Environment and Climate Change Canada
Environnement et Changement climatique Canada

Protocols and performance specifications

for continuous monitoring of gaseous emissions from thermal power generation and other sources.

Canada

Nº de cat. : En83-2/1-7-2023E-PDF
ISBN : 978-0-660-48350-4
EC32102

Environment and Climate Change Canada
Public Information Centre
Place Vincent Massey building
351 St-Joseph boulevard
Gatineau Quebec K1A 0H3
Toll free: 1-800-668-6767
Email: enviroinfo@ec.gc.ca

Aussi disponible en français

Review notice

Abstract

This report outlines specifications for the design, installation, certification, and operation of automated continuous emission monitoring (CEM) systems used to measure gaseous releases of sulphur dioxide, nitrogen oxides, and carbon dioxide from thermal power generation and other sources. The procedures used during certification testing of each installed CEM system are also presented. This report also describes quality assurance and quality control (QA/QC) procedures, including the contents of a site specific QA/QC manual, which must be developed by the system operator for each installed CEM system and approved by the appropriate jurisdictional authority.

ACKNOWLEDGEMENTS

May 2023 version of this guidance document builds on the 1993 and the subsequent 2005 versions of ESP 1/PG/7 report.

Environment and Climate Change Canada (ECCC) acknowledges the contribution of the following individuals along the way:

George Marson, formerly with Environment and Climate Change Canada

David Law, Air Testing Services

Peter Pakalnis, Montrose Environmental

Kirk Easto, RWDI

James Jahnke, Source Technology Associates

Geoff Ross and Lorie Cummings, ECCC.

Organizations that have contributed in terms of providing review feedback and in the process strengthening this historical nationally important document:

Alberta Environment and Protected Areas (represented by Crystal Parrell)

Association of Independent Power Producers of Ontario (Jim Mulvale)

ATCO Electric Limited (Ryan Hunting)

BBP (Kevin Bruce)

Cement Association of Canada (Tracey Canney)

Canadian Gas Association (Christine Cinnamon)

Canadian Boiler Society (David Duthie)

Canadian Petroleum Products Institute (Adolfo Silva)

Capital Power (Phil Friesen)

Cement Association of Canada (George Venta)

Cancoppas Limited (Jake Alaica)

Cement Quebec Incorporated (Marc Brousseau)

CEMSI (Gary Saunders)

CISCO (Walt Bastron)

DOMINION USA (Sean Warden)

DURAG (Luc Sevrette)

Electricity Canada (Shahrzad Simab)

Invenergy (Paul McCardy)

Lafarge (Stephanie VOYSEY)

Lehigh (Eileen Jang)

Limesoft (Serge Bays)

Goreway (Jolie Phillips)

Government of Saskatchewan (Jenna Doyko)

New Brunswick Power (Anthony Bielecki)

Northland Power (Claire Houghton)

Nova Scotia Environment (Sharon Vervaet)

Nova Scotia Power (Debra McLellan, Cameron Moffatt, Heather Holland)

NOVATECH (JC Arenes)

Ontario Power Generation (David Ebsary, Bruce Dang)

Ontario Ministry of the Environment (Stephanie Millson, Lisa Minotti and Denis Maftei)

Ontario Ministry of the Environment (John Hutchison)

Ortech (Tina Sanderson)

Saskatchewan EPB (Michael Holm)

SICK Sensor Intelligence (Jason Loraway)

SNC LAVALIN (François Thibodeau)

Sparton (David Spencer)

US EPA (Steffan Johnson)

WSP (Dave Hofbauer)

Table of Contents

List of Tables

Section 1.0 Introduction

This document provides specifications for the design, installation, and operation of automated continuous emission monitoring systems (CEMS) used to measure releases of sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and other contaminants from large combustion sources such as thermal power generating facilities. The document presents procedures used to determine the various CEMS parameters during initial certification, testing and subsequent long-term operation of the monitoring system.

No specific monitoring system is prescribed in this document. Any system that meets initial certification criteria, specified parameters and quality assurance/quality control (QA/QC) requirements is acceptable. In-situ or extractive CEMS - based on dynamic dilution or direct measurement of the target species - may be used. Time-shared CEMS using a single set of analyzers to determine the emissions of 2 adjacent sources are acceptable.

Guidance is provided to assist the operator in developing a site-specific QA Plan (QAP), in conjunction with the appropriate regulatory agency. The resulting plan is an integral part of the overall requirements for the operation of each CEMS. Each emission monitoring system must produce technically valid data, which may be used for multiple purposes, including emission budget programs. However, this document does not address issues specific to an emission trading program, such as reporting formats, seasonal averaging, data retention requirements, etc., which should be compatible with the policies of the program and defined by the corresponding regulating authority.

While SO_2, NO_x, CO and CO_2 are the pollutants most often associated with the flue gases released from large combustion sources, some or all the concepts and procedures described herein could also be used, as appropriate, for the measurement of emissions of other contaminants and other point sources. In such cases the appropriate regulatory authority that mandates the monitoring may adjust, expand, or reduce the requirements detailed in this document, to reflect the specific concerns and/or constraints related to the need to monitor the particular species in question.

The personnel performing the initial certification and subsequent audits must be trained and experienced in the execution of the tasks and methods described in this document. The application of this guideline may entail health and safety hazards. Individuals performing the certification and audits are responsible for obtaining the required training to meet the occupational health and safety standards applicable to industrial field activities.

Section 2.0 Summary of specifications and protocols

This document provides various partial summaries of the specifications and procedures for the installation, certification, and continued operation of a CEMS, that may serve a quick reference to those familiar with the subject. Worth mentioning are:

Design Specifications Summary (Table 1)
Certification Performance Specifications Summary (Table 3)
Daily and Quarterly Performance Evaluations Summary (Table 6)
Semi-annual or Annual Performance Evaluations Summary (Table 7)

Section 3 outlines the specifications for the overall CEMS and subsystems, along with associate procedures for measuring these parameters. This section will assist the operator during the initial design and/or purchase stages. Specific requirements are provided for the recommended Data Acquisition and Handling System (DAHS).

Specifications for installing the CEMS are given in Section 4. These are used to ensure that a test location meets some minimal requirements with respect to representativeness of the gas flow and equipment maintenance accessibility.

After installation, the CEMS is tested following the protocols provided in Section 5. The emission data are compared with those from some manual (for example, flow) or instrumental reference methods (for example, gas analyzers) to ensure that the specifications have been met. When an installed CEMS has met or surpassed all these specifications, it is deemed to be certified and capable of generating quality-assured emission data.

A QA plan (QAP) must be developed for each CEMS by the operator or a contractor. Section 6 provides the basis for the development of this plan. The QAP must encompass a diverse range of topics, including calibration procedures, maintenance, performance evaluations, and corrective actions. Each CEMS will require a QAP; however, if a number of identical CEMS are operated, a single QAP is acceptable, provided that appropriate records are maintained for each CEMS.

Section 3.0 Design specifications and test procedures

Most CEMS consist of the following 3 basic subsystems: a) sample interface/conditioning, b) gas analyzers; and c) data acquisition and handling system (DAHS). Such systems may monitor compliance with a regulatory limit in terms of pollutant exhaust concentration at a given excess combustion air level, for example, NO_x @ 11%O_2 or limits in terms of emission per heat input.

With the addition of an adequate exhaust gas flow monitor or a fluid fuel meter, then the CEMS may measure the mass emission rate of all the monitored gaseous contaminants.

Specifications for these subsystems are given in Sections 3.1 to 3.5, while Section 3.6 outlines the procedure for verification of some critical specifications. The subsystem specifications are summarized in Tables 1 and 2.

This guideline does not exclude any emission monitoring technology. Components that met the criteria specified in Sections 3.1 to 3.5 and allow the overall CEMS to achieve the certification specifications in Section 5, and the evaluations in Section 6, are acceptable.

3.1 Sample interface/conditioning subsystem specifications

This section provides for the specifications for sample interface/conditioning subsystem for which the location of the port for calibration gas injection is the sole criteria.

3.1.1 Location of the calibration gas injection port

The location of the system calibration gas injection port is the sole criterion for the sample/conditioning subsystem, with the location of this port being specific to the type of CEMS. The location of the ports for the various types of CEMS is given in Table 2. CEMS installed after December 31, 2024, must be able to conduct a daily calibration drift tests and the quarterly linearity tests using as reference flowing calibration gases.

3.2 Gas analyzer subsystem specification

This section provides for specifications for relevant parameters for a gas analyzer, such as operating range, interference, and temperature-response drifts.

3.2.1 Operating range

The operating range of the analyzers must be adequate to the purpose of the monitoring and the emission pattern of the emission source where it is installed. As a general principle the operating range of the analyzers should encompass all expected stack gas levels. Analyzer manufacturers generally guarantee specifications such as linearity, drift, and cross-sensitivity for the full scale (FS) of the analyzer. The FS is expected to be constant through the analyzer’s life and slightly higher than the maximum expected concentration level.

Emission sources with a wide emission range may require dual range analyzers for an accurate coverage of high and low levels (order of magnitude variation). This matter should be determined by the appropriate regulatory authority.

3.2.2 Interference

The manufacturer of new SO_2, NO_x, and CO analyzers installed after December 31, 2024, must certify by a certificate of conformance that the sum of all interferences due to other stack gas components is less than 4.0% of the full scale of each of these analyzers. For O_2 and CO_2 analyzers the interference specification is less than or equal to plus/minus 1.0 % O_2 or CO_2, respectively. In the case of combustion sources fitted with NDIR or FTIR analyzers operating at no-sample condensation condition, the certification must include sample levels of 9% CO_2 and 18% H_2O.

If these analyzers operate preceded by a sample condensation system, then certification applies only to the expected CO_2 and H_2O sample levels of the condensation dried samples.

3.2.3 Temperature-response drifts

The manufacturer of new SO_2, NO_x, and CO analyzers installed at CEMS after December 31, 2024, must certify by a certificate of conformance that the analyzer exhibit a 0 drift less than plus/minus 2.0% of FS setting for any 10^{o}C change over the 5 to 35^{o}C ambient temperature range. In the same test conditions, the SO_2 and CO analyzers must exhibit a span drift of less than 3.0% of FS. The corresponding level of span drift for NO_x analyzers must be less than 4.0% of FS. The procedures outlined in section 3.6.2 must be followed to determine the temperature-response drift.

3.2.4 NO_x converters

If it is not demonstrated that the source NO_2 levels are less than 5% of the NO_x levels, and the CEMS is fitted with a NO_x analyzer that converts NO_2 to NO before analysis, then the converter must be tested semi-annually, by following US EPA Method 7E Section 8.2.4, or the Method 7E alternative Section 16.2. Acceptable conversion efficiency is 90%.

3.2.5 FTIR extractive CEMS

The features that distinguish Fourier Transform Infrared (FTIR) from other gas analyzers are, a) simultaneous monitoring of multiple infrared (IR) absorbing gases; b) computers are necessary to obtain and analyze data; c) chemical concentrations can be quantified using previously recorded IR spectra; and d) analytical assumptions and results, including possible effects of interfering compounds, can be evaluated after the quantitative analysis.

An extractive FTIR may be used as a CEMS component to monitor NO_x, SO_2, CO, and CO_2 emissions from a combustion source, providing that the FTIR meets the applicable analyzer specifications of this document, including the prescribed daily, quarterly, annual, or semi-annual QA/QC tests.

The same FTIR CEMS may be used to monitor emissions of other hazardous contaminants from the source (for example, HCL from cement kilns). For this additional purpose it should follow the specifications developed for this technology, such as EPA PS-15 and PS-18 [1, 2].

---

[1] https://www.epa.gov/emc/performance-specification-15-extractive-fourier-transform-infrared-spectroscopy
[2] https://www.epa.gov/emc/performance-specification-18-gaseous-hydrogen-chloride

Table 1: Design specifications for continuous emission monitoring systems

Subsystem	Parameter	Specification	Text references	
			Specification	Test procedures
Sample interface and conditioning	Location of calibration ports	See Table 2	3.1.1	-
Gas analyzers	Operating range	Set to encompass all expected stack levels of SO_2, NO_x and CO; 0% to 21% of O_2 and 0% to 25% of CO_2	3.2.1	
	Sum of Interferences	Less than or equal to 4.0% FS for SO_2, NO_x and CO analyzers Less than or equal to 1.0% O_2 or CO_2 for O_2 or CO_2 analyzers	3.2.2	certificate of conformance
	Temperature-response drifts for 10°C change within 5-35°C	0 less than or equal to plus/minus 2.0% of FS Span drift for SO_2 and CO less than or equal to plus/minus 3.0% of FS Span drift for NO_x less than or equal to plus/minus 4.0% of FS	3.2.3	3.6.1
	NO_x converters	Semi-annual test for NO_2 greater than 5% NO_x sources	3.2.4	
	FTIR extractive CEMS	Quality assurance requirements	3.2.5	
Flow monitor	Operating range	Lower velocity detection limit: 1 m/s Measurement range approximately 1.2 of maximum potential flow rate.	3.3, 3.3.1	
Data acquisition	Measuring time	Retain 1-minute base averages	3.4	
	Averaging time	Hourly average of greater than or equal to 75% of the possible 1-minute base average readings		
	Data handling and storage	Calculation of required averages and CEMS availability. 3-year minimum data storage.		
	Missing data	Less than or equal to 168 hours interval - backfill Greater than 168 hours interval - alternate CEMS	3.4.1	
Time-shared systems	System cycle time	Less than or equal to 15 minutes for complete 2 streams cycle	3.5	

Table 2: Location of system calibration gas injection ports for specific CEMS

System Type	Subsystem	System calibration gas injection port specification
Extractive	Direct measurement of gas concentration	Calibration gas must be introduced no further down than the sampling probe exit
	Dilution (in-stack or external)	Calibration gas must be introduced prior to dilution
In-situ	Point	Calibration gas must flood the measurement cavity of the analyzer
	Path	Calibration gas must provide a check on the internal optics and all electronic circuitries. System may also include an internal calibration device for simulating a 0 and an upscale calibration value

3.3 Flow monitor subsystem specifications

The gas flow monitor must be able to detect stack gas velocity as low as 1.0 m/s and to cover the full range of gas velocities expected in the flue or duct. Any flow beyond the range of the sensor are deemed to be missing and must be backfilled, as described in Section 3.4.1 of this document.

3.3.1 Operating range

The Full Scale (FS) level of the flow monitor should be set at a value acceptable to the appropriate regulatory authority. A FS approximately 1.2 times the maximum potential flow rate of the source is recommended.

Flow monitors installed at CEMS after December 31, 2024, must have the capability to carry out daily checks (for example, pressure pulse or electronic signal) consisting of 2 reference values: 0 to 20 % of FS and 50 to 70 % of FS. The monitor response, both before and after any adjustment must be recorded by the Data Acquisition and Handling System (DAHS).

The flow monitor of the CEMS may be able to measure levels higher than the QAP defined FS level, however, this high level should not be applied to demonstrate conformance to FS based specifications in Tables 3, 6, and 7.

3.4 Data acquisition and handling system (DAHS) specifications

The CEMS shall include a DAHS to process and record the monitoring data. The basic DAHS functions are a) read and display the levels of stack gas pollutants, diluents, flow, and temperature (if applicable), and b) keep a continuous and permanent record of the data. The DAHS must also record and compute daily 0 and span drifts, providing for backfilling and substitution for missing data. Additionally, the DAHS shall record the process intervals during which fuel is burned (for combustion related processes) or those intervals the monitored contaminants are vented while no combustion is taking place.

DAHS installed after December 31, 2024, must meet the following specifications:

They should be able to accept and retain as 1-minute base averages of the output of the CEMS components (gas and flow analyzers, temperature, et cetera) and, if applicable, pertinent process signals that define source operation.

If the CEMS meets all the Table 3, Table 6 and Table 7 specifications and the monitored process operated continuously, then the 1-hour CEMS average must be based on a minimum of 45 1-minute base averages. That 1-hour is a valid hour. If the process operated less than 60 minutes in the hour, and the base 1-minute CEMS average represents 75% or more of the operating minutes, then the hour is also valid for the availability specifications.

The availability of all the CEMS measurements (SO_2, NO_x, CO, O_2, CO_2, flow, temperature, and moisture, if applicable) shall be calculated monthly with the following Equation 3.1.

$$\text{Percent Availability} = \left(\frac{T_a}{T_{so}}\right) \times 100 \qquad \textbf{Eqn. 3.1}$$

where:
T_a is the total monthly valid CEMS hours.
T_{so} is the total hours the source operated in the month, in other words, hours during which fuel was burned (for combustion related processes) or hours during which contaminants were vented (for non-combustion sources).

The data handling capabilities of the DAHS may be used to compile a quarterly CEMS report in the format and units required by the applicable regulating authority, and to facilitate the annual CEMS audit required by the QA Plan (Table 5, Quality Control Procedures, Subsections 13 to 16). All CEMS data pertinent to regulatory requirements or limits shall be archived in the DAHS, including but not limited to Certification tests, CGA, bias factors and backfilling. The data should be securely stored for a minimum of 3 years.t

3.4.1 Backfilling of missing data

Backfilling should be tailored to the monitored process and described in the CEMS QAP manual. The following recommendations for simple backfilling are presented as examples.

Following initial CEMS certification, or later on at approximately 3-year intervals, a database of 720 quality-assured monitor operating hours should be developed for missing data backfilling. This valid hour database should include all the CEMS collected parameters (for example, concentrations, stack flow, temperature, and moisture). A 720-hour average of each parameter is calculated.

Emissions data during source operation that are missing due to a malfunction of any CEMS component (for example, gas analyzer, flow monitor) may be substituted for a period of up to 168 hours for any single episode by the corresponding 720-hour average from the backfilling data base. For short intervals (in other words, 1-2 hours) the missing data may be substituted by the average of adjacent operating hours, providing that the process operated steadily. The backfilling technique must be fully explained in the QAP developed for each CEMS and accepted by the appropriate regulatory authority. Backfilled data must be flagged and included in the monthly or quarterly emission report.

When a CEMS malfunction extends beyond 168 hours for a single episode, emission must be generated by another certified CEMS or valid reference method. Temporary CEMS used for this purpose must meet the design and performance specifications given in this document. When using a temporary CEMS, the stack gas sample may be extracted from the sample port(s) used for the reference method during certification and RATA of the permanent CEMS.

Data that are backfilled using a procedure other than a certified alternate CEMS or reference method, cannot be credited towards meeting the CEMS availability criteria specified in Section 6.5.1.

All emission data should be quality audited to identify suspected data using procedures described in the QA/QC plan (Section 6.1). The procedure may include automatic flagging of: a) out-of-range concentrations and flows, b) abnormal system calibration response time, c) abnormal heat rate levels (for systems fitted with fuel flow monitors), d) abnormal flow-to-input or flow-to-output (for systems fitted with stack gas flow monitors), and e) abnormal concentrations during periods when the combustion unit did not burn fuel.

The QA-flagged data must be investigated and either accepted or backfilled. The QA-flagged data should be identified in the monthly or quarterly report, along with a summary of reasons for acceptance or backfilling.

