ASME PTC 4.3-2017

[Revision of ASME PTC 4.3-1968 (R1991)]

Air Heaters

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of
Mechanical Engineers

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The American Society of Mechanical Engineers
Two Park Avenue • New York, NY • 10016 USA

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CONTENTS

Mandatory Appendices

Nonmandatory Appendices

Figures

Tables

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

Performance Test Code Committee No. 4 on Stationary Steam-Generating Units was reorganized in May 1958 to rewrite and bring up to date the 1946 edition of the Test Code for Stationary Steam Generating Units.

During the formulation of the new test code, PTC 4.1-1964, the technical committee brought to the attention of the Performance Test Codes Committee that for the air heater, an auxiliary heat-absorption equipment common to all large steam generating units, there existed no performance test code. PTC Committee No. 4 recommended the development of such a test code as part of its assignment.

The Performance Test Codes Committee instructed PTC Committee No. 4 to prepare such a test code as a supplement to be known as PTC 4.3, on air heaters. This test code was developed and its format follows closely that of PTC 4.1, the Test Code for Steam Generating Units.

This test code was approved by the Performance Test Codes Committee on June 9, 1966. Final publication was delayed, however, until a number of suggestions made by the standing Committee were considered and satisfactorily resolved. It was approved and adopted by the Council as a standard practice of the Society by action of the Policy Board, Codes and Standards on November 8, 1967.

The code was subsequently approved as an American National Standard in 1974 by the American National Standards Institute (ANSI).

Work on the current revision began with the first meeting of the reorganized committee on December 16 and 17, 1999, following the publication of PTC 4, on fired steam generators.

The reasons for undertaking this revision were multifold: (a) to include test uncertainty; (b) to minimize the prescriptive guidelines and emphasize the performance-based approach; (c) to address air heater configurations with multiple flow streams; (d) to update measurement methods to include improved instrumentation currently available, and to base combustion calculations on O_2 instead of CO_2; (e) to update nomenclature; and (f) to comply with Society Policy on SI units.

This Code was approved by the PTC Standards Committee on October 12, 2016. It was then approved and adopted by the Council as a Standard practice of the Society by action of the Board on Standardization and Testing on January 5, 2017. The Performance Test Code was also approved as an American National Standard by the ANSI Board of Standards Review on February 14, 2017.

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Performance Test Codes

(The following is roster of the Committee at the time of approval of this Code.)

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General. ASME Codes are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Code may interact with the Committee by requesting interpretations, proposing revisions or a case, and attending Committee meetings. Correspondence should be addressed to:

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

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.

Proposing a Case. Cases may be issued to provide alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Code to which the proposed Case applies.

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.

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.

Attending Committee Meetings. The PTC Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the PTC Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at go.asme.org/PTCcommittee.

INTRODUCTION

ASME Performance Test Codes (PTCs) provide uniform rules and procedures for the planning, preparation, execution, and reporting of performance test results. These codes provide guidelines for test procedures that yield results of the highest level of accuracy based on current engineering knowledge, taking into account test costs and the value of information obtained from testing. PTCs were developed by balanced committees representing many concerned interests.

When tests are conducted in accordance with this Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of actual performance of the equipment tested. ASME PTCs 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 prior to signing the contract, on the method to be used for comparing the results to the contractual guarantees. It is beyond the scope of any PTC to determine or interpret how such comparisons are made.

Test uncertainty is an estimate of the limit of error of a test result. It is the interval about a test result that contains the true value with a given probability or level of confidence. It is based on calculations utilizing statistics, instrumentation information, calculation procedure, and actual test data. Code tests are suitable for use whenever performance must be determined with minimum uncertainty. They are meant specifically for equipment operating in an industrial setting.

PTCs are generally not used in troubleshooting equipment. However, they can be used to quantify the magnitude of performance anomalies of equipment that is suspected to be performing poorly, or to confirm the need for maintenance, if simpler means are not adequate. PTCs are excellent sources or references for simpler routine or special equipment test procedures, and this Code includes a nonmandatory appendix on routine testing and performance monitoring. Conducting periodic performance tests on equipment can uncover the need for further investigation, which can lead to preventive maintenance or modification.

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AIR HEATERS

Section 1
Object and Scope

1-1 OBJECT

(a) This Code provides procedures for conducting performance tests of air heaters to determine the following results:

(1) exit gas temperature
(2) air to gas leakage
(3) fluid pressure losses
(4) other fluid temperatures

(b) It also provides procedures to determine the heat capacity ratio (*X*-ratio) and any or all of the performance results specified above that may be necessary for

(1) checking actual performance against standard or design performance
(2) comparing changes in performance over time with standard or design performance
(3) comparing performance under various operating conditions
(4) determining the effect of changes in equipment

1-2 SCOPE

This Code applies to all air heaters used in industrial application, e.g., air heaters servicing steam generators and industrial furnaces. This specifically includes

(a) combustion gas-to-air heat exchanger including air heaters with multisection air streams

(b) air preheater coils utilizing noncondensing (single phase) steam, water, or other hot fluids

This Code does not cover direct-fired air heaters or gas-to-gas heat exchangers. In the latter application, this Code may be used to determine both the thermal and pressure drop performance, while alternate methods of leakage measurement should be agreed upon between the parties. This Code also does not cover heat exchangers where the heating fluid is condensed while passing through the heater.

Air heaters in parallel shall be tested individually (wherever possible) for purposes of checking actual performance.

1-3 MEASUREMENT UNCERTAINTY

This Code requires pretest and post-test uncertainty analysis in accordance with ASME PTC 19.1. The pretest uncertainty analysis is required in order to effectively plan the test. It allows corrective action to be taken prior to the test, either to decrease the uncertainty to a level consistent with the agreed-upon uncertainty, or to reduce the cost of the test while still attaining the objective. The post-test uncertainty analysis is used to determine the uncertainty intervals for the actual test. This analysis should confirm the pretest systematic and random uncertainty estimates. It serves to either validate the quality of the test results or to expose problems.

Typical values of test uncertainties for various unit configurations and performance parameters for an air heater undergoing a performance test in accordance with this Code are presented in Table 1-3-1.

Table 1-3-1 Typical Test Uncertainties

Parameters	Bi-Sector	Multi-Sector
Corrected exit gas temperature, °F (°C)	2–6 (1–3)	2–6 (1–3)
Corrected air-to-gas leakage, % leakage	1–2	1–2
Corrected fluid pressure differential, in. wg (Pa)	±0.5 (±125)	±0.5 (±125)
Corrected exit air temperature, °F (°C)	2–6 (1–3)	Not applicable
Corrected exit air temperature, weighted average, °F (°C)	Not applicable	2–6 (1–3)

Section 2
Definitions of Terms and Symbols

2-1 GENERAL

The Code on Definitions and Values (ASME PTC 2) defines the meaning and values of basic technical terms and numerical constants that are used throughout this Code.

NOTE: For the purposes of this Code, the term *flue gas* shall be used interchangeably with the term *hot fluid* to describe the hot heat transfer fluid passing through the air heater.

