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A Best Practices Guideline for Understanding and Minimizing Uncertainty in CO_2 and Stack Flow Measurements

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ABSTRACT

There is considerable interest within the U.S. electric utility industry in quantifying heat rate improvements using plant-installed continuous emissions monitoring systems (CEMS) instrumentation. However, the limitations to doing so surround the accuracy (or conversely, the uncertainty) of these CEMS measurements. The ability to accurately measure the two key parameters of the heat rate equation - the flue gas carbon dioxide concentration and stack volumetric flow rate – is of key importance. To further the understanding of the accuracy of heat rate measurements using CEMS instrumentation, the Electric Power Research Institute (EPRI) and its members developed this study to quantify the lowest achievable uncertainty through the implementation of a series of best practices to the unit CEMS equipment, i.e., the carbon dioxide (CO_2) and stack flow monitors.

The purpose of this report is to evaluate available information on the performance of CO_2 CEMS and continuous flow monitors, and identify the uncertainty and biases of measurement system parameters with the greatest effect on measurement data quality. Then, using knowledge gained regarding the uncertainty and biases of the system parameters, recommend enhancements to the operation, calibration, maintenance, and auditing of these systems that would extend the usefulness of the CEMS and flow monitors to provide a primary means of unit heat rate determination.

In support of this effort, EPRI developed a multi-faceted approach to identify the state of current industry best practices, and a methodology for achieving reduced uncertainty in the measurements. The approach involved conducting an open literature search pertaining to CEMS operation; contacting end-users for supplemental information regarding CEMS operation, calibration, tune-ups and maintenance practices; determining industry best practices related to pre-RATA flow monitor calibrations, reference methods used, and pre-RATA adjustments; summarizing the effects of different reference method practices on measurement uncertainty; and establishing target uncertainties and identifying whether the instrumentation can achieve same.

Keywords

Continuous emissions monitoring system (CEMS)
Stack flow rate measurement
Carbon dioxide concentration
Heat rate
Measurement Uncertainty

EXECUTIVE SUMMARY

There is considerable interest within the U.S. electric utility industry to quantify heat rate improvements using plant-installed continuous emissions monitoring systems (CEMS) instrumentation. However, the accuracy (or conversely, the uncertainty) of these measurements is a source of some debate. The ability to reliably measure the two key parameters of the heat rate equation - the flue gas carbon dioxide concentration and volumetric flow rate - has become critical due to the recent promulgation of Greenhouse Gas (GHG) policy affecting new units, and proposed rules for existing units. To further the understanding of the accuracy of heat rate measurements using CEMS instrumentation, EPRI and its members developed this study to quantify the lowest achievable uncertainty through the implementation of a series of best practices to the unit CEMS equipment, i.e., the carbon dioxide (CO_2) and flow monitors.

This project is a continuation of an applied research test program conducted by CleanAir Engineering for EPRI in 2014. In 2014, CleanAir conducted a heat rate evaluation on a 40 year old coal-fired unit with a gross capacity of 350 MW using two different techniques, i.e., heat rate based on the input/output method (ASME PTC 4 and ASME PTC 46), and heat rate based on the plant CEMS output. An uncertainty analysis of the results showed that the uncertainty associated with the heat rate calculation using the plant CEMS was approximately 5% at high load.

The purpose of this report is to evaluate available information on the performance of CO_2 CEMS and continuous flow monitors, and identify the uncertainty and biases of measurement system parameters having the greatest effect on measurement data quality. Then, using knowledge gained regarding the uncertainty and biases of the system parameters, recommend enhancements to the operation, calibration, maintenance and auditing of these systems that would extend the usefulness of these CEMS and flow monitors to provide a primary means of unit heat rate determination.

In support of this effort, EPRI developed a multi-faceted approach to identify the state of current industry best practices, and a methodology for achieving reduced uncertainty in the measurements. The approach involved conducting an open literature search pertaining to CEMS operation; contacting end-users for supplemental information regarding CEMS operation, calibration, tune-ups and maintenance practices; determining industry best practices related to pre-RATA flow monitor calibrations, reference methods used, pre-RATA adjustments; summarizing the effects of different reference method practices on measurement uncertainty; and establishing target uncertainties and identifying whether the instrumentation can achieve same.

A model was developed to estimate the uncertainty for the heat rate calculation. The model allows estimation of the uncertainties of the various measurements used to calculate a unit heat rate; hourly heat input including flue gas flow rate, flue gas CO_2 concentration, and the carbon-based fuel factor, and the power output. The model then propagates these individual measurement uncertainties to the final heat rate result.

Findings

A review of previous studies, industry practices, CEMS operational and calibration practices, QA/QC procedures, and reference method enhancements, together with the results from the uncertainty analysis lead to the following key findings:

1. Through implementation of the best practices and procedures identified in this study, the uncertainty associated with the heat rate calculation using plant-installed CEMS instrumentation at 2014 host site could be reduced by approximately 50 percent, to the range of 2.0 to 2.5 percent.
2. Several of the best practice procedures and recommendations identified in this study are not currently being utilized by end users, or by the stack testing industry. Adoption of these practices may require heightened awareness through education and training.

Recommendations – CO_2 CEMS Operation

The following list presents the best practice recommendations for CO_2 CEMS operations.

Sampling System

- Determine source-level and calibration gas molecular weights and dynamically correct CEMS response for changes in the dilution ratio of the sampling system due to temperature, pressure, and molecular weight variations.
- Perform a daily check of the system integrity by alternating between introducing calibration gas standards to the probe and directly to the analyzer.
- Follow a preventive maintenance schedule for probe and sampling system inspection and maintenance.
- Perform a weekly check of the dilution air for contamination with target compounds.
- Sample from a location that is representative of the measurement area measurement. Determine probe placement based on stratification test results.

CO_2 Analyzer

- Use a calibration span that is close to the actual stack gas concentrations. A span value as low as 14% CO_2 (taking into account the dilution ratio of the sampling system) is within the limits of the regulations.
- Perform daily CO_2 calibration error checks with calibration gas standards that are representative of the actual stack gas concentrations. A span value of 14% CO_2 allows high-level span gases as low as 11.2% CO_2 to be used.
- Determine system response time (cycle time) and be consistent in the use of this cycle time throughout the calibrations.
- CEMS analyzers are susceptible to ambient temperature changes. Minimize analyzer drifts by careful siting of analyzer racks or redirecting airflow to maintain analyzer temperature within a ±3°F band.
- Correct analyzer readings for sample pressure fluctuations, unless already done so by analyzer.
- Consider the application of a bias adjustment factor (BAF) if a constant offset bias is diagnosed between reference method test and plant CEMS results.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use calibration gases with a certified accuracy of 1%.
- Use EPA blind calibration gas audit reports as a guide to choosing calibration gas vendors.
- Be consistent with the calibration gas standard concentrations used during the daily calibration error check.

QA/QC Plan

- Rigorously implement the preventative maintenance schedule defined in the quality assurance and control plan.
- Consider creating quality control charts of key system performance parameters.
- Review monitoring and calibration data on a weekly basis.

Recommendations – Continuous Flow Monitor Operation

The following list presents the best practice recommendations for continuous flow monitor system operations.

Flow Monitors – Ultrasonic

- All ultrasonic flow monitors should undergo a daily calibration auto-check, which would include a zero and an upscale system check.
- Ultrasonic flow monitors should undergo a daily interference check which involves purging the transmitter and receiver.
- At a minimum, a quarterly maintenance schedule should be implemented and followed. Quarterly maintenance activities would include visual inspection of the purge nozzle assemblies, and replacement of the purge air filters.

Flow Monitors – Differential Pressure

- Differential pressure flow monitors should undergo a daily calibration check, which would include a zero and an upscale span check of the pressure transducers.
- Differential pressure flow monitors should undergo a daily interference check which involves leak checking the system, and back-purging the pitots.
- A full system calibration should be performed on an annual basis. This would include an electronic test of the pressure transducers and DP transmitters, and the RTDs.

Siting of Flow Monitors

- Computational fluid dynamic (CFD) modeling should be utilized when siting continuous flow monitors in stacks. CFD modeling can aid in identifying and visualizing advanced flow features such as recirculation zones, swirl decay, and velocity profile development. CFD models of stacks can also provide a low cost and efficient means of simulating the effect of using turning vanes, bluff bodies, etc. to mitigate flow stratification, and non-axial flow conditions.

Stack Diameter Verification

- The diameter of the stack at the flow monitor location should be checked using laser distance meters. At least two stack diameter measurements should be obtained, and an average diameter calculated. These measurements should be obtained with the unit on-line operating at normal load conditions in order account for thermal expansion.

Flow Monitor Redundancy

- In the case of ultrasonic flow monitors, which make up approximately two-thirds of all stack flow monitors, the use of two (or more) pairs of ultrasonic units that measure different paths (typically in an X-pattern) could produce more accurate results. It is believed that using redundant ultrasonic monitors in an X-pattern technique will cancel the effect of the pitch flow.

Recommendations – CO_2 Measurement Reference Method Testing

A RATA is performed to identify and quantify the uncertainty of the CO_2 CEMS relative to reference methods. If a systematically low bias is detected between the CO_2 CEMS and the reference methods, the preferable course of action is to determine the cause of the bias and eliminate the problem. Alternatively, Part 75 provides a regulatory remedy. To compensate for a systematically low CEMS measurement detected during a RATA, a bias adjustment factor can be derived from the RATA data and applied to subsequent CO_2 CEMS measurements. The following list presents the best practice recommendations for CO_2 reference method testing.

Testing

- Always perform a 24-point stratification test prior to the start of the RATA to sufficiently characterize the stack cross section.
- Consider the use of a fixed 6-point sampling probe for measurements at minimally stratified stacks to provide enhanced sample point location consistency.
- Consider the use of a fixed 12-point sampling probe for measurements at stratified stacks to provide enhanced sample point location consistency.
- Select the span of the reference method system so that the CO_2 calibration gas standards are as close as possible to the actual stack gas concentrations in order to increase measurement accuracy.
- After initial span and zero adjustments of the reference method analyzer, repeat the procedure to check for drift in adjustments.
- Determine the system response time and be consistent in its use throughout the reference method test, calibration error and system bias checks.

- Consider adopting quality control limits for analyzer calibration error, system bias and drift that are more stringent than the reference method requirements.
- CO_2 analyzers are susceptible to ambient temperature changes. Minimize analyzer drifts by careful siting of analyzer racks or redirecting of airflow to maintain analyzer temperature within a ±3°F band.
- Allow sufficient time for the analyzer to warm up.
- Use a calibrated temperature sensor such as a 4-wire Class-A high temperature resistance temperature detector (RTD) capable of measuring temperature to within ±0.5°F to obtain average stack temperature for determining moisture content in saturated stacks.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use EPA Protocol calibration gases with a certified accuracy of better than 1% of cylinder gas tag value.
- Use EPA blind calibration gas audit reports as a guide to selecting calibration gas vendors.
- Do not over-pressurize the measurement system and analyzer during calibration error and system bias checks.

Recommendations – Flow Measurement Reference Method Testing

The following summary presents the best practice recommendations for reference method flow measurements.

General

- Carefully plan the RATA and analyze tradeoffs between various test and instrumentation options. For example, use of an auto positioning probe will eliminate systematic uncertainty associated with human interaction and control of the measurement instrumentation. However, auto positioning probes rely on the use of the S-Type Pitot probe which is inherently less accurate than the 3-D Pitot probe.
- A pre-RATA tune-up is recommended. If a pre-RATA tune-up is performed, the tester should incorporate as many recommendations contained herein as possible.
- Results from the pre-RATA tune-up can be used to make adjustments to the correlation curve (ultrasonic monitors) and the K factor (differential pressure monitors). It is recommended that flow monitor output agrees with the reference method results to within ± 1 percent.
- A test plan should be prepared for each RATA.

Instrumentation

- The use of an auto positioning probe will eliminate uncertainty associated with human control of, and interaction with the probe and measurement instrumentation. Based on a review of available data among various sources, the use of the auto positioning probe (yaw-nulled mode) will reduce measurement uncertainty by 1-2 percent.
- If an auto positioning probe is not an option, the tester should use a calibrated DAT or spherical 3-D velocity probe. The DAT probe appears to provide consistently lower uncertainty results than the spherical probe.
- The S-Type Pitot probe should not be used for manual testing. If manual testing is to be employed, the tester should use a 3-D velocity probe.
- If manual testing is employed, the tester should utilize a micromanometer that has a certified accuracy as a percent of reading, not as a percent of full scale.

Calibration

- Use a velocity probe calibrated over the flow velocity range of interest.
- The velocity probe should be calibrated in a wind tunnel under conditions anticipated in the field (i.e., velocity, temperature, and turbulence).
- If manual testing is to be employed, the tester should consider utilizing EPA Preliminary Method 007 as the best practice calibration approach for the 3-D velocity probe. Pre-007 will minimize human interaction (yaw-nulling) with the Pitot probe during the test which should improve uncertainty.
- The calibration of 3-D pitot probes should be performed in the range of turbulence intensities expected to be present when the calibrated instrument is used in the field. These calibrations can be conducted by NIST. Note: This approach will likely require a preliminary test of the stack in order to characterize the stack flow turbulence intensity factor. [Comment: While this enhanced calibration procedure would reduce the uncertainty associated with flow measurements, it is recognized that this calibration approach may not be pragmatic for most applications due primarily to the added expense, and lack of formal procedures.]

Testing

- Perform stack traverses using the optimal number of sample points. The use of 12 points for a flow RATA will most likely lead to discretization errors. The tester should consider using 48 total traverse points across two diameters for a RATA.
- The velocity decay due to wall effects should always be measured, and the results corrected accordingly.
- The stack diameter should be verified and measured in the field using a laser distance meter. At least two separate stack diameters should be measured, and the average diameter obtained.
- The velocity probe should be inserted into the stack and allowed to reach the temperature of the effluent gas stream before commencing any testing.

Recommendations – Other

The use of the default or standard F_c-factors as listed in Table 1 in 40 CFR Part 75 Appendix has the potential to introduce additional positive bias (uncertainty) to the heat rate calculation. In order to eliminate this additional uncertainty, the Fc-factor should be calculated on a case-by-case basis whenever possible rather than using the standard Fc-factor. This best practice should be implemented when conducting heat input calculations.

Recommendations – Overview

Table ES-1 provides a summary of the highest priority best practices identified as part of this study and provides estimates pertaining to their implementation and resulting effect on the heat rate uncertainty calculation.

References and Industry Standards

This study produced this guideline prescribing best practices. Those recommendations were identified from interactions with industry experts and from key industry and US EPA publications. Those sources are identified and credited in the Bibliography.

Table ES-1
Prioritized Best Practices and Estimated Effect on Heat Rate Uncertainty

Best Practice Description	**Systematic Uncertainty**	**Estimated Heat Rate Calculation Uncertainty Improvement**
CO_2 CEMS Operation		
Sample from a location that is representative of the measurement area measurement. Determine sampling points based on enhanced stratification test results.	Spatial	3-5%
Span the system with CO_2 calibration gas standards that are more representative of the actual stack gas concentrations in order increase measurement accuracy.	Instrumental	7-10%
Use EPA Protocol gases with a certified accuracy of 1%.		
Perform a daily check of the system integrity by alternating between introducing calibration gas standards to the probe and directly to the analyzer.		
CO_2 RATA Testing		
Conduct a 24- point stratification test	Spatial	3-5%
Use a 6- point sampling probe in minimally stratified stacks		
Use a 12- point sampling probe in stratified stacks		
Span the system with CO_2 calibration gas standards that are more representative of the actual stack gas concentrations in order increase measurement accuracy.	Instrumental	3-5%
Use EPA Protocol gases with a certified accuracy of 1%.		
Use a calibrated Class A RTD for stack gas temperature determination for determining stack gas moisture.		
Flow Monitor Operation		
Use CFD modeling to choose optimum location for flow monitor(s).	Spatial	2-3%
Conduct daily calibration and interference checks.	Instrumental	1-2%
Flow Monitor RATA Testing		
Enhanced flow RATA testing should utilize 48-points on two diameters.	Spatial	7-10%
Verify stack internal diameter using laser detection meter.		
Use an Auto Positioning probe for flow RATA testing.	Instrumental	8-12%
The velocity Pitot probe should be wind tunnel calibrated under conditions anticipated in the field (i.e., velocity, temperature, and turbulence).		
Utilize a micromanometer that has a certified accuracy as a percent of reading, not as a percent of full scale.		
Results from a pre-RATA tune-up should be used to calibrate flow monitors. Flow monitor output should agree with the reference method results to within ± 1 percent.		

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INTRODUCTION

During the past 40 years, the U. S. Environmental Protection Agency (EPA) has promoted the use of continuous emission monitoring systems (CEMS) in both allowance trading programs as well as for compliance determination purposes. Throughout this period, the electric utility industry has continually dealt with increasingly complex and evolving regulatory and equipment-related CEMS issues.

EPA has over the past several years begun to develop and implement its Greenhouse Gas (GHG) policy affecting new units, and it is likely to propose rules for existing units. It is believed that these GHG rules will require emissions and potentially heat rate reporting using CEMS, which in turn will result in renewed importance in the accuracy and precision of carbon dioxide (CO_2) and stack flow monitors.

There is keen interest within the electric utility industry as it relates to quantifying heat rate improvements using plant-installed CEMS instrumentation. However, the accuracy of these measurements is a source of some debate. In support of expanding the knowledge base, EPRI would like to quantify the lowest achievable uncertainty through the implementation of a series of best practices to the unit CEMS equipment, i.e., the CO_2 and flow monitors.

In order to further the understanding of the accuracy of heat rate measurements using CEMS instrumentation, the following scope of work (Task 1) was developed:

- Perform an open literature research for information on industry practices for CEMS operation, calibration, and maintenance.
- Follow-on contact with end users to gather supplemental data not available in open literature.
- Determine recommended and actual practices for instrument operation, tune-ups, calibration, and routine maintenance, including frequency of these actions, types of corrective adjustments made, and effectiveness of corrective procedures.
- Determine industry practices for pre-RATA flow monitor calibrations, including choice of reference methods, level of adjustments made, and prevalence of intermediate adjustments.
- Summarize potential effects of different reference method practices such as choice of method, hardware selection, method uncertainty, and data averaging periods.
- Establish target uncertainties and identify procedures/methodologies to achieve same.
- Determine if a target "closure" uncertainty of 1% of the heat rate calculation using CEMS instrumentation is feasible.

Based on the research findings in Task 1, this document was developed. It represents a "best practices" guide for operating, calibrating, and maintaining a CO_2 CEMS and flow monitors to provide the highest degree of data accuracy practical.

Background

CleanAir Engineering (CleanAir) has been engaged by EPRI to evaluate the use of CEMS for the determination of heat rate (see Eqn. 1) and boiler performance monitoring. If proven to be applicable, CEMS can provide the boiler heat input (see Eqn. 2), which is one half of the inputs required to calculate heat rate and by far the most difficult to measure directly.

$$Heat\ Rate = \frac{Heat\ Input\ (BTU/hr)}{Power\ Output\ (kW)} \tag{1}$$

$$Heat\ Input\ (HI) = Q\left(\frac{1}{F_c}\right)\left(\frac{\%CO_2}{100}\right) \tag{2}$$

Where:

HI = Hourly heat input, MMBtu/hr

Q = hourly flue gas flow rate, scfh (from stack flow monitor)

F_c = carbon-based F-factor for applicable fuel, e.g., 1,800 scf CO_2/MMBtu (for bituminous coal)

$\%CO_2$ = flue gas CO_2 concentration, % vol. (from stack CEMS)

The goal of the project is to demonstrate the level of closure on the “true” boiler heat input that can be achieved when high quality CEMS data are available.

This project is a continuation of work CleanAir performed for EPRI in 2014. In 2014, CleanAir conducted a heat rate evaluation on a 40 year old coal-fired unit with a gross capacity of 350 MW using two different techniques, i.e., heat rate based on the input/output method (ASME PTC 4 and ASME PTC 46), and heat rate based on the plant CEMS output. An uncertainty analysis of the results showed that the uncertainty associated with the heat rate calculation using the plant CEMS was approximately 5% at high load [EPRI 2014].

The 2014 EPRI study focused solely on the uncertainty associated with the heat input calculation. The reported uncertainty of 5% does not include the uncertainty associated with the power output measurement. The 2014 EPRI study also did not take into consideration any potential bias associated with using the industry standard or default Fc-factor.

In most modern power plants, the plants are equipped with power meters which measure gross turbine output. These power meters typically have an accuracy of 0.1%, although there are meters with measurement accuracy as low as 0.04%. Downstream of the turbine, the high voltage and high current is stepped down using transformers. There is an uncertainty associated with the voltage and current transformer meters (referred to as metering class transformers), which is 0.3% for each [CleanAir 2015-1].

Applying root sum square analysis, the total uncertainty for the gross power output measurement is estimated to be approximately 0.4% as shown in Equation 3:

$$U_{Power\ Output} = \sqrt{0.1^2 + 0.3^2 + 0.3^2} = 0.4\% \tag{3}$$

While the estimated uncertainty of 0.4% associated with the power output measurement is less than a tenth of the reported uncertainty of 5% for the heat input calculation, it should be a consideration given the objective of the current effort to achieve “closure” for the heat rate calculation of 1% or less. It should be noted that quantifying the uncertainty associated with power output measurements is beyond the scope of the current effort, and the value of 0.4% is assumed representative of “real world” applications, and will be used in the subsequent analysis.

Accordingly, solving for the heat input uncertainty formula shown in Equation 4, one arrives at a target uncertainty for the heat input calculation of approximately 0.9% as shown in Equation 5. The target uncertainty of 0.9% would represent the combined uncertainties of the CO_2 CEMS and the flow monitor system as indicated in Equation 6.

$$U_{Heat\ Rate} = \sqrt{U^2_{Heat\ Input} + U^2_{Power\ Out}} = 1.0\% \qquad (4)$$

$$U_{Heat\ Input} = \sqrt{1^2 - (0.4)^2} = 0.9\% \qquad (5)$$

$$U_{Heat\ Input} = \sqrt{U^2_{CO2\ CEMs} + U^2_{Flow\ Monitor}} = 0.9\% \qquad (6)$$

It should also be noted that use of the default or standard F_c-factors as listed in Table 1 in 40 CFR Part 75 Appendix has the potential to introduce additional positive bias (uncertainty) to the heat rate calculation. When the F_c-factors were developed in the 1970’s, an average value for the theoretical CO_2 generated by combustion for various fuel sources was determined as a result of an extensive literature survey [Neulicht 1974]. At the time, the variability about the mean was reported to be as high as 5.9% for lignite, and as low as 1.0% for butane and propane. One investigator reported that using the standard F_c-factor resulted in an average positive bias (uncertainty) in heat rate calculations of the order of 2.2% for a bituminous coal burning utility boiler, and 1.6% for a utility boiler burning lignite, when compared to the as-fired coal analyses [McRanie 1997]. Therefore, to eliminate this additional uncertainty, the F_c-factor should be calculated on a case-by-case basis whenever possible rather than using the standard F_c-factor.

Stack CEMS Accuracy and Heat Rate

After installing a 40 CFR Part 75 CEMS, many utilities discovered that CEMS-based heat rates (Btu/kWh) were consistently higher than heat rates based on conventional heat rate calculation methods, such as input/output and output/loss methods. Since the generation (kWh) component of the heat rate is the same for CEMS-based and conventional heat rate calculation methods, the discrepancy was caused by the CEMS-based heat input values being higher than heat input values for the conventional heat rate calculation methods. For many generating units, the CEMS-based heat input was up to 20% higher than that for conventional heat rate methods [EPRI 1997].

Given the electric utility industry’s more than 50-year history with the conventional heat rate determination methods, many utility personnel immediately suspected that the CEMS-based heat input values were erroneously high (rather than the heat input values for conventional heat rate methods being erroneously low). This suspicion was supported in many cases by the fact that the CEMS-based heat input value was thermodynamically improbable.

Of the three variables used in calculating CEMS-based heat input values (flue gas flow rate value, F_c-factor, and flue gas CO_2 concentration), positive bias in the volumetric flow rate was suspected to be the most likely contributor to the high CEMS-based heat input values. Errors in flow measurements were suspected because the flow monitors were new and unproven, whereas CO_2 instruments and F_c-factors had been used for many years.

The effect of problems with flue gas volumetric flow rate measurements could be far reaching. Erroneously high volumetric flow rate measurements would translate into over-reporting of SO_2 and NO_X allowances, as well as under-estimating unit efficiency as defined by the heat rate. Even without regulatory considerations, these issues should be addressed, as they can lead to financial implications as well.

Financial Implications of Heat Rate Measurement Uncertainty

Heat rate provides a measure of how efficiently a power plant converts heat energy input (Btus) into electrical generation output (kWh). Heat rate is the heat energy input per unit of electrical energy output. Heat rate is also the inverse of plant efficiency, accordingly, the lower the heat rate, the more efficient the unit. Heat rate has direct implications on the operating cost of the plant, that is, the lower the heat rate, the less fuel (Btu) that is required to generate a kWh of electrical output.

Typical units of heat rate are Btu_t/kWh_e, where the subscripts refer to thermal (t) and electrical (e) forms of energy. In theory, 3,412 Btu of thermal energy is equivalent to 1 kWh of electric energy. Because of inefficiencies in converting heat energy to electricity (combustion, turbine losses, etc.), heat rates for all generating technologies will exceed 3,412 Btu_t/kWh_e. For a given power plant, heat rate depends on a number of factors including the plant design, its operating conditions, and its level of electrical power output. A typical U.S. coal-fired power plant has a nominal heat rate of 10,000 Btu/kWh and a corresponding generation efficiency (η%) of 3,412/10,000, or 0.3412 (34.12%).

The heat content of coal is in the range of 8,000 Btu/lb to 13,000 Btu/lb. Coal costs range from \$1.5/MMBtu to \$3.0/MMBtu, or approximately \$24/ton to \$78/ton. A typical large coal plant consumes several thousand tons of coal per day. Consider a 500 MW coal-fired utility boiler having a heat rate of 10,000 Btu/kWh, and a capacity factor of 50%, which burns \$2.50/MMBtu coal. A 1% (100 Btu/kWh) improvement (reduction) in net heat rate would translate into an annual savings of approximately \$550,000 in avoided fuel cost. These potential savings are shown graphically in Figure 1-1 below for varying levels of heat rate improvement and unit size.

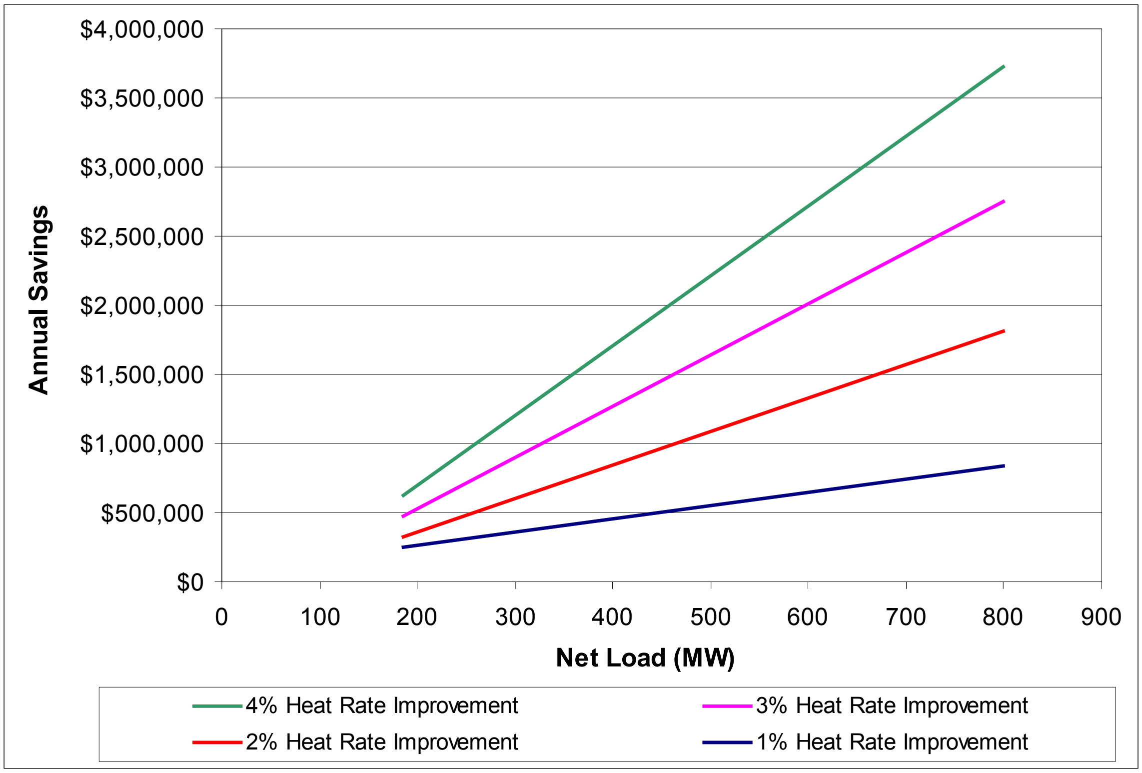

Figure 1-1
Financial Effect of Heat Rate Improvements on Coal-Fired Utility Boilers

Heat rate improvement is also the most readily available means to reduce CO_2 and all other emissions. It is commercially proven and is the most cost-effective and immediately available control process for lowering CO_2. The 1% heat rate reduction described above also corresponds to a 1% reduction in CO_2 emissions, or approximately 40,000 tons/year, which could amount to significant savings if new regulations permit trading of CO_2 credits or impose a “fee” on CO_2 emissions. For example, the 1% reduction in CO_2 emissions may be worth $400,000 per year assuming a $10/ton price for carbon offset credits. Accordingly, it is apparent that the over-reporting of emissions and the inability to accurately quantify heat rate improvements could have multimillion dollar implications on a large utility.

Because heat rate improvements on utility boilers tend to be relatively small and incremental, i.e., of the order of 1%-5%, it is desirable to have a high degree of confidence in the measurements which enter into the heat rate calculations discussed previously. Without the highest possible level of reliability (low uncertainty) in the heat rate related measurements, the utility owner/operator may not be fully cognizant of savings being realized by the plant, nor may he/she be motivated to spend additional time and capital on further improvements.

350 Coal Fired Unit CEMS RATA Uncertainty Summary

In the 2014 test program conducted at a 350 coal fired unit, the concentration of CO_2 in the stack gas and the volumetric flow rate of the stack gas were used in the calculation of heat rate and boiler efficiency. The reliability (uncertainty) of the flow monitor and CEMS measurements was verified by direct comparison to the reference methods (RM) during the RATA testing.

The uncertainty analyses followed procedures outlined in ASME PTC 4 and ASME PTC 19.1. For both the volumetric flow rate and CO_2 concentration measurements, four quantities were evaluated to determine the uncertainty of each parameter. These quantities are defined as follows:

- Offset: The offset represents the bias or the average difference between the RM and the CEMS values for the RATA runs.
- Comparison Uncertainty: The comparison uncertainty represents the bias uncertainty or (95% CI) standard error between the RM and the CEMS values for the RATA runs; or the fluctuation in the sampling mean due to random sampling error.
- Spatial Uncertainty: The spatial uncertainty represents the uncertainty associated with the RATA measurement location. For the flow RATAs, the spatial variation uncertainty was determined by multiplying the average spatial uncertainty coefficient times the ratio of the average volumetric flow rate to the average velocity. For the CO_2 RATAs, the spatial variation uncertainty was determined by multiplying the spatial uncertainty coefficient time the ratio of the student's t-values for the three-point RATA traverse and the six-point spatial distribution test.
- Instrumental Uncertainty: The instrumental uncertainty represents the systematic uncertainty in the reference parameters attributable to the combined uncertainty in the measurements necessary to calculate said measured parameters.

The values for the offset and systematic uncertainty parameters from the 2014 study are summarized in Table 1-1.

Table 1-1
CEMS and Flow Monitor Uncertainty Summary – 350 Coal Fired Unit

Parameter	CEMS Average Value	Offset	Systematic Uncertainty			Total	Total Uncertainty (%)
			Comparison	Spatial	Instrumental		
Flow – High (scfm)	49,045,400	872,200	591,757	802,645	1,557,500	1,849,384	3.8
Flow – Low (scfm)	36,035,300	25,000	222,514	1,166,130	1,774,765	2,135,219	5.9
CO_2 – High (%, vol.)	10.17	0.20	0.08	0.25	0.21	0.33	3.2

The total systematic uncertainty of the boiler heat input can be determined by applying a root sum square analysis to the individual flow and CO_2 CEMS uncertainties. The uncertainty of the boiler heat input at high load is given by the following expression:

$$U_{Heat\ Input,High\ Load} = \sqrt{U_{Flow}^2 + U_{CO2}^2} = \sqrt{(3.8)^2 + (3.2)^2} = 5.0\%$$

A CO_2 RATA was not performed at low load, however using the high load CO_2 uncertainty results; the systematic uncertainty of the boiler heat input at low load is given by:

$$U_{Heat\ Input,Low\ Load} = \sqrt{U_{Flow}^2 + U_{CO2}^2} = \sqrt{(5.9)^2 + (3.2)^2} = 6.7\%$$

The combined average uncertainty for heat input for both loads was determined to be 5.9%. The complete uncertainty calculation from the 2014 study is included as Appendix B of this report.

2

PLANT CO_2 CEM OPERATION

Background

The U.S. EPA has focused its efforts on developing a GHG policy for electric generating units (EGUs). As mentioned in the previous section, proposed rules implementing the policy may require gross heat rate (GHR) reporting based on monitoring results from CEMS installed at coal-fired power plants as part of compliance with the Acid Rain Program monitoring requirements laid out in 40 CFR Part 75.

As a result, the accuracy of stack gas flow and CO_2 measurements have received renewed attention as highlighted by a recent report assessing the uncertainties and biases for each measurement [EPRI 2014]. The sources of error identified for the CO_2 measurement system were associated with the choice of sampling location, sampling system and analyzer biases.

The plant CEMS accuracy and biases are evaluated via a relative accuracy test audit (RATA) by comparing the CEMS performance against independent reference method results. The most common reference method for certifying a CO_2 CEMS is U.S. EPA Method 3A. This method specifies the procedures for extracting a representative sample from the stack and analyzing it using a properly calibrated instrumental CO_2 analyzer, which is assumed to yield the *true* CO_2 concentration in the stack. The specifications for this method are found in 40 CFR Part 60 Appendix A. Ultimately, errors in plant CEMS and reference method measurements manifest themselves in the following uncertainties [EPRI 2014]:

- The average difference between the plant CEMS and reference method measurements performed during a RATA of the plant CEMS.
- The variation about the average difference between the plant CEMS and reference method measurements.
- The variation about each reference method measurement introduced by the spatial variation (stratification) in the CO_2 concentrations measured across the stack by the reference method.
- The instrumental uncertainty of the reference method including uncertainties introduced by the instrumentation, sampling system and measurement method.

Consequently, reducing the uncertainty in the final plant CEMS results can be achieved by ensuring that the plant CEMS: measures a representative flue gas sample, is operated and maintained in accordance with applicable quality control procedures, and any measurement errors are minimized to the greatest extent possible.

Current Instrumentation and Uncertainty

Dilution Probe

Currently, utilities monitor CO_2 content in stack gases primarily to correct pollutant concentrations to a consistent diluent level. Analyzers monitoring the CO_2 content in stack gases are integrated as part of the overall pollutant plant CEMS. These systems consist of a sampling system that extracts a representative gas sample from the stack and conditions the sample which is then transported to an analyzer for subsequent analysis while maintaining the integrity of the sample. At facilities that are subject to 40 CFR Part 75 regulations, this is typically accomplished by diluting the sample prior to transport to the analyzer. Reducing the dew point of the gas sample prevents condensation during transport to the analyzer and eliminates the need to remove the moisture prior to analysis. Furthermore, it provides a concentration measurement on a wet basis consistent with the wet basis of flow measurements. This allows emission rates to be calculated without knowledge of the flue gas moisture content. Dilution ratios typically encountered at 40 CFR Part 75 CEMS installations range from 10-to-1 to 300-to-1, with higher dilution ratios reserved for highly saturated gas streams.

Despite the advantages of the dilution approach, employing dilution probes can contribute to the error in CO_2 measurements. Dilution systems employ an eductor-jet pump and critical orifices to maintain a constant dilution ratio and sample flow rate. The dilution ratio of these systems is fine-tuned during initial installation and finalized by introducing a calibration gas standard of known concentration to the probe and measuring the system response. Once the system is set up, the dilution ratio is assumed to be constant throughout operation. However, this is not always the case as the flow through a critical orifice is dependent on temperature and pressure changes of the gas entering the orifice, as well as the physical properties (e.g., molecular weight) of the gas passing through the orifice.

