ASME PTC 40-2017
(Revision of ASME PTC 40-1991)

Flue Gas Desulfurization Units

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of
Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

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NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Code. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

When the twin issues of environmental protection and the need to assure a reliable supply of energy became important public concerns in the 1970s, The American Society of Mechanical Engineers (ASME) Board on Performance Test Codes began to explore the possibility of addressing these concerns within the test code framework. As a result of these discussions, the PTC 40 Committee on Flue Gas Desulfurization (FGD) units was organized in 1978; it held its first meeting in April 1979. The PTC 40 Code draft was approved by the Board on Performance Test Codes on May 11, 1990. The Code was adopted by the American National Standards Institute as an American National Standard on March 19, 1991.

In 2006, the ASME Performance Test Code Standards Committee restarted the PTC 40 Committee. This edition of ASME PTC 40 addresses advances in new technology. Specifically, this edition applies to different types of FGD systems: wet FGD, dry FGD, and regenerable FGD. It applies the various U.S. Environmental Protection Agency (EPA) methods that exist today.

This Code was approved by the PTC Standards Committee on March 13, 2017, and approved and adopted as an American National Standard on May 23, 2017.

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Proposing Revisions. Revisions are made periodically to the Code to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Code. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Code. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

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Interpretations. Upon request, the PTC Standards Committee will render an interpretation of any requirement of the Code. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC Standards Committee.

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at http://go.asme.org/InterpretationRequest. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the PTC Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
Edition:	Cite the applicable edition of the Code for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. Please provide a condensed and precise question, composed in such a way that a "yes" or "no" reply is acceptable.
Proposed Reply(ies):	Provide a proposed reply(ies) in the form of "Yes" or "No," with explanation as needed. If entering replies to more than one question, please number the questions and replies.
Background Information:	Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in the format described above may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Code requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

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Section 1
Object and Scope

1-1 OBJECT

The object of this Code is to establish standard procedures for conducting and reporting of performance tests of flue gas desulfurization (FGD) systems and reporting the results in terms of the following categories:

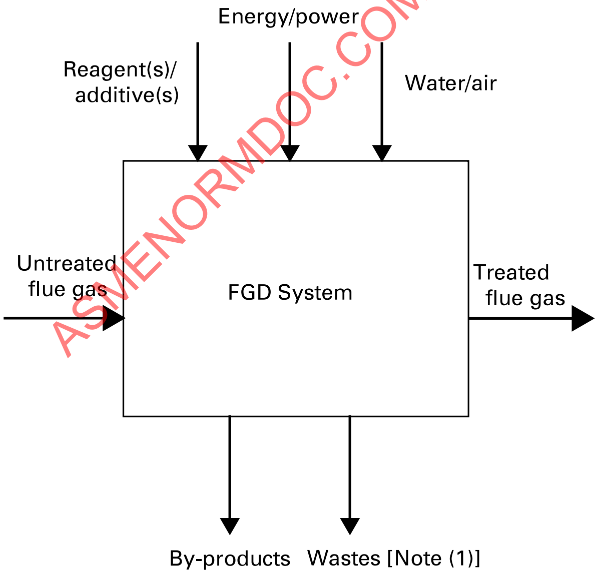
(a) emissions reduction
(b) consumables and utilities
(c) waste and by-product characterization and amount

1-2 SCOPE

The application of this Code is limited to the process and equipment employed to remove sulfur dioxides from flue gas or other sulfur-dioxide-laden gas streams. The methodology described in this Code may be adapted for assessment of removal of other emissions if agreed to by the parties to the test. The performance of an FGD system is defined to be the characterization of inputs and outputs (see Figure 1-2-1).

This Code does not apply to removal of sulfur oxides from gases during the combustion process, e.g., fluidized bed combustion (see ASME PTC 4).

Figure 1-2-1 FGD System Inputs and Outputs



NOTE: (1) Waste streams include purge streams used for process control.

This Code covers the following types of systems:

(a) Dry FGD System. An FGD system process in which a flue gas containing sulfur oxides passes through an alkaline material but is not saturated with moisture; the gas leaves the reactor at a temperature above the adiabatic saturation, thus producing a dry by-product or dry waste product.

(b) Wet FGD System. An FGD system process in which a flue gas containing sulfur oxides passes through an alkaline material and is saturated with moisture, thus producing a wet by-product or wet waste product.

(c) Regenerable FGD System. An FGD system process that regenerates and recycles the sorption medium.

This Code does not cover in detail other FGD system processes such as dry sorbent injections, seawater, and ammonia; however, the principles are still applicable.

1-3 UNCERTAINTY

The underlying philosophy of this Code is to achieve test results of the lowest uncertainty based on current technology and knowledge with respect to testing, taking into account test cost and value of the information obtained. To accomplish this and because of the various FGD systems covered by this Code, this Code establishes an upper limit of the uncertainty of each parameter. Exceeding the upper limit of any parameter's uncertainty requirement is allowable only if it is demonstrated that the selection of all instrumentation for a test will result in a test uncertainty equal to or less than what it would have been had all parameters' uncertainty requirements been followed.

A pretest uncertainty analysis is required. It serves to establish the expected level of uncertainty for a test. The pretest uncertainty shall be calculated in accordance with the procedures defined herein and by ASME PTC 19.1.

A post-test uncertainty analysis is also required. It is used to determine the uncertainty for the actual test. This analysis should confirm the pretest systematic and random uncertainty estimates, and validate the quality of the test results.

The maximum uncertainty for the tests permitted by this Code could be influenced by the physical configuration and FGD system process, as well as the sensitivity of the corrected results to the process variables. The sum of the applicable test uncertainty limits of each parameter shown in Table 1-3-1 shall result in the expected test uncertainty for that parameter.

Table 1-3-1 Expected Test Uncertainties

Parameter	Expected Uncertainty, %
Measured SO_2	±5
SO_2 removal efficiency	±1
Reagent consumption	±5
Electrical power consumption	±1.5
Water consumption by calculation	±10
Water consumption by direct measurement	±2
Flue gas pressure drop	±1.5

Section 2
Definitions and Descriptions of Terms

2-1 DEFINITIONS

additive: substance added to a liquid or gas stream to cause a chemical or physical reaction to enhance the SO_2 sorption process; generally, the additive is not consumed as part of the absorption reaction. Other substances can be added and should be recorded, but for the purposes of this Code, only those mentioned in subsection 1-2 are being addressed.

alkalinity: capacity of an alkaline material to neutralize SO_2.

alkalinity, reactive: alkalinity determined by acid titration and expressed as moles of alkali per mole of SO_2 (absorbed or inlet).

alkalinity, total: theoretical expression of alkalinity determined from a chemical analysis of the material.

by-product: material generated by the removal of SO_2 with the FGD system that has commercial value.

consumption, compressed air: compressed air consumed by the FGD system.

consumption, energy/power: compilation of all energy/power inputs to the FGD system.

consumption, water: water added to the FGD system.

effluent: stream exiting the FGD system, whether solid, liquid, or gas (except treated flue gas).

emission rate (E_{SO2}): mass rate at which SO_2 is emitted.

entrainment: suspension of liquid droplets in the flue gas stream.

flue gas: gaseous products of combustion.

flue gas desulfurization (FGD) system: the process and equipment employed to remove sulfur oxides from flue gas or other sulfur-oxide-laden gas stream. The system may include process or equipment required for the conversion of the sulfur oxides to an essentially nonvolatile sulfur species for disposal or other use. The to-be-treated gas stream or streams are typically generated by the combustion of fossil fuels, but may include other gas streams (e.g., from smelting processes). The definition of FGD system in this Code does not address the removal of sulfur oxides from gases directly during the combustion process.

grit: impurities in as-received calcined lime, e.g., uncalcined carbonate, hard-burned lime, insoluble silicates, aluminates, sulfates, and ferrites, that were in the limestone before it was calcined. Grit may also include some external impurities, e.g., refractory brick pieces and tramp iron.

L/G ratio: liquid-to-gas ratio is defined as the volumetric flow rate of reagent-laden liquid per volumetric flow rate of flue gas. Flue gas volume is typically based on saturated gas flow.

liquor: solution of liquid and dissolved solids.

purge stream: process stream that exits the FGD system and is considered part of waste streams. It is controlled to maintain FGD system operating parameters and chemistry within a certain value.

reagent: any chemical compound, usually an alkali, used in the FGD system either to remove SO_2 by chemical reaction or to regenerate another chemical compound.

reagent liquor/slurry: medium by which one or more reagents are added to an FGD system process.

reheat: heat-addition process by which the temperature of the outlet flue gas (stack gas) from the absorber is increased.

removal efficiency (%R): ratio of removed SO_2 to input SO_2, expressed in percent.

run: as used throughout this Code, a subdivision of the test. A run consists of a complete set of observations and recorded data taken at regular intervals, made for a period of time with the independent variables maintained constant within the variations permitted by the parties to the test.

slurry: mixture of liquid and suspended solids.

standard conditions (S): defined as 20°C (68°F) for temperature and 760 mm Hg (29.92 in. Hg) for atmospheric pressure.

steady state: condition of the system when transients (e.g., pressure, temperature, concentration, and flow rate) in the system have dampened out and the system is in chemical and thermodynamic equilibrium.

Table 2-2.1-1 Symbols and Descriptions of Constants

		Values and Units		
Symbol	**Description**	**SI**	**Metric Customary**	**Industry Customary**
K_1	Concentration conversion factor	1	1	1.660×10^{-7} (lb/dscf)/ppm
K_2	Mass conversion factor	1	kg/10^6 mg	1
M_{CaCO3}	Molecular weight of $CaCO_3$	100.09 kg/kg-mol	100.09 g/g-mol	100.09 lb/lb-mol
M_{CaO}	Molecular weight of CaO	56.08 kg/kg-mol	56.077 g/g-mol	56.08 lb/lb-mol
M_{SO2}	Molecular weight of SO_2	64.06 kg/kg-mol	64.064 g/g-mol	64.06 lb/lb-mol
N	Normality of acid solution	2	2	2
P_{std}	Standard absolute pressure	1.013×10^5 N/m^2 [Note (1)]	7.60×10^2 mm Hg	2.992×10^1 in. Hg
R	Ideal gas constant	$8.314 \times 10^{-3} \dfrac{\text{J}}{(\text{kg-mol})\text{K}}$	$6.236 \times 10^{-2} \dfrac{(\text{mm Hg})\text{m}^3}{(\text{g-mol})\text{K}}$	$2.185 \times 10^{1} \dfrac{(\text{in. Hg})\text{ft}^3}{(\text{lb-mol})^\circ\text{R}}$
T_{std}	Standard absolute temperature (20°C/68°F)	293.16 K	293.16 K	527.67°R

NOTE: (1) N/m^2 = Pa.

stoichiometric ratio, inlet basis (SRI): moles of reactive alkali added per moles of SO_2 inlet. SRI is normally used in dry-scrubbing processes (e.g., spray dryers, circulating-dry-scrubbers type dry reactors).

stoichiometric ratio, removal basis (SRR): moles of reactive alkali added per moles of SO_2 removed. SRR is normally used in wet scrubbing processes.

temperature, adiabatic saturation: for a given mixture of gas and vapor, temperature below which no more vapor can be added at specified conditions (partial pressure of vapor is equal to vapor pressure of the liquid at the gas–vapor mixture temperature).

temperature, approach to adiabatic saturation: difference between the actual temperature of a given gas–vapor mixture and the adiabatic saturation temperature of that gas–vapor mixture.

test: throughout this Code, the word "test" is applied only to the entire performance evaluation.

waste: material generated by the removal of SO_2 with the FGD system that has no commercial value and requires disposal; it may include purge streams.

2-2 DESCRIPTIONS OF TERMS

2-2.1 Constant Terms

The constants shown in Table 2-2.1-1 are defined in three different sets of units. In this Code, International System (SI) units are the primary units, and Metric Customary (MC) units and U.S. Industry Customary (IC) units are provided as secondary units. These terms are used in Section 5 and elsewhere in this Code.

Some of the U.S. Industry Customary units are seemingly unusual combinations of other sets of units [e.g., concentration conversion factor $K_1 = 1.660 \times 10^{-7}$ (lb/dscf)/ppm]. These units arise from their use in analytical measurement devices and are the standard units used in the industry.

2-2.2 Variable Terms

The variables shown in Table 2-2.2-1 are defined in the same three sets of units as are shown in Table 2-2.1-1. The Metric Customary or Industry Customary units are most commonly used in testing.

2-3 ABBREVIATIONS

The following abbreviations are used throughout the text of this Code:

acfm: actual cubic feet per minute
AR: absorber recycle
Ar: argon
As: arsenic
BOD_5: biological oxygen demand during 5 days of incubation (by aerobic biological organisms to break down organic material)
C: carbon
$CaCl_2$: calcium chloride
$CaCO_3$: calcium carbonate
CaO: calcium oxide
$Ca(OH)_2$: calcium hydroxide
$CaSO_3$: calcium sulfite
$CaSO_4$: calcium sulfate
Cd: cadmium
CEMS: continuous emission monitoring system
Cl: chloride
Co: cobalt
CO_2: carbon dioxide
COD: chemical oxygen demand
Cr: chromium
Cu: copper
dscf: dry standard cubic foot
EPA: U.S. Environmental Protection Agency

Table 2-2.2-1 Symbols and Descriptions of Variables

Symbol	Description	Units		
		SI	MC	IC
A_{CS}	Cross-sectional area of tank	m^2	m^2	ft^2
$C_{Cl,P}$	Concentration of chloride in purge stream	mg/L	mg/L	ppm
C_{SO2}	SO_2 dry mass concentration at uncorrected conditions	mg/m^3 i.N. ($mg/N{\cdot}m^3$) [Note (1)]	mg/m^3 i.N. ($mg/N{\cdot}m^3$) [Note (1)]	ppmdv
$C_{SO2,Corr}$	Corrected SO_2 concentration at reference %O_2	mg/m^3 i.N. ($mg/N{\cdot}m^3$) [Note (1)]	mg/m^3 i.N. ($mg/N{\cdot}m^3$) [Note (1)]	ppmdv
E	Total electric energy used during sample time	W·s	kW·h	kW·h
E_{SO2}	SO_2 emission rate	ng/J	ng/J	lb/MBtu
F_c	Carbon-dioxide-based *F* factor; ratio of the gas volume of combustion components (carbon dioxide only) per unit of heat content of the fuel (EPA Method 19)	scm/J (20°C, 1 atm)	scm/J (20°C, 1 atm)	scf/MBtu (68°F, 29.92 in. Hg)
F_d	Oxygen-based *F* factor; ratio of the gas volume of combustion components (excluding water) per unit of heat content of the fuel (EPA Method 19)	scm/J (20°C, 1 atm)	scm/J (20°C, 1 atm)	scf/MBtu (68°F, 29.92 in. Hg)
G_r	Average molecular reagent flow rate during any particular FGD system run for reagent, *r*	kg-mol/s	g-mol/s	lb-mol/s
G_{rt}	Average total flow rate of all reagents into the FGD system during any particular FGD system run	kg-mol/s	g-mol/s	lb-mol/s
G_s	Average mass flow rate of reagent, corrected for purity	kg/s	g/min	lb/min
G_{SO2}	Mass flow rate of SO_2	kg/h	kg/h	lb/hr
G_{solids}	Mass flow of solids in slurry (cumulative)	kg/h	kg/h	lb/hr
HHV	Higher heating value	kJ/kg	kcal/kg	Btu/lb
HI	Heat input	J/s	cal/s	Btu/hr
h_{in}	Enthalpy of heating fluid at inlet of heat exchanger	J/g	cal/g	Btu/lb
h_{out}	Enthalpy of heating fluid at outlet of heat exchanger	J/g	cal/g	Btu/lb
L_i	Tank level of the reagent tank at time interval, *i*	m	m	ft
L_o	Initial level of the reagent tank at the start of the FGD system run	m	m	ft
m	Mass of heating medium other than fuel	kg	kg	lb
m_{fuel}	Mass of heating fuel	kg	kg	lb
P_{in}	Inlet pressure	Pa	mbar	in. H_2O
P_{out}	Outlet pressure	Pa	mbar	in. H_2O
PR	Reagent purity (mass fraction)	...	...	...
Q_{CaO}	Average volumetric flow rate of CaO consumed	m^3/s	m^3/min	gpm
Q_P	Average volumetric flow rate of the purge stream	m^3/s	m^3/min	gpm
Q_s	Average volumetric flow rate of reagent liquor/slurry discharged into the FGD system during any particular FGD system run	m^3/s	m^3/min	gpm
Q_{sd}	Dry volumetric stack gas flow rate corrected to standard conditions	m^3/s dry (20°C, 1 atm) [Note (2)]	m^3/h i.N. dry ($N{\cdot}m^3/h$ d) (20°C, 1 atm) [Notes (1) and (2)]	dscf/min (68°F, 29.92 in. Hg) [Note (2)]

Table 2-2.2-1 Symbols and Descriptions of Variables (Cont'd)

Symbol	Description	Units		
		SI	MC	IC
$r\%$	Average weight percentage of reagent r in the reagent liquor/slurry analyses for any particular FGD system run	%	%	%
SRI	Stoichiometric ratio based on inlet SO_2	...	...	...
SRR	Stoichiometric ratio based on removal SO_2	...	...	...
t	Duration of any particular FGD system run	s	min	min
V_s	Volume of sample	m^3	ml	ml
V_t	Volume of acid solution used to titrate	m^3	ml	L
wt%	Weight percentage of reagent/slurry	%	%	%
%MCR	Percent maximum continuous rating condition	...	...	...
$\%O_2$	Percent O_2 in flue gas by volume, dry basis	%	%	%
$\%O_{2\ \mathrm{Ref}}$	Percent O_2 reference	...	...	...
$\%R$	Percent SO_2 removal (mass or molar)	%	%	%
ΔH	Average pressure drop across orifice meter	N/m^2	mm H_2O	in. H_2O
ΔP_{TOT}	Total pressure drop	Pa	mbar	in. H_2O
ρ_g	Density of the FGD system inlet flue gas flow traverse	kg/m^3	g/m^3	lb/gal
ρ_S	Density of the reagent liquor/slurry as analyzed	kg/m^3	g/m^3	lb/gal

NOTES:

(1) i.N. is "in Normal" conditions, i.e., at 0°C, 1 atm. In the past it was often abbreviated by "N," e.g., Nm^3 instead of m^3 i.N. The unit N in most recent context is reserved for "newton."

(2) Conditions in parentheses are the standard conditions for those units of measurement.

EPRI: Electric Power Research Institute
F: fluoride
Fe_2O_3: iron oxide
FGD: flue gas desulfurization
H: hydrogen
HCl: hydrochloric acid
Hg: mercury
HHV: higher heating value
H_2O: water
MBtu: one million British thermal units (in the United States, often referred to as MMBtu or mmBtu)
MCR: maximum continuous rating condition (of a boiler)
$MgCO_3$: magnesium carbonate
MgO: magnesium oxide
$Mg(OH)_2$: magnesium hydroxide
Mn: manganese
N_2: nitrogen gas
$NaHCO_3$: sodium bicarbonate
NaOH: sodium hydroxide
O_2: oxygen
OEM: original equipment manufacturer
Pb: lead
ppmdv: parts per million by dry volume
R_2O_3: generic expression from trivalent metal oxides, with R (including Fe, Al, Cr)
RATA: relative accuracy test audit
Sar: sulfur content in coal, as received
scf: standard cubic feet
scfm: standard cubic feet per minute
scm: standard cubic meter
Se: selenium
SEM: scanning electron microscope
SiO_2: silicon dioxide (silica)
SO_2: sulfur dioxide
SO_3: sulfite ion
SO_4: sulfate ion
SRI: stoichiometric ratio, inlet based
SRR: stoichiometric ratio, removal based
TDS: total dissolved solids
TGA: thermogravimetric analysis
TSS: total suspended solids
V: vanadium
XRF: x-ray fluorescence
Zn: zinc

Section 3
Guiding Principles

3-1 INTRODUCTION

This Section provides guidance on the conduct of overall plant testing, and outlines the steps required to plan, conduct, and evaluate a Code test of FGD system performance.