2-2 DEFINITIONS

absolute sensitivity (influence) coefficient: unit change in result per unit change of the measured parameter.

acceptance test: the evaluating action(s) to determine if a new or modified piece of equipment satisfactorily meets its performance criteria, permitting the purchaser to "accept" it from the supplier.

accuracy: the closeness of agreement between a measured value and the true value.

accuracy check: the process of comparing the response of an instrument to a standard over some measurement range (also see *calibration*).

additive: a substance added to a gas, liquid, or solid stream to cause a chemical or mechanical reaction.

air, corrected theoretical: the theoretical air adjusted for unburned carbon and additional oxygen required to complete the sulfation reaction.

air, excess: air supplied to burn a fuel in addition to the corrected theoretical air. Excess air is expressed as a percentage of the corrected theoretical air in this Code.

air heater: a heat exchanger that transfers heat from a high-temperature medium, e.g., hot gas, to an incoming air stream. Regenerative air heaters include bi-sector, tri-sector, and quad-sector types with fixed or rotating heating elements. Recuperative air heaters include tubular, plate, and heat pipe types.

air heater air-to-air leakage: air that leaks from a high pressure air stream to a lower pressure air stream, e.g., primary air to secondary air leakage.

air heater leakage: mass of airflow passing from all air-side streams to the heat transfer fluid. Note that this calculated value will include any ingress air that may be present between the air heater gas inlet and gas outlet test planes.

air, infiltration/ingress: air that leaks into the steam generator and/or air heater setting (same as *setting infiltration*).

air, other: combustion air other than primary air, secondary air, and infiltration air, e.g., tertiary air, that is encountered in the combustion processes covered by this Code.

air preheater coils: a heat exchanger that typically uses steam, condensate, and/or glycol to heat air entering the steam generator and is often used to control corrosion in regenerative and recuperative air heaters.

air, primary: the transport and drying air for the coal from the pulverizers to the burners in pulverized coal fired applications. The primary air is often at a temperature different from that of the secondary air as it leaves the regenerative air heaters in large steam generators, and typically represents less than 25% of the total combustion air. Oil and gas fired steam generators usually do not have primary air. Primary air is the air used for fluidizing the bed material at the base of the combustion chamber in circulating fluidized beds.

air, secondary: the balance of the combustion air not provided as primary air in pulverized and fluid bed applications. All of the combustion air leaving the air heater is usually referred to as secondary air in oil and gas fired steam generators. Secondary air may be split into overfire air or other streams as it enters the furnace; however, it remains secondary air up to and including the wind box.

air temperature rise: the increase in temperature of the airflow passing through the air heater. For multi-sector air heaters, this parameter is defined as the composite air temperature increase of the total airflow (from all streams) passing through the air heater.

air, theoretical: amount of air required to supply the exact amount of oxygen necessary for complete combustion of a given quantity of fuel. Theoretical air and stoichiometric air are synonymous.

analysis, proximate: laboratory analysis, in accordance with the appropriate ASTM standard, of a fuel sample providing the mass percentages of fixed carbon, volatile matter, moisture, and noncombustibles (ash).

analysis, ultimate: laboratory analysis, in accordance with the appropriate ASTM standard, of a fuel sample providing the mass percentages of carbon, hydrogen (excluding hydrogen in moisture), oxygen (excluding oxygen in moisture), nitrogen, sulfur, moisture, and ash.

as-fired fuel: fuel in the condition as it enters the steam generator boundary.

ash: the noncombustible mineral-matter constituent of fuel that remains after complete burning of a fuel sample in accordance with appropriate ASTM standards.

ash, bottom: all residue removed from the combustion chamber other than that entrained in the flue gas leaving the steam generator boundary.

ash, fly: particles of residue entrained in the flue gas leaving the steam generator boundary.

ash pit: a pit or hopper located below a furnace where residue is collected and removed.

bias error: see *error, systematic*.

calcination: the endothermic chemical reaction that takes place when carbon dioxide is released from calcium carbonate to form calcium oxide, or from magnesium carbonate to form magnesium oxide.

calcium to sulfur molar ratio (Ca/S): the total moles of calcium in the sorbent feed divided by the total moles of sulfur in the fuel feed.

calcium utilization: the percent of calcium in the sorbent that reacts with sulfur dioxide (SO_2) to form calcium sulfate ($CaSO_4$). It is sometimes called sorbent utilization.

calibration: the process of comparing the response of an instrument to a standard over some measurement range and adjusting the instrument to match the standard if appropriate (also see *accuracy check*).

capacity: the maximum main steam mass flow rate the steam generator is capable of producing on a continuous basis with specified steam conditions and cycle configuration (including specified blowdown and auxiliary steam flow). This is frequently referred to as maximum continuous rating.

capacity, peak: the maximum main steam mass flow rate the steam generator is capable of producing with specified steam conditions and cycle configuration (including specified blowdown and auxiliary steam flow) for intermittent operation, i.e., for a specified period of time without affecting future operation of the unit.

combustion chamber: an enclosed space provided for the combustion of fuel.

combustion efficiency: a measure of the completeness of oxidation of all fuel compounds. It is usually quantified as the ratio of actual heat released by combustion to the maximum heat of combustion available.

combustion split: the portion of energy released in the dense bed region of a fluidized bed, expressed as a percentage of the total energy released.

composite air temperature: the mass weighted average temperature of all the air streams either entering or leaving a multi-sector air heater.

coverage: the percentage of observations (measurements) of a parameter that can be expected to differ from the true value of the parameter by no more than the uncertainty.

credits: energy entering the steam generator envelope other than the chemical energy in the as-fired fuel. These credits include sensible heat (a function of specific heat and temperature) in the fuel, entering air, and atomizing steam; energy from power conversion in the pulverizers, circulating pumps, primary air fans, and gas recirculation fans; and chemical reactions, e.g., sulfation. Credits can be negative, e.g., when the air temperature is below the reference temperature.

dehydration: the endothermic chemical reaction that takes place when water is released from calcium hydroxide to form calcium oxide, or from magnesium hydroxide to form magnesium oxide.

design conditions: see *specified conditions*.

dilute phase: the portion of the bed in a circulating fluidized bed combustion chamber above the secondary air inlet ducts (made up primarily of the circulating particulate material).

efficiency, fuel: the ratio of the output to the input as chemical energy of fuel.

efficiency, gross: the ratio of the output to the total energy entering the steam generator envelope.

energy-balance method: Formerly the "heat loss method." A method of determining steam generator efficiency by a detailed accounting of all energy entering and leaving the steam generator envelope.

error, random: sometimes called precision error, random error is a statistical quantity and is expected to be normally distributed. Random error results from the fact that repeated measurements of the same quantity by the same measuring system, operated by the same personnel, do not yield identical values.

error, systematic: sometimes called bias error; the difference between the average of the total population and the true value. The true systematic or fixed error that characterizes every member of any set of measurements from the population.

error, total: combination of systematic error and random error.

exit gas temperature: the average temperature of the flue gas leaving the steam generator boundary. This temperature may or may not be adjusted for air heater leakage.

fixed carbon: the carbonaceous residue less the ash remaining in the test container after moisture and the volatile matter has been driven off in making the proximate analysis of a solid fuel in accordance with the appropriate ASTM standard. Also see *volatile matter*.

flue gas: the gaseous products of combustion including excess air.

flue gas (hot fluid) exit temperature — excluding leakage: the temperature at which the flue gas would have exited the air heater if there were no leakage. If leakage is present, this parameter is calculated by energy balance. For the purposes of the energy-balance calculations, the temperature of the leakage flow, including any ingress air, is assumed to be the same as the entering air stream(s).

flue gas (hot fluid) exit temperature — including leakage: the measured temperature of the flue gas exiting the air heater.

flue gas (hot fluid) side effectiveness: the ratio of the flue gas temperature drop, excluding leakage, to the temperature head.