The actual dilution ratio of a dilution probe can be calculated from the dilution ratio (DR) established under some previous controlled operating conditions, i.e., during initial setup or daily calibration error checks, as follows [Jahnke 2000]:

$$DR = 1 + (DR_0 - 1)\frac{p_0}{p}\frac{\sqrt{MW}}{\sqrt{MW_0}}f(T) \tag{1}$$

Where:

DR_0 = Initial dilution ratio

p_0 = Stack pressure during dilution ratio setup (in. Hg)

p = Stack pressure (in. Hg)

MW_0 = Molecular weight of the sample gas during dilution ratio setup (lb/lb-mole)

MW = Molecular weight of the sample gas (lb/lb-mole)

$f(T)$ = Temperature variation correction factor

The molecular weight bias of the dilution ratio arises when CO_2 gas standards, with molecular weights that are larger than that of actual stack gas, are used during initial setup and daily calibration error checks. According to Equation 1, the dilution ratio of the sampling system increases resulting in lower CO_2 concentrations measured for the gas standard. This may be compensated for by upward adjustment of the analyzer response (either automatically at a pre-determined threshold or by an operator). As a result, when actual stack gas is sampled, and the dilution ratio is lower due to the lower molecular weight of the stack gas (compared to the CO_2 gas standard used during calibration), the concentrations measured by the analyzer increase beyond the true value resulting in a positive measurement bias.

The magnitude of this bias depends on how close the molecular weight of the calibration gas compares to the composition of the actual stack gas. Positive measurement biases between 2% to 5% have been reported [Berry 1998, Roberson 2014]. Table 2-1 shows the change in dilution ratio calculated via Equation 1 for a range of stack gas compositions sampled with a dilution system that was calibrated with a gas standard of 12% CO_2 (dry basis) in a balance of nitrogen (N_2) assuming constant operating conditions (pressures and temperatures).

Table 2-1
Dilution System Molecular Weight Bias

Compounds	Calibration Gas	Stack Gas Composition	
	(%dv)	(%wv)	(%wv)
CO_2	12	10	10
H_2O	0	12	5
O_2	0	9	9
%Δ Molecular Weight		3.9%	1.5%
%Δ Dilution Ratio		2.0%	0.8%

Besides the molecular weight bias, sampling probe dilution ratios are affected by pressure fluctuations upstream of the critical orifice defining the sample flow. According to Equation 1, any variation in pressure in front of the critical orifice can be readily compensated for based on continuous stack pressure readings. The dilution ratio is not only influenced by the pressure upstream of the critical orifice, but also by pressure changes in the eductor-jet pump system which will affect the dilution air flow and ratio.

Dilution ratios are also affected by changes in the gas temperature upstream of the critical orifice and variations in the dilution air temperature. For out-of-stack dilution probes, which allow for tighter temperature control, temperature corrections are usually not necessary, i.e., the temperature variation correction factor f(T) listed in Equation 1 is set to one. In-stack dilution probes require compensation for temperature variations. Correction factors for in-stack probes have been determined empirically based on stack temperatures [Berry 1998]. One proposed correction factor is calculated as follows:

$$f(T) = \frac{\sqrt[4]{T}}{\sqrt[4]{T_0}} \qquad (2)$$

Where:

T_0 = Absolute stack temperature during dilution ratio setup (°R or °K)

T = Absolute stack temperature (°R or °K)

The above considerations can be combined to continuously correct the dilution ratio of in-situ and out-of-stack dilution probes for temperature, pressure and molecular weight fluctuations in the stack gas.

$$[CO_2]_{corr} = [CO_2]_{meas} \cdot DR \qquad (3)$$

Where:

$[CO_2]_{corr}$ = Corrected source level CO_2 concentration (%wv)

$[CO_2]_{meas}$ = Diluted CO_2 concentration measured by the analyzer (%wv)

Some dilution probe vendors implement the above referenced dilution rate corrections in their dilution system packages using additional probe operating parameters in a customized correction algorithm [Brown 2010]. Others provide third-party software packages that allow the retrofitting of existing dilution systems with a dilution correction algorithm [Romero 2005]. In the absence of these proprietary dilution ratio correction implementations, the following procedure has been suggested as an interim solution (see Table 2-2) [Berry 1998]. Successful implementations of various algorithms have been reported, offsetting reductions between independent reference method and plant CEMS results during certification testing [Roberson 2014, Brown 2010, Romero 2005].

Dilution Air Supply

Air supply is another important component of the CEM sampling system. This allows the air used to dilute the sample gas stream to the desired concentration range suited for the CO_2 analyzer. The quality of the dilution air should be checked at regular intervals as contamination can result in a measurement bias. Quality checks can be performed by zeroing the CO_2 analyzer with zero air and then flowing the dilution air directly to the analyzer and checking its response.

Dilution air supplies consist of a variety of filters and scrubber columns. A regular inspection of critical components and operating parameters is recommended to ensure consistent operation.

Table 2-2
Procedure to Correct for Molecular Weight Bias and Pressure Fluctuations

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1. Flow calibration gas directly to analyzer and zero and span CO2 analyzer directly at diluted level. Choose calibration gas concentration close to actual stack gas concentration and take dilution into account for analyzer calibration gas, e.g. for a 12% CO2 source level span and 100-to-1 dilution ratio, span the analyzer with a 1200 ppm CO2 gas standard. Make sure to flow the calibration gas at the same regulator pressure and flow rate used for the sample and calibration gases during normal operation.
2. Flow source level calibration gas (e.g. 12% CO2) to the probe and adjust eductor pressure control so that analyzer response to diluted sample matches calibration gas concentration at the desired dilution ratio. This is the initial dilution ratio (DR0).
3. Record sample/stack pressure, critical orifice/stack temp and molecular weight of calibration gas (p0, T0, MW0). These are the initial operating conditions.
4. Input the initial values into the correction algorithm considering the specific probe design (in-situ or out-of-stack dilution probes).
5. Use sample/stack pressure (p) and critical orifice/stack temp (T) measured during regular operation for dynamic dilution rate calculation and CO2 concentration correction according to equations 1 through 3. Calculate molecular weight based on CO2 and O2 readings, if an O2 analyzer is installed as part of the CEMS. If no O2 analyzer is present, calculate stack gas O2 content from CO2 readings and fuel specific fuel factor (EPA Method 3B).

$$\%O_2 = 20.9\% - F_o \cdot \left(\frac{\%CO_2}{100\% - \%H_2O}\right) \tag{4}$$

$$\%N_2 = 100\% - \left(\%CO_2 + \frac{\%O_2}{100\% - \%H_2O} + \%H_2O\right) \tag{5}$$

$$MW = \frac{1}{100\%} \cdot \left(44 \cdot \%CO_2 + 18 \cdot \%H_2O + 28 \cdot \%N_2 + \frac{32 \cdot \%O_2}{100\% - \%H_2O}\right) \tag{6}$$

Where:

$\%O_2$ = Percent oxygen by volume on a dry basis (%dv). 0% during calibration.

$\%CO_2$ = Percent carbon dioxide on a wet basis (%wv) during sampling and dry basis during calibration (%dv).

$\%H_2O$ = Percent moisture by volume. Based on recent stack test result and assumed to remain constant. 0% during calibration.

$\%N_2$ = Percent nitrogen by volume on a wet basis (%wv) during sampling and dry basis (%dv) during calibration.

F_o = Fuel factor. Chose fuel factor specific to fuels burned.

MW = Continuously calculated molecular weight of the stack gas during sampling.

6. Perform daily calibration checks using a span gas level that is similar to the one used during dilution rate setup. Calibration gases with CO_2 concentrations that resemble actual stack gas concentrations are preferred for increased accuracy. Use consistent flow rates and calibration gas pressures.

Analyzer

CEMS biases can originate from a variety of sources within the system. The analyzer can also have a significant effect on the measurement error. Biases introduced by the analyzer can be caused by interferences in the detection step by compounds other than the target compound, ambient effects, and system calibration. Interferences in the detection step are typically addressed by selecting a measurement technique that is specific to the target compound only, removing the interfering species prior to detection, or measuring the target compound as well as the interfering species in order to determine their contribution to the measured signal, and subsequently applying a correction based on those measurements.

In the case of CO_2, the predominant principle of detection found in analyzers currently installed in the industry is non-dispersive infrared (NDIR) spectrometry. The NDIR approach is often combined with a variety of optical filters to minimize cross interferences between compounds other than CO_2 present in the stack gas. A common approach is the use of the established gas filter correlation (GFC) technique. This approach removes the biases imparted by interfering compounds in the detection step by spectra correlation. Analyzers based on this analytical technique are relatively linear (linearity of about ±1.0% of the analyzer scale), and typically exhibit accuracies of ±1.0% of the analyzer scale with a precision of ±1.0% of the analyzer reading [ThermoScientific 2015, Teledyne 2010, Servomex 2014]. With an analyzer scale of 20% CO_2 and a source level reading of 10.0% CO_2, this would result in a nominal accuracy of ±0.2% CO_2 and a precision of ±0.1% CO_2.

The performance of each analyzer can be affected by a variety of factors, such as changes in ambient temperature and pressure, vibrations, etc. The majority of these can be minimized by system design or compensated for by the application of a correction factor. If not already implemented by the analyzer manufacturer, the need for reducing the error in CO_2 measurements requires consideration of pressure and temperature compensation. Besides changing the gas density in the sample gas cell (temperature and pressure), fluctuating temperatures can affect the electronic circuitry resulting in analyzer span and zero drift. Temperature fluctuations should be minimized by siting the analyzer in a temperature controlled enclosure or shelter with well dispersed airflows. Ambient pressure corrections should be performed on the raw analyzer signal prior to any dilution ratio correction. The measured CO_2 concentrations are corrected as follows:

$$[CO_2]_{corr} = [CO_2]_{meas} \frac{p_{std}}{p_{amb}} \qquad (4)$$

Where:

$[CO_2]_{corr}$ = Corrected CO_2 concentration (%dv or %wv)

$[CO_2]_{meas}$ = Diluted CO_2 concentration measured by the analyzer (%dv or %wv)

p_{std} = Pressure at standard conditions (29.92 in. Hg)

P_{amb} = Ambient pressure during measurement (in. Hg)

Calibration

Periodic calibration checks evaluate CEMS performance. These checks provide an independent assessment of the system operation by establishing the system response to a gas standard in comparison to a National Institute of Standards and Technology (NIST) gaseous standard reference material (SRM). Procedures for tracing gas standards to NIST SRMs were established in the U.S. EPA Traceability Protocol Number 1 and its revisions [U.S. EPA 1997].

The measurement range of the analyzer is a compromise between the need to prevent full-scale exceedances (large range) and the necessity to ensure good measurement accuracy and maintain a good signal-to-noise ratio (lower range). To meet these objectives, Section 2.1 of Appendix A to 40 CFR Part 75 specifies that the analyzer scale must be selected so that actual stack gas concentrations fall within 20 to 80% of its full-scale range. As a result, analyzer ranges are set so that source level CO_2 concentrations of up to 20% CO_2 can be measured.

The maximum potential CO_2 concentration (MPC) for utility boilers is 14% CO_2 (Section 2.1.3.1 of Appendix A to 40 CFR Part 75). In order to provide for a more accurate calibration around the expected stack gas concentration levels (generally between 9%-12% CO_2) rather than analyzer range, Section 2.1.3.1 of Appendix A to 40 CFR Part 75 allows the use of a separate calibration span value, which sets the upper limit of the analyzer's calibration and is smaller or equal to the analyzer range. Calibration span values are typically set so that the measured stack gas concentrations fall within 20% to 100% of the span. In the case of utility boilers, the calibration span value should be set between 14% (MPC) and 20.0% (Section 2.1.3.1 of Appendix A to 40 CFR Part 75). This allows the use of a high-level concentration calibration gas with concentrations from 11.2% to 14% CO_2 (80.0% to 100.0% of span) for analyzer span calibrations (daily calibration error checks), ultimately providing for a more accurate measurement.

Before reaching the analyzer, the source level sample and CO_2 gas standards are diluted according to the sampling probe dilution ratio. As a result, the gas concentrations seen by the analyzer are much lower than the source levels encountered in the stack. Thus, the span of the CO_2 analyzer is a function of the dilution ratio of the sampling probe, i.e., a system span value of 14% at a dilution ratio of 100-to-1 would translate into a span value of 1,400 ppm CO_2 as measured at the analyzer.

Compressed cylinder gases used as calibration gas standards for 40 CFR Part 75 quality control measures are required to be produced and certified in accordance with the EPA Traceability Protocol for Assay and Certification of Gaseous Calibration Standards [U.S. EPA 1997]. Such gases, also known as EPA Protocol 1 gases, must be certified to have an analytical uncertainty of not more than ±2% (inclusive) of the certified concentration (tag value) of the gas mixture (40 CFR Part 75, Appendix A, Section 5.1.4(b)). As gas standards with an analytical uncertainty of ±1% have become readily available, it is recommended to use Protocol 1 gases with the increased accuracy for a tighter control of the measurement error.

The capability of gas manufacturers to provide accurate gas standards is periodically checked by the U.S. EPA [U.S. EPA 2011]. Results of a recent blind audit of EPA protocol calibration gas cylinder mixtures produced by specialty gas manufacturers with an accuracy claim of ±1.0% of the certified tag value are listed in Table 2-3 and summarized in Figure 2-1. Although some manufacturers were not able to meet specifications, most of the CO_2 gas standards supplied were well within the accuracy claim of ±1.0% of the gas standards tag value, with a median accuracy of 0.4% and mean of 0.6%.

Table 2-3
U.S. EPA 2010 Blind Audit Results for CO_2 Calibration Gases

Producer	State	Cylinder	Low	Mid	High
Air Liquide	CO	3	0.14	0.26	0.10
	MI	3	0.63	0.21	0.33
	TX	3	0.01	0.08	0.26
Airgas	IL	6	0.82	2.66*	0.54
	NC	3	0.37	0.47	0.06
	NJ	3	0.33	0.76	1.69**
Linde	NJ	3	0.54	0.21	0.04
Liquid Technology	FL	3	3.24*	0.97	0.49
Matheson Tri-Gas	OH	6	0.45	0.53	0.94
Praxair	CA	3	0.15	0.31	1.05**
	PA	6	0.56	0.55	1.19**
Red Ball Oxygen	LA	3	0.52	0.44	0.31
Scott-Marrin	CA	3	0.13	0.27	0.56
Specialty Air Technologies	CA	3	0.19	0.61	0.19
Specialty Gases of America	OH	6	0.24	0.38	0.92

* Fails protocol requirements (±2%)

** Meets protocol requirements (±2%), but fails ±1% accuracy claim

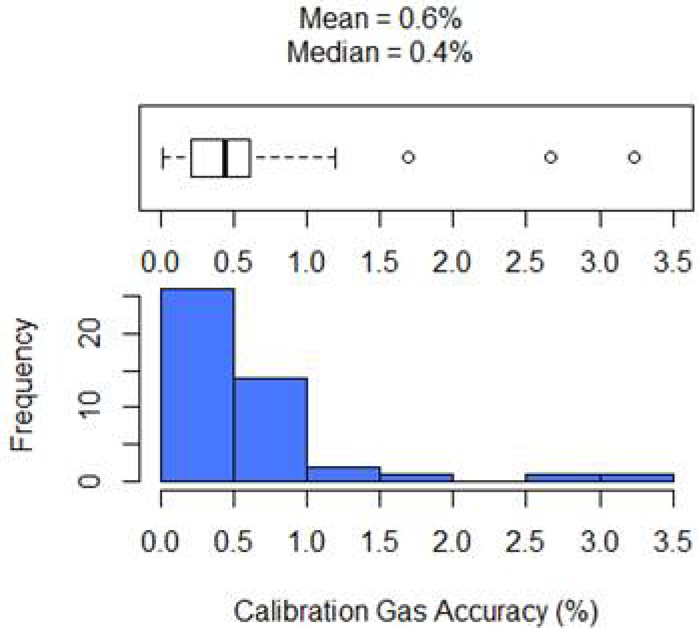


Figure 2-1
Financial Calibration Gas Audit Result Histogram and Box Plot

To ensure the consistent quality of the gas standard used for daily calibration checks, it is good practice to cross check the tag value of newly purchased calibration gases. This is best achieved by flowing the newly purchased calibration gas directly to the analyzer previously calibrated by the outgoing calibration gas. If the analyzer response deviates by more than ±1.0% from the tag value of the new gas cylinder, that cylinder should be removed from service. For a tighter control, consider using the median (0.4%) of the U.S. EPA blind audit results as a decision guideline. It is also good practice to verify that new zero level gas standards used for daily calibration error checks are not contaminated.

After the calibration error check, the regulation allows for the adjustment of analyzer settings to compensate for any analyzer drift that occurred between calibration checks. This can be done daily or after a maximum calibration error control limit is exceeded. While this approach ensures accurate measurements, it may mask issues that might arise in each CEM subsystem by continuous adjustment of the analyzer span and zero settings away from the analyzer baseline calibration. Therefore, it is good practice to periodically introduce zero and span calibration gas standards of appropriate concentration directly to the analyzer to gauge any system and analyzer trends.

For instance, if a span calibration gas of 12% CO_2 is used for the system calibration error checks of a CEMS employing a 100-to-1 ratio dilution probe, then the concentration of the span gas used for the direct analyzer calibration check should be 1,200 ppm CO_2. A staged probe and analyzer calibration check approach helps to diagnose problems that affect the sample integrity, such as sampling system leaks, filter pluggage, etc., that would otherwise remain undetected and eventually necessitate longer system outages for corrective actions and maintenance.

Care should be taken to flow the calibration gas standard to the analyzer or different parts of the sampling system at flow rates and delivery pressures identical to those encountered during regular monitoring. In addition to the required calibration error check, others have suggested to frequently perform multipoint analyzer calibrations in order to generate data of the highest confidence [U.S. EPA 1994]. Recommended intervals are every three months, any time after a major disassembly of components, or when the zero or span checks give results that are outside the established performance limits.

System Response Time

CEMS response times are expressed in terms of cycle times, which is the time it takes for 95.0% of the step change to be achieved between the stable stack emissions value and the stable ending of a calibration gas reading. Cycle times are typically divided into upscale and downscale cycle times, which correspond to the time it takes the CEMS to respond to a high-level or zero calibration gas standard introduced to the probe prior to any filter or sample conditioning equipment. Upscale and downscale cycle times can be based on the order of minutes and may vary due to the physiochemical properties of the target compound, although CO_2 does not commonly adsorb or react with the sampling system surfaces.

Biases due to the system response times can occur when calibrations are performed and not enough time is allowed to elapse between introducing the calibration gas standard to the time the calibration is completed. This may result in analyzer span and zero levels adjusted based on premature system responses. According to 40 CFR Part 75 Appendix A, a stable reading of stack emissions or calibration gas concentrations is equivalent to a reading with a change of less than 2.0% of the span value for two minutes, or a reading with a change of less than 6.0% from the measured average concentration over six minutes. The reading is considered stable if it changes by no more than 0.2% CO_2 for two minutes (40 CFR Part 75 Appendix A). The cycle time of the analyzer is then set as the slower of the two cycle times (upscale or downscale).

To avoid biases introduced from incomplete calibrations or inconsistent cycle times, properly characterize the system response and be consistent in the application of the cycle times from calibration to calibration. Consider using the alternative definition of a stable CO_2 reading when determining the system response.

Measurement Location

A potentially significant source of bias in CO_2 measurements is concentration stratification in the stack [U.S. EPA 1994, EPRI 2014]. The tip of the sampling probe for the CEMS should be located at a point representative of the average concentration profile within the stack. The ability to do this becomes more critical as the variation in concentration within the cross section of the stack becomes more severe. If the stack concentration is relatively uniform, i.e. there are minimal or no spatial differences in CO_2 concentrations across the stack, different sampling locations will not result in a significant bias in the CO_2 measurements.

Stratified stacks could give rise to a discrepancy in CO_2 concentrations measured by the probe unless it is properly sited. This discrepancy could be addressed by applying a bias adjustment factor (BAF), normally determined during a RATA. This would result in more accurate measurements as long as the stratification profile in the stack does not change with different load or plant operating conditions. However, if the stratification profile changes with different operating conditions, then the application of a single BAF has the potential to yield measurements that are not representative of the overall stack CO_2 concentration.

The position of the plant CEMS measurement location is defined in Performance Specification 3 (specification and test procedures for O_2 and CO_2 continuous emission monitoring systems in stationary sources) (40 CFR Part 60 Appendix B), requiring the plant CEMS measurement location to be at a point in the stack that yields CO_2 measurements that are representative or can be corrected to become representative of the total CO_2 concentration at the measurement location cross section and subsequently will pass a RATA conducted using an independent reference method.

The representativeness of the measurement location is typically determined by conducting a stratification test according to guidelines in Section 6.5.6 of Appendix A to 40 CFR Part 75. If this test indicates that the plant CEMS measurement location does not yield representative measurement results, then the CEMS probe may be moved to a position that more closely matches the average CO_2 concentration in the stack as determined by the comprehensive stratification test.

Moving a plant CEMS probe after installation may be difficult to achieve. However, as mentioned above, under certain conditions (stable stratification), a BAF is justified to correct the measurement location bias, ultimately leading to more accurate CO_2 measurements. This is possible since the specifications for a CO_2 monitor are strictly performance based. This allows for the use of a variety of correction approaches as long as they are used consistently throughout certification, routine measurements and quality assurance/quality control (QA/QC) checks, and the CEMS ultimately passes the RATA. However, before applying a BAF, it is recommended to analyze all available data carefully to investigate and thoroughly understand the cause of the system bias, and to eliminate the bias if possible.

Current Operating Practices and Procedures

Discussion of 40 CFR Part 75 Requirements

Procedures and criteria for plant CEMS siting, operation, quality control measures and assurance programs are described in detail in Performance Specification 3 (Specifications and Test Procedures for O_2 and CO_2 Continuous Emission Monitoring Systems in Stationary Sources) of 40 CFR Part 60 Appendix B and the respective paragraphs of 40 CFR Part 75, Appendix A (Specifications and Test Procedures) and Appendix B (Quality Assurance and Quality Control Procedures). The data quality objectives detailed in these regulations are listed in Table 2-4, along with typical corrective actions taken in case that the objectives are not met.

Table 2-4
40 CFR Part 75 System Data Quality Objectives

Test	Frequency	Criteria	Corrective Action	
2 Point Calibration Error Test	Daily	$\lvert R - A \rvert \leq 1.0\%\ CO_2$	Adjust analyzer zero and span	40 CFR 75, App. B, Section 2.1.4(a)
3 Point Linearity Error Check (LE)	Quarterly	$LE = 100\% \cdot \lvert R - A \rvert / R \leq 5.0\%$ or $\lvert R - A \rvert \leq 0.5\%\ CO_2$	Adjust analyzer zero and span	40 CFR 75, App. A, Section 3.2.
Relative Accuracy (RA) Test Audit	Semiannual	$7.5\% < RA \leq 10.0\%$ or $\pm 1.0\%\ CO_2$	Identify and eliminate problem	40 CFR 75, App. A, Section 3.3.3
	Annual	$RA \leq 7.5\%$ or $\pm 0.7\%\ CO_2$	Identify and eliminate problem	40 CFR 75, App. B, Section 2.3.1.2

R = Reference value of low -, mid - or high - level calibration gas introduced into the monitoring system

A = Average of the monitoring system responses

LE = Percentage linearity error, based upon the reference value

RA = Relative accuracy

Relative accuracy demonstrates the accuracy of the plant CEMS relative to its deviation from the reference method. As such, the relative accuracy is expressed as the percentage of the average concentration levels encountered during the RATA, rather than a percentage of the instrument span. Specifically, the relative accuracy is defined as the absolute mean difference between the gas concentrations determined by the plant CEMS and the value determined by the reference method, plus the 2.5% error confidence coefficient of a series of tests divided by the mean of the reference method. RATAs can be performed on an annual basis if the relative accuracy during the previous audit for the monitor was ≤7.5% (or ±0.7% for CO_2).

In order to increase the accuracy in heat rate calculations, it is important to minimize calibration and linearity errors below the data quality limit currently accepted for CO_2 reporting purposes. A recent study on CO_2 measurement uncertainty and its influence on the boiler heat rate calculations concluded that current measurement errors resulted in a substantial uncertainty of the calculated heat rate. A case study determined the contribution of CO_2 measurement error to the boiler heat rate uncertainty to be approximately 5% at high load [EPRI 2014].

In terms of actual CO_2 concentrations, this corresponded to an uncertainty of approximately 0.5% CO_2 at a measured average CO_2 concentration of 10.2% CO_2 on (wet basis). Accordingly, the data quality objectives listed in Table 2-4, although appropriate for CO_2 reporting purposes, are not sufficient to ensure more accurate heat rate results. Consequently, the control limit for the daily calibration error check and quarterly assessed linearity error should be much less than the regulatory limits of 1.0% and 0.5% CO_2, respectively, mandated in 40 CFR Part 75.

To achieve a 50% reduction in the overall uncertainty in the heat rate calculation, as suggested as a target in a recent report [EPRI 2014], the control limits should be comparable to the CO_2 analyzer uncertainty specifications (reported by the analyzer manufacturers). The majority of the analyzer manufacturers report an uncertainty of about 1.0% of the analyzer range. Assuming a source level range of 20% CO_2, this would translate into a control limit of 0.20% CO_2.

The ability to achieve and maintain the highest possible data quality objectives requires the implementation of a quality assurance and quality control (QA/QC) program, as is required by 40 CFR Part 75 Appendix B Section 1. The QA/QC plan should address maintenance measures such as regular removal and cleaning of sampling probe, vacuum pump inspection and/or replacement, etc. These measures should be aimed at preventing problems from developing over time and establish control limits on key system performance indicators such as calibration drift and linearity error that would trigger preventive maintenance actions.

Another useful tool for detecting deviations from expected performance levels are quality control charts. Plotting key system performance indicators over time can help detect the onset of performance deterioration and help maintain system measurement accuracy at optimum levels.

Discussion of 40 CFR Part 60 Requirements

Facilities regulated in 40 CFR Part 60 are subject to CEMS operating requirements and quality control procedures described in Performance Specification 3 of 40 CFR Part 60 Appendix B as well as the respective paragraphs of 40 CFR Part 60, Appendix F (Quality Assurance Procedures). The data quality objectives detailed in these regulations are shown in Table 2-5.

Similar to 40 CFR Part 75 Appendices A and B, the quality assurance procedures in 40 CFR Part 60 check the quality of the CEMS data by estimating accuracy and thus control and improve data quality by implementing quality control policies and corrective actions. Each facility must have a written quality control plan which describes procedures for CEM systems calibration, calibration drift determination and CEMS adjustment, preventive maintenance measures and corrective actions, and accuracy audit procedures. Although there are certain similarities in the quality assurance program, quality control requirements of 40 CFR Part 75 are more restrictive than those of 40 CFR Part 60.

Table 2-5
40 CFR Part 60 System Data Quality Objectives

Test	Frequency	Criteria	Corrective Action	
2 Point Calibration Drift Test (CD)	Daily	$\lvert Ref - AR \rvert \leq 1.0\%\ CO_2$	Adjust analyzer zero and span	40 CFR 60, App. F, Section 4
Cylinder Gas Audit (CGA)	Quarterly	$A = 100\% \cdot (C_m - C_a)/C_a = \pm 15.0\%$	Identify and eliminate problem	40 CFR 60, App. F, Section 5.1.2
Relative Accuracy Audit (RAA)	Quarterly	$RA = 100\% \cdot (C_m - C_a)/C_a = \pm 15\%$	Identify and eliminate problem	40 CFR 60, App. F, Section 5.1.3
Relative Accuracy (RA) Test Audit	Annual	$RA \leq 20\%$ or $\pm 1.0\%\ CO_2$	Identify and eliminate problem	40 CFR 60, App. F, Section 5.1.1

Ref = Reference value of low -, mid - or high - level calibration gas introduced into the monitoring system in $\%CO_2$, dry basis

AR = Average of the monitoring system responses in $\%CO_2$, dry basis

A = Accuracy of the CEMS in percent

C_m = Average CEMS response during audit in $\%CO_2$, dry basis

C_a = Average audit value (CGA certified calibration gas value or three-run average for RAA) $\%CO_2$ (dry basis for CGA and wet basis for RAA)

RA = Relative accuracy in percent

Discussion of End User Survey

A survey was conducted among 10 industry end users to determine current measurement approaches and operating practices for CO_2 CEMS. The surveyed individuals consisted primarily of environmental professionals representing a cross section of the power industry. The complete survey can be found in Appendix A. Highlights of the survey pertaining to current CEMS instrumentation and operating procedures are as follows:

- Sampling system: All facilities surveyed condition the sample gas extracted from the stack via dilution. Dilution ratios depend on the stack gas composition, in particular the moisture content, and range from 11:1 to 300:1.
- Analyzer technology: All analyzer models used for CO_2 measurements are based on the non-dispersive infrared (NDIR) spectroscopy combined with the gas filter correlation (GFC) technique. Majority of systems are set to a source level span of 20% CO_2.

- Daily calibration error checks: Calibration error checks are predominantly performed with high-level span gases of about 18% CO_2. Three respondents acknowledged the use of mid-level gases that are closer in concentration to the actual CO_2 content of the stack gas. One respondent reported the use of varying calibration gas concentrations for the calibration error check. Results are typically well below 0.5% CO_2, with three respondents reported typical calibration errors of less than 0.2% CO_2. Several respondents have established calibration error control limits that trigger preventive maintenance actions. The trigger level used is 0.5% CO_2. Once a trigger level is exceeded, corrective actions involve a data review in order to determine the best cause of action or a cleaning of probe and filters. The majority of the respondents pointed out that corrective action is rarely needed as the CO_2 monitor is the most reliable among all of the monitors in the plant CEMS. One respondent pointed out that barometric pressure changes cause a swing in system response, which is indicative of a lack of a compensation of the sampling system's dilution ratio.
- Quarterly linearity check: Similarly to the calibration error check results, respondents indicated that linearity error checks rarely fail. The majority of checks yield linearity errors of less than 3% of the gas standard concentrations or less than 0.5% CO_2. Two correspondents indicated typical linearity error results of less than 2%. Unlike the calibration error check, only a few respondents reported the existence of an error control limit that triggers preventive maintenance actions. Trigger level is a linearity error of 3%.
- Relative accuracy test audit: All facilities conduct RATA programs on an annual basis. Prior to the RATA, facilities typically inspect the system either as part of a regular maintenance program or as extra maintenance. System checks can include extra calibration checks or simple visible inspections. RATA results are well within limits ($RA < 7.5\%$), with most respondents reporting relative accuracy results of less than 4%.
- Quality assurance and quality control (QA/QC) plan: Regulations require the implementation of a QA/QC plan. Respondents reported daily, monthly, quarterly, semi-annual or annual inspections. Inspections typically require the completion of a list of checks, data reviews and system status report perusal. Most frequent component failures are pumps, analyzer infrared light sources and gas filter correlation wheels, resulting in pump rebuilds and faulty equipment replacement action. All system check results and maintenance actions are captured in a maintenance log.

Other Considerations

Non-dispersive infrared (NDIR) spectrometry combined with gas filter correlation (GFC) has been the traditional technique used for the measurement of CO_2 stack gas concentrations. This is largely due to the simplicity of its design, its ruggedness, sensitivity and cost. Although sufficient for stack gas monitoring applications, when evaluating uncertainties in CO_2 measurements, one needs to consider improvements in measurement technologies that provide a more accurate and precise measurement. However, CO_2 analyzers are only one component in an extractive CEMS, and improvement in their accuracy, although important, may only contribute marginally to the increase in measurement accuracy of the entire CEMS. Nonetheless, a reduction in analyzer uncertainty is worth the consideration if the ultimate goal is to minimize measurement error to the greatest extent possible within the CEMS configurations currently in use in the industry.

Potential replacements for currently installed CO_2 analyzers are based on more advanced laser-based spectroscopic techniques, such as Cavity Ringdown Spectroscopy (CRDS) or Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS). Instruments based on these measurement techniques generally provide superior accuracy and precision compared to the more traditional NDIR approach. Reported instrument accuracies and precision are better than 0.1% and 0.01% of the analyzer span, respectively [Piccaro 2015, Los Gatos Research 2015]. For source level measurements this would result in analyzer uncertainties of below 0.02% CO_2 with a measurement precision of a fraction of that. Very low instrument drift would allow for the potential reduction in calibration frequencies. However, these advantages must be moderated by the increased optical system complexity and cost compared to traditional NDIR-based instrumentation.

Best Practices Recommendations for CEM Operation

The following list presents the best practice recommendations for CEMS operations. The items in this list are deduced from the discussion in the preceding sections.

Sampling System

- Determine source-level and calibration gas molecular weights and dynamically correct CEMS response for changes in the dilution ratio of the sampling system due to temperature, pressure, and molecular weight variations.
- Check system integrity by alternating between introducing calibration gas standards to the probe and directly to the analyzer on a quarterly basis.
- Follow a preventive maintenance schedule for probe and sampling system inspection and maintenance.
- Check the dilution air for contamination with target compounds on a weekly basis.
- Sample from a location that is representative of the measurement area. Determine probe placement based on stratification test results.

CO_2 Analyzer

- Use a calibration span that is close to the actual stack gas concentration. A span value as low as 14% CO_2 (taking into account the dilution ratio of the sampling system) is within the limits of the regulations.
- Perform daily CO_2 calibration error checks with calibration gas standards that are representative of the actual stack gas concentrations. A span value of 14% CO_2 allows high-level span gases as low as 11.2% CO_2 to be used.
- Determine system response time (cycle time) and be consistent in the use of this cycle time throughout the calibrations.
- CEMS analyzers are susceptible to ambient temperature changes. Minimize analyzer drift by careful siting of analyzer racks or redirecting airflow to maintain analyzer temperature within a ±3°F band.
- Correct analyzer readings for sample pressure fluctuations, unless already done so by analyzer.
- Consider the application of a BAF if a constant offset bias is diagnosed between reference method test and plant CEMS results.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use calibration gases with a certified accuracy of 1%.
- Use EPA blind calibration gas audit reports as a guide in choosing calibration gas vendors.
- Be consistent with the calibration gas standard concentrations used during daily calibration error checks.

QA/QC Plan

- Rigorously implement the preventative maintenance schedule defined in the quality assurance and control plan.
- Consider implementing maintenance limits for key system performance parameters. Violating a maintenance limit does not mean that the system is out-of-compliance, but will trigger corrective actions to avoid violating the applicable control limits. Maintenance limits can be set at half the respective control limit.
- Consider creating quality control charts of key system performance parameters.
- Review monitoring and calibration data on a weekly basis.

3

FLUE GAS FLOW RATE MONITORS

Background

Instruments that measure flue gas velocity (flow) are inherently in-situ monitors, because a direct, real-time gas measurement must be made. Most commercially available flue gas flow monitors operate using one of four principles for measuring velocity and volumetric flow: 1) ultrasonic pulse detection, 2) differential pressure, 3) thermal detection, and 4) audible acoustic detection. The four varieties of flow monitors are stack or duct-mounted and operate as a component system (which would include a microcomputer, pressure transmitters, and temperature transmitters). Ultrasonic and differential pressure flow monitors combined represent approximately 95% of the market share of installed flow monitors in the U.S. electric utility market.

Flow rate monitors began to be applied in U.S. electric utilities after 1993, when the EPA Acid Rain Program mandated their installation for the calculation of SO_2 allowances. An “allowance” is an emission rate, expressed as tons of SO_2 per year, which is calculated from hourly emissions data. Emissions allowances for SO_2 and NO_X are allocated, banked, sold, and traded as a commodity, and accordingly have a commercial value. The EPA believed that the most reliable and accurate means of quantifying and reporting emissions allowances would be the use of flow monitors, since flow monitors can be certified, calibrated, and audited. The EPA promoted the use of flow rate monitors to calculate SO_2 mass emission rates, which resulted in the installation of over 1000 flow monitors at electric utility facilities in the 1990s [Jahnke 2000].

Flow monitors are an integral part of a plant CEMS wherein emissions regulations specify the continuous monitoring of pollutant mass emission rates. This can be seen by examining the following relationships:

$$E_s = c_s Q_s \qquad (1)$$

and

$$Q_s = A_s v_s \qquad (2)$$

Where:

E_s = pollutant mass rate (lb/hr, tons/yr, kg/hr)

c_s = pollutant concentration (lb/ft^3, mg/m^3)

A_s = stack or duct area (ft^2, m^2)

v_s = stack gas velocity (ft/s, m/s)

with the application of the appropriate conversion factors (e.g., lb to tons, seconds to hours, etc.).

The following discussion of flow rate monitoring techniques and instruments is not intended to be an exhaustive treatment of all the methods currently available. It emphasizes those that are currently being used for monitoring flow in industrial and/or utility stacks or flues.

To ensure this study contained modern best practices key industry and US EPA publications were reviewed. Much of the information contained in this section comes from recommendations and interactions with industry experts. All sources are identified and credited in the Bibliography.

Ultrasonic Flow Monitors

Ultrasonic flow monitors represent the most widely used flue gas flow monitoring device in the U.S. electric utility market. Approximately 65% of all flow monitors used in the EPA Part 75 Acid Rain Program are ultrasonic type monitors [EPA 2010], and approximately 50% of end users surveyed for this report utilize ultrasonic flow monitors. The Teledyne Ultraflow 100 and 150 models are the most widely used, and Teledyne supplies approximately 85% of the installed ultrasonic flow monitors in the U.S. All of the end users interviewed for this report who utilize ultrasonic monitors, use the Teledyne Ultraflow monitor.

Principle of Operation

The volumetric flow rate of stack gas is measured by transmitting ultrasonic pulses across the stack in both directions as depicted in Figure 3-1. The tone pulses are accelerated or retarded due to the gas velocity in the stack. Ultrasonic flow monitors measure the time it takes ultrasonic sound pulses to travel with the direction of flow of the stack gas and against the direction of flow of the stack gas. Ultrasonic pulses in the range of 50 kHz are transmitted both upstream and downstream of the flow. Stack flow can be calculated based on the difference in the times required to traverse the stack in both directions.