This Code includes procedures for testing the FGD system to determine various types of test goals. It also provides specific instructions for multiple-party tests conducted to satisfy or verify guaranteed performance specified in a commercial agreement.

3-1.1 Test Goals

The goal of this Code is to establish the performance level of an FGD system for the established design conditions. The testing includes comparing actual performance to guarantee or reference performance for the following criteria as applicable:

(a) percent SO_2 removal efficiency
(b) actual SO_2 emission rate
(c) reagent consumption as a stoichiometric value or actual mass rate
(d) water and compressed air consumption
(e) wastewater flow rate and characterization
(f) by-product characterization
(g) electric power consumption
(h) pressure drop
(i) steam use

3-1.2 General Precautions

Reasonable precautions should be taken when preparing to conduct a Code test. Indisputable records shall be made to identify and distinguish the equipment to be tested and the exact method of testing selected. Descriptions, drawings, or photographs all may be used to serve as a permanent, explicit record. Instrument location shall be predetermined, agreed to by the parties to the test, and described in detail in test records. Redundant, calibrated instruments should be provided for those instruments susceptible to in-service failure or breakage.

3-1.3 Agreements and Compliance to Code Requirements

This Code is suitable for use whenever performance shall be determined with minimum uncertainty. Strict adherence to the requirements specified in this Code is critical to achieving that objective.

3-1.4 Acceptance Tests

This Code may be incorporated by reference into contracts to serve as a means to verify commercial guarantees for FGD system performance. If this Code is used for guarantee acceptance testing or for any other tests where there are multiple parties represented, those parties shall mutually agree on the exact method of testing and the methods of measurement, as well as any deviations from the Code requirements.

3-1.4.1 Prior Agreements. The parties to the test shall agree on all material issues not explicitly prescribed by the Code as identified throughout the Code and summarized as follows:

(a) approval of the test plan by all parties to the test
(b) designation of representatives from each of the parties to the test
(c) contract or specification requirements regarding operating conditions, base reference conditions, performance guarantees, test boundary, and environmental compliance
(d) requirements in support of a Code test, including test fuel supply and thermal and electrical host's ability to accept loads
(e) notification requirements prior to test preparation to ensure all parties have sufficient time to be present for the test
(f) reasonable opportunity to examine the plant and agree that it is ready to test
(g) modifications to the test plan based on preliminary testing
(h) valve lineup checklist
(i) operations of equipment outside of the suppliers' instructions
(j) plant stability criteria prior to starting a test
(k) permissible adjustments to plant operations during stabilization and between test runs
(l) duration of test runs
(m) resolution of nonrepeatable test run results

(n) criteria for rejection of test readings

3-1.4.2 Data Records and the Test Log. A complete set of data and a complete copy of the test log shall be provided to all parties to the test. All data and records of the test shall be prepared to allow for clear and legible reproduction. The completed data records shall include the date and time of day the observation was recorded. The observations shall be the actual readings without application of any instrument corrections. The test log should constitute a complete record of events. Erasures on or destruction or deletion of any data record, page of the test log, or any recorded observation is not permitted. If a correction is made to a record or log, the alteration shall be entered so that the original entry remains legible and an explanation is included. Manually collected test data and observations shall be entered on prepared forms that constitute original data sheets authenticated by the test participants' signatures. Where automatic data collection methods are used, printed output or electronic files shall be authenticated by the test coordinator and other representatives of the parties to the test. When no paper copy is generated, the parties to the test shall agree in advance to the method used for authenticating, reproducing, and distributing the data. The electronic data files shall be copied onto electronic media and distributed to each of the parties to the test. The data files shall be in a format that is easily accessible to all.

3-1.5 Test Boundary

The test boundary identifies the energy streams that shall be measured to calculate corrected results. The test boundary is an accounting concept used to define the streams that shall be measured to determine performance. All input and output energy streams required for test calculations shall be determined with reference to the point at which they cross the boundary. Energy streams within the boundary need not be determined unless they verify base operating conditions or they relate functionally to conditions outside the boundary.

The methods and procedures of this Code have been developed to provide flexibility in defining the test boundary for a test. In most cases, the test boundary encompasses all equipment and systems on the FGD system site. However, specific test objectives may mandate a different test boundary.

For this Code to apply, the test boundary shall encompass a discrete FGD system. This means that the following energy streams shall cross the boundary:

(a) untreated flue gas
(b) reagent(s)/additives
(c) energy/power
(d) water/air
(e) by-products
(f) wastes
(g) treated flue gas

For a particular test, the specific test boundary shall be established by the parties to the test.

3-1.6 Required Measurements

Some flexibility is required by this Code in defining the test boundary, since it is somewhat dependent on a particular plant design. In general, measurements or determinations are required for the following:

(a) Flue Gas Flow. Flue gas flow is measured into or out of the FGD system. The location for volumetric flow measurement should be selected based on the highest reasonable accuracy that can be obtained. Measurement points in ducts should have at least eight equivalent diameters straight length upstream and two equivalent straight lengths downstream from the measurement point. Many FGD systems do not have the space to allow optimal flow measurement at the FGD system inlet. The outlet ducting may also have suboptimal locations for flow measurement. An engineering analysis for a flow straightener may be developed to ensure adequate flow measurement accuracy. If the ductwork design is not suitable for flue gas flow measurements, the flue gas flow from the boiler may be calculated using heat and mass balance around the boiler. This calculation can also be used to confirm flue gas flow measurements completed at the FGD system inlet.

As an alternative, the flue gas flow may be measured at the stack. Stack flow measurement may be preferred since emissions testing ports are generally available, sufficient upstream and downstream straight lengths are available, and emissions compliance monitoring is often conducted concurrently with the FGD system performance test.

If the stack is the location for the flow measurement, careful evaluation of potential error in the measurement should be made. Flue gas leakage or air in-leakage potential should be considered.

(b) Reagent(s) or Additives. The quality, analysis, and quantity of reagent or other chemical additives that affect the corrected removal efficiency or corrected stoichiometric ratio shall be determined for correction to the design conditions. Corrections for reagent injection rate are limited to variations attributable to differences between test and design reagent characteristics.

(c) Energy/Power. The total power consumption for the installed equipment is determined through the use of watt-hour meters, and the total average power consumption is determined by averaging continuous amperage measurements at the electrical feeds to the switchgear. These tests shall determine the maximum instantaneous and average power requirements over the test period(s).

(d) Water and Air. The installed flowmeters at the tie-in points shall be used to continuously measure the consumption of water and/or air. These values shall then be corrected for process variations (gas temperature,

composition, etc.) prior to being compared to the guaranteed values.

(e) Waste and/or By-Product. The quality and quantity of waste or by-products are dependent on the specification requirements that may include excess reagent measured in the by-product. To test the quality of the waste or by-products, samples shall be taken and analyzed for each test run or based on an overall composite. Quantities of liquid or solid waste or by-products need to be measured by applicable test methods.

3-1.7 Criteria for Selection of Measurement Locations

Measurement locations are selected to provide the lowest level of measurement uncertainty. The preferred location is at the test boundary, but only if the measurement location is the best location for determining required parameters.

3-1.8 Specific Required Measurements

The specific measurements required for a test depend on the particular FGD system design and the test boundary required to meet the specific test intent.

3-1.9 Design, Construction, and Start-Up Considerations

During the design phase of the FGD system, consideration should be given to accurately conducting acceptance testing for its performance. Consideration should also be given to the requirements of instrumentation accuracy, calibration, recalibration, documentation requirements, and location of permanent plant instrumentation to be used for testing. Adequate provisions for installation of temporary instrumentation where plant instrumentation is not adequate to meet the requirements of this Code shall also be considered during the design stages.

3-2 TEST PLAN

A detailed test plan shall be prepared prior to conducting a Code test to document all issues affecting the conduct of the test and to provide detailed procedures for performing the test.

The test plan should include the schedule of test activities, designation and description of responsibilities of the test team, test procedures, and report of results.

3-2.1 Schedule of Test Activities

A test schedule should be prepared that includes the sequence of events and anticipated time of test, notification of the parties to the test, test plan preparations, test preparation and conduct, and preparation of the report of results.

3-2.2 Test Team

The test plan shall identify the test team organization that shall be responsible for the planning and preparation, conduct, analysis, and reporting of the test in accordance with this Code. The test team should include test personnel needed for data acquisition, sampling and analysis, and operations; other groups needed to support the test preparations and implementation; and outside laboratory and other services.

A test coordinator shall be designated and shall be responsible for executing the test in accordance with the test requirements. The test coordinator shall be responsible for establishing a communication plan for all test personnel and all parties to the test. The test coordinator shall also ensure that complete written records of all test activities are prepared and maintained. The test coordinator shall coordinate the setting of required operating conditions with the plant operations staff.

The parties to the test shall observe the test and confirm that it was conducted in accordance with the test requirements. They should also have the authority, if necessary, to approve any agreed-upon revisions to the test requirements during the test.

It is recommended that the test team meets the requirements of ASTM D7036 or ISO 17025.

3-2.3 Test Procedures

The test plan should include test procedures that provide details for the conduct of the test. The following are included in the test procedures:

(a) object of test

(b) method of operation

(c) test acceptance criteria for test completion

(d) base reference conditions

(e) defined test boundary identifying inputs and outputs and locations of measurements

(f) operating, performance, and environmental requirements

(g) complete pretest uncertainty analysis, with systematic uncertainties established for each measurement and an estimate of random uncertainties

(h) specific type, location, and calibration requirements for all instrumentation and measurement systems, and frequency of data acquisition

(i) measurement requirements for applicable emissions, including measurement location, instrumentation, and frequency and method of recording

(j) sample, collection, handling, and analysis method and frequency for fuel, reagent, by-product, etc.

(k) method of plant operation

(l) identification of testing laboratories to be used for fuel, reagent, reactivity, and by-product analyses

(m) required operating disposition or accounting for all internal thermal energy and auxiliary power consumers having a material effect on test results

(n) required levels of equipment cleanliness and inspection procedures

(o) procedures to account for performance degradation, if applicable

(p) valve lineup requirements

(q) preliminary testing requirements

(r) pretest stabilization criteria

(s) required steadiness criteria and methods of maintaining operating conditions within these limits

(t) allowable variations from base reference conditions, and methods of setting and maintaining operating conditions within these limits

(u) number of test runs and durations of each run

(v) test start and stop requirements

(w) data acceptance and rejection criteria

(x) allowable range of fuel, reagents, additives, and other inputs

(y) correction curves with curve-fitting algorithms, foundation data, or a performance model

(z) sample calculations or detailed procedures specifying test-run data reduction, and calculation and correction of test results to base reference condition

(aa) the method for combining test runs to calculate the final test results

(bb) requirements for data storage, document retention, and test report distribution

(cc) test report format, contents, inclusions, and index

3-3 TEST PREPARATIONS

All parties to the test shall be given timely notification, as defined by prior agreement, to allow them the necessary time to respond and to prepare personnel, equipment, or documentation. Updated information should be provided as it becomes known.

A test log shall be maintained during the test to record any occurrences affecting the test, the time of the occurrence, and the observed resultant effect. This log becomes part of the permanent record of the test.

The safety of personnel and care of instrumentation involved in the test should be considered. For example, personnel should have safe access to test point locations, and should be provided with suitable utilities and safe work areas. Appropriate measures should be taken to prevent extreme temperature, vibration, or other ambient conditions from damaging instrumentation or shifting its calibration.

Documentation shall be developed or be made available for calculated or adjusted data to provide independent verification of algorithms, constants, scaling, calibration corrections, offsets, base points, and conversions.

3-3.1 Test Apparatus

Instrumentation used for data collection shall be at least as accurate as instrumentation identified in the pretest uncertainty analysis. This instrumentation may be either permanent plant instrumentation or temporary test instrumentation.

3-3.2 Data Collection

Data shall be recorded by automatic data-collecting equipment or by a sufficient number of competent observers. Automatic data logging and advanced instrument systems shall be recently calibrated to the required accuracy. No observer shall be required to take so many readings that lack of time may result in insufficient care and precision. Consideration shall be given to specifying duplicate instrumentation and taking simultaneous readings for certain test points to attain the specified accuracy of the test.

3-3.3 Location and Identification of Instruments

Transducers shall be located to minimize the effect of ambient conditions, e.g., temperature or temperature variations, on uncertainty. Care shall be used in routing lead wires to the data collection equipment to prevent electrical noise in the signal. Manual instruments shall be located so that they can be read with precision and convenience by the observer. All instruments shall be marked uniquely and unmistakably for identification. Calibration tables, charts, or mathematical relationships shall be readily available to all parties to the test. Observers recording data shall be instructed on the desired degree of precision of readings.

3-3.4 Test Personnel

Test personnel are required in sufficient number and expertise to support the execution of the test (see para. 3-2.2). Operations personnel shall be sufficiently familiar with the test operating requirements to operate the equipment accordingly.

3-3.5 Equipment Inspection and Cleanliness

Since an ASME PTC 40 test is not intended to provide detailed information on individual components, this Code does not provide corrections for the effect of any equipment that is not in a clean and functional state. Prior to conducting a test, the cleanliness, condition, and age of the equipment should be determined by inspection of equipment and/or review of operational records. Cleaning should be completed prior to the test, and equipment cleanliness agreed upon by the parties to the test.

The plant should be checked to ensure that equipment and subsystems are installed and operating in accordance with their design parameters and that the plant is ready to test.

When the manufacturer or supplier is a party to the test, they should have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust equipment or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the equipment for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions. Any actions taken shall be documented and immediately reported to all parties to the test.

3-3.6 Preliminary Test Run

Preliminary test runs, with records, serve to determine if equipment is in suitable condition to test, to check instruments and methods of measurement, to check adequacy of organization and procedures, and to train personnel. All parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If such a preliminary test run complies with all the necessary requirements of the appropriate test code, it may be used as an official test run within the meaning of the applicable code. Reasons for a preliminary run may include, but are not limited to, the following:

(a) to determine whether the plant equipment is in suitable condition for the conduct of the test
(b) to make adjustments, the needs of which were not evident during the preparation of the test
(c) to check the operation of all instruments, controls, and data acquisition systems
(d) to ensure that the estimated uncertainty as determined by the pretest analysis is reasonable by checking the complete system
(e) to ensure that the facilities operation can be maintained in a steady-state performance
(f) to ensure that the fuel and reagent characteristics and analyses are within permissible limits (refer to Table 3-4.2.5-1), and that sufficient quantity is on hand to avoid interrupting the test
(g) to ensure that process boundary inputs and outputs are not constrained other than those identified in the test requirements
(h) to familiarize test personnel with their assignments
(i) to retrieve sufficient data to fine-tune the control system if necessary

3-4 CONDUCT OF TEST

This subsection provides guidelines on the actual conduct of the performance test.

3-4.1 Starting and Stopping Tests and Test Runs

The test coordinator is responsible for ensuring that all data collection begins at the agreed-upon start of the test, and that all parties to the test are informed of the starting time.

3-4.1.1 Starting Criteria. Prior to the start of each performance test, the following conditions shall be satisfied:

(a) *Test Requirements.* The agreed-upon test requirements for operation, configuration, and disposition for testing have been met, including
   (1) equipment operation and method of control unit configuration, including required process waste or by-product flow
   (2) valve lineup
   (3) availability of consistent fuel and reagent(s) within the allowable limits for the test (by analysis as soon as practicable preceding the test)
   (4) plant operation within the bounds of the performance correction curves, algorithms, or programs
   (5) equipment operation within agreed-upon limits and operating modes
   (6) for a series of test runs, completion of internal adjustments required for repeatability
(b) *Stabilization.* The plant has operated for a sufficient period of time at test load to demonstrate and verify stability in accordance with the criteria in para. 3-4.2.
(c) *Data Collection.* Data acquisition system or systems are functioning, and test personnel are in place and ready to collect samples or record data.

3-4.1.2 Stopping Criteria. Tests are normally stopped when the test coordinator is satisfied that requirements for a complete test run have been satisfied (see paras. 3-4.4 and 3-4.5). The test coordinator should verify that methods of operation during test, specified in para. 3-4.2, have been satisfied. The test coordinator may extend or terminate the test if the requirements are not met.

Data logging should be checked to ensure completeness and quality. After all test runs are completed, equipment operating only for purposes of the test (such as vent steam) should be secured and, if appropriate, operation control should be returned to normal dispatch functions.

3-4.2 Methods of Operation Prior to and During Tests

All equipment necessary for normal and sustained operation at the test conditions shall be operated during the test or accounted for in the corrections. Intermittent operation of equipment within the test boundary should be accounted for in a manner agreeable to all parties.

Operating equipment includes, but is not limited to, material handling equipment, wastewater treatment equipment, environmental control equipment, and sump pumps.

3-4.2.1 Operating Mode. The operating mode of the plant during the test should be consistent with the goal of the test. The corrections used in the general

Table 3-4.2.4-1 Test Proximity to Design Conditions

Parameter	Test Criteria [Note (1)]
Sulfur loading at inlet to FGD system process	<20% differential
Flue gas mass flow rate	90% to 100% of design/ performance point
Average inlet flue gas temperature	±10°C (18°F)
Fly ash mass loading	≤ maximum design rate
Reagent reactivity	Within contractual or agreed-upon limits
Reagent purity	Within contractual or agreed-upon limits

NOTE: (1) Contract or agreed-upon criteria may be different and, if so, may be substituted for the values listed in this Table.

performance equation and the development of correction curves are affected by the operating mode of the plant.

The plant equipment should be operated in a manner consistent with the basis of design or guarantee, and that will permit correction from test operating conditions to base reference conditions.

3-4.2.2 Valve Lineup and System Isolation. A system isolation checklist shall be developed to meet the goals of the test. The checklist should be divided into three categories, as follows:

(a) *Manual Valve Isolation Checklist.* The manual valve isolation checklist should be a list of manual valves that should be closed during normal operation, and that affect the accuracy or results of the test if they are not secured. These valve positions should be checked before and after the test.

(b) *Automatic Valve Isolation Checklist.* The automatic valve isolation checklist is a list of valves that should be closed during normal operation but may, from time to time, cycle open. As in (a), these are the valves that affect the accuracy or results of the test if they are not secured. These valve positions should be checked prior to the preliminary test and monitored during subsequent testing. (To the extent available from the plant control system, these valve positions should be continually monitored during the test.)

(c) *Test Valve Isolation Checklist.* The test valve isolation checklist is a list of those valves that should be closed during the performance test. These valves should be limited to valves that shall be closed to accurately measure the FGD system performance during the test.

No valves normally open should be closed for the sole purpose of changing the maximum performance of the plant.

The valves on the test valve isolation checklist should be closed prior to the preliminary test. The valves may need to be opened between test runs.

Effort should be made to eliminate leaks through valves that are required to be closed during the test, and to determine the magnitude of any valve through-leakage if elimination is not possible.