flue gas (hot fluid) temperature drop — excluding leakage: the decrease in the temperature of the flue gas passing through the air heater, based on the fluid exit temperature excluding leakage.

fluidized bed: a bed of suitably sized combustible and noncombustible particles through which a fluid (air in fluidized bed steam generators) is caused to flow upward at a sufficient velocity to suspend the particles and to impart to them a fluid-like motion.

fluidized bed, bubbling: a fluidized bed in which the fluidizing air velocity is less than the terminal velocity of most of the individual particles. Part of the gas passes through the bed as bubbles. This results in a distinct bed region because an insignificant amount of the bed is carried away by the fluidizing air.

fluidized bed, circulating: a fluidized bed in which the fluidizing air velocity exceeds the terminal velocity of most of the individual particles, so that they are carried from the combustion chamber and later reinjected.

furnace: an enclosed space provided for the combustion of fuel.

heat capacity ratio (X-ratio): the ratio of the mean heat capacity of the air passing through the air heater to the mean heat capacity of the flue gas passing through the air heater. For a multi-sector air heater, the air-side component is based on the composite air-side temperatures. See para. 5-5.9.

heating value, higher: the total energy liberated per unit mass of fuel upon complete combustion as determined by appropriate ASTM standards. The higher heating value includes the latent heat of the water vapor. When the heating value is measured at constant volume, it must be converted to a constant pressure value for use in this Code.

heating value, lower: the total heat liberated per unit mass of fuel minus the latent heat of the water vapor in the products of combustion as determined by appropriate ASTM standards (not used in this Code).

humidity ratio: mass of water vapor in a gas per pound of dry gas (also see *specific humidity*).

influence coefficient: see *absolute* and/or *relative sensitivity (influence) coefficient*.

input from fuel: the total chemical energy available from the fuel. Input is based on the higher heating value.

input–output method: a method of determining steam generator efficiency by direct measurement of output and input (I/O method).

instrument: any tool or device used in the measurement of the present value of a physical, electrical, or chemical variable. These variables can include pressure, temperature, fluid flow, voltage, electric current, chemical composition, density, viscosity, size, and power. This includes sensors and any ancillary equipment used to transmit, display, and record these variables.

losses: the energy that exits the steam generator envelope other than the energy in the output stream(s).

loss on ignition: commonly referred to as LOI. The loss in mass of a dried dust sample, expressed as a percentage of the initial mass, that occurs when the sample is heated in the presence of oxygen. Typically used to approximate unburned carbon in residue.

maximum continuous rating: see *capacity*.

measurement error: the true (unknown) difference between the measured value and the true value.

moisture: water in fuel or sorbent as determined by the appropriate ASTM standard(s), or water in the liquid or vapor phase, present in other streams.

outliers: a data point judged to be spurious or erroneous.

output: energy absorbed by the working fluid that is not recovered within the steam generator envelope.

parties to a test: those persons and companies participating in the test.

precision error: see *error, random*.

primary variables: those used in calculations of test results. They are further classified as shown below.

Class 1: those that have a relative sensitivity (influence) coefficient of 0.2 or greater

Class 2: those that have a relative sensitivity (influence) coefficient of less than 0.2 [Refer to ASME PTC 19.1 for the determination of relative sensitivity (influence) coefficients.]

purge: to introduce air into the furnace or the boiler flue passages in such volume and manner as to completely replace the air or gas–air mixture contained within.

recycle rate: the mass flow rate of material being reinjected into a furnace or combustion chamber.

recycle ratio: the recycle rate divided by the fuel mass flow rate.

reference temperature: the datum temperature to which streams entering and leaving the steam generator envelope are compared for calculation of sensible heat credits and losses.

reinjection: the return or recycle of material back to the furnace.

relative sensitivity (influence) coefficient: percent change in result per percent change in measured parameter.

residue: the solid material remaining after combustion. Residue consists of fuel ash, spent sorbent, inert additives, and unburned combustible matter.

run: a complete set of observations made over a period of time, with one or more of the independent variables maintained virtually constant.

secondary variables: variables that are measured but do not have a major effect on the result.

sensitivity: the ratio of the change in a result to a change in a parameter; see *absolute* and/or *relative sensitivity (influence) coefficient*.

setting infiltration: see *air, infiltration/ingress*.

sorbent: chemical compound(s) that reacts with and captures a pollutant, or, more generally, a constituent that reacts with and captures another constituent.

specific humidity: mass of water vapor in gas per pound of wet gas (also see *humidity ratio*).

specified conditions: the specified contract design conditions of all parameters at the test boundary. See also *standard conditions*.

spent bed material: the bed drain residue removed from a fluidized bed.

spent sorbent: solids remaining after evaporation of the moisture in the sorbent, calcination/dehydration, and weight gain due to sulfation.

standard conditions: the values of all the external parameters, i.e., parameters at the test boundary to which the test results are corrected. The standard conditions may be the specified design conditions or a set of user-defined boundary conditions. Non-contract boundary conditions are referred to within this document as standard conditions and are typically used for performance monitoring.

standard deviation: standard deviation of the mean unless otherwise specified. Several types of standard deviation are defined in statistical analysis (e.g., population standard deviation, sample standard deviation, and standard deviation of the mean).

sulfation: the exothermic chemical reaction that takes place when calcium oxide unites with oxygen and sulfur dioxide to form calcium sulfate.

sulfur capture: see *sulfur retention*.

sulfur retention: the fraction of the sulfur that enters with the fuel that does not leave the steam generator as SO_2.

supplemental fuel: fuel burned to supply additional energy to the steam generator or to support combustion.

temperature head: the temperature of the flue gas entering the air heater minus the temperature of the air entering the air heater. For a multi-sector air heater, this air temperature is the composite air temperature.

test: at least two runs at the same conditions that yield comparable results, or multiple sets of runs at multiple conditions, for the purpose of determining performance characteristics.

test boundary: identifies the location of the mass or energy streams that enter or leave the envelope of the equipment being tested.

tolerance: the acceptable difference between the test result and its nominal or guaranteed value. Tolerances are contractual adjustments to test results or to guarantees and are not part of the Performance Test Codes.

traceable: availability of records demonstrating that the instrument or calibration gas can be traced through a series of calibrations to an appropriate ultimate reference such as National Institute for Standards and Technology (NIST).

unburned combustible: the combustible portion of the fuel that is not completely oxidized.

uncertainty: the estimated error limit of a measurement or result for a given coverage. Uncertainty defines a band within which the true value is expected to lie with a certain probability. Test uncertainty includes both random uncertainty and systematic uncertainty.

uncertainty, random: an estimate of the plus-or-minus limits of random error with a defined level of confidence (usually 95%).

uncertainty, systematic: an estimate of the plus-or-minus limits of systematic error with a defined level of confidence (usually 95%).

uncertainty, test: test uncertainty combines random and systematic uncertainties.

user defined: a set of boundary conditions that may reflect typical fuel and operating conditions, which may be something other than design conditions.

volatile matter: the portion of mass, except water vapor, that is driven off in a gaseous form when solid fuel is heated in accordance with the applicable ASTM standard. Also see *fixed carbon*.

X-ratio: see *heat capacity ratio*.

2-3 CALCULATION ACRONYMS

The acronyms used throughout this Code are built from symbols from the following groups. Wherever possible, for steam generator applications, these abbreviations follow the methodology set forth in ASME PTC 4, Fired Steam Generators.