Two transceivers are located opposite each other on the stack at a minimum angle of 10 degrees; however, a traverse angle of 45 degrees is typical and tends to provide the best results, as long as the traverse path length is not so long that the ultrasonic pulses become difficult to detect [Jahnke 2000]. In each transceiver, a piezoelectric transducer transmits ultrasonic pulses over the path, L, to the opposite transceiver. The transducers convert both electric signals to acoustic signals and acoustic signals to electric signals. The speed at which the pulse crosses the stack is dependent on whether it travelling in the direction of or against the flow.

The stack gas velocity can be obtained from the following expression:

$$V_s = \frac{L}{2\cos\Theta}\left[\frac{1}{t_a} - \frac{1}{t_b}\right] \qquad (3)$$

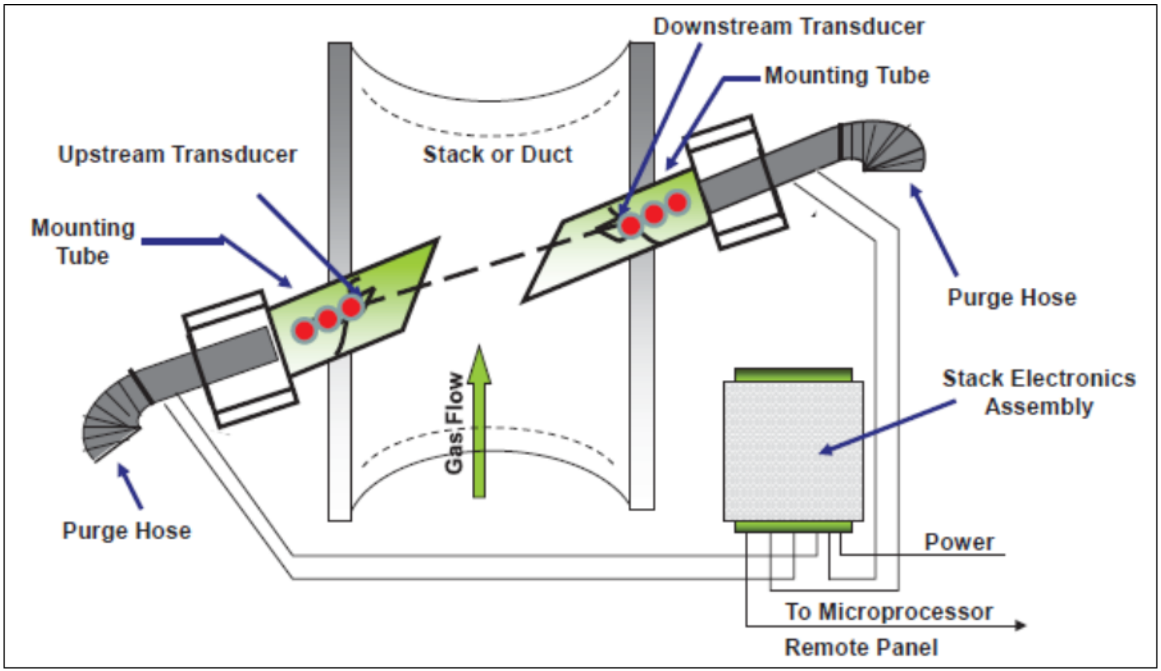
Where:

L = path length between transceiver A and B

t_a = forward transit time from upstream transceiver A to downstream transceiver B

t_b = reverse transit time from downstream transceiver B to upstream transceiver A

θ = angle between stack and path length



Source: Teledyne Monitor Labs

Figure 3-1
Typical Ultrasonic Flow Monitor Installation

In other situations, particularly where two ducts are exhausting into a single stack or in locations where a second access platform is cost prohibitive, a shallower angle, resulting in upstream/downstream transducer offsets as small as 4 feet may be used. If the reduced transducer offset results in pitch-angle errors, a dual set of transducer assemblies (X-pattern) can be installed. In this arrangement, two sets of ultrasonic transducers are purported to cancel out the pitch effect. One set exhibits a positive bias with respect to the pitch, the other a negative bias. This "X" pattern provides an average flow measurement directly up the stack and has the potential added benefit of multiple certifications of both transducer assembly sets. This redundancy ensures nearly 100% instrument availability [Teledyne 2006].

Ultrasonic sensors check their calibration by electronically substituting signals to cross-check the electronics and by introducing a known delay in the pulse. These methods are basically internal electronic checks and are not independent of the system.

Ultrasonic sensors are unique among flow monitors in that the sensing elements of the system are not located in the duct or stack. However, the transceivers can be exposed to the flue gas, and particulate matter can foul the transceivers. Blowers, which pass clean air across the sensors, are designed to keep them clean and free of particulate build-up.

There are four commercial suppliers of ultrasonic flow monitors for power plant stack applications that were identified for this report. Table 3-1 provides a summary of the design and performance characteristics of several commercially available ultrasonic flow monitors.

Table 3-1 was compiled from equipment manufacturer’s specifications available on company websites.

Table 3-1
Summary of Design Specifications for Commercially Available Ultrasonic Flow Monitors

Parameter	Teledyne Ultraflow 150	ThermoScientific TS Flow 100	Forney F-8200	Durag D-FL 200
Type	Across-the-stack, single chord or X-pattern	Across-the-stack, single chord	Across-the-stack, single chord	Across-the-stack, single chord
Range	0 to 200 fps.	0 to 131 fps	0 to 98 fps	0 to 131 fps
Accuracy	Typically < 5% above 10 fps, site dependent (vs. EPA Method 2)	± 0.33 fps	±2% of measurement range	< 2%
Resolution	0.1 fps	0.1 fps	Not reported	Not reported
Long-term Repeatability	±0.3 fps	±0.3 fps	Not reported	Not reported
Response Time	As low as 5 seconds (adjustable)	1-300 seconds (user selectable)	1-180 seconds (user selectable)	1-180 seconds (user selectable)
Drift	±1% reading over full range	Not reported	Not reported	< 0.3% or measuring range/month
Temperature	±3°F Accuracy	Not reported	Not reported	Not reported
Duct Diameter	From 3 to 45 feet	6'-7" to 49'-3"	Up to 33 feet	Up to 33 feet
Operating Temperature	-40°F to 650°F	Up to 428 °F	Up to 392°F	0 - 392°F
Operating Pressure	-30 to 20 inches of H2O	Not reported	Not reported	-50 to +20 hPa
Moisture	Dry to saturated, including condensed water	Not reported	Wet stacks (below dewpoint)	Wet stacks (below dewpoint)
Particulate	≤300 mg/m3	≤10,000 mg/m3	Not reported	Not reported

Notes: 1. References to specific equipment manufacturers does not connote endorsement by EPRI.
2. Data compiled from manufacturer's equipment specifications.

Uncertainty of Ultrasonic Flow Monitors

Ultrasonic flow monitors measure on a stack chord or diameter; a line average is not the same as an area average. However, [Traina 1992] calculated that for typical circular stacks, the difference between the two measurement methods will be on the order of 3-5%. This bias can be incorporated into the calculation algorithms of the monitor control system.

Problems of stratification are not as straightforward, but can be minimized either by the proper selection of the measurement path or by adjusting the monitor data to match reference method results through the calculation algorithms.

The choice of measurement paths have been discussed in detail by both [Traina 1992] and [Kearney 1993]. In an attempt to address the problem of measuring volumetric flow in a highly stratified duct, Kearney developed an algorithm to match possible measurement paths against the average velocity determined by EPA Method 2. Although this procedure was successful in this application, its success was dependent upon several assumptions: namely (1) the stratification pattern was stable and independent of load, and (2) the Reference Method 2 data could be correlated with a measurement path not in the cross-section, but at an angle to it (on the order of 45-degrees). The validity of the second assumption depends on the stratification pattern persisting through the duct.

It has been recommended not to site flow monitoring systems in locations where swirling, non-axial flow is present. However, it is often difficult to find such locations where the flow is completely axial. For an ultrasonic monitor installed in a stack having a pitched flow component, the vector component of flow along the path decreases the sound pulse time of flight to the downstream transducer and increases the time of flight to the upstream transducer. Since the velocity is determined by subtracting the reciprocals of the two times of flight, the flow will be biased high. One solution to this problem, suggested by [Traina 1992], is to orient the measurement path so that the monitoring system is perpendicular to the pitch. The path measurement will be less sensitive to the effect of the pitch and more amenable to stable correlations and bias corrections.

Differential Pressure Flow Monitors

Approximately 30% of all flow monitors used in the EPA Part 75 Acid Rain Program are differential pressure type flow monitors [EPA 2010]. Three different types of commercially available flow monitoring devices are based on measuring differential pressure: S-type pitot tubes, the Fechheimer dual-manifold pitot probe, and annubars. The principles of operation, which differ somewhat among these three types of flow monitoring devices, are discussed in the following sections.

The Pitot Probe – Principle of Operation

The S-type pitot tube is designed after the Stausscheibe or reverse type pitot tube as described in EPA Method 2 in Appendix A to 40 CFR Part 60. The probe is constructed of two in-line tubes. The sampling point of the probe consists of two opposing open faces perpendicular to the traverse axis. The impact and wake pressures can be continuously monitored using pressure transducers (capacitance type or other). Using a thermocouple to monitor stack temperatures, the velocity can be can be calculated (stack gas molecular weight or fluid density is estimated) using the following equation:

$$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad (4)$$

Where:

v_s = velocity of the gas

K_p = dimensional constant

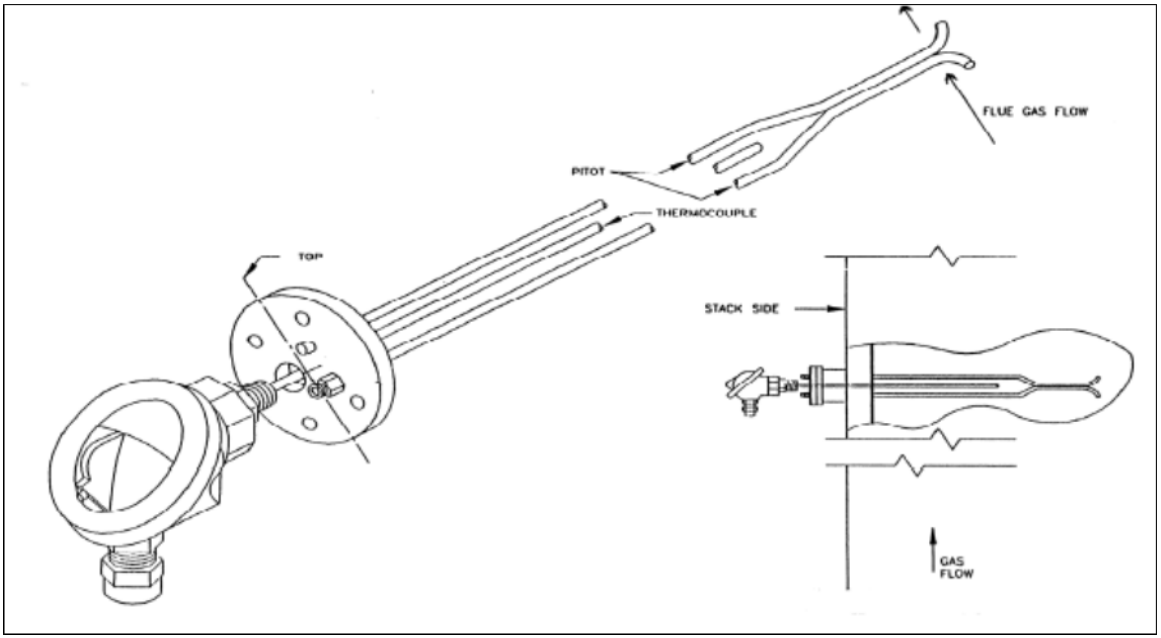
C_p = Pitot tube calibration constant

T_s = absolute temperature of the stack gas

P_s = absolute pressure of the stack gas

M_s = molecular weight of the stack gas

Plugging of probes is avoided by periodically back-purging the probe with high pressure air. Several probes are required for multipoint monitoring. The position and number of points are determined using Method 1 in Appendix A to 40 CFR Part 60. The multipoint averaging is performed in a pitot manifold and a differential pressure transmitter registers the averaged pressures. Approximately 60% of all differential pressure type flow monitors installed as part of EPA Part 75 Acid Rain Program are the S-Type Pitot tube design and are supplied by one manufacturer (EMRC) [EPA 2010]. This continuous flow rate monitoring technique has been used by industry for many years for mass emissions monitoring. Figure 3-2 presents a schematic of the EMRC S-Type Pitot probe.



Source: EMRC

Figure 3-2
EMRC Type-S Pitot Differential Pressure Probe

The EMRC Gas Flow Monitor

The EMRC Gas Flow Monitor includes an in situ flow sensor utilizing a variety of designs and materials (appropriate metallurgy/ceramic, etc.) to fit a large variety of flow measurement applications. Other subsystems include pressure signal conditioning interface, differential pressure transducer and temperature measurement subsystem (Type-K thermocouple or RTD) and a primary reference and pressure auto-calibration subsystem (also available for the Type-K thermocouple transmitter). The EMRC instrument package is located off-stack allowing for ease of maintenance and control. Off-stack instrumentation is packaged routinely in indoor and/or outdoor cabinetry, although it is preferable to locate instrumentation in a thermally controlled instrument/control room for ease of maintenance and enhanced performance.

The specifications of the EMRC flow monitor as reported by the manufacturer are as follows:

• Size	Manufactured to fit the needs of its customers
• Weight	Stationary @ 100 - 250 lbs.
• Power	115v, 60hz Operating Cabinet
• Temperature	30°-120°F (Some units have internal heaters)
• Probe Temperature	-2000°F (melting point of probe material) or ceramics up to ~3000°F
• Recorder Outputs	4-20 ma standard, all others upon request
• Performance Sensitivity	~2fps
• Response Time	~1-2 seconds to 100% of final reading
• Linearity	±2% of full scale

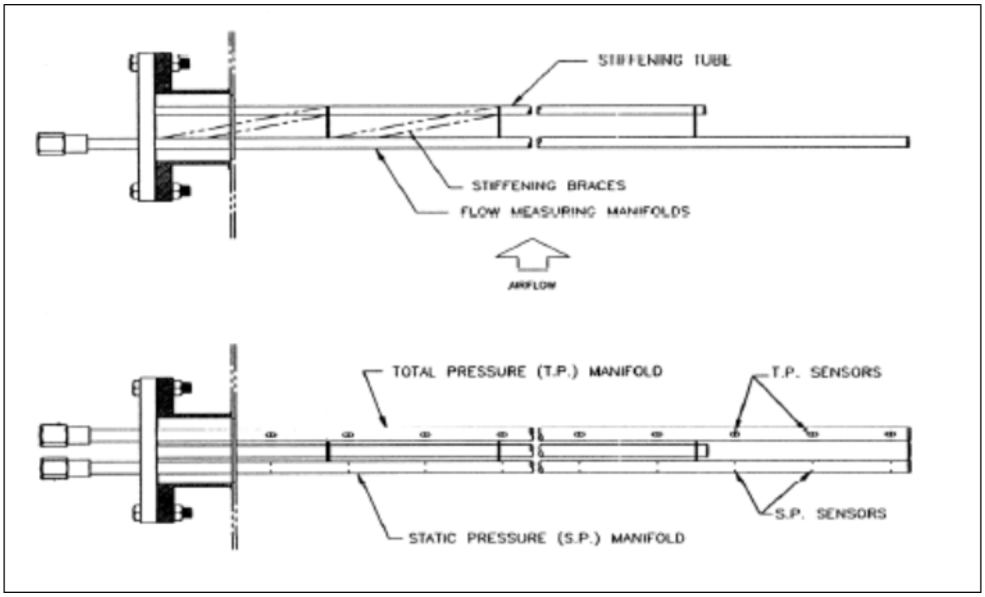
• Repeatability	<1% Zero Drift: ~2% of full scale Span Drift: ~2% of full scale
• Accuracy	~2% of full scale

Averaging Differential Pressure Probes

The averaging differential pressure or Fechheimer pitot probe consists of flow sensors mounted on two multipoint averaging manifolds. Figure 3-3 shows a schematic of the Fechheimer pitot probe assembly. The probe design consists of two manifolds (tubes) welded together with a truss plate. The truss maintains a distance between the manifolds in a plane perpendicular to the flow and the stack wall. One manifold averages multiple points of impact pressure, and the other averages multiple points of wake pressure. The impact and wake pressure averages are registered by the flow transmitter. Port locations will be site specific; therefore, stack dimension must be carefully specified before the probe is constructed.

An averaging probe typically averages only on one diameter. If two probes are installed perpendicular to each other, the flow would be more completely characterized. The accuracy of an averaging probe is dependent, as is the pitot tube, on the constancy of its calibration constant (C_p) and assumptions associated with the stack gas density.

This technology is used in numerous gas flow monitoring applications other than flue gas. Approximately 30% of all differential pressure type flow monitors in the Acid Rain Program were the Air Monitor Corporation's Fechheimer pitot probe and were supplied by one manufacturer [EPA 2010].



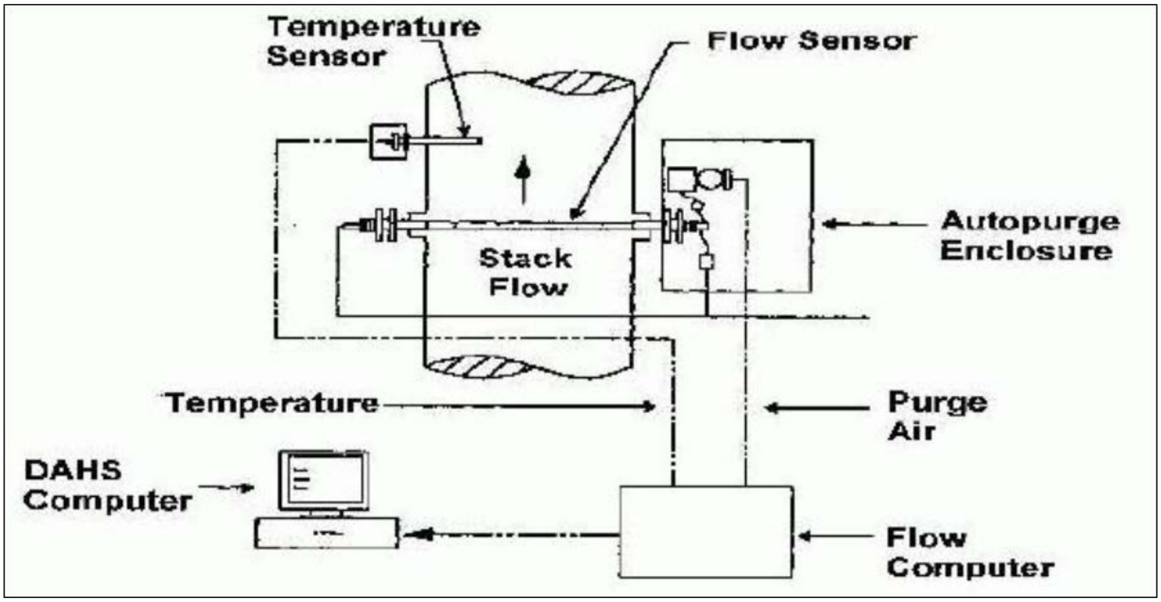
Source: Air Monitor Corp.

Figure 3-3
Air Monitor Corporation Fechheimer Probe

Annubar Flow Probe

The annubar flow monitoring technology is a multipoint, dual-chambered probe. The probe averages multiple in-line (impact and wake pressures) sample points across the stack diameter as shown in Figure 3-4.

The position and number of points are typically determined using Method 1 in Appendix A to 40 CFR Part 60. The interior of the probe consists of tubes within a tube. The exterior tube shrouds two averaging changer tubes. The inner tubes consist of the impact differential pressure chamber and the wake differential pressure chamber. Precision pressure points are tapped through the exterior tube into the inner tubes. The pressure registered at the flow transmitter is the average across the stack. This technology is manufactured by Dieterich Standard/Rosemount. Approximately 10% of all differential pressure type flow monitors in the EPA Part 75 Acid Rain Program are annubar type probes [EPA 2010].



Source: RMB Consulting, Inc.

Figure 3-4
Rosemount/Dieterich Standard Annubar Flow Monitor

All of the differential pressure flow rate systems include an electronic, flow-indicating transmitter that receives pressure and temperature signals from the stack, calculates the exhaust gas flow rate, and automatically performs electronic drift checks and system purging.

Uncertainty of Differential Pressure Flow Monitors

Differential pressure systems are designed around pressure sensing tubes. Small openings in the tubes sense impact or wake pressures; gas is not extracted into the tube. Bias problems, outside of stratification effects, can occur with respect to these tube openings.

For example, the ideal performance of a differential pressure sensing system requires the flue gas flow to be perpendicular to the tube. If the gas approaches at an angle, the differential pressure between the impact and wake pressure ports will be different. Since the flue gas velocity is calculated from the square root of the differential pressure, the velocity will be biased. The velocity can be biased either high or low, depending upon the probe design and the angle of the flow with respect to the facing plane of the tube.

The flow direction may be non-normal to the tube if (1) the probe is twisted, sags, or oscillates with the flow; (2) the flow itself is swirling; or (3) the flow direction otherwise changes over the cross-section. Swirling, cyclonic flow can contribute to some of the greatest errors in flow measurement, because the angles of attack to the probe are far from perpendicular. Differential pressure sensors are not calibrated to such arbitrary angles, so installation of these systems where cyclonic flow is present should be avoided.

Probe plugging is also of some concern in differential pressure sensing systems. If the probe system is calibrated versus Reference Method 2 over the cross-section, by conducting a pre-RATA, a plugged opening on an averaging probe will not contribute to the pressure average and may cause a bias. Such bias is difficult to quantify. However, with probe blowback systems, probe plugging is rarely a problem. In severe situations the probe blowback frequency and/or pressure can be increased. Condensation of flue gas moisture by molecular diffusion can occur in the pitot lines. This problem can be eliminated if the lines are included in the periodic blowback.

Differential pressure system calibration checks are usually performed downstream of the probe. The checks are designed to test the performance of the pressure transducers, by first sealing off the probe from the system and then pressurizing the remaining plumbing of the system. This procedure does not actually check the probe problems discussed above and serves principally to test for leaks and electronic issues.

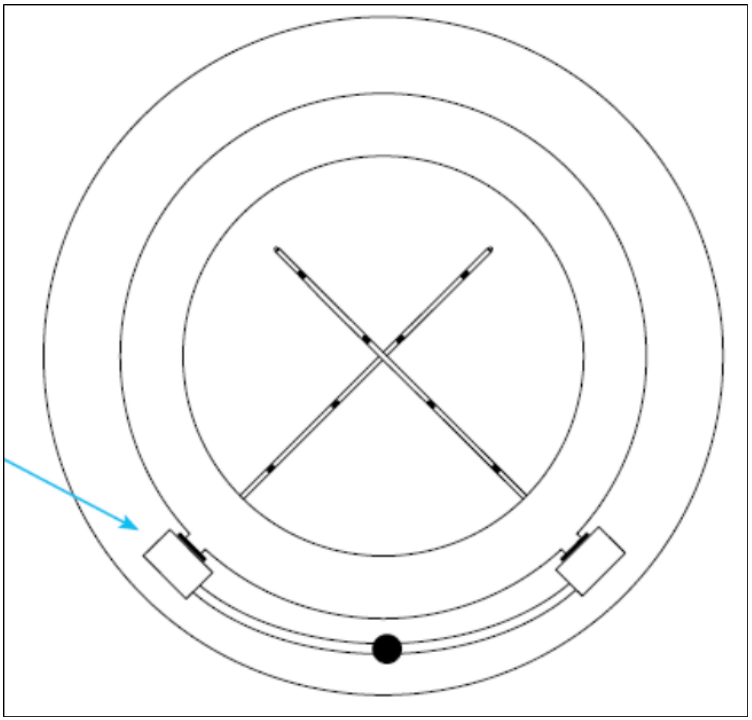
Thermal Flow Monitors

Less than 5% of the flow rate monitors installed as part of the Part 75 Acid Rain Program flow rate monitoring were thermal flow monitors [EPA 2010]. Kurz Instruments supplied these monitors.

Thermal Flow Monitors – Principle of Operation

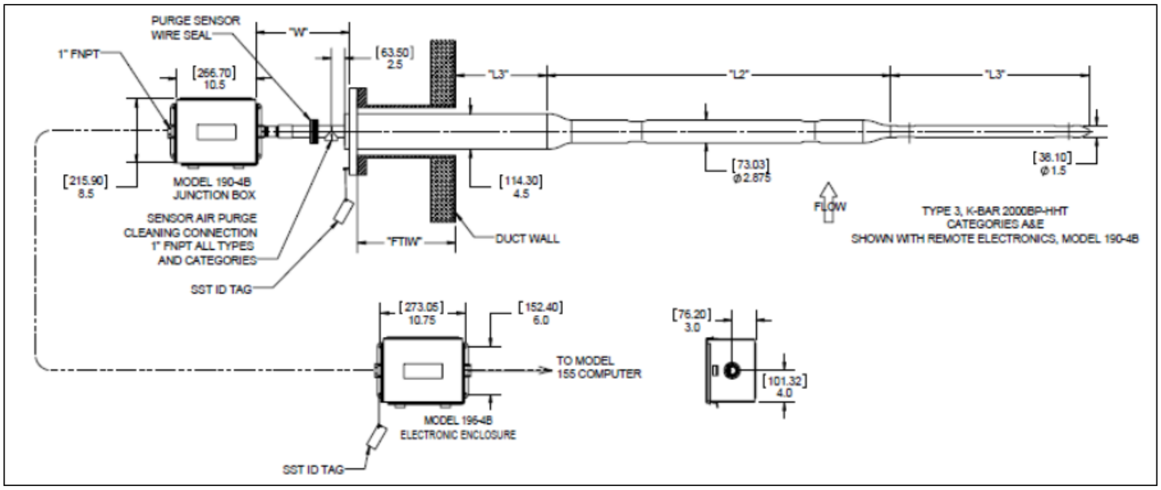
Thermal flow monitors are based on the transfer of heat from a heated body to the flowing gas. The flowing gas transfers the heat away to cool the body – the greater the flow, the greater the cooling. In thermal sensing systems used for stack monitoring, the heated body (sensor) is not allowed to cool. Instead, more power is sent to the sensor to maintain its original temperature in these constant-temperature anemometers. For heated wire sensors, the mass flow rate of the gas is proportional to the amount of power input [Jahnke 2000].

The monitors are available for both single-point and multipoint analysis, and non-sensing components of the systems can be constructed from various corrosion-resistant metals. Multiple thermal flow sensors can be easily combined in arrays to measure the average flow rate over the cross section of a duct or stack. Each sensor makes an independent measurement; therefore it is possible to monitor the gas flow distribution over the cross section. Such arrays are useful in ductwork where the flow is stratified. Figure 3-5 shows the Kurz Model KBAR-200B thermal flow sensor as applied to two chords in a large stack. Figure 3-6 shows details of a multi-sensor Kurz KBAR-2000B.



Source: Kurz Instruments, Inc.

Figure 3-5
Thermal Flow Sensor Installed on Two Stack Chords



Source: Kurz Instruments, Inc.

Figure 3-6
Details of the Kurz Model KBAR-2000B Probe

Kurz Model KBAR-2000B Thermal Flow Monitor Specifications

- Type Thermal mass flow meter
- Velocity Range 0-12,000 SFPM
- Repeatability ±0.25% of reading
- Accuracy ±1.0% of reading +20 SFPM
- Velocity Time Constant 1 second for velocity changes at 6,000 SFPM (constant temperature)
- Process Temperature Time Constant 8 seconds for velocity changes at 6,000 SFPM (constant velocity)
- Velocity Angle Sensitivity < 2% per degree angle up to 20°
- Velocity-dependent correction factors for flow rate
- Operating Gas Temperature -40 to 500°F
- Operating Pressure Up to 150 psig
- EPA Mandatory GHG Certification 40 CFR 98.34(c)(1)

Current Operating Practices and Procedures

Discussion of 40 CFR Part 60 and Part 75 Requirements

Procedures and criteria for evaluating the acceptability of flow monitor systems are described in detail in Performance Specification 6 (Specifications and Test Procedures for Continuous Emission Rate Monitoring Systems in Stationary Sources) of 40 CFR Part 60 Appendix B and the respective paragraphs of 40 CFR Part 75, Appendix A (Specifications and Test Procedures) and Appendix B (Quality Assurance and Quality Control Procedures). The installation and measurement location specifications, performance test procedure, calculations, and data analysis procedures of Performance Specification 2 are applicable to PS-6.

Table 3-2 below compares the requirements for the certification of flow monitors for Part 60 New Stationary Source CEM systems and Part 75 Acid Rain Program CEM systems. Part 75 offers an incentive program for the required frequency of RATA testing which is based on the test results. For example, if the deviation between the monitor and the reference method is between 7.5% and 10% (or ±2.0 ft/sec), then the RATA must be performed every six months. Also, if the deviation between the monitor and the reference method is equal to or less than 7.5% (or ±1.5 ft/sec), then the RATA is performed annually.

Table 3-2
Comparison of Part 75 and Part 60 Requirements for Flow Monitor Certification

Test	Part 75	Part 60
Initial 7-day Calibration Drift Test	Performed for 7 consecutive unit on-line operating days. Performance Specification: Flow ≤ 3.0% of span	The performance specifications have an either/or statement on test condition. Calibration drift to be performed once every 24 hours (as practical) for 7 consecutive calendar days (no wordage on whether process has to be on or off-line). Or, calibration drift to be performed for 7 consecutive unit operating days (to bring in line with Part 75 for dual reporting systems). Performance Specification: Flow ≤ 3.0% of span
Relative Accuracy Test Audit (RATA)	Performed on a semiannual or annual basis, dependent on the results of the previous RATA (Part 75 incentive program). Flow RATAs must be performed at 3 operating load levels; low, mid, and high. See Footnote 1 for RATA incentive performance specification limits.	Performed on an annual basis. Gas and flow monitor RATAs are performed while process is operating at 50% or greater load conditions. Performance Specification: Flow ≤ 20% of reference method of 10% of applicable standard.

1 Semiannual: 7.5% ≤ RA ≤10% or ±2.0 fps.
Annual: RA ≤7.5% or ±1.5 fps.

For flow CEMS, the on-going Part 75 data quality objectives for year-round reporters are listed in Table 3-3 along with typical corrective actions taken in case that the objectives are not met.

Table 3-3
Performance Specification for Part 75 Continuous Flow Monitors

Test	Frequency	Criteria	Corrective Action	Comment
Calibration Error Test	Daily	Pass/Fail	Identify and correct the problem	Calibrations are not required when the unit is not in operation.
Interference Check	Daily	Pass/Fail	Identify and correct the problem	Check not required when the unit is not in operation.
RATA	Semiannual or Annual	Semiannual: 7.5% ≤ RA ≤ 10% or ±2.0 fps. Annual: RA ≤ 7.5% or ±1.5 fps.	Identify and correct the problem. Repeat RATA	
Flow-to-load ratio or gross heat rate test	Quarterly			Required only in QA operating quarters.
Leak Check	Quarterly	Pass/Fail	Identify and correct the problem	Applies only to DP-type flow monitors

Relative accuracy represents the accuracy of the plant flow CEMS relative to its deviation from the reference method. As such, the relative accuracy is expressed as the percentage deviation between the monitor response and the average reference method result encountered during the RATA. Specifically, the relative accuracy is defined as the absolute mean difference between the gas concentrations determined by the plant CEMS and the value determined by the reference method, plus the confidence coefficient of a series of tests divided by the mean of the reference method. RATAs are typically performed on a semiannual basis for Part 60 and Part 75 installations. However, Part 75 has an incentive program which allows the RATA to become an annual requirement if the relative accuracy during the previous audit for the flow monitor was ≤7.5% (or ±2.0 ft/s).

In order to increase the accuracy in heat rate calculations, it is important to minimize relative accuracy errors far below the data quality limits currently accepted by Part 60 and Part 75 for CO_2 mass emission reporting purposes. A recent study on CEMS measurement uncertainty and its influence on the boiler heat rate calculations concluded that current measurement errors resulted in a substantial uncertainty of the calculated heat rate. A case study determined the combined contribution of flow and CO_2 measurement error to the boiler heat rate uncertainty to be approximately 5% at high load [EPRI, 2014]. In terms of actual flow rate, this corresponds to an uncertainty of approximately 1.85 MMSCFM at a measured average flow rate of 49.0 MMSCFM (a 3.8% systematic error). In light of this, it becomes clear that the data quality objectives listed in Table 3-3, although appropriate for flow CEMS reporting purposes, are not sufficient to ensure more accurate heat rate results.

Discussion of End User Survey Results

A telephone survey was conducted by CleanAir of ten industry end users in order to determine current measurement approaches, and operating and maintenance practices for continuous flow monitoring systems. The individuals surveyed consisted primarily of utility environmental professionals with firsthand knowledge of CEMS operations. The complete survey is provided in Appendix A of this report. Highlights of the survey pertaining to flow monitor instrumentation and operating procedures are as follows:

- Monitoring Systems: Five of the ten utilities surveyed utilize ultrasonic flow monitors. Five of the ten utilities surveyed utilize differential pressure measurement systems. One utility utilizes both ultrasonic and differential pressure systems.
- Analyzer Manufacturer/Model: All of the ultrasonic systems used by the respondents were Teledyne Ultraflow. All five ultrasonic end users reported using the Teledyne Ultraflow 150, one of the ultrasonic respondents reported using both the Teledyne Ultraflow 100 and the 150. Three of the differential pressure system end users reported using the EMRC gas flow monitoring system. One differential pressure system end user reported using both the Dieterich Standard and newer Rosemount models. One differential pressure system end user reported using the Air Monitor Corporation Pitot-Fechheimer system.
- Daily Calibration Error Checks (Ultrasonic Systems): All ultrasonic flow monitor end users reported that their systems undergo a daily calibration auto-check. The daily calibration check of the Teledyne ultrasonic flow monitor consists of an internal electronic check of the system. This is not a calibration per se, but is an integrity check of the system operation. An internal zero check is performed by electronically substituting the signal going with the flow for the one going against the flow. This should result in tA = tB and vs = 0. An upscale system check is performed by introducing a known delay in the tone pulses and monitoring the delay. The results of the daily calibration check are either pass or fail. No adjustments are ever made to the zero and span since the monitor is drift free (i.e., ±1%).
- Daily Calibration Error Checks (Differential Pressure Systems): All of the EMRC end users reported that their systems undergo a daily automated calibration. In the EMRC system, the daily calibration auto-check consists of a dynamic calibration system wherein the pressure transducers are zero and span checked. One of the EMRC end users reported that they perform quarterly transducer calibration span checks and a full system calibration annually. The end users of the Dieterich Standard and Air Monitor differential pressure flow monitors also reported daily calibration checks.
- Interference Checks (Ultrasonic Systems): Three of five ultrasonic flow monitor end users report that their systems perform a daily interference check. In the Ultraflow system, the interference check consists of confirming that the purge air system is functioning, and purging the transmitter and receiver. If there is an obstruction, an alarm status condition occurs. Two of the five Ultraflow end users reported not being aware of an interference check.
- Interference Checks (Differential Pressure Systems): All of the EMRC system end users reported that their systems perform daily interference checks. In the EMRC system, the

interference check consists of pressurizing the sampling system for a pre-determined time period (typically 1-minute) to determine if there are any leaks present, and also back-purging the pitots with clean, dry, compressed air. The end user of the Air Monitor system said that an interference test was not performed, or was not applicable to the installed system. The end user of the Dieterich-Standard/Rosemount system stated that they conduct linearity checks and CEMS technicians visually observe the system.

- Relative Accuracy Test Audit: Seven of ten end users perform their RATAs on an annual basis. One respondent stated that they conducted RATAs semi-annually. One respondent stated that they performed RATAs annually, sometimes semi-annually. One respondent was not aware of the RATA frequency. Nine of ten respondents reported conducting RATAs at multiple loads (two or three). One respondent reported conducting RATA tests at a single load. Seven of ten respondents reported performing some type of pre-tests or checks of their systems. System checks can include pre-RATA testing, extra calibration checks or simple visible inspections. Four of ten respondents reported making adjustments to their correlation curves based on the pre-RATA results. RATA results are well within limits (relative accuracy ≤ 7.5% or ≤ 10%). The majority of the respondents stated that their monitors were consistently higher than the reference method results. Only four respondents reported actual relative accuracy results, of those four, most respondents reporting relative accuracy results of less than 5%.
- Quality Assurance and Quality Control (QA/QC) Plan: Regulations require the implementation of a QA/QC plan. Respondents reported daily, monthly, quarterly, semi-annual or annual inspections. Inspections typical require the completion of a list of checks, data reviews and system status report perusal. Most frequent component failures reported were transducer issues, and filter pluggage. Other maintenance checks include Pitot condition and thermocouple calibration. All system check results and maintenance actions are captured in a maintenance log.
- Flow Monitors and Heat Rate Improvement: Four of ten respondents reported in the affirmative that they plan to invest more time, capital, etc. on flow rate and CO_2 measurements in order to improve the accuracy of their heat rate calculations given the current regulatory environment and focus on GHG emissions. Two respondents stated that plant engineers are constantly working on these issues.