3-4.2.3 Equipment Operation. Plant equipment required for normal plant operation shall be operated as defined by the respective equipment suppliers' instructions (to support the overall objectives of the plant test). Equipment that is necessary for plant operation or that would normally be required for the plant to operate at base reference conditions shall be operating or accounted for in determining auxiliary power loads. An equipment checklist for electrical auxiliaries shall be developed.

The equipment checklist shall include a tabulation of the required operating disposition of all electric and nonelectric internal energy consumers that have the potential to affect corrected FGD system performance by more than 25 kW, as well as the actual status during testing, provided the total energy consumption of small energy users does not add up to more than 2%.

Any changes in equipment operation that affect test results by more than 2% will invalidate a test run, or may be quantified and included in test result calculations. A switchover to redundant equipment, e.g., a standby pump, is permissible. Intermittent nonelectrical internal energy consumption and electrical auxiliary loads, e.g., prorating or proportioning, shall be accounted for in an equitable manner and applied to the power consumption of a complete equipment operating cycle over the test period. Examples of intermittent loads include wastewater treatment regeneration, makeup water pump, material handling, FGD system purge, heat tracing, and flue gas reheating.

3-4.2.4 Proximity to Design Conditions. It is desirable to operate the plant during the test as closely as possible to the base reference performance conditions, and within the allowable design range of the plant and its equipment so as to limit the magnitude of corrections to removal efficiency and stoichiometric ratio. Table 3-4.2.4-1 was developed based on limiting the overall test uncertainties. Excessive corrections to plant performance parameters can adversely affect overall test uncertainty. To maintain compliance with Code requirements, the actual test should be conducted within the criteria given in Table 3-4.2.4-1 or other operating criteria that result in overall compatibility with test uncertainty targets.

3-4.2.5 Stabilization. The length of operating time necessary to achieve the required steady state should depend on previous operations; see Table 3-4.2.5-1.

3-4.2.6 Boiler Load. A test may be conducted at any load condition, as required to satisfy the goals of the test. At no time should the actual test conditions exceed any equipment ratings provided by the manufacturer.

3-4.2.7 Fuel and Reagent(s). Consumption and properties of fuel and reagent(s) should be maintained as constant as practicable for the duration of the preliminary test and actual test. Permissible deviations in fuel

Table 3-4.2.5-1 Stabilization Parameters for FGD System

Parameter	Maximum Allowable Variation in Parameters for Wet and Dry FGD System: From 48 h to 8 h Prior to Data Collection [Note (1)]	Maximum Allowable Variation in Parameters for Wet and Dry FGD System: From 8 h Prior to Data Collection Through Data Collection [Note (1)]
Boiler load, MW gross [Note (2)]	20%	5%
Absorber gas flow, scfm [Note (2)]	20%	10%
FGD system inlet temperature	30°C (54°F)	15°C (27°F)
Boiler O_2	2.0%	0.5%
FGD system inlet sulfur, lb/MBtu [Note (2)]	20%	10%
FGD system inlet particulate loading, lb/MBtu	Not to exceed design basis	Not to exceed design basis
Absorber/slurry pH [Note (3)]	0.3 pH	0.1 pH
Absorber/recycle slurry density	Percent of solids varies by not more than 2%	Percent of solids varies by not more than 1%
Reagent slurry	Percent of solids varies by not more than 2%	Percent of solids varies by not more than 2% for wet FGD system and not more than 1% for dry FGD system
Number of absorber recycle (AR) pumps, atomizers, and spray nozzles in service	Per design basis	Per design basis
Absorber/slurry density set point	Per design basis	Per design basis
Emission or SO_2 removal control set point	Per design basis	Per design basis

NOTES:
(1) The hourly durations are given as a guide only and may vary greatly depending on project-specific conditions. The stabilization period required is dependent on process design and operating conditions that impact the residence time of reagent in the process. For complete steady-state conditions, sufficient time is required to allow turnover of solids or liquids in the process. Sulfur level of the test fuel as compared to the maximum design sulfur level is a major consideration in the length of stabilization required. The specific stabilization periods should be agreed to by the parties to the test.
(2) Variation shall be calculated as the difference between the high and low values.
(3) Applies to wet FGD system only.

properties for various fuels and components are specified in Table 3-4.2.4-1.

3-4.2.8 Emissions. Throughout the tests, the plant shall be operated in accordance with the emissions limits outlined in the test plan.

3-4.3 Adjustments Prior to and During Tests

3-4.3.1 Permissible Adjustments During Stabilization Periods or Between Test Runs. Any adjustments may be made to the equipment and/or operating conditions, but the requirements for determination of stable operation (see para. 3-4.2.5) still apply.

Typical adjustments prior to tests are those required to correct malfunctioning controls or instrumentation, or to optimize performance for current operating conditions. Recalibration of suspected instrumentation or measurement loops is permissible. Tuning and/or optimization of the FGD system is permissible. Adjustments to avoid corrections or to minimize the magnitude of performance corrections are permissible.

3-4.3.2 Permissible Adjustments During Test Runs. Permissible adjustments during tests are those required to correct malfunctioning controls, maintain equipment in safe operation, or maintain plant stability. FGD systems should function automatically unless the controls are required to be operated manually to maintain stability criteria. Switching from automatic to manual control, and adjusting operating limits or set points of instruments or equipment, should be avoided during a test.

3-4.3.3 Impermissible Adjustments. Any adjustments that would result in equipment being operated beyond manufacturer's operating, design, or safety limits and/or specified operating limits are not permitted. Adjustments or recalibrations that would adversely affect the stability of a primary measurement during a test are also not permitted.

3-4.4 Duration of Runs, Number of Test Runs, and Number of Readings

3-4.4.1 Duration of Runs. A test run shall be of sufficient duration to ensure that the data reflects the average efficiency and/or performance of the FGD system. Potential deviations in the measurable parameters due to controls, fuel, and typical plant operating characteristics should be considered when determining test run duration. The recommended test durations are shown in Table 3-4.4.1-1.

Table 3-4.4.1-1 FGD System Test Durations

Parameter Measured	Location Measured	Test Run Durations and/or Frequency	Reason for Measurement
SO_2	FGD system inlet	3 × 2 h	SO_2 removal efficiency guarantee
	Stack	3 × 2 h	SO_2 removal efficiency guarantee or emission rate
Gas flow	FGD system inlet and stack	3 × 1 h	Gas flow Moisture Temperature Pressure
$Ca(OH)_2$ flow rate	Slurry storage tank	1 × 8 h avg.	CaO reagent consumption guarantee
Pebble lime sample	Lime feeder	Grab sample at least every 2 h	Reactivity: ASTM C110 Reagent consumption guarantee
Limestone	Limestone feeder to reagent preparation system	Once daily	Grab sample: ASTM C50 Reactivity: vendor specific Composition: ASTM C25
Lime slurry sample	Lime slurry tank	Grab sample at least every 2 h	Density Availability: ASTM C25 Total solids: EPA 160.2
Limestone slurry sample	Limestone slurry storage tank	Grab sample at least every 2 h	Grab sample: EPRI A1 Reagent grind
Absorber slurry sample	Absorber reaction tank	Grab sample at least every 2 h	Grab sample: EPRI A1 Dissolved chlorides
Gypsum sample	Conveyor belt	Grab sample at least every 2 h	Stoichiometric ratio Oxidation ratio Gypsum composition Moisture
Water flow rate	Varies per plant	1 × 8–24 h avg.	Water consumption guarantee Wastewater generation guarantee
Power consumption	Varies per plant	1 × 24 h avg.	Power consumption guarantee
Flue gas pressure drop (typically only static pressure drop)	Varies per plant	3 × 5 min – 1 h	Pressure drop guarantee
Coal	Varies per plant	1 per day	Per ASTM D2234/D2234M

GENERAL NOTES:

(a) Other emissions or guarantee parameters should be measured during the same test period.

(b) An FGD system test is expected to be conducted over an 8 h period consisting of multiple test runs, or (typically for consumables) a single test run average.

(c) Pressure measurements are made in accordance with ASME PTC 19.2. Because flow separation and large-scale turbulent gas flow conditions may be present in large gas ducts, the total pressure should be measured at several locations in ducts. These locations should be selected in accordance with ASME PTC 19.2 for determination of measurement locations for velocity and flow.

The test coordinator may determine that a longer test period is required. The recommended times shown in Table 3-4.4.1-1 are generally based on continuous data acquisition. Depending upon the personnel available and the method of data acquisition, the length of a test may need to be increased to obtain a sufficient number of samples of the measured parameters to attain the required test uncertainty. When point-by-point traverses are required, the test run should be of sufficient length to complete at least one full traverse. Test runs using blended or waste fuels may also require longer durations if variations in the fuel are significant. Test run duration should consider transit times of samples to measurement devices.

3-4.4.2 Number of Test Runs. A run is a complete set of observations with the unit at stable operating conditions. A test is the average of a minimum of 3 runs.

After completion of the first test run that meets the criteria for an acceptable test run (that may be the preliminary test run), the data should be consolidated, and preliminary results calculated and examined to ensure that the results are reasonable.

3-4.4.3 Evaluation of Test Runs. When comparing results from two test runs (X_1 and X_2) and their uncertainty intervals, the parties to the test should consider the following three cases that are illustrated in Figure 3-4.4.3-1:

(a) *Case I.* A problem clearly exists when there is no overlap between uncertainty intervals. One of the following is likely the cause: uncertainty intervals have been grossly underestimated, an error exists in the measurements, or the true value is not constant. Investigation to identify bad readings, or overlooked or underestimated systematic uncertainty, etc., is necessary to resolve this discrepancy.

(b) *Case II.* When the uncertainty intervals completely overlap, as in this case, one can be confident that there has been a proper accounting of all major uncertainty components. The smaller uncertainty interval, $X_2 \pm U_2$, is wholly contained in the interval, $X_2 \pm U_1$.

(c) *Case III.* This case, where a partial overlap of the uncertainty exists, is the most difficult to analyze. For both test run results and uncertainty intervals to be correct, the true value lies in the region where the uncertainty intervals overlap. Consequently, the larger the overlap, the more confidence there is in the validity of the measurements and the estimate of the uncertainty intervals. As the difference between the two measurements increases, the overlap region shrinks.

Should a run or set of runs fall under Case I or Case III, the results from all of the runs should be reviewed in an attempt to explain the reason for excessive variation. If the reason for the variation cannot be determined, then either increase the uncertainty band to encompass the runs to make them repeatable, or conduct more runs so that the precision component of uncertainty may be calculated directly from the test results.

The results of multiple runs shall be averaged to determine the mean result. The uncertainty of the result is calculated in accordance with ASME PTC 19.1.

3-4.4.4 Number of Readings. Sufficient readings shall be taken within the test duration to yield total uncertainty consistent with frequency and timing of durations. Ideally at least 30 sets of data should be recorded for all nonintegrated measurements of primary parameters and variables. There are no specific requirements for the number of integrated readings or for measurements of secondary parameters and variables for each test run.

Multiple instruments should be used as needed to reduce overall test uncertainty. The frequency of data collection is dependent on the particular measurement and the duration of the test. To the extent practical, at least 30 readings should be collected to minimize the random error impact on the post-test uncertainty analysis. The use of automated data acquisition systems is recommended to facilitate acquiring sufficient data.

Calibration or adequate checks of all instruments shall be carried out, and those records and calibration reports shall be made available to the test personnel.

3-4.4.5 Sample Quantities. Sufficient sample quantities for chemical analysis shall be taken within the test duration.

3-5 CALCULATION AND REPORTING OF RESULTS

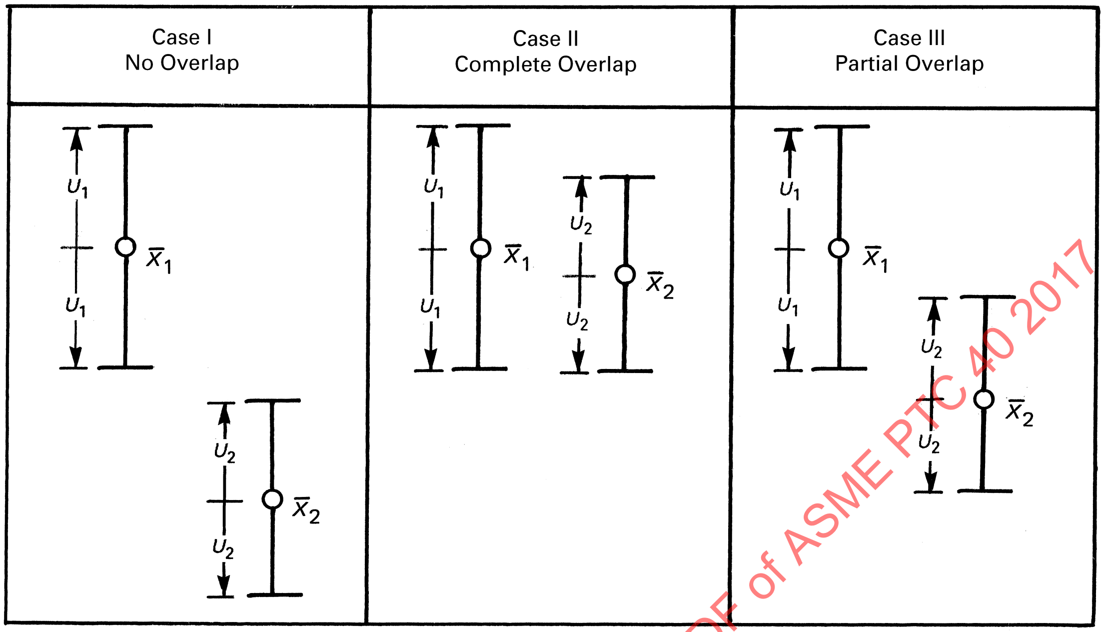
The data taken during the test should be reviewed and rejected in part or in whole if it is not in compliance with the requirements for the constancy of test conditions. Each Code test shall include pretest and post-test uncertainty analyses, and the results of these analyses shall fall within Code requirements for the type of plant being tested. Methods for review of data, significance of readings, and calculation of uncertainty may not be applicable to regulatory or legal requirements for reporting of SO_2 emission data.

3-5.1 Causes for Rejection of Readings

Upon completion of the test or during the test itself, the test data shall be reviewed to determine if data from certain time periods should be rejected prior to the calculation of test results. Refer to ASME PTC 19.1 for data rejection criteria. Any plant upsets that cause test data to violate the requirements of Table 3-4.2.4-1 shall be rejected.

Should serious inconsistencies that affect the results be detected during a test run or during the calculation of the results, the run shall be invalidated completely, or it may be invalidated only in part if the affected part is at the beginning or at the end of the run. A run that has been invalidated shall be repeated, if necessary, to attain the

Figure 3-4.4.3-1 Evaluation of Test Runs



test objectives. During the test, should any control system set points be modified that affect stability of operation beyond Code-allowable limits as defined in Table 3-4.2.4-1, test data shall be considered for rejection from the calculations of test results.

An outlier analysis of spurious data should also be performed in accordance with ASME PTC 19.1 on all primary measurements after the test has ended. This analysis will highlight any other time periods from which data should be rejected prior to calculating the test results.

3-5.2 Uncertainty

3-5.2.1 Introduction. Test uncertainty and test tolerance are not interchangeable terms. This Code does not address test tolerance, which is a contractual term.

Procedures relating to test uncertainty are based on concepts and methods described in ASME PTC 19.1, which specifies procedures for evaluating measurement uncertainties from both random and systematic errors, and the effects of these errors on the uncertainty of a test result.

3-5.2.2 Pretest and Post-Test Uncertainty Analyses

(a) A pretest uncertainty analysis shall be performed so that the test can be designed to meet Code requirements. Estimates of systematic and random errors for each of the proposed test measurements should be used to help determine the number and quality of test instruments required for compliance with Code or contract specifications.

The pretest uncertainty analysis shall include an analysis of random uncertainties to establish permissible fluctuations of key parameters, in order to attain allowable uncertainties. In addition, a pretest uncertainty analysis can be used to determine the correction factors that are significant to the corrected test. Also, pretest uncertainty analysis should be used to determine the level of accuracy required for each measurement to maintain overall Code standards for the test.

(b) A post-test uncertainty analysis shall also be performed as part of a Code test. The post-test uncertainty analysis will identify whether the allowable test uncertainty described in Section 1 has been met.

3-5.3 Data Distribution and Test Report

At the conclusion of the test, copies of all data shall be distributed by the test coordinator to those requiring such information. A test report shall be written in accordance with Section 6 of this Code and distributed by the test coordinator. A preliminary report incorporating calculations and results may be required before the final test report is submitted.

Section 4
Instruments and Methods of Measurement

4-1 RESULTS TO BE DETERMINED

The following results shall be determined as part of this Code:

(a) percent SO_2 removal (%R)
(b) stoichiometric ratio (SRI or SRR)
(c) energy/power consumption
(d) water/compressed-air consumption and characterization
(e) reagent consumption and characterization
(f) waste and by-product production and characterization

4-2 METHODS OF MEASUREMENT

4-2.1 Flue Gas

FGD system performance tests may be combined with regulatory compliance tests. In such cases, the parties to the test should contact the regulatory agency and determine what test modifications, if any, may be required.

The flue gas parameters listed in Table 4-2.1-1 are used either for direct measurement of performance guarantees or for making corrections that affect performance guarantees. Measurement shall be at the inlet and outlet of the FGD system, as appropriate.

Sulfur content analysis and appropriate combustion calculations can provide valuable background information for interpretation of other required measurement data. The fuel analysis would be used if SO_2 removal is based on fuel sulfur content in lieu of measured SO_2 content at the FGD system inlet. Fuel analysis should be used for determining appropriate F_d and F_c factors in lieu of the EPA standard factors. The F_d and F_c factors at the FGD system inlet and the stack shall be consistent.

4-2.2 Reagent(s)

This paragraph covers the testing parameters for, and properties of, reagents before reaction. Refer to paras. 5-2.2.3 and 5-2.3 for reagent stoichiometry.

4-2.2.1 General

(a) Reagent(s) include the following:

(1) any alkali or reagent introduced individually into the FGD system. Such alkali is separate from that in the flue gas stream

(2) any secondary SO_2 removal chemical flow necessary to regenerate the primary reagent(s)

(3) any additives for improving performance of SO_2 removal reagents

(b) The following are not considered reagents:

(1) chemicals that are added to aid in the FGD system process but do not result in increased SO_2 removal (such as flocculants used in a thickener)

(2) chemicals that are added to improve process water quality but do not increase SO_2 removal

(c) Fly ash alkalinity may be of interest in some processes and may warrant quantification.

4-2.2.2 Dry FGD System

(a) Chemical Analysis. Principal constituents for which the reagent or reagent solid, liquor, and/or slurry are typically analyzed include, but are not limited to, the following:

(1) CaO
(2) $Ca(OH)_2$
(3) $Mg(OH)_2$
(4) $NaOH$
(5) MgO
(6) $NaHCO_3$

The reagent or reagent/liquor and/or slurry shall be analyzed to determine the weight percent of the sample represented by each constituent reagent compound. Such analysis may include reagents specific to a particular system, including performance additives. Density of any reagent should also be determined.

Where applicable, the primary analytical methods for these constituents are described in the standard methods published by the American Society for Testing and Materials (ASTM International), such as ASTM C25, and in EPRl CS-3612 (latest amended version and supplements).

