 (T1&T2)	R45 (T1&T2)
Durag	1.325	1.305
ESA	0.7578	0.7336
Sigrist	0.4779	0.4626
Oxygen	10.8	10.1
Moisture	46.69	47.72
Stack Temperature	178.8	178.0

Particulate Concentration (mg/dscm @ 7% O ₂)	1.85	1.77	2.11	1.25
--	------	------	------	------

Appendix D

Summary of M5i and CEMS Data for Phase 3 Testing

Appendix D: Summary of M5i and CEMS Data for Phase 3 Testing.

Phase 3 ***** Date	19-Oct					20-Oct				
Reference Method 5i - Time	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
Start Time	8:19	10:59	14:43	16:34	19:04	8:55	10:47	14:13	15:56	17:33
Port Stop 1	8:49	11:29	15:13	16:58	19:34	9:25	11:17	14:43	16:26	18:03
Port Start 1	9:01	11:49	15:21	17:28	19:41	9:30	11:36	14:50	16:32	18:16
Port Stop 2	9:14	-	-	17:33	19:52	-	-	-	-	-
Port Start 2	9:24	-	-	17:44	20:17	-	-	-	-	-
Port Stop 3	-	-	-	17:52	-	-	-	-	-	-
Port Start 3	-	-	-	18:00	-	-	-	-	-	-
Stop Time	9:42	12:20	15:51	18:23	20:36	10:00	12:06	15:20	17:02	18:46
Total =	1:01	1:01	1:00	1:00	1:00	1:00	1:00	1:00	1:00	1:00
Reference Method 5i - Data	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
Average Durag (mg/dscm)	16.38	23.61	19.44	39.48	61.42	41.26	25.10	21.00	20.89	30.35
Average ESA (mg/Nm ³)	9.151	13.41	10.61	21.70	33.59	23.63	14.15	12.25	12.00	17.29
Average Sigrist (mg/m ³ PLA)	5.771	8.459	6.692	13.69	21.18	14.90	8.930	7.710	7.564	10.90
Average Oxygen Percent	10.8	10.9	10.2	10.2	10.0	9.75	9.70	9.80	9.65	9.90
Average Moisture Percent	47.97	47.07	49.07	48.79	49.06	46.72	47.46	45.74	46.49	46.90
Average Stack Temperature (°F)	178.4	177.5	177.7	177.2	178.1	178.5	177.9	177.3	177.5	177.6
Average Abs Stack Press (in Hg)	29.44	29.44	29.44	29.44	29.44	29.44	29.44	29.44	29.44	29.44
Incinerator Data	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35
Average Sigrist (mg/m ³ PLA)	0.253909	0.511662	0.239761	1.425907	3.218443	0.529626	0.343226	0.228386	0.367018	0.544798
Average Durag (mA) @ dscm	5.581	6.583	5.891	8.654	9.457	8.433	6.579	5.834	5.848	6.894
Average ESA (mg/Nm ³)	8.67	10.30	9.21	19.69	29.21	20.95	12.50	10.55	10.31	10.86
Average Stack Pressure (mm Hg)	758.08	758.58	757.74	758.24	757.10	758.37	758.62	758.37	758.01	758.03
Average Stack Temperature (°F)	177.3	177.2	178.2	178.1	177.2	178.3	177.5	178.5	178.6	178.6
Average Oxygen Percent	10.4	10.2	10.1	9.9	10.1	10.0	10.1	10.0	9.9	9.9
Ave Primary Waste Feed Rate (lb/hr)	263.3	269.6	259.5	311.0	339.4	0.0	288.3	285.4	286.9	286.4
Ave Aqueous Waste Feed Rate (lb/hr)	176.5	176.6	176.4	255.4	306.5	305.9	180.9	183.3	183.3	256.7
Ave Secondary Waste Feed Rate (lb/hr)	259.0	259.4	259.0	313.3	351.9	0.0	284.2	309.5	309.4	308.9
Ave Solid Waste Feed Rate (lb/hr)	0.0	0.0	0.0	0.0	0.0	0.0	112.2	127.5	152.6	163.2
Ave Saturation Pressure (mm Hg)	366.14	365.38	373.92	372.60	365.22	374.50	367.63	376.21	376.69	376.90
Average Moisture Percent	48.30	48.17	49.35	49.14	48.24	49.38	48.46	49.61	49.69	49.72

(continued)

Phase 3 ***** Date	21-Oct				22-Oct				24-Oct	
Reference Method 5i - Time	R36	R37	R38	R39	R40	R41	R42	R43	R44	R45
Start Time	9:00	10:40	12:14	8:04	10:30	12:08	14:28	16:00	8:24	11:07
Port Stop 1	9:30	11:10	12:44	8:34	11:00	12:38	14:58	16:30	9:24	12:07
Port Start 1	9:37	11:16	12:51	8:55	11:10	12:43	15:03	16:34	9:34	12:15
Port Stop 2	-	-	-	-	-	-	-	-	-	-
Port Start 2	-	-	-	-	-	-	-	-	-	-
Port Stop 3	-	-	-	-	-	-	-	-	-	-
Port Start 3	-	-	-	-	-	-	-	-	-	-
Stop Time	10:07	11:46	13:21	9:25	11:40	13:13	15:33	17:04	10:34	13:15
Total =	1:00	1:00	1:00	1:00	1:00	1:00	1:00	1:00	2:00	2:00
Reference Method 5i - Data	R36	R37	R38	R39	R40	R41	R42	R43	R44	R45
Average Durag (mg/dscm)	3.945	6.708	10.78	27.11	31.21	25.07	25.37	27.04	1.325	1.305
Average ESA (mg/Nm ³)	2.256	3.786	6.152	15.25	17.36	13.93	14.05	15.16	0.7578	0.7336
Average Sigrist (mg/m ³ PLA)	1.423	2.387	3.880	9.617	10.93	8.785	8.862	9.558	0.4779	0.4626
Average Oxygen Percent	10.7	9.88	9.88	9.60	9.85	9.88	9.83	9.90	10.75	10.1
Average Moisture Percent	46.71	47.40	46.81	47.59	48.24	48.23	48.39	47.77	46.69	47.72
Average Stack Temperature (°F)	178.6	179.0	179.1	178.7	178.5	179.2	179.3	179.2	178.8	178.0
Average Abs Stack Press (in Hg)	29.49	29.49	29.49	29.54	29.54	29.54	29.54	29.54	29.69	29.69
Incinerator Data	R36	R37	R38	R39	R40	R41	R42	R43	R44	R45
Average Sigrist (mg/m ³ PLA)	0.011863	0.054513	0.031211	0.383198	0.599869	0.286351	0.320300	0.305484	0.018696	0.017807
Average Durag (mA) @ dscm	4.305	4.525	4.415	6.616	6.373	6.353	6.659	6.916	4.475	4.421
Average ESA (mg/Nm ³)	0.55	3.13	4.52	12.58	12.99	10.75	11.36	11.96	0.08	0.14
Average Stack Pressure (mm Hg)	758.70	759.81	760.08	761.75	762.90	763.66	764.61	764.85	763.89	764.29
Average Stack Temperature (°F)	178.5	179.1	179.4	179.1	179.1	179.7	180.1	179.7	178.4	178.9
Average Oxygen Percent	10.2	9.9	10.0	9.8	9.8	9.8	9.6	9.8	10.2	10.1
Ave Primary Waste Feed Rate (lb/hr)	64.3	189.7	243.1	141.4	237.2	260.9	258.7	258.4	261.7	256.6
Ave Aqueous Waste Feed Rate (lb/hr)	0.0	0.0	0.0	281.4	252.2	286.6	303.4	307.1	0.0	0.0
Ave Secondary Waste Feed Rate (lb/hr)	28.2	0.0	108.9	127.7	240.9	258.4	259.6	260.9	258.9	253.1
Ave Solid Waste Feed Rate (lb/hr)	258.7	323.2	370.3	340.2	332.2	342.7	334.9	71.8	0.0	0.0
Ave Saturation Pressure (mm Hg)	376.00	381.38	383.77	381.41	381.44	385.90	389.84	386.02	375.68	379.41
Average Moisture Percent	49.56	50.19	50.49	50.07	50.00	50.53	50.99	50.47	49.18	49.64