Best Practice Recommendations for Continuous Flow Monitor Operation

The two principal continuous flow monitoring technologies in current use are ultrasonic and differential pressure probes. Neither technology has a means of direct calibration as does CO_2 CEMS which are calibrated on a daily basis against a calibration gas standard. Ultrasonic flow monitors check their “calibration” by electronically substituting signals to cross-check the electronics and by introducing a known delay in the pulse. Differential pressure monitors check their “calibration” by leak checking the sampling system (downstream of the probe) and pressure transducers.

Flow CEMS are required to be audited by and achieve relative accuracy metrics in comparison to manual EPA Reference Methods, i.e., Method 2, 2F, 2G, and 2H. Accordingly, the greatest gains to be achieved in reducing the uncertainty of flow monitors will be realized in reducing the inherent biases associated with the reference methods, and maintaining the day-to-day operation of the monitor as close as possible to the audit results. Reducing the uncertainty of the reference methods will be addressed in a later section. There are however certain steps that can be taken pertaining to siting and redundancy that can improve the accuracy of flow monitors.

Flow Monitors – Ultrasonic

- All ultrasonic flow monitors should undergo a daily calibration auto-check, which would include a zero and an upscale system check.
- Ultrasonic flow monitors should undergo a daily interference check which involves purging the transmitter and receiver.
- At a minimum, a quarterly maintenance schedule should be implemented and followed. Quarterly maintenance activities would include visual inspection of the purge nozzle assemblies, and replacement of the purge air filters.

Flow Monitors – Differential Pressure

- Differential pressure flow monitors should undergo a daily calibration check, which would include a zero and an upscale span check of the pressure transducers.
- Differential pressure flow monitors should undergo a daily interference check which involves leak checking the system, and back-purging the pitots.
- A full system calibration should be performed on an annual basis. This would include an electronic test of the pressure transducers and DP transmitters, and the temperature transmitter.

Flow Monitor Siting

Flow monitors are typically located according to the guidelines defined in Section 8 of Performance Specification 2 whereby monitors are positioned at least two equivalent diameters downstream from the nearest flow disturbance, and at least a half equivalent diameter upstream from the nearest flow disturbance. The EPA recommends (but does not require) performing a flow profile study following the procedures in 40 CFR Part 60, Appendix A, Method 1, Sections 11.5 or 11.4 for each of the three operating load levels to determine the acceptability of the potential flow monitor location and to determine the number and location of flow sampling points required to obtain a representative flow value.

The flow in power plant stacks is turbulent and inhomogeneous, caused in part by the fact that the gases usually take a sharp 90-degree turn as they travel out of the scrubber and into the stack. Two investigators have documented the benefits of utilizing computation fluid dynamics (CFD) modeling to identify the optimum location for flow monitors thereby reducing systematic error [Romero and Bryant]. CFD modeling can aid in identifying and visualizing advanced flow features such as recirculation zones, swirl decay, and velocity profile development. CFD models of stacks can also provide a low cost and efficient means of simulating the effect of using turning vanes, bluff bodies, etc. to mitigate flow stratification, and non-axial flow conditions. CFD model results are typically validated by field testing using reference methods. CFD modeling should be utilized when siting continuous flow monitors in stacks.

Accurate Stack Diameter Measurements

Accurate knowledge and measurement of the diameter of the stack at the flow monitor sample plane is of critical importance to reduce the total uncertainty of the volumetric flow measurement. The stack diameter is a second order parameter in the volumetric flow rate calculation; hence, small errors in this measurement contribute significantly to the total uncertainty. Stack and duct cross-sectional measurements obtained from old blueprints or outdated drawings can introduce biases of from 1% to 2% into the volumetric flow/pollutant mass rate measurement [Traina, 1992]. Warping or settled fly ash in horizontal ducts can lead to further errors. This bias will, however, not become evident if the same incorrect dimensions are used in both the flow CEMS and the source tester RATA calculations. Cross-sectional dimensions should therefore not be assumed, but measured directly. The diameter of the stack at the flow monitor location should be checked using laser distance meters. Commercially available laser meters measure accurately up to ± 1mm. At least two stack diameter measurements should be obtained, and an average diameter calculated. These measurements should be obtained with the unit on-line operating at normal load conditions in order account for thermal expansion.

Flow Monitor Redundancy

In the case of ultrasonic flow monitors, which make up approximately two-thirds of all stack flow monitors, the use of two (or more) pairs of ultrasonic units that measure different paths (typically in an X-pattern) could produce more accurate results. It is believed that using redundant ultrasonic monitors in an X-pattern technique will cancel the effect of the pitch flow. One set exhibits a positive bias with respect to the pitch, the other a negative bias. This technique of multi-path metering is being studied currently as part of an ongoing research project at The National Institute of Standards and Technology (NIST) in order to characterize the accuracy gains using multiple separate transmitter/receiver units [NIST 2014].

4

CO_2 MEASUREMENT REFERENCE METHOD TESTING

Background

A key procedure for verifying the performance of a plant CEMS subject to 40 CFR Part 75 (the acid rain program) and 40 CFR Part 60, is the relative accuracy test audit (RATA). A RATA evaluates the plant CEMS performance by comparing it against independent reference method measurements. These reference methods are considered the true value of the CO_2 concentration in the stack and provide the standard for the CEMS. Thus, it is imperative to strive for the highest measurement accuracy and precision possible for the reference method measurement with a reasonable amount of effort and cost.

However, the reference method test has limited effect on the accuracy of the plant CEMS measurement. That accuracy is controlled primarily by plant CEM sampling system operation, choice of analyzer, system calibration procedures and choice of plant CEMS measurement location. The assumption is if the plant CEMS probe is positioned at a representative location in the stack and operated according to best practices, and the independent reference method is performed as controlled as possible from a similarly representative stack location, then both measurements should yield similar results.

A RATA is performed to identify and quantify the uncertainty of the CO_2 CEMS relative to the reference methods. If a systematically low bias is detected between the CO_2 CEMS and the reference methods, the preferable course of action is to determine the cause of the bias and eliminate the problem. Alternatively, Part 75 provides a regulatory remedy. To compensate for a systematically low CEMS measurement detected during a RATA, a bias adjustment factor can be derived from the RATA data and applied to subsequent CO_2 CEMS measurements.

Reference Method Requirements and Uncertainty

Reference methods are characterized as either manual or instrumental. Manual methods typically extract a gas sample from the stack into a sample medium that serves to retain and/or pre-concentrate the target compound for later analysis in a laboratory. The instrumental analyzer method extracts the gas sample and analyzes it in real-time by a calibrated analyzer. The most frequently used reference method for the measurement of CO_2 in stack gases is EPA Method 3A ("Determination of O_2 and CO_2 Concentrations in Emissions from Stationary Sources – Instrumental Analyzer Procedure"). Specifications for Method 3A are found in Appendix A of 40 CFR Part 60. The RATA procedures are established in Performance Specification 3, Appendix B to 40 CFR Part 60. This section briefly summarizes the test procedures and specifications of both Performance Specification 3 and EPA Method 3A.

Performance Specification 3 (CO_2)

RATAs provide the means for evaluating the acceptability of plant CEMS shortly after installation and then at regular intervals as specified in the respective regulations, i.e. semi-annually or annually for CO_2. However, both the RATA and the performance specification are not designed to evaluate the installed plant CEMS performance over an extended period of time. They also do not identify specific calibration techniques and other repetitive procedures to assess plant CEMS performance. The procedures regarding how to maintain, calibrate and operate the plant CEMS are established by the equipment manufacturers, and in Appendix A to 40 CFR Part 75 and Appendix F to 40 CFR Part 60.

Besides RATA procedures and performance criteria, Performance Specification 3 also includes requirements for CEMS installation and measurement location, data analysis calculations, as well as reference method measurement location during RATAs. The measurement location of the plant system CEMS is critical to obtaining a CO_2 measurement result that is directly representative or can be corrected to be representative of the total CO_2 concentration. Ideally, the measurement location of the plant CEMS is determined by conducting a stratification test according to guidelines also established in the performance specification. However, this may not always be possible before the initial plant CEMS installation.

In general, it is recommended to perform a stratification test prior to RATA to fully characterize the stack and to select reference method traverse points that ensure a representative sample. The stratification test should be conducted at a minimum of 12 points, located according to EPA Method 1, with measurements following the reference method procedures of EPA Method 3A, which will be summarized later in this section.

The pre-requisite for a stratification test is that the unit tested operates at normal load under steady state conditions (i.e., ±3% load variation). Stratification test result acceptance criteria and the reference method traverse point selection are developed in Performance Specification 3, and are established in greater detail in Section 6.5.6.3 of Appendix A to 40 CFR Part 75 as well as in EPA Method 3A. The appropriate stratification acceptance criteria and ramifications for the reference method traverse point selection are listed in Table 4-1.

Table 4-1
Stratification Acceptance Criteria and Traverse Point Selection

Difference from Mean Concentration	Stratification	No. of Reference Method Traverse Points
> 10% or 0.5% CO_2	Stratified	12 traverse points with sampling point selection according to EPA Method 1
≤ 10% or 0.5% CO_2	Minimally stratified	3 traverse points located at 0.4, 1.2 and 2.0 m for stack diameters greater than 2.4 m (7.8 ft), or at 16.7, 50.0 and 83.3% of the stack diameter for smaller stacks.
≤ 5% or 0.3% CO_2	Un-Stratified	Single point

A RATA must comprise a minimum of nine sets of paired plant CEMS and reference method tests. A total of 12 tests can be conducted and up to three data sets may be rejected, as long as the total number of reference method runs used in calculating the RATA results is equal to or greater than nine. Subsequently, the relative accuracy of the plant CEMS is calculated according to data analysis procedures in Performance Specification 3 and the reader is directed to Section 12 of the Performance Specification 3 (Appendix B to 40 CFR Part 60) for further details.

EPA Method 3A (CO_2)

EPA Method 3A details the procedures, data quality assurance, and quality control requirements for shorter term measurements of CO_2 in stack gases from stationary sources using an instrumental analyzer. The method does not prescribe the use of a specific analyzer type based on a particular principle of detection. Instead, any analyzer can be used as long as the performance requirements of the method are met. The mandatory data validation requirements as well as quality assurance and quality control procedures and criteria are listed in Table 4-2. For further detail on the method procedures, the reader is directed to EPA Method 3 in Appendix A to 40 CFR Part 60.

Table 4-2
Summary of Method Quality Assurance and Quality Control Procedures and Criteria

Affected Component	QA/QC Specification	Acceptance Criteria	Frequency
Analyzer	Interference Gas Check	Sum of responses ≤2.5% of the calibration span	Manufacturer
Calibration Gases	Traceability Protocol	Valid certificate with uncertainty of ≤2.0% tag Value	Manufacturer
	High-Level Gas	Equal to calibration span	Each test
	Mid-Level Gas	40% to 60% of calibration span	Each test
	Low-Level Gas	<20% of calibration span	Each test
Sample Extraction	Probe, filter and sample line temperature	Dry-basis systems: keep sample above the dew point by heating, prior to sample conditioning Wet-basis systems: keep sample above the dew point at all times by heating or dilution	Each test
Analyzer Performance	3-point analyzer calibration error (or 3-point system calibration error for dilution systems)	Within ±2.0% of the analyzer calibration span for low-, mid-, and high-level calibration gases, or ±0.5% CO_2	Before initial run and after a failed system bias or drift test
System Performance	System response time	Determines minimum sampling time per point.	During initial sampling system bias test
	System purge time	≥2 times system response time	Before first run and when probe is removed from the stack
	System bias (or pre- and post-run 2-point system calibration error for dilution systems)	Within ±5.0% of the analyzer calibration span for low-scale and upscale calibration gases, or ±0.5% CO_2	Before and after each run
	Drift	<3.0% of calibration span for low- and mid- or high-level gases, or ±0.5% CO_2	After each test run
	Minimum sample time at each point	2 times the system response time	Each sample point
	Stable sample flow (surrogate for maintaining system response time)	Within ±10.0% of flow rate established during response time check	Each run
Sample Point Selection	12-point Stratification test	Concentration at all points within: ±5.0% of mean for 1-point sampling, or ±0.3% CO_2 ±10.0% of mean for 3-point sampling, or ±0.5% CO_2 >10.0% of mean for 12-point sampling	Prior to first run
Data	Recording Frequency	≤1 minute average	During run
	Average Run Concentration	Run average ≤ calibration span	Each run

There is overlap between the plant CEMS performance specification and the reference method test procedures. These both address the selection of reference method sampling points for the purpose of either conducting a RATA (Performance Specification 3) or general requirements for measuring CO_2 in stack gases of stationary sources (EPA Method 3A). Both procedures allow for the use of either dry-basis or wet-basis measurement systems. As a result, when using a dry-basis system, as it is often done for a plant CEMS RATA, the obtained CO_2 measurements require a moisture correction to correct the reference method results from a dry to a wet basis, which is consistent with plant CEMS measurements. This requires the simultaneous measurement of stack gas moisture via EPA Method 4 (Determination of Moisture Content in Stack Gases) of Appendix A of 40 CFR Part 60.

EPA Method 4

Flue gas moisture determination utilizing EPA Method 4 involves the extraction of a gas sample at a constant rate from the stack, removing the moisture from the sample stream and determining the moisture content gravimetrically. The application of this approach is limited to stack gas streams that are not saturated nor contain water droplets, as under those conditions the method may be positively biased. Instead, for saturated gas streams, the moisture measurement is based on the average stack gas temperature determined from individual temperature measurements performed at each traverse point. The moisture content is subsequently calculated based on either saturation vapor pressure tables or psychometric charts. Temperature sensors are required to be capable of measuring to within ±1°C (2°F).

In order to obtain representative measurements of the stack gas moisture content, EPA Method 4 prescribes a minimum of 12 sampling points traversing the stack. This requirement is moderated in Section 6.5.6(a) of Appendix A to 40 CFR Part 75, making the sampling point selection for moisture contingent upon the results of the stratification test, with the final sampling point selection criteria consistent with EPA Method 3A.

Instrumentation, End-User Practices and Uncertainty

Whether conducted as part of a RATA or diagnostic test, EPA Method 3A test configurations generally consists of an in-stack particulate filter (often times a sintered filter element, or frit), a heated probe and sample line, a sample gas conditioning system, CO_2 analyzer and data acquisition system. In addition, some setups may include a flow panel to introduce calibration gas standards to the different parts of the system in order to perform calibration error, system bias and drift tests with relative ease. Figure 4-1 shows a typical CO_2 reference method setup.

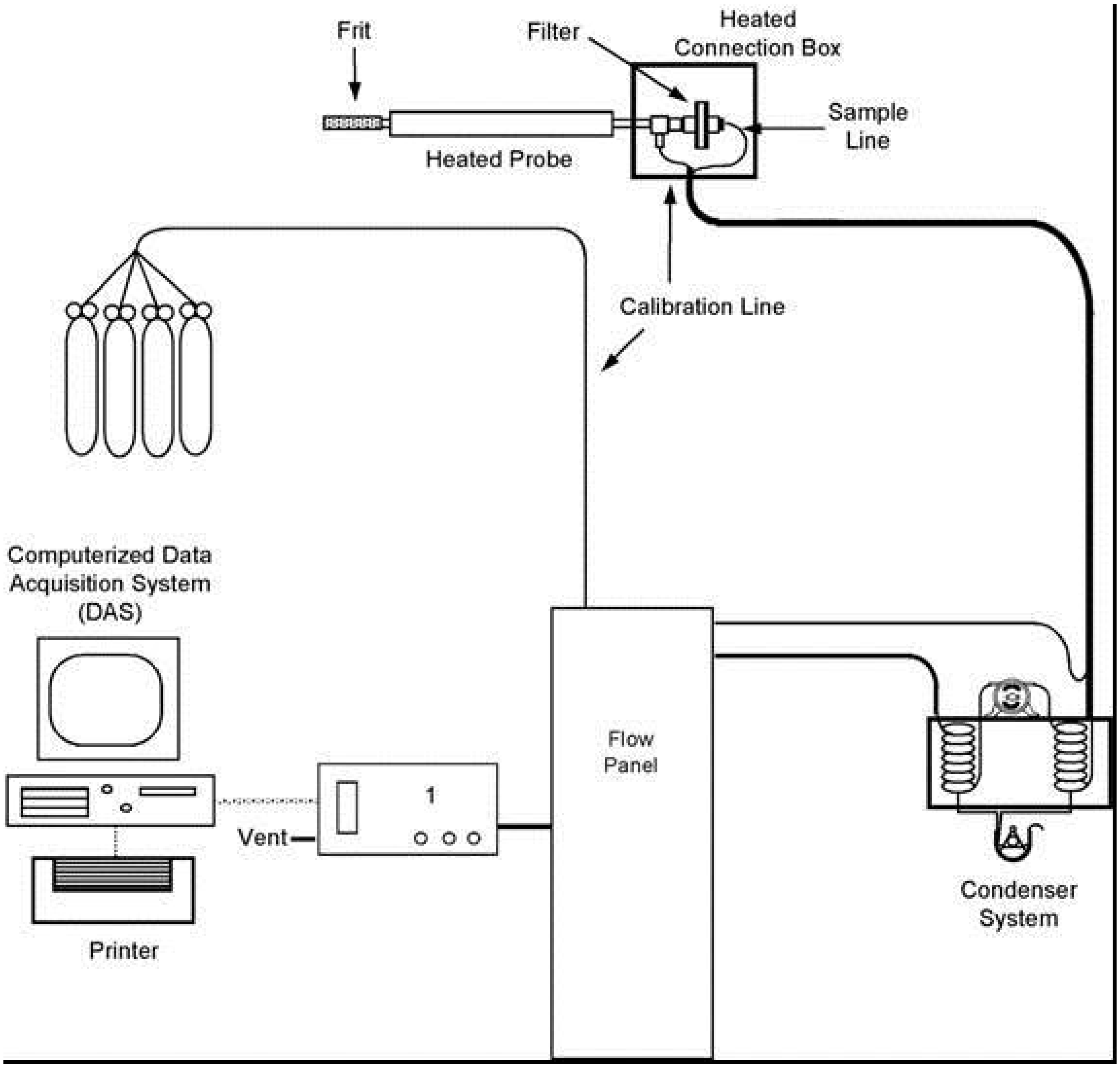


Figure 4-1
Schematic of a Typical EPA Method 3A Test Setup

This section of the report discusses the system components encountered and operating practices used during reference method testing. Improvements to current instrumentation and operating practices are discussed, as well as the implications related to CO_2 reference method measurement errors.

Sampling System

Although the use of a wet-basis sampling system including a dilution probe for certifying a plant CEMS is attractive due to the consistency it would provide in terms of the moisture basis of the results, test companies primarily use dry-basis systems for RATAs of plant CEMS, which feature simple sampling probes similar to the one depicted in Figure 4-1. This is in part due to the simple setup and ease of use of the sampling system. Dry-system sampling probes are also not affected by differences in molecular weight between calibration gas and actual stack gases, ambient pressure and stack temperature fluctuations the way dilution systems are. As a result, the use of a simple extractive sampling system followed by moisture removal serves to identify and partially correct plant CEMS dilution probe related biases.

Measurement Location

As with the plant CEMS measurement location, the reference method probe position should be at a point representative of the average concentration profile within the stack. This is important in stacks where concentrations within the cross section of the stack are stratified. This could potentially impart a bias on the reference method measurement results if taken from a measurement location not representative of the actual mean CO_2 stack gas concentration. The procedure and selection criterion for reference method sampling points is detailed in EPA Method 3A, and Performance Specification 3.

To determine reference method measurement locations that yield a representative measurement of CO_2 stack gas concentrations, a comprehensive 12-point stratification test should be conducted with the reference method system prior to each RATA. If the results indicate a minimally stratified stack (concentration at all points within ±5.0% of mean or ±0.3% CO_2), which is often the case, the reference method measurement location reduces to a single point within the stack. For stratified stack gases (concentration at all points within ±10.0% of mean or ±0.5% CO_2) that require the sampling from three fixed sampling points, dry-basis extraction probes have been designed that allow sequential sampling from three defined sampling points in the stack without moving the probe between measurements, ensuring consistent sampling locations.

Analyzer

Analyzers employed for EPA Method 3A testing are usually identical in their principle of detection to those installed in plant CEMS, which are based on NDIR spectrometry combined with GFC. These analyzers provide a good combination of simplicity and ruggedness with acceptable accuracy and precision of about ±1.0% of the analyzer scale and ±1.0% of reading, respectively [ThermoScientific 2015, Teledyne 2015]. For an analyzer with a scale of 20% CO_2 measuring CO_2 stack gas concentrations of 10%, this would result in a nominal accuracy of ±0.2% CO_2 and a precision of ±0.1% CO_2 or better.

One way to increase accuracy in the detection step is to replace the NDIR-based analyzers with more advanced instruments based on CRDS and OA-ICOS. Instruments based on these measurement techniques generally provide superior accuracy and precision of better than 0.1% and 0.01% of the analyzer range, respectively [TigerOptics 2015, Picarro 2015, Los Gatos Research 2105], resulting in exceptional linearity over the entire measurement range. However, these advantages come with an increase in complexity and cost compared to traditional

NDIR-based instrumentation, resulting in a three- to four-fold increase in initial capital cost of the instrumentation.

Similar to plant CEMS CO_2 analyzers, analyzers that are part of the reference method measurement system can be influenced by a variety of factors, such as changes in ambient pressure, temperature, vibrations, etc. Some of these changes directly affect the measurement (gas density changes), and instrument manufacturers have included algorithms to compensate for the effects [ThermoScientific 2015]. Other environmental changes can affect the electronic circuitry causing a drift in analyzer calibration.

The short test period during EPA Method 3A testing and the extensive quality assurance and quality control measures before and after each sampling run could cause pressure and temperature fluctuations on the sample gas density and ultimately on the measurement results, which can be quantified and corrected for. Conversely, the effect of temperature fluctuations on the electronic circuitry and analyzer drift can be minimized by siting the analyzer in a temperature-controlled enclosure or shelter with well dispersed airflows. Temperature variations of ±2°F about an ambient mean temperature of 72°F measured close to a CO_2 analyzer during a recent CO_2 RATA did not result in any significant analyzer drift [CleanAir 2015-3].

Calibration and System Performance

Reference method systems are typically calibrated by introducing a high-, mid- and low-level calibration gas directly to the analyzer and checking / adjusting its response. It is common practice to choose the high-level calibration gas to be the approximate CO_2 concentration of the analyzer scale. For a more accurate measurement, consider calibrating the analyzer using a high-level calibration gas with CO_2 concentrations that closely match those encountered in actual stack gas. Keep in mind that the calibration span of the instrument is set by the high-level calibration gas and must be chosen so that the average CO_2 concentration determined during a reference method test run does not exceed the calibration span.

For coal-fired boilers it is recommended to choose a calibration span of 14% CO_2 identical to the one suggested for plant CEMS in a previous section. Key analyzer and system performance criteria are tied to the calibration span of the analyzer rather than the analyzer scale, which has an effect on the reference method data quality criteria. In particular, analyzer calibration error, system drift and bias check criteria will become more stringent, providing higher data quality. However, all three key performance indicators allow for an alternative quality control limit of ±0.5% CO_2, which for stack gas concentrations of 10% CO_2 amounts to a tolerance of ±5% of reading. A revision of this alternative control limit should be taken into consideration to reflect the need for higher quality reference method data.

A prerequisite for strict data quality control limits are high quality calibration gas standards. EPA Method 3A requires the use of EPA Protocol 1 gases with a certified uncertainty of ±2.0% of the cylinder gas tag value. As gas standards with a certified uncertainty of ±1% have become readily available, it is recommended to use EPA Protocol 1 gases with the increased accuracy in support of a more accurate measurement. Care should be taken in choosing the calibration gas standard provider. EPA blind audit results indicate a noticeable difference in gas manufacturer's capabilities to provide accurate gas standards [EPA 2011]. In order to ensure consistent quality of high-, mid-, and low-level calibration gases used when implementing the quality assurance procedures of EPA Method 3A, cross check the tag value of newly purchased calibration gases.

System Response Time

The response time for the measurement system used for reference method testing is defined as the time it takes the system to respond to the introduction of a calibration gas standard at the probe to within 95% of a stable response for both the low-level and high-level calibration gas. Biases due to system response times can arise when calibration and bias checks are performed and not enough time is allowed to pass between the introduction of the calibration gas and the time the calibration or bias check is completed. The result is that analyzer zero and span adjustments as well as bias corrections are based on premature system responses ultimately affecting the CO_2 measurement.

In addition, the measurement response time determines the minimum time the sampling probe needs to remain at a sampling point before the analyzer delivers measurement results that are representative of the stack gas concentrations at the sampling point. As a result, incorrect system response times affect the measurement results since the system is not given sufficient time to purge the stack gas collected from the previous sampling point.

To avoid this potential bias, properly characterize the system response to low- and high-level calibration gas standards and be consistent in the application of the response times from calibration to calibration and bias check to bias check. Consider the use of an alternative definition of a stable CO_2 reading according to 40 CFR Part 75 Appendix A, which states that a reading of calibration gas concentrations is considered stable if it changes by no more than 0.2% CO_2 in two minutes.

Moisture Measurement

An integral part of reference method testing for plant CEMS performance certification is determining the stack gas moisture content according to EPA Method 4 and EPA Method 3A reference testing. The need for this measurement arises when dry-basis CO_2 measurement results have to be converted to a moisture basis consistent with plant CEM system results.

One challenge in stack testing is collecting a sample that is representative of the stack gas composition. To ensure that moisture content measurements yield representative results, the sampling point selection should mirror those determined for measurements according to EPA Method 3A.

Wet scrubbers present another challenge, as the measured flue gas moisture has the potential to be biased high. This is due to saturated stack gas conditions and the presence of water droplets that might be counted towards the flue gas moisture content. For those circumstances, EPA Method 4 recommends the calculation of stack gas moisture content based on either saturation vapor pressure tables or psychometric charts using stack gas temperature measurements. To obtain representative stack gas temperatures, it is recommended to perform temperature measurements while traversing the stack with the reference method probe.

With this approach, the accuracy of the temperature measurement is critically important as the saturation pressure calculation is sensitive to variations in temperature [EPRI 2014]. EPA Method 4 requires the use of a calibrated temperature sensor capable of measuring temperature to within ±1°C (2°F). A common practice is the use of a special Type-K thermocouple (ASTM E320/E230M – 12). For a more accurate temperature measurement, the use of a 4-wire Class-A Resistance Temperature Detector (RTD) with calibration tolerances of ±0.5°F for gas temperature measurement is recommended [CleanAir 2015-2].

Best Practices Recommendations

The following list presents the best practice recommendations for reference method testing. The items in this list are deduced from the discussion in the preceding sections.

Testing

- Always perform a 24-point stratification test prior to the start of the RATA to sufficiently characterize the stack cross section.
- Consider use of fixed 6-point sampling probe for measurements at minimally stratified stacks to provide sample point location consistency.
- Consider use of a fixed 12-point sampling probe for measurements at stratified stacks to provide enhanced sample point location consistency.
- Select the span of the reference method system so that the CO_2 calibration gas standards that are as close as possible to the actual stack gas concentrations in order to increase measurement accuracy.
- After initial span and zero adjustments of the reference method analyzer, repeat the procedure to check for drift in adjustments.
- Determine the system response time and be consistent in its use throughout the reference method test, calibration error and system bias checks.
- Consider adopting quality control limits for analyzer calibration error, system bias and drift that are more stringent than the reference method requirements.
- CO_2 analyzers are susceptible to temperature changes. Minimize analyzer drift by careful siting analyzer racks or redirecting of airflow to maintain analyzer temperature within a ±3°F band.
- Allow sufficient time for the analyzer to warm up.
- Use a calibrated temperature sensor such as a 4-wire Class-A high temperature resistance temperature detector (RTD) capable of measuring temperature to within ±0.5°F to obtain average stack temperature for determining moisture content in saturated stacks.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use EPA Protocol calibration gases with a certified accuracy of better than 1% of cylinder gas tag value.
- Use EPA blind calibration gas audit reports as a guide to selecting calibration gas vendors.

- Do not over-pressurize the measurement system and analyzer during calibration error and system bias checks.

Review of Internal RATA Testing

Plant CEMS performance tests (RATAs) are typically performed on an annual basis as part of the data quality assurance requirements of 40 CFR Part 75 Appendix B and 40 CFR Part 60 Appendix F. As mentioned in a previous section, the RATA consists of a set of plant CEMS CO_2 measurements that are compared to results concurrently obtained from a series of independent reference method tests. The result is a plant CEMS accuracy expressed relative to the reference method measurements determined by:

$$RA = \frac{[|\bar{d}|+|CC|]}{\overline{RM}} \times 100 \qquad (1)$$

Where:

RA = Relative accuracy in %

$|\bar{d}|$ = Absolute value of the mean differences between plant CEMS and reference method measurements

$|CC|$ = Absolute value of the confidence coefficient

$\overline{RM}$ = Average reference method value

The 2.5% error confidence coefficient (CC) used in Equation 1 is calculated as:

$$CC = t_{0.975} \frac{S_d}{\sqrt{n}} \qquad (2)$$

Where:

$t_{0.975}$ = t-value for the 97.5% error confidence (2.306 for 9 test runs)

S_d = Standard deviation of the mean differences between plant CEM and reference method measurements

N = Number of data points

As shown in Equations 1 and 2, smaller relative accuracies correspond to closer agreements between plant CEMS and reference method test results. Therefore, improving relative accuracies can be achieved by minimizing the difference between both measurements and reducing the standard deviation of the mean differences.

This section presents the results of 21 RATAs performed by CleanAir Engineering over several years at coal-fired power plants utilizing a variety of air pollution control equipment resulting in dry- and wet-stack gas conditions. The RATA results focus on what they reveal about existing plant CEMS biases and how best operating practices for plant CEMS affect measurement uncertainty, as well as the effect of reference method best practices on the reported relative accuracy.

Plant CEM System and Reference Method Difference

During a RATA, the average CO_2 concentration determined by the plant CEMS and reference method measurement system are compared to determine the difference between both measurement results as well as the variation in the difference from run-to-run. These are synonymous for plant CEMS CO_2 measurement biases and influence the imprecision in both measurements. The difference can be introduced by biases imparted on the measurement results by both the plant CEMS and the reference method measurement systems. Possible sources include plant CEMS sampling biases, calibration biases and choice of sampling location for plant CEMS and reference method systems alike, etc. All of these biases and their relative implications have been discussed in previous sections.

Figure 4-2 shows the differences between average plant CEMS and reference method results compiled from 21 RATAs at coal-fired power plants in form of a box plot and histogram. The median and mean difference are -0.10%wv and -0.14%wv CO_2, respectively, indicating that the reference method typically reads lower than the plant CEMS. However, the spread in the differences prohibits the determination of any origin.

It is important to note that it is assumed during RATAs that the reference method test is bias-free or performed in such a manner to minimize possible biases to the greatest extent possible. In reality, reference method measurements are affected by measurement errors as well, and the difference in results is affected by contributions from both plant CEMS and reference method measurement errors alike. The implementation of best practices would serve to limit these errors and as a result limit their propagation in the resulting differences.

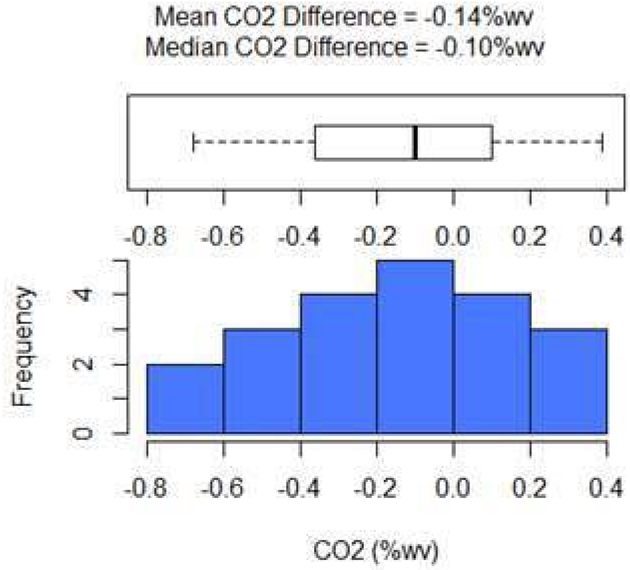


Figure 4-2
Average Differences between Plant CEMS and RM Results during RATAs

CEMS and Reference Method Difference Variation

Besides the difference between plant CEMS and reference method measurements, the relative accuracy determined during a RATA is also based on the variation between the plant CEMS and reference method measurements (see Equation 2). This is done in order to account for the imprecision in both measurements when determining the instrument's relative accuracy. Figure 4-3 shows the histogram and box plot of the standard deviation of the mean differences for 21 RATA tests.

Based on the mean of 0.08%wv CO_2, a 2.5% error confidence coefficient of 0.06%wv CO_2 can be calculated. This is well within the precision specifications of a single NDIR analyzer, which typically provides for accuracy of 1% of reading or less [ThermoScientific 2015], or 0.11%wv CO_2 at the average RATA CO_2 concentration level of 11.1%wv CO_2 encountered during the 21 tests.

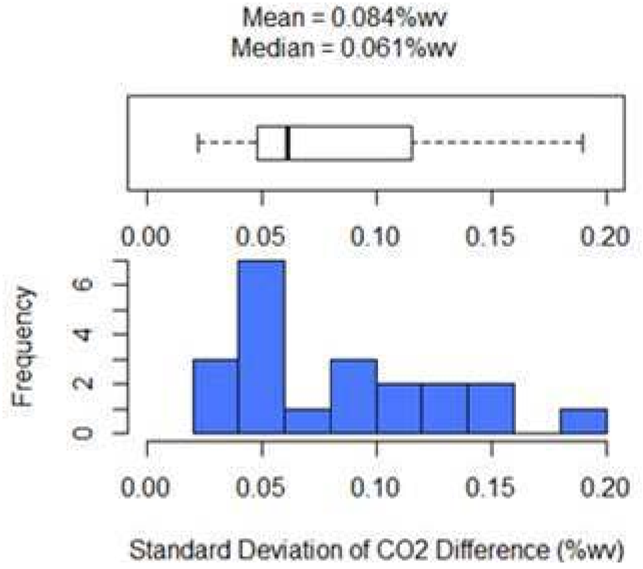


Figure 4-3
Average Differences between Plant CEMS and RM Results during RATAs

Spatial Variation of CO_2 Concentrations

Plant CEMS and reference method results can agree but could fail to provide a measurement that is representative of the total CO_2 concentration in the stack if the measurement location is not selected correctly. To avoid this scenario, the measurement locations for both the plant CEMS and the reference method measurements are selected based on results of a stratification check. The standard deviation of the mean stack CO_2 concentrations determined in 13 pre-RATA stratification checks are presented in Figure 4-4. The figure indicates that the majority of the stacks tested were considered un-stratified with a median and mean standard deviation of 0.12%dv and 0.10%dv CO_2, respectively. The larger standard deviations in Figure 4-4 correspond to reference method tests that were conducted with instruments having a span greater than 17.7% CO_2, providing potentially less accurate measurements than those calibrated at concentrations close to actual stack gas concentrations.

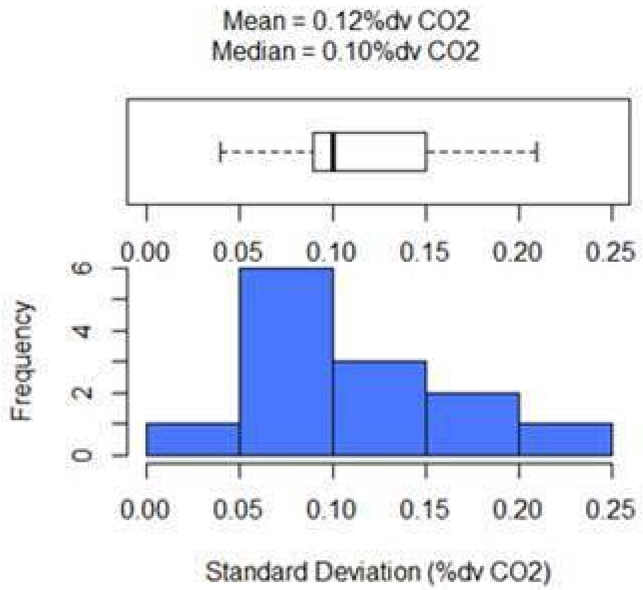


Figure 4-4
Pre-RATA Stratification Check Results

Relative Accuracy Results

The relative accuracy results for 21 RATAs can be seen in Figure 4-5 with resultant mean and median relative accuracies of 3.1% and 2.8%, respectively. To put these results into perspective, it has to be determined which relative accuracies are attainable when all biases are removed and only the analyzer measurement errors remain. Considering analyzer accuracies of 1% calibration span, a combined accuracy of $\sqrt{1^2 + 1^2} = 1.4\%$ can be calculated. Consequently, for instruments spanned at 14% CO_2, a measurement accuracy of 0.2% CO_2 is attainable. This would result in a minimum relative accuracy of 1.8% based on average CO_2 stack concentrations of 11.1%wv as determined from the 21 RATA test results.

On average, relative accuracies determined during current RATAs are higher than this limit. Implementing best practices for both plant CEMS and reference method measurements would reduce the spread in relative accuracies currently achieved and bring them closer to the relative accuracy limit of 1.8%.