3.5 Time-shared systems

After December 31, 2024, new time-shared CEMS will be limited to monitoring emissions from 2 adjacent sources using a single set of monitors for pollutants, diluents and temperature (and, if required, separate exhaust flow monitors). One complete measurement cycle of both sources must be completed within 15 minutes, thus generating for each source 4 measurement of concentration and emissions for each hour. That is a valid hour for time-shared systems. The DAHS shall keep separate records of the data from each source. RATA should be performed while the CEMS is in time-shared mode and must be done for both monitored sources, not necessarily simultaneously.

Data shall be reduced to valid 1-hour averages, computed using at least 1 data point in each 15- minute quadrant of an hour during which the unit combusted fuel or vented contaminants. If representative data is unavailable due to emission source shut down or CEMS calibration during the hour, then a valid partial hour may be computed from at least two data points separated by a minimum of 15 minutes in which the combustion source operated. All valid measurements during an hour shall be used to calculate the hourly averages. Monthly availability is to be calculated with Equation 3.1.

There are 2 options available to determine the CEMS average while performing RATA in time-shared mode: 1) the runs can be 21 minutes long and the average computed from whatever data is recorded by the DAHS for the emission point tested during the 21 minutes; or 2) the runs can be extended up to 1 hour to capture 4 CEMS sampling cycles for the emission point being tested. Then, match up the DAHS data with the corresponding set of reference method data.

3.6 Test procedures for verification of design specifications

This section recommends test procedures for verification of design specifications.

3.6.1 Analyzer temperature-response 0 and span drifts

The procedure to determine the 0 and span response to ambient temperature changes is the following. The analyzer must be placed in a climate-controlled chamber in which the temperature can be varied from 5 to 35°C. Sufficient time must be allowed for the analyzer to warm up, and then the analyzer must be calibrated at 25°C using appropriate 0 and span gases. The temperature of the chamber must be adjusted to 35, 15 and 5°C. It should be ensured that the analyzer temperature has stabilized. The power to the analyzer must not be turned off over the duration of this test.

When the analyzer has stabilized at each climate chamber temperature, each of the calibration gases must be introduced at the same flow or pressure conditions, and the response of the analyzer must be noted.

The temperature-response 0 drift is calculated from the difference between the indicated 0 reading and the reading at the next higher or lower temperature. The analyzer is acceptable if the difference between all adjacent (in other words, 5/15, 15/25, and 25/35^{o}C) 0 responses are less than 2.0% of the FS setting. The temperature-response span drift is calculated from the differences between adjacent span responses. The analyzer is acceptable if the difference between all adjacent span responses meets the Table 1 specifications.

3.6.2. Manufacturer's certificate of conformance

The specifications for both interference and temperature-response drifts have been met if the analyzer manufacturer certifies that an identical randomly selected analyzer, manufactured in the same quarter as the delivered unit, was tested according to procedures suitable to the analyzer type (extractive dry or wet, in-situ, et cetera) and were found to meet the specifications.

Section 4.0 Installation specifications

This section contains guidance for selecting a suitable sampling site on the flue or duct and to determine if the location would allow sampling in a manner representative of the exhaust gas flow.

4.1 Location of the sampling site

The probe or in-situ analyzer must be installed in a location that is accessible at all times, so that routine maintenance can be performed on schedule, as outlined in the QA Plan (QAP). Sufficient shelter should be provided on outdoor installations so that maintenance can be safely performed during intemperate weather conditions without detriment to either the CEMS or service personnel. The degree of exposure, seasonal weather conditions, servicing and maintenance, susceptibility and protection from lightning strikes, and vibration of the duct and or platform are some of the considerations when siting a probe or in-situ analyzer.

Before a flow rate sensor is permanently installed, it should be ensured that cyclonic flow is not present at the desired sampling location. The presence of a cyclonic flow pattern would add considerable complexity to both certification and operation of the installed sensor. It is recommended that an alternate location be found if cyclonic flow pattern is verified at a proposed site. The protocols given in this report relate only to sources for which the gas flow pattern has been demonstrated to be non-cyclonic.

4.2 Representativeness

The sampling probe or in-situ analyzer must be installed in a location where the flue gases are well mixed. The degree of turbulence and mixing time are major factors that influence the extent of stratification of the flue gases.

The extent of stratification of the flue gases at any location must be determined using applicable test methods. It is therefore recommended that the procedures outlined in Section 4.2.1 be carried out at the analyzer installation site to determine the extent of stratification before installing the CEMS. If significant gas stratification of any of the measured species is present at the proposed location, then serious consideration should be given to selecting another location within the exhaust, where the flow has been determined to be non-stratified.

If stack flow monitoring is a component of the CEMS, then it is recommended that the adequacy of the sampling site be assessed with respect to the selected flow monitoring system as well as to the reference method to be used for the initial certification and the annual or semi-annual RATA.

It is recommended that the flow monitor and the reference method ports be located where the flow is unidirectional and fully developed. The guideline for this condition (EPA Method 1, Section 11.1.1) requires a straight length equivalent to 10 diameters of a cylindrical stack or duct, which may be unavailable or too expensive to build. A Computational Fluid Dynamic (CFD) study for less-than-ideal stack locations may estimate the degree of stratification and vorticity that may be expected, prior to selecting the CEMS location. If possible, before the flow monitor is installed, velocity traverses may be carried out following ECCC 1/RM/8 Method A or US EPA Method 1. If the flow is multidirectional, (for example, average rotational angle greater than or equal to 15 degrees) the installation of straighteners may be considered, or the use of more complex reference methods such as US EPA Method 2G (2 dimensional probes), Method 2F (3 dimensional probes) and Method 2H (velocity decay near stack wall). These methods then must be used for Certification and subsequent RATAs. The location of the sampling ports must be selected to avoid interference between the flow monitor and the reference method.

If a single-point velocity sensor is selected for installation, the sensing tip must be located at a point yielding representative velocity measurements over the full range of loads. The velocity profile data must be used to select the optimum measurement point.

4.2.1 Stratification test procedure

A minimum of 9 sampling points must be used in the stack or duct, applying the procedures for selecting stack testing sampling points (see Reference Methods in the Glossary, page 43). If the stratification test is conducted to evaluate the suitability of a sampling location prior to installing a CEMS, then the test may be conducted simultaneously with 2 similar portable monitoring systems, 1 sampling at a stationary point (generally the center point) and the other sampling sequentially all the traverse points. Note that the stratification test must be carried out for each gas to be monitored by the proposed CEMS, including the diluent gases.

If the concentration of the gas measured at the fixed location (stability reference measurement) varies by more than 10% for more than 1 minute during the test, then the test must be done when more stable conditions prevail. If an extractive CEMS is already installed and the stratification test is only for confirmation purposes, then the CEMS may be used a reference system. The degree of stratification for each species is calculated at each traverse point using Equation 4.1.

$$ST_i = \left[\frac{C_i - C_{avg}}{C_{avg}}\right] \times 100 \qquad \textbf{Eqn. 4.1}$$

where:
ST_i is stratification (%)
C_i is the concentration of the measured species at point i
C_{avg} is the average of all measured concentrations

The stack or duct gases are considered to be stratified if any calculated value using Equation 4.1 exceeds 10.0%.

Section 5.0 Certification performance specifications and test procedures

To achieve certification, an installed CEMS must meet all the performance specifications summarized in Table 3. The specifications are relevant to each pollutant and diluent gas measured, as well as the stack gas flow measurement (if applicable) and the overall CEMS.

Table 3: Certification performance specifications summary

Parameter	Component	Levels	Specification	Reference	Test procedure
24-hr calibration drift	SO_2, NO_x and CO analyzers	Low Level (0 to 20% FS)	Less than or equal to plus/minus 2.5% of FS difference **or** Less than or equal to plus/minus 2.5 ppm absolute difference	5.1.2	5.3.2
		High Level (80 to 100% FS)	Less than or equal to plus/minus 5.0% of FS difference **or** Less than or equal to plus/minus 2.5 ppm absolute difference		
	O_2 and CO_2 gas analyzers	(0 to 20% FS), (80 to 100% FS)	Both levels less than or equal to plus/minus 0.5% O_2 (or CO_2) diff.		
	Stack gas flow monitor	(0 to 20% FS), (50 to 70% FS)	Both levels less than or equal to plus/minus 3.0% of FS difference **or** Plus/minus 0.6 m/s absolute difference	5.1.3	5.1.3
3-run set linearity	SO_2, NO_x, and CO analyzers	(0 to 20% FS), (40 to 60% FS) (80 to 100% FS)	All levels less than or equal to plus/minus 2.5% of FS abs. avg. diff. **or** Less than or equal to plus/minus 5 ppm absolute avg. difference	5.3.3	5.3.3
	O_2 and CO_2 gas analyzers	(0 to 20% FS), (40 to 60% FS) (80 to 100% FS)	All levels less than or equal to plus/minus 0.5% O_2 or CO_2 absolute average difference		
System Response	Dedicated analyzer	-	Less than or equal to 200 seconds for 90% change	5.1.4	5.3.4
	Time-shared system	-	Less than or equal to 5 minutes for 90% change		
Relative Accuracy (RA)	SO_2 analyzers	-	Less than or equal to 10.0% Relative Accuracy (RA) **or** Less than or equal to 15.0 ppm abs. avg. difference	5.1.5	5.3.1 to 5.3.5.6
	NO_x, and CO analyzers	-	Less than or equal to 10.0% Relative Accuracy (RA) **or** Less than or equal to 8.0 ppm abs. avg. difference		
	O_2 and CO_2 gas analyzers	-	Less than or equal to 10.0% RA **or** Less than or equal to plus/minus 1.0 % O_2 (or CO_2) absolute avg. difference		
	Stack gas flow monitor	-	Less than or equal to 10.0% RA **or** Less than or equal to 0.6 m/s absolute average difference		
	Stack gas temperature	-	Less than or equal to 10.0% RA **or** Less than or equal to plus/minus 10°C absolute average difference		
	Stack gas moisture monitor	-	Less than or equal to 10.0% RA **or** Less than or equal to 1.5% H_2O absolute average difference		
Bias	SO_2, NO_x and CO analyzers	-	Less than or equal to plus/minus 5.0% of FS **or** Less than or equal to plus/minus 5 ppm abs. diff.	5.1.6	5.3.6
	O_2 and CO_2 analyzers	-	Less than or equal to plus/minus 5.0% of FS **or** Less than or equal to plus/minus 0.5% abs. diff.		
	Stack gas flow monitor	-	Less than or equal to plus/minus 5.0% of FS **or** Less than or equal to plus/minus 0.6 m/s abs. diff.		
	Stack gas temperature	-	Less than or equal to plus/minus 5.0% of FS **or** Less than or equal to plus/minus 10°C abs. diff.		
	Stack gas moisture monitor	-	Less than or equal to plus/minus 5.0% of FS **or** Less than or equal to plus/minus 1.5% abs. diff.		

Orientation sensitivity	Flow monitors sensitive to gas velocity direction	-	Less than or equal to plus/minus 4.0% of the FS value measured at 0 orientation	5.1.7	5.3.7 to 5.3.7.2

In this Table **<u>or</u>** identifies a specification that the operator can apply as alternative.

Certification of the different sub-systems of the CEMS (flow, pollutants, diluents, moisture, et cetera) may be conducted jointly or separately. For example, if certification was attempted jointly and the appropriate regulatory agency determines that all but 1 of the monitoring sub-systems passed the requirements, then only the failed sub-system test must be repeated.

The specifications are described in Section 5.1. The gases used during certification are described in Section 5.2, while the applicable test procedures are outlined in Section 5.3.

5.1 Certification performance specifications

It is recommended, but not mandatory, that after a new CEMS has been installed according to the manufacturer's written instructions, the entire CEMS should operate for a conditioning period of not less than 168 hours, prior to the operational test period (OTP), during which the emission source should operate. During the conditioning period, the entire CEMS should operate normally (that is, analyzing the pollutant and diluent gases) with the exception of periods during which calibration procedures are carried out as well as other procedures indicated in the QA plan (QAP).

5.1.1 Operational test period (OTP)

The OTP is a 168-hour cumulative time period during which most of the performance specification tests are carried out. The process unit (for example, boiler) must be operating when the measurements are made. However, for the 7-day calibration drift test the CEMS may be tested on 7 24-hour intervals on non-consecutive days. No unscheduled maintenance, repairs, or adjustments to the CEMS are allowed during the OTP. The procedures in the QAP must be followed as if the CEMS was generating emission data.

CEMS systems installed at sources that operate less than 1,500 hours annually may be exempted from the OTP and calibration drift tests.

5.1.2 Calibration drift

The calibration drift specification is applicable to each gas analyzer as stated in Table 3. That table also includes flow monitoring calibration drift specifications.

At 24-hour intervals over the 168-hour OTP, the CEMS response to the calibration gases, as indicated by the DAHS, must not deviate from the certified value of the appropriate gas by an amount exceeding:

SO_2, NO_x, and CO analyzers

Low level: less than or equal to plus/minus 2.5% of the Full Scale (FS) setting, **<u>or</u>** less than or equal to plus/minus 2.5 ppm absolute difference
High level: less than or equal to plus/minus 5.0% of the Full Scale (FS) setting, **<u>or</u>** less than or equal to plus/minus 2.5 ppm absolute difference

O_2 and CO_2 analyzers

Low and high level: less than or equal to plus/minus 0.5% O_2 (or CO_2) absolute difference

Flow monitor

Low and high level: less than or equal to 3.0% of the FS setting **<u>or</u>** 0.6 m/s absolute difference.

In this section **<u>or</u>** identifies a specification that the operator can apply as alternative to the % FS specification.

5.1.3 Stack gas flow calibration

CEMS installed after December 31, 2024, that are fitted with flow monitor, must design, and equip the monitor to allow a daily calibration test consisting of at least 2 reference values: 0 – 20% of FS or an equivalent reference value (for example, pressure pulse or an electronic signal) and 50 to 70% of FS. Flow monitor response, both before and after any adjustment, must be recorded by the DAHS. Design the monitor to allow the calibration of the entire system, from the probe tip (or transducer) to the DAHS.

Introduce the reference signal corresponding to the values specified values to the probe tip (or equivalent), or to the transducer. During the 7-day certification test period, conduct the calibration error test while the unit is operating (as close to 24-hour intervals as practicable). In the event of a unit outage, after the commencement of the test, the 7 consecutive operating days need not be 7 consecutive calendar days. Record the flow monitor responses by means of the DAHS. If the flow monitor operates within the calibration error performance specification, the flow monitor passes the calibration drift test. Do not perform any corrective maintenance, repair, or replacement upon the flow monitor during the 7-day test period, other than that required in the QAP.

Flow monitors installed on sources that operate less than 1,500 hours per year are exempted from this 7-day calibration drift test requirement.

5.1.4 System response time

CEMS using dedicated analyzers must be able to achieve 90% response in less than 200 seconds to a step change in concentration of gas at the probe. This interval includes the time required to convey the sample through the sampling line. The specification is applicable to SO_2, NO_x, CO, O_2, and CO_2 monitoring. It is acknowledged that the specification may be overly stringent for gases, such as NH_3 and HCl, which may be tested for sample integrity by other methods.

For time-shared systems, the system response time is acceptable if the average of 3 increasing and 3 decreasing values is not greater than 5 minutes, for each analyzer on each stream, for a 90% response to a step change in concentration of gas at the probe exit. Note that this includes the lag time.

System response time must be tested according to procedures in Section 5.3.4.

5.1.5 Relative accuracy (RA)

The relative accuracy for an SO_2 analyzer must not exceed 10.0% **<u>or</u>** 15.0 ppm absolute average difference with the reference method measurements.

The relative accuracy for a NO_x or CO analyzer must not exceed 10.0% **or** 8.0 ppm absolute average difference with the reference method measurements.

The relative accuracy for an O_2 or CO_2 gas analyzer must not exceed 10.0% **or** 1.0 % absolute average difference with the reference method measurements.

The relative accuracy for a stack gas flow monitor must not exceed 10.0% **or** 0.6 m/s absolute average difference with the reference method measurements.

The relative accuracy of the stack gas temperature monitor must not exceed 10.0% **or** plus/minus 10^{o}C absolute average difference with the reference method measurements.

The relative accuracy for the stack gas moisture monitor must not exceed 10% **or** plus/minus 1.5% H_2O absolute average difference with the reference method.

Relative accuracy must be tested according to procedures in Section 5.3.5. In this section **or** identifies a specification that the operator can apply as alternative to RA.

5.1.6 Bias

The bias of the SO_2, NO_x or CO gas analyzers must not exceed plus/minus 5.0% of the FS value **or** less than or equal to plus/minus 5 ppm absolute difference.

The bias of the O_2 or CO_2 gas analyzer must not exceed plus/minus 5.0% of the FS value **or** less than or equal to plus/minus 0.5% absolute difference.

The bias of the stack gas flow monitor must not exceed plus/minus 5.0% of the FS value **or** less than or equal to plus/minus 0.6 m/s absolute difference.

The bias of the stack gas temperature monitor must not exceed plus/minus 5.0% of the FS value **or** less than or equal to plus/minus 10^{o}C absolute difference.

The bias of the stack gas moisture monitor must not exceed plus/minus 5.0% of the FS value **or** less than or equal to plus/minus 1.5% absolute difference.

In this section **or** identifies a specification that the operator can apply as alternative to the %FS specification.

Bias must be tested according to the calculations in Section 5.3.6.

If a bias does not exceed plus/minus 5.0% of the FS value, and the reference method RATA average was greater than 30% of the CEMS FS, then the data that is subsequently generated must be corrected for bias. Otherwise BAF equals 1.0. In both cases, the next RATA should be performed with BAF equals 1.0.

5.2 Calibration gases

The gases used by the reference method during the relative accuracy test audit (RATA) must be U.S. Environmental Protection Agency (EPA) Protocol grade.

The gases used by the CEMS during linearity audits (CGA), and the 7-day drift for certification, as well as those for the alternate linearity audits (Section 6.3.1.6) must be EPA Protocol grade.

Gases used for daily CEMS calibration and response time tests must be certified to an accuracy of 2.0% by the manufacturer but may be used if desired.

The QAP should specify a method of cross-referencing successive gas cylinders to identify out-of-specification cylinders before the new cylinders are used to calibrate the CEMS. All the applicable Table 3 specifications must be met, otherwise the CEMS is not certified and must be fixed and retested.

5.3 Certification test procedures

The procedures used during certification testing of each installed CEM system are presented here.

5.3.1 Operational test period (OTP)

During the OTP, the process and the CEMS should ideally operate without interruption and produce a record of the emissions data using the DAHS. This record must be kept for the duration required by the appropriate regulatory authority. Sampling may be interrupted if the process shuts down, or for short intervals during the daily calibrations and specified procedures contained in the QAP.

During the OTP, no unscheduled maintenance, repairs, or adjustments to the CEMS may be carried out. Otherwise, the OTP must be restarted. Calibration adjustments may be performed at 24 plus/minus 2 hours intervals or more frequently if specified by the manufacturer and stated in the QAP. Automatic 0 and calibration adjustments made without operator intervention may be carried out at any time, but these adjustments must be documented by the DAHS.