2-3.1 Property Symbols

Af: flat projected surface area

Aid: area, inside dimension

Cp: mean specific heat at constant pressure

D: dry

Dg: any dry gas, typically air or flue gas

Dn: density

H: enthalpy

Hca: convective heat transfer coefficient

HHV: higher heating value, mass basis

HHVcv: higher heating value, constant volume basis

HHVv: higher heating value, volume basis

Ht: height

M: mass

Mo: mole

Mp: percent mass

Mq: mass per unit energy

Mr: mass flow rate

Mv: mass per unit volume

Mw: molecular weight

P: pressure

Pb: atmospheric/barometric pressure

Pp: partial pressure

Ps: saturation pressure

Q: energy

Qp: percent fuel input energy

Qr: heat transfer rate

R: universal gas constant

Rhm: relative humidity

Rq: required

Se: stack effect

Sg: specific gravity

T: temperature

Tdb: dry-bulb temperature

Thf: hot face temperature

Twb: wet-bulb temperature

v: velocity

vh: velocity head

Vp: percent volume

2-3.2 Function Symbols

Ad: additional

Di: difference (delta)

Fr: fractional

Mn: mean

Sm: sum

2-3.3 Equipment, Stream, and Efficiency Symbols

A: air

Ac: air heater coil

Ah: air heater

Al: air leakage

Ap: ash pit

Aq: air quality control equipment

As: ash

B: credit

Bd: blowdown

C: carbon

Ca: calcium

Cb: carbon burned

Cbo: carbon burnout

Cc: calcium carbonate

Cf: coefficient

Ch: calcium hydroxide

Clh: calcination and/or hydration

Cm: combustion

CO: carbon monoxide

CO2: carbon dioxide

Coal: coal

Cw: cooling water

E: efficiency, percent

Ec: economizer

El: electrical

Ev: evaporation

F: fuel

Fc: fixed carbon

Fg: flue gas

Fo: fuel oil

G: gaseous fuel

Gr: gross

Hc: hydrocarbons, dry basis

I: input

In: inerts

L: loss

Lg: leakage

Mc: magnesium carbonate

Mh: magnesium hydroxide

N2: nitrogen

N2a: atmospheric nitrogen

NOx: nitrogen oxides

O: output

O2: oxygen

Pc: products of combustion

Pcu: products of combustion uncorrected for sulfur capture

Pr: pulverizer rejects

Rh: reheat

Rs: residue

Ry: recycle

S: sulfur

Sb: sorbent

Sc: sulfur capture

Sh: superheat

Slf: sulfation

SO2: sulfur dioxide

Src: surface radiation and convection

Ssb: spent sorbent

St: steam

Th: theoretical

To: total

Ub: unburned

W: water

Wv: water vapor

X: auxiliary

Xp: percent excess

Xr: X-ratio

2-3.4 Location, Area, Component, and Constituent Symbols

En: inlet or entering

f: fuel, specific or related

j: fuel, sorbent related

k: fuel, sorbent constituent

Lv: outlet, exit, or leaving

m: measured

Re: reference

z: location (refer to Figs. 2-3.4-1 through 2-3.4-6 for specific locations)

2-3.5 Correction Symbols

Cr: reading or computational correction

Ds: design

2-3.6 Computational Acronyms Used In Section 5 — Computation of Results

See subsection 5-10.

2-3.7 Uncertainty Acronyms Used in Section 5 — Computation of Results

See subsection 5-10.

2-3.8 General List of Symbols Used In Section 7

See subsection 7-7.

2-4 ABBREVIATIONS

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

A/D: analog to digital

AFBC: atmospheric fluidized bed combustion

AH: air heater

APC: air preheater coils

APH: air preheater

API: American Petroleum Institute

Ar: argon

ASTM: American Society for Testing and Materials

C: carbon

Ca/S: calcium-to-sulfur ratio

$Ca(OH)_2$: calcium hydroxide

CaO: calcium oxide

$CaSO_4$: calcium sulfate

CB: gasified carbon

CO: carbon monoxide

CO_2: carbon dioxide

CO_3: carbonate

CT: current transformer

DCS: distributed control system

EPA: Environmental Protection Agency

ESP: electrostatic precipitator

FC: fixed carbon

FD: forced draft

FEGT: furnace exit gas temperature
FG: flue gas
FID: flame ionization detector
FW: feedwater
GPA: Gas Processors Association
H_2: hydrogen
H_2S: hydrogen sulfide
HHV: higher heating value
HHVF: higher heating value of fuel
HHVGF: higher heating value of gaseous fuels
I/O: input/output
ID: induced draft
K_2O: potassium oxide
kW·h: kilowatt-hour
LOI: loss on ignition
MAF: moisture and ash free
MB: megabyte
$Mg(OH)_2$: magnesium hydroxide
$MgCO_2$: magnesium carbonate
MgO: magnesium oxide
N_2: nitrogen
N_2O: nitrous oxide
Na_2O: sodium oxide
NH_3: ammonia
NIST: National Institute of Standards and Technology
NO: nitric oxide
NO_2: nitrogen dioxide
NO_x: nitrogen oxides
O_2: oxygen
O_3: ozone
PA: primary air
ppmdv: parts per million on a dry volume basis
ppmv: parts per million on a wet volume basis
PT: potential transformer
PTC: Performance Test Code
RAM: random access memory
RH: reheater, relative humidity
RTD: resistance temperature device
S: sulfur
SDI: spatial distribution index
SH: superheater, superheated
SI: International System of Units
SiO_2: silicon dioxide, silica
SO_2: sulfur dioxide
SO_3: sulfur trioxide
SO_x: sulfur oxides
TC: thermocouple
TGA: thermogravimetric analysis
THC: total hydrocarbons
VM: volatile matter

2-5 ABBREVIATIONS FOR THE BOUNDARY FIGURES

2-5.1 Property Symbols

Mr: mass rate
P: pressure
T: temperature

2-5.2 Equipment and Stream Symbols

A: air
Al: air leakage
Fg: flue gas
HF: hot fluid (including the hot fluid in preheating coils)
P: primary
S: secondary

2-5.3 Location Symbols

En: entering
i, j: coordinates of a point within a grid
Lv: leaving

2-5.4 Correction/Design Symbols

Cr: reading or computational correction
Ds: design or standard condition

2-5.5 Air Heater/Air Preheater Boundaries

7: air entering air preheater coil
8: air entering air heater
9: air leaving air heater
14: gas entering air heater
15: gas leaving air heater
HF: hot fluid entering or leaving air preheater coil

2-5.6 Sequence

Note that abbreviations in this Section are arranged in the following sequence: Property > Stream > Location > Correction/Design. For example, in a multi-sector air heater, *MrSAlFg* refers to the mass flow of secondary air leakage to the flue gas stream. Similarly, *TA9* refers to the temperature of the air stream at location 9 (the air heater air outlet).