Appendix E

CEMS Sample Spreadsheet Calculations

Appendix E

Summary Spreadsheet Calculations: Durag LINEAR Calibration (Phase 3)

Run No.	n	X _i PM CEM Response	Y _i Reference Method	Sxx	Syy	Sxy	Predict RefMeth			
		Sx	Sy				y _i	(y _i - Y _̄) ²	(Y _i - Y _̄) ²	Y ²
26	1	5.581	16.38	0.571	59.264	5.815	16.866	0.237	59.264	268.304
27	2	6.583	23.61	0.061	0.219	-0.116	26.433	7.970	0.219	557.432
28	3	5.891	19.44	0.198	21.514	2.066	19.826	0.149	21.514	377.914
29	4	8.654	39.48	5.371	237.212	35.695	46.206	45.243	237.212	1558.670
30	5	9.457	61.42	9.738	1394.401	116.530	53.873	56.957	1394.401	3772.416
31	6	8.433	41.26	4.396	295.210	36.024	44.096	8.044	295.210	1702.388
32	7	6.579	25.10	0.059	1.044	0.248	26.395	1.677	1.044	630.010
33	8	5.834	21.00	0.252	9.476	1.546	19.282	2.952	9.476	441.000
34	9	5.848	20.89	0.239	10.165	1.557	19.416	2.174	10.165	436.392
35	10	6.894	30.35	0.311	39.334	3.497	29.402	0.898	39.334	921.123
36	11	4.305	3.945	4.126	405.350	40.898	4.684	0.545	405.350	15.563
37	12	4.525	6.708	3.281	301.728	31.464	6.784	0.006	301.728	44.997
38	13	4.415	10.78	3.692	176.845	25.551	5.734	25.465	176.845	116.208
39	14	6.616	27.11	0.078	9.191	0.848	26.748	0.131	9.191	734.952
40	15	6.373	31.21	0.001	50.861	0.261	24.428	45.995	50.861	974.064
41	16	6.353	25.07	0.000	0.983	0.016	24.237	0.694	0.983	628.505
42	17	6.659	25.37	0.104	1.668	0.417	27.159	3.199	1.668	643.637
43	18	6.916	27.04	0.336	8.772	1.717	29.612	6.617	8.772	731.162
44	19	4.475	1.325	3.465	517.713	42.352	6.307	24.816	517.713	1.756
Total =	19	120.391	457.488	36.280	3540.952	346.387	457.488	233.768	3540.952	14556.493

Average	\bar{X} = 6.336	$f = 17$	Standard error of estimate		s_e = 3.708
	\bar{Y} = 24.078		Standard error of sample		s_y = 14.026
(general equation) $y = b_1x + b_0$		(slope) $b_1 = 9.5477$		125% of Max CEMS	Max Predict Y
{coefficients for linear equ.}		(intercept) $b_0 = -36.4191$			
{CEMS response at emission limit (solution)}		$X = 6.581$		10.82	66.90
{sigma at the emission limit}		$d = 0.0543$		Round to nearest whole number >>>>> n' must be greater that or equal to 2	
		$Tf = 2.110$			
		$CI (\pm) = 1.823$			
{confidence interval calculations}		$Yc\text{-lower} = 24.594$		{tolerance interval calculations}	
		$Yc\text{-upper} = 28.240$		$SSE = 233.77$	
				$SST = 3541.0$	
{correlation coefficient}		$r = 0.9644$		$R = 0.9664$	
		$r^2 = 0.9301$		$R^2 = 0.9340$	
		PS-11		EXCEL	
				$Vf = 1.400$	
				$n' = 18$	
				$Un' = 1.183$	
				$Kt = 1.656$	
				$TI (\pm) = 6.142$	
				$Yt\text{-lower} = 20.276$	
				$Yt\text{-upper} = 32.559$	
				$CI\% = 6.90$	
				$TI\% = 23.25$	

Appendix E (continued)

Summary Spreadsheet Calculations: Durag LOGARITHMIC Calibration (Phase 3)

Run No.	X_i PM CEM Response		Y_i Reference Method		Predict RefMeth						
	n	x	Ln(x)	Sy	Sxx	Syy	LnSxy	y_i	$(y_i - \bar{y})^2$	$(Y_i - \bar{Y})^2$	Y^2
26	1	5.581	1.719	16.38	0.011	59.264	0.796	17.887	2.272	59.264	268.304
27	2	6.583	1.884	23.61	0.004	0.219	-0.029	27.778	17.373	0.219	557.432
28	3	5.891	1.773	19.44	0.002	21.514	0.229	21.125	2.841	21.514	377.914
29	4	8.654	2.158	39.48	0.112	237.212	5.164	44.162	21.925	237.212	1558.670
30	5	9.457	2.247	61.42	0.180	1394.401	15.834	49.477	142.624	1394.401	3772.416
31	6	8.433	2.132	41.26	0.096	295.210	5.317	42.613	1.830	295.210	1702.388
32	7	6.579	1.884	25.10	0.004	1.044	0.062	27.742	6.978	1.044	630.010
33	8	5.834	1.764	21.00	0.003	9.476	0.182	20.543	0.209	9.476	441.000
34	9	5.848	1.766	20.89	0.003	10.165	0.181	20.687	0.041	10.165	436.392
35	10	6.894	1.931	30.35	0.012	39.334	0.677	30.543	0.037	39.334	921.123
36	11	4.305	1.460	3.945	0.132	405.350	7.307	2.338	2.582	405.350	15.563
37	12	4.525	1.510	6.708	0.098	301.728	5.439	5.323	1.917	301.728	44.997
38	13	4.415	1.485	10.78	0.114	176.845	4.491	3.849	48.033	176.845	116.208
39	14	6.616	1.889	27.11	0.004	9.191	0.202	28.078	0.936	9.191	734.952
40	15	6.373	1.852	31.21	0.001	50.861	0.209	25.836	28.878	50.861	974.064
41	16	6.353	1.849	25.07	0.001	0.983	0.026	25.648	0.334	0.983	628.505
42	17	6.659	1.896	25.37	0.005	1.668	0.095	28.466	9.583	1.668	643.637
43	18	6.916	1.934	27.04	0.012	8.772	0.329	30.734	13.645	8.772	731.162
44	19	4.475	1.499	1.325	0.105	517.713	7.377	4.658	11.108	517.713	1.756
Total =	19	120.391	34.632	457.49	0.900	3540.952	53.887	457.488	313.149	3540.952	14556.493