If the test period is fragmented due to process shutdown, the times and dates of this period should be recorded, and the test continued when the source resumes operation. If the test is interrupted due to CEMS failure, the entire test period must be started after the problem has been rectified.

The performance specification tests outlined in Sections 5.3.2 to 5.3.6. must be carried out during the OTP, with the exception of the Relative Accuracy Test Audit (RATA) (Section 5.3.5) which may be conducted during the OTP or during the 168 hours period immediately following the OTP. It is recommended that the calibration drift tests be completed before attempting the relative accuracy tests, to minimize the risk associated with repeating the latter.

5.3.2 Calibration drift test protocols

The calibration drift must be determined for each pollutant and diluent gas analyzer, and stack gas flow monitor at approximately 24 plus/minus 2 hours intervals over the 168-hour test period.

On the first day of the operational test period, the low and high calibration gases are injected 3 times sequentially at the primary CEMS port, until a stable level is reached. The values are recorded by the DAHS. Then the CEMS must continue analyzing the stack gas. Twenty-four hours later, without any adjustment to the analyzers, the sequence is repeated, the values are recorded. The drift may be corrected before the start of the next 24-hour calibration drift cycle, and so on for 7 days. Calculate the drift with Equation 5.1.

$$D_c = 100 \times \frac{|A-R|}{FS}$$ **Eqn. 5.1**

Where:
D_c is the concentration calibration drift (%)
A is the avg. of the CEMS responses to the low- or high-level calibration gas (% or ppm)
R is the certified concentration of the low- or high- level test gas
FS is the full scale setting of the analyzer (% or ppm)

Perform the 7-day calibration drift of the flow monitor, introducing sequentially the 2 reference levels (for example, pressure pulse or electronic signal, Section 5.1.3) at about 24-hour intervals, while the unit is operating. At the end of each 24-hour interval the reference levels are introduced sequentially, and the stable levels are recorded in the DAHS. If process outage occurs after the commencement of the drift test, the 7-day testing may be extended to additional days. Calculate the drift with Equation 5.2.

$$D_f = 100 \times \frac{|A_f - R_f|}{FS}$$ **Eqn. 5.2**

Where:
D_f is the flow calibration drift (%)
A_f is the actual stack gas velocity as measured by the CEMS (m/s)
R_f is the reference stack gas velocity corresponding to the pressure pulse or electronic signal level (m/s)
FS is the flow analyzer full scale (m/s)

5.3.3 Linearity check test protocol

The CEMS must operate normally during this test, with all pressures, temperatures and flows at nominal values. Introduce each test gas at the primary CEMS calibration port and allow the system response to stabilize, then record the measured concentration in the DAHS. Challenge the system 3 times with low-, mid-, and high- level of each reference gas, alternating the order in which the reference gas is presented to the analyzer. Low level is 0.0 to 20.0% of FS, mid-level is 40.0 to 60.0% of FS, and high-level is 80.0 to 100.0 % of FS. Determine the linearity, at each level with Equation 5.3.

$$LE\ \% = \frac{|R - A|}{FS} \times 100$$ **Eqn. 5.3**

Where:
LE is the percent FS linearity error, based upon the reference value
R is the reference value of low-, mid- or high- level calibration gas introduced into the monitoring system
A is the average of the 3 system responses to either the low-, mid- or high-level reference gas
FS is the analyzer full scale (ppm or %)

SO_2, NO_x, and CO analyzers shall not deviate from the reference value by more than plus/minus 2.5% of FS, as calculated using Eqn. 5.3, or alternatively less than or equal to plus/minus 5 ppm absolute average difference.

CO_2 and O_2 analyzers shall not deviate from the reference value by more than plus/minus 0.5% CO_2 or O_2 absolute average difference.

5.3.4 CEMS response time test protocol

This test may be performed during OTP concurrently with the linearity check test. The test consists of measuring the time required to achieve a 90% response from a step change in the sample concentration level. Sample flow rate, pressure, and other CEMS parameters must be at the nominal values specified in the QAP. Low- and high-level calibration gas must be introduced alternately at the system calibration gas injection port while the DAHS records the analyzer output. When a steady state is reached, the input gas is switched to the second calibration gas until again a steady output is reached. The sequence must be carried out a total of 3 increasing and 3 decreasing concentration changes.

Using the output of the DAHS, calculate the average time required for the CEMS to achieve 90% response to the low- and high-level gases for both the increasing and decreasing sequence. The lag time of extractive systems (in other words, the time necessary to convey the gas sample though the sampling line) must be included in the calculation of response time.

5.3.5 Relative accuracy (RA) test protocols

This test is a comparative evaluation of CEMS performance applying an independent reference method as specified by the appropriate regulatory authority. The test is carried out on each pollutant and diluent gas analyzer as well as on the stack gas flow monitor.

The emission source must be operating at a representative load (see Glossary) or at greater than 50% maximum heat input (the latter for sources that did not operate in the previous quarter) while combusting the primary fuel normal for that unit. The CEMS must be operated in a routine manner during this test, and no adjustments, repairs, or modifications to any portion of the system may be carried out other than those actions outlined in the QAP. As the system includes the hardware and software of the DAHS, the parameters in the DAHS may not be modified during the test.

5.3.5.1 Reference method sampling point for non-stratified exhaust gases

Where it has been demonstrated, using the procedures outlined in Section 4.2.1 that the flue gases are not stratified, the RM testing may be carried out at a single test point in the flue or duct, with the gas extraction point being not closer than 7.5 cm from any wall.

When certifying in-situ path systems, the RM probe tip must be located no closer than 30 cm from the inner 50% of the measurement path. The RM probe must be positioned so that it will not interfere with the operation of the CEMS under test.

5.3.5.2 Reference method sampling point in presence of stratified flow

If the gas flow has been found to be stratified using the procedures outlined in Section 4.2.1 or if the stratification test has not been performed, the RM sample must be collected at several points in the gas flow.

A “measurement line” that passes through the centroids of the flue or duct must be established. This line should be located within 30 cm of the CEMS sampling cross-section. Three sampling points must be located at 16.7, 50.0, and 83.3% along the length of the “measurement line”. Other sampling points may be selected if it can be demonstrated that they will provide a representative sample of the exhaust gas flow over the test period.

5.3.5.3 Test methods

Either the reference methods listed in the Glossary or those specified by the appropriate regulatory authority may be used as reference methods. Manual grab sampling reference methods are not acceptable for CEMS certification.

5.3.5.4 Sampling strategy

Nine comparisons of the RM and the CEMS results must be conducted to evaluate the performance of the CEMS being tested. Within each run, the reference method sampling rate must be carried out at a fixed sampling rate; that is, the sampling rate must not be adjusted over the duration of the run, except to maintain the flow at the initial rate. Sampling must be carried out for 30 minutes during each test, at the single point for non-stratified flow, or divided equally over the 3 sampling points for stratified flow testing.

Preliminary testing may be performed before the date set for Certification or RATA. Their results shall not be considered part of the Certification or RATA sets.

The operator may choose to carry out up to 12 sets of comparisons. Should this option be exercised, the results of a maximum of 3 tests may be rejected from the test data if an appropriate statistical test (for example, Grubbs test, see Appendix C.5) applied to the data demonstrates that these results are outliers. A minimum of 9 RM tests must be available after statistical rejection of data. All data must be reported, including the outliers, along with all calculations.

All diluent gas, moisture, and stack gas flow measurements (if applicable) must be conducted simultaneously with the RM pollutant concentration measurements.

5.3.5.5 Correlating reference method and CEMS measurements

To correlate the data from the CEMS and RM tests, it is imperative that the beginning and end of each test period be clearly marked on the DAHS and that the time be synchronized with the RM crew test time. After each test is completed, compare the CEMS results with the data derived from the RM results over the exact time period that the test was performed.

The CEMS results and the RM results must be correlated on the same basis. Thus, corrections may need to be applied for moisture, temperature, pressure, etc. The auxiliary RM measurements (such as stack gas moisture or barometric pressure) are used to make any adjustments to the RM results, whereas the auxiliary measurements of the CEMS are used to make any adjustments to the CEMS results.

5.3.5.6 Calculations

The relative accuracy of the CEMS must be calculated using the Equation 5.4. for SO_2, NO_x, CO, O_2, CO_2, temperature, and moisture (if applicable).

(i) Calculation of relative accuracy

The relative accuracy is calculated using Equation 5.4.

$$\mathrm{RA} = \left[\frac{|\mathrm{d}|+|\mathrm{cc}|}{\mathrm{RM}}\right] \times 100 \qquad \textbf{Eqn. 5.4}$$

where:
RA is the percent relative accuracy
d is the mean difference between the CEM system and RM results
cc is the confidence coefficient
RM is the average of the reference method results

(ii) Calculation of differences

The absolute value of the difference between the CEM system and RM results is calculated using Equation 5.5.

$$|d| = \left|\frac{1}{n}\sum_{i=1}^{n} d_i\right|$$ **Eqn. 5.5**

where:
d_i is the difference between an RM value and a corresponding CEM system value ($d_i = CEM_i - RM_i$) for the i^{th} test run
n is the number of data pairs
Note: The numeric signs for each data pair must be retained. The absolute value of the sum of differences is used, not the sum of absolute values of the differences.

(iii) Calculation of confidence coefficient and standard deviation

The values of the confidence coefficient and standard deviation are determined from Equations 5.6 and 5.7, respectively.

$$|cc| = \frac{t_{0.025} \times stdev}{\sqrt{n}}$$ **Eqn. 5.6**

where:
cc is the confidence coefficient
$t_{0.025}$ is the t value from Table 4 for a 1-tailed t-test corresponding to the probability that a measured value will be biased low at a 95% level of confidence
stdev is the sample standard deviation of the differences of the data pairs from the relative accuracy test, calculated using Equation 5.7
n is the number of data pairs

$$stdev = \sqrt{\frac{\sum_{i=1}^{n}(d_i)^2 - \frac{1}{n}\left[\sum_{i=1}^{n}(d_i)\right]^2}{n-1}}$$ **Eqn. 5.7**

where parameters are defined as above.

Table 4: t values

n-1	5	6	7	8	9	10	11	12	13	14
$t_{0.025}$	2.571	2.447	2.365	2.306	2.262	2.228	2.201	2.179	2.160	2.145

Note: These are t values for 1-tailed t-test at a 95% confidence level.

(iv) Calculation of reference flow-to-load ratios

If the CEMS includes a stack gas flow monitor, the flow-to-load (load being either gross power or steam flow) during RATA may be used as future reference for quarterly checks of stack gas flow data, carried out from a set of hours in which the unit operated at loads plus/minus 10% of the RATA.

If the combustion unit produces exclusively electric power or steam, the reference flow-to-load ratio can be calculated from RATA data by the Equation 5.8.

$$R_{ref} = \frac{Q_{ref}}{L_{ref}}$$ **Eqn. 5.8**

where:
R_{ref} is the reference flow-to-load ratio during RATA, in (WSm^3/h)/MW or (WSm^3/h)/(tonne of steam/h)

Q_{ref} is the average stack gas flow measured during the most recent flow RATA, WSm^3/h
L_{ref} is the average gross electric output or steam output during the most recent flow RATA runs, in MW or (tonne of steam/h)

To perform the quarterly flow-to-load CEMS flow check, the DAHS must be able to record the hourly stack gas flow and the outputs of electric power or steam, as explained in section 6.3.3.

5.3.6 Bias test calculations

A bias or systematic error is considered to be present if the absolute average difference between the CEMS and RM results (Eqn. 5.5) exceeds the absolute value of the confidence coefficient (Eqn. 5.6).

$$\mathrm{Bias} = |\mathrm{d}| - |\mathrm{cc}|$$ **Eqn. 5.9**

The bias is acceptable if (|d|- |cc|) is less than or equal to 5.0% FS **Eqn. 5.10**

Alternatively, bias is also acceptable if the absolute difference is less than 5 ppm for SO_2, NO_x and CO measurements; or less than 0.5% O_2 or CO_2 for O_2 or CO_2 analyzers; or less than 0.6 m/s for stack gas flow; or less than 10ºC for stack gas temperature; or less than 1.5% H_2O for stack gas moisture.

If the bias is acceptable and the average RM is less than 30% of the FS, then subsequent CEMS measurements should be corrected by a bias adjustment factor (BAF) using equations 5.11 and 5.12. The use of a BAF in any measurement must be stated in the QAP and the quarterly reports. The next RATA should be done with BAF equals 1.0.

$$\mathrm{CEMS_{adjusted}} = \mathrm{CEMS_{monitor}} \times \mathrm{BAF}$$ **Eqn. 5.11**

where:
$\mathrm{CEM_{adjusted}}$ is the data adjusted for bias
$\mathrm{CEM_{monitor}}$ is the data provided by the monitor
BAF is the bias adjustment factor, defined by Equation 5.12

$$\mathrm{BAF} = \frac{\mathrm{RM}}{\mathrm{CEM_{RATA\ avg}}}$$ **Eqn. 5.12**

where:
BAF is the bias adjustment factor
$\mathrm{CEM_{RATA\ avg}}$ is the average CEM results during RATA
RM is the average of the reference method results

5.3.7 Orientation sensitivity test protocols

This test is intended as a check for flow monitors that are sensitive to the orientation of the sensor in the gas flow, such as differential pressure flow sensors. This only applies to stack gas velocity monitors such as pitot tubes and other based on Bernoulli principle.

5.3.7.1 Test procedures

During a period of steady normal flow condition, the sensor in the gas flow must be rotated a total of 10 degrees on each side of the 0-degree position (directly into the gas flow with no cyclonic flow patterns) in increments of plus 5 or minus 5 degrees, noting the response of the sensor at each angle relative to the 0-degree position. If such a rotation does not alter the 0-degree measurement by more than plus/minus 4.0% then the sensor has passed the orientation sensitivity test.

5.4 Recertification and diagnostic testing

Permanent replacement, modification, or changes to a CEMS that may affect its ability to accurately measure emissions, require system recertification. Examples of these situations include: the permanent replacement of an analyzer or the entire CEMS or the change the location or orientation of a sampling probe.

Temporary (less than 360 hours) replacement of an analyzer with a similar analyzer, for example, requires less than a complete recertification of the CEMS. It may be limited to diagnostic tests such linearity audit (CGA) of the replacement analyzer.

Section 6.0 Quality assurance and quality control

The operator must develop a written Quality Assurance Plan (QAP) for each installed CEMS. A quality assurance plan is a management program to ensure that the necessary day-to-day quality control activities are adequately performed. The QAP becomes a reference to ensure that the environmental monitoring and reporting procedures are verified and documented, so that uncertainties in the reported data can be controlled and quantified.

6.1 Quality assurance/quality control manual

The written manual of the QAP Plan must describe the complete program of activities to be implemented to ensure that the data generated by the CEMS will be complete, accurate, and precise. As a minimum, the manual must include the QA/QC procedures specified in this report. The recommended Table of Contents of the QAP manual is shown in Table 5.

6.1.1 Quality assurance (QA) activities

This section of the manual should describe how the QA program is managed, provide personnel pertinent qualifications, and describe the QA reporting subsystem. It must describe the CEMS, how it operates, and the procedures for calibration and inspection. It must also include preventative maintenance and performance evaluation procedures.

6.1.2 Quality control (QC) activities

This section should provide detailed descriptions of the step-by-step procedures required to operate and evaluate the CEMS, including details about daily, quarterly, semi-annual, and annual performance evaluations. Procedures for these activities are provided in Sections 6.2 to 6.5. A summary of acceptable results is outlined in Sections 6.2 and 6.3.

Table 5: Table of Contents of the QAP manual

Subsection	Contents
Quality assurance policies and system descriptions	
1 Quality Assurance Goals and Objectives	Specific system goals relating to precision, accuracy, and completeness. Emission standards and emission reporting requirements.
2 CEM System Description and Design Considerations	Detailed system description, including principles of operation, sample location layout, flow and temperature measurement, sample conditioning system, analyzer layout, CEM shelter, and data handling system. Design considerations and engineering evaluation of CEMS options, including sample location, extractive vs. in situ, flow monitoring, and supplier. Includes a detailed list of CEMS component serial and model numbers.
3 Exceptions/Clarifications/ Alternative Methods	Any exceptions/clarifications or alternative methods relating to this document or reference test methods.
4 Organization and Responsibilities	Description of the organization of personnel involved with the CEMS and its quality system. Defines the roles and responsibilities of the personnel involved as related to CEMS operation and maintenance, control of documents/records, and control of data.
5 Calibration and Quality Control Checks	Description of the calibrations and QC checks that are performed on a routine basis, generally daily, to determine whether the system is functioning properly. Includes daily 0 and calibration checks and visual checks of system operating indicators, such as vacuum and pressure gauges, rotameters, analyzer displays, LEDs, and so on.

Subsection	Contents
6 Data Acquisition and Analysis	Description of the data acquisition system and analysis program. Includes references to data completeness, validation, reporting, storage, and revision management. Includes roles and responsibilities of the personnel involved in the data handling.
7 Preventative Maintenance Policy	Description of the CEMS preventative maintenance program, including how preventative maintenance scheduling is determined and maintained along with roles and responsibilities of the personnel involved.
8 Corrective Action Program	Description of the policies for correcting any CEMS system non-conformance. Parameters such as CEMS downtime/reliability should be addressed. Roles and responsibilities of the personnel involved in the corrective action program.
9 Performance Evaluations/Audits	Description of the policies and specifications for performance evaluations/audits (in other words, stack quarterly audits and RATAs). Describe the action necessary to ensure that the appropriate evaluations are carried out on the appropriate schedule.
10 Document Control System	Description of the policies and systems used to control all the documents that form part of the CEM system's quality system. Lists how and where the related documents are located, how they are reviewed and revised, and how they are approved for use by authorized personnel prior to issue.
11 Reports and Records	Description of all reports and records collected including method of collection, person responsible, data storage location, data security, data distribution, and length of data storage.
12 Modifications and Upgrades	Description of the policies regarding modifications and upgrades to the CEMS.
13 Training and Qualification Policy	Training and qualification policy for CEMS maintainers, CEMS coordinators, computer and programming technicians, data validators, quarterly audit, and RATA testers. Includes educational and experience requirements, on-the-job training, job shadowing, and classroom training requirements.
14 References	References for QA/QC plan.
Quality control (standard operating) procedures	
1 Startup and Operation	Lists in detail complete, step-by-step procedures for the start-up and operation of the CEMS.
2 Daily CEM System Operation and Inspection	Detailed description of daily routine operation and inspection of the CEMS. Includes descriptions of equipment and data validation procedures and examples of daily equipment checks and/or logbook entries.
3 Daily and Manual Calibration Procedures	Lists in detail complete, step-by-step procedures for daily and manual calibrations. References to specific OEM documentation/manuals are acceptable. Includes schedule for manual (mid-point) calibration, if done.
4 Gas Bottle Check Procedures	Description of procedure to cross-reference cylinder gases. Gases can be cross-referenced to previous gas bottles and quarterly bottles. Specifications for rejection of gas bottle to be stated.
5 Preventative Maintenance Procedures	Detailed description of the CEMS preventative maintenance procedures along with the preventative maintenance schedule.
6 Spare Parts List and Inventory Procedures	Detailed descriptions of the spare parts inventory available for the CEMS, along with a description of the procedures for obtaining spare parts from inventory and ensuring that the spare parts inventory is maintained.
7 Corrective Maintenance Procedures	Detailed descriptions of the non-routine maintenance that is performed when the system or part of the system fails. References to specific OEM documentation/manuals are acceptable.
8 Data Backfilling Procedures	Procedures for data backfilling when a CEMS is not available. Data backfilling algorithms to be based on process variables.
9 Data Backup Procedures	Procedures for regular backup of data in hard or soft copy.
10 Data Quality Assessment Procedures	Procedures to identify suspected data. Includes automatic flagging of a) out-of-range concentrations and flows, b) abnormal system calibration response times, c) abnormal flow-to-input or flow-to-output levels, and d) abnormal concentrations during periods when the combustion unit burned no fuel.
11 CEM System Security	Includes security actions for CEMS equipment software and data.
12 Data Approval and Reporting Procedures	Procedure for approval and reporting of CEMS data. Includes any systems for review, modifications, approval, summary, and release of data.