Fig. 2-3.4-1 Tubular/Plate Air Heater

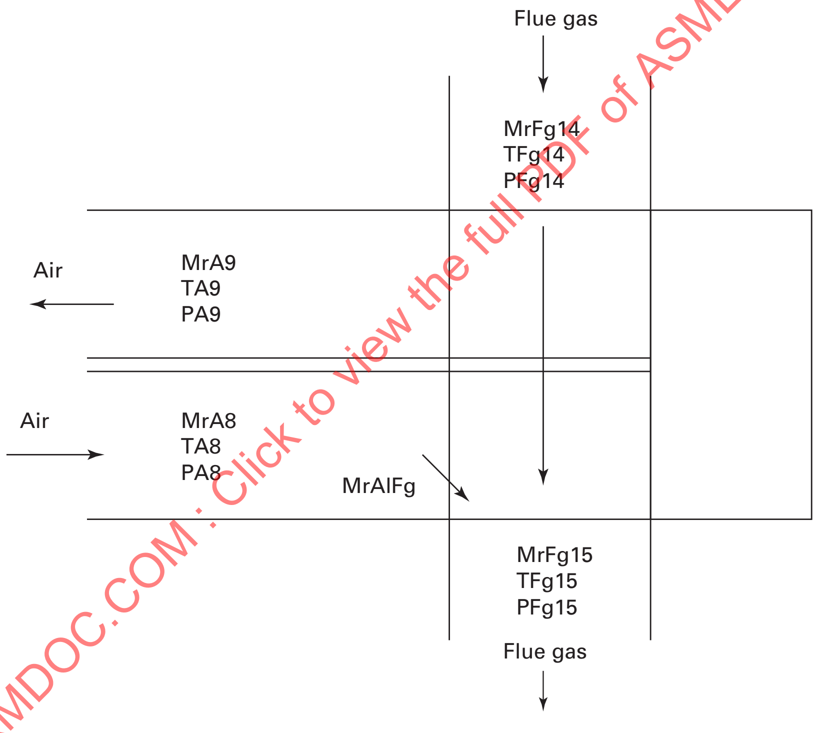


Fig. 2-3.4-2 Basic Regenerative Air Heater

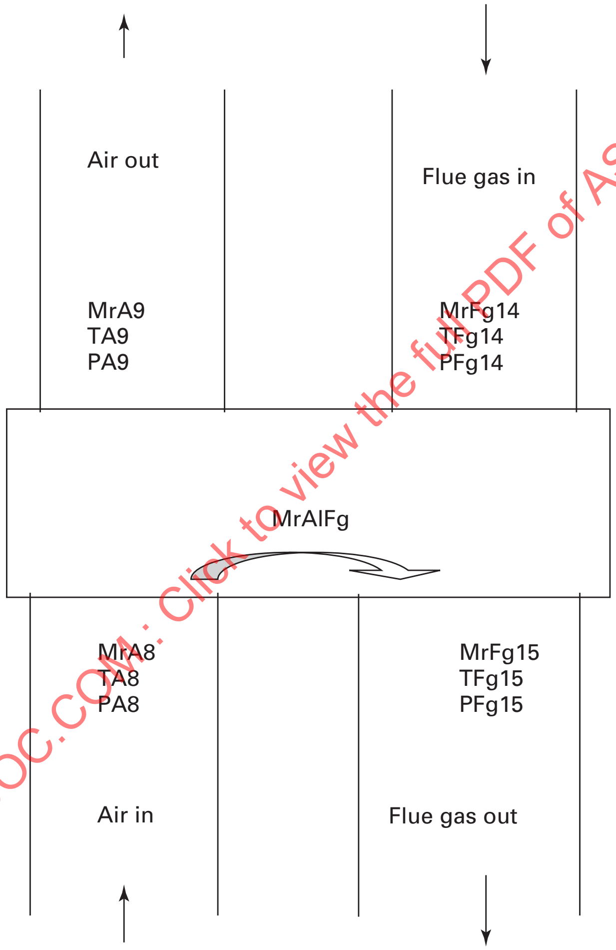


Fig. 2-3.4-3 Tri-Sector Air Heater

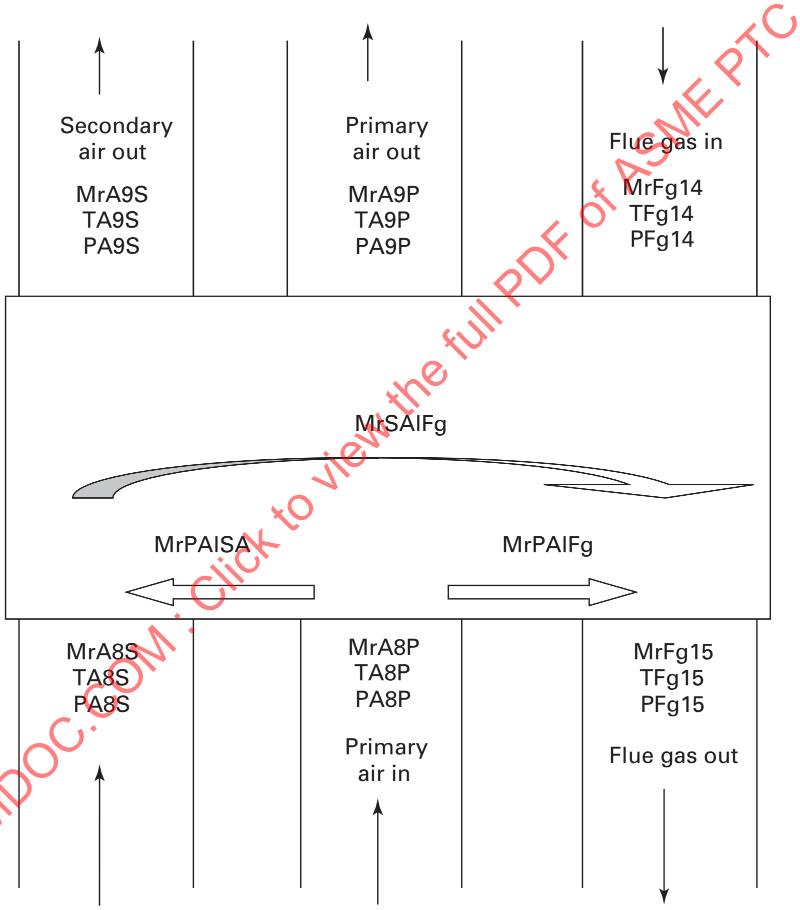


Fig. 2-3.4-4 Quad-Sector Air Heater

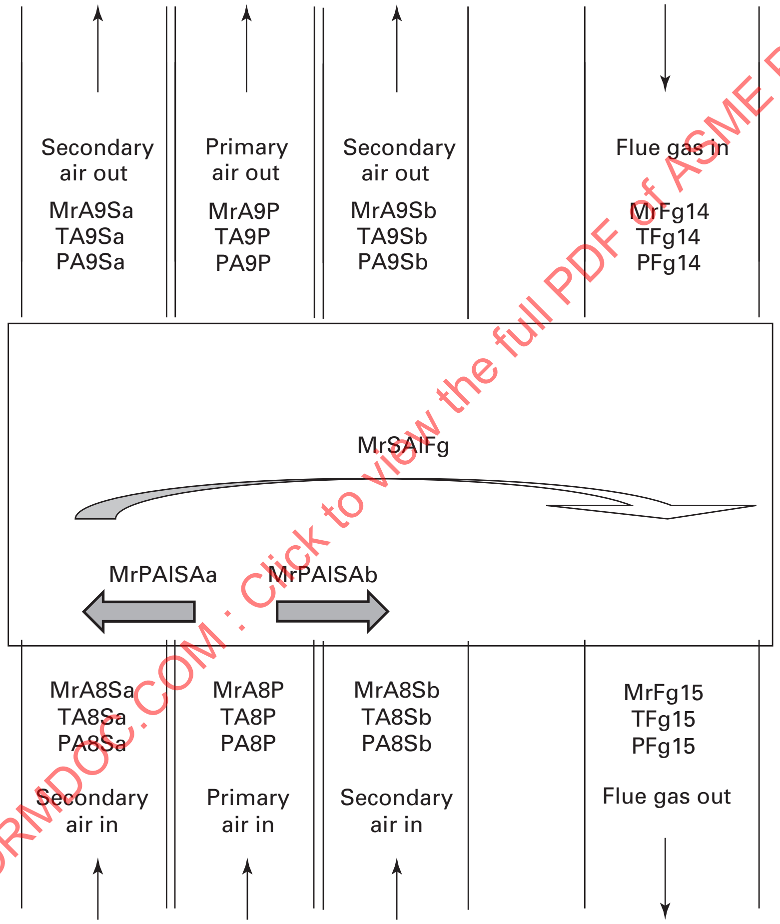


Fig. 2-3.4-5 Air Heater Using Intermediate Fluid

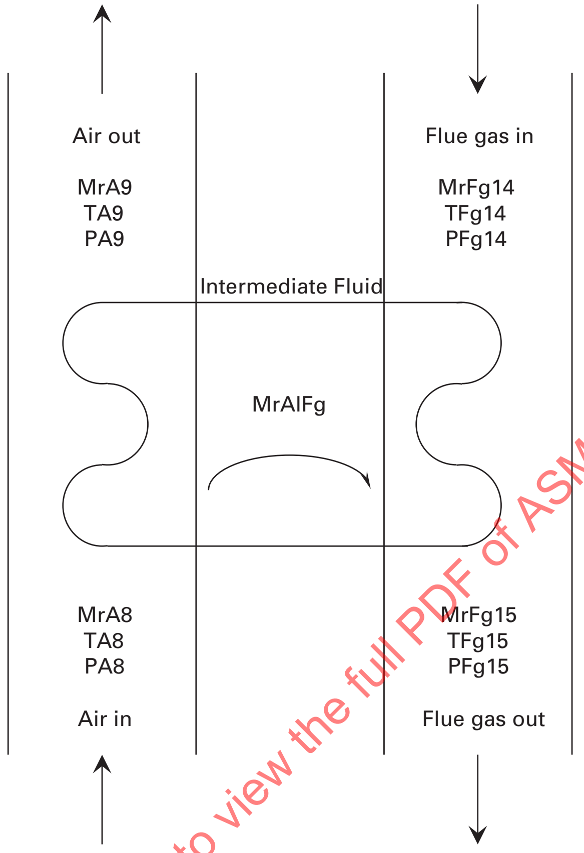
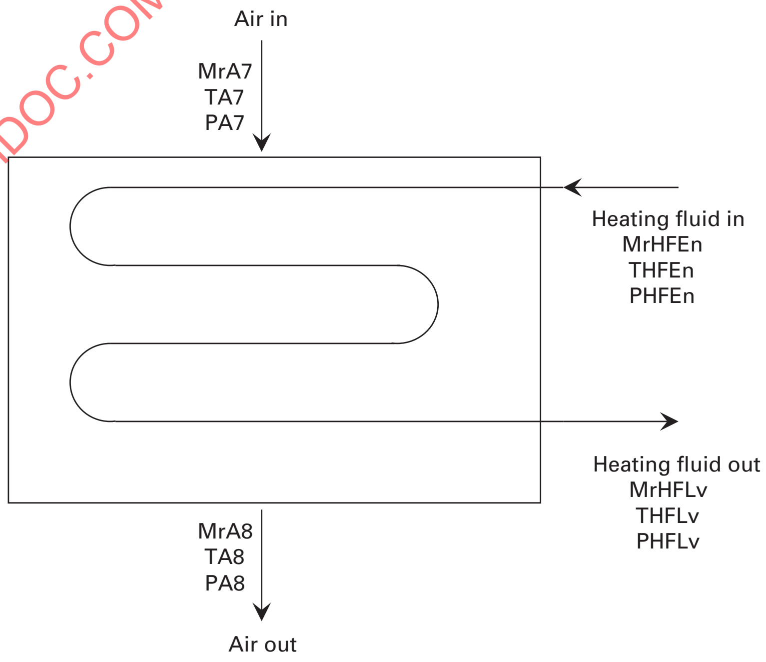


Fig. 2-3.4-6 Fluid-to-Air Air Heater Noncondensing Heating Fluid



Section 3
Guiding Principles

3-1 INTRODUCTION

The primary purpose of this Code is to provide a standard for the planning and execution of tests to determine air heater performance. Furthermore, this Code is intended for guarantee compliance testing (acceptance testing) or other tests that require high levels of accuracy and repeatability. The requirements of ASME PTC 4.3 are designed to minimize test uncertainty and will necessitate the use of rigorous test practices to allow the test to be considered a "Code" test.

It is recognized that routine testing does not require compliance with the strict standards mandated by this Code. Tests for information, troubleshooting, or other reasons that do not require this level of detail are discussed in Nonmandatory Appendix J.

Fundamental test principles are as follows:

(a) *O_2 Analysis.* The necessary stoichiometric calculations are based on flue gas oxygen (O_2) analysis (only) in combination with laboratory fuel analysis. This Code does not include procedures or calculations to support the use of carbon dioxide (CO_2) analyzers.

(b) *Pretest Velocity Traverse.* This Code requires a pretest point-by-point velocity traverse by a three-dimensional probe of all test planes around the air heater, in order to determine whether velocity weighting of the air and/or gas parameters is required.

(c) *Multiple Air Heater Configurations.* Each air heater within a multiple air heater configuration on a given unit shall be tested individually wherever possible. The procedures and necessary supporting data are discussed in subsection 3-5.

(d) *Pretest Uncertainty Analysis.* This Code requires the use of a pretest uncertainty analysis as discussed in para. 3-2.2.