Average	$\ln(\bar{X}) = 1.823$ $\bar{Y} = 24.078$	$f = 17$	Standard error of estimate	$SL = 4.292$
			Standard error of sample	$SV = 14.026$
(general equation) $y = b_1(\ln(x)) + b_0$	(slope) $b_1 = 59.8992$ (intercept) $b_0 = -85.1014$	125% of Max CEMS	Max Predict Y	
{coefficients for logarithmic equ.}		10.82	57.55	
{CEMS response at emission limit (solution)}	$X = 6.435$			$Vf = 1.400$ $n' = 18$ $Un' = 1.183$ $Kt = 1.656$
{sigma at the emission limit}	$d = 0.05$ $Tf = 2.110$ $CI (+/-) = 2.11$		Round to nearest whole number >>>> n' must be greater than or equal to 2	$TI (+/-) = 7.108$
{confidence interval calculations}	$Yc\text{-lower} = 24.307$ $Yc\text{-upper} = 28.528$		{tolerance interval calculations}	$Yt\text{-lower} = 19.309$ $Yt\text{-upper} = 33.526$
{correlation coefficient}	$r = 0.9520$ $r^2 = 0.9064$ PS-11	$SSE = 313.149$ $SST = 3541.0$ $R = 0.9548$ $R^2 = 0.9116$ EXCEL		$CI\% = 7.99$ $TI\% = 26.91$

Appendix E (continued)

Summary Spreadsheet Calculations: Durag POLYNOMIAL Calibration (Phase 3)

Run No.	n	X _i	Y _i	Delta cal using observed PM									
		PM CEM Response	Ref Method	Predict RefMeth							using observed PM		
		S ₁	S ₃	S ₂	S ₅	S ₄	S ₆	S ₇	Y _i	(y _i - Y) ²	D	(Y-Y) ²	Y ²
26	1	5.581	16.38	31.148	173.835	970.171	91.417	510.197	16.698	0.101	0.075	59.264	268.304
27	2	6.583	23.61	43.336	285.280	1877.999	155.425	1023.160	26.031	5.860	0.090	0.219	557.432
28	3	5.891	19.44	34.704	204.441	1204.359	114.521	674.643	19.542	0.010	0.076	21.514	377.914
29	4	8.654	39.48	74.892	648.113	5608.769	341.660	2956.725	46.594	50.604	0.234	237.212	1558.670
30	5	9.457	61.42	89.435	845.785	7998.592	580.849	5493.088	55.028	40.856	0.618	1394.401	3772.416
31	6	8.433	41.26	71.115	599.717	5057.413	347.946	2934.225	44.318	9.349	0.185	295.210	1702.388
32	7	6.579	25.10	43.283	284.760	1873.439	165.133	1086.409	25.993	0.797	0.090	1.044	630.010
33	8	5.834	21.00	34.036	198.563	1158.419	122.514	714.747	19.017	3.934	0.075	9.476	441.000
34	9	5.848	20.89	34.199	199.996	1169.579	122.165	714.419	19.146	3.043	0.075	10.165	436.392
35	10	6.894	30.35	47.527	327.653	2258.838	209.233	1442.452	29.009	1.798	0.096	39.334	921.123
36	11	4.305	3.945	18.533	79.785	343.473	16.983	73.113	5.394	2.101	0.279	405.350	15.563
37	12	4.525	6.708	20.476	92.652	419.251	30.354	137.350	7.297	0.347	0.202	301.728	44.997
38	13	4.415	10.78	19.492	86.058	379.947	47.594	210.126	6.343	19.685	0.237	176.845	116.208
39	14	6.616	27.11	43.771	289.592	1915.940	179.360	1186.644	26.345	0.585	0.091	9.191	734.952
40	15	6.373	31.21	40.615	258.840	1649.589	198.901	1267.598	24.042	51.386	0.086	50.861	974.064
41	16	6.353	25.07	40.361	256.411	1628.979	159.270	1011.840	23.853	1.481	0.086	0.983	628.505
42	17	6.659	25.37	44.342	295.275	1966.238	168.939	1124.964	26.755	1.919	0.092	1.668	643.637
43	18	6.916	27.04	47.831	330.800	2287.810	187.009	1293.352	29.221	4.759	0.096	8.772	731.162
44	19	4.475	1.325	20.026	89.615	401.026	5.929	26.534	6.863	30.667	0.217	517.713	1.756
Total =	19	120.391	457.488	799.122	5547.171	40169.831	3245.200	23881.588	457.488	229.280	3.000	3540.952	14556.493