Subsection	Contents
13 Quarterly Audit Procedures	Detailed procedures on conducting quarterly audit procedures. Includes roles and responsibilities, gas bottle requirements, scheduling, and test methods.
14 Semi-annual Relative Accuracy Test Audit Procedures	Detailed pretest sampling plan for executing RATAs. Pretest plan to include organization plan, sampling points, scheduling, test methods, calibration requirements, reporting schedule, reporting format, and site safety plan.
15 Bias Procedures	Describes process of assessing and correcting for bias. Includes roles and responsibilities for assessing and approving bias factors.
16 Annual System Audit Procedures	Describes procedure for annual system audit. Includes selection of auditor, scheduling, audit plan, and reporting.
17 Managing Change	Procedure for managing change when upgrades are required due to failure of equipment, changes in regulation, changes in system management. Includes approval process for accepting changes with roles and responsibilities. Addresses replacement of CEMS.

6.2 Daily performance evaluations

This section presents the specifications and the test procedures for 24-hour calibration drifts for gas analyzers and flow meters.

6.2.1 Calibration drift

Calibration of the CEMS is an important aspect of the QA/QC program. Table 6 summarizes the specifications for the 24-hr calibration drift of analyzers and flow monitors able to carry out these daily evaluations.

6.2.1.1 Frequency

The calibration drift of each gas analyzer and flow monitor must be determined daily. It is a good practice to check the drift of each analyzer even during a few days in which the combustion unit is down, but the operator may skip the daily calibration during extended periods in which the combustion unit does not burn fuel. However, the CEMS should be successfully calibrated immediately prior to process restart, to avoid using the backfilling option (Section 3.4.1).

If an on-line calibration check has been passed, and the source is off-line 24 hours later, then this second calibration check may be passed off-line, not later than 26 hours after the previous on-line calibration. The data bracketed between these 2 successful calibrations shall be considered valid.

6.2.1.2 Test gases

EPA Protocol gases or gases certified to an accuracy of 2.0% may be used for the daily calibration of gas analyzers.

6.2.1.3 Calibration gas injection port

The location of the applicable calibration gas injection port for each type of CEMS can be found in Table 2. Care must be taken to ensure that the calibration checks are carried out at the same CEMS operating conditions that are used during monitoring (for example, pressure, flow, temperature, et cetera). For in-situ type analyzers installed before December 31, 2024, that do not have the capability of accepting a flowing reference gas, daily calibration checks may continue to be performed with manufacturer supplied sealed cells containing a known concentration of reference gas.

6.2.1.4 Test procedures

Low and high reference levels must be used. For gas analyzers: low level is 0.0% to 20.0% FS, and high level is 80.0% to 100.0% FS. For stack gas flow monitors that have the capability to carry out daily checks (for example, pressure pulse or electronic signal) low level is 0.0% to 20.0% FS, and high level is 50.0% to 70.0% FS. Before any adjustment the low and high levels must be read and recorded by the DAHS. If a dual range instrument is used, then the drift of both ranges must be checked daily.

Enough time must be allowed to ensure that the gas analyzer or flow monitor attains a steady output, as indicated by the DAHS.

6.2.1.5 Adjustment of analyzers/monitors

A gas analyzer, or flow monitor, should be adjusted whenever the daily low- or high- level calibration drift approaches the following levels:

SO_2, NO_x, and CO analyzers
    Low-level: 2.5% of FS setting **or** 2.5 ppm absolute difference
    High-level: 5.0% of FS setting **or** 2.5 ppm absolute difference
O_2 and CO_2 analyzer
    Low- or high-level: 0.5% O_2 (or CO_2)
Flow monitor
    Low- or high-level: 3.0% of the FS setting or 0.6 m/s absolute difference

In this section, **or** identifies a specification that the operator can apply as % FS alternative.

A DAHS shall keep a record of the extent of each low- or high-level adjustment carried out. The data collected in the previous 24 hours is considered valid unless the drift reached twice the Section 6.2.1.5 specifications.

6.2.1.6 Out-of-control period

An out-of-control period occurs when either the low- or high-level calibration drift of a gas analyzer or flow monitor exceeds twice the Section 6.2.1.5 specification. This out-of-control period begins with the minute of the calibration drift check and ends with the minute after corrective action has been taken and the system has demonstrated that is operating satisfactorily. When a gas analyzer or flow monitor is out-of-control, the data generated by the specific component are considered missing and do not qualify for meeting the requirement for system availability. Missing data must be backfilled using the criteria provided in Section 3.4.1.

6.2.1.7 Tabulation of data

All calibration drift data should be recorded and tabulated by hour, day and month, with the magnitude of the drifts in ppm for pollutant analyzers, percent for diluent gas analyzers and flow-related level for flow monitors.

6.2.1.8 Quantification of drifts

If the DAHS or CEMS automatically compensates data for drifts, the system must be able to store unadjusted concentrations of the calibration gases, unadjusted flow levels and the magnitude of all adjustments.

6.3 Quarterly performance evaluations

During each quarter, a cylinder gas audit (CGA) must be performed, unless it is a quarter in which RATA is carried out. Special provisions apply to in-situ type analyzers installed before December 31, 2024, that do not have the capability of accepting a flowing calibration gas. The following summarizes the requirements for these tests, all of which must appear in the QAP.

6.3.1 Cylinder gas audit (CGA)

This audit investigates the linearity error of the analyzers and ranges used during the previous quarter. The 3-level cylinder gas tests must be performed no closer than 30 days for 2 adjacent quarters. Units operating less than 1,500 hours per year, should perform this test annually.

6.3.1.1 Test gases

Protocol gases at low (0 to 20% FS), mid (40 to 60% FS), and high (80 to 100% FS) levels for each pollutant and diluent gas analyzer must be used.

6.3.1.2 Calibration gas injection port

The CGA test gases must be introduced at the CEMS system calibration gas port specified in Table 2.

6.3.1.3 Test procedures

The CEMS must be operating normally during the test with all pressures, temperatures, and sample flows at nominal values. Each test gas must be introduced, and the system response allowed to stabilize. Then the concentration of the pollutant or diluent gas is indicated and recorded by the DAHS. The average response of the system to the 3 challenges of each gas for each pollutant or diluent gas analyzer levels must be calculated.

6.3.1.4 Calculations

The average linearity response each of the low-, mid- and high-level test gases should be calculated, for each analyzer, using Equation 6.1.

$$\text{Linearity (\%)} = \frac{(\text{R}-\text{A})}{\text{FS}} \times 100$$ **Eqn. 6.1**

where:

R is the certified concentration of the reference gas (% or ppm)

A is the average of the 3 system responses to either the low-, mid-, or high-level reference gas (% or ppm)

FS is the designated full-scale value of the analyzer (% or ppm)

6.3.1.5 Acceptance criteria

SO_2, NO_x, and CO analyzers shall not deviate from the reference value by more than 2.5% of FS (as calculated using Eqn. 6.1), or by the alternate absolute difference criterion of Table 3.

CO_2 and O_2 analyzers shall not deviate from the reference value by more than plus/minus 0.5% CO_2 or O_2.

An out-of-control period occurs when the cylinder gas audit exceeds the specification as presented in this section.

6.3.1.6 Alternate quarterly analyzer audit

Where the type of CEMS does not allow a flowing reference gas (in other words, certain type of in-situ analyzers installed before December 31, 2024), an independent check on the CEMS performance must be carried out every quarter, unless it is a quarter in which RATA is scheduled to be carried out. To that effect, the response for each gas being monitored is compared with the measurements of an extractive portable analyzer that meets the corresponding (for example, NO_x, O_2, et cetera) reference method specifications. The results from the portable analyzer must be correlated to the CEMS measurements on the same basis (moisture, pressure, et cetera). The combustion source should operate at a representative level. The portable analyzer must be calibrated with low- and high-level Protocol gas suited to the full scale of the stationary CEMS, and then extract a continuous stack gas sample from a point within 0.3 m from the stationary CEMS sensing path. After a stabilization period, the readings are logged every minute for 21 minutes concurrently with the DAHS readings of the stationary CEMS. The stack gas extraction and logging are repeated for the next sampling period of the same duration, and so on for a minimum of 6 test periods of 21 minutes each. The calibration of the portable analyzer may be checked, and if necessary adjusted, in between these 21-minute test periods. The relative accuracy of the concurrent CEMS measurements is calculated using Equations 5.4 to 5.7 (Section 5.3.5.6)

For this alternative test the acceptable relative accuracy for SO_2, NO_x, and CO analyzers must not exceed 15.0% RA **or** 15.0 ppm absolute average difference. The corresponding RA level for O_2 and CO_2 analyzers must not exceed 15.0% RA **or** 1.0% O_2 (or CO_2) absolute average difference. In this section **or** identifies a specification that the operator can apply as alternative to RA. An out-of-control condition occurs when this Alternate Quarter Analyzer Audit exceeds the specifications.

6.3.1.7 Out-of-control period

This period begins with the minute after the completion of the test that determined the out-of-control condition and ends with the minute after correction action has been taken and the system has demonstrated that it is operating satisfactorily. When an analyzer or system is out of control, the data generated by the specific analyzer or system are considered missing and do not qualify for meeting the system availability requirements. Missing data must be backfilled using the criteria described in Section 3.4.1.

6.3.2 Stack gas flow check

The accuracy of the stack gas flow monitor must be audited quarterly, by either reference methods (RM) or b) the flow-to-load procedure described in Section 6.3.3.

The RM audit comprises 3 consecutive RM runs (each for a minimum of 30 minutes), to determine stack gas molecular weight (CO_2 and O_2), temperature, velocity, and moisture. The average RM results and concurrent CEMS flow results are then compared at standard conditions.

E_f, the average of the absolute difference between the RM and the corresponding CEMS flow results is calculated as follows:

$$E_f = \frac{1}{3 \times FS} \sum_{i=1}^{3} |d_i| \qquad \textbf{Eqn. 6.2}$$

Where:
d_i is the difference between an RM value and the corresponding CEMS value for the i^{th} test run (m/s)
FS is the CEMS flow monitor full scale (m/s)

Acceptable results are as follows: E_f less than or equal to 10% of FS, or average absolute difference less than or equal to 1.2 m/s.

6.3.3. Analysis of flow-to-load data

If the emission source generates exclusively electricity or steam and the quarter includes a minimum of 168 hours of valid CEMS data of load levels within plus/minus 10% of the average load of the last RATA, then the average flow-to-load ratio may be calculated using Equation 6.3.

$$R_h = \frac{Q_h}{L_h} \qquad \textbf{Eqn. 6.3}$$

where:
R_h is the quarterly average flow-to-load ratio from the hours in which the unit load was within plus/minus 10% of the average load of the last RATA, in (WSm^3/h)/MW or (WSm^3/h)/(tonne of steam/h)
Q_h is the average stack gas flow from the quarterly hours in which the unit load was within plus/minus 10% of the average RATA load, WSm^3/h
L_h is the average unit load from the quarterly hours in which the unit load was within plus/minus 10% of the average RATA load, in MW or (tonne of steam/h)

Periods of diverse fuel blends, output ramping, scrubber bypass, or other non-representative hourly data must be excluded from the calculation of average R_h. In electric generating units (EGU) that operate less than 1,500 hours per year, the potential data base may encompass the preceding 12 months of unit operation.

E_Δ, the relative absolute difference between R_h and R_{ref} (the latter based on the last RATA and calculated with Equation 5.8), is calculated using Equation 6.4.

$$E_\Delta = \frac{|R_h - R_{ref}|}{R_{ref}} \times 100 \qquad \textbf{Eqn. 6.4}$$

where:
E_Δ is the relative absolute difference between the average flow-to-load ratio and the reference flow-to-load ratio, %
R_h is the average flow-to-load ratio, as calculated by Eqn. 6.2
R_{ref} is the flow-to-load reference ratio from last RATA, as calculated by Eqn. 5.8

Acceptable flow-to-output results are as follows:

$\mathrm{E}_{\mathrm{MW\ or\ } \Delta_\mathrm{q}}$ less than or equal to 10% for output levels greater than or equal to 60 MW electric output or 274 (tonne of steam/h)

$\mathrm{E}_{\mathrm{MW\ or\ } \Delta_\mathrm{q}}$ less than or equal to 15%, for output levels less than 60 MW electric output or 274 (tonne of steam/h)

The key parameters of the daily and quarterly performance evaluations are summarized in Table 6.

Table 6: Daily and quarterly performance evaluations summary

Parameter	Component	Levels	Specification	References	
				Specification	Test procedure
Daily Performance Evaluations				6.2.1	6.2.1.1 to 6.2.1.8
24-hr calibration drift	SO_2, NO_x and CO analyzers	Low Level (0 to 20% FS)	Less than or equal to plus/minus 2.5% of FS difference* **<u>or</u>** Less than or equal to plus/minus 2.5 ppm absolute difference*		
		High Level (80 to 100% FS)	Less than or equal to plus/minus 5.0% of FS difference* **<u>or</u>** Less than or equal to plus/minus 2.5 ppm absolute difference*		
	O_2 and CO_2 analyzers	Low Level (0 to 20% FS) High Level (80 to 100% FS)	All levels less than or equal to plus/minus 0.5% O_2 or CO_2 absolute difference*		
	Stack gas flow monitor	Low Level (0 to 20% FS) High Level (50 to 70% FS)	All levels less than or equal to plus/minus 3.0% of FS difference* **<u>or</u>** 0.6 m/s absolute difference. *		
Quarterly Performance Evaluations					
Analyzers linearity audits (CGA)	SO_2, NO_x, and CO analyzers	(0 to 20% FS), (40 to 60% FS) (80 to 100% FS)	All levels, less than or equal to plus/minus 2.5% of FS avg. diff. **<u>or</u>** Less than or equal to plus/minus 5 ppm abs. avg. difference	6.3.1.5	6.3.1.1 to 6.3.1.4
	O_2 and CO_2 gas analyzers	(0 to 20% FS), (40 to 60% FS) (80 to 100% FS)	All levels, absolute average difference less than or equal to plus/minus 0.5% O_2 or CO_2		
Alternate "CGA" audit**	SO_2, NO_x and CO analyzers	Greater than or equal to 6 concurrent RM runs	RA less than or equal to 15% **<u>or</u>** less than or equal to 15 ppm absolute average difference	6.3.1.6	6.3.1.6
	O_2 and CO_2 analyzers	Greater than or equal to 6 concurrent RM runs	RA less than or equal to 15% **<u>or</u>** less than or equal to 1.0% absolute average difference		
Stack gas flow check alternatives	Flow RM test	Greater than or equal to 3 RM test runs, each of greater than or equal to 30 minutes duration	Difference between concurrent CEMS and RM averages must be less than or equal to plus/minus 10% FS **<u>or</u>** less than or equal to plus/minus 1.2 m/s	6.3.2	6.3.2
	Flow-to-load analysis	electric output greater than or equal to 60 MJ/s or heat output greater than or equal to 171 MJ/s	Less than or equal to plus/minus 10% absolute relative difference in flow-to-load ratios	6.3.2	6.3.3

		electric output less than 60 MJ/s or heat output less than 171 MJ/s	Less than or equal to plus/minus 15% absolute relative difference in flow-to-load ratios		

*Out-of-control condition: greater than 2 times above the specification

** For analyzers installed before 2024 that cannot be calibrated with flowing reference gas

In this Table **or** identifies a specification that the operator can apply as alternative specification.

6.3.4 F-factor systems test

F-factor CEMS uses fuel flowmeters to determine the heat input (GJ/h) to the combustion unit and stack gas analyzers to measure the levels of gaseous pollutants (SO_2, NO_x, CO, in ppm) and diluents (O_2, CO_2, in %). Then, they apply combustion F-factors (Sm^3/GJ) to calculate emission rates (kg/h). (Appendix B, B.2 Energy input method – metering of fuel flows). Their stack gas analyzers must perform the daily and quarterly performance evaluations of Table 6, except those for stack gas flow monitors, and meet the corresponding Table 6 specifications. The cylinder gas audit (CGA) is waived in quarters wherein Relative Accuracy (RA) is tested.

The heat input monitoring may be voluntarily assessed by a heat-to-load analysis similar to that described in section 6.3.3 for flow-to-load analysis. However, this paper exercise provides a general indication of accuracy (from plus/minus 10 to plus/minus 15% difference with the ratio calculated for the RATA conditions depending on the rate of heat output) and would not determine out-of-control condition.

In F-factor CEMS, the heat input to the combustion unit must be continuously monitored and the data reduced to hourly averages. A certified fuel flowmeter or a commercial billing meter may be used.

The flowmeters certification and re-calibration frequency should follow the most recent version of the applicable consensus standards (ASME, API, AGA, ISO, cited in 40 CFR 75 Appendix D, Sections 2.3.5. and 2.3.6). The QAP Manual must identify the flowmeter type; the calibration standard; and the date of each re-calibration. Additional periodic determination of fuel gross calorific value (GCV) may be necessary to demonstrate that the hourly heat input to the CEMS is accurate within plus/minus 2.0% FS. Fuel FS value is that corresponding to the maximum heat input to the generating unit.

Commercial billing metering is subject to the following conditions:

a) A gas or oil flowmeter used for commercial billing is satisfactory to provide hourly heat output to the CEMS, if less than 5.0% of the metered flow is diverted for uses other than the combustion unit.
b) Additional periodic determination of fuel gross calorific value (GCV) may be necessary to demonstrate that the hourly heat input to the CEMS is accurate within plus/minus 2.0% FS.

The audit procedures of the heat input component of the CEMS must be described in the QAP Manual and carried out at the recommended frequency.

The semi-annual or annual RATAs are passed if: a) the fuel flowmeter meets the flowmeter prescriptions of the QAP Manual, and b) the stack gas analyzers meet the Relative Accuracy (RA) or alternative limits of Tables 6 or 7. Otherwise, the CEMS will be in out-of-control condition. Section 6.4.2 Exemptions from Semi-annual Evaluations are applicable to F-factor CEMS.