(e) *Performance-Based Standards.* This Code includes provisions for users to employ a performance-based approach in the design and execution of a test program. That is, the user is free to apply any of the techniques or equipment detailed in this Code in order to meet the objectives of the test. The performance (or objective) based approach allows the user to incorporate considerations of cost and physical plant configuration, among other issues, into the design of the test. Contrast this with a prescriptive standard that effectively defines the only choices available for the selection of test equipment and measurement techniques.

(f) *Choice of Technology.* The instrumentation and methods of measurement discussed in the Code are considered to be consistent with best practice at the time of writing. It is not the intention of this Code to exclude the use of technology not yet available at the time of publication, provided that this technology yields equivalent or superior accuracy to the techniques discussed in Section 4. Note that this Section specifically excludes the use of certain instruments and methods that are not considered to be suitable for the conduct of a Code test.

(g) *Selection of Supporting Standards.* This Code requires the use of other PTC codes and supplements where referenced. However, where other organizations' standards (e.g., ISA, ASTM, GPA) are referenced in this Code, parties to the test may mutually agree to use other internationally recognized standards.

(h) *Units With Cold Primary Air Systems.* Total gas flow entering the air heater(s) shall be calculated stoichiometrically using O_2 and the ultimate fuel analysis. The gas flows to identical air heaters shall be apportioned by velocity traverse. See para. 4-7.1 and subsection 5-4.

3-2 PREPARATION FOR THE TEST

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 give a permanent, explicit record. Instrument location shall be predetermined, agreed by the parties to the test, and described in detail in test records. Redundant (backup) calibrated instruments should be provided for those instruments susceptible to in-service failure or breakage.

For acceptance and other official tests, the manufacturer or supplier shall 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 must be documented and immediately reported to all parties to the test.