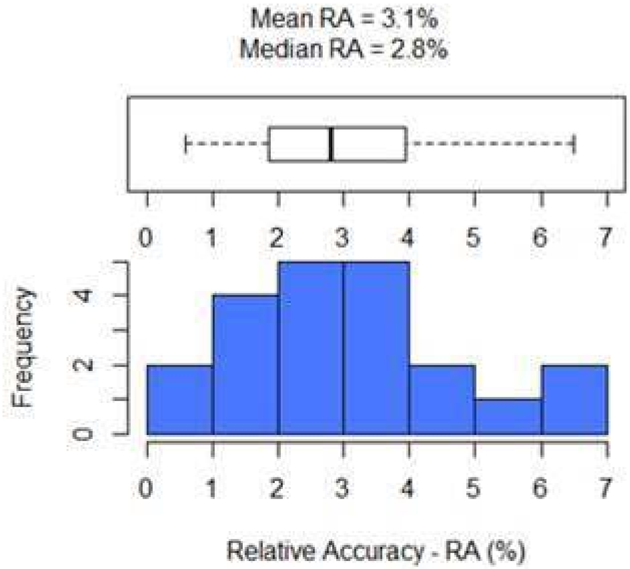


Figure 4-5
Results from 21 Historical RATAs

Conclusion

Table 4-3 summarizes the projected improvements (reduction in systematic uncertainty) that can be achieved through implementation of reference method best practices.

Table 4-3
Stratification Acceptance Criteria and Traverse Point Selection

Bias and Systematic Uncertainties	EPRI (2014)	Actual	Best Practice
Offset	0.20	0.14	0
Comparison	0.08	0.07	0.07
Spatial	0.25	0.16	0.13
Instrumental	0.18	0.18	0.07 - 0.16
Total	0.32	0.25	0.16 - 0.22

5

FLOW MEASUREMENT REFERENCE METHOD TESTING

Introduction and Background

Over the past several years, considerable attention has been given to the accuracy of CEMS measurements. Power generation companies are concerned with meeting applicable measurement standards, as well as avoiding the over-reporting of emissions. Numerous studies [Sarunac 1996] reported evidence that the procedures specified in the EPA regulations for certifying the accuracy of flow monitors result in measured gas flow rates which are higher than actual values. This resulted in modifications to the EPA reference methods which permit utilities to use more accurate equipment and procedures for calibrating flow monitors.

The flow rate of the stack flue gas is measured continuously by a flow monitor. Periodic calibrations of the equipment are mandated by the EPA to ensure accurate flow measurements. EPA regulations stipulate the frequency of calibrations, as well as the equipment and procedures used for equipment calibration and certification. Until 1999, EPA procedures mandated the use of a Type-S Pitot probe in the straight up mode, and the use of the Equal Area Method (EAM) to convert probe measurements into volumetric flow rates.

After calibrating flow monitors in accordance with these EPA requirements, utilities found their CEMS flow instruments indicating stack flue gas flow which were significantly higher (10% or higher) than actual flow rates. The flow measurement studies that followed indicated that the positive flow bias errors were attributable to the Type-S Pitot design, use of the default value for the probe calibration coefficient (C_p), use of the EAM, velocity head measurement errors, and neglecting the effect of velocity decay near the wall.

In response to industry criticism, and after conducting an extensive field study [EPA 1999], the EPA updated its flow measurement Reference Methods and calculation procedures in 1999. The new methods and procedures allow yaw-nulling of the S-Type Pitot, use of three-dimensional velocity probes, and application of a wall correction factor to the EAM. Yaw-nulling allows determination of the tangential flow component (the radial component is not determined) and therefore, reduces the S-Type Pitot error. Use of the 3-D probe allows determination of all three velocity components and eliminates the S-Type Pitot error. Use of the wall correction factor decreases or eliminates the flow correction error.

To provide recommendations for best practices, information on stack flow measurements is summarized in this section. The EPA methods were reviewed in detail in this section, permitting the quantification of the measurement uncertainty of stack flow measurements. A literature search was conducted in an attempt to identify both historical and recent research in the area of stack flow measurement uncertainty improvement. All information sources are properly referenced and credited in the Bibliography.

Review of Reference Methods Used for Stack Gas Velocity Determination

The following sections provide a brief overview of the procedures, requirements and uncertainty of the EPA Reference Methods currently in use for velocity and flow measurements.

EPA Method 2

EPA Method 2 is the reference method that describes how to determine the average stack gas velocity and volumetric flow rate using an S-Type Pitot tube that includes a temperature sensor (shown in Figure 5-1). The method employs the principals of EPA Method 1 in selecting an appropriate sampling location and determining the minimum number of sampling points to provide reliable velocity and volumetric flow rate determination. The method only applies to flows that are not swirling or cyclonic as identified in EPA Method 1. This method combines measurements and calculations to determine the gas flow rate. Specific guidelines are provided for what materials should be used and what dimensions are critical.

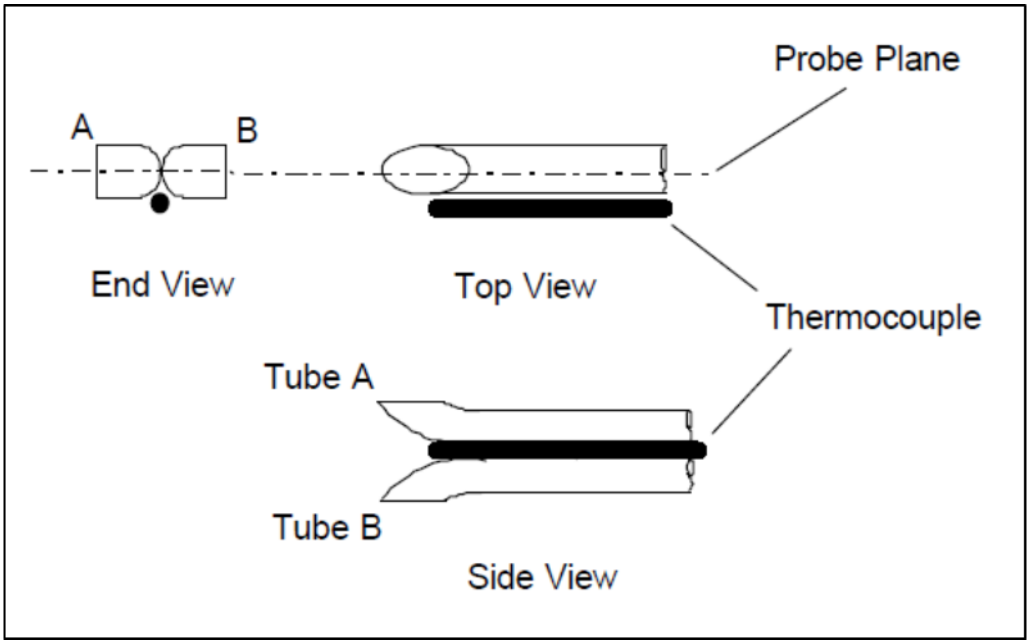


Figure 5-1
S-Type Pitot Tube

The method recommends that each Pitot probe be calibrated in a wind tunnel using a standard Pitot as reference. A copy of the wind tunnel certification and calibration coefficient must accompany the probe. If the Pitot probe is not wind tunnel calibrated, a baseline calibration coefficient value of 0.84 is assigned to the Pitot [Vollaro 1978]. The baseline calibration coefficient of 0.84 is biased high in the range of 1-3% in comparison to wind tunnel calibration results [Trang 2012]. The Pitot must be visually inspected after each use in the field. If there is any visually damage, the Pitot probe must be repaired and recalibrated. Also, after each field use, the Pitot tube opening alignment must be checked, and the inter-component spacing of the probe assembly are checked. If the face opening alignment is no longer within the method specification, the damaged Pitot must be replaced. If the inter-component spacings have changed, the original spacings must be restored, or the Pitot must be recalibrated.

The pressure "head" or difference between the static and dynamic measurements is typically very small and can be measured with an inclined manometer, Magnehelic gauge, or pressure transducer. The gas temperature is measured with a thermocouple, mercury thermometer, bimetallic thermometer, or other gauge capable of measuring temperatures to within 1.5% of the minimum absolute stack temperature. The pressure and temperature measurement devices must be calibrated in accordance with Sections 6.2.1 and 10.3.1 of EPA Method 2, respectively.

The equation governing the response of the Pitot tube is based on the Bernoulli equation, and is commonly given as:

$$v = \sqrt{\frac{2(p_t - p_s)}{C_p \rho}} \qquad (1)$$

Where p_t is the total or impact pressure, p_s is the static pressure, and C_p is the probe calibration constant. According to EPA Method 2, the average stack gas velocity can be calculated for a Type S Pitot tube using:

$$v_s = K_p C_p \sqrt{\frac{(p_t - p_s) T_s}{P_s M_s}} \qquad (2)$$

Where:

V_s = average stack gas velocity (ft/sec)

K_p = velocity equation constant

C_p = Pitot tube probe constant

pt – ps = difference between total and static pressures measured with Pitot tube (in. H_2O)

T_s = absolute stack temperature (°R)

P_s = absolute stack pressure (in. Hg)

M_s = molecular weight of the wet stack gas (lb/lbmol)

Advantages of EPA Method 2

The following are the advantages of EPA Method 2:

- The S-type pitot is reasonably accurate (i.e., ±5%) in gas streams where the flow is axial and the velocity is between 10 and 100 ft/sec. If the pitot is to be used outside this flow range, it should (must) be calibrated at the measured flow rate.
- [Vollaro 1976] conducted a study of the accuracy of the S-Type Pitot at low flow rates. In this study he calibrated twelve Type-S Pitot tubes against a standard Pitot at velocities ranging from 6.7 ft/sec to 17 ft/sec. Each Pitot tube had been previously calibrated at higher velocities, ranging from 25 to 58 ft/sec, providing "reference" C_p for each Pitot tube. In general, the C_p varied little from the "reference" C_p. The average difference was 2.1% with an average deviation of 1.3%.

- The S-Type pitot was designed for flow measurement applications where there is excessive particulate, such as coal-fired boiler gas streams. When it was developed, it was deemed an improvement over the standard pitot design due to the following factors: 1) it is more rugged; 2) it will not plug as easily as a standard pitot and it is easy to purge; 3) it is essentially straight, therefore it can be inserted into pipes or ducts; and 4) since the one aperture faces downstream, there is a slight aerodynamic low pressure wake at the opening, resulting in a pressure that is lower than static pressure, and a P that is larger and more readable than that produced by a standard pitot. The large apertures of the Type-S Pitot tube make it less susceptible to plugging when used in particulate-laden gas streams or gas streams with entrained water droplets.

Limitations of EPA Method 2

It is often assumed that if a properly calibrated S-Type Pitot tube is used, conforming to Method 2 requirements, then the measurements will be accurate. However, a number of limitations associated with the use of the Type-S Pitot have been identified under a range of conditions. These limitations include the following:

- The S-Type pitot when used in the “straight-up” configuration does not account for non-axial (i.e., swirling or cyclonic) flow conditions, i.e., yaw and pitch angles.
- EPA Method 2 does not account for velocity decay near the stack or duct walls.
- Pitots are calibrated in wind tunnels, where conditions approximate those of an ideal gas, i.e., air at constant temperature and pressure, incompressible, non-turbulent flow.
- Bernoulli’s equation only applies under steady state conditions. Therefore the Pitot tube should be left in the stack long enough for thermal equilibrium to occur between the hot stack end of the pitot and the pressure measurement end. If a non-stable temperature gradient is set up then the measurement of dynamic pressure will potentially be in error. If temperature differences occur between the two pressure tubes in the pitot, then the gas in these will have different densities, which may lead to further errors.
- The longer the S-Type Pitot tube probe is, the more likely it is to deflect when inserted into a test port. This deflection can introduce bias to the results. [Kang 2013] found that the Pitot tube coefficient increases up to 4% as the pitch angle increases to +10°. [Kang 2013] also found that the Pitot coefficient decreases up to -2% for pitch angles to -10°.
- Misalignment of the Pitot tubes axes in either the longitudinal or transverse planes, whether the result of manufacturing defects or field use, can introduce pitch and yaw angles leading to errors in the coefficient.

EPA Method 2F

In EPA Method 2F, a 3-D probe is used to determine the velocity pressure and the yaw and pitch angles of the flow velocity vector in a stack or duct. The method determines the yaw angle directly by rotating the probe to null the pressure across a pair of symmetrically placed ports on the probe head. The pitch angle is calculated using probe-specific calibration curves. From these values and a determination of the stack gas density, the average axial velocity of the stack gas is calculated. The average gas volumetric flow rate in the stack or duct is then determined from the average axial velocity. This method may be used only when the average stack duct velocity is greater than or equal to 20 ft/sec.

EPA Method 2F allows the use of either a five-hole prism-shaped probe (shown in Figure 5-2) or a five-hole spherical probe (shown in Figure 5-3). The testing can be conducted either manually by an operator, or automatically using a computer-controlled system to position the Pitot probe at individual points and perform yaw angle determinations.

The velocity pressure (ΔP) measuring devices used during wind tunnel calibrations and field testing must be one of the following types: electronic manometers (e.g., pressure transducers), fluid manometers, or mechanical pressure gauges (e.g., Magnehelic gauges). Use of electronic manometers is recommended. Under low velocity conditions, use of electronic manometers may be necessary to obtain acceptable measurements. The differential pressure measuring device must be capable of measuring and displaying pressure differentials of ±1% of full scale.

3-D probes are calibrated in a laboratory wind tunnel against a standard Pitot (Prandtl type) probe at two nominal velocities, typically 60 and 90 ft/sec. Probes are required to be calibrated before initial use in the field. 3-D probes are required to be recalibrated within 12 months of its first field use after its most recent calibration or after 10 field tests, whichever occurs later. In addition, whenever there is visible damage to the 3-D probe head, the probe must be re-calibrated before being used in the field.

Multi-hole probes are fluid mechanics instruments designed to measure the flow velocity and pressure through direct measurement of the pressures at the probe tip, and then using the pressures to calculate a velocity. These probes measure flow velocity and pressure by interfering (as little as possible) with the flow in a particular and consistent manner. Calibration of the probe at a known flow velocity and angle, followed by processing of the raw pressure data provides a non-dimensional pressure coefficient map to which subsequent measured pressures are non-dimensionalized and compared. In this way, the unknown velocity vector, as well as the total and static pressure at the measurement location may be determined.

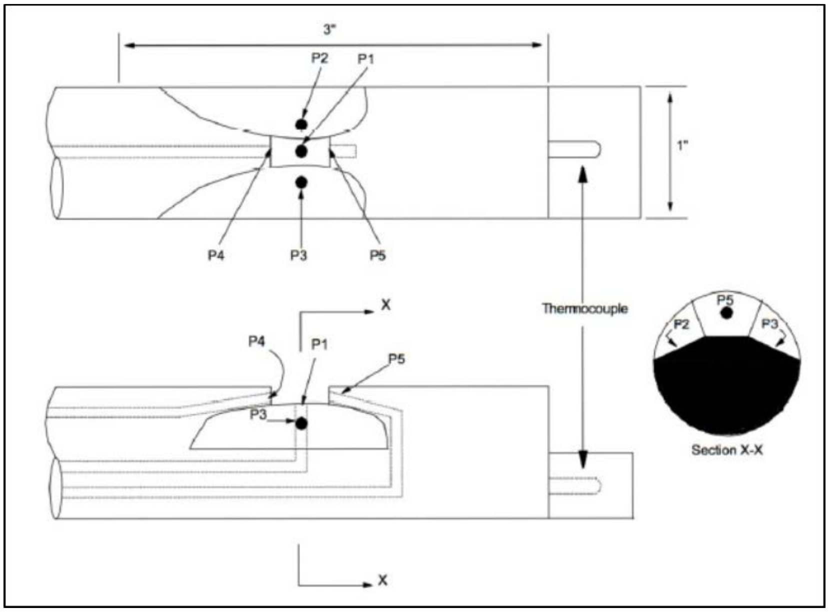


Figure 5-2
Five-Hole Prism 3-D Velocity Probe

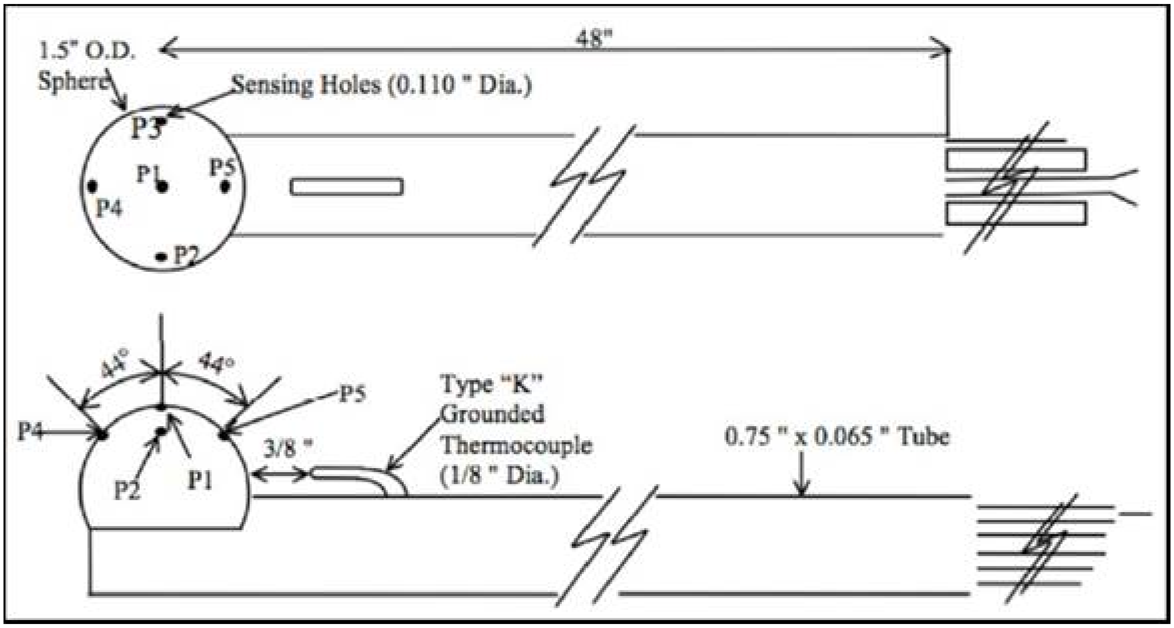


Figure 5-3
Five-Hole Spherical 3-D Velocity Probe

EPA Method 2G

In EPA Method 2G, a 2-D probe (typically a 3-hole wedge probe or S-Type pitot) is used to measure the velocity pressure and the yaw angle of the flow velocity vector in a stack or duct. Alternatively, these measurements may be made by operating one of the three-dimensional (3-D) probes described in Method 2F, in yaw determination mode only. From these measurements and a determination of the stack gas density, the average near-axial velocity of the stack gas is calculated. The near-axial velocity accounts for the yaw, but not the pitch, component of flow. The average gas volumetric flow rate in the stack or duct is then determined from the average near-axial velocity.

The velocity pressure (ΔP) measuring devices used during wind tunnel calibrations and field testing must be one of the following types: electronic manometers (e.g., pressure transducers), fluid manometers, or mechanical pressure gauges (e.g., Magnehelic gauges). Use of electronic manometers is recommended. Under low velocity conditions, use of electronic manometers may be necessary to obtain acceptable measurements.

The yaw angle of flow is measured using either a digital inclinometer or a protractor wheel and pointer assembly. Either device must be capable of measuring and displaying the rotational position of the probe to within ±1°.

The 2G probe is calibrated in a wind tunnel using a Prandtl probe as reference. The probe is calibrated at two nominal wind tunnel velocity settings of 60 ft/sec and 90 ft/sec, and the average of these calibrations are used to generate a calibration coefficient, C_p.

EPA Method 2H

EPA Method 2H describes the procedures and calculations used to determine the correction for velocity decay near the wall in stacks greater than 1.0 m (3.3 ft.) in diameter. The method is used to adjust (correct) the average stack gas velocity obtained under Method 2, 2F, or 2G. The method contains two possible procedures; one uses velocity measurements and the other uses a generic adjustment factor. The calculation-based procedure derives a wall effects adjustment factor from velocity measurements taken using Method 2, 2F, or 2G at 16 (or more) traverse points specified under Method 1, and a total of eight (or more) wall effects traverse points specified under Method 2H. The calculation-based procedure which uses velocity measurements is not applicable for horizontal circular ducts where a build-up of particulate matter or other material in the bottom of the duct is present.

A default wall effects adjustment factor of 0.9900 for brick and mortar stacks and 0.9950 for all other types of stacks and ducts may be utilized without taking wall effects measurements in a stack or duct.

When, the calculation-based procedure is conducted as part of a relative accuracy test audit (RATA) or other multiple-run test procedure, the wall effects adjustment factor derived from a single traverse (i.e., single RATA run) may be applied to all runs of the same RATA without repeating the wall effects measurements. Alternatively, wall effects adjustment factors may be derived for several traverses and an average wall effects adjustment factor applied to all runs of the same RATA. When the calculation-based procedure is used, the minimum wall effects adjustment factor that may be used is 0.9700.

EPA Preliminary Method 007

EPA Preliminary Method 007 (Pre-007) was developed as an alternative to EPA Method 2F. EPA PM-7 is reported to be applicable for the determination of yaw angle, pitch angle, axial velocity and the volumetric flow rate of a gas stream in a stack or duct using a three-dimensional (3-D) probe. This method may be used only when the average stack or duct gas velocity is greater than or equal to 20 ft/sec.

The main difference of Pre-007 in comparison to the current Reference Method 2F, is that in Pre-007 during use of the probe in actual field tests, no yaw nulling is required, i.e., the probe does not have to be rotated in order to find the flow yaw angle by equating pressures P2 and P3 (refer to Figure 5-2 above). Instead, at every measurement point along the stack diameter, the 5 pressures are acquired and proper data-reduction algorithms are used to generate, from these 5 pressures, both flow angles, pitch and yaw, as well as the velocity magnitude. It is anticipated that the proposed method will yield significant time savings in field stack measurements as well as better measurement accuracies since less human-operator involvement is required thus reducing the probability of human error. The developers of Pre-007 report that the new method will result in time savings on the order of 70% [U.S. EPA].

The developers of Pre-007 report that using the above calibration system and procedures with regular 3-D probes, they repeatedly achieve calibration accuracies as high as 0.25° in the pitch and yaw angles and 0.5% in the velocity magnitude, in the range ±20° in pitch and yaw.

Uncertainty of Stack Flow Measurements

The average flow rate in a stack flow CEMs is obtained by measuring the average gas velocity, the gas density, and the cross-sectional area of the stack. EPA reference methods and ISO standards mandate the use of S-Type or 3-dimensional Pitot probes to measure the flow velocity in industrial stacks or ducts. The S-Type Pitot tube was designed to measure flow velocity in high dust environments for industrial stacks, which has large pressure orifices and strong tubes compared with the standard Pitot tube. The flow velocity can be obtained by measuring differential pressure between an impact orifice and a wake orifice based on the Bernoulli equation. The S-Type Pitot tube coefficient (C_P) is used to calculate the flow velocity by measuring the differential pressure with the S-Type Pitot tube according the following equation:

$$v = C_p\sqrt{\frac{2\Delta P}{\rho}} \qquad (1)$$

Where ΔP is the differential pressure between the impact (total) and the wake (static) orifices. The Greek letter rho (ρ) is the density of stack gas. The S-Type Pitot tube is typically calibrated in a wind tunnel of an accredited calibration laboratory. However, the S-Type Pitot tube is usually installed and utilized in stacks having harsh environments such as high temperature, particulate-laden and wet gas streams which are markedly different than the laboratory wind tunnel. It is also difficult to observe and check the inside of the stack for the precise installation and alignment of the S-Type Pitot tube. Therefore, misalignments such as yaw angle rotation are likely to occur during the use of the S-type Pitot tube inside of the stack.

As the diameter of stack increases, the number of sampling points for measuring velocity distributions in the stack should increase according to EPA Method 1. Since the inserted length of S-Type Pitot tube also increases, a pitch angle misalignment of S-Type Pitot tube can result due to the deflection of the tube in large diameter stacks. In addition, the gas flow rate can vary due to unstable process conditions. This would result in a change in flow velocity (Reynolds number) in the stack, which is measured by S-Type Pitot tube. Since S-Type Pitot tubes are used in different installation alignments and velocity range conditions from calibration conditions, the accuracy of flow rate measurements using calibrated S-Type Pitot tube coefficients can be negatively affected. Finally, flow asymmetry resulting from recirculation zones, swirl decay, and velocity profile development can induce systematic error or bias in the mean flow velocity measurement. Consequently, the area average velocity over the cross section cannot be determined completely by measuring the velocity at only two chords (diameters) as dictated by EPA Methods 1-2.

[Lee et al. 2014] developed the following model equation to define continuous flow rate measurements:

$$Q = V\frac{\pi D^2}{4}\frac{P}{29.92}\frac{460}{T}(1 - B_{wo}) \qquad (2)$$

The above equation can be expanded for continuous stack flow rate measurements using differential pressure probes as follows,

$$Q = C_p \sqrt{\frac{2\Delta P}{\rho}} \frac{\pi D^2}{4} \frac{P}{29.92} \frac{460}{T} (1 - B_{wo}) \quad (3)$$

where Q is the dry gas flow rate (ft^3/sec), V is the gas velocity (ft/sec), C_p is the S-Type Pitot tube dimensionless calibration coefficient, ΔP is the dynamic pressure (in H_2O), ρ is the gas density (lb/ft^3), D is the stack diameter (ft.), P is the stack pressure (in Hg), T is the stack gas temperature (R), and B_{wo} is the water content of the stack gas (%, vol.).

CleanAir applied Equation 3 to a recently completed flow RATA test conducted on a large coal-fired utility boiler. The RATA consisted of ten EPA Method 2 runs conducted at the stack test location at high load. Two stack diameters were tested, six points per diameter for a total of twelve points. An uncertainty analysis was performed to estimate the combined uncertainty of the point flow measurements. Assuming that the input measurements for Equation 3 were mutually independent, the following equation was applied to estimate the combined uncertainty for the gas flow.

$$\frac{u_c(y)}{y} = \sqrt{\sum_{i=1}^{N} s_i^2 \left(\frac{u(x_i)}{x_i}\right)^2} \quad (4)$$

The standard uncertainty, $u(x_i)$, for each input measurement, xi, used to compute the gas flow (y = Q), is listed in Table 5-1. The non-dimensional sensitivity coefficient, given as:

$$s_i = \frac{\partial y}{\partial x_i} \frac{x_i}{y} \quad (5)$$

is also listed in the table to reflect the weight applied to the standard uncertainty of each component. Estimates of the relative expanded uncertainty (twice the relative standard uncertainty for a 95% confidence interval) of the flow measurements were ±4.96%. The combined standard uncertainty for flow measurement can be expressed as

$$u(Q) = \sqrt{Q^2 \left[\left(\frac{u(C_p)}{C_p}\right)^2 + \left(\frac{u(\Delta P)}{2\Delta P}\right)^2 + \left(\frac{u(\rho)}{2\rho}\right)^2 + \left(\frac{2u(D)}{D}\right)^2 + \left(\frac{u(P)}{P}\right)^2 + \left(\frac{u(T)}{T}\right)^2 + \left(\frac{u(1-B_{wo})}{1-B_{wo}}\right)^2 + \left(\frac{u(\Delta V_D)}{\Delta V_D}\right)^2\right]} \quad (6)$$

where ΔV_D is an additional parameter introduced to account for the flow velocity distribution. The uncertainty, $u(\Delta V_D)$, due to the velocity distribution in the cross section of the stack was determined by standard deviation of the measured velocity distribution profile.

Table 5-1
Uncertainty Budget for a Stack Flow Rate Measurement

Measurement Component (x_i)	Value	Unit (x_i)	Standard Uncertainty $u(x_i)$	Relative Standard Uncertainty $u(x_i)/x_i$, %	Sensitivity Coefficient	Uncertainty Contribution
C_p	0.84	-	0.0126	1.50[b]	1	1.50%
ΔP	1.04	in H_2O	0.0124[a]	1.19	0.5	0.59%
ρ	0.0705	lb/ft^3	0.0007[e]	0.93	0.5	0.46%
D	28.0	ft	0.0241[d]	0.09	2	0.18%
P_s	29.28	in Hg	0.0502[a]	0.17	1	0.17%
T_s	590.8	°R	0.45[c]	0.08	1	0.08%
1-B_{wo}	85.2	%	0.30	0.35	1	0.35%
ΔV_D	61.56	ft/s	1.09	1.77	1	1.77%
Q	1,993,250	scfm				
Combined uncertainty of the flow rate measurement						2.48%
95% confidence level						2
Expanded uncertainty						4.96%

Notes: [a]EPA Method 2, [b]ASTM D3154, [c]Manufacturer's specification for Type K thermocouple, [d]Manufacturer's specification, [e]Lee et al. (2014).

Measurement uncertainty was based on uncertainty estimates quoted from EPA reference methods. In the absence of an estimate for a component measurement uncertainty in EPA methods, uncertainty standards from ASTM D3154 were applied. Accuracy information from manufacturer's technical specifications was applied where applicable. The accuracy for the stack diameter was assumed as ±0.5 in. from manufactured technical specification, and then its standard uncertainty became 0.024%, assuming a rectangular distribution.

The relative expanded uncertainty for the flow measurement was estimated to be 4.96% for a coverage factor (k=2) at a 95% confidence level. The estimated uncertainty is similar to estimates (approximately 5%) in previous studies [Evans 2009, Boze 2010 and EPRI 2014].

The measurement component with the highest sensitivity coefficient of two is the stack diameter (D). This makes sense given that it appears as a second order polynomial in the flow rate Equation 3. It should be noted that EPA Method 2 does not mandate the direct measurement of the stack diameter. The method allows for the use of blueprint or reference drawings as one possible source for this component. Relying on the accuracy of outdated drawings or previous measurements for the source of the stack diameter can introduce significant errors to the test results.

The method of measurement is critical. In most cases, when the measurement is made in the field, the testing company will use a long probe, conduit, or pole to measure across the stack. The probe is inserted until it touches the opposite wall, marked, removed, and measured. This method is prone to a variety of potential errors including not holding the probe horizontally, flexing or bending of a long probe in the stack, hitting an internal support rather than the opposite wall, etc.

Another method would involve measuring the circumference of the stack at the test plane location, and accounting for the stack wall thickness. This method is also susceptible to biases.

The most reliable method is to use a laser distance meter (rangefinder). A minimum of two stack diameters should be measured, and an average diameter determined. There are numerous commercially available laser distance meters having ranges between 100-300 feet, with accuracies of ± 1/16 in. (0.25 mm) or less.

The two largest contributors to the overall uncertainty in the above flow rate measurement analysis were the Pitot tube calibration factor and the uncertainty due to the velocity distribution. Wind tunnel calibration of the Pitot tube probe can reduce the uncertainty associated with the calibration coefficient. The uncertainty due to the velocity distribution is a function of the number of traverse points. As the number of traverse points is increased (i.e., as the flow velocity profile is more accurately defined), the uncertainty or discretization error decreases.

Several studies [Romero 2005 and Bryant 2014] have shown that by increasing the number of traverse points from 12 (as in the current example) to 48 on two diameters, the bias (uncertainty) due to flow asymmetry can be reduced by a factor of 2 or more. A combination of lower component measurement uncertainty, and an adequate number of traverse points suggests that it is possible to reduce the expanded uncertainty to approximately ± 1.0% for similar flow distributions using EPA Method 2, 2G, or 2F. It should be noted that the magnitude of the discretization errors and the optimal number of traverse points are highly site specific and depend on parameters such as: stack and breeching geometry, flow velocity profile, and the stack wall roughness.

Current End-User Practices

Discussion of End User Survey Results

A telephone survey was conducted by CleanAir of ten utility industry end users in order to determine current measurement approaches, and operating and maintenance practices for continuous flow monitoring systems. The individuals surveyed consisted primarily of utility environmental professionals with firsthand knowledge of CEMS operations, maintenance and testing. The complete survey is provided in Appendix A of this report. Highlights of the survey pertaining to flow monitor certification and audit testing procedures and results are as follows:

- Relative accuracy test audit: Seven of ten end users perform their RATAs on an annual basis. One respondent stated that they conducted RATA testing semi-annually. One respondent stated that they performed RATAs annually, sometime semi-annually. One respondent was not aware of the RATA frequency. Nine of ten respondents reported conducting RATAs at multiple loads (2 or 3). One respondent reported conducting RATAs at a single load. Seven of ten respondents reported performing some type of pre-tests or checks of their systems. System checks can include conducting pre-RATAs, extra calibration checks or simple visible inspections. Four of ten respondents reported that they conduct pre-RATAs of their systems, and all four reported making adjustments to their correlation curves based on the pre-RATA results. RATA results are well within limits (relative accuracy ≤ 7.5% or ≤ 10%). The majority of the respondents stated that their monitors were consistently higher than the reference method results. Only four respondents reported actual relative accuracy results, of those four, most respondents reporting relative accuracy results of less than 5%.
- Reference methods used for RATAs: Only six of ten end users reported the reference methodology used for RATA testing. Of the six respondents who reported, five use 3-D probes (Method 2F) and determine the wall effects (Method 2H) correction factor. One respondent reported using Method 2 only.

Review of Historical RATA Testing Results

CleanAir conducted a review of its internal historical flow RATA results conducted over the past several years. A total of 15 RATAs were reviewed and analyzed. The testing included results from various sources including coal-fired utility boilers, cement kilns, and paper mills. The types of installed flow monitors included both ultrasonic and differential pressure. All of the ultrasonic monitors were Teledyne. The differential pressure monitors were from two vendors including EMRC and Dieterich Standard. The reference methods used included Method 2 (with and without wall effects 2H), and Method 2F (with and without wall effects). Figure 5-4 shows a box histogram plot of the overall relative accuracy (RA) results for all fifteen tests. The mean result for all tests combined was 3.8%. The distribution of the data was from 0.8% to 7.8%. Figure 5-5 and Figure 5-6 show the results for the differential pressure and ultrasonic flow monitors, respectively. The mean for the differential pressure monitors was 4.2%, and the mean for the ultrasonic monitors was 3.7%.

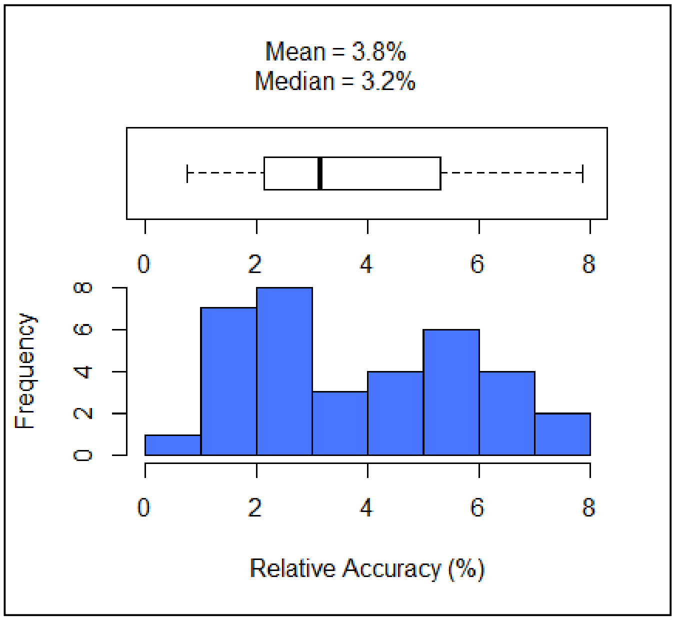


Figure 5-4
Distribution of Historical Flow RATA Test Results (All Data)

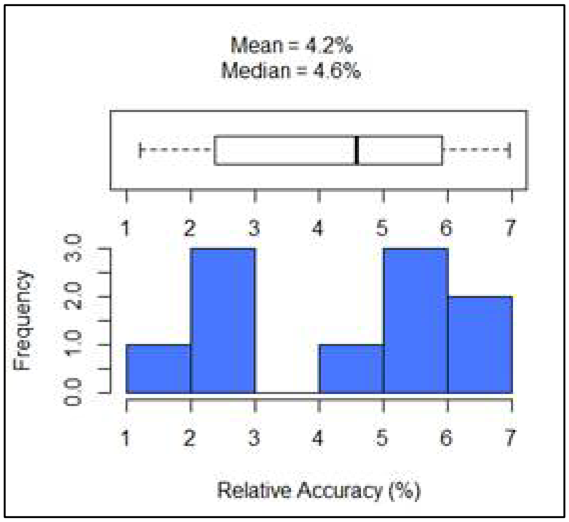


Figure 5-5
Distribution of Differential Pressure Flow RATA Test Results

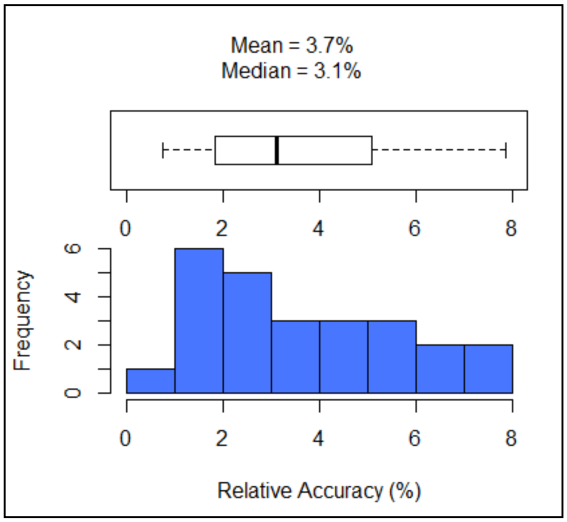


Figure 5-6
Distribution of Ultrasonic Flow RATA Test Results

Results of Literature Search

A general literature search was conducted in an attempt to identify both historical and recent research in the area of flow measurement uncertainty improvement. The reference material reported on herein provides relevant information regarding improvements that can be made to reference method testing to improve the level of closure on the "true" stack flow rate measurement.