Average	$\bar{X} = 6.336$ $\bar{Y} = 24.078$	A matrix =	<table><tr><td>19.0</td><td>120.4</td><td>799.1</td></tr><tr><td>120.4</td><td>799.1</td><td>5547.2</td></tr><tr><td>799.1</td><td>5547.2</td><td>40169.8</td></tr></table>	19.0	120.4	799.1	120.4	799.1	5547.2	799.1	5547.2	40169.8	Standard error of estimate	sp = 3.786	Standard error of sample	sy = 14.026	
19.0	120.4	799.1															
120.4	799.1	5547.2															
799.1	5547.2	40169.8															
	$f = 16$	determinant A = 77317.2626	<div>Coefficients for confidence interval calculations</div> <table><tr><td>D = 7.732E+04</td></tr><tr><td>C₀ = 1.719E+01</td></tr><tr><td>C₁ = -5.215E+00</td></tr><tr><td>C₂ = 3.781E-01</td></tr><tr><td>C₃ = 1.612E+00</td></tr><tr><td>C₄ = -1.189E-01</td></tr><tr><td>C₅ = 8.915E-03</td></tr></table>					D = 7.732E+04	C ₀ = 1.719E+01	C ₁ = -5.215E+00	C ₂ = 3.781E-01	C ₃ = 1.612E+00	C ₄ = -1.189E-01	C ₅ = 8.915E-03			
D = 7.732E+04																	
C ₀ = 1.719E+01																	
C ₁ = -5.215E+00																	
C ₂ = 3.781E-01																	
C ₃ = 1.612E+00																	
C ₄ = -1.189E-01																	
C ₅ = 8.915E-03																	
(general equation) $y = b_0 + b_1x + b_2x^2$ (coefficients for quadratic equ.)	<table><tr><td>$b_0 = -27.9362$</td></tr><tr><td>$b_1 = 6.8812$</td></tr><tr><td>$b_2 = 0.2000$</td></tr></table>		$b_0 = -27.9362$	$b_1 = 6.8812$	$b_2 = 0.2000$												
$b_0 = -27.9362$																	
$b_1 = 6.8812$																	
$b_2 = 0.2000$																	
(adjustment to source emission)	<table><tr><td>$b_0' = -54.3534$</td></tr></table>		$b_0' = -54.3534$	Round to nearest whole number >>>> n' must be greater than or equal to 2													
$b_0' = -54.3534$																	
(CEMS ponse at emission limit (solution to quadratic))	<table><tr><td>sign = 1</td></tr><tr><td>X = 6.624</td></tr></table>		sign = 1	X = 6.624	<table><tr><td>Vf = 1.418</td></tr><tr><td>n' = 11</td></tr><tr><td>Un' = 1.203</td></tr><tr><td>Kt = 1.7059</td></tr></table>					Vf = 1.418	n' = 11	Un' = 1.203	Kt = 1.7059				
sign = 1																	
X = 6.624																	
Vf = 1.418																	
n' = 11																	
Un' = 1.203																	
Kt = 1.7059																	
(delta at the emission limit)	<table><tr><td>D = 0.0911</td></tr><tr><td>TI = 2.120</td></tr><tr><td>CI (+/-) = 2.4228</td></tr></table>		D = 0.0911	TI = 2.120	CI (+/-) = 2.4228	(tolerance interval calculations)											
D = 0.0911																	
TI = 2.120																	
CI (+/-) = 2.4228																	
(confidence interval calculations)	<table><tr><td>Yc-lower = 23.994</td></tr><tr><td>Yc-upper = 28.840</td></tr></table>		Yc-lower = 23.994	Yc-upper = 28.840	<table><tr><td>SSE = 229.2804</td></tr><tr><td>SST = 3541.0</td></tr><tr><td>R = 0.9671</td></tr><tr><td>R² = 0.9352</td></tr><tr><td>EXCEL</td></tr></table>					SSE = 229.2804	SST = 3541.0	R = 0.9671	R ² = 0.9352	EXCEL			
Yc-lower = 23.994																	
Yc-upper = 28.840																	
SSE = 229.2804																	
SST = 3541.0																	
R = 0.9671																	
R ² = 0.9352																	
EXCEL																	
(correlation coefficient)	<table><tr><td>r = 0.9629</td></tr><tr><td>r² = 0.9272</td></tr><tr><td>PS-11</td></tr></table>		r = 0.9629	r ² = 0.9272	PS-11	<table><tr><td>$b_2 \sim 0.200$</td></tr><tr><td>$b_2 > 0$, therefore the polynomial curve has a minima</td></tr><tr><td>The minima is below the extrapolated range</td></tr><tr><td>(from data) Max CEM Response = 9.457</td></tr><tr><td>derivative Xmax = -17.20</td></tr><tr><td>extrapolated CEM range (125%) = 10.82</td></tr><tr><td>Max Predict Y = 69.95</td></tr></table>					$b_2 \sim 0.200$	$b_2 > 0$, therefore the polynomial curve has a minima	The minima is below the extrapolated range	(from data) Max CEM Response = 9.457	derivative Xmax = -17.20	extrapolated CEM range (125%) = 10.82	Max Predict Y = 69.95
r = 0.9629																	
r ² = 0.9272																	
PS-11																	
$b_2 \sim 0.200$																	
$b_2 > 0$, therefore the polynomial curve has a minima																	
The minima is below the extrapolated range																	
(from data) Max CEM Response = 9.457																	
derivative Xmax = -17.20																	
extrapolated CEM range (125%) = 10.82																	
Max Predict Y = 69.95																	
	<table><tr><td>CP% = 9.17</td></tr><tr><td>TP% = 24.44</td></tr></table>		CP% = 9.17	TP% = 24.44													
CP% = 9.17																	
TP% = 24.44																	

Appendix E (continued)

Summary Spreadsheet Calculations: ESA LINEAR Calibration (Phase 3)

Run No.	n	X_i PM CEM Response	Y_i Reference Method	Sxx	Syy	Sxy	Predict RefMeth			
		Sx	Sy				y_i	$(y_i - \bar{y})^2$	$(Y_i - \bar{Y})^2$	Y^2
26	1	8.67	9.15	5.720	18.906	10.399	10.856	2.909	18.906	83.741
27	2	10.30	13.41	0.580	0.008	0.068	12.658	0.566	0.008	179.828
28	3	9.21	10.61	3.428	8.347	5.349	11.453	0.711	8.347	112.572
29	4	19.69	21.70	74.450	67.255	70.761	23.033	1.778	67.255	470.890
30	5	29.21	33.59	329.365	403.644	364.618	33.553	0.001	403.644	1128.288
31	6	20.95	23.63	97.781	102.635	100.179	24.426	0.633	102.635	558.377
32	7	12.50	14.15	2.069	0.424	0.936	15.089	0.881	0.424	200.223
33	8	10.55	12.25	0.262	1.560	0.639	12.934	0.468	1.560	150.063
34	9	10.31	12.00	0.565	2.247	1.127	12.669	0.447	2.247	144.000
35	10	10.86	17.29	0.041	14.371	-0.764	13.276	16.109	14.371	298.944
36	11	0.55	2.26	110.493	126.407	118.183	1.884	0.138	126.407	5.090
37	12	3.13	3.79	62.910	94.344	77.040	4.735	0.900	94.344	14.334
38	13	4.52	6.15	42.792	53.980	48.062	6.271	0.014	53.980	37.847
39	14	12.58	15.25	2.306	3.066	2.659	15.177	0.005	3.066	232.563
40	15	12.99	17.36	3.719	14.907	7.445	15.630	2.993	14.907	301.370
41	16	10.75	13.93	0.097	0.186	-0.134	13.155	0.601	0.186	194.045
42	17	11.36	14.05	0.089	0.303	0.164	13.829	0.049	0.303	197.403
43	18	11.96	15.16	0.807	2.759	1.492	14.492	0.446	2.759	229.826
44	19	0.08	0.76	120.595	162.341	139.920	1.365	0.368	162.341	0.574
Total =	19	210.170	256.483	858.068	1077.689	948.142	256.483	30.018	1077.689	4539.975