(b) Parameters of Interest. Other parameters that may be of interest in the FGD system process include, but are not limited to, the following:

(1) pH
(2) reagent liquor/slurry temperature
(3) reactivity (see ASTM C110)
(4) particle size distribution
(5) weight percent of solids
(6) makeup water composition
(7) slaking water composition

Table 4-2.1-1 Flue Gas Parameters Required From Tests

Flue Gas Parameter	Test Method [Note (1)]	Test Duration
SO_2 concentration, ppmdv	EPA Method 6C [Note (2)]	2 h min.
SO_2 emission rate, lb/MBtu	EPA Method 19 [Note (3)]	N/A
SO_2 flow rate, lb/hr	By calculation	N/A
O_2 and CO_2, %	EPA Method 3 or 3A [Notes (4) and (5)]	2 h min.
Moisture, %	EPA Method 4 [Note (5)]	As required per stack traverse
Gas flow, wet or dry scfm	EPA Methods 1 and 2, 2F, or 2G [Notes (5) and (6)]	As required per stack traverse
Flue gas pressure drop, in. wc [Note (7)]	See para. 4-2.3.3.3	See para. 4-2.3.3.3

NOTES:
(1) EPA methods listed are as published in the Code of Federal Regulations, Title 40 (40 CFR), Part 60 (see Nonmandatory Appendix D).
(2) For all emissions measured by continuous emission monitoring systems (CEMS), the CEMS relative accuracy test audit (RATA), meeting all requirements of 40 CFR, Part 75 or other mutually agreed-upon CEMS calibration, shall be performed no more than 30 days prior to the start of the performance test.
(3) The F_d or F_c factor shall be consistent with the fuel being fired.
(4) Test shall be concurrent with that for SO_2 concentration.
(5) EPA Method 2 may be combined with other tests, such as those for particulate matter.
(6) Alternatively, ASME PTC 4 may be used, utilizing heat and mass balance around the boiler.
(7) Pressure measurements are made in accordance with ASME PTC 19.2. Because flow separation and large-scale turbulent gas flow conditions may be present in large gas ducts, the total pressure should be measured at several locations in ducts. These locations should be selected in accordance with ASME PTC 19.2 for determination of measurement locations for velocity and flow.

The parameters listed in (1) through (7)shall be determined by the methods specifically referenced in (a), by the methods in Standard Methods for the Examination of Water and Waste Water (specified or latest edition), or by EPA analytical methods promulgated under the authority of Section 304(h) of the Clean Water Act.

(c) Methods of analysis and calculation for constituent-compound reporting not described in the documents referenced in (a) and (b) are subject to agreement by the parties to the test.

4-2.2.3 Wet FGD System

(a) Chemical Analysis. Principal constituents for which the reagent liquor/slurry is typically analyzed include, but are not limited to, the following:

(1) CaO
(2) $Ca(OH)_2$
(3) $Mg(OH)_2$
(4) NaOH
(5) MgO
(6) $CaCO_3$
(7) $MgCO_3$
(8) $NaHCO_3$

The reagent or reagent liquor/slurry shall be analyzed to determine the weight percent of the sample represented by each constituent reagent compound. Such analysis may include reagents specific to a particular system, including performance additives. Density of any reagent should also be determined.

Where applicable, the primary analytical methods for these constituents are described in EPRl CS-3612 (latest amended version and supplements). Where additional analytical methods are required, SM 5210 or SM 5220 from Standard Methods for the Examination of Water and Waste Water, and ASTM standard methods (see Nonmandatory Appendix D) shall be used.

Measurement uncertainty for the chemical analyses are included as part of the referenced analytical methods.

Methods of analysis and calculation for constituent-compound reporting not described in the references cited above are subject to agreement by the parties to the test.

(b) Parameters of Interest. Other parameters that may be of interest in the FGD system process may include, but are not limited to, the following:

(1) pH
(2) reagent liquor/slurry temperature
(3) organic acids
(4) alkalinity
(5) reagent grindability
(6) reactivity
(7) weight percent of solids
(8) calcium
(9) magnesium
(10) sulfur
(11) carbonate
(12) free moisture
(13) sulfite
(14) sulfate

The parameters listed in (1) through (14) shall be determined per the methods referenced in (a). Methods of analysis and calculation for constituent-compound reporting not described in the references cited in (a), such as x-ray fluorescence (XRF) or thermogravimetric analysis (TGA), are subject to agreement by the parties to the test.

The measurement of limestone reactivity is a significant issue for which a specific industry standard is not currently available. ASTM International is in the process of developing a standard reactivity test, but it is currently not available. Each FGD system vendor has its own test method and acceptable limestone reactivity basis that further complicates evaluation of the limestone reactivity. The use of any limestone reactivity test is subject to agreement by the parties to the test.

4-2.2.4 Flow Measurement. The quantity of reagent used during the performance test shall be measured either based on a drop in the level of reagent in the tank or by a direct recording of reagent flow rate.

(a) Level Drop (Liquids). Where the FGD system contains a tank for storage or dilution of reagent or reagent liquor/slurry, prior to the start of FGD system testing, this tank should be isolated during the run and the level of reagent in the tank, or "tank level," recorded at the start and the conclusion of the run. Nonisolable seal water dilution is permitted if the liquor and/or slurry sample is taken before dilution occurs.

Tank level can be measured by calibrated instrumentation or by manual techniques, depending on tank configuration and slurry type. Reagent consumption for the FGD system can be accurately measured by change in level only if the process is at steady state. Measurement of change in level should be a direct physical measurement. The limitations of the measurement device(s) should be well-known before using this method. It is expected that the measurement uncertainty shall be within 1% for this method. Mutual agreement by all parties to the test shall be secured for the method employed.

It is assumed that the tank used for such flow measurement contains reagent liquor and/or slurry in its final form. All dilutions should be conducted before the tank is isolated for the test run. Where sufficient reagent storage is not available to allow the tank to operate during the entire run without additional reagent makeup to the tank, quantity measurement shall be by volumetric flow, as described in (b). If the tank cannot be isolated during system operation, then quantity measurement shall be by volumetric flow, as described in (b).

(b) Volumetric Flow (Liquids). Existing flowmeters in the FGD system should be used to monitor flow rates of reagents into the FGD system if agreed to by all parties to the test or if the level drop method is impractical. Differential pressure meters shall be constructed in conformance with ASME PTC 19.5. Meters not covered in ASME PTC 19.5, and whose use is agreed to by the parties to the test, shall be installed and calibrated in accordance with the manufacturer's recommendations.

Volumetric flow measurements shall be recorded at intervals of no longer than 5 min, totalized at the end of each test run, and (where possible) continuously recorded.

(c) Dry Mass and Volumetric Flow (Solids). Solid reagent flow may be measured by dry mass flow-measuring devices, or by volumetric flow. It is expected that the measurement uncertainty for dry mass flow-measuring devices shall be within 2%.

The accuracy of dry volumetric flow measurement depends on specific conditions, e.g., reagent type and degree of aeration.

(d) Dry Mass Weight (Solids). Solid reagent weight measurement should be determined by direct measurement of material from feed bins by load cells or a strain gauge device. The storage bin should be isolated during the run, and the bin weight should be recorded at the start and the conclusion of the run. It is expected that the uncertainty for the dry mass weight measurement shall be within the accuracy of the weight-measuring device.

4-2.3 Energy/Power Consumption

4-2.3.1 Introduction. The energy and power parameters to be measured during the FGD system test depend on the system configuration. Paragraphs 4-2.3.1.1 through 4-2.3.3.3 provide guidance on measurement location and methods.

4-2.3.1.1 Inputs to Be Included. The direct energy and power inputs to the FGD system, including electrical, thermal, and mechanical parameters, shall be measured.

Devices whose energy and power consumption are typically measured include

(a) material-handling systems
(b) pumps
(c) compressors
(d) blowers
(e) fans (dedicated to the FGD system)
(f) agitators
(g) feed preparation systems
(h) waste by-product systems

4-2.3.1.2 Inputs to Be Excluded. All nonprocess energy or power loads should be excluded from this test. Examples of nonprocess loads include lighting, heating, ventilating, air conditioning, cranes, and elevators.

4-2.3.1.3 Optional Inputs

(a) Potential and kinetic energy may be neglected if agreed to by the parties to the test.

(b) Power effects of both gas and liquid streams may be neglected if agreed to by the parties to the test.

(c) Chemical heats of reaction may be neglected if agreed to by the parties to the test.

4-2.3.2 Measurement Duration. All measurements should be made over the test period, and time averaged. For cycling and intermittent loads that do not run continuously during the test period, the readings may be taken over a representative period (e.g., 24 h) and time averaged to account for those devices that have intermittent duty cycles.

4-2.3.3 Measurement Methods

4-2.3.3.1 Power. Attach calibrated watt-hour meters or recording wattmeters on the FGD system energy/power supply.

All nonessential loads that are deemed to be nonprocess related shall be shut off. For nonprocess loads that cannot be shut off during testing, calibrated watt-hour meters or recording wattmeters should be used to measure their power consumption during the test.

After the run, the energy values indicated by the nonprocess watt-hour meters or recording wattmeters shall be deducted from the values obtained from the FGD system electrical supply for the same period of time.

However, to achieve this practically, it may be necessary to separate the electrical feed into process and nonprocess equipment. It is expected that the measurement uncertainty for the calibrated meters shall be within 1%.

The electrical test measurements shall be in accordance with IEEE Std 120.

4-2.3.3.2 Thermal Energy. Thermal energy is defined as the heat added to the FGD system to sustain a condition required by the process design. Typical thermal energy measurements include, but are not limited to, flue gas reheat and seal or purge air heat. Sources of thermal energy/power may include, but are not limited to, hot air, hot water, steam, hot fluids, and fuels.

If thermal heating is accomplished by direct fuel firing, thermal energy/power is obtained by measuring the quantity (or flow rate) and heat content of the fuel.

Flow shall be measured in accordance with ASME PTC 19.5. Heat content (calorific value, heating value) for gaseous fuel shall be analyzed using gas chromatography in accordance with ASTM D1945. Liquid fuel heating value shall be determined by bomb calorimeter in accordance with ASTM D4809.

If heating is accomplished by a medium other than fuel, thermal energy shall be determined by measuring the difference between the heat inputs and outputs of the heating media. The heat inputs and outputs are based on the measured flow, temperature, and pressure of the heating media. Enthalpy of the medium shall be determined using the NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP).

Temperatures shall be measured in accordance with ASME PTC 19.3.

Pressure shall be measured in accordance with ASME PTC 19.2.

The thermal properties of the heating media should be evaluated in accordance with the latest edition of the ASME International Steam Tables for Industrial Use if steam or hot water is used.

If a heating medium other than steam or hot water is used, NIST REFPROP shall be used as the reference or the reference properties shall be agreed to by the parties to the test.

4-2.3.3.3 Pressure Drop. Mechanical energy/power consumption is usually manifested by a pressure drop resulting from gas and liquid flow through the FGD system.

The gas and liquid flow rates are governed by the steam generator load and the FGD system design considerations. The primary pressure drop of interest is typically that of the flue gas. However, the pressure drop in water and slurry lines is also of interest. Energy consumption is directly related to the product of the fluid (gas or liquid) flow rate and the total pressure (static + velocity head) drop across the device.

Equipment performance guarantees are usually expressed as pressure drop at a specific flow rate. Measured flow rates are seldom exactly those on which the guarantees for the FGD system are based. Therefore, a correction for flow rate versus the pressure drop shall be developed to determine compliance at flow rates other than design. Duct and system head loss curves should form the basis for pressure drop correction curves.

Pressure measurements are made in accordance with ASME PTC 19.2. Because flow separation and large-scale turbulent gas flow conditions may be present in large gas ducts, the total pressure should be measured at several locations in ducts. These locations should be selected in accordance with ASME PTC 19.2 for determination of measurement locations for velocity and flow.

4-2.4 Water

Flow measurement and analysis of water inputs to the FGD system may be required, depending on the boundaries chosen. Effluent from the FGD system is discussed in paras. 4-2.5 and 4-2.6.

4-2.4.1 Flow Measurement Methods. Flow measurement shall be determined as specified in ASME PTC 19.5.

4-2.4.2 Chemical Analysis. The following are constituents and characteristics of water inputs that may be of interest in the FGD system process:

(a) calcium
(b) sodium
(c) chloride
(d) “P” alkalinity; the “P” refers to the pH indicator phenolphthalein (endpoint 8.2 to 8.3)
(e) sulfites
(f) sulfates
(g) total phosphate
(h) pH

(i) total suspended solids (TSS)

(j) magnesium

(k) potassium

(l) "M" alkalinity; the "M" refers to the pH indicator methyl orange (endpoint 4.2 to 4.5)

(m) thiosulfates

(n) orthophosphate

(o) carbonates

(p) total dissolved solids (TDS)

Parameters listed in (a) through (p) shall be determined per methods in Standard Methods for the Examination of Water and Waste Water, or per EPA analytical methods promulgated under the authority of Section 304(h) of the Clean Water Act.

4-2.5 By-Product

Measurement of by-product flow and/or analysis of by-product characteristics may be required, depending on the boundaries chosen for the FGD system. By-product from the FGD system may be either sold in the form of gypsum or landfilled. In addition to evaluating FGD system operation, performance tests may provide the information needed to determine whether the by-product is of salable quality or is waste that should be disposed.

4-2.5.1 Dry FGD System By-Product. The qualities of the by-product of a dry FGD system are not covered in the Code because they are not determined as part of a typical dry FGD system performance test.

4-2.5.2 Wet FGD System By-Product

(a) Measurement Methods. Methods for measuring by-product flow are not described in this Code, as they are subject to agreement by the parties to the test.

(b) Physical Characteristics

(1) Commercial-Grade Gypsum. The typical physical characteristics of commercial-grade gypsum by-product include free moisture and particle size as determined by a laser diffraction method. Additional characteristics that may be of interest include, but are not limited to, the following:

(-a) specific surface area (Blaine), as determined by ASTM C204

(-b) density

(-c) toxicity characteristic leaching procedure (TCLP) by EPA Method 1311

(-d) particle shape

(2) Disposable By-Product. The physical characteristics of disposal by-product include, but are not limited to, the following:

(-a) permeability, as determined by EM 1110-2-1906, Appendix VII

(-b) unconfined compressive strength, as determined by ASTM D2166

(-c) solids content, as determined by EPRI Method F1 or ASTM D2216

(-d) density

(-e) TCLP by EPA Method 1311

Where applicable, the primary analytical methods for these constituents are described in the Standard Methods published by ASTM International, e.g., ASTM C471M, and EPRI CS-3612. The measurement uncertainty is included as part of the referenced test method.

(c) Chemical Analysis

(1) Commercial-Grade Gypsum

(-a) The chemical analysis of commercial-grade gypsum by-product typically determines the following:

(-1) gypsum purity, $\%CaSO_4 \times 2H_2O$.

(-2) amount of water-soluble chloride, as determined by ASTM C471 or by ISE probe on filtrate of gypsum cake.

(-3) total water-soluble salts, as determined from filtrate of gypsum cake, measurement of anions and cations, excluding $CaSO_4$. $CaSO_4$ is soluble in water, which will result in a high bias of results.

(-4) pH, as determined from filtrate of gypsum cake.

(-b) Additional analyses may be done to determine levels of other constituents, including, but not limited to, the following:

(-1) $CaSO_3 \times \frac{1}{2}H_2O$

(-2) acid insoluble

(-3) SiO_2

(-4) R_2O_3

(-5) $CaCO_3$

(-6) $MgCO_3$

(-7) fly ash, as determined by scanning electron microscope (SEM)

(-8) ammonia, as determined by ASTM D1426 or EPA Method 350.2

There are other tests that may be performed, but this is left up to the parties to the test.

(2) Disposable By-Product. The chemical analysis of disposable by-product may include, but is not limited to, the following:

(-a) $\%CaSO_4 \times 2H_2O$

(-b) $\%CaSO_3 \times \frac{1}{2}H_2O$

(-c) amount of fly ash, as determined by SEM

(-d) amount of lime

(-e) amount of acid insolubles

Where applicable, the primary analytical methods for these constituents are described in the ASTM Standard Methods, such as ASTM C471M, and EPRI CS-3612. Methods of analysis and calculation for constituent-compound reporting not referenced in ASTM C471M or EPRI CS-3612, e.g., XRF or TGA, are subject to agreement by the parties to the test. The measurement uncertainty is included as part of the referenced test method.

4-2.6 Purge Stream Quantity and Quality

4-2.6.1 Introduction. Measurement of purge-stream flow and analysis of purge-stream(s) constituents may be required, depending on the boundaries chosen for the FGD system (see Figure 1-2-1). This is expected to apply predominantly to a wet FGD system, where a liquid purge stream for chloride and/or fines control is often required with systems having more tightly closed water loops. The purge stream is considered to be the untreated stream to purge chlorides and/or fines and other compounds from the FGD system. Even if treatment is required and the treatment is part of the supplier's scope, it is considered to be outside the scope of this Code (see Figure 1-2-1). It can be assessed as an optional item by the parties to the test (see para. 4-2.6.4).

Performance test results can provide evaluative information on FGD system operating practices and may help determine the suitability for disposal of the purge stream (s).

4-2.6.2 Inputs to Be Included. Listed below are constituents and other parameters that may be of interest if the FGD system purge stream(s) is being evaluated. The scope of relevant parameters depends on the treatment system employed (parameters undergoing treatment) and the effluent requirements at the supplier's scope limit(s). Therefore, the analyses to be performed, sampling frequency, and importance of the purge-stream evaluation are reviewed on a case-by-case basis, depending on the project requirements and scope. The list below is considered to be representative of an untreated purge stream leaving the FGD system. Additional parameters can be added as needed for projects if agreed to by all parties to the test. Most, if not all, of these parameters would equally apply to the treated stream leaving a purge treatment system. The parameters include

(a) purge stream flow rate, m^3/h (gpm)
(b) purge stream temperature, °C (°F)
(c) pH or pH range
(d) total suspended solids (TSS), mg/L
(e) total dissolved solids (TDS), mg/L
(f) sulfite (SO_3^{2-}), mg/L
(g) sulfate (SO_4^{2-}), mg/L
(h) chloride (Cl^-), mg/L
(i) fluoride (F^-), mg/L
(j) silica (SiO_2), mg/L
(k) chemical oxygen demand (COD), mg/L
(l) biological oxygen demand (BOD_5), mg/L
(m) ammonium (NH_4^+), mg/L
(n) nitrate, mg/L
(o) total nitrogen, mg/L
(p) heavy metals (μg/L), such as
  (1) arsenic (As)
  (2) cadmium (Cd)
  (3) chromium (Cr)
  (4) cobalt (Co)
  (5) copper (Cu)
  (6) lead (Pb)
  (7) manganese (Mn)
  (8) mercury (Hg)
  (9) selenium (Se)
  (10) vanadium (V)
  (11) zinc (Zn)
(q) grease, mg/L
(r) oil, mg/L

4-2.6.3 Inputs to Be Excluded. There are no known specific exclusions.

4-2.6.4 Optional Inputs. Any flows or streams entering a purge stream treatment subsystem may be included, to assess their potential influence on both treated purge effluent flow rate and composition. Examples include

(a) flow rates of process or auxiliary streams supporting a purge treatment system, e.g., treatment chemicals and wash water

(b) composition of streams entering the purge treatment subsystem relative to parameters and constituents of interest

4-2.6.5 Measurement Duration. All measurements should be made over the test period, and either time averaged or approximated by a suitable number of representative readings or samples taken over the duration of the test period. For cycling or intermittently operating processes that do not run continuously during the test period (e.g., primary or secondary gypsum hydrocyclones), the readings or samples shall be taken over a longer representative period (minimum of 24 h, unless agreed otherwise) and time averaged, where applicable, to account for intermittent duty operation.