EPA's Comparative Analysis of Manual and Automated Flow Measurement Probes (1999)

A comprehensive, comparative analysis of the various types of manual (and automated) stack flow measurement devices was reported by The Cadmus Group for the U.S. Environmental Protection Agency (EPA) in 1999 [EPA 1999]. During the summer of 1997, the EPA conducted week-long field tests at three electric utility sites (DeCordova, Lake Hubbard, and Homer City) to evaluate potential improvements to EPA Method 2. The technical improvements grew out of a technical review of Method 2 and draft EPA Method 2F (3-D flow measurements), extensive preliminary wind tunnel and field testing, and comments provided by the industry on the performance of currently available technology.

Three test sites were chosen to provide a range of flow conditions under which the flow measurement equipment and procedures could be evaluated. One site had near axial flow, another had flow with moderate yaw and pitch angles, and the third had flow with a significant yaw component. Two sites were gas-fired and the third was coal-fired, which provided an opportunity to compare in-stack measurements of gas flow with calculations of volumetric flow using engineering methods for more than one type of fuel.

A total of nine probe/procedure combinations were tested as part of the EPA study. The nine tested probe/procedure combinations included the following:

- Manual Type S probe straight-up (standard Method 2 procedure)
- Manual Type S probe yaw-nulled
- Automated Type S probe straight-up
- Automated Type S probe yaw-nulled
- DAT 3-D probe
- Spherical 3-D probe
- Modified Kiel probe
- French probe
- Prandtl probe

A standard Type-S Pitot probe meeting the design specifications of Method 2 was used in the study. When used in accordance with the procedures prescribed in Method 2, the probe is referred to as the “straight-up” probe; that is, it is positioned so that an imaginary line connecting the impact port and the static port is parallel to the longitudinal axis of the stack. In this configuration, it measures total velocity. During the EPA program, the manual Type S probe was also operated in the “yaw-null” mode that included determining the yaw component of the flow.

An automated version of the Type-S probe, manufactured by United Sciences Testing, Inc. (the USTI Autoprobe Type-S probe) was also evaluated in both the straight-up and yaw-nulled modes. Two configurations of the Autoprobes were operated in the EPA field study: a single Autoprobe was moved from port to port like the other tested pitots, and a four-probe configuration (referred to as the “baseline” Autoprobe) was mounted in four separate ports and collected data from these locations for the duration of the field tests.

Two types of 3-D probes were evaluated in this field study: the five-hole prism DAT and the spherical probes. Both the DAT and spherical head 3-D probes are prescribed in Method 2F. The spherical head probe was recommended for consideration by the Electric Power Research Institute (EPRI). EPA had the spherical probes used in the study specially fabricated from stainless steel. Two sets of four spherical probes, a total of eight probes, were ultimately fabricated after the welds on the first set sustained thermal damage during the first field test.

The modified Kiel probe utilized was a standard Kiel probe with a wake port and two Fechheimer ports added. The modified Kiel probe was suggested for use by EPA and was not commercially available.

The French probe used was a cylindrical probe with a solid stainless steel head, an impact port with a 15° chamfer on the probe head, and a wake port located at a 180° offset from the impact port. This probe head design did not meet the specifications of Method 2 at the time of testing. The French probe, designed by Southern Company Services, was not commercially available.

The Prandtl probe used in the study was the accepted standard that is used both to calibrate flow rates in wind tunnels and to establish calibration coefficients for other types of Pitot probes.

In conjunction with testing the probes, new field calibration and operational procedures were performed and evaluated as potential method improvements. Digital inclinometers were also tested to evaluate these angle measuring devices for performing yaw-nulling, rotational position calibration, and horizontal straightness checks. A laser device was used to measure stack diameters, and the results were compared to values obtained by calculating the diameter from measurements of the circumference of the stack.

The field testing approach consisted of collaborative field testing using multiple stack testing teams performing simultaneous measurements using Method 2 and pre-selected alternatives to Method 2. The collaborative (multi-team) approach ensured that the data collected each tested alternative were representative of and supported an assessment of the extent and sources of variability in the measurements. Concurrent with the test team measurements, in-stack measurements were made using the Autoprobe. A 16 EPA Method 1 traverse was conducted in all stacks. The DeCordova and Homer City units were tested at high load, and the Lake Hubbard unit was tested at high and low loads.

The test results from the various measurement techniques were analyzed using a central tendency analysis. The degree to which any one method differs from the long-term sample mean can be assessed by comparison with a baseline. The baseline for this assessment was the mean of all methods (the grand mean). The grand mean used to derive the values in Table 5-2 was created by first calculating the mean of all probes on each run, and then calculating the means of those values. The methods that consistently measure values that are much lower or higher than the grand mean are less likely to be good indicators of the true, long-term volumetric flow, as represented by the long-term sampling mean. The magnitude of a method's difference from the grand mean is an important consideration because the larger the difference, the more questionable the measurements. In this study, central tendency analysis was used as an indicator of the closeness (i.e., accuracy) of each method's measurements to the true, but unknown, long-term mean.

Table 5-2
Uncertainty Budget for a Stack Flow Rate Measurement

Method	**DeCordova**	**Lake Hubbard**		**Homer City**	**Mean Absolute Difference (%)**
	High Load	**High Load**	**Low Load**	**High Load**	
Prandtl	4.3%	2.2%	N/A	N/A	3.3%
Modified Kiel	3.6%	7.3%	N/A	0.3%	2.5%
Type S (straight-up)	3.5%	6.0%	3.4%	6.9%	4.9%
Type S (yaw-nulled)	2.9%	2.2%	2.4%	2.3%	2.5%
Spherical	0.9%	1.4%	7.4%	0.9%	2.7%
French	1.8%	-2.0%	N/A	-3.3%	2.4%
DAT	0.5%	-1.0%	-2.3%	-0.9%	1.2%
Man. AP (straight-up)	1.0%	1.3%	N/A	N/A	1.2%
Man. AP (yaw-nulled)	0.8%	0.3%	N/A	-0.1%	0.4%
AP (straight-up)	0.3%	1.2%	0.9%	2.7%	1.3%
AP (yaw-nulled)	0.3%	-0.1%	-0.4%	-1.6%	0.6%
ASME PTC 4.1	-2.2%	1.2%	2.1%	-1.3%	1.7%
BTCE[1]	-1.3%	-1.5%	0.0%	-3.4%	1.6%
CO_2 F-Factor	-2.6%	0.6%	1.4%	0.7%	1.3%
MMBtu	-1.5%	0.2%	1.6%	-1.6%	1.2%

[1] BTCE – Boiler/Turbine Cycle Efficiency Method

The principal findings that emerge from the EPA study can be summarized as follows:

- The manual 1-dimensional probes (i.e., the Prandtl and Type-S straight-up) had the worst performance characteristics, i.e., 3.3% and 4.9% difference from the grand mean, respectively.
- The manual 2-dimensional probes (i.e., the modified Kiel and the Type-S yaw-nulled) had the same performance characteristics, i.e., 2.5% difference from the grand mean.
- Accounting for the yaw component of flow improved the Type-S Pitot results by 2.4%.
- The spherical 3-dimensional probe demonstrated a 2.7% difference from the grand mean. The DAT 3-dimensional probe results showed a 1.2% difference from the grand mean. If one eliminates the Lake Hubbard low load results as a likely outlier from the spherical probe average, the spherical probe had a 1.1% difference from the grand mean.
- The Autoprobe (straight-up configuration) resulted in a 1.3% difference from the grand mean. The Autoprobe (yaw-nulled) resulted in a 0.6% difference from the grand mean.

Table 5-3 shows a statistical analysis of the variability in each probe type using the matrix data. For each probe, the coefficient of variation (CV, defined as the standard deviation divided by the mean times 100) is shown. The data were obtained over four to eight runs, hence the calculated CV represent the temporal sampling variation associated with each probe. A small CV indicates that the probe provided consistent measurements over the course of the matrix.

Table 5-3
Uncertainty Budget for a Stack Flow Rate Measurement

Method	**CV (%)**				**Average CV (%)**
	DeCordova	**Lake Hubbard**		**Homer City**	
	High Load	**High Load**	**Low Load**	**High Load**	
Spherical	0.90%	19.70%	7.39%	0.93%	7.23%
French	1.62%	3.28%	N/A	4.18%	3.03%
Modified Kiel	1.39%	5.19%	4.04%	1.24%	2.96%
DAT	2.66%	3.02%	3.14%	2.08%	2.72%
Type-S (yaw-nulled)	2.61%	3.23%	1.76%	3.18%	2.69%
Type-S (straight)	1.88%	2.31%	1.04%	1.58%	1.70%
Prandtl	0.63%	1.27%	N/A	N/A	0.95%
AP (16-pt straight up)	0.27%	0.37%	0.91%	0.98%	0.63%
AP (16-pt yaw-nulled)	0.32%	0.42%	0.63%	0.99%	0.59%
CO_2 F-Factor	1.25%	0.69%	0.76%	1.90%	1.15%
BTCE[1]	0.57%	0.30%	2.22%	0.98%	1.02%
ASME PTC 4.1	1.12%	0.41%	0.43%	2.02%	0.99%
MMBTu	0.26%	0.38%	0.64%	1.95%	0.81%

Note: CV = coefficient of variation (standard deviation/mean) x 100%.

The following conclusions can be drawn based on a review of the variability results:

- The variances associated with the Autoprobe are consistently small (CV < 1.0%).
- The Prandtl probe, while only tested at two sites, showed the lowest variability of the manual methods.
- The S-Type Pitot (straight up) had an average CV of less than 2%.
- The spherical 3-D probe had the highest average CV.
- Relatively high CV's (between 2.7% and 3.0%) were associated with the Type-S (yaw-nulled), DAT, modified Kiel, and French probes.

Table 5-4 shows the results from Lake Hubbard Station comparing manual (S-Type Pitot nulled) versus automated results from Matrix Runs 9-12. The data represents the percentage difference between the various testers' results compared to the calculated flow rate value using the BTCE (Boiler Turbine Cycle Efficiency) Method which was generated from plant operating parameters.

An examination of this data shows significant differences between the results from testers using manual methods and the automated probe approach. The yaw-nulled S-Type test results show a consistent high bias. The manual testers averaged over approximately 4.3% higher that the BTCE method flow rate calculation. The Autoprobe results measuring the same points (2) averaged 1.78% high in comparison to the BTCE results. This indicates that the manual testers were 1.2% to 4.1% higher than the automated results when comparing the same points. This is a very good indication of the effect of the human interaction on velocity measurement uncertainty.

The variance (square of the standard deviation) in the manual data was approximately 40 times greater than the variance in the automated data (2). The overall repeatability (defined as the CV) of the manual data was 41%, while the overall repeatability for the Autoprobe data was 15%, and the repeatability for same points (2) was 16%.

The Autoprobe conducted both 16 and 48 point traverses, both corrected and uncorrected for yaw. The automated yaw corrected 48 point results show an agreement with the calculated BTCE value of better than 1% on all runs. The standard deviation was approximately 10 times better than the manual test results. The 16 point manual test results were more than 3.0% higher than the automated 48 points when both were yaw corrected.

Table 5-4
Volumetric Flow Percent Difference from BTCE Matrix Runs 9-12 S-Type Probes Nulled

	% Difference from BTCE				**Average (%)**	**STDEV (%)**
	Run 9	**Run 10**	**Run 11**	**Run 12**		
S-10 Nulled (16 pt)	6.29	5.37	2.50	3.22	4.35	1.54
S-11 Nulled (16 pt)	2.85	6.36	4.59	3.99	4.45	1.27
S-12 Nulled (16 pt)	2.83	4.12	7.41	6.13	5.12	1.77
S-13 Nulled (16 pt)	4.58	0.05	2.32	6.52	3.37	2.42
Autoprobe 16-pt Straight (1)	2.87	2.23	2.37	1.79	2.32	0.39
Autoprobe 16-pt Nulled (2)	1.62	1.81	1.47	2.21	1.78	0.28
Autoprobe 48-pt Straight (3)	1.41	1.27	1.29	1.42	1.35	0.07
Autoprobe 48-pt Nulled (4)	0.52	0.49	0.45	0.90	0.59	0.18
BTCE	0.00	0.00	0.00	0.00	0.00	0.00
	Comparison vs. Autoprobe Average					
Manual Teams	**(1)**	**(2)**	**(3)**	**(4)**		
S-10 Nulled Avg.	+2.03	+2.57	+3.00	+3.76		
S-11 Nulled Avg.	+2.13	+2.67	+3.10	+3.86		
S-12 Nulled Avg.	+2.81	+3.35	+3.78	+4.53		
S-13 Nulled Avg.	+1.05	+1.59	+2.02	+2.78		

Table 5-5 compares the Autoprobe measurement results to the most commonly used 3-D velocity probe (DAT hemispherical). The data generated by the manual testers using the 3-D velocity probes differs considerably from the data generated by the Autoprobe. The most significant difference was the variance between individual manual testers' results. Unlike the Autoprobe data, no two manual test teams got the same results. This is borne out in the wide spread in the standard deviation results comparing the 3-D DAT probe to the Autoprobe.

The average results of one manual tester (K-DAT) were more than 4.0% higher than another manual tester (M-DAT). This was a surprising result since all manual testers were using the same type of probe, testing the same points. The 16-point traverse results are expected to have a high bias of approximately 1.5% to 3.0% as a result of the lack of sufficiently accounting for the wall flow effect. Even the 48-point traverses are expected to result in a high bias from the wall effect in the range of 0.5% to 1.0%.

The average absolute error of the manual 3-D probe testers was 1.80%, while the average error of the 16-point Autoprobe test was 1.55%. The variance (square of the standard deviation) in the manual data was approximately 10 times greater than the variance in the automated data (2). The overall repeatability (CV) of the manual data was 59%, while the overall repeatability for the Autoprobe data was 12%, and the repeatability for same points (2) was 18%.

Two of the manual testers read higher than the Autoprobe even when the Autoprobe used 16 points and no correction for yaw, and two read lower. If one took all of the 3-D probe data on average, the high bias might be said to be removed. Unfortunately, the inconsistency between testers exposes a potential problem. The year-to-year test results may vary considerably as compared to what can be expected from the Autoprobe or even manual Type-S Pitot testing.

Given the above findings, the Autoprobe would appear to be a better option in comparison to manual measurement techniques for lowering uncertainty in flow measurement results when conducting annual audit testing of flow monitoring devices.

Table 5-5
Volumetric Flow Percent Difference from BTCE Matrix Runs 14-17, 3-D DAT Probes

	% Difference from BTCE				**Average (%)**	**STDEV (%)**
	Run 14	**Run 15**	**Run 16**	**Run 17**		
E-DAT (16 pt)	2.66	0.81	3.54	2.76	2.44	1.00
K-DAT (16 pt)	3.38	3.27	3.58	4.10	3.58	0.32
M-DAT (16 pt)	-0.34	-1.42	0.44	-0.90	-0.56	0.69
T-DAT (16 pt)	-1.08	-0.78	2.41	1.96	0.63	1.57
Autoprobe 16-pt Straight (1)	1.85	1.68	1.91	1.74	1.80	0.09
Autoprobe 16-pt Nulled (2)	2.01	1.39	1.51	1.28	1.55	0.28
Autoprobe 48-pt Straight (3)	1.29	1.06	1.10	0.96	1.10	0.12
Autoprobe 48-pt Nulled (4)	1.28	0.87	0.91	0.84	0.98	0.18
BTCE	0.00	0.00	0.00	0.00	0.00	0.00
	Comparison vs. Autoprobe Average					
Manual Teams	**(1)**	**(2)**	**(3)**	**(4)**		
E-DAT Avg.	+0.65	+0.90	+1.34	+1.47		
K-DAT Avg.	+1.79	+2.04	+2.48	+2.61		
M-DAT Avg.	-2.31	-2.10	-1.66	-1.53		
T-DAT Avg.	-1.17	-0.92	-0.48	-0.35		

Recent Developments in Multi-Hole Pitot Technology and Calibration

Multi-hole Pitot (MHP) probes are based on the fact that the static pressure varies over a solid surface immersed in the flow, from the maximum value, which is equal to the stagnation pressure to low values the order of the base pressure in the wake of the body. Measuring the pressure at distinct points over the body of a probe can provide all the necessary information on velocity components and in-field pressures. This requires careful calibration. Many different shapes have been employed for the tip of a MHP as for example cones, spherical or cylindrical surfaces or hemispherical surfaces. These probes must be inserted in the flow at the point where a measurement is required. They therefore provide point measurements. And they interfere with the flow. Probe interference is in principle calibrated out, but there are limitations that depend on the dimensions of the tip and the local spatial variations of the flow.

Multi-hole pressure probes, such as five-hole and seven-hole probes, have in many cases provided the easiest-to-use and most cost-effective method for steady state, three component flow velocity and pressure measurements in research and industry applications. In industrial applications, non-intrusive flow measurements techniques such as Laser-Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV), although powerful, have been traditionally avoided, since they require painstaking efforts in order to be used successfully. Costly components, complex setups, troublesome flow “seeding” requirements, lack of flexibility, ruggedness and mobility and ease of misalignment often render such techniques impractical. For steady-state measurements, MHP probes are often favored even over Hot-Wire Anemometry, due to the susceptibility of the latter to frequent wire damage and the need for repetitive calibration.

Conventional MHP probes communicate the pressures (five or seven) at the ports of the probe tip, to the pressure transducers through long pressure tubing. In field or in wind-tunnel measurements, the use of tubing several feet long is typical. As a result, in an unsteady flow field, where the pressures at the probe tip are changing rapidly, the pressures measured by the transducers have a phase lag with respect to the true pressures at the tip, and their magnitudes are attenuated. The faster the change in the flow (and therefore the tip pressures) the larger the discrepancy between the transducer pressures and the tip pressures, and hence, the larger the measurement error. This is one reason why conventional multi-hole probes have only been used for steady-state measurements, i.e., for measurements in flows that are not changing over time or are changing very slowly. Such probes therefore have a measurement frequency response that does not exceed a few Hertz. The longer the pressure tubing, the lower their frequency response.

The second limitation of the MHP probes relates to the fluid mechanics around the probe tip in unsteady flows. Although MHP probe calibration techniques for steady-state measurements are well established today, largely unresolved issues persist pertaining to the calibration of such instruments for measurement in unsteady and turbulent flows.

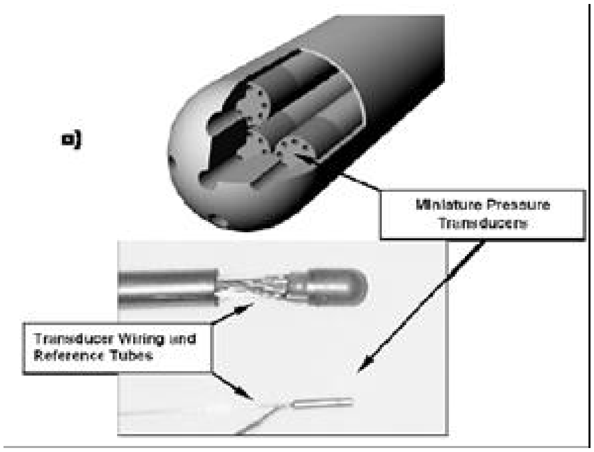
The Use of Embedded Transducers

Aeroprobe Corporation has developed a MHP probe that overcomes both of these limitations discussed above by embedding the pressure transducers at or near the probe tip, thus eliminating or minimizing the pressure tubing from the tip to the transducers and by successfully accounting for the flow inertial effects. The availability, in the market, of miniature pressure transducers has allowed them to be embedded at or near the tip without significantly increasing the probe tip dimensions. Keeping the probe tip diameter small is important in terms of spatial resolution of the measurements, i.e., the ability of the probe to distinguish flow changes spatially [Aeroprobe 2006].

The Aeroprobe Fast Response Probe shown in Figure 5-7 has pressure-sensors embedded in the body of the instrument to eliminate the attenuation of the high-frequency part of the signal, common to all external sensor probes. In addition, the probe is acoustically calibrated to correct even for the miniscule attenuation caused by the short internal tubing. These probes have a frequency response of 3.0 kHz or greater. They retain the <0.8% velocity measuring accuracy of the standard probes as well as the maximum incidence angle of 70° for seven-hole probes. Figure 5-8 shows a cut-away detail of the probe head which shows the embedded miniature pressure transducers.

Source: Aeroprobe Corp.

Figure 5-7
Aeroprobe Fast Response



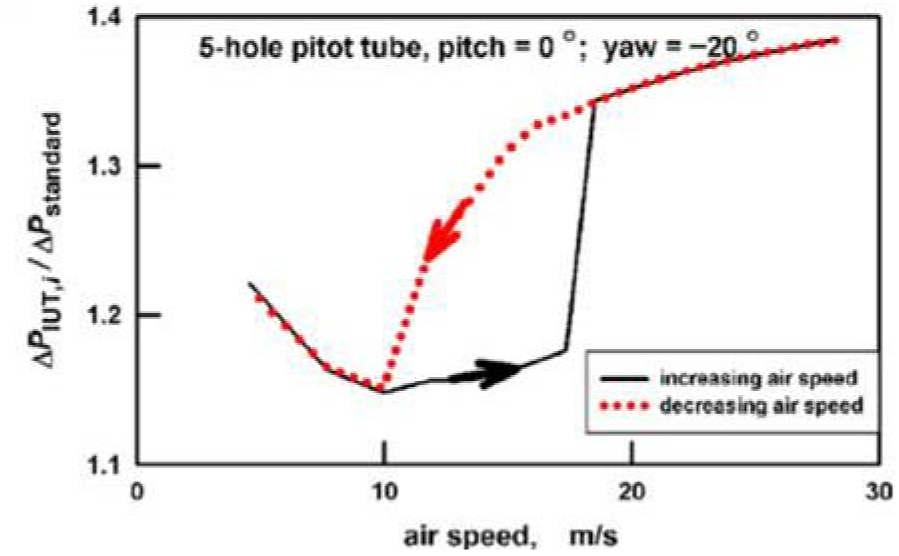
Source: Aeroprobe Corp.

Figure 5-8
Probe Probe Tip Detail

Effect of Turbulence on MHP Probe Calibration

The National Institute of Standards and Technology (NIST) conducted a laboratory study [Crowley 2013] examining the effect of turbulence on MHP probe calibrations. When calibrating a commercially-manufactured MHP probe in NIST's low-turbulence wind tunnel, they found hysteresis in certain ranges of airspeed, pitch angle, and yaw angle. In the worst case, the hysteresis caused a calibration error of 30%.

During calibration of a cone-shaped, five-hole Pitot probe, NIST discovered that when the tube was oriented in the range of 20°±5° away from the tunnels axis, strong hysteresis was found in the measured values of pressure differences as the air speed was increased and decreased (see Figure 5-9).



Source: NIST

Figure 5-9
Characterization of Observed Hysteresis in a Commercial 5-Hole Pitot

NIST defined a calibration factor (C_i) to characterize the hysteresis, as follows:

$$C_i = \Delta P_{IUT,i} / \Delta P_{standard}$$

Where:

$\Delta_{PIUT,I}$ = pressure difference between the center hole and the ith off-axis hole of the instrument under test (IUT).

$\Delta P_{standard}$ = differential pressure measured by a 1-D Pitot tube that NIST routinely uses a check-standard for measurements of air speed.

The check was located one meter away from the IUT and in the same cross sectional plane of the wind tunnel.

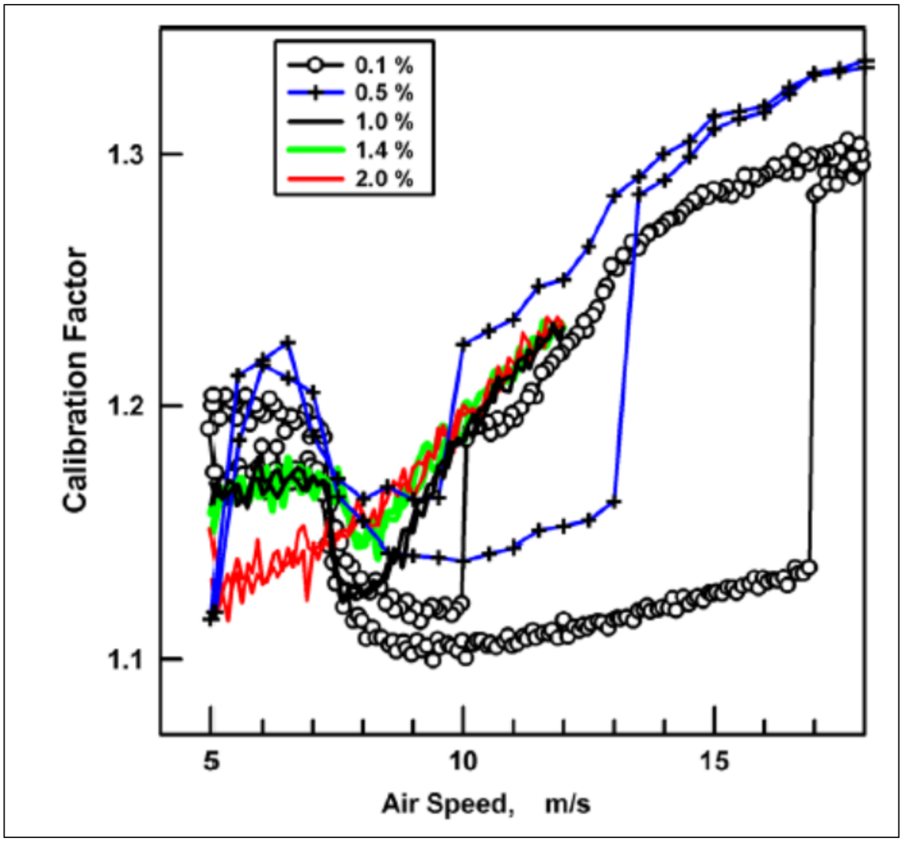
As is indicated in Figure 5-9, $\Delta_{\mathrm{PIUT},i}$ was smaller when the air speed increased than when the air speed decreased. NIST verified that the hysteresis did not originate in the pressure sensors and associated instruments. Instead, the flow resulted from the flow interacting with the MHP probe itself. Using flow visualization techniques, NIST was able to document that there was flow separation and strong recirculation occurring around the probe head. The hysteresis is caused by a flow transition connected with the recirculation zone. A light bump of the Pitot probe when the velocity is increasing can cause the transition to occur at a lower velocity. Similarly, by increasing the amount of turbulence present in the wind tunnel, the hysteresis disappears and the shape of the calibration curve in the region near the hysteresis changes [Crowley 2013].

NIST defined the percentage turbulence intensity T in the wind tunnel using the ratio

$$T/(1\%) = 100 \text{ x } \mathrm{rms}(v) / (v)$$

where the numerator is the root-mean-square (rms) fluctuation of the velocity and the denominator is the average free stream velocity. NIST utilized a commercially-available hot wire anemometer to measure the rms fluctuations. Turbulence was induced in the wind tunnel by means of a double wire mesh screen installed on a moveable track upstream of the Pitot probe.

Figure 5-10 shows the calibration curves generated by NIST for the MHP probe oriented at 20° yaw and 0° pitch away from the tunnel's axis with the different values of T. When T is greater than 1% the hysteresis is not present, however, the shape of the calibration curve is T dependent. With T=2%, the calibration curve is approximately linear in the region near the hysteresis. Over the entire range of $0.25\% < T < 2\%$ that NIST was able to produce for the experimental study, the calibration of the MHP probe was dependent on the turbulent intensity. The 1-D Pitot static tube that was used a check standard, was oriented along the flow direction during all of the calibrations, did not exhibit T dependence greater than its uncertainty.



Source: NIST

Figure 5-10
Calibration Results for the Test Pitot under Varying Turbulence Intensities

The primary findings of the NIST study were as follows [Crowley 2013]:

- In order to produce a relevant calibration for a MHP probe in the range of 20°±5° away from the tunnel's longitudinal axis, the turbulence level must match the level (or anticipated) level present in the flow in which the probe will be used.
- Flow separation and recirculation are common phenomena; therefore, the hysteresis observed by NIST is likely to occur during the calibration of other MHP probes at other pitch and yaw angles.
- In the case of the five-hole, conical Pitot probe, the detachment of flow caused hysteresis that was observed to be as large as 30%.
- The structure of the detached flows depends on the turbulent intensity (T). Therefore, calibration of MHP probes should be performed in the range of turbulence intensities expected to be present when the calibrated instrument is used in the field.
- The turbulent intensity in smokestack is most likely of the order of 2% or greater. Therefore, the hysteresis will not be observed due to the high level of turbulence and the calibration performed in a non-turbulent wind tunnel (less than the turbulence level in the stack) will be irrelevant in the stack.

Calibration of 3-D Velocity Probes at Low Velocity

EPA Method 2F requires that 3-D velocity probes be wind tunnel calibrated at two velocity conditions, i.e., 60 fps and 90 fps. There is concern within the industry regarding the accuracy of 3-D Pitot probes at low velocities since flow monitor RATA tests are conducted at three load conditions inclusive of low, mid, and high loads.

[EPA 1997] conducted experimental wind tunnel tests of two different types of 3-D Pitot probes at multiple velocities in order to characterize the performance of the probes across the range of velocities tested. EPA tested three DAT probes and one spherical probe using procedures consistent with EPA Method 2F. In the EPA experiments, two sets of calibration curves were created for each probe, one set by averaging data obtained at two velocities, 60 and 90 fps, and another set by averaging data at three velocities, 30, 60, and 90 fps. The three-velocity computation was performed to see if it yielded more accurate values of velocity outside the range of calibration dictated by Method 2F.

The cross-probe velocity accuracy results are summarized in Table 5-6 below. The results of the experimental testing supported the following findings on velocity accuracy:

- <u>Overall Performance:</u> Across all pitch angles and all velocities, whether using the 60/90 or 30/60/90 fps calibration curves, the average absolute deviations from the actual axial velocities never exceeded 3.4% for the spherical probe and the three DAT probes. For one of the DAT probes (3D-1), the average absolute deviations were 0.7% or less.
- <u>Comparative results using the 60/90 and 30/60/90 fps calibration curves:</u> For all probes over all tested velocities, the difference between the average absolute deviations obtained with the 60/90 and that obtained with the 30/60/90 calibration curves never exceeded ±1.2%.
- <u>Patterns in velocity deviations (I):</u> When using the 60/90 fps calibration curves, the greatest average absolute velocity deviations for all probes over all pitch angles (-30° to +30°) and velocities always occurred at the 90 fps velocity setting.
- <u>Patterns in velocity deviations (II):</u> Except for one occurrence with DAT probe 3-D-3 at +10° using the 60/90 fps curves, the largest velocity errors occurred at the pitch angles settings of -30°, -20°, 20°, and 30°.
- Over the pitch angle ranges ±30° and ±20°, the velocity accuracy of all tested 3-D probes was within 5.5% of the true axial velocity. In the ±10° pitch angle range, the velocity accuracy of all tested 3D probes was within 3.8% of the true axial velocity.
- No significant gain in accuracy was attained by developing calibration curves at three velocities rather than at the two specified in Method 2F.
- In order to minimize error in the flue gas velocity measurement, calibration curves for 3-D probes should be developed at velocity settings close to, or possibly bracketing, the prevailing velocity where the probe will be used.

Table 5-6
Summary of EPA Experimental 3D Probe Velocity Accuracy Results

Probe ID	Calibration Curve	Average Absolute Deviation (over the ±30° pitch range)			Maximum Deviation and Conditions When it Occurs		
		30 fps	60 fps	90 fps	Deviation	Pitch Angle	Nominal Velocity
DAT Probe (3D-1)	60/90	0.5%	0.6%	0.7%	+3.0%	-30°	90 fps
	30/60/90	0.7%	0.5%	0.5%	-2.2%	-30°	30 fps
	Difference	0.2%	0.1%	0.2%			
DAT Probe (3D-2)	60/90	1.7%	1.0%	3.4%	+4.4%	+20°	30 fps
	30/60/90	2.9%	0.6%	2.2%	+5.5%	+20°	30 fps
	Difference	1.2%	0.4%	1.2%			
DAT Probe (3D-3)	60/90	0.8%	0.8%	2.3%	-3.8%	+10°	90 fps
	30/60/90	1.6%	0.5%	1.5%	+3.6%	+30°	30 fps
	Difference	0.8%	0.3%	0.8%			
Spherical (MS5-2)	60/90	1.1%	1.2%	2.4%	+4.7%	-20°	90 fps
	30/60/90	1.5%	0.6%	1.6%	-5.2%	-30°	30 fps
	Difference	0.4%	0.6%	0.8%			

Note: The wind tunnel had no measurable yaw flow component, i.e., $\cos\theta = 1$.

Micromanometers and Measurement Uncertainty:
The Difference between "Accuracy of Reading" and "Accuracy of Full Scale"

Velocity measurement instruments (i.e., micromanometers) express their accuracy in one of two ways:

- Percent of full scale deflection or FSD
- Percent of reading or indicated value

These two accuracy claims are equal only at the maximum capacity of the measuring device. If a meter's accuracy is based on a percentage of its full reading capability, the error is a fixed value. For example, an error of ±0.5% of full scale, in a 100 in. water column (WC) differential pressure micromanometer is ±0.5 in. WC. This is the uncertainty all of the time, so as you move away from the full scale capability, the 0.5 in. WC error becomes a much larger percentage. At 50 in. WC, you are risking a 1% error. At 10 in. WC you have a potential 5% error. On the other hand, if the device has an error expressed as a percentage of the actual reading, then a 0.5% error of 10 in. WC is only ±0.05 in. WC; a 10 times better result. This is shown graphically in Figure 5-11 below.

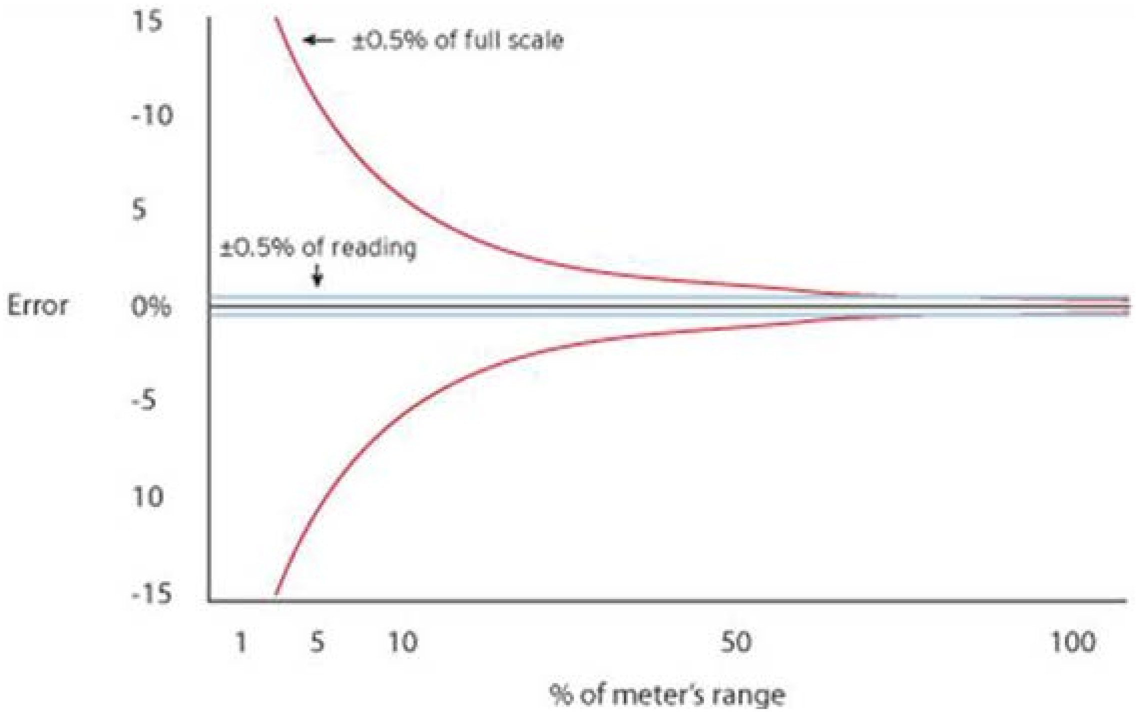


Figure 5-11
Accuracy of Reading vs. Accuracy of Full Scale

This is an important consideration when choosing a micromanometer for RATAs or wind tunnel calibrations of Pitot probes. Table 5-7 below provides a summary of the design and performance characteristics of several commercially available micromanometers. Table 5-7 was compiled from equipment manufacturer's specifications available on company websites.