Average	\bar{X} = 11.062	f = 17	Standard error of estimate		s_L = 1.329
	\bar{Y} = 13.499		Standard error of sample		s_V = 7.738
(general equation) $y = b_1x + b_0$		(slope) b_1 = 1.1050		125% of Max CEMS	Max Predict Y
{coefficients for linear equ.}		(intercept) b_0 = 1.2764			
{CEMS response at emission limit (solution)}		X = 12.305		36.51	41.62
{sigma at the emission limit}		d = 0.0544		Round to nearest whole number >>>>> n' must be greater that or equal to 2	
		Tf = 2.110			
		CI (\pm) = 0.654			
{confidence interval calculations}		$Yc\text{-lower}$ = 14.219		{tolerance interval calculations}	
		$Yc\text{-upper}$ = 15.527		$Yt\text{-lower}$ = 12.672	
{correlation coefficient}		r = 0.9851		$Yt\text{-upper}$ = 17.074	
		r^2 = 0.9705		$CI\%$ = 4.40	
		$PS\text{-}11$		$TI\%$ = 14.80	
		SSE = 30.02			
		SST = 1077.7			
		R = 0.9860			
		R^2 = 0.9721			
		EXCEL			

Appendix E (continued)

Summary Spreadsheet Calculations: ESA LOGARITHMIC Calibration (Phase 3)

Run No.	X_i		Y_i		Predict						
	PM CEM		Reference								
	n	x	Ln(x)	Sy	Sxx	Syy	LnSxy	y_i	$(y_i - \bar{y})^2$	$(Y_i - \bar{Y})^2$	Y^2
26	1	8.67	2.160	9.15	0.032	18.906	-0.783	14.284	26.344	18.906	83.741
27	2	10.30	2.332	13.41	0.124	0.008	-0.031	15.035	2.639	0.008	179.828
28	3	9.21	2.220	10.61	0.058	8.347	-0.695	14.547	15.500	8.347	112.572
29	4	19.69	2.980	21.70	1.000	67.255	8.203	17.859	14.752	67.255	470.890
30	5	29.21	3.375	33.59	1.945	403.644	28.019	19.578	196.323	403.644	1128.288
31	6	20.95	3.042	23.63	1.128	102.635	10.762	18.130	30.254	102.635	558.377
32	7	12.50	2.526	14.15	0.298	0.424	0.355	15.878	2.988	0.424	200.223
33	8	10.55	2.356	12.25	0.142	1.560	-0.470	15.139	8.347	1.560	150.063
34	9	10.31	2.333	12.00	0.125	2.247	-0.530	15.039	9.235	2.247	144.000
35	10	10.86	2.385	17.29	0.164	14.371	1.536	15.265	4.099	14.371	298.944
36	11	0.55	-0.598	2.26	6.645	126.407	28.982	2.262	0.000	126.407	5.090
37	12	3.13	1.141	3.79	0.704	94.344	8.148	9.842	36.680	94.344	14.334
38	13	4.52	1.509	6.15	0.222	53.980	3.463	11.444	28.008	53.980	37.847
39	14	12.58	2.532	15.25	0.305	3.066	0.967	15.906	0.431	3.066	232.563
40	15	12.99	2.564	17.36	0.341	14.907	2.256	16.046	1.726	14.907	301.370
41	16	10.75	2.375	13.93	0.156	0.186	0.170	15.221	1.667	0.186	194.045
42	17	11.36	2.430	14.05	0.203	0.303	0.248	15.462	1.993	0.303	197.403
43	18	11.96	2.482	15.16	0.252	2.759	0.833	15.686	0.277	2.759	229.826
44	19	0.08	-2.526	0.76	20.301	162.341	57.407	-6.142	47.603	162.341	0.574
Total =	19	210.170	37.618	256.483	34.144	1077.689	148.841	256.483	428.864	1077.689	4539.975

Average $\text{Ln}(X) = 1.980$
 $\bar{Y} = 13.499$

$f = 17$

Standard error of estimate $s_e = 5.023$
 Standard error of sample $s_y = 7.738$

(general equation) $y = b_1(\text{Ln}(x)) + b_0$
 (coefficients for logarithmic equ.)

(slope) $b_1 = 4.3592$
 (intercept) $b_0 = 4.8684$

CEMS	Max Predict Y
36.51	20.55

(CEMS response at emission limit (solution))

$X = 9.93$

Round to nearest whole number >>>>
 n' must be greater than or equal to 2

(sigma at the emission limit)

$d = 0.06$

$Tf = 2.110$

$CI (n') = 2.50$

(confidence interval calculations)

$Yc\text{-lower} = 12.376$
 $Yc\text{-upper} = 17.371$

(correlation coefficient)

$r = 0.7607$
 $r^2 = 0.5786$

$SSE = 428.864$
 $SST = 1077.7$
 $R = 0.7759$
 $R^2 = 0.6021$

EXCEL

(tolerance interval calculations)

$Vf = 1.400$
 $n' = 18$
 $Un' = 1.183$
 $Kt = 1.656$

$Tf (\pm) = 8.319$

$Yt\text{-lower} = 6.555$
 $Yt\text{-upper} = 23.192$

$CI\% = 16.79$

$TI\% = 55.93$

Appendix E (continued)

Summary Spreadsheet Calculations: ESA POLYNOMIAL Calibration (Phase 3)