Flow rate is preferably measured by a flowmeter over a 24-h test period. Shorter times can be agreed upon by all parties to the test. Alternatively, in the presence of buffer or storage facilities, tank level measurements may be performed, as long as proper account can be taken of possible incoming and outgoing streams.

When taking samples from buffer tanks, it should be taken into consideration that physical and chemical properties of the tank contents do change slowly, and may represent time periods prior to the official test window. Consideration of the tank's retention time and appropriate starting and/or final tank volume should be given to assess properties (e.g., composition or temperature) representative of the test period. Under steady operation, only minor changes in properties out of the buffer tank are expected.

4-2.6.6 Measurement Methods

4-2.6.6.1 Methods

(a) Liquid flow shall be measured as indicated in para. 4-2.2.4.

(b) Solid flow, if applicable, shall be measured as indicated in para. 4-2.2.4.

4-2.6.6.2 Physical Characteristics. The physical characteristics of the purge stream(s) may include, but are not limited to, temperature, solids and dissolved solids content, pH, and density.

(a) Solids content shall be measured by EPRI Method F1 or ASTM D2216.

(b) Density shall be measured by EPRI Method D3.

(c) Additional characteristics that may be of interest include, but are not limited to, the following:

(1) biological oxygen demand (BOD_5)

(2) chemical oxygen demand (COD)

4-2.6.6.3 Chemical Analysis. The typical chemical analysis of a purge stream includes

(a) sulfite (SO_3^{2-}) by EPRI Method M2 or equivalent

(b) sulfate (SO_4^{2-}) by EPRI Method I3 or equivalent

(c) chloride (Cl^-) by EPRI Method I3 or equivalent

(d) fluoride (F^-) by EPRI Method I3 or equivalent

(e) silica (SiO_2) by EPA Method 6010 or equivalent

(f) COD by SM 5220 or equivalent

(g) BOD_5 by SM 5210 or equivalent

(h) ammonium (NH_4^+) by EPA Method 350.1 or equivalent

(i) nitrate by EPRI Method I3 or equivalent

(j) total nitrogen, calculated from EPA Method 351.2 data

(k) heavy metals (μg/L), such as

(1) arsenic (As) by EPA Method 6010 or equivalent

(2) cadmium (Cd) by EPA Method 6010 or equivalent

(3) chromium (Cr) by EPA Method 6010 or equivalent

(4) cobalt (Co) by EPA Method 6010 or equivalent

(5) copper (Cu) by EPA Method 6010 or equivalent

(6) lead (Pb) by EPA Method 6010 or equivalent

(7) manganese (Mn) by EPA Method 6010 or equivalent

(8) mercury (Hg) by EPA Method 1669/245.7 or equivalent

(9) selenium (Se) by EPA Method 6010 or equivalent

(10) vanadium (V) by EPA Method 6010 or equivalent

(11) zinc (Zn) by EPA Method 6010 or equivalent

(l) oil and grease by EPA Method 1664B or equivalent

Section 5
Computation of Results

5-1 CALCULATION OF PERCENT SO_2 REMOVAL (%R)

This subsection provides the method of calculation to determine the percent removal of sulfur dioxide (SO_2) from a flue gas stream. The calculation approach uses either the emission rate, as determined by EPA Method 19, or the corrected concentration reduction of SO_2 from the dry flue gas stream.

NOTE: All EPA methods cited in Section 5 are as published in the Code of Federal Regulations, Title 40, Part 60. See Nonmandatory Appendix D.

The SO_2 concentration is measured at the inlet and outlet of the FGD system.

5-1.1 Calculation of Flue Gas Flow Rate (Q_{sd})

Flue gas flow rate (Q_{sd}) shall be measured following EPA Methods 2, 2F, and/or 2G in combination with EPA Methods 1, 3/3A, and 4. If the ductwork design is not suitable for flue gas flow measurements, the flue gas flow from the boiler may be calculated per ASME PTC 4 using heat and mass balance around the boiler. This calculation may also be used to confirm flue gas flow measurements completed at the FGD system.

5-1.2 Calculation of Corrected SO_2 Concentration

SO_2 concentration is determined from EPA Method 6C or from a recently RATA-approved CEMS. For determination of corrected SO_2 concentration, the measured O_2 or CO_2 from EPA Method 3 or 3A is used.

The corrected SO_2 concentration, in parts per million by dry volume (ppmdv), is calculated as follows:

$$C_{\text{SO2 Corr}} = C_{\text{SO2}}\left[\frac{20.9 - \%O_{2\text{ Ref}}}{20.9 - \%O_2}\right] \tag{5-1-1}$$

where $\%O_{2\text{ Ref}}$ is typically 3% or 6%.

5-1.3 Calculation of SO_2 Mass Flow Rate

The SO_2 mass flow rate is determined using the results of para. 5-1.1 and eq. (5-1-1) and the following equation:

$$G_{\text{SO2}} = K_1 \times K_2 \times C_{\text{SO2}} \times Q_{\text{STD}} \tag{5-1-2}$$

5-1.4 Calculation of SO_2 Removal

The percent SO_2 removal is determined either by using corrected concentration as calculated by EPA Method 19 or by eq. (5-1-1), or by using results for inlet and outlet SO_2 emission rates, E_{SO2}, and the following equations, respectively:

$$\%R = 100\left[\frac{C_{\text{SO2 Corr in}} - C_{\text{SO2 Corr out}}}{C_{\text{SO2 Corr in}}}\right] \tag{5-1-3}$$

$$\%R = 100\left[\frac{E_{\text{SO2 in}} - E_{\text{SO2 out}}}{E_{\text{SO2 in}}}\right] \tag{5-1-4}$$

5-2 CALCULATION OF REAGENT STOICHIOMETRY AND CONSUMPTION

5-2.1 Units

Results shall be expressed in gram-moles (pound-moles) of reagent required per minute, G_r, to maintain the measured SO_2 removed as determined during the FGD system performance test.

5-2.2 Dry FGD System Reagent Consumption

5-2.2.1 Reagent Liquid/Slurry Flow Rate. The reagent consumption is calculated in mass consumption of reagent per mass of inlet SO_2. The reagent flow rate is calculated and divided by the mass of inlet SO_2 to determine the stoichiometry.

The first step in determining the individual reagent flow rate is to calculate the reagent liquor and/or slurry flow rate, Q_s. The reagent can be measured directly; however, there are inherent inaccuracies associated with measuring slurry liquids. An accurate tank level drop during the test can be used. For the level drop method, Q_s is calculated as follows:

$$Q_{S,i} = \frac{(L_0 - L_i) \times A_{CS}}{t_i - t_0} \tag{5-2-1}$$

where

A_{CS} = tank cross-sectional area
L_i = tank level at time t_i
L_0 = tank level at start of drawdown test
$Q_{S,i}$ = cumulative slurry volumetric flow from time t_0 to time t_i

t_i = time of tank level measurement at interval i
t_0 = time of tank level measurement at start of drawdown test

For mass flow measurements, the recorded cumulative volumetric flow rates are determined by eq. (5-2-2).

$$G_{S,i} = Q_{S,i} \times \rho_{S,i} \tag{5-2-2}$$

where
$G_{S,i}$ = cumulative mass flow rate, kg/min (lb/min)
$\rho_{S,i}$ = average slurry density over test period from t_0 to t_i, kg/m^3 (lb/gal)

Alternatively, the cumulative solids mass flow can be determined by eq. (5-2-3) when a measure of weight percentage of solids in the slurry is available. It is recommended that a grab sample of slurry be collected at each tank measurement interval.

$$G_{\text{Solids},i} = G_{S,i} \times \%\text{wt}_i \tag{5-2-3}$$

where
$G_{\text{Solids},i}$ = cumulative solids mass flow, kg solids/min (lb solids/min)
$\%\text{wt}_i$ = weight percent at each interval of tank measurement

5-2.2.2 Calculation of Individual Reagent Flow Rate

(a) To determine the individual reagent flow rate, the quantity of available $Ca(OH)_2$ per volume of slurry shall be determined. This is accomplished by performing the method per ASTM C25 using HCl as the titrant. The following should be applied to ASTM C25 to assist with determining the reactive $Ca(OH)_2$ per volume of slurry:

(1) Titration Reaction

$$2HCl + Ca(OH)_2 --- >>> CaCl_2 + 2H_2O$$

(2) Lime Hydration Reaction

$$CaO + H_2O >>> Ca(OH)_2$$

Therefore, since 1 mole of CaO is required to create 1 mole of $Ca(OH)_2$, eqs. (5-2-4a), (5-2-4b), and (5-2-5) are calculated on a CaO basis.

(b) Reactive CaO is calculated using eqs. (5-2-4a) and (5-2-4b)

(SI Units)

For mg/ml,

$$C_{CaO} = \frac{N \times V_t \times M_{CaO}}{2 \times V_s} \tag{5-2-4a}$$

(U.S. Customary Units)

For lb/gal,

$$C_{CaO} = \frac{\frac{2.2046 \times 10^{-6}\ \text{lb}}{\text{mg}} \times N \times V_t \times M_{CaO}}{2 \times V_s \times 2.6417 \times 10^{-4}\ \text{gal/ml}} \tag{5-2-4b}$$

where
C_{CaO} = concentration of reactive CaO, mg/ml (lb/gal)
M_{CaO} = molecular weight of CaO, mg/mmol
N = normality of acid solution, milliequivalents/ml = 2.000
V_S = volume of sample, ml
V_t = volume of acid solution used to titrate, ml
2 = milliequivalents of HCl required per millimole of HCl [$2HCl + Ca(OH)_2 >>> CaCl_2 + 2H_2O$]

Once a concentration of available CaO is determined, the individual reagent flow rate can be calculated using eq. (5-2-5)

$$Q_{CaO} = C_{CaO} \times Q_s \times 60\ \text{min/hr} \tag{5-2-5}$$

where
Q_{CaO} = reagent flow rate of CaO, mg/h (lb/hr)

5-2.2.3 Dry FGD System Stoichiometry Calculation. For SRI, the moles of reagent per moles of SO_2 into the FGD system are calculated from

$$\text{SRI} = G_{rt} M_{SO2} / G_{SO2\ \text{in}} \tag{5-2-6}$$

where the total reagent molar flow rate, G_{rt}, is the sum of the individual reagent molar flow rates. For example, reagent molar flow rates for reagents r_1, r_2, and r_3 can be added together as follows:

$$G_{rt} = G_{r1} + G_{r2} + G_{r3} \tag{5-2-7}$$

The total reagent molar flow rate, G_{rt}, represents the total alkali content available to the FGD system for chemical reaction.

5-2.3 Wet FGD System Reagent Stoichiometry Calculation

5-2.3.1 Wet FGD System Limestone Stoichiometry Calculation. The $CaCO_3/SO_2$ molar ratio is defined as the molar ratio of the sum (total sulfur and reactive $CaCO_3$) to total sulfur in the waste solids

$$\text{SRR } CaCO_3 = \frac{1 + [(\text{moles of } CO_3) - (\text{moles of Mg})]}{\text{moles of sulfur}}$$

Limestone stoichiometric ratio is determined by chemical analysis of the washed cake solids that exit the wet FGD system vacuum dewatering filter, and will include only the reactive limestone fraction of the solids and exclude the dolomitic limestone fraction. This equation assumes suitably reactive limestone is used based on mutually agreed-upon test methods.

5-2.3.2 Wet FGD System Lime Stoichiometry Calculation

$$\text{SRR lime} = \frac{\text{moles of calcium} - (\text{moles of chloride}/2)}{\text{moles of sulfur}}$$

5-2.3.3 Wet FGD System Sodium Stoichiometry Calculation

$$\text{SRR NaOH} = \frac{\text{moles of sodium} - \text{moles of chloride}}{2 \times \text{moles of sulfur}}$$

5-2.3.4 Wet FGD System Calculation of Reagent Stoichiometry. The reagent stoichiometry may also be calculated from the average reagent molar flow rate divided by the average SO_2 removed mass flow.

The SRR is the moles of reagent per mole of SO_2 removed as calculated from

$$\text{SRR} = G_{rt} M_{SO2} / (G_{SO2\ \text{in}} - G_{SO2\ \text{out}}) \tag{5-2-8}$$

where total reagent molar flow rate, G_{rt}, is the sum of the individual reagent molar flow rates as shown in eq. (5-2-7) for the dry FGD.

5-2.4 Wet FGD System Calculation of Reagent Consumption

Reagent mass consumption is a function of the stoichiometric ratio, SO_2, removed in the wet FGD and the reagent purity. An example calculation for a limestone-based system is shown below.

$$G_s = (\text{SRR CaCO}_3)(G_{SO2\ \text{in}} - G_{SO2\ \text{out}})(M_{CaCO3}) / [(M_{SO2})(\text{PR})]$$

where

PR = purity reagent

For this example of a limestone wet FGD system, reagent purity is defined as the mass fraction of reactive calcium carbonate in dry limestone.

5-3 CALCULATION OF ENERGY/POWER CONSUMPTION

5-3.1 Calculation of Thermal Energy/Power

(a) *Heating Media Other Than Fuel.* If a heating medium other than fuel is used, the calculation of thermal energy/power is as follows:

$$q = m \times (h_i - h_o) \tag{5-3-1a}$$

The inlet and outlet enthalpies of the heating fluid are calculated from reference properties (e.g., ASME Steam Tables) based on the measured temperature and pressure of the fluid.

(b) *Fuel.* If a fuel is used to accomplish heating, the calculation shall be of the following form:

$$q = m_{\text{fuel}} \times \text{HHV} \tag{5-3-1b}$$

5-3.2 Calculation of Mechanical Energy and Power

Mechanical energy and power can be measured directly using the methods in para. 4-2.3.3. Where direct measurements are impractical, pressure drop can be used to determine mechanical energy required for the process. Mechanical energy and power may be expressed either as pressure drop at a measured flow rate or in horsepower (hp).

(a) *Gas Phase.* When dealing with gas flow, mechanical energy/power is calculated using the following method. In both cases, when multiple total pressure values are measured across the cross section of large ducts, the total pressure used in the calculation should be the average of the measured values. See ASME PTC 19.2 for detailed analysis of gas phase pressure drop measurement.

The pressure drop at a measured gas flow rate is as follows:

$$\Delta P_{\text{TOT}} = P_{\text{in}} - P_{\text{out}} \tag{5-3-2a}$$

where

P_{in} = inlet gas flow pressure, mm H_2O (in. H_2O)
P_{out} = outlet gas flow pressure, mm H_2O (in. H_2O)
ΔP_{TOT} = total pressure drop, mm H_2O (in. H_2O)

The gas flow rate used as reference for this pressure drop should be the inlet gas flow.

(b) *Liquid Phase.* When dealing with liquid flow, mechanical energy/power is calculated using the following method.

The pressure drop at a measured liquid flow rate is as follows:

$$\Delta P_{\text{TOT}} = P_{\text{in}} - P_{\text{out}} \tag{5-3-2b}$$

where

P_{in} = inlet liquid flow pressure, mm H_2O (in. H_2O)
P_{out} = outlet liquid flow pressure, mm H_2O (in. H_2O)
ΔP_{TOT} = total pressure drop, mm H_2O (in. H_2O)

5-3.3 Calculation of Electrical Energy/Power

The total FGD system electrical energy consumption shall be measured based on the input energy to the FGD system. A watt-hour meter or wattmeter shall record the energy data (three-phase amps, phase volts, power factor, and kilowatts) that shall be averaged over a specified period, preferably 24 h but not less than 12 h.

$$\text{Power} = 3 \times (\text{phase volts}) \times (\text{phase current}) \times (\text{power factor}) \tag{5-3-3a}$$

or

$$\text{Power} = (\text{phase volts}) \times (\text{three-phase current}) \times (\text{power factor}) \quad (5\text{-}3\text{-}3b)$$

Finally,

$$\text{Energy} = \text{power} \times \text{elapsed time} \quad (5\text{-}3\text{-}4)$$

For further discussion, see IEEE Std 120.

5-4 CALCULATION OF WATER CONSUMPTION

Calculations of water consumption are dependent on the measurement method chosen in Section 4, and the calculation required should be considered in the selection of such methods. Water consumption and production can be measured by direct flow measurement or tank level changes over the test period.

Since sources and consumers of water within an FGD system vary depending on the particular FGD system process, the identification and monitoring of these sources and consumers shall be considered in developing the specific test procedure. In addition, FGD system processes often include intermittent consumers of water, e.g., mist eliminator wash cycles. Such intermittent usage shall be considered when determining the test duration and system operating sequence to ensure that the measured water usage over the test period is representative of the long-term water consumption. Water consumption measurements and calculation may also need to account for the large reserve of water in the system and the fluctuations that can occur in that reserve of water due to changes in the liquid levels in makeup water tanks, reclaimed water tanks, reagent slurry tanks, reaction tanks, sumps, etc. Any level changes in these tanks shall be evaluated and accounted for or shown to have potential volume changes that are insignificant in the final water consumption calculation.

Potential water usage that cannot be easily measured or monitored, e.g., washdown hose stations or reclaimed water from ponds, should be confirmed as isolated for the test. Otherwise, any necessary water usage from such sources should be documented.

Evaporation losses to the flue gas stream are typically the major sources of water consumption, but they can also represent the largest uncertainty in water consumption determination. The test method should identify a calculation method for correcting the water flow to the actual flue gas conditions. Psychometric charts in conjunction with flue gas characteristics at the inlet and outlet of the system, guarantee correction curves, or other method for correcting the evaporative losses to the design condition should be identified and agreed upon by all parties prior to the testing. Other correction curves may also be required to adjust water usage for variables such as fuel sulfur content.

Since different qualities of water, e.g., demineralized water, service water, or filtered water, can have separate guarantees, the use of such water supplies may require separate measurements during the test period.

5-5 CALCULATION OF WASTE OR BY-PRODUCT

Calculations of waste or by-product characteristics are included in the measurement and/or lab analysis methods in Section 4 and are not addressed here.

If a waste or by-product flow rate and/or mass production is of interest, then the test should include appropriate measurements and methods.

5-6 PURGE STREAM CALCULATION

Typically, the purge stream flow rate in a wet FGD system is defined up front during the design on the basis of a certain chlorine input to the system and the operating chloride concentration. The amount of chlorine input and the selected operating chloride define the amount of purge required at a certain chloride concentration of the purge stream(s), wastes, and by-products, as per the system boundaries shown in Figure 1-2-1.

The specification or contract typically defines a maximum value for the chlorine input to the FGD system. The input is driven by

(a) chlorine content in the range of fuels to be considered (often the largest contributor)

(b) chloride input through water sources (fresh water, higher chloride cooling tower blowdown, or other sources)

(c) other chloride or chlorine sources entering the system (through additives, etc.)

Additionally, in cases with low chloride input or fairly open loops, the amount of purge may be driven more by the amount of fines that have to be purged to maintain operability (e.g., of solids filtration equipment) than by the level of chlorides. In the fines-driven purge case, the minimum amount of purge required is typically specified by the original equipment manufacturer (OEM) and can be verified by flow measurement.