Table 5-7
Summary of Design Specifications for Commercially Available Micromanometers

Parameter	Shortridge Instruments ADM–880C	FlowKinetics FKT 3DP1A	TSI Incorporated DP-Calc 8710
Differential Pressure	±2% of reading, ±0.001 in WC from 0.05 to 50.00 in WC, (0.0001 to 60 in WC FS), 20 psid safe pressure.	Accuracy at 25°C: Typically within ±0.1% of full scale (±0.22% max)	Accuracy: ±2% of reading, ±0.001 in WC from 0.05 to 15 in WC, Range: ±15 in WC, 150 in WC max Resolution: 0.00001 in WC
Air Velocity	±3% of reading, ±7 fpm 50 to 8,000 fpm pitot tube (30,000 fpm FS), 50 to 5,000 fpm Airfoil; 50 to 2,500 fpm VelGrid.	Up to 25,000 fpm	25 to 8,000 fpm Pitot probe 25 to 5,000 fpm Air Flow probe 25 to 2,500 fpm Velocity matrix Accuracy: 3% of reading, ±7 fpm Resolution: 0.1 fpm
Air Flow	Accuracy is ±3% of reading, ±7 fpm 100 to 2,000 cfm, Range is 25 to 2,500 supply	Not reported	Not reported
Temperature	±0.5°F accuracy from 32°F to 158°F	±1.8°F accuracy from 100°F to 900°F	±0.5°F accuracy from 32°F to 160°F
Absolute Pressure	±2% of reading, ±0.1 in Hg from 14 to 40 in Hg, 60 psia maximum safe pressure	±0.5% of full scale Range: 2.2 – 16.7 psi	Accuracy: ±2% of reading, Range: 15 to 40 in Hg Resolution: 0.001 in Hg
Ambient Range	Full range compensation from 40°F to 140°F	32°F to 158°F	40°F to 140°F
Air Density Correction	Local or standard (mass flow) air density correction range is 14 to 40 in Hg and 32°F to 158°F.	Not reported	Not reported
Position Sensitivity	Unaffected by position.	Not reported	Not reported
Memory	2000 readings, sequence labeled, sum, average, minimum and maximum.	Not reported	1000 values
Calibration	Calibration certified NIST traceable.	Calibration certificate with traceability to NIST standards	NIST traceable calibration certificated provided.
Readout	10 digit, 0.4”, high contrast, liquid crystal display.	4 line large character, LCD with LED backlight	6 digit LCD, 0.75” character height, multi-line sectored, high contrast backlight
Meter Weight	38 ounces (1.08 kg), including batteries.	2.93 lb (1.33 kg)	17 oz. (0.5 kg)
Size	6.0” x 6.4” x 2.7”	3.9” x 8.7” x 7.5”	7.4” x 4.5” x 2.3”

Battery Life	3000 readings per charge, 500 recharge cycles.	(8) 1.5V AA batteries, 30 hours; 100V to 240 VAC auto-switching power supply	(4) AA batteries, AC adaptor

Note: 1. References to specific equipment manufacturers does not connote endorsement by EPRI.
2. Data compiled from manufacturer's equipment specifications.

Best Practices Recommendations for Reference Method Flow Measurements

The following summary presents the best practice recommendations for reference method flow measurements. The recommendations contained herein are deduced from the foregoing discussion and literature search.

General

- Carefully plan the RATA and analyze tradeoffs between various test and instrumentation options. For example, use of an auto positioning probe will eliminate systematic uncertainty associated with human interaction and control of the measurement instrumentation. However, an auto positioning probe relies on the use of the S-Type Pitot probe which is inherently less accurate than the 3-D Pitot probe.
- A pre-RATA tune-up is recommended. If pre-RATA testing is performed, the tester should incorporate as many recommendations contained herein as possible.
- Results from pre-RATA testing can be used to make adjustments to the correlation curve (ultrasonic monitors) and the K factor (differential pressure monitors). Flow monitor output should agree with pre-RATA results ± 1 percent.
- A test plan should be prepared for each RATA.

Instrumentation

- The use of an auto positioning probe will eliminate uncertainty associated with human control of, and interaction with the probe and measurement instrumentation. Based on a review of available data among various sources, the use of an auto positioning probe (yaw-nulled mode) will reduce measurement uncertainty by 1-2%.
- If the auto positioning probe is not an option, the tester should use a calibrated DAT or spherical 3-D velocity probe. The DAT probe appears to provide consistently lower uncertainty results than the spherical probe.
- The S-Type Pitot probe should not be used for manual testing. If manual testing is to be employed, the tester should use a 3-D velocity probe.
- If manual testing is employed, the tester should utilize a micromanometer that has a certified accuracy as a percent of reading, not as a percent of full scale.

Calibration

- Use a velocity probe calibrated over the flow velocity range of interest.
- The velocity probe should be calibrated in a wind tunnel under conditions anticipated in the field (i.e., velocity, temperature, and turbulence).

- If manual testing is to be employed, the tester should consider utilizing EPA Preliminary Method 007 as the best practice calibration approach for the 3-D velocity probe. Pre-007 will minimize human interaction (yaw-nulling) with the Pitot probe during the test which should improve uncertainty.
- The calibration of 3-D pitot probes should be performed in the range of turbulence intensities expected to be present when the calibrated instrument is used in the field. These calibrations can be conducted by NIST. (Note: This approach will likely require a preliminary test of the stack in order to characterize the turbulence intensity factor.)

Testing

- Perform stack traverses using the optimal number of sample points. The use of 12 points for flow RATA will most likely lead to discretization errors. The tester should consider using 48 total sample points (across two diameters) for a RATA.
- The velocity decay due to wall effects should always be measured, and the results corrected accordingly.
- The stack diameter should be verified and measured in the field using a laser distance meter. At least two separate stack diameters should be measured, and the average diameter obtained.
- The velocity probe should be inserted into the stack and allowed to reach the temperature of the effluent gas stream before commencing any testing.

6

DISCUSSION OF BEST PRACTICE EFFECTS ON UNCERTAINTY

Table 6-1 presents a summary of results from the EPRI [EPRI 2014] heat rate study conducted at a 350 MW coal fired unit. In this study, CleanAir conducted comparative heat rate testing using the input/output method (ASME PTC 4 and ASME PTC 46), and heat rate based on the plant CEMS output.

The uncertainty analyses followed procedures outlined in ASME PTC 4 and ASME PTC 19.1. For both the volumetric flow rate and CO_2 concentration measurements, four quantities were evaluated to determine the uncertainty of each parameter. These quantities are defined as follows:

- Offset: The offset represents the bias or the average difference between the RM and the CEMS values for the RATA runs.
- Comparison Uncertainty: The comparison uncertainty represents the bias uncertainty or (95% CI) standard error between the RM and the CEMS values for the RATA runs; or the fluctuation in the sampling mean due to random sampling error.
- Spatial Uncertainty: The spatial uncertainty represents the uncertainty associated with the RATA measurement location. For the flow RATAs, the spatial variation uncertainty was determined by multiplying the average spatial uncertainty coefficient times the ratio of the average volumetric flow rate to the average velocity. For the CO_2 RATAs, the spatial variation uncertainty was determined by multiplying the spatial uncertainty coefficient time the ratio of the student's t-values for the three-point RATA traverse and the six-point spatial distribution test.
- Instrumental Uncertainty: The instrumental uncertainty represents the systematic uncertainty in the reference parameters attributable to the combined uncertainty in the measurements necessary to calculate said measured parameters.

The values for the offset and systematic uncertainty parameters from the 2014 study are summarized in Table 6-1.

Table 6-1
CO_2 CEMS and Flow Monitor Uncertainty Summary – 350 MW Coal Fired Unit (2014)

Parameter	CEM Average Value	Offset	Systematic Uncertainty			Total	Total Uncertainty (%)
			Comparison	Spatial	Instrumental		
Flow – High (scfm)	49,045,400	872,200	591,757	802,645	1,557,500	1,849,384	3.8
Flow – Low (scfm)	36,035,300	46,000	222,514	1,166,130	1,774,765	2,135,219	5.9
CO_2 –High (%, vol.)	10.17	0.20	0.08	0.25	0.18	0.32	3.1

The total systematic uncertainty for each parameter (i.e., flow and CO_2) is determined by applying a root sum square analysis to the comparison, spatial, and instrumental uncertainties as follows:

$$U_{Total} = \sqrt{U^2_{Comparison} + U^2_{Spatial} + U^2_{Instrumental}}$$

The total systematic uncertainty of the boiler heat input can be determined by applying a root sum square analysis to the individual flow and CO_2 CEMS uncertainties. The uncertainty of the boiler heat input at high load is given by the following expression:

$$U_{Heat\ Input,High\ Load} = \sqrt{U^2_{Flow} + U^2_{CO2}} = \sqrt{(3.8)^2 + (3.1)^2} = 4.9\%$$

A CO_2 RATA was not performed at low load, however using the high load CO_2 uncertainty results; the systematic uncertainty of the boiler heat input at low load is given by:

$$U_{Heat\ Input,Low\ Load} = \sqrt{U^2_{Flow} + U^2_{CO2}} = \sqrt{(5.9)^2 + (3.1)^2} = 6.7\%$$

The average uncertainty for heat input for both loads was determined to be 5.9%.

Enhanced Uncertainty Analysis

The 2014 project results indicate that the instrumental and spatial uncertainties represent the majority of the total uncertainty associated with the CO_2 and flow RATA data. The following analysis provides an estimate for an enhanced total systematic uncertainty for flow and CO_2 applying the recommendations contained in this report.

Spatial Uncertainty – Flow RATA

The average spatial uncertainty in axial velocity for the 2014 host site unit flow RATA at high load was 1.6%. A 16 point traverse was conducted at there. According to the findings of [Romero 2005] and [Bryant 2014], increasing the number of traverse points from 16 (as in the current example) to 48 on two diameters, the bias (uncertainty) due to flow asymmetry can be reduced by a factor of approximately two. Therefore, for the enhanced systematic uncertainty analysis, an average spatial uncertainty of 0.8% will be applied at both high and low loads.

Spatial Uncertainty – CO_2 RATA

The average spatial uncertainty for that unit's CO_2 RATA was determined based on the results of a 6-point stratification test, and a 3-point RATA test. The average spatial uncertainty at high load was determined to be 0.25%, v/v or 2.5% uncertainty. By increasing the number of points in the stratification test to 24, and increasing the number of points in the RATA test to 12, it is estimated that the spatial uncertainty can likewise be reduced by a factor of two.

Instrumental Uncertainty – Flow RATA

The instrumental uncertainty for that unit's flow RATA was determined to be 1.58 MMSCFH which is 3.2 percent of the measured flow of 49.4 MMSCFH. The two dominant factors in the instrumental uncertainty of the flow were the uncertainty of the Pitot coefficient (F_2), and the uncertainty associated with the measurement of the velocity differential pressure. Table 6-2 shows the overall instrumental uncertainty of the volumetric flow rate at high load as determined in 2014, and also shows an estimated enhanced uncertainty.

Table 6-2
Enhanced Instrumental Systematic Uncertainty for Flow RATA at High Load

				Systematic Uncertainty		**Enhanced Systematic Uncertainty**	
Parameter	**Units**	**Value**	**High Load Sensitivity Value**	**Parameter Units**	**Uncertainty (SCFH)**	**Enhanced Parameter Units**	**Enhanced Uncertainty (SCFH)**
Pitot Coefficient	-	1.052	4.7004E+07	0.02104	988,971	0.01	470,043
Static Pressure	in. Hg	29.26	1.6900E+06	0.1	168,997	0.1	168,997
Temperature	°R	593	8.3387E+04	2.83	235,985	1	83,387
Gas Molecular Weight	lb/lb_{mol}	28.33	8.7272E+05	0.151	131,781	0.151	131,781
Apparent Velocity Pressure	in. w.c.	0.628	3.9370E+07	0.03	1,181,095	0.01256	494,485
Diameter	ft	17	5.8175E+06	0.0241	140,201	0.0052	30,251
Yaw Angle	radians	0.0332	1.6423E+06	0.0349	57,316	0.0052	8,599
Pitch Angle	radians	0.0609	3.0151E+06	0.0349	105,229	0.0052	15,787
Volumetric Flow (@ standard conditions)	**scfh**	**49,448,526**			**1,583,881**		**720,815**
Uncertainty (%)					**3.2%**		**1.5%**

It is believed that the tolerance associated with the Pitot probe calibration can be reduced to 1.0% by employing the recommendations of this report. The thermocouple tolerance can be reduced from 2.83 °R to 0.5 °R by utilizing a 4-wire Class A RTD instead of a Type-K thermocouple. The uncertainty of the velocity pressure was due to the relatively high tolerance (0.03 in. w.c.) assigned to the calibration of the Magnehelic gauge. If a micromanometer were utilized instead having an accuracy of ±2% of reading, the velocity pressure would be markedly reduced. The yaw and pitch angle were assigned a tolerance of ± 2 degrees. This could be lowered, for example, by using an auto positioning probe, which has an accuracy of ± 0.3 degrees. Accordingly, the potential exists to reduce the instrumental systematic uncertainty of the flow RATA test by approximately 55% at high load.

Table 6-3 shows the overall instrumental uncertainty of the volumetric flow rate at low load as determined in 2014, and also shows an estimated enhanced uncertainty.

Table 6-3
Enhanced Instrumental Systematic Uncertainty for Flow RATA at Low Load

				Systematic Uncertainty		**Enhanced Systematic Uncertainty**	
Parameter	**Units**	**Value**	**Low Load Sensitivity Value**	**Parameter Units**	**Uncertainty (SCFH)**	**Enhanced Parameter Units**	**Enhanced Uncertainty (SCFH)**
Pitot Coefficient	-	1.052	3.450E+07	0.02104	725,880	0.01	345,000
Static Pressure	in. Hg	29.22	6.211E+05	0.1	62,110	0.1	62,110
Temperature	°R	588	-3.086E+04	2.83	-87,333	1	-30,860
Gas Molecular Weight	lb/lb_{mol}	28.38	6.394E+05	0.151	96,549	0.151	96,549
Apparent Velocity Pressure	in. w.c.	0.338	5.369E+07	0.03	1,610,700	0.01256	674,346
Diameter	ft	17	5.817E+06	0.0241	140,190	0.0052	30,248
Yaw Angle	radians	0.0279	1.381E+06	0.0349	48,197	0.0052	7,181
Pitch Angle	radians	0.0426	2.107E+06	0.0349	73,534	0.0052	10,956
Volumetric Flow (@ standard conditions)	**scfh**	**36,294,412**			**1,780,294**		**767,454**
Uncertainty (%)					**4.9%**		**2.1%**

Instrumental Uncertainty – CO_2 CEMS RATA

The instrumental uncertainty of the CO_2 CEMS RATA was determined utilizing the combined uncertainties of the dry CO_2 reading attributable to the calibration gas, and the uncertainty of the water vapor concentration, according to the following expression:

$$B_{[CO_2],inst} = \sqrt{(\theta^{[CO_2]}_{[CO_2]_{dry}} B_{[CO_2]_{dry}})^2 + (\theta^{[CO_2]}_{[H_2O]} B_{[H_2O]})^2}$$

The sensitivity of the wet concentration of CO_2 to the measured dry CO_2 concentration is determined by:

$$\theta_{[CO_2]_{dry}}^{[CO_2]} = \frac{\partial[CO_2]}{\partial[CO_2]_{dry}} = \frac{(100 - [H_2O])}{100} = \frac{100 - 16.3}{100} = 0.837$$

The sensitivity of the wet concentration of CO_2 to the moisture concentration is determined by

$$\theta_{[H_2O]}^{[CO_2]} = \frac{\partial[CO_2]}{\partial[H_2O]} = \frac{-[CO_2]_{dry}}{100} = \frac{12.5}{100} = 0.125$$

The uncertainty of the water vapor concentration was calculated based on the uncertainty of the temperature measurement. The Method 4 results showed that the gas was oversaturated with respect to water vapor, so the water vapor concentration was calculated based on the saturation pressure at the measured gas temperature. A combined tolerance of ± 2°F was assumed for the control console temperature readout and the Type K thermocouple. The uncertainty of the calibration gas was assumed to be 1%.

The instrumental uncertainty for CO_2 concentration for the RATA is summarized in Table 6-4.

Table 6-4
Instrumental Uncertainty for the CO_2 RATA

				Systematic Uncertainty	
Concentration	**Units**	**Value**	**Sensitivity**	**Parameter Units**	**Wet Concentration**
Dry CO_2	% dry	12.5	0.837	0.125	0.105
H_2O	% wet	16.3	0.125	1.225	0.15
Wet CO_2	**% wet**	**10.4**			0.18

Table 6-5 shows the enhanced instrumental uncertainty for the CO_2 RATA using optimized tolerances for the calibration gas and the meter/thermocouple. The enhanced tolerance used for the calibration gas was 0.6%, which is consistent with the EPA blind audit (mean) results reported in Section 2 of this report as well as the relative accuracy results reported by Air Liquide for the CO_2 calibration gases supplied for the 2014 host site test program. An enhanced parameter unit for the water vapor concentration was calculated using a tolerance of ± 0.5°F for the console temperature readout and thermocouple.

Table 6-5
Enhanced Instrumental Uncertainty for the CO_2 RATA

				Enhanced Systematic Uncertainty	
Concentration	**Units**	**Value**	**Sensitivity**	**Enhanced Parameter Units**	**Wet Concentration**
Dry CO_2	% dry	12.5	0.837	0.075	0.063
H_2O	% wet	16.3	0.125	0.413	0.054
Wet CO_2	**% wet**	**10.4**			0.083

Enhanced Systematic Uncertainty and Effect on Heat Input Uncertainty

Table 6-6 provides the values for the enhanced systematic uncertainty parameters based upon the foregoing discussion and analysis.

Table 6-6
Enhanced CO_2 CEMS and Flow Monitor Uncertainty Summary – 350 MW Coal Fired Unit

Parameter	CEM Average Value	Offset	Systematic Uncertainty			Total	Total Uncertainty (%)
			Comparison	Spatial	Instrumental		
Flow – High (scfm)	49,045,400	872,200	591,757	401,322	720,815	1,015,288	2.1
Flow – Low (scfm)	36,035,300	46,000	222,514	583,065	767,454	989,173	2.8
CO_2 –High (%, vol.)	10.17	0.20	0.08	0.125	0.083	0.17	1.7

The enhanced total systematic uncertainty of the boiler heat input can be determined by applying a root sum square analysis to the individual flow and CO_2 CEMs uncertainties. The enhanced uncertainty of the boiler heat input at high load is given by the following expression:

$$U_{Heat\ Input,High\ Load(Enhanced)} = \sqrt{U^2_{Flow,Enhanced} + U^2_{CO2,Enhanced}} = \sqrt{(2.1)^2 + (1.7)^2}$$
$$= 2.7\%$$

The enhanced systematic uncertainty of the boiler heat input at low load is given by:

$$U_{Heat\ Input,Low\ Load(Enhanced)} = \sqrt{U_{Flow,Enhanced}^2 + U_{CO2,Enhanced}^2} = \sqrt{(2.8)^2 + (1.7)^2} = 3.3\%$$

The average enhanced uncertainty for heat input for both loads was determined to be 3.0%.

The uncertainty for the heat rate calculation would be given by the following expression:

$$U_{Heat\ Rate,Enhanced} = \sqrt{U_{Heat\ Input,Enhanced}^2 + U_{Power\ Out}^2}$$

At high load, the uncertainty associated with the heat rate calculation would be:

$$U_{Heat\ Rate,High\ Load(Enhanced)} = \sqrt{(2.7)^2 + (0.4)^2} = 2.7\%$$

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CONCLUSIONS AND RECOMMENDATIONS

The effect of problems with flue gas volumetric flow rate and CO_2 measurements could be far reaching. Erroneously high volumetric flow rate measurements would translate into over-reporting of SO_2 and NO_x allowances, as well as under-estimating unit efficiency as defined by unit heat rate.

This report examined sources of uncertainty and bias in continuous flow monitors and CO_2 CEMS instrumentation and measurements from modern power plants, while also investigating procedures and techniques to mitigate the biases and improve the accuracy of the continuous monitors and reference method measurements. The following are the findings of the report, the recommendations to reduce uncertainty, and suggested enhancements to the reference methods used to characterize the accuracy of the instruments.

Recommendations – CO_2 CEMS Operation

The following list presents the best practice recommendations for CO2 CEM system operations.

Sampling System

- Determine source-level and calibration gas molecular weights and dynamically correct CEMS response for changes in the dilution ratio of the sampling systems due to temperature, pressure, and molecular weight variations.
- Check system integrity by alternating between introducing calibration gas standards to the probe and directly to the analyzer on a daily basis during the RATA.
- Follow preventive maintenance schedule for probe and sampling system inspection and maintenance.
- Check the dilution air for contamination with target compounds on a weekly basis.
- Sample from a location that is representative of the area measurement. Determine probe placement based on stratification test results.

CO_2 Analyzer

- Use a calibration span that is close to the actual stack gas concentration. A span value as low as 14% CO_2 (taking into account the dilution ratio of the sampling system) is within the limits of the regulations.
- Perform the daily CO_2 calibration error checks with calibration gas standards that are representative of the actual stack gas concentrations. A span value of 14% CO_2 allows high-level span gases as low as 11.2% CO_2 to be used.
- Determine system response time (cycle time) and be consistent in the use of this cycle time throughout the calibrations.
- CEMS analyzers are susceptible to temperature changes. Minimize analyzer drift by careful siting of analyzer racks or redirecting airflow to maintain analyzer temperature within a ±3°F band.

- Correct analyzer readings for sample pressure fluctuations, unless already done so by analyzer.
- Consider the application of a bias adjustment factor if a constant offset bias is diagnosed between reference method test and plant CEMS results.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use calibration gases with a certified accuracy of 1%.
- Use EPA blind calibration gas audit reports as a guide to choosing calibration gas vendors.
- Be consistent with the calibration gas standard concentrations used during the daily calibration error check.

QA/QC Plan

- Rigorously implement the preventative maintenance schedule defined in the quality assurance and control plan.
- Consider creating quality control charts of key system performance parameters.
- Regularly review monitoring and calibration data.

Recommendations – Continuous Flow Monitor Operation

The following list presents the best practice recommendations for continuous flow monitor system operations.

Flow Monitors – Ultrasonic

- All ultrasonic flow monitors should undergo a daily calibration auto-check, which would include a zero and an upscale system check.
- Ultrasonic flow monitors should undergo a daily interference check which involves purging the transmitter and receiver.
- At a minimum, a quarterly maintenance schedule should be implemented and followed. Quarterly maintenance activities would include visual inspection of the purge nozzle assemblies, and replacement of the purge air filters.

Flow Monitors – Differential Pressure

- Differential pressure flow monitors should undergo a daily calibration check, which would include a zero and an upscale span check of the pressure transducers.
- Differential pressure flow monitors should undergo a daily interference check which involves leak checking the system, and back-purging the pitots.
- A full system calibration should be performed on an annual basis. This would include an electronic test of the pressure transducers and DP transmitters, and the thermocouple transmitter.

Siting of Flow Monitors

- CFD modeling should be utilized when siting a continuous flow monitor in a stack installation. CFD modeling can aid in identifying and visualizing advanced flow features such as recirculation zones, swirl decay, and velocity profile development. CFD models of stacks can also provide a low cost and efficient means of simulating the effect of using turning vanes, bluff bodies, etc. to mitigate flow stratification, and non-axial flow conditions.

Stack Diameter Verification

- The diameter of the stack at the flow monitor location should be checked using laser distance meters. At least two stack diameter measurements should be obtained, and an average diameter calculated. These measurements should be obtained with the unit on-line operating at normal load conditions in order account for thermal expansion.

Flow Monitor Redundancy

- The use of two (or more) pairs of ultrasonic units that measure different paths (typically in an X-pattern) could produce more accurate flow measurement results. It is believed that using redundant ultrasonic monitors in an X-pattern technique will cancel the effect of the pitch flow. One set exhibits a positive bias with respect to the pitch, the other a negative bias.

Recommendations – CO_2 Measurement Reference Method Testing

The following list presents the best practice recommendations for CO_2 reference method testing.

Testing

- Always perform a 24-point stratification test prior to the start of the RATA to sufficiently characterize the stack cross section
- Consider the use of a fixed 6-point sampling probe for measurements at minimally stratified stacks to provide enhanced sample point location consistency
- Consider the use of a fixed 12-point sampling probe for measurements at stratified stack to provide enhanced sample point location consistency.
- Select the span of the reference method system so that the CO_2 calibration gas standards are as close as possible to the actual stack gas concentrations in order to increase measurement accuracy.
- After initial span and zero adjustment of the analyzer, repeat the procedure to check for drift in adjustments
- Determine the system response time and be consistent in its use throughout the reference method test, calibration error and system bias checks.
- Consider adopting quality control limits for analyzer calibration error, system bias and drift that are more stringent than the reference method requirements.
- CO_2 analyzers are susceptible to temperature changes. Minimize analyzer drifts by careful siting of analyzer racks or redirecting of airflow to maintain analyzer temperature within a $\pm 3^{o}$F band.
- Allow sufficient time for the analyzer to warm up.

- Use a calibrated temperature sensor such as a 4-wire Class-A high temperature resistance temperature detector (RTD) capable of measuring temperature to within ±0.5°F to obtain average stack temperature for determining moisture content in saturated stacks.

Calibration Gases

- Cross check newly purchased calibration gas cylinders to confirm their cylinder tag value.
- Cross check newly purchased zero level calibration gases to confirm that no contaminants are present.
- Use EPA Protocol calibration gases with a certified accuracy of better than 1% of cylinder gas tag value.
- Use EPA blind calibration gas audit reports as a guide to selecting calibration gas vendors.
- Do not over-pressurize the measurement system and analyzer during calibration error and system bias checks.

Recommendations – Flow Measurement Reference Method Testing

The following summary presents the best practice recommendations for reference method flow measurements.

General

- Carefully plan the pre-RATAs and RATAs and analyze tradeoffs between various test and instrumentation options.
- A pre-RATA tune-up is recommended. If a pre-RATA is performed, the tester should incorporate as many recommendations contained herein as possible.
- Results from the pre-RATA can be used to make adjustments to the correlation curve (ultrasonic monitors) and the K factor (differential pressure monitors). Flow monitor output should agree with pre-RATA results within ± 1 percent.
- A test plan should be prepared for each RATA.

Instrumentation

- The use of an auto positioning probe will eliminate uncertainty associated with human control of, and interaction with the probe and measurement instrumentation. Based on a review of available data among various sources, the use of an auto positioning probe (yaw-nulled mode) will reduce measurement uncertainty by 1-2%.
- If an auto positioning probe is not an option, the tester should use a calibrated DAT or spherical 3-D velocity probe. The DAT probe appears to provide consistently lower uncertainty results than the spherical probe.
- The S-Type Pitot probe should not be used for manual testing. If manual testing is to be employed, the tester should use a 3-D velocity probe.
- If manual testing is employed, the tester should utilize a micromanometer that has a certified accuracy as a percent of reading, not as a percent of full scale.

Calibration

- Use a velocity probe calibrated over the flow velocity range of interest.

- The velocity probe should be calibrated in a wind tunnel under conditions anticipated in the field (i.e., velocity, temperature, and turbulence).
- If manual testing is to be employed, the tester should consider utilizing EPA Preliminary Method 007 as the best practice calibration approach for the 3-D velocity probe. Pre-007 will minimize human interaction (yaw-nulling) with the Pitot probe during the test which should improve uncertainty.
- The calibration of 3-D pitot probes should be performed in the range of turbulence intensities expected to be present when the calibrated instrument is used in the field. These calibrations can be conducted by NIST (Note: This approach will likely require a preliminary test of the stack in order to characterize the turbulence intensity factor.).

Testing

- Perform stack traverses using the optimal number of sample points. The use of 12 points for a flow RATA will likely lead to discretization errors. The tester should consider using 48 total sample points (across two diameters) for a RATA.
- The velocity decay due to wall effects should always be measured, and the results corrected accordingly.
- The stack diameter should be verified and measured in the field using a laser distance meter. At least two separate stack diameters should be measured, and the average diameter obtained.
- The velocity probe should be inserted into the stack and allowed to reach the temperature of the effluent gas stream before commencing any testing.

Recommendations – Other

The following best practice should be implemented when conducting heat input calculations.

- The use of the default or standard F_c-factors as listed in Table 1 in 40 CFR Part 75 Appendix has the potential to introduce additional positive bias (uncertainty) to the heat rate calculation. In order to eliminate this additional uncertainty, the F_c-factor should be calculated on a case-by-case basis whenever possible rather than using the standard F_c-factor.

Recommendations – Overview

Table 7-1 provides a summary of the highest priority best practices identified as part of this study and provides estimates pertaining to their implementation and resulting effect on the heat rate uncertainty calculation.

Table 7-1
Prioritized Best Practices and Estimated Effect on Heat Rate Uncertainty

Best Practice Description	Systematic Uncertainty	Estimated Heat Rate Calculation Uncertainty Improvement
CO_2 CEMS Operation		
Sample from a location that is representative of the measurement area measurement. Determine sampling points based on enhanced stratification test results.	Spatial	3-5%
Span the system with CO_2 calibration gas standards that are more representative of the actual stack gas concentrations in order increase measurement accuracy.	Instrumental	7-10%
Use EPA Protocol gases with a certified accuracy of 1%.		
Perform a daily check of the system integrity by alternating between introducing calibration gas standards to the probe and directly to the analyzer.		
CO_2 RATA Testing		
Conduct a 24-point stratification test	Spatial	3-5%
Use a 6- point sampling probe in minimally stratified stacks		
Use a 12- point sampling probe in stratified stacks		
Span the system with CO_2 calibration gas standards that are more representative of the actual stack gas concentrations in order increase measurement accuracy.	Instrumental	3-5%
Use EPA Protocol gases with a certified accuracy of 1%.		
Use a calibrated Class A RTD for stack gas temperature determination for determining stack gas moisture.		
Flow Monitor Operation		
Use CFD modeling to choose optimum location for flow monitor(s).	Spatial	2-3%
Conduct daily calibration and interference checks.	Instrumental	1-2%
Flow Monitor RATA Testing		
Enhanced flow RATA testing should utilize 48-points on two diameters.	Spatial	7-10%
Verify stack internal diameter using laser detection meter.		
Use an auto positioning probe for flow RATA testing.	Instrumental	8-12%
The velocity Pitot probe should be wind tunnel calibrated under conditions anticipated in the field (i.e., velocity, temperature, and turbulence).		
Utilize a micromanometer that has a certified accuracy as a percent of reading, not as a percent of full scale.		
Results from pre-RATA tune-ups should be used to calibrate flow monitors. Flow monitor output should agree with the reference method results to within ± 1 percent.		

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QUESTIONNAIRE

Question No.	Flue Gas Flow Rate Monitoring System – End User Questionnaire	Utility A	Utility B	Utility C	Utility D	Utility E	Utility F	Utility G	Utility H	Utility I	Utility J
1	*Please describe the type of stack gas flow monitoring device(s) installed on your units, or in your system (i.e., differential pressure, ultrasonic, or thermal).*	Annubar differential pressure	Pitot differential pressure transducer, measuring inches water column.	Ultrasonic	Almost all differential pressure, at least one ultrasonic.	Ultrasonic	Differential pressure	Mostly ultrasonic	Ultrasonic	Differential pressure, S-type pitot tube	Ultrasonic
2	*What are the manufacturer name(s) and model number(s)?*	Dieterich Standard ST94003-01001, and new Rosemount models	EMRC	Teledyne Ultraflow 150	Differential pressure monitors are by EMRC. Ultrasonic by Teledyne.	Teledyne Ultraflow 100 and 150	Air Monitor Corporation, Mass Tron	Teledyne Ultraflow 150	Teledyne Ultraflow 150	EMRC, model number not known	Teledyne Monitoring Labs 150
3	*How long has the equipment been installed?*	Since 1995, new Rosemount models since 2015.	Since 1994	More than 10 years	EMRCs installed 1993	Since 1993	For 10 years	Since 2004	New plant, 2-3 years.	Since 2009	Since 2012
4	*Is the flow monitoring instrument calibrated on a daily, weekly, monthly basis?*	Daily calibration checks	Daily auto calibration	Daily calibration checks, not actually calibrated.	Daily calibration checks	Daily calibration checks	Daily	Daily calibration check, certified every year.	Daily calibration checks	Not calibrated annually, but daily calibration check.	Not calibrated, no way to do external calibration on stack flow monitors. Do daily calibration checks.
5	*Please describe the type of calibration procedure performed?*	Daily calibration checks	Quarterly transducer and calibration check. Full calibration annually.	Checked if failing.	Typical differential pressure calibration.	Not known	Zero and span	Performed electronically	Runs at same time as other checks, such as interference check. Result is either pass or fail. Includes zero and span calibrations. Takes about 5 minutes.	Daily zero and daily span check.	Daily check, zero and upscale reference.
6	*Please describe the type and frequency of interference check procedure performed?*	Do linearity checks and CEM technicians visually observe analyzer.	Daily interference check	Not known	For EMRCs, pressurize system, hold pressure for certain time to check for plugs or back-purge.	Check that purge air blower is still working, check faults from data logger and sensor from air purge meter.	Not applicable	Daily, meeting EPA requirements.	Both sides transmit and receive. If there is an obstruction the unit gives an interference message.	Daily interference check to see if it is plugged. Line pressurized for one minute, to see if it can hold pressure. If can hold, then considered a pass.	With new ultrasonic monitors, there is no real interference check to be done. It is just an internal check, a signal is sent and when it gets back it checks if it is OK. Just a formality to keep within compliance. Interference checks were designed for differential pressure monitors.
7	*How often do you perform a RATA test of your flow monitor?*	Annually mostly, sometimes semi-annually	Annually	Semi-annually	Annually	Annually	Not known	Annually	Annually	Annually	Annually
8	*Are you required to meet Part 60 or Part 75 RATA requirements?*	Part 75	Both Part 60 and 75	Part 60	Part 75	Part 75	Part 75	Part 75	Part 75	Part 75	Part 75

Question No.	Flue Gas Flow Rate Monitoring System – End User Questionnaire	Utility A	Utility B	Utility C	Utility D	Utility E	Utility F	Utility G	Utility H	Utility I	Utility J
9	*Do you conduct flow RATAs at single or multiple unit loads?*	As per requirements.	Two loads. This year three load due to 5-year requirement.	Three loads (low, medium and high)	Multiple loads, some exceptions. If qualify, will do 1-load flow RATA every 5 years.	Three loads, one load from time-to-time depending on load data.	One load most recently, historically dependent on load swings.	Varies, some units at three loads, some at single load.	Last time conducted at multiple loads, time before at a single load.	Have done single-load RATAs in the past, but most recently two-load RATAs based on load data.	Usually two loads, every few years do three loads.
10	*What is the required relative accuracy that your system(s) is required to achieve?*	7% or 10%	Not known	<10% error	7.50%	As close to reference method as possible.	RATA result <7.5%	± 10%	Question skipped due to time constraints	7.50%	7.50%
11	*Does your flow monitoring system typically exceed (i.e., lower than) the relative accuracy target? By how much?*	Does not exceed 10%	Always within specification, never exceeded.	Sometimes	Usually 2-5%	Not known	Yes, <5%	Varies, but always passes.	No; last RATA in September 2014, both units were within 2-3%.	Changes every year, last year was approximately 4%, so exceeded target by about 3.5% based on target of 7.5%.	Yes, but sometimes above, sometimes below. Some units have bias adjustment factor.
12	*Is your flow monitoring system typically higher than or lower than the RATA result?*	Meets 7%, within 3% RA	Question skipped	Not known	Always passes	Typically slightly higher to avoid bias factor.	Higher	Varies	Thought higher	Higher	Historically higher, but if reads wrong is recalibrated to stack test result.
13	*What EPA Reference Method or Methods (i.e., 2, 2F, 2G, or 2H) do you use when conducting a RATA test?*	2F, 2H if needed	Method 2	Not known	Methods 2 and 2H	Methods 2G and 2H	Method 2F	Not known	Not known	Not sure, thought autoprobe Method 2G	Methods 2F and 2G, plus wall adjustment.
14	*Do you ever conduct pre-RATA tests/checks of your flow monitor(s)?*	No, but perform QA on gas analyzer. At all sites, the first 3 runs of the RATA are used as a gauge.	No	No	Yes	Yes	Yes	Rarely, mostly just engineering checks.	Yes	No	Yes, use two runs prior to RATA, with results sometimes incorporated into RATA, if OK.
a	*If yes, how prevalent are these tests?*	Not applicable	Not applicable	Not applicable	For every RATA	On new flow monitors, for example.	Before every RATA	Not applicable	Is first step. CEM technicians come in late the night before and perform checks.	Not applicable	Every RATA
b	*What reference methods do you use?*	Not applicable	Not applicable	Not applicable	Method 2	Not known	Not known	Not known	Not known	Not applicable	Methods 2F and 2G
c	*Do you make adjustments to your system based on these pre-RATA tests?*	Adjust K-factors in some instances, if discrepancy is found after RATA has started or if above normal.	Not applicable	Not applicable	Yes, make adjustment to flue coefficient for each of 3 loads.	Not known	Yes, had to raise K factor because of condensation in lines due to air in-leakage.	Yes, change curve factors.	Adjust the number in the correlation curve.	Not applicable	Yes, adjustments made to match stack test results.
15	*Do you perform routine maintenance of your flow monitors? Please describe briefly.*	As per Part 75 requirements.	Check diaphragm and thermocouple annually, brush clean. Is dry stack.	Yes, according to QA/QC manual, includes routine maintenance.	Yes	Most routine maintenance performed to keep ports cleared out. Corrective maintenance consists mostly of replacing transducers, when they quit working or get stuck.	Purge check, filter change and leak check.	Yes, per manual. Filter change, check for wear to transducers, damage and plugs.	Very little, blower filter changed quarterly, clean sensors twice per year.	Yes, inspect and clean pitots, change filters, etc.	Yes, weekly, monthly and quarterly. Not sure exactly what is done.
16	*Given the current regulatory environment and focus on GHG emissions, does your company plan to invest more time, capital, etc. on flow rate and CO_2 measurements? What about heat rate improvement?*	Not on flow rate and CO_2 measurements. Investment on heat rate improvement depends on final EPA rule outcome.	No	Program to improve heat rate does not involve flow monitor, because of problems with flow readings at some plants, such as equipment interferences.	No	No, nothing wrong with measurements.	No	Yes	Yes, given that it is a new plant.	Yes	Yes, plant engineers are constantly working on it, watching flow and heat rate. Use EPA CO_2 control chart as sense-check.