Acceptance and other official tests shall be conducted as promptly as possible following initial equipment operation and preliminary test runs. Prior to each run, the equipment should be operated for sufficient time to demonstrate that intended test conditions have been established, e.g., steady state. Agreement on procedures and time should be reached before commencing the test.

Once testing has started, readjustments to the equipment that can influence the results of the test should require repetition of any test runs conducted prior to the readjustments. The only permissible adjustments are those that are appropriate for reliable and continuous operation of the equipment and are agreed to in advance by all parties to the test.

3-2.1 Pretest Agreements

Any acceptance test will require that the various parties to the test reach agreement on a number of issues that will define the scope and execution of the test. These items shall be documented in the test plan and test report, and shall include but not be limited to the following:

(a) object of test.

(b) location and timing of test.

(c) test boundaries.

(d) number of copies of original data required.

(e) permissible deviations in totally corrected flue gas exit temperature excluding leakage.

(f) establishment of acceptable operating conditions, including but not limited to the stability of the equipment [including, for critical parameters, the maximum short-term fluctuations, the maximum long-term deviations, the averaging period for the long-term deviations, and the measurement to be used for each, i.e., station thermocouple(s), individual test thermocouple, average of all test thermocouples], the air inlet temperature, the position of dampers around the air heater, and the set points of critical parameters and the means of controlling them. See Table 3-2.1-1 for typical stability guidelines.

(g) standard or design conditions.

(h) allocations of responsibility for all conditions that affect the test.

(i) organization of personnel, including designation of lead test engineer.

(j) number of load points, duration of test runs, and the procedures to be followed during the test.

(k) cleanliness of the heat transfer surfaces and how this will be maintained during the test.

(l) pretest inspection of equipment, including condition of those air heater components affecting air leakage.

(m) if applicable, the fuel to be fired and sorbent used, the methods of obtaining samples, conducting laboratory analyses of those samples, and estimating systematic uncertainty.

(n) observations and data to be collected during the test to comply with the test objectives.

(o) selection and calibration of test instrumentation and the methods of measurement to be employed during the test (see Section 4), e.g.,

(1) location of measurements

(2) number and location of points in grids

(3) type of sensor (thermocouple type, RTD, thermometer, manometer, transducer, S-type pitot, Fechheimer, orifice, paramagnetic O_2 analyzer, Orsat, etc.)

(4) method of recording individual data points (manual or, if electronically, the type of data acquisition equipment)

(5) frequency of measurements

(6) for measurements in grids, point to point or composite sampling

(7) method of calibration/accuracy check

(-a) loop or individual component accuracy check

(-b) number of points and range to be covered

(-c) for thermocouples, individual or representative (from spool)

(8) components of the systematic uncertainty and their values (excluding accuracy check data effects)

(-a) systematic uncertainty of primary standards

(-b) tap location

(-c) corrections for known interferences (e.g., NO concentration with paramagnetic O_2 analyzers)

(9) method of correcting measured data and determining accuracy check effects on systematic uncertainty

(10) procedure to address drift in instrumentation, including maximum allowable drift (zero or span) of oxygen analyzers

(p) maximum systematic uncertainty for each performance parameter defined in the test objective.

(q) distribution of residue quantities between various collection points, and their methods of sampling, analysis, and estimating systematic uncertainty.

(r) type of probe to be used for the pretest velocity traverse. As noted in paras. 3-1(b) and 3-2.5, a probe capable of measuring both yaw and pitch is required for the initial pretest velocity traverse. Based on the results of previous testing, the users may option to select a three-dimensional, two-dimensional, or nondirectional probe.

(s) for identical air heaters arranged in parallel, the maximum flow imbalance that can exist and still assign equal split of the total gas flow between the multiple streams. See para. 3-5.1.

(t) how to determine flow splits for nonidentical air heaters.

(u) the systematic uncertainty of the "electronics" (any lead wires, junctions, data acquisition/display equipment, or any other items in the loop, excluding

the sensor and permanently attached wiring) for any measurement system (temperature, flue gas analysis, etc.) that does not have a calibration (or accuracy check) of the entire loop, and if a calibration (or accuracy check) is not performed on the "electronics." See para. 4-5.4.2 and Mandatory Appendix III.

(v) methods of correction and values used for corrections for deviations of test conditions from standard or design conditions.

(w) methods of computing results.

(x) methods of comparing test results with standard or design performance conditions.

(y) basis to be used for rejection of outlier data or a test run.

(z) criteria to establish the requirement for flow weighting.

(aa) estimate of efficiency losses and uncertainty of the losses, if fuel input is calculated by the energy-balance method.

(ab) values of estimated parameters and their systematic uncertainties.

(ac) method or instrumentation to be used to calculate random uncertainty for measurements that require traverses.

(ad) when testing air preheating coils with a condensable fluid, the minimum amount of superheat at the hot fluid exit. See subsection 5-8.

(ae) for direct-fired air heaters or gas-to-gas heat exchangers, the method of leakage measurement.

3-2.2 Pretest Uncertainty Analysis

A pretest uncertainty analysis is a mandatory requirement of this Code. This analysis allows 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. An uncertainty analysis is useful to determine the number of observations. This analysis will be useful in determining test variables, e.g., grid densities and the frequency of data collection, that may require refinement to improve the quality of the test.

This investigation will also include a sensitivity analysis that will serve to highlight those parameters that are most critical to the calculation of the final result. Tables J-1.2.4-4, J-1.2.4-5, and J-1.2.4-6 in Nonmandatory Appendix J summarize the parameters that generally have a primary influence on the calculation of flue gas temperature, leakage, pressure drop, and air/gas mass flows.

3-2.3 Selection and Training of Test Personnel

All personnel to participate in the test shall be trained for the particular activities they will be responsible for during the test. A lead test engineer shall be designated to ensure proper execution of the test and assessment of test results. Equipment operators shall be familiar with the calibration and proper use of their hardware, including minor repairs of test equipment as required. They should also be knowledgeable of the expected range of data to be collected at their individual test plane location. Note that both the pretest velocity traverse and the preliminary test are useful in this regard to either train test personnel or to confirm their suitability to conduct the test.

3-2.4 Pretest Checkout

The lead test engineer (see para. 3-2.3) must ensure that the equipment to be tested is in good operating condition. In particular, the tightness of tubes, condition of seals, cleanliness of all heat transfer surfaces, and the condition of all ductwork and equipment inside the test boundary should be examined and placed in proper operating condition. Bypass dampers, recirculating dampers, and valves associated with air-preheating coils should be checked for their ability to provide a tight shutoff if these devices are not to be used during the test.

3-2.5 Pretest Traverse

Each test shall also include a mandatory pretest velocity traverse of all air and flue gas planes at each load point to determine whether flow weighting will be required. However, traverse(s) at the air inlet plane(s) may be waived if air preheater coils will not be in service during the test. Temperature, velocity (differential pressure), and, for flue gas locations, the percentage of O_2 shall be measured at each point in the traverse. This pretest traverse must employ a probe capable of measuring both yaw and pitch, unless all parties agree that a two-dimensional or nondimensional probe is sufficient.

3-2.6 Preliminary 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, to train personnel, and to verify the attainability of the target test uncertainty. They are also useful to highlight the need for minor operational or equipment adjustments that were not evident during the preparation for the test. 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 this Code, it may be used as an official test run with the consent of all parties to the test.

3-3 METHOD OF OPERATION DURING TEST

3-3.1 Stability of Test Conditions

A test is a combination of a series of runs for the purpose of determining performance. A run consists of a complete set of observations made for a period of time for a specific set of operating conditions. It is important that all controlling parameters remain within previously established limits throughout the run. Conditions shall be set at specified levels and be maintained stable for a minimum of 30 min prior to the start of each run.