For a chlorides-driven purge, the flow can be more variable over time due to fluctuations in the input variables described in (a) through (c). The OEM often provides a guarantee not to exceed a certain flow rate, so the party responsible for a purge treatment system can size it based on a maximum expected flow rate. Given that all chloride and chlorine inputs are fixed, the chloride discharge is fixed, too. In the case where chloride practically leaves the system only by means of a purge stream (with no other major chloride sinks such as ponding of liquid gypsum slurry), the product of purge flow rate times purge chloride concentration (equal to mass flow) is constant [see eqs. (5-2-4a) and (5-2-4b)]. In that case, the purge flow rate is inversely proportional to the chloride concentration in the purge stream, i.e.,

$$Q_{P1} \times C_{CL,P1} = Q_{P2} \times C_{CL,P2} \tag{5-6-1}$$

where

$C_{CL,P1}$ = chloride concentration, mg/L (ppm), of purge stream for condition 1
$C_{CL,P2}$ = chloride concentration, mg/L (ppm), of purge stream for condition 2
Q_{P1} = purge flow rate, m^3/h (gpm), for condition 1
Q_{P2} = purge flow rate, m^3/h (gpm), for condition 2

As long as the purge flow rate leaving the FGD system does not exceed that maximum, no calculations are required, which is the case in the majority of tests and therefore concludes the test.

In a system with more than one chloride stream leaving the system, a complete chloride/chlorine mass balance may have to be performed around the FGD system boundary, and the allowable purge flow rate determined from the remaining streams entering or leaving the system. Many times, a correction curve for purge flow as a function of fuel chlorine and possibly additional parameters (fuel sulfur and chloride in water sources) help simplify the task of doing the chloride balance.

Heavy metals are often an additional quality being monitored in chloride purge streams. The concentrations of heavy metals in the purge stream typically behave like the dissolved chlorides. They show their highest concentration as the liquor is concentrated the most, i.e., at the highest chloride concentration. At an operating chloride concentration lower than the design point, the heavy metals are expected to be lower than at the design point.

Should the purge flow rate exceed the maximum expected value, then a closer look at the chloride material balance is warranted, typically following the test, to determine why the flow rate has been exceeded. Possible reasons include, but are not limited to, higher input than designed for from fuel or other sources such as water, and operation of the system at a lower chloride concentration than designed for or advised by the OEM.

The flow rates of all incoming streams that may contribute to chloride input then need to be measured and analyzed for chlorine and chloride content to determine whether a higher load of chloride or chlorine entered the FGD system, leading to the higher purge rate or higher than expected operating chloride concentration. The root cause for the excess then needs to be addressed.

Section 6
Report of Results

6-1 GENERAL

The performance test report documents the data, calculations, and processes employed in conducting the performance test. The report presents specific information to demonstrate that all objectives of the test have been met, and to describe the test procedures and pertinent results. The nature of the information gathered should be complete and thorough in the judgment of the parties to the test. The information should include all raw data, all calculations, the final tabulated reduced data, and as much general information concerning the facility as is deemed relevant to the test. This Section provides guidance on both content and format of information typically included in the performance test report, including the executive summary, test results, and appropriate appendices.

6-2 TITLE PAGE AND TABLE OF CONTENTS

The title page contains the title of the test, the name and location of the plant on which the test was conducted, the unit designation, the names of those who conducted and approved the test, and the date the report was prepared. The table of contents lists major subdivisions of the report to the third level, as well as titles of tables, figures, and appendices.

6-3 GENERAL INFORMATION

The general information section of the report gives the reader information needed to understand the basis of the test and shall include the following:

(a) owner
(b) name and location of the plant
(c) designation of the unit
(d) steam generator manufacturer
(e) steam generator description and size
(f) date of first commercial operation
(g) description of auxiliary apparatus, the operation of which may influence the test results
(h) description of the FGD system
(i) manufacturer's predicted performance data sheets
(j) contractual obligations and guaranteed performance data
(k) name of head test coordinator/director
(l) test personnel, their affiliations, and test responsibilities
(m) dates of test

6-4 EXECUTIVE SUMMARY

The executive summary briefly describes the objectives, results, and conclusions of the test, and includes the signatures of the test director(s), reviewer(s), and approver(s). Tabular or graphical presentation may be used to give a quick picture of the essential findings.

6-5 REPORT CONTENT

6-5.1 Introduction

The introduction states the purpose of the test and relevant background information, e.g., age, unusual operating characteristics, and problems, of the unit to be tested.

6-5.2 Objectives and Agreements

The objectives and agreements section addresses the authorization for the testing, objectives of the test, required test uncertainty, contractual obligations and guarantees, operating conditions, test contractor, test representative parties, and any other stipulations.

6-5.3 Test Description and Procedures

The test description and procedures section includes the following:

(a) a schematic of the FGD system boundary showing the locations of all measured parameters and process flow diagram
(b) a list of equipment and auxiliaries being tested, including nameplate data
(c) description of testing, including test conditions (e.g., unit load and time durations), methods, and criteria
(d) determination of steady-state conditions
(e) methods of measurement and a list and description of the test instruments identified in the system diagram
(f) a list of ancillary equipment used for additional data collection
(g) a summary of key measurements and observations
(h) the magnitude of primary uncertainties in measurement and sampling

(i) correction factors to be applied because of deviations, if any, of test conditions from those specified

(j) the methods of calculation from observed data and calculation of probable uncertainty

(k) sample calculations

6-5.4 Results

Test results are presented computed on the basis of test operating conditions, instrument calibrations only having been applied, and as corrected to specified conditions if test operating conditions have deviated from those specified. Test uncertainty is also stated in the results. Tabular and graphical presentations of the test results are included.

FGD system performance test results include

(a) percent SO_2 removal (%R)

(b) stoichiometric ratio (SRI or SRR)

(c) energy and power consumption

  (1) electrical

  (2) thermal

  (3) mechanical

(d) water consumption and characterization

(e) compressed air consumption and characterization

(f) reagent consumption and characterization

(g) waste and/or by-product production and characterization

(h) comparison of measured performance versus designed performance

6-5.5 Uncertainty Analysis

The uncertainty analysis section provides sufficient detail to document the target uncertainty and demonstrate that the test has met this target. Primary measurement uncertainties, including method of application, are included in this section.

6-5.6 Conclusions and Recommendations

The conclusions and recommendations section discusses the test, the test results, and the conclusions. Conclusions directly relevant to the test objectives as well as other conclusions or recommendations drawn from the test are included.

6-6 APPENDICES

Appendices and accompanying illustrations may be included to clarify the circumstances, equipment, and methodology of the test; to describe the instrument calibration methods used; to provide additional details of calculations, including a sample set of computations, and descriptions of any special testing apparatus; to present results of preliminary inspections and trials; and to provide any supporting information required to make the report a complete, self-contained document of the entire undertaking.

Appendices include

(a) test logs and charts

(b) data sheets

(c) instrument calibration sheets

(d) analytical data

(e) detailed calculations

(f) correction curves

(g) uncertainty analyses and calculations

(h) other pertinent information

Section 7
Uncertainty Analysis

7-1 GENERAL

This Section describes the methodology to be used in developing the uncertainty analysis of the performance test. Uncertainty calculations provide pretest and post-test estimates of the accuracy expected from the test methods proposed in this Code, and also help identify those measurements that significantly affect the test results and the correction factors that should be determined. Uncertainty calculations are required for every test carried out in accordance with the Code. Pretest uncertainty calculations should be included in the test procedure. Post-test uncertainty calculations shall be included in the test report.

7-2 INTRODUCTION

Test uncertainty is an estimate of the limit of error of a test result. It is the interval about the test result that contains the true value within a level of confidence. This Code uses a 95% confidence interval for uncertainty calculations. The primary technical reference for uncertainty calculations is ASME PTC 19.1, which provides general procedures for determining the uncertainties in individual test measurements for both random errors and systematic errors, and for tracking the propagation of these errors into the uncertainty of a test result. This Section provides an approach to uncertainty calculations specific to FGD system performance tests. Pretest and post-test uncertainty analyses are an indispensable part of a performance test.

(a) Pretest Uncertainty Analysis. In planning a test, a pretest uncertainty analysis allows corrective action to be taken prior to the test, either to decrease the uncertainty to a level consistent with the overall objective of the test, or to reduce the cost of the test while still attaining the objective. This is most important when deviations from Code-specified instruments or methods are expected. An uncertainty analysis is useful to determine the number of observations required to meet the Code criteria for tests.

(b) Post-Test Uncertainty Analysis. A post-test uncertainty analysis determines the uncertainty for the actual test. This analysis should confirm the pretest systematic and random uncertainty estimates. It serves to validate the quality of the test results or to expose problems.

A sample calculation for uncertainty is shown in Nonmandatory Appendix C.

Test results should be reported using the following form:

$$R \pm U_R$$

7-3 OBJECTIVE OF UNCERTAINTY ANALYSIS

The objective of a test uncertainty analysis is to estimate the limit of error of the test results, which is the interval about a test result that contains the true value within a given level of confidence.

This Code does not cover nor discuss test tolerances; test tolerances are defined as contractual agreements regarding an acceptable range of test results.

7-4 DETERMINATION OF OVERALL UNCERTAINTY

7-4.1 Types of Uncertainty

The total uncertainty is comprised of two types of errors.

(a) Systematic Error. A systematic error is the portion of the total error that remains constant in repeated measurement of the true value in a test process. Systematic error is caused by measurement characteristics that are inherent to a particular method of measurement, not to a particular plant or test. The estimated value of each systematic error is obtained by nonstatistical methods, and it has many potential sources. This is usually an accumulation of individual errors not eliminated through calibration.

(b) Random Error. A random error is an error due to limitations or repeatability of measurements. Random error is the portion of total error that varies in repeated measurements of the true value through the test process. Estimates of random error are derived by statistical analysis of repeated independent measurements. The random error may be reduced by increasing the number of instruments or the number of readings taken.

In general, the overall uncertainty of a measurement is calculated as the square root of the sum of the squares (SRSS) of the systematic and random uncertainties. Sensitivity coefficients are used to correct the individual parameter's uncertainty for the impact on the total uncertainty.

Table 7-5.1-1 Expected Uncertainty for FGD System Testing

Parameter	Expected Uncertainty, %
Measured SO_2	±5
SO_2 removal efficiency	±1
Reagent consumption	±5
Electrical power consumption	±1.5
Water consumption by calculation	±10
Water consumption by direct measurement	±2
Pressure drop	±1.5

7-4.2 Sources of Error

Identification of sources of error that affect the test result should be undertaken to determine if they are random or systematic. Error sources may be grouped into the following categories:

(a) calibration error — residual error not removed by the calibration process

(b) installation error — results from nonideal instrumentation installation

(c) data acquisition error — typically results from analog-to-digital conversion

(d) data reduction error — introduced through truncation, round-off, nonlinear curve fitting or data storage algorithms

(e) sampling error — introduced by sampling techniques

(f) correction methodology error — introduced by using correction formula

(g) interpolation error — results from curve fitting or the shape of a curve between discrete formulation points

(h) model error — occurs when equipment and system models do not properly account for changes in input parameters or actual unit response

7-5 CALCULATION OF UNCERTAINTY

7-5.1 General

The elements of uncertainty calculations for a complete test can be presented in tabular form, as shown in Table 7-5.1-1. The test uncertainty associated with each measured parameter includes the effects of its sensitivity, systematic uncertainty, and random uncertainty.

7-5.2 Input Uncertainties

(a) Uncertainties of Recommended Methods. The uncertainties of the recommended ASME PTC 40 methods are as follows:

(1) velocity: ±5%
(2) volumetric flow rate: ±5.6%
(3) particulate matter: ±12.1%
(4) SO_2: ±4% of reading

(b) Statistical Parameters. The elements of uncertainty calculations for a complete test can be presented in tabular form, as shown in Nonmandatory Appendix C. The statistical parameters to be used are as follows:

(1) Measured Parameter: the fluid or energy stream parameter that crosses the test boundary, required for test calculation.

(2) Sensitivity: the percent change in corrected result caused by a unit change in the measured parameter.

(3) Systematic Uncertainty ($b_{\bar{X}}$): inherent systematic error for the type X of measurement.

(4) Combined Standard Uncertainty ($u_{R,\mathrm{SYS}}$): the product of sensitivity and systematic uncertainty.

(5) Standard Deviation of the Mean ($S_{\bar{X}}$): statistically determined for multiple measurements of the same variable.

(6) Random Standard Uncertainty (u_R): the product of sensitivity and the standard deviation.

The uncertainty of a measurement, u_X, is the root-sum-square total of overall systematic and random uncertainties

$$u_{\bar{X}} = \sqrt{\left(b_{\bar{X}}^{\,2} + S_{\bar{X}}^{\,2}\right)} \tag{7-5-1}$$

where

$b_{\bar{X}}$ = systematic uncertainty of the measurement
$S_{\bar{X}}$ = random uncertainty of the measurement
$u_{\bar{X}}$ = overall uncertainty of the measurement

The uncertainty of the result, u_R, is calculated from the overall test random and systematic uncertainty terms

$$u_R = \sqrt{\left(b_R^{\,2} + S_R^{\,2}\right)} \tag{7-5-2}$$

where

b_R = systematic uncertainty of the result
S_R = random uncertainty of the result
u_R = overall uncertainty of the result

The expanded uncertainty at 95% confidence is given by

$$u_{R,95} = 2u_R \tag{7-5-3}$$

7-6 SENSITIVITY COEFFICIENTS

Sensitivity coefficients indicate the absolute or relative effect of a measured parameter on the test result. Relative sensitivity coefficients that are calculated during the pretest uncertainty analysis identify the parameters with the largest impacts on the test objectives. A relative sensitivity coefficient should be calculated for each measured parameter to determine its influence on test results. Correction calculations are required for all measured parameters with relative sensitivity coefficient values greater than 0.002. The relative sensitivity coefficient, θ, is calculated by either of the equations below.

(a) Partial Differential Form

$$\theta = \frac{\left(\frac{\partial R}{R}\right)}{\left(\frac{\partial X}{X_{\text{avg}}}\right)} = \frac{X_{\text{avg}}}{R}\left(\frac{\partial R}{\partial X}\right) \tag{7-6-1}$$

where

R = corrected test results

X_{avg} = measured parameter, average value

∂R = change (partial differential) in corrected test result

∂X = change (partial differential) in measured parameter

(b) *Finite Difference Form*

$$\theta = \frac{\left(\frac{\Delta R}{R}\right)}{\left(\frac{\Delta X}{X_{\text{avg}}}\right)} = \frac{X_{\text{avg}}}{R}\left(\frac{\Delta R}{\Delta X}\right) \tag{7-6-2}$$

where

ΔR = change (finite difference) in corrected test result

ΔX = change (finite difference) in measured parameter, typically $0.01X_{\text{avg}}$

7-7 SYSTEMATIC UNCERTAINTY

Identification of the systematic error is an important step of the uncertainty analysis. Failure to identify a significant systematic error will lead to reporting a more accurate test than the true uncertainty for the test. The process requires a thorough understanding of the test objectives and methods of the test. Careful consideration of published data, calibration information, and use of engineering judgment are required to eliminate or understand the systematic errors in measurements.

Systematic uncertainty of a measurement is identified as $b_{\overline{X}}$. The individual systematic uncertainties can be combined into the systematic uncertainty of the result, b_R. The systematic uncertainty of the result can be calculated according to the SRSS rule

$$b_R = \sqrt{\sum_{i=1}^{n} \left(b_{\overline{X}_i}\theta_i\right)^2} \tag{7-7-1}$$

where

b_R = systematic uncertainty of the result of a measured parameter, i

$b_{\overline{X}_i}$ = systematic uncertainty of the result

n = number of measured parameters

θ_i = relative sensitivity coefficient for measured parameter, i

The systematic uncertainty is assumed to have a normal distribution. If the positive and negative systematic uncertainty limits are not symmetrical, positive and negative values of the random uncertainty shall be calculated separately. If different values of the systematic uncertainty have been calculated for positive and negative systematic uncertainty limits, the larger value should be used to compute the total uncertainty.

7-8 RANDOM STANDARD UNCERTAINTY FOR SPATIALLY UNIFORM PARAMETERS

The standard deviation, s_X, is a measurement of the dispersion of the sample measurements. Test measurements need to be reduced to average values and the standard deviation calculated before the performance and uncertainty calculations can be executed. The random standard uncertainty is calculated using the sample standard deviation. For a result, R, calculated from many measured parameters, there is a combined standard uncertainty for the result, s_R, for the combined measurement parameters.

(a) *Sample Mean.* The mean for the sample is calculated from

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{7-8-1}$$

where

N = number of readings for each set

X_i = set of readings for i = 1 to N

$\overline{X}$ = average values for measurement set k

(b) *Pooled Averages.* For parameters measured several times during a test period that have M sets of measurements with N readings for each set, the average value for measurement set k is as follows:

$$\overline{\overline{X}} = \frac{1}{M}\sum_{k=1}^{M} \overline{X}_k \tag{7-8-2}$$

where

M = number of sets of measurements

$\overline{\overline{X}}$ = sample set pooled average

$\overline{X}_k$ = average value for measurement set k

(c) *Sample Standard Deviation.* For measurements that do not exhibit spatial variations, the standard deviation, s_x, of an averaged measurement, $\overline{X}$, based on statistical analysis is calculated from the N multiple measurements of X according to the equation

$$s_X = \left(\sum_{i=1}^{N} \frac{\left(X_i - \overline{X}\right)^2}{N - 1}\right)^{1/2} \tag{7-8-3}$$

where

N = number of times the parameter is measured

s_X = standard deviation

(d) Random Standard Uncertainty of the Mean. The random standard uncertainty of the mean of an averaged measurement $\overline{X}$, based on statistical analysis, is calculated from the N multiple measurements of X according to the equation

$$s_{\overline{X}} = \frac{s_X}{\sqrt{N}} \tag{7-8-4}$$

where

$s_{\overline{X}}$ = standard deviation of the mean

(e) Random Standard Uncertainty of the Result. The random standard uncertainty of the result, s_R, is determined from the propagation equation (see ASME PTC 19.1). There are two forms. The absolute random standard uncertainty is determined using

$$s_R = \left[\sum_{i=1}^{l} (\theta_i s_{\overline{X}_i})^2\right]^{\frac{1}{2}} \tag{7-8-5}$$

The relative random standard uncertainty of a result is

$$\frac{s_R}{R} = \left[\sum_{i=1}^{l} \left(\theta'_i \frac{s_{\overline{X}_i}}{\overline{X}_i}\right)^2\right]^{\frac{1}{2}} \tag{7-8-6}$$

where

l = number of test runs
R = corrected result, as defined in eq. (7-6-1)
θ = absolute sensitivity coefficient
θ' = relative sensitivity coefficient

7-9 CORRELATED SYSTEMATIC STANDARD UNCERTAINTY

For multiple measurements where systematic errors of measurements are not independent, systematic errors are correlated. Examples include measurements of different parameters taken with the same instrument, or multiple instruments calibrated with the same standard. For these cases, ASME PTC 19.1 should be consulted to address the proper approach for uncertainty calculations. The general equation for calculating the correlated systematic uncertainty is

$$b_R = \sum_{i=1}^{l} (\theta i b i)^2 + 2 \sum_{i=1}^{l-1} \sum_{k=i+1}^{l} \theta_i \theta_k b_{ik} \tag{7-9-1}$$

NONMANDATORY APPENDIX A
WET FGD SYSTEM SAMPLE CALCULATION

A-1 GENERAL

This Appendix provides a sample calculation for how ASME PTC 40 is applied to a wet FGD system to determine if the measured performance meets the provided guarantees.