6.4 Semi-annual performance evaluations

Two test procedures are involved in the semi-annual performance evaluation: a relative accuracy test and a bias test. These are carried out for each pollutant and diluent gas measured, as well as for stack gas flow and stack gas moisture (if applicable). Table 7 presents a summary of these evaluations.

6.4.1 Relative accuracy and bias tests

This section presents the procedures for carrying out the relative accuracy and bias tests, the acceptance criteria, and the frequency of evaluation.

6.4.1.1 Frequency and timing of evaluations

A relative accuracy (RATA) and Bias performance evaluation should be carried out every 2 quarters, no less than 4 months apart. Cylinder gas audits (CGA) must be carried out on the quarters without RATA evaluations.

6.4.1.2 Test procedures

RATA and Bias must be tested according to procedures and calculations in Sections 5.3.5 and 5.3.6. Only 1 load level, that the emission source is running at the time, needs to be tested.

6.4.1.3 Acceptance criteria

The performance specifications of Section 5.1.5 and 5.1.6 must be met, providing that the CEMS includes the monitored parameter. The bias test and specifications of Section 5.3.6 should be followed.

6.4.1.4 Out-of-control period

An out-of-control period occurs when the relative accuracy or bias tests exceed the specifications cited in Section 6.4.1.4. This period begins with the minute after the completion of the test and ends with the minute after corrective action has demonstrated that it is operating satisfactorily. When an analyzer, monitor, or system is out of control, the data generated by the specific analyzer, monitor or system are considered missing and do not qualify for meeting the requirements for system viability. Missing data must be backfilled using the criteria provided in Section 3.4.1.

6.4.2 Exemptions from semi-annual evaluations

The semi-annual tests may be waived and conducted annually if all the following conditions have been met, providing that the CEMS includes the monitored parameter:

- The system availability is greater than 90% annually.
- The CGA tests are conducted with flowing test gases.
- The previous **2** RATA evaluations were passed on the first attempt (by less than or equal to 10% RA or by the alternative specification)
- Sources that operate less than 1,500 hours per year are waived from semi-annual evaluations. In these sources RATA must be performed every 2 years.

6.5 Annual performance evaluations

Each CEMS system and the QA/QC procedures must be evaluated annually by an independent inspector.

6.5.1 Availability

The CEMS availability for each pollutant analyzer; diluent gas analyzer; flow and temperature monitor, is calculated using Equation 3.1 of Section 3.4. For units that operate more than 1,500 hours per year must be at least 90% annually. CEMS availability for units that operate less than 1,500 hours per year should be at least 80% annually.

6.5.2 Independent inspection

The CEMS and the QA/QC program must be evaluated by an independent inspector every 12 plus/minus 1 months. The inspector must review the QAP, the CEMS operation and other associated records to determine if the QAP is being followed. The inspector must note any changes in the system or the procedures since the previous inspection and produce a concise report about the following:

- Site and source identification
- Independent reviewer identification
- Brief description of the emission source and CEMS, including the Full Scale (FS) setting of analyzers and monitors (description may be omitted in subsequent annual reports, unless there were significant changes)

Existence of a written QAP in accordance with PG/7 Table 5

Data Summary

- Time period assessed
- Total period hours of source operation
- Total period hours of quality assured CEMS data concurrent with source operation
- Total period out-of-control hours for each analyzer or monitor
- Total backfilled hours for each analyzer or monitor
- Results of quarterly performance tests (CGAs, flow audit, if applicable)
- Results of semi-annual or annual evaluations (RATAs)

Narrative

Discussion of non-compliance issues, corrective actions to out-of-control occurrences and recommendations to improve CEMS performance.

6.6 Criteria for acceptable quality assurance/quality control procedures

Repeated out-of-control periods during quarterly or semi-annual evaluations indicate that the QA/QC procedures are inadequate or that the CEMS is incapable of generating acceptable data. Repeated out-of-control situations from the same or different causes should be investigated, and corrective action must be taken. Should the out-of- control periods continue to occur after these actions are completed, it may be necessary to replace the monitoring system.

6.7 Quality assurance reporting requirements

Within 30 days of the end of each quarter, the CEMS operator must prepare a concise report of the results of performance evaluations carried out within the quarter. The daily calibration drift data should be summarized for each analyzer in the CEMS using a control chart format. For sources operating more than 1,500 hours annually, the quarterly 3-level cylinder gas tests and flow test results must be reported, as well as the results of any relative accuracy and bias test conducted during the quarter.

As a minimum, the report must contain the following information:

- Source/CEMS system owner and address;
- Identification (manufacturer, model, serial number and full scale) and location of the CEMS analyzers
- Control charts of daily drift for each analyzer;
- RATA (if applicable) and quarterly 3-level cylinder gas test results;
- System evaluation findings, observations, and recommendations; and
- Summary of all corrective action taken if the CEMS (or analyzers) were found to be out of control.

For every fourth quarter, the report must also include annual availability.

A summary of the key specifications of the semi-annual or annual performance evaluations is presented in Table 7.

Table 7: Semi-annual or annual performance evaluations summary

Parameter	Component	Level	Specification	References	
				Specification	Test procedure
Relative Accuracy Test Audit (RATA)	SO_2 analyzers	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 15 ppm absolute average difference	5.1.5	5.3.1 to 5.3.5.6
	NO_x, and CO analyzers	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 8 ppm absolute average difference		
	O_2 and CO_2 analyzers	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 1.0% O_2 (or CO_2) absolute average difference		
	Stack gas flow monitor	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 0.6 m/s absolute average difference		
	Stack gas temperature	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 10°C absolute average difference		
	Stack gas moisture monitor	Representative load level	Less than or equal to 10.0% RA **or** Less than or equal to 1.5% H_2O absolute average difference		
Bias	SO_2, NO_x and CO analyzers	Representative load level	Less than or equal to 5.0% FS **or** Less than or equal to plus/minus 5 ppm abs. diff.	5.1.6	5.3.6
	O_2 and CO_2 analyzers	Representative load level	Less than or equal to 5.0% FS **or** Less than or equal to plus/minus 0.5% abs. diff.		
	Stack gas flow monitor	Representative load level	Less than or equal to 5.0% FS **or** Less than or equal to plus/minus 0.6 m/s abs. diff.		
	Stack gas temperature	Representative load level	Less than or equal to 5.0% FS **or** Less than or equal to plus/minus 10°C abs. diff.		
	Stack gas moisture monitor	Representative load level	Less than or equal to 5.0% FS **or** Less than or equal to plus/minus 1.5% abs. diff.		
F-Factor system	Fuel flowmeter	Representative load level	Heat input calibrated less than or equal to plus/minus 2.0% FS or commercial billing flowmeter		
CEMS availability	Units operating greater than or equal to 1,500 h/yr	-	Greater than or equal to 90% yearly	6.5.1	3.4
	Units operating less than 1,500 h/yr	-	Greater than or equal to 80% yearly		
Independent Inspection	-	-	Evaluation by an independent inspector	6.5.2	-

In this Table **or** identifies a specification that the operator can apply as alternative specification.

Out-of-Control condition results from exceeding the RA or Bias specifications and the corresponding alternative specification (not just 1 of the 2).

Section 7.0 Determination of carbon dioxide emissions

This section provides for estimation of combustion exhaust gas CO_2 by monitoring the exhaust gas O_2 level or CO_2 level on a wet and dry basis.

7.1 Introduction

CEMS is a suitable technique for quantifying CO_2 emissions from stationary point sources on facilities designated by the Greenhouse Gas Reporting Program of ECCC. It may be an appealing option for large combustion units already fitted with SO_2 or NO_x CEMS and equipped with stack gas volumetric flow rate monitor. For this application, the CO_2 CEMS is subject to QA activities similar to those described in Sections 5 and 6.

Currently CEMS can quantify total CO_2 emissions and is unable to differentiate biomass and fossil origin. If the monitored source combusts both fuel types, follow the directions of the most recent version of the ECCC Canada's Greenhouse Gas Quantification Requirements.

The annual CO_2 mass emissions must be calculated from hourly average CEMS mass emission rates using Equation 7.1.

$$E_u = \frac{\sum_{h=1}^{Hr} ER_h\, T_h}{1000} \qquad \textbf{Eqn. 7.1}$$

Where:
E_u is the CO_2 emissions from the combustion source "u", during the calendar year, in tonnes
ER_h is the hourly CO_2 mass emission rate from the combustion source, in kg/hr
T_h is the combustion source operating time, in hours or fraction of an hour
Hr is the number of hourly CO_2 emission rates during the calendar year
1000 kg per tonne

The hourly average CO_2 mass emission rates, in kg/hour, must be determined according to the formulas 7.2 to 7.6, or by the backfilling of missing data discussed in Section 3.4.1.

7.2 Wet carbon dioxide measurement systems

When both the stack gas CO_2 concentration and flow rate are measured on wet basis, the hourly average CO_2 mass emission rate must be calculated using Equation 7.2

$$ER_h = 1.799\ Q_w\ CO_{2,w} \qquad \textbf{Eqn. 7.2}$$

Where:
ER_h is the hourly CO_2 mass emission rate from the combustion source, in kg/hr
1.799 is the CO_2 gas density in kg/Sm^3 @ ECCC reference conditions
Q_w is the hourly average stack gas volumetric flow rate in WSm^3/h
$CO_{2,w}$ is the hourly average CO_2 stack gas concentration, in volume percent on a wet basis

7.3 Dry carbon dioxide measurement systems

When the stack gas CO_2 concentration is measured on dry basis and the stack gas flow is measured on wet basis, then the hourly average CO_2 mass emission rate must be calculated using Equation 7.3.

$$ER_h = 1.799\ Q_w\ CO_{2,d}\ (1 - H_2O)$$ **Eqn. 7.3**

Where:
ER_h is the hourly CO_2 mass emission rate from the combustion source, in kg/hr
1.799 is the CO_2 gas density in kg/Sm^3
Q_w is the hourly average stack gas volumetric flow rate on wet basis, WSm^3/h
$CO_{2,d}$ is the hourly average CO_2 stack gas concentration, as fraction of dry volume.
H_2O is the hourly average stack gas moisture content, as volume fraction

7.4 Wet oxygen measurement systems

In the combustion of fuels of known composition (for example, Appendix A, Table A-1), without the addition of water, steam, or CO_2 from calcination, it is possible to calculate the combustion exhaust gas CO_2 and H_2O levels by monitoring the exhaust gas O_2 level. In this case the QA provisions of Sections 5 and 6 will be performed with respect to O_2 reference gases, but the required RATA should be done on a percent calculated CO_2 basis.

When both the stack gas O_2 concentration and flow rate are measured on wet basis, the hourly average CO_2 concentration wet basis must be calculated using Equation 7.4, and then the mass emission rate is calculated using Equation 7.2.

$$CO_{2w} = \frac{100\ F_c}{20.9\ F_d}\left[20.9(1 - H_2O) - O_{2w}\right]$$ **Eqn. 7.4**

Where:
CO_{2w} is the hourly calculated average CO_2 concentration during unit operation, as wet volume fraction
F_c is the ratio of the carbon dioxide volume generated by the combustion of a given fuel to the amount of heat produced (Appendix A, Eqn. A-13)
F_d is the ratio of the stoichiometric volume of dry gas generated by the atmospheric combustion of a given fuel to the amount of heat produced (Appendix A, Eqn. A-11)
H_2O is the stack gas moisture content, volumetric fraction
O_{2w} is the hourly average O_2 concentration during unit operation, volumetric wet fraction

For any hour where Equation 7.4 results in a negative average CO_2 value, then the average CO_2 value for that hour shall be recorded as 0.0% CO_{2w}. The stack gas moisture level may be calculated by Appendix B, Equation B-5 and Table B-1. Other stack gas moisture monitoring systems may be proposed providing that are able to calculate stack gas H_2O with an error of less than or equal to 1.5% on annual basis.

7.5 Dry oxygen measurement systems

In the combustion of fuels of known composition (for example, Appendix A, Table A-1), without the addition of water or steam, or the release of CO_2 by calcination, or other significant side reactions, it is possible to calculate exhaust gas dry CO_2 levels by monitoring the exhaust gas dry O_2 level. In this case, the QA provisions of Sections 5 and 6 will be performed with respect to O_2 reference gases, but all the required RATA should be done on a percent calculated CO_2 basis.

When the stack gas O_2 concentration is measured on dry basis, the hourly average dry CO_2 concentration must be calculated using Equation 7.5, and then the mass emission rate is calculated using Equation 7.3.

$$CO_{2d} = \frac{100\ F_c}{20.9\ F_d}[20.9 - O_{2d}]$$ **Eqn. 7.5**

Where:
CO_{2d} is the hourly average CO_2 concentration during unit operation, percent by volume, dry basis
F_c is the ratio of the CO_2 volume generated by the combustion of a given fuel to the amount of heat produced (Appendix A, Eqn. A-13)
F_d is the ratio of the stoichiometric volume of dry gas generated by the atmospheric combustion of a given fuel to the amount of heat produced (Appendix A, Eqn. A-11)
O_{2d} is the hourly average O_2 concentration during unit operation, volumetric percent, dry basis

For any hour where Equation 7.5 results in a negative CO_2 value, then 0.0% CO_{2w} shall be recorded as the CO_2 value for that hour.

Glossary

In this document

“Accuracy” means the extent to which the results of a calculation or the readings of an instrument approach the true value of the calculated or measured quantities

“Analyzer” is the device that measures pollutant or diluent concentration in the exhaust stream of an emission source

“Appropriate regulatory authority” means any federal, provincial, territorial or local government that has or could exercise regulatory or other authority over monitored emissions

“Availability” means the number of valid monitoring hours divided by the hours the combustion unit burns fuel or vents contaminants

“Backfilling” means the substitution of monitoring data during a monitoring out-of-control period by a technique approved by an appropriate regulatory authority

“Bias” means systematic error resulting in measurements that are consistently low or high relative to the reference value. Bias exists when the difference between continuous emission monitoring system data and the reference method exceeds random error

“Calibration gas” means a known concentration of (1) a gas that is traceable to either a standard reference material or the U.S. National Institute of Standards and Technology, (2) an authorized certified reference gas, or (3) a U.S. Environmental Protection Agency protocol gas

“Calibration” means the procedure of testing a device to bring it to a desired value (within a specified tolerance) for a particular input value (typically the value of the reference standard)

“Calibration check” means the procedure of testing a device against a known reference standard without adjusting its output

“Calibration drift” means the difference between (1) the response of a gas analyzer to a reference gas and the known value of the reference gas, 2) the response of a flow monitor to a reference signal and the known value of the reference signal

“Conditioning period” is a recommended “break in” period in which a continuous emission monitoring system samples and analyzes the stack gas emissions prior the Certification test series

“Continuous emission monitoring system” means the complete equipment for sampling exhaust gases, conditioning, calculating emissions, and recording data

“Data point” means the measured signal output received from an analyzer or monitor at a scan rate at least as fast as the analyzer response time

“Drift” means an undesired change in CEMS output over a time period, that is unrelated to input or equipment adjustments

“Flow monitor” is the continuous emission monitoring system component that monitors the actual velocity and temperature of the gas emission stream

“FS” means full scale

“Full scale” means the upper value of the analyzer operating range

“Generating unit” means a fuel-fired combustion device used for electricity generation

“Heat input rate” means the product of the gross calorific value of the fuel and the fuel feed rate into the combustion device and does not include the heat derived from preheated combustion air, recirculated flue gases or exhaust from other sources

“Interference rejection” means the ability of a continuous emission monitoring system to measure a gaseous specie without responding to other gases or substances, within specified limits

“Load” means production rate or output rate of an industrial process unit (for example, electric output from a power unit or mass of steam from a boiler)

“Measurement range” is a design concentration interval for which the manufacturer specifies the linearity, drift, and cross sensitivity of the analyzer

“Net energy output” means gross energy output minus unit service power requirements

“Nitrogen oxides” means nitric oxide (NO) and nitrogen dioxide (NO_2), collectively expressed as nitrogen dioxide

“Operational test period” means a mandatory 168-hour period following the installation of a new continuous emission monitoring system, during which some of the performance specification tests are carried out

“Out-of-control period” means a period when the output of the analyzer, flow monitor, or data acquisition and handling system does not accurately represent the stack emissions

“Performance specification” means a technical guidance document used for evaluating the acceptability of CEMS at the time of installation and whenever specified in regulations

“Precision” means the measure of the range of values of a set of repeated measurements. Indicates reproducibility of the observations

“Protocol gas” means a calibration gas mixture prepared and analyzed according to the EPA Traceability Protocol for Assay and Certification of Gaseous Calibration Standards, May 2012, EPA-600/R-12/531, as amended from time to time

“**Quality system**” means a structured system consisting of the policies, objectives, principles, organizational authority, responsibilities, accountability, and implementation plan of an organization for ensuring quality in its work processes, products, services and activities

“Range” means the algebraic difference between the upper and lower limit of the group of values within which a quantity is measured, received, or transmitted

“Raw data” means the original, un-manipulated value obtained from an analyzer or device

“Reference method” means any applicable ECCC method for the measurement of stack gas flow and concentrations, such as methods A to F, or those by an appropriate regulatory authority such as U.S. EPA methods 1, 2, 2F, 2G, 2H, 3A, 4, 6C, 7E and 10

"Relative accuracy" is the absolute mean difference between a series of concurrent measurements made by a continuous emission monitoring system and an appropriate reference method plus the 2.5% error confidence internal coefficient, divided by the mean of the reference method measurements

"Representative load" is the operating level required by the appropriate regulatory authority, or the operating level prevailing at the time RATA is performed

"Standard conditions" means at 101.325 kPa pressure and 25^{o}C temperature

"**Units of the standard**" means any applicable emission limit set by ECCC, or by an appropriate regulatory authority

"Valid data" means data of known and documented quality that satisfy, at a minimum the requirements set out in this document

"Valid hour" means an hour during which the combustion unit burned fuel and the associated continuous emission monitoring system produced a minimum equivalent to 45 minutes of valid data

"0 air material" means high purity air, or inert gas such as nitrogen, with less than 0.1 parts per million v/v level of the gas being analyzed, or less than 0.1 % of the span value, whichever is greater. It may include a) a gas mixture certified by the supplier, b) ambient are conditioned by a certified 0 air generator; or c) conditioned and purified ambient air provided by a conditioning system concurrently supplying dilution air to the CEMS. This is equivalent to 0 level reference gas for SO_2, NO_x, and CO