Question No.	Carbon Dioxide (CO_2) CEM System – End User Questionnaire	Utility A	Utility B	Utility C	Utility D	Utility E	Utility F	Utility G	Utility H	Utility I	Utility J
1	Do you currently monitor for CO_2? If so, under what provision (40 CFR 75)?	Yes, Part 75	Yes, Parts 60 and 75	Yes, Part 60	Yes, Part 75	Yes, Part 75	Yes, Part 75	Yes, Part 75	Yes, Part 75	Yes, Part 75	Yes, Part 75
2	What is the model and manufacturer of your CO_2 analyzer?	Fuji Electric Type ZRH and Servomex 4900	Thermo Scientific 410I	Teledyne 200E	Teledyne and Thermo Scientific	Teledyne API 360 and California Analytical ZR8	Thermo Scientific 410i	Thermo Scientific C-series, e.g. 42C	Teledyne Monitor Labs TML 20	California Analytical Model 601	Thermo Scientific 410i
3	What type of sampling probe do you use? Model/Manufacturer? What is your typical dilution ratio?	EPM probe, dilution ration not known.	EPM, dilution at stack 20:1; at inlet 100:1.	M&C SP2000, dilution 300:1	M&C, dilution 100:1	M&C SP2000 and SP2006, dilution 200:1 and 250:1.	M&C, model not known, dilution 100:1	M&C, model not known, dilution 100:1	Universal dilution probe, ratio 50:1.	M&C, model not known, dilution 100:1.	EMP dilution extractive probe, model 797, dilution 11:1.
4	Do you perform daily calibration error tests? What is the level of your calibration gas standard? How long do these tests take on the average? What are typical daily test results: CE < 1%, CE < 0.5% etc.?	Yes, daily calibration checks. Bottle 17.91%-18.2% CO_2 (three levels of gases). Duration is 30 minutes, but not just testing CO_2, other gases too.	Yes, daily calibration checks. Calibration gas approximately 18%. Duration is 15 minutes on just CO_2. Results <0.5% typical.	Yes, duration is 30 minutes including zero, span and recovery. Approx. 11% span at mid-level. Results <0.5% typical.	Yes, 80-100% of span, duration is approx. five minutes.	Yes, level of calibration gas standard to mimic stack gas 11-12.5% CO_2. Duration is 15-25 minutes including recovery. Results very close, error within 0.1%	Yes, daily zero, daily span. Duration is approx. 15 minutes. Typical result is a pass, as shown automatically on DCS. Reference is 17.8%. Result CE <0.5%.	Yes, daily calibration error test. Gas level varies. Test done automatically, 15 minutes in duration for CO_2. Results within 2%.	Yes, daily. Level of gas standard is 18%. Automatic calibration runs zero gas with CO_2 span, plus mid-level NO_x, etc. Entire duration is 30 minutes, including purge and recovery time. Results around 0.5% typical.	Yes, daily zero and daily span. Calibration gas levels are 0% and approx. 18%. Duration on whole, including zero, span and sample is approx. 35 minutes. Typical results are very close, a tenth off or spot on.	Yes, daily. Gas level varies, usually spanned at mid-level. For mid-level, 11% is used for daily calibration, for span 20%. Test run automatically, takes 20-30 minutes depending on instrument. Depends on sample flow rate and length of umbilical. Rarely fails, results <1%.
5	Do you have any maintenance limits for the daily calibration error test at which preventive maintenance actions are triggered? Note: reaching a preventive maintenance limit does not indicate that the system is out of control.	Error limit is 1% allowable, normally 0.1-0.2%.Trigger limit is 0.5%.	Yes, maintenance triggered at 0.5%, failure at 1%.	Warning on error if >0.5% or >1%.	Yes, if calibration fails.	Yes, at half of performance specification, e.g., 0.5%	If test fails, DCS sends maintenance request. Daily 1% error limit.	If fail, adjust analyzers.	Yes	Yes, when get a warning at 2.5%.	Maintenance level is 0.5%
6	What are the most likely corrective and/or maintenance actions performed on a daily basis?	Daily calibration data review, alarm on failure.	Barometric swing changes.	Not known	Not known	Very rarely, monitor is very reliable.	Re-run of calibration checks.	Daily calibration checks.	Nothing, CO_2 monitor is the most reliable one.	None, unit is solid. Do clean probe and change filters.	Not known
7	Do you perform quarterly linearity checks? How long do these tests take on the average? What are typical test results: LE < 5%, 4%, 3% etc? What criteria do you typically apply: LE ≤ 5% or |R-A |≤ 0.5%?	Quarterly linearity check. Duration is approx. 60-75 minutes, Part 75 criteria. LE <3%.	Quarterly linearity check. Duration is 3-3.5 hours rolled in with other checks. LE <1%. RA <0.5%, always well below.	Yes, duration is 10 minutes per phase (low, medium, high), 30 minutes per run. LE <3%, RA <0.5%.	Yes, duration is 60 minutes. Result is pass/fail. Part 75 criteria.	Yes, duration depends on if it is a similar dual range system, up to four hours. LE <7.5%	Yes, typical result is a pass (never fail). Part 75 requirements built into DCS system.	Yes, duration is approx. four hours. Results +/- 5%.	Yes, does not include zero, low-mid-high for three gases. Duration is 30 minutes per run for 1.5 hours in total. Results are 3-4%. LE <5%.	Yes, duration is approx. three hours. Typical results <2%. Apply RA criteria.	Yes, takes three hours, hard to say what is typical. LE criteria.
8	Do you have any maintenance limits for the quarterly linearity check at which preventive maintenance actions are triggered? Note: reaching a preventive maintenance limit does not indicate that the system is out of control.	Trigger for action is pass/fail	No, CO_2 analyzer is very reliable, always passes.	Trigger at >0.5%	Only if check fails	Not known	Yes	No	Yes, at 0.5%.	Yes, at 3%.	No, because none given in regulations. If looks like linearity is creeping up, then take a look with calibration gas to see where error is. CO_2 not a big deal, typically very low.
9	How often do you perform a RATA (semi-annually or annually)?	Annually; concurrent with flow RATA.	Annually	Annually	Annually	Annually	Annually	Annually	Annually	Annually	Annually

Question No.	Carbon Dioxide (CO_2) CEM System – End User Questionnaire	Utility A	Utility B	Utility C	Utility D	Utility E	Utility F	Utility G	Utility H	Utility I	Utility J
10	Are you performing any work / preventive maintenance prior to a RATA?	Preventative maintenance consists of pre-test	Weekly, monthly, quarterly and annual maintenance.	No, just daily calibration checks.	CEMS technicians check instrument before RATA.	Blow calibration gas, check that the response is per operating manual.	No	Yes	No	Yes, visually inspect sample probe to make sure it is clean and has no leaks.	Yes, all preventative maintenance done prior to RATA. Remove and rebuild probe, clean, check that it is leak-free and operating properly.
11	What are your typical RATA test results? Which criteria do you apply: (a) annual RATA - RA ≤ 10% or $\lvert R-A \rvert \le 1\%$, or (b) semi-annual RATA - RA ≤ 7.5% or $\lvert R-A \rvert \le 0.7\%$	CO_2 RATA has fewest issues out of all gases	<7.5%, +/- 0.7%, always well below; within 1-2% range.	2-3%	Almost always passes.	A few percent, absolute percentage difference for CO_2.	Typical result is a pass. RATA RA <10%	Within tolerance	Never failed	<2%, apply primary RA standard.	Always very close. April 2015 RA 4.21%, reading close to stack tester results, e.g. <0.3%
12	What reference methods do you use for a RATA - Method 3, 3A or 3B?	Method 3A	Method 3A	Not known	Method 3A	Method 3A	Method 3A	Not known	Not known	Not known	Method 3A
13	Do you have a preventive maintenance and inspection program? Do you perform daily, weekly, monthly, quarterly, semi-annually and/or annually inspections?	Part 75 requires QA/QC plan	As required by Parts 60 and 75.	Yes, daily.	Yes, monthly inspections, daily calibration and interference checks.	Not specifically for CO_2	Yes, daily checks, monthly and quarterly inspections.	Yes, quarterly, semi-annually and annually.	Yes, particulate filters changed yearly. Internal pump rebuilt yearly.	Yes, daily, monthly and annually.	Yes, maintenance performed alongside that of other monitors, following standard protocol.
14	What do you typically inspect during each of these visits? Do you maintain a check list for each visit?	Numerous form-based procedures and check lists	Have maintenance management system with checklists; keep own log sheets.	Review data, look for errors, check graphs. Automated systems prints reports stating pass or fail.	Check daily calibration, diffusion and desiccant using checklist.	Not applicable	Yes, use checklist. Not known what checks.	Yes, manual inspection using checklist.	Question skipped due to time constraints.	Inspect filters, check for leaks. Use checklist.	Not known
15	Which CO_2 analyzer components are most prone to failure and how do you recognize an upcoming failure?	Not known	Vacuum pump failure	Question skipped due to time constraints	Not known	Question skipped due to time constraints	Pump, pump failure.	Pump diaphragms, recognize failure by calibration drift.	GSC wheel that spins, lost motor couple of times.	Not aware of any analyzer parts that are prone to failure. Unit is solid.	CO_2 monitor is very solid, with few problems. Usually pumps and IR sources.
16	What are the most frequent corrective actions taken during preventive maintenance?	Pump rebuild and filter replacements	Replace vacuum pump sooner	Question skipped due to time constraints	Not known	Question skipped due to time constraints	None	Question skipped due to time constraints	Lost photo detector	Not known	Not known
17	Do you maintain a system log or any other log?	Yes	Yes	Question skipped due to time constraints	Yes	Yes	Yes	Yes, electronic log.	Written log and digital.	Yes	Yes, CEMS technicians keep daily logs, track daily activities completed daily.
18	Do you think that your future monitoring needs for CO_2 are met with your current set-up?	Yes	Yes, meet future needs. Own engineering checks for heat rate, have results close to calculations.	Yes, because readings have to be accurate. Data needed for heat rate factors and for calibration checks. Not going to do anything different to what is already required for NO_x and MATS.	Yes	Yes	Yes	Yes	Yes	Equipment-wise yes, but can do better job of keeping it accurate.	Yes

B

350 MW COAL FIRED UNIT UNCERTAINTY ANALYSIS

B.1.1 CEMS RATA Uncertainty Summary

The concentration of CO_2 in the stack gas and the volumetric flow rate of stack gas are used in the calculation of heat rate and boiler efficiency. The accuracy of the CEMS measurements is verified by the comparison to a reference method during the RATA testing. This appendix describes in detail the systematic uncertainty of CEMS measurements of volumetric flow and CO_2 concentration.

For both volumetric flow and CO_2 concentration, four quantities were evaluated to determine the uncertainty of each parameter. These are

- the offset between the reference method and the CEMS reported as determined by the average difference between the reference method and the CEMS value for RATA test runs
- the bias uncertainty associated with estimated by the variation of the difference about offset
- the spatial variation at the measurement location of the value of the reference parameter in the RATA
- the systematic uncertainty in the reference parameter attributable the uncertainty in the measurements in order to calculate the measured parameter

The values for the offset and systematic uncertainty are summarized in Table B-1.

Table B-1
CEMS Uncertainty Summary

			Systematic Uncertainty			
Parameter	**CEMS Average**	**Offset**	**Comparison**	**Spatial**	**Instrumental**	**Total**
Flow(scfm)	49,045,400	872,200	591,757	802,645	1,557,500	1,849,384
Flow(scfm)	36,024,300	46,000	235,418	1,133,634	1,774,765	2,136,603
CO_2(%)	10.17	0.20	0.08	0.25	0.21	0.33

The total systematic uncertainty for a parameter is calculated by:

$$B_{total} = \sqrt{B_{com}^2 + B_{spatial}^2 + B_{inst}^2}$$

B.1.2 Flow RATA Comparative Data

For the gas flow RATA, flow was measured with the CEMS simultaneously with a 16 point flow traverse using a 3-D probe utilizing EPA Method 2F. This comparison was made for a high load, 330 MW (gross), and a minimum load point of 235 MW. A total of 10 runs were made at each load point. The flow rate comparison for the high load is presented in Table B-2. The flow rate comparison for the minimum load is presented in Table B-3.

Table B-2
High Load Flow Comparison

Run	**Reference Flow (scfm x 10^{-3})**	**CEMS Flow (scfm x 10^{-3})**	**Difference (scfm x 10^{-3})**
1	49,449	47,298	2,151
2	49,521	48,036	1,485
3	50,911	48,813	2,098
4	49,739	48,765	974
5	49,706	49,283	423
6	50,152	49,552	600
7	49,977	49,515	462
8	49,730	50,028	-298
9	50,318	49,457	861
10	49,673	49,707	-34
Average	**49,918**	**49,045**	
Average difference			**872**
Standard deviation			**827**

Table B-3
Flow Comparison at Minimum Load

Run	**Reference Flow (scfm x 10^{-3})**	**CEMS Flow (scfm x 10^{-3})**	**Difference (scfm x 10^{-3})**
1	36,294	36,104	190
2	36,351	36,072	279
3	35,779	36,042	-263
4	36,320	35,933	387
5	36,026	35,933	93
6	35,960	36,054	-94
7	35,565	35,853	-288
8	36,620	36,174	446
9	35,416	35,962	-546
10	36,372	36,116	256
Average	**36,070**	**36,024**	
Average difference			**46**
Standard deviation			**329**

The bias uncertainty associated with the comparative difference is calculated by:

$$\mathrm{B_{comp}} = \frac{\mathrm{t_{n-1,95}} \mathrm{s}_{\Delta q_{\mathrm{sw}}}}{\sqrt{\mathrm{n}}}$$

The bias uncertainty associated with for the high load flow RATA is:

$$\mathrm{B_{comp}} = \frac{2.262 * 827x10^3}{\sqrt{10}} = 592{,}000\ scfm$$

For the minimum load flow RATA:

$$\mathrm{B_{comp}} = \frac{2.262 * 329x10^3}{\sqrt{10}} = 235{,}000\ scfm$$

B.1.3 Axial Velocity Spatial Variation

The spatial uncertainty due to spatial variation in for the average axial velocity is calculated by

$$B_{v_a,spatial} = \frac{t_{m-1,95} s_{v_a}}{\sqrt{m}}$$

$$s_{v_a} = \sqrt{\frac{\sum_{i=1,m}(v_{a,i} - \bar{v}_a)^2}{m-1}}$$

The spatial variation for four of the 10 RATA flow tests is summarized in Table B-4.

Table B-4
Spatial Variation for High Load Flow Runs

Run	**1**	**3**	**5**	**8**
Traverse Point	**Axial Velocity (fps)**	**Axial Velocity (fps)**	**Axial Velocity (fps)**	**Axial Velocity (fps)**
1	60.57	59.96	61.38	62.32
2	60.07	62.89	60.82	56.83
3	55.99	64.52	62.31	60.04
4	57.95	65.83	61.93	61.23
5	55.81	60.46	57.44	57.49
6	58.05	59.97	60.02	61.35
7	59.5	62.23	59.41	61.18
8	61.9	61.25	60.47	57.28
9	61.85	60.38	62.35	62.58
10	61.36	59.78	59.75	62.63
11	61.25	61.24	59.38	61.38
12	62.3	61.68	61.48	60.89
13	62.34	62.69	61.5	62.33
14	62.79	64	60.35	62.86
15	61.95	62.55	58.86	59.98
16	61.48	62.14	59.99	58.65
Average	60.32	61.97	60.47	60.56
Number	16	16	16	16
Spatial Variance	2.24	1.75	1.34	2.01
Student's t	2.13	2.13	2.13	2.13
Spatial Uncertainty	**1.20**	**0.93**	**0.72**	**1.07**

The average spatial uncertainty in axial velocity for the four chose runs was 0.98 ft/sec which is 1.6% of the average velocity. The flow rate uncertainty is calculated by:

$$B_{Q_{sw,spatial}} = \theta_{v_a}^{Q_{sw}} B_{v_{a,spatial}}$$

The flow rate sensitivity coefficient to axial velocity is calculated by:

$$\theta_{v_a}^{Q_{sw}} = \frac{\partial Q_{sw}}{\partial v_a} = \frac{Q_{sw}}{\bar{v}_a}$$

For the high load test Run 1:

$$\theta_{v_a}^{Q_{sw}} = \frac{49{,}448{,}526}{60.32} = 819{,}736\ scfh/fps$$

For the high load runs the flow uncertainty due to spatial variation is:

$$B_{Q_{sw,spatial}} = 0.98 * 819{,}736 = 802{,}645\ scfm$$

The spatial variation for four of the runs at the minimum load is summarized in Table B-5.

Table B-5
Spatial Variation for Minimum Load Flow Runs

Run	**1**	**3**	**5**	**7**
Traverse Point	**Axial Velocity (fps)**	**Axial Velocity (fps)**	**Axial Velocity (fps)**	**Axial Velocity (fps)**
1	41.28	45.96	44.83	42.75
2	43.28	45.31	46.03	45.41
3	42.66	44.68	45.38	43.52
4	44.1	42.87	42.94	44.32
5	40.77	39.08	37.73	38.59
6	41.52	40.52	39.23	37.85
7	39.88	41.19	40.75	38.64
8	44.04	42.72	42.8	37.85
9	44.18	44.17	42.82	42.59
10	44.87	46.74	44.87	45.79
11	42.87	45.5	45.52	47.48
12	43.54	44.22	44.27	45.48
13	47.9	42.12	43.64	43.34
14	48.61	42.9	46.21	44.9
15	48.6	42.16	47.42	46.69
16	44.86	44.22	44.97	46.13
Average	43.94	43.40	43.71	43.21
Number	16	16	16	16
Spatial Variance	2.63	2.09	2.62	3.27
Student's t	2.13	2.13	2.13	2.13
Spatial Uncertainty	**1.40**	**1.11**	**1.39**	**1.74**

The average spatial uncertainty for axial velocity for the minimum load runs was 1.41 fps, which is 3.2% of the average velocity. For the minimum load test Run 1:

$$\theta_{v_a}^{Q_{sw}} = \frac{36{,}294{,}412}{43.94} = 826{,}093\ scfh/fps$$

For the high load runs the flow uncertainty due to spatial variation is:

$$B_{Q_{sw,spatial}} = 1.41 * 826{,}093 = 1{,}133{,}634\ scfm$$

B.1.4 Systematic Uncertainty for Measured Parameters during Flow RATA

The volumetric flow rate at standard conditions is calculated by:

$$\mathrm{Q_{sw}} = 3600 * \mathrm{A_s \bar{v}_s} \frac{\mathrm{\bar{P}_s T_{std}}}{\mathrm{P_{std} \bar{T}_s}}$$

The average velocity at the measurement point is calculated by the average of the axial velocities calculated at each measurement point. The axial velocity at each measurement point is calculated by:

$$\mathrm{v_{a,i}} = \mathrm{K_p F_2} \left[\frac{\Delta \mathrm{P_{1-2,i} T_{s,i}}}{\mathrm{\bar{P}_s M_s}}\right]^{1/2} \cos \varphi_{\mathrm{y}} \cos\varphi_{\mathrm{F}}$$

For purposes of evaluating the sensitivity for individual test parameters (only), these equations will be combined.

$$\mathrm{Q_{sw}} = 3600\mathrm{A_s K_P \bar{F}_2} \frac{\mathrm{T_{std}}}{\mathrm{P_{std}}} \mathrm{\bar{P}_s^{1/2} \bar{T}_s^{-1/2} M_s^{1/2} \Delta\bar{P}_{1-2}^{1/2}} \cos\bar{\varphi}_{\mathrm{y}} \cos\bar{\varphi}_{\mathrm{F}}$$

The sensitivity coefficients for parameters are determined by computing the partial derivative of the flow equation with respect to the parameter. For instance, the sensitivity coefficient for the differential pressure, ΔP_{1-2}, is:

$$\theta_{\Delta \mathrm{P_{1-2}}}^{\mathrm{Q_{sw}}} = \frac{\partial \mathrm{Q_{sw}}}{\partial \Delta \mathrm{P_{1-2}}} = 1/2 \frac{\mathrm{Q_{sw}}}{\mathrm{\bar{P}_{1-2}}}$$

The overall systematic uncertainty for the volumetric flow rate at standard conditions is:

$$\mathrm{B}_{\mathrm{Q_{sw}},inst} = \left[\sum_{\mathrm{j=1,m}} (\theta_{\mathrm{j}}^{\mathrm{Q_{sw}}} \mathrm{B_j})^2\right]^{1/2}$$

The sensitivity coefficients for parameters affecting the volumetric flow are presented in Table B-6. The values for the parameters used in the sensitivity calculations were from the Run 1 of the high load RATA.

Table B-6
Parameter Flow Sensitivity Coefficients

Parameter	Units	Value	Sensitivity Coefficient Equation	High Load Sensitivity Value
Pitot coefficient		1.052	$\theta_{F_2}^{Q_{sw}} = \frac{Q_{sw}}{\bar{F}_2}$	4.700E+07
Static pressure	inHg	29.27	$\theta_{P_s}^{Q_{sw}} = \frac{1}{2}\frac{Q_{sw}}{\bar{P}_S}$	8.447E+05
Temperature	°R	592	$\theta_{T_s}^{Q_{sw}} = -\frac{1}{2}\frac{Q_{sw}}{\bar{T}_S}$	-4.176E+04
Gas molecular weight	lbm/mole	28.21	$\theta_{M_s}^{Q_{sw}} = \frac{1}{2}\frac{Q_{sw}}{M_S}$	8.764E+05
Apparent velocity pressure	inwg	0.649	$\theta_{\Delta P_{1-2}}^{Q_{sw}} = \frac{1}{2}\frac{Q_{sw}}{\overline{\Delta P}_{1-2}}$	3.810E+07
Yaw angle	radians	0.05410	$\theta_{\varphi_y}^{Q_{sw}} = -\frac{Q_{sw}}{\cos\varphi_y}\sin\varphi_y$	2.678E+06
Pitch angle	radians	0.05934	$\theta_{\varphi_F}^{Q_{sw}} = -\frac{Q_{sw}}{\cos\varphi_F}\sin\varphi_F$	2.938E+06
Volumetric flow @ standard conditions	scfh	49,448,526		

The overall instrumental uncertainty of the volumetric flow rate at high load is presented in Table B-7.

Table B-7
Instrumental Uncertainty for Flow RATA at High Load

				Systematic Uncertainty	
Parameter	**Units**	**Value**	**Sensitivity Value**	**Parameter Units**	**scfm**
Pitot coefficient		1.052	4.700E+07	0.02104	988,971
Static pressure	inHg	29.27	8.447E+05	0.1	84,470
Temperature	°R	592	-4.176E+04	2.83	-118,126
Gas molecular weight	lbm/mole	28.21	8.764E+05	0.263	230,218
Apparent velocity pressure	inwg	0.649	3.810E+07	0.0300	1,142,878
Yaw angle	radians	0.0541	2.678E+06	0.0349	93,481
Pitch angle	radians	0.0593	2.938E+06	0.0349	102,548
Volumetric flow @ standard conditions	**scfh**	**49,448,526**			**1,541,939**

The instrumental uncertainty of the flow RATA at high load is 1.5 million scfm which is 3.1 percent of the measured flow of 49.4 million scfm. The dominant factors in the parametric uncertainty of the flow are the uncertainty of the pitot coefficient, F2, and the uncertainty of the measurement of the velocity differential pressure. The uncertainty of the velocity pressure was due to the relatively high tolerance, 0.03 inwg, assigned to the calibration of the Magnahelic pressure gauge in the calibration report of the RATA. The uncertainty due to velocity pressure measurement could be reduced by using a more accurate pressure gauge or (perhaps) by reducing the calibration tolerance.

The overall instrumental uncertainty of the volumetric flow rate at minimum load is presented in Table B-8.

Table B-8
Instrumental Uncertainty for Flow RATA at Minimum Load

				Systematic Uncertainty	
Parameter	**Units**	**Value**	**Sensitivity Value**	**Parameter Units**	**scfm**
Pitot coefficient		1.052	3.450E+07	0.02104	725,888
Static pressure	inHg	29.25	6.204E+05	0.1	62,042
Temperature	°R	588	-3.086E+04	2.83	-87,293
Gas molecular weight	lbm/mole	28.31	6.410E+05	0.263	168,379
Apparent velocity pressure	In7wg	0.338	5.369E+07	0.0300	1,610,699
Yaw angle	radians	0.0541	2.678E+06	0.0349	93,481
Pitch angle	radians	0.0593	2.938E+06	0.0349	102,548
Volumetric flow @ standard conditions	**scfh**	**36,294,412**			**1,783,351**

The instrumental uncertainty of the flow RATA at minimum load is 1.8 million scfm which is 4.9 percent of the measured flow of 36.3 million scfm. The dominant factors in the parametric uncertainty of the flow are the uncertainty of the pitot coefficient, F2, and the uncertainty of the measurement of the velocity differential pressure. The uncertainty of the velocity pressure was due to the relatively high tolerance, 0.03 inwg, assigned to the calibration of the Magnahelic pressure gauge in the calibration report.

Some of the parameters used to calculate the volumetric flow at standard conditions are not measured quantities but are derived from measured parameters based on equations found Method 2F or other EPA methods. For instance, the static pressure is calculated from the measured barometric pressure and the gauge pressure of the duct by:

$$P_s = P_{bar} + \frac{P_g}{13.6}$$

The sensitivity of the static pressure, Ps, to the barometric pressure, P_{bar}, is:

$$\theta^{P_s}_{P_{bar}} = \frac{\partial P_s}{\partial P_{bar}} = 1$$

The sensitivity of the static pressure, Ps, to the duct gauge pressure, P_g, is:

$$\theta^{P_s}_{P_g} = \frac{\partial P_s}{\partial P_g} = \frac{1}{13.6} = 0.0735$$

The accuracy of the devices used to measure the barometric pressure and duct pressure for the 2014 host site unit RATA (June 21, 2012) were not defined in the RATA report. For this analysis, an accuracy of 0.1 in. Hg was assumed the barometric pressure sensor and accuracy of 0.03 in. wg was for the duct pressure sensor. Based on these values, the systematic uncertainty of the static pressure is:

$$B_{P_s} = \sqrt{\left(\theta^{P_s}_{P_{bar}} B_{P_{bar}}\right)^2 + \left(\theta^{P_s}_{P_g} B_{P_g}\right)^2}$$

$$B_{P_s} = \sqrt{(1 * 0.10)^2 + (0.0753 * .03)^2} = 0.10 \text{ inHg}$$

The systematic uncertainty for temperature is based on the systematic uncertainty of the box temperature meter and the head temperature sensor.

$$B_{T_s} = \sqrt{B^2_{T_{meter}} + B^2_{T_{sensor}}}$$

The calibration tolerance for the box temperature meter is ±5°F. However, based on the calibration form of the RATA report, the maximum deviation at any point was 2°F. An uncertainty of 2°F will be used for the meter uncertainty. The calibration tolerance for the temperature sensor is ±2°F. The stack temperature uncertainty is, therefore:

$$B_{T_s} = \sqrt{2^2 + 2^2} = 2.8°\text{F}$$

The molecular weight of the gas, Ms, is calculated by:

$$M_s = \frac{100\ M_d}{100 - \%H_2O} + 0.18 * \%H_2O$$

The dry molecular weight of the stack gas is determined by:

$$M_d = 0.44\%CO_2 + 0.32\%O_2 + 0.28(100 - \%CO_2 - \%O_2)$$

Therefore:

$$M_s = \frac{100[0.44\%CO_2 + 0.32\%O_2 + 0.28(100 - \%CO_2 - \%O_2)]}{100 - \%H_2O} + 0.18 * \%H_2O$$

$$M_s = \frac{28 + 16 * \%CO_2 + 4 * \%O_2}{100 - \%H_2O} + 0.18 * \%H_2O$$

The sensitivity of the gas molecular weight to component concentrations is determined by:

$$\theta^{M_s}_{\%CO_2} = \frac{\partial M_s}{\partial \%CO_2} = \frac{16}{100 - \%H_2O}$$

$$\theta^{M_s}_{\%O_2} = \frac{\partial M_s}{\partial \%O_2} = \frac{4}{100 - \%H_2O}$$

$$\theta^{M_s}_{\%H_2O} = \frac{\partial M_s}{\partial \%H_2O} = \frac{28 + 16 * \%CO_2 + 4 * \%O_2}{(100 - \%H_2O)^2} + 0.18$$

Since the CO_2 and O_2 analyzers were calibrated with gases with a certified accuracy of 1% of nominal concentration immediately before the measurement, the systematic uncertainty of the gas concentrations is 1% of the measured concentration. The moisture concentration was measured using EPA Method 4. The uncertainty associated with moisture determination is detailed in Section B.1.7. The systematic uncertainty for the gas molecular weight is calculated by:

$$B_{M_s} = \sqrt{\left(\theta^{M_s}_{\%CO_2} B_{CO_2}\right)^2 + \left(\theta^{M_s}_{\%O_2} B_{O_2}\right)^2 + \left(\theta^{M_s}_{\%H_2O} B_{\%H_2O}\right)^2}$$

The sensitivity and uncertainty values for run 1 of the high load RATA are summarized in Table B-9.

Table B-9
Uncertainty for Gas Molecular Weight

				Systematic Uncertainty	
Concentration	**Units**	**Value**	**Sensitivity**	**Parameter Units**	**Molecular Weight**
CO_2	% dry	12	0.188	0.120	0.023
O_2	% dry	7.3	0.047	0.073	0.003
H_2O	% wet	15	0.214	1.220	0.262
Molecular Weight	**lbm/mole**	**28.38**			**0.263**

B.1.5 CO_2 Comparison of CEM Measurements and Traverse Data

The CO_2 readings from the CEMS were compared to those calculated based on measurements CO_2 concentrations measured method EPA 3A and moisture measurements made using EPA

Method 4. The comparison was made for a total of nine runs. The comparative values for CO_2 concentration are summarized in Table B-10.

Table B-10
CO_2 Concentrations for CEMS and Reference Method

	CO_2 Concentration		
Run	**Reference**	**CEMS**	**Deviation**
1	10.4	10.2	0.2
2	10.4	10.2	0.2
3	10.3	10.2	0.1
4	10.4	10.1	0.3
5	10.3	10.2	0.1
6	10.4	10.2	0.2
7	10.3	10.2	0.1
8	10.3	10.1	0.2
9	10.5	10.1	0.4
Average	10.37	10.17	0.20
Root mean square deviation			0.22
Number of runs			9
Student's t			2.31
Systematic uncertainty			0.17

The average deviation is the expected offset, q_{CO_2}, for CO_2 values calculated by the CEMS. The root mean square deviation is used to calculate the uncertainty interval about the average value.

$$B_{CO2,comp} = \frac{t_{n-1,95}\Delta_{CO2}^{rms}}{\sqrt{n}}$$

$$B_{CO2,comp} = \frac{2.31 * 0.22}{\sqrt{9}} = 0.17 \text{ percent}$$

B.1.6 Spatial Variation of CO_2 Concentration

The spatial variation of the CO_2 concentration for the measurement location used in the RATA was evaluated based on the stratification summary of the RATA report. The spatial distribution of CO_2 concentration is summarized in Table B-11.

Table B-11
Spatial Distribution of CO2 Concentration

Point	CO_2 Concentration
1	12.288
2	12.405
3	12.325
4	12.021
5	12.067
6	12.147
Mean	12.209
Spatial variance	0.140
Number	6
Student's t	2.571
Spatial uncertainty	0.147

The spatial uncertainty for CO_2 concentration for the six point stratification traverse is calculated by:

$$B_{CO_2,spatial}^{strat} = \frac{s_{CO_2} t_{95,m-1}}{\sqrt{m}}$$

$$\mathrm{B}_{\mathrm{CO_2,spatial}}^{\mathrm{strat}} = \frac{0.14 * 2.571}{\sqrt{6}} = 0.147 \text{ percent}$$

For the RATA test, the CO_2 concentration was determined by a three point traverse. The estimate of the spatial uncertainty for the RATA test is calculated by:

$$B_{CO_2,spatial} = \mathrm{B}_{\mathrm{CO_2,spatial}}^{\mathrm{strat}} \frac{t_{95,2}}{t_{95,5}}$$

$$\mathrm{B}_{\mathrm{CO_2,spatial}} = 0.147 \frac{4.302}{2.571} = 0.25 \text{ percent}$$

B.1.7 CO_2 Concentration Instrumental Uncertainty

The wet CO_2 concentration used as the reference in the RATA was determined by:

$$[CO_2] \quad = \frac{(100 - [H_2O])[CO_2]_{dry}}{100}$$

The instrumental uncertainty of the wet concentration of CO_2 during the RATA is determined by:

$$B_{[CO_2],inst} = \sqrt{\theta^{[CO_2]}_{[CO_2]_{dry}} B_{[CO_2]_{dry}})^2 + \theta^{[CO_2]}_{[H_2O]} B_{[H_2O]})^2}$$

The sensitivity of the wet concentration of CO_2 to the measured dry CO_2 concentration is determined by:

$$\theta^{[CO_2]}_{[CO_2]_{dry}} = \frac{\partial[CO_2]}{\partial[CO_2]_{dry}} = \frac{(100 - [H_2O])}{100}$$

The sensitivity of the wet concentration of CO_2 to the moisture concentration is determined by:

$$\theta^{[CO_2]}_{[H_2O]} = \frac{\partial[CO_2]}{\partial[H_2O]} = \frac{-[CO_2]_{dry}}{100}$$

The instrumental uncertainty for CO_2 concentration for the RATA is summarized in Table B-12.

Table B-12
Instrumental Uncertainty for CO_2 RATA

	Parameter Units			Systematic Uncertainty	
Concentration		**Value**	**Sensitivity**	**Parameter Units**	**Wet Concentration**
Dry CO_2	% dry	12.5	1.19	0.125	0.15
H_2O	% wet	16.3	0.13	1.225	0.15
Wet CO_2	**%wet**	**10.4**			0.21

The moisture concentration of the stack gas was determined by EPA Method 4 during each run of the CO_2 RATA. The moisture concentration calculated from the mass of the collected water and the total volume of gas sampled was moisture fraction calculated based the saturation pressure of water at the measured stack temperature and the stack static pressure.

For all of CO_2 RATA runs, as well as the flow RATA runs, the moisture fraction water calculated based on the collected mass exceeded the saturation concentration of water vapor. [Note: This result is not an indication of measurement error, but the expected result based on the oversaturated conditions which are normal at the stack outlet of a scrubber.)

As required by Method 4, the moisture concentration of the test runs was calculated based on the saturation water concentration. The moisture concentration is calculated from the saturation pressure of water at the measured stack temperature by:

$$[H_2O] = \frac{100P_{sat}\{T_s\}}{P_s}$$

The instrumental uncertainty of the moisture concentration is calculated by:

$$B_{[H_2O]} = \sqrt{(\theta_{T_s}^{[H_2O]} B_{T_s})^2 + (\theta_{P_s}^{[H_2O]} B_{P_s})^2}$$

The sensitivity coefficient of moisture concentration to stack temperature is determined by:

$$\theta_{T_s}^{[H_2O]} = \frac{\Delta[H_2O]}{\Delta T_s} = \frac{[H_2O]_{T_s+\Delta T_s} - [H_2O]_{T_s-\Delta T_s}}{2\Delta T_s}$$

For a stack temperature of 132°F and an incremental change in stack temperature of 3°F:

$$\theta_{T_s}^{[H_2O]} = \frac{17.7 - 15.1}{2 * 3} = 0.434 \frac{percent\ H_2O}{°\mathrm{F}}$$

The sensitivity coefficient of relative humidity to static pressure is calculated by:

$$\theta_{P_s}^{[H_2O]} = \frac{\partial[H_2O]}{\partial P_s} = \frac{-100P_{sat}\{T_s\}}{P_s^2}$$

For a stack temperature of 132°F and a static pressure of 29.27 in. Hg:

$$\theta_{P_s}^{[H_2O]} = \frac{100 * 4.787}{29.27^2} = -0.559 \frac{percent\ H_2O}{inHg}$$

The systematic uncertainty of the moisture concentration is:

$$B_{[H_2O]} = \sqrt{(0.434 * 2.82)^2 + (-0.559 * 0.10)^2} = 1.22\ percent$$

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