Run No.	X_i PM CEM Response							Y_i Ref Method	Delta cal using observed PM				
	n	S_1	S_3	S_2	S_3	S_4	S_6	S_7	Predict RefMeth	$(Y_i - Y_j)^2$	D	$(Y_i - Y_j)^2$	Y^2
									Y_i				
26	1	8.67	9.15	75.169	651.714	5650.364	79.339	687.871	10.933	3.177	0.067	18.906	83.741
27	2	10.30	13.41	106.090	1092.727	11255.088	138.123	1422.667	12.772	0.407	0.071	0.008	179.828
28	3	9.21	10.61	84.824	781.230	7195.128	97.718	899.984	11.544	0.873	0.069	8.347	112.572
29	4	19.69	21.70	387.696	7633.736	150308.266	427.273	8413.005	23.073	1.885	0.141	67.255	470.890
30	5	29.21	33.59	853.224	24922.676	727991.365	981.164	28659.798	33.011	0.336	0.825	403.644	1128.288
31	6	20.95	23.63	438.903	9195.007	192635.405	495.049	10371.266	24.417	0.620	0.167	102.635	558.377
32	7	12.50	14.15	156.250	1953.125	24414.063	176.875	2210.938	15.230	1.166	0.081	0.424	200.223
33	8	10.55	12.25	111.303	1174.241	12388.247	129.238	1363.456	13.053	0.644	0.072	1.560	150.063
34	9	10.31	12.00	106.296	1095.913	11298.861	123.720	1275.553	12.783	0.614	0.071	2.247	144.000
35	10	10.86	17.29	117.940	1280.824	13909.749	187.769	2039.176	13.400	15.130	0.073	14.371	298.944
36	11	0.55	2.26	0.303	0.166	0.092	1.241	0.682	1.552	0.495	0.327	126.407	5.090
37	12	3.13	3.79	9.797	30.864	95.979	11.850	37.091	4.573	0.619	0.161	94.344	14.334
38	13	4.52	6.15	20.430	92.345	417.401	27.807	125.688	6.185	0.001	0.112	53.980	37.847
39	14	12.58	15.25	158.256	1980.866	25045.088	191.845	2413.410	15.319	0.005	0.062	3.066	232.563
40	15	12.99	17.36	168.740	2191.934	28473.221	225.506	2929.328	15.774	2.517	0.064	14.907	301.370
41	16	10.75	13.93	115.563	1242.297	13354.691	149.748	1609.786	13.277	0.426	0.073	0.186	194.045
42	17	11.36	14.05	129.050	1466.003	16653.799	159.608	1813.147	13.960	0.008	0.075	0.303	197.403
43	18	11.96	15.16	143.042	1710.778	20460.899	181.314	2168.511	14.629	0.282	0.079	2.759	229.826
44	19	0.08	0.76	0.006	0.001	0.000	0.061	0.005	0.998	0.058	0.371	162.341	0.574
Total =	19	210.170	256.483	3182.880	58506.2	1261547.7	3785.247	68441.360	256.483	29.263	3.000	1077.689	4539.975

Average	X̄ = 11.062 Ȳ = 13.499	A matrix =	19.0 210.2 3182.9 210.2 3182.9 58506.2 3182.9 58506.2 1261547.7	Standard error of estimate	sp = 1.352	Standard error of sample	sy = 7.738
	f = 16	determinant A =	1560890862		D = 1.561E+09 C ₀ = 3.795E-01 C ₁ = -5.056E-02 C ₂ = 1.387E-03 C ₃ = 8.866E-03 C ₄ = -2.836E-04 C ₅ = 1.044E-05		
(general equation) y = b ₀ + b ₁ x + b ₂ x ² (coefficients for quadratic equ.)	b ₀ = 0.9033 b ₁ = 1.1812 b ₂ = -0.0028	Coefficients for confidence interval calculations					
(adjustment to source emission)	b ₀ ' = -13.9700	Round to nearest whole number >>>> n' must be greater than or equal to 2				Vf = 1.418 n' = 13 Un' = 1.195 Kt = 1.6945	
(CEMS response at emission limit (solution to quadratic))	sign = 1 X = 12.179					TI (+/-) = 2.2916	
(delta at the emission limit)	D = 0.0797 TI = 2.120 CI (+/-) = 0.8095					Yt-lower = 12.5816 Yt-upper = 17.1648	
(confidence interval calculations)	Yc-lower = 14.064 Yc-upper = 15.683						
(correlation coefficient)	r = 0.9846 r ² = 0.9695 PS-11	SSE = 29.2629 SST = 1077.7 R = 0.9863 R ² = 0.9728 EXCEL				b ₂ ~ -0.003 b ₂ < 0, therefore the polynomial curve has a maxima (from data) Max CEM Response = 29.210 derivative Xmax = 210.27 extrapolated CEM range (125%) = 36.51 Max Predict Y = 40.29	
	CP% = 5.44 TP% = 15.41						

Appendix E (continued)

Summary Spreadsheet Calculations: Sigrist LINEAR Calibration (Phase 3)

Run No.	n	X _i PM CEM Response	Y _i Reference Method	Sxx	Syy	Sxy	Predict RefMeth			
		Sx	Sy				y _i	(y _i - Y _i) ²	(Y _i - ȳ) ²	Y ²
26	1	0.253909	5.7710	0.065158	7.510	0.700	7.091	1.743	7.510	33.304
27	2	0.511662	8.4590	0.000006	0.003	0.000	8.525	0.004	0.003	71.555
28	3	0.239761	6.6920	0.072581	3.310	0.490	7.012	0.103	3.310	44.783
29	4	1.425907	13.6900	0.840408	26.818	4.747	13.612	0.006	26.818	187.416
30	5	3.218443	21.1800	7.340163	160.494	34.323	23.585	5.783	160.494	448.592
31	6	0.529626	14.9000	0.000418	40.815	0.131	8.625	39.373	40.815	222.010
32	7	0.343226	8.9300	0.027537	0.175	-0.069	7.588	1.801	0.175	79.745
33	8	0.228386	7.7100	0.078839	0.642	0.225	6.949	0.579	0.642	59.444
34	9	0.367018	7.5640	0.020207	0.897	0.135	7.720	0.024	0.897	57.214
35	10	0.544798	10.9000	0.001269	5.706	0.085	8.710	4.798	5.706	118.810
36	11	0.011863	1.4230	0.247314	50.245	3.525	5.745	18.676	50.245	2.025
37	12	0.054513	2.3870	0.206713	37.508	2.784	5.982	12.923	37.508	5.698
38	13	0.031211	3.8800	0.228444	21.450	2.214	5.852	3.889	21.450	15.054
39	14	0.383198	9.6170	0.015869	1.222	-0.139	7.811	3.263	1.222	92.487
40	15	0.599869	10.9300	0.008226	5.850	0.219	9.016	3.663	5.850	119.465
41	16	0.286351	8.7850	0.049648	0.075	-0.061	7.272	2.290	0.075	77.176
42	17	0.320300	8.8620	0.035672	0.123	-0.066	7.461	1.964	0.123	78.535
43	18	0.305484	9.5580	0.041488	1.095	-0.213	7.378	4.752	1.095	91.355
44	19	0.018696	0.4779	0.240564	64.537	3.940	5.783	28.139	64.537	0.228
Total =	19	9.674221	161.716	9.520525	428.475	52.969	161.716	133.774	428.475	1804.897