Units, abbreviations, and acronyms

In this document,

|d|	Absolute difference
avg	Average
BAF	Bias adjustment factor
BTU	British Thermal Unit
CEMS	Continuous Emission Monitoring System
CFR	U.S. Code of Federal Regulations
cm	Centimetre
CO_2	Carbon dioxide
DSm^3/GJ	Dry standard cubic metre per gigajoule
DSm^3/MJ	Dry standard cubic metre per megajoule
ECCC	Environment Canada and Climate Change
EPA	U.S. Environmental Protection Agency
F-factors	F_c, F_d, or F_w combustion factors
F_c	Ratio of the carbon dioxide volume generated by the combustion of a given fuel to the amount of heat produced (Sm^3/Mj)
F_d	Ratio of the stoichiometric volume of dry gas generated by the atmospheric combustion of a given fuel to the amount of heat produced (DSm^3/Mj)
FS	Full scale
F_w	Ratio of the stoichiometric volume of dry gas generated by the dry air combustion of a given fuel to the amount of heat produced (WSm^3/Mj)
g/GJ	Grams per gigajoule
GCV	Gross Calorific Value
GJ/h	Gigajoules per hour
GJ/MWh	Gigajoules per megawatt-hour
$H_2O\%$	Moisture content of the stack gas (% v/v)
ISO	International Organization for Standardization
K	Kelvin degrees
kg/GJ	Kilograms per gigajoule
kg/h	Kilograms per hour
kg/MWh	Kilograms per megawatt-hour
kg/Sm^3	Kilograms per standard cubic metre
kJ/kg	Kilojoule per kilogram
kPa	Kilopascal
LEDs	Light-emitting diodes
m/s	Metres per second
m^3/GJ	Cubic metres per gigajoule
$m^3/kg\text{-}mol$	Cubic metres per kilogram-mole
m^3/s	Cubic metres per second
MJ/MWh	Megajoules per megawatt-hour
MJ/s	Megajoules per second

MW	Megawatt
MWh	Megawatt-hr
ng/J	Nanograms per joule
NO	Nitric oxide
NO_2	Nitric dioxide
NO_x	Nitric oxides ($NO + NO_2$)
^oC	Degree Celsius
OEM	Original Equipment Manufacturer
OTP	Operational Test Period
ppm	Parts per million
P_{std}	ECCC standard pressure, 101.325 kPa
QA	Quality Assurance
QC	Quality Control
RA	Relative Accuracy
RATA	Relative Accuracy Test Audit
RM	Reference Method
Sm^3/GJ	Standard cubic metres per gigajoule
Sm^3/h	Standard cubic metres per hour
Sm^3/MJ	Standard cubic metres per megajoule
Sm^3/MWh	Standard cubic metres per megawatt-hour
SO_2	Sulphur dioxide
v/v	Volume per volume basis
WSm^3/GJ	Wet standard cubic metres per gigajoule
WSm^3/h	Wet standard cubic metres per hour
WSm^3/MJ	Wet standard cubic metres per megajoule
WSm^3/MWh	Wet standard cubic metres per megawatt-hour

Bibliography

General References

- AB CEMS Code Review Questions and Responses, (Dec. 2018)
- Alberta Environmental Protection, Continuous Emission Monitoring System (CEMS) Code, 111 pp (Apr. 2021)
- Alberta Environmental Protection, Electronic reporting of continuous emission monitoring (CEMS) information user manual. Version 3, Section 10 (backfilling, p.34-37, accessed 17 Aug 2022)
- ECCC, Reference methods for source testing: measurement of releases of fine particulate matter from stationary sources (methods G to I, 2017)
- ECCC, Reference methods for measuring releases of particulate from stationary sources (methods A to F, 2014)
- ECCC, Quantification of Carbon Dioxide Releases by Continuous Emission Monitoring Systems from Thermal Power Generation (2012)
- Environment Ontario, Guideline for the Installation and Operation of Continuous Emission Monitoring (CEM) Systems (2016)
- Graham, D et al, Validated method for flue gas flow rate calculation with reference to EN 12952-15, 81 pages, (2012)
- HovaCAL, Dry and wet calibration gas generator specifications., various models 4 pp, (2020)
- Institute for Clean Air Companies (ICAC), Guidelines for specification and selection of DAHS for CEMS applications, 17 pp, (2013)
- International Carbon Action Partnership (ICAP), Canada-Quebec Cap-and Trade System (2020)
- Jahnke, Jim, Continuous Emission Monitoring, Wiley 2nd. Edition, 426 pp (2000)
- Jahnke, Jim, Greenhouse Gas Monitoring, Draft of Chapter 14 of not yet published 3rd. Edition of Continuous Emission Monitoring
- Jernigan, J and Dene, C., Advances in CEMS & Flow Monitoring, (estimated 2013)
- Johnson, A.N. Faster more accurate, stack-flow measurements, J. of Air & Waste Mgmt. Assoc. 70:3, 283-291, (2020)
- Lacrosse, J., Real time emission measurements using FTIR spectroscopy (EPA Method 320), 62 slides PP, (2010)
- Nova Scotia Environment, Standards for Quantification, Reporting and verification of Greenhouse Gas Emissions, 217 pp, (2018)
- Olsen, D. et al, Impact of Oxidation Catalysts on Exhaust NO2/NOx Ratio from Lean-Burn NG Engines, J. Air & Waste Mgmt. Assoc. 60:867– 874 (2010)
- Paraschiv, L.S. et al, Calculation of combustion air required for burning solid fuels (coal/biomass/solid fuel) and analysis of flue gas compositions, 9 p (2020)
- Schakenbach, J. et al, Fundamentals of Successful Monitoring, Reporting, and Verification under a Cap-and-Trade Program, 7 pp, (2006)
- Schwartz, J. et al, Continuous Emission Monitors - Issues and Predictions, Air & Waste, 44:1 p 16-20 (1994)
- Thermo Fisher, Review of CEMS Regulations
  40 CFR Part 60 vs Part 75, 40 slides PP, (2019)
- UK Environmental Agency, TGN M20 QA of CEMS, 72 pp (2018)
- US EPA EMTIC, 40 CFR Part 60 Appendix B Performance Specification 2 Definition of Normal Load, (1992)
- US EPA, FR /Vol. 84, No. 240 / December 13, 2019 / Proposed Test Methods Updates (2019)

- US EPA, Performance Specification 6 for Flow Rate, 4 pp, (2017)
- US EPA, 40 CFR 75 § 72.2 Definitions, accessed (16/06/2020
- US EPA, 40 CFR 75 appendix A, section 6.5.2.1 (2020)
- US EPA, An Operator's Guide To Eliminating Bias In CEM Systems, 122 p, (1994)
- US EPA, Method 19 Determination of sulfur dioxide removal efficiency and particulate matter, sulfur dioxide, and nitrogen oxides emission rates (2017)
- US EPA, Method 2F: Determination of stack gas velocity and volumetric flow rate with three-dimensional probes, 57 pp (2017)
- US EPA, Method 2G: Determination of stack gas velocity and volumetric flow rate with 2-dimensional probes, 53 pp (2017)
- US EPA, Method 2H: Determination of stack gas velocity taking into account velocity decay near the stack wall, 26 pp, (2017)
- US EPA, Method 3A: Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources, 4 pp (2017)
- US EPA, Method 6C: Determination of sulfur dioxide emissions from stationary sources, 5 pp (2017)
- US EPA, Method 7E: Determination of nitrogen oxides emissions from stationary sources, 27pp, (2018)
- US EPA, Monitoring requirements 40 CFR § 60.13, 7 pp (current, 1987 most recent bibliographic reference)
- US EPA, Part 75 Emission Monitoring Policy Manual, (2019)
- US EPA, Performance Specification 2 for Sulfur Dioxide and Nitrogen Oxide, 15 pp, (2019)
- US EPA, Performance Specification 3 for Oxygen and Carbon Dioxide and, 3 pp, (2019)
- US EPA, Plain English Guide to the Part 75 Rule, 118 pp, (2009)
- US EPA, Traceability Protocol for Assay and Certification of Gaseous Calibration Standards, EPA 600/R-12/531, 174 pp, (2012)
- Wikipedia, Grubb test for outliers *(accessed 11/06/2020)*

FTIR References

- ABB ACF5000 hot FTIR CEMS specifications, 16 pp (2020)
- ABB Monitoring cement plant stack emissions using FTIR, (2019)
- Coleman M., et al, Equivalency of a portable FTIR method to the EU RM for monitoring emissions to air of CO, NOx, SO2, HCl, and H2O, 8 p, (2015)
- FTIR CEM Performance Specifications Modification Considerations, PP EPA/ICAC Emission Measurements Roundtable Meeting, (17 Sep 2013)
- ICAC, White Paper: Guide to FTIR technology for compliance testing, performance specification, and CEM of target gases (2013)
- Larjava, K.T. et al, Field Measurements of Flue Gases from Combustion of Miscellaneous Fuels Using a Low-Resolution FTIR Gas Analyzer, 6 p, (1997)
- MKS MultiGas 2030 FTIR analyzer specs, 4 pp, (2020)
- Mosca, S. et al, Assessment of N2O emission from cement plants: Measurements with FTIR and NDIR (2014)
- Pellikka, T. et al, SO2 emission measurement with the European RM, EN 14791, and alternative methods, 9 pp, (2019)
- Reagen, W et al, FTIR Method Validation at a Carbon Bed Solvent Recovery Unit for Four Gaseous HC, Environ. Sci. Technol. (1999), 33,1752-1759
- Sick CEMS solutions MCS100FT, 12 pages brochure and specs. (2020)
- US EPA, Method 320, Vapor Phase Organic and Inorganic Emissions by Extractive FTIR, 50 pp

with Addendums (2019)

- US EPA, Method 321, Measurement of gaseous HCL emissions at Portland cement kilns by FTIR spectroscopy, 16 pp, (2017)
- US EPA, Performance Specification 15 for Extractive FTIR spectroscopy (2019)
- US EPA, Performance Specification 18 for HCl CEMS at stationary sources, (2015)
- US EPA, Protocol for the use of extractive FTIR spectrometry for stationary gaseous emissions, 20 pp, (1995)
- US EPA, Response to Comments on Proposed Rule Performance Specification 18 – for HCL, 103 pp, (2015)
- US EPA, Technical Amendments to Procedure 6, (2017)

Tunable Diode Lasers (TDL) references

- Henry.H., and Tran.P., Tunable diode laser (TDL) based HCl CEMS ... for Portland Cement, IEEE-IAS/PCA, pp. 1-5, (2014)
- Cacciatori, G, HCl CEMS Development to Meet EPA's Draft PS 18, PP 39 pp presented at EUEC (2015) (in situ)
- Cemteks NH3 TDL Model 7000 datasheet, 2 p, downloaded 06/2020 (in situ)
- Dene, C.E., et al, Laboratory investigation of three district emission monitors for HCl, J. of the Air & Waste Manage. Assoc., 66:12 1191-1201, (2016)
- DS-011A: TDL-406TM Rackmount Laser Gas Analyzer (extractive), Applied Analytics Data Sheet No. DS-011A — Revised 15 July (2019)
- Emerson (Rosemount) Hybrid QCL-TDL multi-component CEMS (extractive), downloaded 06/2020
- Lemieux, P.M., The Application of TDL as a Fast-Response System to Measure Transient Emissions from Rotary Kilns, 17 pp, (1997)
- Liptack, B, Analysis and Analyzers, Volume II, 1314 pp, (2016)
- The ATAC Luminos TDL hydrogen sulphide (H_2S) analyser Model 34, brochure with specs, downloaded 06/2020
- Yokogawa TDL8000 in-situ Specs, 24 pp, (2019)

Cavity Ring Down Spectroscopy (CRDS) references

- Dene, C.E., et al, Laboratory investigation of three distinct emission monitors for HCl, J. of the Air & Waste Mgmt. Assoc., 66:12 1191-1201, (2016)
- Los Gatos Research, Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS)
- Picarro, Frequently Asked Questions about CRDS, 6 p. Technical Addendum, 5 p, downloaded (2020)
- Tiger Optics, Products Guide Issue 1 (2020)

Carbon Dioxide CEMS

- ASTM D6866-16 Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis
- ASTM D7459-08 (2016) Standard Practice for Collection of Integrated Samples for the Speciation of Biomass (Biogenic) and Fossil-Derived Carbon Dioxide Emitted from Stationary Emission Sources
- ECCC, Canada's Greenhouse Gas Quantification Requirements, Version 4.0, December 2020
- Bryant, R., Bundy, M., Zong, R., Evaluating measurements of carbon dioxide emissions using a precision source - A natural gas burner, Journal of the Air and Waste Management Association, 65(7):863-870, 2015
- Huang, J, Gurney, K.R., Comparing two national datasets of CO_2 Emissions for U.S. Powerplants
- Liggio, J., et al, Measured Canadian oil sands CO_2 emissions are higher than estimates made using internationally recommended methods, April 2019

- Nova Scotia Environment, Standards for Quantification, Reporting and verification of Greenhouse Gas Emissions, 217 pp, (Feb. 2018)
- Ontario Ministry of the Environment, Conservation and Parks, Guideline for Quantification, Reporting and Verification of Greenhouse Gas Emissions, July 2019, 262 pp
- Quick, J., Carbon dioxide emission tallies from 210 U.S. coal-fired power plants: A comparison of two accounting methods, Journal of the Air and Waste Management Association, 64(1):73-79, 2014
- U.S. EPA, 40CFR§75 App. G, Determination of CO_2 Emissions
- U.S. EPA, 40CFR§98.33 Tier 4 Calculation Methodology, (4) Tier 4 Calculation Methodology
- U.S. EPA, Greenhouse Gas Inventory Guidance, Direct Emissions from Stationary Combustion Sources, 22 pp
- **Low NO_x Turbine Emissions**
- ECCC Guidelines for the Reduction of Nitrogen Oxide Emissions from Natural Gas-fuelled Stationary Combustion Turbines, November 2017
- Bivens, Robert J., Startup and Shutdown NO_x Emissions from Combined-Cycle Combustion Turbine Units, presented at EPRI CEM User Group Meeting, Chicago, Illinois, May 24, 2002
- Macak, Joseph J., Evaluation of Gas Turbine Startup and Shutdown Emissions, paper # 546, Session No. EI-2a
- Suess, David T., Development of Startup and Shutdown Permit Limits Based Upon Historical Data from Combustion Sources Monitored by Continuous Emission Monitoring Systems Manuscript 2009-A-597-AWMA

Appendix A Emission calculation by combustion F-factors

Appendix A presents F-factor for selected fuels, equations used for measurement of concentration of pollutants using F-factors, and the method(s) of calculation of customized F-factors.

A.1 Introduction

Combustion F-factors are used to calculate pollutant emissions rates expressed in units of mass per energy, such as ng/J. They may also be used to give a true mass emission rate (weight per time) if the heat input to the combustion process is accurately known.

The F_c factor is the ratio of the carbon dioxide volume generated by the combustion of a given fuel, to the amount of heat produced. The F_d factor is the ratio of the stoichiometric volume of dry gas generated by the complete atmospheric combustion of a given fuel, to the amount of heat produced. The F_w factor is the ratio of the stochiometric volume of wet gas generated by the complete dry air combustion of the fuel, to the amount of heat produced.

The F-factor to use in calculating emissions is determined by the diluent gas monitored. CEMS with CO_2 analyzers should use F_c factors, whereas those with O_2 analyzers should used F_c factors or F_w factors. CEMS with both O_2 and CO_2 analyzers should use the F-factor that produces the most accurate exhaust volume estimates, taking in consideration the expected O_2 and CO_2 levels.

Note that the reference conditions of the ECCC F-factors are 25°C and 101.325 kPa. Factors generated at other reference conditions, must be adjusted to the ECCC reference. F-factors for other fuels may be developed using equations A-11, A-12 and A-13, but their application will require approval by the appropriate regulatory authority before being applied to CEMS.

Table A-1: F-factors for selected fuels

CEMS using F-factor formulas can potentially produce erroneous high emission values during combustion start up or shut down periods, in which a formula denominator becomes 0 or near 0 value (for example, Eqns. A-1, A-3, A-4, A-5 or A-6, when measured stack gas oxygen is approximately 20.9 %). This is avoided by setting a minimum stack gas carbon dioxide level and a maximum oxygen level. For boilers, a minimum of 5.0 % CO_2 or a maximum 14.0 % O_2 may be substituted for the measured diluent gas value for any operating period in which the hourly average CO_2 concentration is less than 5.0 % CO_2 or the hourly average O_2 Concentration is greater than 14.0 %. For stationary turbines, a minimum concentration of 1.0 % CO_2 or a maximum concentration of 19.0 % O_2 may be substituted for the measured diluent gas concentration for any operating period in which the hourly average CO_2 concentrations is less than 1.0 % CO_2, or the hourly average O_2 concentration is greater than 19.0 % (*reference: 40 CFR75 Appendix F, Section 3.3.4.1*). The cap for extreme dilution levels must be disclosed in the QA Plan.

Fuel	Type	F_d (dSm³/GJ)*	F_w (wSm³/GJ)*	F_c (Sm³CO₂/GJ)*
Solid	Anthracite	277	288	54.2
	Bituminous coal	267	286	49.2
	Subbituminous coal	263	301	49.2
	Lignite	273	310	53
	Petroleum Coke	268	-	50.5
	Tire Derived Fuel	280	-	49.1
	Wood bark	268	-	50.2
	Wood residue	269	-	52.1
	Municipal solid waste	268	-	50.5
Oil	Crude, residual, or distillate	255	289	39.3
Gas	Natural gas	240	295	28.4
	Propane	238	281	32.5
	Butane	238	284	34.1

* Reference conditions 101.325 kPa and 25˚C

A.2 Oxygen-based F_d factor measurement systems

When the CEMS measurements are on dry basis for both oxygen ($\%O_{2d}$) and pollutant (C_d) concentrations, the Equation A-1 may be used to calculate the emission rate of the pollutant, in kg/GJ units.

$$E_x = C_{xd} K_x F_d \left[\frac{20.9}{(20.9 - \%O_{2,d})}\right] \qquad \textbf{Eqn. A-1}$$

where:
E_x is the emission rate of the pollutant x, (kg/GJ)
C_{xd} is the dry-basis concentration of the pollutant x in stack gas, (ppm, dry)
K_x is the ppm to kg/Sm^3 conversion factor for pollutant x, (kg/Sm^3/ppm)
F_d is the ratio of the stoichiometric volume of dry gas generated by atmospheric combustion of a given fuel, to the amount of heat produced, (DSm^3/GJ)

20.9 is the oxygen volumetric fraction on ambient air, %
$\%O_{2,d}$ is the percent dry-basis concentration of oxygen in stack gas, (%, v/v)

The K_x values for SO_2, NO_x, CO and CO_2 are:

SO_2	2.618 x 10^{-6} kg/Sm^3/ppm
NO_x (as NO_2)	1.880 x 10^{-6} kg/Sm^3/ppm
CO	1.145 x 10^{-6} kg/Sm^3/ppm
CO_2	1.799 x 10^{-6} kg/Sm^3/ppm

The values of K_x for other gases can be calculated using the following formula:

$$K_x = \frac{273.15 \times MW_x}{T_{std} \times 1\,000\,000 \times 22.414}$$ **Eqn. A-2**

where:
MW_x is the molecular weight of gas x
T_{std} is the ECCC standard temperature (298.15 K)
22.414 is the molar volume at 273.15 K and 101.325 kPa, (m^3/kg-mol)

A.3 Oxygen-based F_w measurement systems

This factor is used in systems employing wet-basis analyzers. The F_w factors may be used where no water, other than that generated by the combustion process, is introduced into the exhaust gas flow.