A-2 DESIGN PARAMETER CALCULATIONS

A-2.1 FGD System Inlet Wet Gas Flow

The FGD system inlet gas mass flow, for each FGD system inlet, is calculated from the FGD system inlet gas volumetric flow in units of actual cubic feet per minute (acfm) and gas density. The volumetric flow is calculated from the static and velocity pressures measured during the FGD system inlet flue gas flow traverse, using a two-dimensional Fechheimer probe at both FGD system inlet flue positions in accordance with EPA Test Methods 1 and 2G. Flue gas flow in acfm is determined from velocity and static pressure measurements, as well as from gas density data (reference EPA Test Method 3). The inputs for these calculations include laboratory test reports for coal, reagents, and by-products.

The system described has left and right flue gas inlets. The following calculation is made to convert the right and left inlet flow rates from the actual cubic feet per minute to kilograms per hour:

$$G_{\text{in, right or left}} \times 60 \times \rho_g \times 0.454$$

where

0.454 = conversion of lb to kg
60 = minutes per hour
$G_{\text{in, right or left}}$ = right or left inlet flow, acfm
ρ_g = gas density of flue gas, lbm/ft^3, corrected for actual conditions

The total FGD system inlet gas flow, G_{in}, is then calculated as follows:

$$G_{\text{in}} = G_{\text{in, right}} + G_{\text{in, left}}$$

where

$G_{\text{in, left}}$ = gas flow at left FGD system inlet, kg/h
$G_{\text{in, right}}$ = gas flow at right FGD system inlet, kg/h

As shown in Table A-2.1-1, the calculated FGD system inlet gas flow rate in each of the three test runs is lower than the specified contract value of 2 924 000 kg/h. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements.

A-2.2 Percent of Maximum Continuous Rating Condition (%MCR)

The percent of MCR (%MCR) is calculated from the ratio of the tested inlet gas flow to the design inlet gas flow in kilograms per hour. The equation to determine the %MCR is as follows:

$$\%\text{MCR} = G_{\text{in}}/2\,924\,000 \times 100\%$$

where

G_{in} = kg/h as defined in Table A-2.1-1
$2\,924\,000$ = design FGD system inlet gas flow, kg/h

Table A-2.2-1 shows the %MCR for each of the three test runs.

The calculated %MCR of the FGD system in each of the three test runs is lower than the specified contract value of 100%. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements.

A-2.3 FGD System Inlet SO_2 Concentration

The FGD system inlet SO_2 concentration is determined by averaging the right and left inlet flue gas SO_2 concentrations, which are determined using EPA Test Method 6C. The FGD system inlet O_2 is determined using EPA Method 3. Please note that all the data in this Appendix is corrected to 6% O_2. The following equation is used to correct the SO_2 concentration from the actual measured % O_2 to the specified 6% O_2:

$$C_{\text{SO2 corr}} = C_{\text{SO2}} \times (20.9 - 6)/(20.9 - \text{O}_{2\text{ actual}})$$

where

C_{SO2} = actual FGD system inlet SO_2 concentration (right or left), ppmdv

Table A-2.1-1 FGD System Inlet Gas Flow Rate

Test Run Number	Gas Density, ρ_g, lb/ft^3		FGD System Inlet Flue Gas Flow Rate, G_{in}				
			acfm		kg/h		
	Right Inlet	Left Inlet	Right Inlet	Left Inlet	Right Inlet	Left Inlet	Total, kg/h
1	0.056	0.058	899 599	903 456	1 372 284	1 427 388	2 799 673
2	0.056	0.057	831 222	830 791	1 267 979	1 289 953	2 557 932
3	0.056	0.057	731 005	893 218	1 115 104	1 386 882	2 501 986

Table A-2.2-1 Percent MCR

Test Run Number	FGD System Inlet Gas Flow, kg/h	Calculated %MCR
1	2 799 673	96
2	2 557 932	87
3	2 501 986	86

$C_{SO2\ corr}$ = corrected FGD system inlet SO_2 concentrations (right or left), ppmdv
$O_{2\ actual}$ = actual O_2 concentration, ppmdv

The average inlet SO_2 concentration, in parts per million by dry volume (ppmdv), is then calculated as follows:

$$C_{SO2\ avg} = (C_{SO2\ left} + C_{SO2\ right})/2$$

As shown in Table A-2.3-1, the calculated average FGD system SO_2 concentration corrected for 6% O_2 is lower than the specified contract values of 1 266 ppmdv. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements.

Table A-2.3-1 FGD System Inlet SO_2 Concentration

Test Run Number	Actual O_2 Concentration, %		FGD System Inlet SO_2 Concentration, ppmdv				
			Uncorrected		Corrected to 6% O_2		Average, Corrected to 6% O_2
	Right Inlet	Left Inlet	Right Inlet	Left Inlet	Right Inlet	Left Inlet	
1	5.3	6.0	524	573	500	573	537
2	7.0	6.2	473	489	507	496	501
3	7.0	6.2	526	464	563	470	517

A-2.4 FGD System Inlet Particulate Concentration

The FGD system inlet particulate concentration is determined from the average of the particulate concentration in the FGD system right and left inlet flues determined by EPA Test Method 5.

The following equation is used to convert right and left inlet particulate concentrations from grams per dry standard cubic meter (g/dscm, at 20°C, 1 atm) to Metric Customary units of milligrams per cubic meter in normal conditions (mg/m^3 i.N., at 0°C, 1 atm):

$$PC_{in,\ right\ or\ left} \times 1\,000\ mg/g/0.9317406$$

where

0.9317406 = temperature conversion factor of dscm to m^3 i.N.
$PC_{in,\ right\ or\ left}$ = particulate concentration at right or left inlet, g/dscm

The average FGD system inlet particulate concentration, PC_{in}, is then calculated as follows:

$$PC_{in} = (PC_{in,\ right} + PC_{in,\ left})/2$$

where

$PC_{in,\ left}$ = particulate concentration at left FGD system inlet, mg/m^3 i.N.
$PC_{in,\ right}$ = particulate concentration at right FGD system inlet, mg/m^3 i.N.

As shown in Table A-2.4-1, the calculated average flue gas inlet particulate loading is less than the specified contract value of 80 mg/m^3. No correction, as provided in the test plan, is made to the relevant test results.

A-2.5 FGD System Inlet Temperature

The FGD system inlet temperature is measured, in multiple evenly distributed locations at both flue gas inlet locations, right and left, using the thermocouples installed on the probes during the gas particulate determination by EPA Method 5. The results are averaged to determine the FGD system inlet temperature.

$$T_{inlet} = (T_{right} + T_{left})/2$$

where

T_{inlet} = FGD system inlet temperature, °C
T_{left} = FGD system left inlet temperature, °C
T_{right} = FGD system right inlet temperature, °C

As shown in Table A-2.5-1, the average FGD system inlet temperature is within the contract-specified limits of 132°C to 160°C, but above the minimum limit of 132°C. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements for the raw water consumption.

Table A-2.4-1 FGD System Inlet Particulate Concentration

	Inlet Particulate Concentration				
	g/dscm		mg/m^3 i.N.		
Test Run Number	Right Inlet	Left Inlet	Right Inlet	Left Inlet	Average, mg/m^3 i.N.
1	0.03487	0.07471	37	80	59
2	0.11723	0.00913	126	10	68
3	0.04934	0.00779	53	8	31

Table A-2.5-1 FGD System Inlet Temperature

	FGD System Inlet Temperature, °C		
Test Run Number	Right	Left	Average
1	151	162	157
2	152	160	156
3	152	169	161

A-2.6 Weight Percent of Chlorides and Fluorides in Coal

The dry weight percent of chlorides, %Cl, and fluorides, %F, in the coal is determined from laboratory analysis and from the following equations. Results are shown in Table A-2.6-1.

$$\%\mathrm{Cl} = \mathrm{Cl\ in\ coal,\ ppm} \times (1/1\,000\,000) \times 100\%$$

$$\%\mathrm{F} = \mathrm{F\ in\ coal,\ ppm} \times (1/1\,000\,000) \times 100\%$$

As shown in Table A-2.6-1, the chloride content of the coal is lower than the specified contract value of 0.05%, and the fluoride content is lower than the specified contract value of 0.015%. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements.

A-2.7 Dry Weight Percent Sulfur in Coal

The dry weight percent of sulfur, %S, in the coal is determined from laboratory analysis. Results are shown in Table A-2.7-1.

The coal sulfur is below the specified contract maximum value of 1.5%. Appropriate correction, as provided in the test plan, is made to the relevant test results to reflect the difference between the actual test conditions and the contract requirements.

Table A-2.6-1 Dry Percent Chlorides and Fluorides in Coal

	Chloride in Coal		Fluoride in Coal	
Test Run Number	ppm	%	ppm	%
1	101.4	0.010	31.3	0.003
2	78.6	0.008	25.8	0.003
3	83	0.008	25.8	0.003

Table A-2.7-1 Dry Percent Sulfur in Coal

Test Run Number	Sulfur in Coal, %
1	0.66
2	0.74
3	0.68

Table A-2.8-1 Available $CaCO_3$, Dry

Test Run Number	Calcium Concentration, mmol/g	Available $CaCO_3$, %
1	8.970	89.8
2	8.838	88.5
3	8.950	89.6
Calculated result	...	89.3% average

Table A-3.1-1 Limestone/Sulfur Dioxide Ratio (Maximum)

Test Run Number	Moles of $CaCO_3$	Moles of Magnesium	Moles of Sulfur	Limestone/Sulfur Dioxide Molar Ratio
1	1.1966	0	5.5510	1.00
2	1.2014	0	5.2720	1.00
3	1.8021	0	5.7520	1.01

A-2.8 Dry Available Calcium Carbonate ($CaCO_3$)

The dry weight percent of available calcium carbonate, $\%CaCO_3$, in the limestone slurry is determined from laboratory analysis and the following equation. Results are shown in Table A-2.8-1.

$$\begin{aligned} \text{Available } CaCO_3 &= \text{mmole/g } CO_3 \\ &\times (1 \text{ mole } CaCO_3/1 \text{ mole } CO_3) \times 100.08 \\ &\text{g/mole } CaCO_3 \times (1 \text{ mole}/1\,000 \text{ mmole}) \times 100\% \end{aligned}$$

The contract-specified value for available $CaCO_3$ is 95%. As shown in Table A-2.8-1, the available $CaCO_3$ in the test limestone is lower than the specified limestone composition. Correction shall be made to the applicable results due to this off-spec item.

A-3 PERFORMANCE GUARANTEE CALCULATIONS

A-3.1 Limestone/Sulfur Dioxide Stoichiometric Ratio (Maximum)

The limestone-to-sulfur-dioxide ratio (see Table A-3.1-1) is determined from the laboratory analysis of total sulfur and carbonate in the solid phase of the gypsum cake, as taken from the gypsum conveyor belts performance test submitted separate from this report, and using the following equation from para. 5-2.3.1:

Table A-3.2-1 Sulfur Dioxide Removal Efficiency (Minimum)

Test Run Number	FGD System Inlet SO_2 at 6% O_2, ppmdv	FGD System Outlet Concentration (Uncorrected)		FGD System Outlet SO_2 at 6% O_2, ppmdv	%MCR	Sulfur in Coal, wt%	FGD System SO_2 Removal Efficiency, %	
		SO_2, ppmdv	O_2,%				Actual	Corrected Guarantee
1	537	26	5.6	26	96	0.66	95.2	93.7
2	501	26	5.8	26	87	0.74	94.9	93.5
3	517	28	5.8	27	86	0.68	94.7	93.6

$$\mathrm{SRR\ CaCO_3} = \frac{1 + [(\text{moles of } CO_3) - (\text{moles of Mg})]}{\text{moles of sulfur}}$$

The contract-guaranteed value for the limestone-to-sulfur ratio equals 1.03.

A-3.2 Sulfur Dioxide Removal Efficiency (Minimum)

The actual sulfur dioxide removal efficiency (see Table A-3.2-1) is calculated from the SO_2 concentrations of the FGD system inlet and outlet as measured by EPA Method 6C corrected to 6% O_2. Reference para. A-2.3 for the inlet SO_2 concentration, and test data for the outlet SO_2 and O_2 data.

$$\%R = (C_{SO2\ in} - C_{SO2\ out})/(C_{SO2\ in}) \times 100\%$$

The guaranteed SO_2 removal efficiency is 92.1% at the design conditions of 100%MCR and 1.5% sulfur. If these design conditions are not met during the test, the guaranteed SO_2 removal efficiency shall be corrected to reflect the difference between the design coal sulfur and gas flow, and the actual test conditions. The following correction-curve equation corrects for the difference between the design conditions and the actual test conditions per the approved performance test plan:

$$Y = A + B(X) + C(Z) + D(X^2) + E(XZ) + F(Z^2)$$

where

A = 98.782738
B = −0.0621825
C = −3.93571
D = 0.00036507
E = −0.0096429
F = 1.375
X = %MCR (see para. A-2.2)
Y = guaranteed SO_2 removal efficiency
Z = measured percent of sulfur in coal

Table A-3.3-1 Sulfur Dioxide Allowable Emission Concentration (Maximum)

Test Run Number	FGD System Outlet SO_2 Concentration Maximum, ppmdv, Corrected for 6% O_2
1	26
2	26
3	27

A-3.3 Sulfur Dioxide Allowable Emission Concentration (Maximum)

The sulfur dioxide allowable emission concentration is measured at the FGD system outlet using EPA Method 6C and corrected to 6% O_2.

The contract-guaranteed value for maximum SO_2 FGD system outlet concentration is 100 ppm at 6% O_2.

See Table A-3.3-1.

A-3.4 Static Pressure Drop

The pressure drop, ΔP, is calculated from the static pressures measured by a multidirectional Fechheimer probe during traversing of the FGD system inlet and outlet flues for gas flow by EPA Method 2G. The calculation is as follows:

$$\Delta P = P_{in,\ avg} - P_{out,\ avg}$$

where

$P_{in,\ avg}$ = average inlet gas flow pressure, kPa_g
$P_{out,\ avg}$ = average outlet gas flow pressure, kPa_g

The guarantee is 3.23 kPa_g at 2.924×10^6 kg/h inlet gas flow. If the inlet gas flow is not at design conditions, then the guarantee is corrected via a correction curve.

The correction curve equation is as follows:

$$Y = AX^2 + BX$$

where

A = −9.8 E−8
B = 0.0014
X = FGD system inlet gas flow; see section A-2
Y = guaranteed pressure drop, kPa

The contract-guaranteed value for the FGD system pressure drop corrected for the proper gas flow varied, as shown in the “Corrected Guaranteed Pressure Drop” column (last column) in Table A-3.4-1. The measured pressure drop is lower than the guaranteed value for all three test runs as shown in bold type in the “Measured Pressure Drop” column of the same table.

Table A-3.4-1 Static Pressure Drop

Test Run No.	Inlet Static Pressure, in. wc			Outlet Static Pressure, in. wc	Measured Pressure Drop		FGD System Inlet Gas Flow, kg/h	Corrected Guaranteed Pressure Drop, kPa_g
	Right	Left	Average		in. wc	kPa_g		
1	9.9	10.0	10.0	−0.8	10.8	2.67	2.800 E+6	3.15
2	10.1	10.0	10.0	−0.8	10.8	2.70	2.558 E+6	2.94
3	9.5	10.0	9.8	−0.8	10.6	2.64	2.502 E+6	2.89

A-3.5 Gypsum Production (Minimum)

Gypsum production is defined as the amount of dry solids gypsum products produced from the SO_2 removal process. The gypsum production rate is calculated from the following equations:

Step 1: Calculate the amount of sulfur (in moles) entering the FGD system.

$$\text{Moles of sulfur} = \text{boiler heat input at 100\%MCR}/\text{HHV coal} \times \text{\%MCR} \times \text{wt\% S}/32$$

where

boiler heat input at 100% MCR = 5 361 000 000 kJ/h
= 1.280743 E+9 kcal/h
HHV = higher heating value of coal, kcal/kg
%MCR = see section A-2
wt% S = weight percentage of sulfur in coal
32 = molecular weight of sulfur, kg S/kg-mole S

Step 2: Determine the amount of SO_2, in moles, reacted (removed) in the scrubber.

$$\text{Moles of } SO_2 \text{ in scrubber} = \text{moles of S entering FGD system} \times (1 \text{ mol } SO_2/1 \text{ mol S}) \times \%SO_2 \text{ removal}$$

where SO_2 removal is determined per para. A-3.2.

Step 3: Determine the moles of gypsum ($CaSO_4 \times 2H_2O$) produced.

$$\text{Moles of } CaSO_4 \times 2H_2O \text{ (produced)} = \text{moles of } SO_2 \text{ (in scrubber)} \times \text{\% scrubber oxidation} \times (1 \text{ mole } CaSO_4 \times 2H_2O/1 \text{ mole } SO_2)$$

where

$$\text{\% scrubber oxidation} = \frac{\text{moles of } CaSO_4 \times 2H_2O}{CaSO_4 \times 2H_2O + CaSO_3 \times \frac{1}{2}H_2O}$$

Step 4: Determine the kilograms of gypsum products produced per hour.

$$\text{Gypsum products produced (kg/h)} = \text{moles of } CaSO_4 \times 2H_2O \times (172 \text{ kg } CaSO_4 \times 2H_2O/\text{kg-mole } CaSO_4 \times 2H_2O)$$

The guarantee is 5 100 kg/h at 0.65 wt% sulfur in coal. If the percent sulfur in fuel is not at design conditions, then the guarantee is corrected via correction curve.

The following correction curve equation corrects for the difference between the design conditions and the actual test conditions per the approved performance test plan:

$$Y = AX$$

where

A = 7 788.235
X = measured wt% sulfur in coal
Y = guaranteed gypsum production, kg/h

The contract-guaranteed value for the minimum gypsum production corrected for the weight percentage of sulfur in the coal is shown in the "Gypsum Production, Corrected" column of Table A-3.5-1. The measured gypsum production is lower than the guaranteed value for all three test runs as shown in bold type in the "Gypsum Production, Measured" column of the same table.

A-3.6 Gypsum Moisture Content (Maximum)

The gypsum cake moisture content is determined from laboratory analysis, with the results shown in the table below. Gypsum cake was collected at the transfer conveyors for this test.

Test Run Number	Measured Free Gypsum Moisture, wt%
1	7.4
2	7.9
3	7.6

Table A-3.5-1 Gypsum Production (Minimum)

Test Run Number	HHV of Coal, kcal/kg	%MCR	Sulfur in Coal, wt%	SO_2 Removal, %	Scrubber Oxidation, %	Gypsum Production, kg/h	
						Measured	Corrected
1	7 106	96	0.66	95.2	99.7	5 818	5 140
2	7 052	87	0.74	94.9	99.7	5 978	5 763
3	7 076	86	0.68	94.7	99.7	5 349	5 296

Table A-3.7-1 Gypsum Purity (Minimum)

Test Run Number	SO_4, mmol/g	Gypsum Purity, %		Available $CaCO_3$, wt%	Inlet Particulate Loading, mg/m^3 i.N.	Fluoride in Coal, wt%	Chloride in Coal, wt%
		Actual	Adjusted				
1	5.70	98.0	92.1	89.8	59	0.003	0.01
2	5.68	97.7	91.3	88.5	68	0.003	0.01
3	5.68	97.7	92.3	89.6	31	0.003	0.01

The contract-guaranteed value is 10% free moisture for the gypsum produced by the FGD system. The measured free moisture is lower than the guaranteed value for all three test runs as shown in the above table.