Average	X̄ = 0.509170		f = 17	Standard error of estimate		se = 2.805
	Ȳ = 8.511			Standard error of sample		sy = 4.879
(general equation) y = b ₁ x + b ₀			{(slope) b ₁ = 5.5636 (intercept) b ₀ = 5.6785	125% of Max CEMS		Max Predict Y
{(coefficients for linear equ.)				4.023054		28.06
{(CEMS response at emission limit (solution))			X = 0.665	Round to nearest whole number >>>>> n' must be greater that or equal to 2		Vf = 1.400 n' = 18 Un' = 1.183 Kt = 1.656
{(sigma at the emission limit)}			d = 0.0552 Tf = 2.110 CI (+/-) = 1.390			TI (+/-) = 4.646
{(confidence interval calculations)}			Yc-lower = 7.989 Yc-upper = 10.770	{(tolerance interval calculations)}		Yt-lower = 4.733 Yt-upper = 14.025
{(correlation coefficient)}			r = 0.8182 r ² = 0.6694 PS-11	SSE = 133.77 SST = 428.5 R = 0.8293 R ² = 0.6878 EXCEL		CI% = 14.83 TI% = 49.53

Appendix E (continued)

Summary Spreadsheet Calculations: Sigrist LOGARITHMIC Calibration (Phase 3)

Run No.	X _i PM CEM Response			Y _i Reference Method			Predict RefMeth				
	n	x	Ln(x)	Sy	Sxx	Syy	LnSxy	y _i	(y _i - Y) ²	(Y _i - Y) ²	Y ²
26	1	0.253909	-1.3708	5.7710	0.001	7.510	-0.076	8.600	8.002	7.510	33.304
27	2	0.511662	-0.6701	8.4590	0.531	0.003	-0.038	10.831	5.628	0.003	71.555
28	3	0.239761	-1.4281	6.6920	0.001	3.310	0.054	8.417	2.976	3.310	44.783
29	4	1.425907	0.3548	13.6900	3.074	26.818	9.080	14.095	0.164	26.818	187.416
30	5	3.218443	1.1689	21.1800	6.592	160.494	32.526	16.688	20.176	160.494	448.592
31	6	0.529626	-0.6356	14.9000	0.582	40.815	4.874	10.941	15.672	40.815	222.010
32	7	0.343226	-1.0694	8.9300	0.108	0.175	0.138	9.560	0.396	0.175	79.745
33	8	0.228386	-1.4767	7.7100	0.006	0.642	0.063	8.262	0.305	0.642	59.444
34	9	0.367018	-1.0023	7.5640	0.157	0.897	-0.375	9.773	4.880	0.897	57.214
35	10	0.544798	-0.6073	10.9000	0.626	5.706	1.890	11.031	0.017	5.706	118.810
36	11	0.011863	-4.4343	1.4230	9.216	50.245	21.519	-1.157	6.658	50.245	2.025
37	12	0.054513	-2.9093	2.3870	2.283	37.508	9.253	3.700	1.723	37.508	5.698
38	13	0.031211	-3.4670	3.8800	4.279	21.450	9.580	1.924	3.827	21.450	15.054
39	14	0.383198	-0.9592	9.6170	0.193	1.222	0.486	9.911	0.086	1.222	92.487
40	15	0.599869	-0.5110	10.9300	0.788	5.850	2.146	11.338	0.166	5.850	119.465
41	16	0.286351	-1.2505	8.7850	0.022	0.075	0.040	8.983	0.039	0.075	77.176
42	17	0.320300	-1.1385	8.8620	0.068	0.123	0.091	9.339	0.228	0.123	78.535
43	18	0.305484	-1.1859	9.5580	0.045	1.095	0.223	9.189	0.136	1.095	91.355
44	19	0.018696	-3.9794	0.4779	6.661	64.537	20.734	0.292	0.035	64.537	0.228
Total =	19	9.674221	-26.5718	161.716	35.231	428.475	112.206	161.716	71.116	428.475	1804.897

Average		Ln(X) = -1.399 Y = 8.511	f = 17		Standard error of estimate Standard error of sample		S _e = 2.045 S _y = 4.879	
(general equation) y = b ₁ (Ln(x)) + b ₀ (coefficients for logarithmic equ.)		(slope) b ₁ = 3.1848 (intercept) b ₀ = 12.9654	125% of Max CEMS 4.023054		Max Predict Y 17.40		Vf = 1.400 n' = 18 Un' = 1.183 Kt = 1.656	
{CEMS response at emission limit (solution)}		X = 0.3243	Round to nearest whole number >>>> n' must be greater than or equal to 2		Vf = 1.400 n' = 18 Un' = 1.183 Kt = 1.656		Tl (+/-) = 3.387	
{sigma at the emission limit}		d = 0.0547 Tf = 2.110 CI (+/-) = 1.01	(confidence interval calculations)		(tolerance interval calculations)		Yt-lower = 5.992 Yt-upper = 12.767	
{correlation coefficient}		Yc-lower = 8.370 Yc-upper = 10.389 r = 0.9079 r ² = 0.8243 PS-11	SSE = 71.116 SST = 428.5 R = 0.9132 R ² = 0.8340 EXCEL		CI% = 10.77 TI% = 36.12			

Appendix E (continued)

Summary Spreadsheet Calculations: Sigrist POLYNOMIAL Calibration (Phase 3)

Run No.	n	X_i PM CEM Response						Y_i Ref Method		Delta cal using observed PM			
		S_1	S_5	S_2	S_3	S_4	S_6	S_7	Predict RefMeth		D	$(Y_i - Y_i)^2$	Y^2
									y_i	$(y_i - Y_i)^2$			
26	1	0.253909	5.7710	0.064	0.016	0.004	1.465	0.372	6.804	1.068	0.061	7.510	33.304
27	2	0.511662	8.4590	0.262	0.134	0.069	4.328	2.215	9.929	2.160	0.087	0.003	71.555
28	3	0.239761	6.6920	0.057	0.014	0.003	1.604	0.385	6.622	0.005	0.063	3.310	44.783
29	4	1.425907	13.6900	2.033	2.899	4.134	19.521	27.835	18.041	18.927	0.480	26.818	187.416
30	5	3.218443	21.1800	10.358	33.338	107.296	68.167	219.390	20.498	0.464	0.988	160.494	448.592
31	6	0.529626	14.9000	0.281	0.149	0.079	7.891	4.180	10.133	22.729	0.092	40.815	222.010
32	7	0.343226	8.9300	0.118	0.040	0.014	3.065	1.052	7.929	1.003	0.058	0.175	79.745
33	8	0.228386	7.7100	0.052	0.012	0.003	1.761	0.402	6.475	1.525	0.065	0.642	59.444
34	9	0.367018	7.5640	0.135	0.049	0.018	2.776	1.019	8.221	0.431	0.059	0.897	57.214
35	10	0.544798	10.9000	0.297	0.162	0.088	5.938	3.235	10.303	0.356	0.097	5.706	118.810
36	11	0.011863	1.4230	0.000	0.000	0.000	0.017	0.000	3.535	4.461	0.163	50.245	2.025
37	12	0.054513	2.3870	0.003	0.000	0.000	0.130	0.007	4.135	3.055	0.133	37.508	5.698
38	13	0.031211	3.8800	0.001	0.000	0.000	0.121	0.004	3.808	0.005	0.149	21.450	15.054
39	14	0.383198	9.6170	0.147	0.056	0.022	3.685	1.412	8.417	1.439	0.061	1.222	92.487
40	15	0.599869	10.9300	0.360	0.216	0.129	6.557	3.933	10.913	0.000	0.116	5.850	119.465
41	16	0.286351	8.7850	0.082	0.023	0.007	2.516	0.720	7.218	2.456	0.058	0.075	77.176
42	17	0.320300	8.8620	0.103	0.033	0.011	2.838	0.909	7.644	1.483	0.057	0.123	78.535
43	18	0.305484	9.5580	0.093	0.029	0.009	2.920	0.892	7.459	4.406	0.057	1.095	91.355
44	19	0.018696	0.4779	0.000	0.000	0.000	0.009	0.000	3.632	9.948	0.158	64.537	0.228
Total =	19	9.674221	161.716	14.446	37.170	111.884	135.310	267.962	161.716	75.921	3.000	428.475	1804.897