The emission rate in kg/GJ may calculated using Equation A-3.

$$E_x = C_{xw} K_x F_w \left[\frac{20.9}{(20.9(1 - H_2O_a) - \%O_{2w})}\right]$$ **Eqn. A-3**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xw} is the wet-basis concentration of pollutant x (ppm)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_w is the ratio of the volume of wet gas generated by the stoichiometric combustion of the fuel with dry air, to the amount of heat produced (WSm^3/GJ)
H_2O_a is the concentration of water vapor in the combustion air (volumetric fraction)
$\%O_{2w}$ is the wet-basis oxygen level in the combustion exhaust gas (%, v/v)

This equation cannot be used in any process in which water is added or removed from the flue gas stream (for example, it is not applicable to CEMS installed after wet scrubbers).

The annual moisture average at the nearest location listed in Table B-1 may be used as an estimate of the concentration (volumetric fraction) of water vapor in the combustion air moisture for the entire calendar year.

If the moisture fraction of the stack gas (H_2O_s) is measured, then the emission rate in kg/GJ may calculated using Equation A-4.

$$E_x = C_{xw} K_x F_d \left[\frac{20.9}{(20.9(1 - H_2O_s) - \%O_{2w})}\right]$$ **Eqn. A-4**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xw} is the wet-basis concentration of pollutant x (ppm)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_d is the ratio of the volume of wet gas generated by the stoichiometric combustion of the fuel with dry air, to the amount of heat produced (WSm^3/GJ)
H_2O_s is the concentration of water vapor in the stack gas (decimal, v/v)
$\%O_{2w}$ is the wet-basis oxygen level in the stack gas (%, v/v)

A.4 Mixed basis measurement systems

When the pollutant concentration is measured on wet basis (C_{xw}) and the O_2 concentration is measured on dry basis ($\%O_{2d}$) then the Equation A-5 may be used:

$$E_x = \frac{(C_{xw}K_xF_d)(20.9)}{(1-H_2O_s)(20.9-\%O_{2d})}$$ **Eqn. A-5**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xw} is the wet-basis concentration of pollutant x, (ppm)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_d is the ratio of the volume of dry gas generated by the stoichiometric combustion of the fuel with dry air, to the amount of heat produced (WSm^3/GJ)
H_2O_s is the concentration of water vapor in the combustion air (decimal, v/v)
$\%O_{2d}$ is the dry-basis oxygen level in the combustion exhaust gas (%, v/v)

When the pollutant is measured on dry basis (C_{xd}) and the O_2 concentration is measured on wet basis ($\%O_{2w}$) then the Equation A-6 may be used:

$$E_x = \frac{C_{xd}K_xF_d\ 20.9}{\left[\frac{(20.9-\%O_{2w})}{(1-H_2O_{ws})}\right]}$$ **Eqn. A-6**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xd} is the dry-basis concentration of pollutant x, (ppm)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_d is the ratio of the volume of dry gas generated by the stoichiometric combustion of the fuel with dry air, to the amount of heat produced (WSm^3/GJ)
$\%O_{2w}$ is the wet-basis oxygen level in the stack gas (percent, v/v)
H_2O_{ws} is the concentration of water vapor in the stack gas (volumetric fraction)

A.5 Carbon dioxide-based F_c factor measurement systems

If carbon dioxide has been selected as the diluent gas, the carbon dioxide-based F-factor (Fc) must be used to determine the pollutant emission rate. The F_c factor may be used on either dry- or wet-basis CEMS, provided that the pollutant and CO_2 are measured on the same basis. The wet method is applicable to in-situ, dilution, and extractive direct-reading wet-basis CEMS.

When the pollutant concentration is measured on dry basis (C_{xd}) and the CO_2 concentration is measured on dry basis, then the emission rate for dry-basis measurements is calculated using Equation A-7.

$$E_x = C_{xd}K_xF_c\left[\frac{100}{\%CO_{2d}}\right]$$ **Eqn. A-7**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
C_{xd} is the dry-based concentration of pollutant x, (ppm, v/v)
F_c is the ratio of the carbon dioxide volume to the heat produced, (Sm^3/GJ)
$\%CO_{2d}$ is the dry-basis CO_2 concentration, (percent, v/v)

The emission rate for wet-basis measurements is calculated using Equation A-8.

$$E_x = C_{xw}K_xF_c\left[\frac{100}{\%CO_{2w}}\right]$$ **Eqn. A-8**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xw} is the wet-based concentration of pollutant x, (ppm, v/v)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_c is the ratio of the carbon dioxide volume to the heat produced, (Sm^3/GJ)
$\%CO_{2w}$ is the wet-basis CO_2 concentration, (percent, v/v)

When the pollutant concentration is measured on wet basis (C_{xw}) and carbon dioxide concentration is measured on dry basis ($\%CO_{2d}$), the following Equation A-9 may be used.

$$E_x = \frac{C_{xw}K_xF_c}{(1-H_2O_s)}\left[\frac{100}{\%CO_{2d}}\right]$$ **Eqn. A-9**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xw} is the wet-based concentration of pollutant x, (ppm, v/v)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_c is the ratio of the carbon dioxide volume to the heat produced, (Sm^3/GJ)
H_2O_s is the concentration of water vapor in the stack gas, (decimal, v/v)
$\%CO_{2d}$ is the dry-basis CO_2 concentration, (%, v/v)

When the pollutant concentration is measured on dry basis (C_{xd}) and carbon dioxide concentration is measured on wet basis ($\%CO_{2w}$), the following Equation A-10 may be used.

$$E_x = C_{xd}K_xF_c(1-H_2O_s)\left[\frac{100}{\%CO_{2w}}\right]$$ **Eqn. A-10**

where:
E_x is the emission rate of pollutant x, (kg/GJ)
C_{xd} is the dry-based concentration of pollutant x, (ppm, v/v)
K_x is the ppm to kg/Sm^3 conversion factor, (kg/Sm^3/ppm)
F_c is the ratio of the carbon dioxide volume to the heat produced, (Sm^3/GJ)

H_2O_s is the concentration of water vapor in the stack gas (decimal, v/v)
$\%CO_{2w}$ is the wet-basis CO_2 concentration, (%, v/v)

A.6 Calculation of customized F-factors

For fuels with compositions differing significantly from typical values or fuels not listed in Table A-1, F-factors may be calculated using the as-fired ultimate analysis and gross calorific value (GCV) of the fuel. Equations A-11 to A-13 can be used to calculate the various F-factors.

$$F_d = 10^4 \times \frac{[(K_{hd}\ \%H)+(K_c\ \%C)+(K_s\ \%S)+(K_n\ \%N)+(K_o\ \%O)]}{GCV}$$ **Eqn. A-11**

$$F_w = 10^4 \times \frac{[(K_{hw}\ \%H)+(K_c\ \%C)+(K_s\ \%S)+(K_n\ \%N)+(K_o\ \%O)+(K_w\ \%H_2O)]}{GCV}$$ **Eqn. A-12**

$$F_c = 10^4 \times \left(\frac{K_{cc}\ \%C}{GCV}\right)$$ **Eqn. A-13**

where:
F_d, F_w, F_c are the volume of combustion components per unit of heat released (m^3/GJ) at 25°C and 101.325 kPa.
%H, %C, %S, %N, %O, $\%H_2O$ are the concentration of hydrogen, carbon, sulphur, nitrogen, and water, respectively, from ultimate fuel analysis (weight percent).
GCV_d is the gross calorific value of the as-fired fuel (kJ/kg)
10^4 is the conversion factor (kJ/GJ/100)
K_{hd} is 22.95 Sm^3/kg, volume of dry exhaust gases resulting from the atmospheric stoichiometric combustion of hydrogen in the fuel
K_c is 9.74 Sm^3/kg, volume of dry exhaust gases resulting from the atmospheric stoichiometric combustion of carbon in the fuel
K_s is 3.65 Sm^3/kg, volume of dry exhaust gases resulting from the atmospheric stoichiometric combustion of sulphur in the fuel
K_n is 0.87 Sm^3/kg, volume of dry exhaust gases resulting from the atmospheric stoichiometric combustion of nitrogen in the fuel
K_o is -2.89 Sm^3/kg, volume of dry exhaust gases avoided due to oxygen in the fuel
K_{hw} is 35.08 Sm^3/kg, volume of wet exhaust gases resulting from the atmospheric stoichiometric combustion of hydrogen in the fuel
K_w is 1.36 Sm^3/kg, volume of water vapor resulting from the water contained in the fuel
K_{cc} is 2.04 Sm^3/kg, volume of carbon dioxide produced by the complete combustion of the fuel

Appendix B Determination of mass emission rates

Appendix B provides for determination of the emission rate of a pollutant on a mass-per-unit-time-basis based on energy input method, and use of real time real-time stack gas flow monitors.

B.1 Introduction

The emission rate of a pollutant, on a mass-per-unit-time basis, may be determined by 1 of 2 methods described in this appendix:

• Monitoring of the fuel flow rate of the process, and, therefore, the energy input rate. The emission rate is then calculated from the measured pollutant stack gas concentration and the stack gas flow, which is calculated by F-factor and diluent concentration.

• Monitoring of the stack gas flow rate, with the mass emission rate calculated from the measured concentration and flow rate

B.2 Energy input method – metering of fuel flows

The calculation of the mass emission rate of a compound is shown as an example in Equation B-1, which applies to the measurement of the pollutant using an oxygen-based dry system:

$$ER_x = HI\ C_{x,d} F_d K_x \left[\frac{20.9}{(20.9 - \%O_{2d})}\right]$$ **Eqn. B-1**

where:
ER_x is the emission rate of pollutant x (kg/h)
HI is the gross heat input (GJ/h)
$C_{x,d}$ is the dry-basis hourly average exhaust gas concentration of the pollutant x (ppm, v/v)
F_d is the ratio of the volume of dry gas resulting from stoichiometric atmospheric fuel combustion to the amount of heat produced (DSm^3/GJ)
K_x is the ppm to kg/Sm^3 conversion factor for pollutant x
$\%O_{2d}$ is the dry-basis hourly average exhaust gas concentration of O_2 (percent, v/v)

Equation B-1 is similar to Equation A-1 in Appendix A, except of the additional term HI, which converts the mass-per-energy rate into a mass per time. Thus, an accurate heat input rate is required to calculate the desired mass emission rate.

The energy entering the combustion process can be determined by measuring the mass fuel flow and its gross calorific value (GCV). The DAHS should be able to accept the signal of the fuel flow meter, and to calculate the heat input in the Equation B-1 units.

B.2.1 Determination of heat input rate for gaseous fuels

The standard volume of gaseous fuel consumed must be measured and recorded by the DAHS and an hourly average calculated. The fuel flow monitor must meet a 2.0% accuracy, as determined by the manufacturer or the system operator. The fuel flow monitor must be calibrated at the frequency recommended by manufacturer to maintain the accuracy within specifications. The volumetric GCV (for example, BTU/Sft^3) of the fuel must be obtained from the fuel supplier on a monthly basis.

The hourly average heat input to the combustion unit is determined by the product of the hourly standard volumetric flow rate by the volumetric GCV provided by the fuel supplier.

The applicable pollutant mass emission rate is determined by inserting the hourly average heat input to the combustion process into Equation B-1. When calculating the mass emission rate for a system using wet-basis analyzers or CO_2 as diluent gas, the appropriate equations from Appendix A should be used, modified to include the value of the hourly heat input (HI).

B.2.2 Determination of heat input rate for liquid fuels

The flow of oil consumed in the combustion process must be measured and recorded on hourly basis. The fuel flow is measured using an in-line flow meter with the data automatically recorded by the DAHS. Any returning fuel flow must be metered by a similar flow meter and the data recorded by the DAHS, that should be able to calculate the net fuel flow.

Each fuel flow meter must meet a 2.0% accuracy specification, as measured by the manufacturer or CEMS operator. Each flow meter must be recalibrated at least annually, or more frequently if specified by the manufacturer in order to meet the cited accuracy specification.

The as-fired liquid fuel must be sampled and analyzed to determine its gross calorific value (GCV). Flow-proportional sampling or continuous-drip sampling must be carried out when the unit is fueled by oil. The hourly samples must be blended into a composite sample and then analyzed for GCV and specific gravity, if necessary. The protocols for fuel sampling and analysis must be included in the QA plan, in consultation with the appropriate regulatory agency.

The applicable pollutant mass emission rate is determined by inserting the hourly heat input to the combustion process into equation B-1. When calculating the mass emission rate for a system using wet-basis analyzers or CO_2 as diluent gas, then the appropriate equations from Appendix A should be used, modified to include the value of the hourly heat input (HI).

B.3 Determination using real-time stack gas flow monitors

The mass emission rate of the target pollutants can be determined from their concentration and the volumetric flow rate of the flue gas. There are several techniques for measuring the flow rate (for example, pitot tubes, ultrasonic meters). Any gas flow rate monitoring system that meets the specifications and passes certification is acceptable and may be used in CEMS.

The procedures to compute hourly mass emissions are the following. The exhaust flow is primarily measured on wet basis, and then adjusted to standard conditions by temperature and pressure measurements using Equation B-2.

$$Q_{stp} = Q_{actual} \times \left(\frac{T_{stp}}{T_{stack}}\right) \times \left(\frac{P_{stack}}{P_{std}}\right) \quad \textbf{Eqn. B.2}$$

Where:
Q_{stp} is the flue gas volumetric flow rate at standard temperature and pressure, WSm^3/h
Q_{actual} is the flue gas volumetric flow rate at actual temperature and pressure, WAm^3/h
T_{stp} is the standard ECCC temperature, K = 273.15 + 25°C
T_{stack} is the flue gas temperature at flow monitoring location, K = 273.15 + °C
P_{stack} is the absolute flue gas pressure (site barometric pressure + flue gas static pressure), kPa
P_{std} is the standard ECCC pressure, 101.325 kPa

When the pollutant concentration is measured in wet basis, the hourly emissions during source operation are calculated using Equation B-3.

$$ER_x = Q_w C_{x,w} K_x \qquad \textbf{Eqn. B-3}$$

where:
ER_x is the emission rate of pollutant x, (kg/h)
Q_w is the wet stack gas volumetric flow rate (WSm^3/h)
$C_{x,w}$ is the wet-basis gas pollutant x concentration (ppm, v/v)
K_x is the ppm to kg/Sm^3 conversion factor for pollutant x

When the pollutant concentration is measured on dry basis (for example, extractive CEMS with sample conditioning by condensation or equivalent), the hourly emissions during source operation are calculated using Equation B-4.

$$ER_x = Q_w C_{x,d} K_x (1 - H_2O_s) \qquad \textbf{Eqn. B-4}$$

where:
ER_x is the emission rate of pollutant x, (kg/h)
Q_w is the wet stack gas volumetric flow rate (WSm^3/h)
$C_{x,d}$ is the dry-basis gas pollutant x concentration (ppm, v/v)
K_x is the ppm to kg/Sm^3 conversion factor for pollutant x
H_2O_s is the concentration of water vapor in the stack gas (decimal, v/v)

The mass emission monitoring by Equation B-3 requires the installation, operation, maintenance, and quality assurance of a continuous stack gas moisture monitoring system for measuring and adjusting the measured dry basis pollutant concentration. The following systems are acceptable:
• a combination of a wet O_2 analyzer and a dry O_2 analyzer; or
• a stack temperature sensor and a water vapor pressure equation or look up table (for demonstrably moisture-saturated exhaust gas)

If the CEMS includes a suitably installed wet O_2 analyzer and a dry O_2 analyzer, then the stack gas moisture can be calculated using Equation B-5.

$$\%H_2O_s = \frac{(O_{2d} - O_{2w})}{O_{2d}} \times 100 \qquad \textbf{Eqn. B-5}$$

where:
$\%H_2O_s$ is the hourly average stack gas moisture content (percent H_2O)
O_{2w} is the wet-basis hourly average O_2 concentration (percent O_2)
O_{2d} is the dry-basis hourly average O_2 concentration (percent O_2)

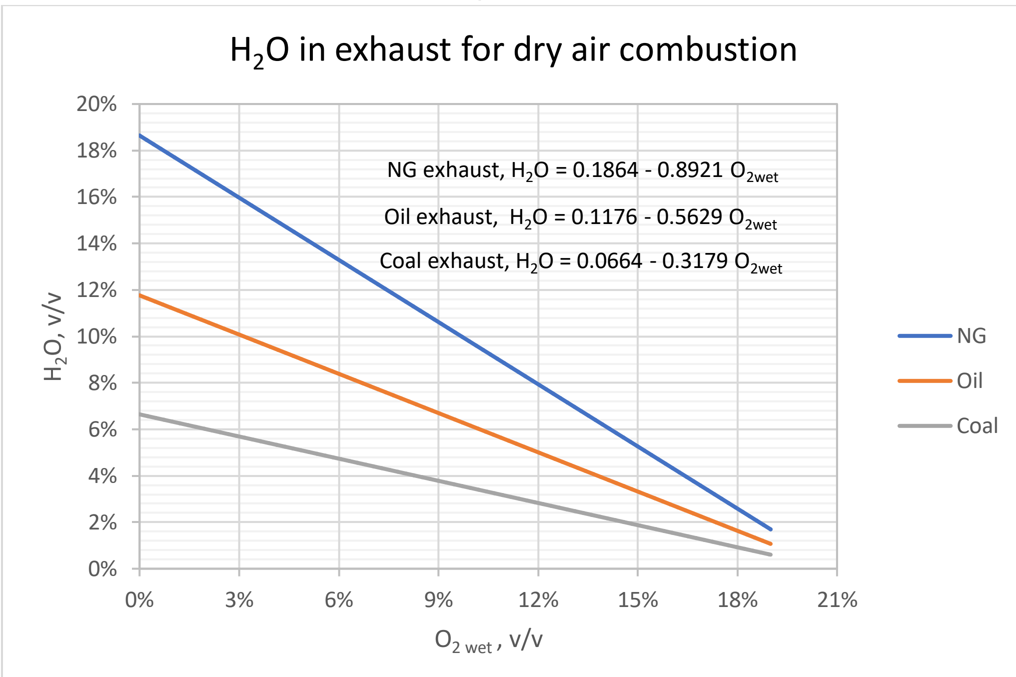
In the combustion of fuels of known composition, without the addition or water or steam, it is possible to estimate stack gas moisture by monitoring the wet O_2 level of the stack gas and the combustion air moisture. This is accomplished by applying Equation B-6 (for combustion in dry air), and then adding the moisture of the combustion air (similar to EPA Method 4 Section 12.2.5).

$$\%H_2O_s = \left[\frac{F_w - F_d}{F_w}\right]\left[1 - \frac{O_{2w}}{0.209}\right]$$ **Eqn. B-6**

where:
$\%H_2O_s$ is the stack gas moisture content (%, v/v)
F_w is the ratio of the volume of wet gas resulting from stoichiometric atmospheric fuel combustion to the amount of heat produced (WSm^3/GJ).
F_d is the ratio of the volume of dry gas resulting from stoichiometric atmospheric fuel combustion to the amount of heat produced (DSm^3/GJ)
O_{2w} is the wet-basis concentration of O_2 in stack gas (decimal, v/v)

Figure B-1 resulted from applying the Eqn. B-6 to F_d and F_w of 3 common fuels listed in Table A-1.