A-3.7 Gypsum Purity (Minimum)

The gypsum purity is calculated by laboratory analysis of the gypsum cake collected at the gypsum transfer conveyors.

$$
\begin{aligned}
\% \text{ gypsum purity} &= \text{mmol/g } SO_4 \\
&\times (1 \text{ mole } CaSO_4{-}2H_2O/1 \text{ mole } SO_4) \\
&\times (172 \text{ g/mole } CaSO_4{-}2H_2O) \\
&\times (\text{mole}/1\,000 \text{ mmol}) \times 100\%
\end{aligned}
$$

The gypsum purity guarantee is 95% based on design conditions of 95% $CaCO_3$ availability in limestone slurry, 80 mg/m^3 i.N. inlet particulate loading, 0.015 wt% F in coal, and 0.05 wt% Cl in coal. If the design conditions are not met, then the gypsum purity guarantee is adjusted per the approved test plan using the following equation:

$$
\begin{aligned}
\text{Adjusted gypsum purity guarantee} &= 95\% \\
&+ (0.6)(\text{actual available } CaCO_3 - 95\%) + (-0.01071) \\
&\times \left(\text{actual inlet particulate loading} - 80 \text{ mg/m}^3 \text{ i.N.}\right) \\
&+ (-1.66667)(\text{actual wt\% F in coal}) \\
&+ (-0.9)(\text{actual wt\% Cl in coal})
\end{aligned}
$$

The contract-guaranteed value varies as a function of limestone purity, inlet particulate loading, and the chloride and fluoride contents of the coal. The adjusted guaranteed gypsum purity and the actual (measured) purity are shown in Table A-3.7-1.

Table A-3.8-1 Gypsum Properties

Items	Gypsum Properties	Units	Guaranteed Value	Measured Value per Test Run [Note (1)]		
				1	2	3
A	pH	N/A	6.5–8	7.1	7.1	7.2
B	$CaSO_3$-½H_2O	%	Max. 0.5	0.2	0.2	0.2
C	$CaCO_3$	%	Max. 1.5	0.8	0.6	0.8
D	Chloride ion	ppm	Max. 120	1	1	1
E	Water-soluble sodium	ppm	Max. 75	26	28	28
F	Water-soluble magnesium	ppm	Max. 50	27	27	27
G	Water-soluble potassium	ppm	Max. 75	3	7	5
H	Total water-soluble salts	ppm	Max. 600	466	428	408
I	SiO_2	%	Max. 1.9	1.02	1.14	1.22
J	Fe_2O_3	%	Max. 1.5	0.02	0.01	0.01
K	Inert content	%	Max. 1.0	0.2	0.2	0.2

GENERAL NOTES:

(a) Items A, D, E, F, G, H, I, and K are from the lab test report and no further calculations are required.

(b) Items B, C, and J are calculated as follows:

(1) For B, $\%CaSO_3$-½H_2O = (ppm $CaSO_3$-½H_2O)/10 000.

(2) For C, $\%CaCO_3$ = mmole/g CO_3 × (1 mol $CaCO_3$/1 mol CO_3) × 100.08 g/mol $CaCO_3$/10.

(3) For J, $\%Fe_2O_3$ = (ppm Fe_2O_3/1 000)/(55.9 g/mol Fe) × (1 mol Fe/2 moles Fe_2O_3) × (159.8 g/mol Fe_2O_3)/10.

NOTE: (1) The measured gypsum properties were in compliance with the contract specifications for all three test runs, the measured pH in each of the three runs was within the guaranteed value, and the measured results for all other properties were lower than the guaranteed values.

A-3.8 Gypsum Properties

Gypsum properties are determined from the gypsum cake, sampled from the gypsum conveyors, by laboratory analysis. Results are shown in Table A-3.8-1.

There are no corrections for any of these guaranteed values.

The measured gypsum properties were in compliance with the contract specifications for all three test runs, as shown in the "Measured Value per Test Run" columns of Table A-3.8-1.

A-3.9 Makeup Water Consumption (Maximum)

The makeup water consumption is recorded from the raw water flowmeter. For this sample calculation, a 24-h run was performed.

The makeup water consumption guarantee is 20 L/s based on 132°C inlet gas temperature and 100% MCR. The following correction curve equation corrects for the difference between the design conditions and the actual test conditions per the approved performance test plan:

Table A-3.9-1 Makeup Water Consumption

	Volume of Water, m^3			Average Makeup Water Consumption, L/s	
Instrument Tag	**At 0 h**	**At 24 h**	**Total Consumed**	**Measured**	**Corrected Guarantee**
56-FQT-RW850	557 666.11	558 862.98	1 196.87	14	29

$$Y = \left(A + BX + CX^2 + DX^3 + EX^4 + FX^5\right)^{1/2} + (\text{slope of curve } L) \times (\text{actual load} - 100\%)$$

where

A = 12 790.887
B = −611.8258
C = 11.670548
D = −0.10867243
E = 0.00049076767
F = −8.5078955 E−7
Slope of curve L = $(0.61181755) + (1.5)(-0.035535208)(\text{load}^{1/2}) + (2.2741562\text{E}{-44})(e^{\text{load}}) - (1.5)(193.4551)(\text{load}^{-2.5})$
X = actual FGD system inlet gas temperature; reference section A-6
Y = new guaranteed water consumption, L/s

Refer to para. A-2.2 for load and para. A-2.5 for FGD system inlet gas temperature.

The contract-adjusted guarantee for the maximum makeup water consumption is shown in the last column of Table A-3.9-1. The measured maximum makeup water consumption was 14 L/s, averaged over a 24-h period, which is lower than the adjusted guaranteed values for the test run.

A-3.10 Power Consumption Guarantee (Maximum)

The power consumption is recorded from power analyzers measuring power from the switchgear(s) (SWGR), power center (PC), and the raw water power center. A 24-h test and three test runs (4 h each) were performed. Table A-3.10-1 is an example of one test run. The power consumption is calculated from the following approved performance test plan equation:

$$\text{Measured power consumption} = \text{SWGR1} + \text{SWGR2} - 0.75 \times \text{raw water}$$

where

SWGR1 = switchgear 1
SWGR2 = switchgear 2

The guaranteed value of 5 923 kW is based on 100% load. If the measured load varies from the design condition, then the guarantee is corrected via a correction curve.

The correction curve equation is as follows:

$$Y = (A \times X) + B$$

where

A = 7.7815
B = 5 144.9
X = %MCR; see section A-2
Y = guaranteed power consumption, kW

Table A-3.10-1 Power Consumption (Test Run 1)

	Power Consumption, kW·h					Average Power Consumption, kW	
	Test Run Time Interval, h						
Location	**0–1**	**1–2**	**2–3**	**3–4**	**Total After 4-h Test Run**	**Measured**	**Corrected Guarantee**
Switchgear (SWGR1)	1 538	1 584	1 548	1 543	6 213	1 553	...
Switchgear (SWGR2)	2 230	2 309	2 245	2 245	9 029	2 257	...
Raw water power center	164.7	165.1	164.7	165.0	659.5	165	...
Calculated result	...	...	...	...	...	3 687	5 890 at 96% MCR

NONMANDATORY APPENDIX B
SEMI-DRY FGD SYSTEM CALCULATIONS

B-1 INTRODUCTION

This Appendix provides a sample calculation for how ASME PTC 40 is applied to a semi-dry FGD system to determine if the measured performance meets the provided guarantees.

B-2 DESIGN PARAMETER CALCULATIONS

B-2.1 Constants

See Table B-2.1-1.

B-2.2 FGD System Inlet Wet Gas Flow

The FGD system inlet gas mass flow, for each FGD system inlet, is calculated from the FGD system inlet gas volumetric flow in units of acfm and gas density as measured by the emission tester. The volumetric flow is calculated from the static and velocity pressures measured during the FGD system inlet flue gas flow traverse, using EPA Test Methods 1 and 2. Flue gas flow in acfm is determined from velocity and static pressure measurements, as well as from gas density data (reference EPA Test Method 3A for CO_2 and O_2 concentrations and moisture from EPA Method 4, all in conjunction with EPA Method 2). See Table B-2.2-1.

B-2.3 Coal Sampling and Analysis Results

See Table B-2.3-1.

B-2.4 Determine Sulfur Content of Fuel per Heat Basis

The sulfur content of coal per heat basis, S_H, is determined using the following equation and values from Table B-2.3-1:

$$\begin{aligned} S_H &= S_{a\,r} / \mathrm{HHV}_d \times 100{,}000 \\ &= 0.32 \times 8{,}800 \times 100{,}000 = 0.364 \text{ lb S/MBtu} \end{aligned}$$

Table B-2.1-1 Constants

Gas	Molecular Weight, lb/lb-mol
O_2	31.998
CO_2	44.01
Ar	39.948
N_2	28.014
H_2O	18.015

B-2.5 Determine F_d Factor

The F_d is calculated by using EPA Method 19 and the as-tested coal analysis, where the coal composition is taken as the fractional composition. See Table B-2.3-1 for values.

$$\begin{aligned} F_d &= 1{,}000{,}000 \times [3.64 \times \mathrm{H} + 1.53 \times \mathrm{C} + 0.57 \times \mathrm{S} \\ &\quad + 0.14 \times (\mathrm{N} - 0.46) \times \mathrm{O}\,] / (HHV_d \times 100) \text{ dscf/MBtu} \\ &= 1{,}000{,}000 \times [3.64 \times 0.0481 + 1.53 \times 0.7012 + 0.57 \\ &\quad \times 0.0044 + 0.14 \times (0.0082 - 0.46) \times 0.165] \\ &\quad /(12{,}105 \times 100) \\ &= 9{,}712 \text{ dscf/MBtu} \end{aligned}$$

B-2.6 Determine Heat Input to the Unit

The heat input, HI, to the boiler is calculated from F_d and the gas flow rate as measured by the emission tester using eq. F-18 from the Code of Federal Regulations, Title 40 (40 CFR), Part 75, Appendix F. See Table B-2.2-1 for values.

$$\begin{aligned} \mathrm{HI} &= Q_w \times 60 \times [(1 - B_{ws}) / F_d] \times [(20.9 - O_2(\text{dry}) \\ &\quad \times 100) / 20.9] \\ &= 2{,}161{,}582 \times 60 \times [(1 - 0.1493) / 9{,}712] \\ &\quad \times [(20.9 - 0.0497 \times 100)/20.9] \\ &= 8{,}658.6 \text{ MBtu/hr} \end{aligned}$$

B-2.7 Mass Sulfur Input to the Unit

The mass sulfur input to the unit is determined from the sulfur content of fuel per heat basis (see para. B-2.4) times the HI (see para. B-2.6) to the unit.

Sulfur feed, $S_f = S_H \times \mathrm{HI} = 0.364 \times 8{,}658.6 = 3{,}152$ lb S/hr

B-2.8 Chlorides and Fluorides From Coal

The dry chloride and dry fluoride contents of the coal are determined, in parts per million, from laboratory analysis; the measurements are converted to the total mass flow rate of the chloride, Cl_m, and fluoride, F_m, by using the HI to the unit and the higher heating value, HHV, of the coal. See Table B-2.3-1 and para. B-2.6 for values.

$$\begin{aligned} Cl_m &= (\mathrm{Cl}/1{,}000{,}000) \times \mathrm{HI} / (\mathrm{HHV}/1{,}000{,}000) \\ &= (100/1{,}000{,}000) \times 8{,}658.4/(8{,}800/1{,}000{,}000) \\ &= 98.4 \text{ lb/hr} \end{aligned}$$

Table B-2.2-1 EPA Methods 2 and 19

EPA Methods 2 and 19 Data	Symbol	Measured Value
Stack flue gas flow (scfm)	Q_w (wet)	2 161 582
Stack flue gas flow (dscfm)	Q_d (dry)	1 838 858
Inlet FGD system moisture (fraction by volume)	B_{wi}	0.133
Stack moisture (fraction by volume)	B_{ws}	0.1493
Stack CO_2% (dry)	CO_2	13.82
Stack O_2% (dry)	O_2	4.97

GENERAL NOTE: Measured value is determined using emission tester.

Table B-2.3-1 Coal Sampling and Analysis Results

Coal Characteristic	Symbol	Measured Value
Carbon content, mass percent dry	C	70.12
Hydrogen content, mass percent dry	H	4.81
Nitrogen content, mass percent dry	N	0.82
Sulfur content, mass percent dry	S	0.44
Oxygen content, mass percent dry	O	16.50
Moisture, mass percent	H_2O	27.30
Sulfur content, mass percent as received	S_{ar}	0.320
Ash content, mass percent dry	...	7.29
Ash content, mass percent as received	...	5.30
Chlorine content, ppm	Cl	100.0
Fluorine content, ppm	F	0.0
Heat value, Btu/lb as received	HHV	8,800.3
Heat value, Btu/lb dry	HHV_d	12,105

GENERAL NOTE: Measured values are determined from lab results.

$$\begin{aligned} F_m &= (\mathrm{F} / 1{,}000{,}000) \times \mathrm{HI} / (\mathrm{HHV} / 1{,}000{,}000) \\ &= (0 / 1{,}000{,}000) \times 8{,}658.4 / (8{,}800 / 1{,}000{,}000) \\ &= 0 \text{ lb / hr} \end{aligned}$$

B-2.9 FGD System Inlet Flue Gas Conditions

The FGD system inlet and outlet flue gas conditions are required to determine the adiabatic saturation temperature of the flue gas. The FGD system inlet and outlet conditions are measured at multiple, evenly distributed locations using the thermocouples installed on the probes during the flue gas flow rate determination by EPA Method 2 and by EPA Method 3A testing. The results are averaged to determine the FGD system inlet flue gas conditions. See Table B-2.9-1.

Table B-2.9-1 FGD System Inlet and Outlet Conditions

FGD System Conditions	Measured Values
Inlet	
Inlet dry bulb temperature — average temperature, °F	300.0
O_2, dry percent volume	5.24
CO_2, dry percent volume	14.37
Moisture, percent volume	11.07
Pressure (P_g), psia	13.80
Outlet	
Outlet dry bulb temperature — average temperature, °F	160.1

(a) Convert dry flue composition values to wet flue gas composition values using the following equation:

$$\begin{aligned} &\text{Concentration wet} = (\text{concentration dry}) \\ &\quad \times (100\% - \%\text{Moisture})/100\% \end{aligned}$$

The equation yields the following results. Argon is assumed to be 0.9% in the flue gas system.

Component	Symbol	Concentration, vol%
O_2 (wet)	O_2w	4.66
CO_2 (wet)	CO_2w	12.78
Argon (wet)	Arw	0.90 (assumed)
Moisture	H_2O	11.07

The wet flue composition value for nitrogen, N_2w, is then calculated as

$$N_2w = 100\% - (O_2w + CO_2w + Arw) = 70.59 \text{ vol\%}$$

(b) Calculate the molecular weight of the flue gas. See Table B-2.9-2.

B-2.10 Adiabatic Saturation Temperature

The adiabatic saturation temperature, T_{sat}, is determined based on the specific humidity, SH; dry-bulb temperature, T_{db}; and duct pressure, P_g. A psychometric curve, program, or other means can be used to calculate the saturation temperature of the gas.

$$T_{\mathrm{sat}} = f\left(\mathrm{SH},\ T_{db},\ P_g\right)$$

Example of Observed System Temperatures	Values
Adiabatic saturation temperature	128.1°F
Average outlet dry bulb temperature	160.1°F
Approach to adiabatic saturation temperature	32.0°F

B-3 CALCULATION OF EMISSIONS AND PERFORMANCE GUARANTEES

Sulfur dioxide and other contractual emissions should be measured and calculated per regulatory agency procedures, e.g., those specified in 40 CFR Part 60, Appendices A-1 through A-7, using a qualified emission tester. Typically no corrections or uncertainty is allowed to be applied to the emission values.

B-3.1 Lime Usage Calculation — Using a Tank Drawdown Test

See Table B-3.1-1 for lime usage measurements.

Step 1: Calculate the tank level drop.

Table B-2.9-2 Determination of Flue Gas Molecular Weight

Component	Concentration in Flue Gas, wet vol%	Molecular Weight, lb/lb-mol	Proportioned Molecular Weight, lb/lb-mol	
			Wet	Dry
O_2 (wet)	4.66	31.998	1.49	1.49
CO_2 (wet)	12.78	44.01	5.62	5.62
Argon (wet)	0.90	39.948	0.36	0.36
N_2 (wet)	70.59	28.014	19.78	19.78
Moisture	11.07	18.015	1.99	0
Total of all components	100	...	29.24	27.25

Table B-3.1-1 Lime Usage Measurements

Parameter	Measurement	Source of Measurement
Time of slurry tank level measurement, hr:min		
Start time	9:00	Test
End time	17:00	Test
Slurry tank level (measured from top), in.		
Starting level	74.5	Test
Ending level	187.2	Test
Lime tank diameter, ft	25.94	Design
Lime slurry titration, lab reference temperature, °F	79.4	Lab
Slurry tank temperature during test, °F	122.2	Test
Pebble lime available, CaO wt% dry	90.00	Lab results
Lime slurry available (CaO Conc1), mg CaO/ml slurry	155.00	Lab test

$$\text{End level} - \text{start level} = 187.2 - 74.5 = 112.68 \text{ in.}$$

Step 2: Calculate the time between measurements of the level of slurry in the tank.

$$\text{End time} - \text{start time} = 17{:}00 - 09{:}00 = 8{:}00 \text{ h}$$

Step 3: Calculate the volume of slurry consumed based on tank size, level drop, and time between measurements.

$$\begin{aligned}\text{Tank area} &= \frac{1}{4}\pi D^2 = \frac{1}{4}\pi (25.94)^2 \\ &= 528.48 \text{ ft}^2\end{aligned}$$

$$\begin{aligned}\text{Slurry consumed, ft}^3/\text{hr} &= \text{tank area} \times \text{slurry height used}/12 \\ &\quad /\text{time (hr)} \\ &= 620 \text{ ft}^3 \text{ slurry/hr}\end{aligned}$$

Step 4: Determine lime available in slurry.

$$\begin{aligned}&\text{Lime slurry available (CaO Conc2)} = \\ &\quad \text{lime slurry available (CaO Conc1)} \times 0.002204623 \text{ lb} \\ &\quad \text{CaO/g CaO} \times 28{,}316.847 \text{ ml/ft}^3/1{,}000 \text{ ml/L} \\ &\quad = 9.68 \text{ lb CaO/ft}^3\end{aligned}$$

Step 5: Calculate the actual lime usage rate.

$$\begin{aligned}\text{Actual lime usage rate} &= \text{lime slurry available (CaO Conc2)} \times \\ &\quad \text{slurry consumed} \\ &= 9.68 \times 620 \\ &= 6{,}002 \text{ lb CaO/hr}\end{aligned}$$

Corrections to the lime usage, shown in Table B-3.1-2, are made for various testing parameters based on guarantee equations or curves agreed to by the supplier and purchaser. The number of correction factors will vary for project specifics.

Corrected lime usage rate for comparison to the guarantee is calculated by

$$\begin{aligned}&\text{Actual lime usage rate}/(C1 \times C2 \times C3) - C4 - C5 \\ &= 4{,}829 \text{ lb/hr}\end{aligned}$$

Additional corrections may be specified, e.g., to correct for alkalinity in the ash.

Table B-3.1-2 Correction Factors

Correction Type	Symbol	Correction Factor
CaO multiplier for approach temperature	C1	1.1160
CaO multiplier for FGD system inlet temperature	C2	1.0000
CaO multiplier for sulfur feed	C3	1.1116
CaO adder for chlorine feed	C4	9.0
CaO adder for fluoride feed	C5	0.0