Average		X̄ = 0.509170 Ȳ = 8.511	A matrix = <table><tr><td>19.000000</td><td>9.674221</td><td>14.446343</td></tr><tr><td>9.674221</td><td>14.446343</td><td>37.170336</td></tr><tr><td>14.446343</td><td>37.170336</td><td>111.884420</td></tr></table>			19.000000	9.674221	14.446343	9.674221	14.446343	37.170336	14.446343	37.170336	111.884420	Standard error of estimate		sp = 2.178	Standard error of sample		sy = 4.879
19.000000	9.674221	14.446343																		
9.674221	14.446343	37.170336																		
14.446343	37.170336	111.884420																		
		t = 16	determinant A = 1362.46																	
(general equation) y = b ₀ + b ₁ x + b ₂ x ² (coefficients for quadratic equ.)			<table><tr><td>b₀ = 3.3666</td></tr><tr><td>b₁ = 14.243</td></tr><tr><td>b₂ = -2.7715</td></tr></table>			b ₀ = 3.3666	b ₁ = 14.243	b ₂ = -2.7715	Coefficients for confidence interval calculations		<table><tr><td>D = 1.362E+03</td></tr><tr><td>C₀ = 1.723E-01</td></tr><tr><td>C₁ = -4.003E-01</td></tr><tr><td>C₂ = 1.108E-01</td></tr><tr><td>C₃ = 1.407E+00</td></tr><tr><td>C₄ = -4.158E-01</td></tr><tr><td>C₅ = 1.328E-01</td></tr></table>		D = 1.362E+03	C ₀ = 1.723E-01	C ₁ = -4.003E-01	C ₂ = 1.108E-01	C ₃ = 1.407E+00	C ₄ = -4.158E-01	C ₅ = 1.328E-01	
b ₀ = 3.3666																				
b ₁ = 14.243																				
b ₂ = -2.7715																				
D = 1.362E+03																				
C ₀ = 1.723E-01																				
C ₁ = -4.003E-01																				
C ₂ = 1.108E-01																				
C ₃ = 1.407E+00																				
C ₄ = -4.158E-01																				
C ₅ = 1.328E-01																				
(adjustment to source emission)		<table><tr><td>b₀' = -6.0127</td></tr></table>	b ₀ ' = -6.0127	Round to nearest whole number >>>> n' must be greater than or equal to 2		<table><tr><td>Vf = 1.418</td></tr><tr><td>n' = 13</td></tr><tr><td>Un' = 1.195</td></tr><tr><td>Kt = 1.6945</td></tr></table>				Vf = 1.418	n' = 13	Un' = 1.195	Kt = 1.6945							
b ₀ ' = -6.0127																				
Vf = 1.418																				
n' = 13																				
Un' = 1.195																				
Kt = 1.6945																				
(CEMS response at emission limit (solution to quadratic))		<table><tr><td>sign = 1</td></tr><tr><td>X = 0.4641</td></tr></table>	sign = 1	X = 0.4641	(tolerance interval calculations)		<table><tr><td>TI (+/-) = 3.6912</td></tr><tr><td>Yt-lower = 5.6881</td></tr><tr><td>Yt-upper = 13.0704</td></tr></table>				TI (+/-) = 3.6912	Yt-lower = 5.6881	Yt-upper = 13.0704							
sign = 1																				
X = 0.4641																				
TI (+/-) = 3.6912																				
Yt-lower = 5.6881																				
Yt-upper = 13.0704																				
(delta at the emission limit)		<table><tr><td>D = 0.0745</td></tr><tr><td>Tf = 2.120</td></tr><tr><td>CI (+/-) = 1.2603</td></tr></table>	D = 0.0745	Tf = 2.120	CI (+/-) = 1.2603	b ₂ < -2.8		b ₂ < 0; therefore the polynomial curve has a maxima Sign of slope does change within extrapolated range (ie. the maxima must exist beyond the CEMS responses)												
D = 0.0745																				
Tf = 2.120																				
CI (+/-) = 1.2603																				
(confidence interval calculations)		<table><tr><td>Yc-lower = 8.119</td></tr><tr><td>Yc-upper = 10.640</td></tr></table>	Yc-lower = 8.119	Yc-upper = 10.640	SSE = 75.9212 SST = 428.5 R = 0.9071 R ² = 0.8228 EXCEL		(from data) Max CEM Response = 3.218443													
Yc-lower = 8.119																				
Yc-upper = 10.640																				
(correlation coefficient)		<table><tr><td>r = 0.8948</td></tr><tr><td>r² = 0.8007</td></tr><tr><td>PS-11</td></tr></table>	r = 0.8948	r ² = 0.8007	PS-11			derivative Xmax = 2.5696												
r = 0.8948																				
r ² = 0.8007																				
PS-11																				
		<table><tr><td>CP% = 13.44</td></tr><tr><td>TP% = 39.35</td></tr></table>	CP% = 13.44	TP% = 39.35			extrapolated CEM range (125%) = 4.02305375 Max Predict Y = 15.81													
CP% = 13.44																				
TP% = 39.35																				

VITA

James A. Calcagno, III received the Bachelor of Science in Mechanical Engineering from the University of New Orleans in Louisiana during 1988. He moved to Huntsville, Alabama to accept a position at Coyne Cylinder Company in Quality Control, where he worked as part of the engineering design team in the improvement and implementation of manufacturing processes. Promoted to Project Engineer, he was responsible for guiding facility compliance with safety and environmental regulations, and he also developed a proficiency in air and water pollution control equipment and permitting. In May 2001, he received the Masters of Science in Environmental Engineering from the University of Tennessee. Currently he is working as a Graduate Research Assistant at the University of Tennessee, where he is also pursuing a Doctors of Philosophy in Civil and Environmental Engineering.