Figure B-1



The formulas in Figure B-1 established by linear regression are able to calculate within +/-0.1% error limit the exhaust gas moisture resulting from complete fuel combustion, for 0% to 800% excess dry ambient air.

The moisture estimate by Equation B-6 requires a single oxygen analyzer, as opposed to the 2 analyzers of Equation B-5, but a change in fuel may necessitate a different calculation equation. If the emission source operates year-round with the same fuel and the same excess combustion air level, then it is acceptable to measure stack gas moisture during RATA and, if successful, apply the same moisture factor until the next RATA. If fuel moisture varies, or excess air changes with load levels (for example, gas turbines), then it is recommended to monitor stack gas moisture levels by Equations B-5 or B-6.

Other stack gas moisture monitoring systems may be proposed for use with Equation B-4 if it is demonstrated that the system calculates stack gas H_2O with an error less than or equal to 1.5% on annual basis. The specific QA activities related to the moisture monitoring system must then be described in the QA Plan.

On annual average, the adjustment for ambient air moisture is rather minor (~ 1% v/v H_2O), given the low temperatures of Canadian weather. Table B-1 shows the 1981-2010 average monthly moisture levels in the provincial and territorial capitals, calculated from the ratio of H_2O partial pressure to the atmospheric pressure. The use of the site historical ambient air moisture (monthly or annual average) is adequate to add to the combustion moisture calculated by Figure B-1.

Table B-1: Monthly average air moisture on Canadian provincial capitals

Monthly average air moisture on Canadian provincial capitals (H_2O vapour pressure/station pressure)														
Location	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	**Avg.**	RSD
Calgary	0.34%	0.34%	0.45%	0.56%	0.79%	1.12%	1.35%	1.23%	0.90%	0.56%	0.45%	0.34%	**0.67%**	54%
Vancouver	0.69%	0.69%	0.79%	0.89%	1.08%	1.28%	1.47%	1.48%	1.28%	1.08%	0.79%	0.69%	**0.98%**	31%
Winnipeg	0.20%	0.20%	0.40%	0.61%	0.91%	1.42%	1.73%	1.52%	1.12%	0.71%	0.41%	0.20%	**0.81%**	68%
Fredericton	0.30%	0.30%	0.40%	0.59%	0.89%	1.29%	1.68%	1.58%	1.28%	0.79%	0.59%	0.40%	**0.79%**	63%
St. John's	0.40%	0.40%	0.50%	0.60%	0.80%	1.10%	1.40%	1.50%	1.20%	0.90%	0.70%	0.50%	**0.80%**	48%
Yellowknife	0.10%	0.10%	0.10%	0.30%	0.50%	0.81%	1.11%	1.11%	0.81%	0.51%	0.20%	0.10%	**0.51%**	78%
Halifax	0.40%	0.40%	0.50%	0.60%	0.90%	1.31%	1.60%	1.70%	1.40%	1.00%	0.70%	0.50%	**0.90%**	53%
Iqaluit	0.10%	0.10%	0.10%	0.20%	0.40%	0.60%	0.80%	0.80%	0.60%	0.40%	0.20%	0.10%	**0.40%**	69%
Toronto	0.40%	0.40%	0.50%	0.70%	1.01%	1.51%	1.71%	1.71%	1.40%	0.90%	0.70%	0.50%	**0.90%**	56%
Charlottetown	0.30%	0.30%	0.40%	0.60%	0.89%	1.29%	1.69%	1.69%	1.29%	0.89%	0.69%	0.40%	**0.89%**	57%
Quebec City	0.20%	0.30%	0.40%	0.50%	0.90%	1.29%	1.69%	1.59%	1.19%	0.79%	0.50%	0.30%	**0.80%**	66%
Regina	0.21%	0.32%	0.42%	0.53%	0.85%	1.27%	1.48%	1.37%	0.95%	0.63%	0.42%	0.21%	**0.74%**	62%
Whitehorse	0.22%	0.22%	0.32%	0.43%	0.54%	0.86%	1.07%	0.97%	0.75%	0.54%	0.32%	0.22%	**0.54%**	57%
1981-2010 ECCC Climate Normals (H_2O vapour pressure/station pressure) https://climate.weather.gc.ca/climate_normals/index_e.html														

When a CEMS fitted with stack gas monitor is installed after a pollution control device that reduces the flue gas temperature so that the exit gas is water saturated, then the stack gas moisture must be determined from the stack gas temperature by applying Equations B-7 and B-8.

$$\%H_2O = 100 \times \frac{P_{H_2O}}{P_{stack}}$$ **Eqn. B-7**

Where:
$\%H_2O$ is the hourly average stack gas moisture during the operation of the combustion unit, % by volume
P_{H2O} is the hourly average partial water pressure of the stack gases as calculated with Eqn. B-8, mmHg
P_{stack} is the hourly average stack gas absolute pressure, mmHg

$$\log_{10} P_{H_2O} = A - \frac{B}{C+T}$$ **Eqn. B-8**

Where:
P_{H2O} is the hourly average partial water pressure of the stack gases as calculated with Eqn. B-8, mmHg
A is a constant equal to 8.0886767

B is a constant equal to 1739.351
C is a constant equal to 234.1
T_{stack} is the hourly average stack gas temperature, °C

Appendix C Relative accuracy and bias example calculations

C-1 Assessment of SO_2 RATA			
CEMS Full Scale (FS)		500	ppm
run Avg.	RM, ppm	CEMS, ppm	d_i, ppm
1	78	73	-5
2	78.6	73	-5.6
3	76.7	72.4	-4.3
4	77.5	74.1	-3.4
5	78.7	72.2	-6.5
6	78.1	74.3	-3.8
7	77.6	72	-5.6
8	77.3	71.1	-6.2
9	79	74.5	-4.5
10	n/a	n/a	n/a
11	n/a	n/a	n/a
12	n/a	n/a	n/a

*adjusted for n-1 degrees of freedom
Average: 77.9 (RM, ppm)
Average: 73.0 (CEMS, ppm)
Sum: -45 (d_i)
Stdeva: 1.069 (d_i)
Count: 9 (d_i, ppm)
$t_{0.025}$: 2.306
$|d| = \left|\frac{\sum d_i}{n}\right|$, ppm: 4.99
$|cc| = 2.306 \times \frac{stdeva(d_i)}{\sqrt{n}}$: 0.82 ($d_i$, ppm)
is RA% less than or equal to 10%? 7.5% (d_i, ppm) (pass)
is |d| greater than Alternate RA limit, plus/minus ppm? 15.0% (pass)
is |d| greater than |cc|? (d_i, ppm) Bias
is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 0.8% (pass)
is Avg. RM greater than 30% FS? no
$BAF = \frac{Avg.\ RM}{Avg.\ CEMS}$: 1.0
runs, n=9 ($^*t_{0.025}$): 2.306
runs, n=10 ($^*t_{0.025}$): 2.262
runs, n=11 ($^*t_{0.025}$): 2.228
runs, n=12 ($^*t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$|d| = \left|\frac{\sum d_i}{n}\right|$

$|cc| = 2.306 \times \frac{stdeva(d_i)}{\sqrt{n}}$

$RM = Avg.$ of reference method measurements

$BAF = \frac{Avg.\ RM}{Avg.\ CEMS}$, if Avg RM is greater than 30% FS

Otherwise BAF equals 1

C-2 Assessment of NO_x RATA			
CEMS Full Scale (FS)		60	ppm
run Avg.	RM, ppm	CEMS, ppm	d_i, ppm
1	20.0	19.0	-1.0
2	20.1	21.8	1.7
3	20.0	22.0	2.0
4	20.1	22.3	2.2
5	19.9	21.8	1.9
6	20.2	22.3	2.1
7	20.0	19.5	-0.5
8	20.1	19.9	-0.2
9	19.9	21.9	2.0
10	n/a	n/a	n/a
11	n/a	n/a	n/a
12	n/a	n/a	n/a

*adjusted for n-1 degrees of freedom

Average: 20.0 (RM, ppm)

Average: 21.2 (CEMS, ppm)

Sum: 10 (d_i)

Stdeva: 1.3 (d_i)

Count: 9 (d_i, ppm)

$t_{0.025}$: 2.306

$|d| = \left|\frac{\sum d_i}{n}\right|$, ppm: 1.13

$|cc| = 2.306 \times \frac{stdeva(d_i)}{\sqrt{n}}$: 1.0 ($d_i$, ppm)

is RA% less than or equal to 10%? 10.60% (d_i, ppm) (fail)

is |d| greater than Alternate RA limit, plus/minus ppm? 8.0 (pass)

is |d| greater than |cc|? (d_i, ppm) Bias

is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 0.2% (pass)

is Avg. RM greater than 30% FS? yes

$BAF = \frac{Avg.\ RM}{Avg.\ CEMS}$: 0.95

runs, n=9 ($^*t_{0.025}$): 2.306

runs, n=10 ($^*t_{0.025}$): 2.262

runs, n=11 ($^*t_{0.025}$): 2.228

runs, n=12 ($^*t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$$|d| = \left|\frac{\sum d_i}{n}\right|$$

$$|cc| = 2.306 \times \frac{\text{stdeva}(d_i)}{\sqrt{n}}$$

$\text{RM} = \text{Avg. of reference method measurements}$

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$, if Avg RM is greater than 30% FS

Otherwise BAF = 1

C-3 Assessment of stack gas flow RATA			
CEMS Full Scale (FS)		30	m/s
run Avg.	RM, m/s	CEMS, m/s	d_i, m/s
1	9.0	9.1	0.1
2	9.0	9.1	0.1
3	9.0	9.1	0.1
4	9.0	9.1	0.1
5	9.0	9.1	0.1
6	9.0	9.1	0.1
7	9.0	9.1	0.1
8	9.0	9.1	0.1
9	9.0	9.1	0.1
10	n/a	n/a	n/a
11	n/a	n/a	n/a
12	n/a	n/a	n/a

*adjusted for n-1 degrees of freedom

Average: 9.0 (RM, m/s)

Average: 9.1 (CEMS, m/s)

Sum: 0.9 (d_i)

Stdeva: 0.00 (d_i, m/s)

Count: 9 (d_i, m/s)

$t_{0.025}$: 2.306

$|d| = \left|\frac{\sum d_i}{n}\right|$, m/s: 0.10

$|cc| = 2.306 \times \frac{\text{stdeva}(d_i)}{\sqrt{n}}$: 0.00

is RA% less than or equal to 10%? 1.1% (d_i, m/s) (pass)

is |d| greater than Alternate RA limit, plus/minus m/s? 0.6 (pass)

is |d| greater than |cc|? (d_i, m/s) Bias

is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 0.3% (pass)

is Avg. RM greater than 30% FS? no

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$: 1.0

runs, n=9 ($^*t_{0.025}$): 2.306

runs, n=10 ($^*t_{0.025}$): 2.262

runs, n=11 ($^*t_{0.025}$): 2.228
runs, n=12 ($^*t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$$|\mathrm{d}| = \left|\frac{\sum \mathrm{d_i}}{\mathrm{n}}\right|$$

$$|\mathrm{cc}| = 2.306 \times \frac{\mathrm{stdeva(d_i)}}{\sqrt{\mathrm{n}}}$$

$\mathrm{RM} = \mathrm{Avg.\ of\ reference\ method\ measurements}$

$\mathrm{BAF} = \frac{\mathrm{Avg.\ RM}}{\mathrm{Avg.\ CEMS}}$, if Avg RM is greater than 30% FS

Otherwise BAF = 1

C-4 Assessment of O_2 or CO_2 RATA			
CEMS Full Scale (FS)		21	% O_2 or CO_2
run Avg.	RM, %	CEMS, %	d, %
1	6.4	5.9	-0.5
2	6.3	6.1	-0.2
3	6.5	6.5	0
4	6.5	6.0	-0.5
5	6.5	6.2	-0.3
6	6.4	5.7	-0.7
7	6.4	6.0	-0.4
8	6.4	5.9	-0.5
9	6.3	6.4	0.1
10	n/a	n/a	n/a
11	n/a	n/a	n/a
12	n/a	n/a	n/a

*adjusted for n-1 degrees of freedom

Average: 6.4 (RM, %)
Average: 6.1 (CEMS, %)
Sum: -3.0 (d_i)
Stdeva: 0.261 (d_i,%)
Count: 9 (d_i, %)
$t_{0.025}$: 2.306

$|\mathrm{d}| = \left|\frac{\sum \mathrm{d_i}}{\mathrm{n}}\right|$%$O_2$ or CO_2: 0.34

$|\mathrm{cc}| = 2.306 \times \frac{\mathrm{stdeva(d_i)}}{\sqrt{\mathrm{n}}}$: 0.20

is RA% less than or equal to 10%? 8.4%
is |d| greater than Alternate RA limit, plus/minus %O2 or CO_2 :1.0
is |d| greater than |cc|? Bias
is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 0.6% (pass)
is Avg. RM greater than 30% FS? yes

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$= 1.06

runs, n=9 (*$t_{0.025}$): 2.306

runs, n=10 (*$t_{0.025}$): 2.262

runs, n=11 (*$t_{0.025}$): 2.228

runs, n=12 (*$t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$$|\text{d}| = \left|\frac{\sum \text{d}_\text{i}}{\text{n}}\right|$$

$$|\text{cc}| = 2.306 \times \frac{\text{stdeva}(\text{d}_\text{i})}{\sqrt{\text{n}}}$$

$\text{RM} = \text{Avg. of reference method measurements}$

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$, if Avg RM is greater than 30% FS

Otherwise BAF = 1

C-5 Assessment of Stack Gas Moisture RATA		
CEMS Full Scale (FS)	20	% H2O
RM, %H2O	CEMS,%H2O	d_i, % H2O
6.1	6.7	0.6
6.1	6.6	0.5
6.2	6.7	0.5
6.2	6.8	0.6
6.1	6.6	0.5
6.1	6.5	0.4
6.2	6.6	0.4
6.1	6.5	0.4
6.3	6.8	0.5

*adjusted for n-1 degrees of freedom

Average: 6.2(RM, % H2O)

Average: 6.6 (CEMS, % H2O)

Sum: 4

Stdeva: 0.078

Count: 9

$t_{0.025}$= 2.306

$|\text{d}| = \left|\frac{\sum \text{d}_\text{i}}{\text{n}}\right|$, H_2O,: 0.49

$|\text{cc}| = 2.306 \times \frac{\text{stdeva}(\text{d}_\text{i})}{\sqrt{\text{n}}}$: 0.06

is RA% less than or equal to 10%? 8.9% pass

is |d| greater than Alternate RA limit, plus/minus H_2O: 1.50 (pass)

is |d| greater than |cc|? Bias

is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 2.1% (pass)

is Avg. RM greater than 30% FS? yes

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$0.93

runs, n=9 ($^*t_{0.025}$): 2.306
runs, n=10 ($^*t_{0.025}$): 2.262
runs, n=11 ($^*t_{0.025}$): 2.228
runs, n=12 ($^*t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$$|d| = \left|\frac{\sum d_i}{n}\right|$$

$$|cc| = 2.306 \times \frac{stdeva(d_i)}{\sqrt{n}}$$

$\text{RM} = \text{Avg. of reference method measurements}$

$\text{BAF} = \frac{\text{Avg. RM}}{\text{Avg. CEMS}}$, if Avg RM is greater than 30% FS

Otherwise BAF = 1

C-6 Assessment of Stack Gas Temperature RATA			
CEMS Full Scale (FS)		500	ºC
run Avg.	RM, ºC	CEMS, ºC	d_i, ºC
1	301.1	316.3	15.2
2	294.3	308.2	13.9
3	295.2	314.7	19.5
4	300.5	295.6	-4.9
5	303.0	314.3	11.3
6	303.2	321.1	17.9
7	294.0	293.5	-0.5
8	298.4	313.4	15
9	305.0	317.0	12
10	n/a	n/a	n/a
11	n/a	n/a	n/a
12	n/a	n/a	n/a

*adjusted for n-1 degrees of freedom
Average: 299.4 (RM, ºC)
Average: 21.2 (CEMS, ºC)
Sum: 99
Stdeva: 8.277
Runs: 9
$t_{0.025}$: 2.306
$|d| = \left|\frac{\sum d_i}{n}\right|$, ºC : 11.04
$|cc| = 2.306 \times \frac{stdeva(d_i)}{\sqrt{n}}$: 6.36 (d_i, ºC)
is RA% less than or equal to 10%? 5.8% (d_i, ºC) (pass)
is |d| greater than Alternate RA limit, plus/minus ppm? 10.0 (fail)
is |d| greater than |cc|? (d_i, ºC) Bias
is $\frac{|d|-|cc|}{FS}$ less than or equal to 5.0% FS? 0.9% (pass)
is Avg. RM greater than 30% FS? yes

$\mathrm{BAF} = \frac{\mathrm{Avg.\ RM}}{\mathrm{Avg.\ CEMS}}$= 0.96
runs, n=9 ($^*t_{0.025}$): 2.306
runs, n=10 ($^*t_{0.025}$): 2.262
runs, n=11 ($^*t_{0.025}$): 2.228
runs, n=12 ($^*t_{0.025}$): 2.201

RA equations: $RA = \left[\frac{|d|+|cc|}{RM}\right] \times 100$

$|\mathrm{d}| = \left|\frac{\sum \mathrm{d_i}}{\mathrm{n}}\right|$

$|\mathrm{cc}| = 2.306 \times \frac{\mathrm{stdeva(d_i)}}{\sqrt{\mathrm{n}}}$

$\mathrm{RM} = \mathrm{Avg.\ of\ reference\ method\ measurements}$

$\mathrm{BAF} = \frac{\mathrm{Avg.\ RM}}{\mathrm{Avg.\ CEMS}}$, if Avg RM is greater than 30% FS
Otherwise BAF = 1

C-7 Grubbs Test to Identify RATA Outliers						
Run #	RM	CEMS	d_i	Grubbs	**Critical G values** for deletion of outliers	
1	72.8	75.1	2.3	0.46		
2	68.9	69.9	1	0.86	runs	G, 95% confidence
3	72	73	1	0.86	n	
4	72	73.6	1.6	0.68	6	1.82
5	68.7	69.9	1.2	0.8	7	1.94
6	70.1	76	5.9	0.65	8	2.03
7	67.6	73.8	6.2	0.74	9	2.11
8	67.5	71.6	4.1	0.1	10	2.18
9	73.3	74.5	1.2	0.8	11	2.23
10	75	80	5	0.37	12	2.29
11	80	92	12	2.54	13	2.33
12	75	79	4	0.064	14	2.37

Avg. di = $\mathrm{CEMS_i} - \mathrm{RM_i}$= 3.8
Stdeva= $\mathrm{Sdtdeva(d_i)}$ = 3.237
Set Size= $\mathrm{COUNT(d_i)}$= 12
Grubs= $\left|\frac{\mathrm{d_i - Avg.d_i}}{\mathrm{Stdeva(d_i)}}\right|$
Maximum calculated Grubbs in set= 2.54
Remove from the list the run that produces a calculated **Grubbs greater than** the **Critical G value** for the set size, starting with the maximum calculated Grubbs.
Source: Frank E. Grubbs, Procedures for Detecting Outlying Observations in Samples, Technometrics, 11:1, 1-21, (1969)