All test runs shall be conducted while the equipment is at steady-state conditions. Steady state is defined by the process operating in a condition of thermal and chemical equilibrium. In the case of a steam generator or a combustion furnace, it is required that the combustion process remain constant. If equipment such as air preheater coils are to be tested separately, only the airflow and outlet temperature need to be at steady state. For the purposes of this Code, refer to Table 3-2.1-1.

It is recommended that, as the run progresses, pertinent data be monitored continuously, to permit an assessment of the conduct of the run. The pretest agreements shall include a table of allowable maximum variations in operating parameters similar to Table 3-2.1-1. During a test run, each observation of an operating parameter shall not vary from the reported mean for that condition by more than the allowable "long-term deviation." Long-term deviation is defined as the maximum deviation of the average, over an agreed-upon period of time, from the overall test average. Furthermore, the maximum variation between any point and the preceding point shall not exceed the "short-term fluctuation" limit. Plant instrumentation may be used to determine deviation of operating parameters where test instrumentation is not available, e.g., when point-to-point traverses are utilized to measure temperature and O_2. Figure 3-3.1-1 illustrates the application of the agreed limits.

3-3.2 Duration of Runs

The duration of each run shall be a minimum of 2 hr and shall be extended as necessary to permit the collection of consistent observations. Furthermore, when the test data is collected via traverse(s), each run shall include a minimum of two traverses at each required test plane. Readings shall be taken at such a frequency as may be necessary to determine a value that represents a true average and to meet the uncertainty analysis/random error requirement.

3-3.3 Adjustments During Test

Control dampers in the vicinity of the air heaters that might affect gas and airflow distribution between multiple air heaters or sectors of multi-sector air heaters shall not be operated (moved) to cause the limits shown in Table 3-2.1-1 to be exceeded during a test run. This is to include systems in place to control coal mill exit temperature (tempering air) and control of air heater fouling (air bypass or hot air recirculation).

Air leakage control devices (e.g., adjustable sector plates, axial seals, hoods on stationary matrix heaters, etc.) shall not be operated (moved) manually during a test. If any of these devices are automatically controlled, then care should be taken so that the test is paused and data is not collected while the automatic system is in operation.

Air heater sootblowers shall not be operated during a test run. Operation of upstream sootblowers, especially if the blowing medium is air, may jeopardize the validity of the data. The data during sootblowing should be compared to the data just prior to and following sootblowing periods. The run should be rejected if there are differences that impact the result.

3-3.4 Rejection of Runs

If serious inconsistencies affecting the results are detected during a run or during the calculation of the results, the run must be invalidated completely, or it may be invalidated only in part if the affected part is at the beginning or end of the run. A run that has been invalidated must be repeated to attain the test objectives. The decision to reject a run is the responsibility of the lead test engineer and the designated representatives of the parties to the test.

Refer to Table 3-2.1-1 for an example for rejecting a run. For coal firing, the guideline for maximum long-term deviation of inlet excess oxygen concentration is 0.5% O_2 (absolute) from the mean. In this case, the suspect data is compared with the mean O_2 value as defined by data collected up to that point in time. A deviation of this magnitude is normally only caused by a failure in the sampling system or by a significant change in the process conditions. Both of these events are examples of sufficient cause to invalidate the data in question — either in whole or in part.

Note that the pretest checkout [subpara. 3-2.1(y)] requires that the parties to the test agree on the basis to be used for rejecting data or a test run in its entirety.

3-3.5 Number of Runs and Repeatability Criteria

A test shall consist of a minimum of two runs that satisfy the repeatability requirements of this Code at each specified condition. The criterion for repeatability is that the corrected results from the runs in question all fall within the uncertainty intervals of each other. Figure 3-3.5-1 illustrates this graphically.

Prior to this comparison, the results must be normalized (corrected) to a standard or design set of conditions. The calculated uncertainty is then applied to the corrected results for each run for the purpose of determining repeatability.

3-3.6 Multiple Runs

The results of multiple runs that satisfy the requirements of this Code shall be averaged to determine the average test result. The test report shall include the calculated uncertainties of each individual test run.

3-4 COMPARING RESULTS WITH STANDARD OR DESIGN PERFORMANCE

Operating conditions at the time of the test may differ from the standard or design conditions that were used to establish design or guarantee performance levels. Subsection 5-6 provides methods for applying corrections during the calculation of test results to account for many of these differences. Parties to the test shall record their agreement on the correction method.

3-5 MULTIPLE AIR HEATER CONFIGURATIONS

The performance of air heaters within a multiple air heater unit configuration should be determined individually wherever possible. This has the advantage of being able to compare performance between air heaters. The individual air heaters may be tested simultaneously or sequentially at the discretion of the lead test engineer, considering factors such as uncertainty and cost. However the data are collected, it is preferred that the performance of each air heater be calculated as a separate, distinct system. Refer to subsections 4-7.1, 5-4.1, and 5-4.2.

3-5.1 Multiple Air Heaters of the Same Design/Type

Identical air heaters arranged in parallel will normally not require special attention or procedures to partition air and gas flows. Generally, the performance of these individual air heaters can be determined by assigning an equal split of the total air and gas flow between the multiple systems.

If the pretest velocity traverses indicate a significant entering gas flow difference between the multiple air heaters, then the total flow must be proportioned accordingly. Generally, a flow imbalance of 10% or more from the mean is considered to be significant for this purpose. In any case, this value must be agreed upon in the pretest agreement; see subpara. 3-2.1(s).

Once entering gas flow through each air heater is determined, the airflow through each air heater can be calculated by energy balance.

3-5.2 Multiple Air Heaters of Different Designs/Types

This section covers configurations including primary air heater(s) in parallel with one or more secondary air heaters.

For different air heaters arranged in parallel, it is first necessary to determine the flue gas flow split between the multiple air heaters in the system. Fundamentally, one of the airflows on one of the air heaters must be known or measured. In practice, this is usually the outlet airflow of the primary air heater(s), as these process signals are generally calibrated. For a given airflow and tested leakage value, the inlet gas flow to that air heater can be calculated via energy balance (see para. 5-4.2).

The balance of the total gas flow (see para. 5-3.5.9) is then assigned to the remaining air heaters in a similar manner to para. 3-5.1.

3-6 UNCERTAINTY

By agreement prior to the test, the parties to the test shall establish the maximum uncertainty for each performance parameter.

A performance test must be designed and conducted to obtain both a positive and a negative uncertainty less than or equal to the established maximum uncertainty. The choices of which parameters to measure, which parameters may be estimated, what estimated values to use, and the use of fewer or alternative instruments will strongly influence the ability to meet the maximum uncertainty. It is then the responsibility of the lead test engineer to design a test that will meet this uncertainty level. Parties to the test shall reach agreement on these choices prior to the test.

Note that this Code employs uncertainty only as a measure of the quality of the test. Specifically, the parties to the test must reach agreement on the test maximum uncertainty level.

3-7 REFERENCES TO OTHER CODES AND STANDARDS

The necessary instruments and procedures for making measurements are prescribed in Section 4 and should be used in conjunction with the following ASME Performance Test Codes and Supplements on Instruments and Apparatus and other pertinent publications for detailed specifications on apparatus and procedures involved in the testing of air heaters. These references are based upon the latest information available when this Code was published. In all cases, care should be exercised to refer to the latest revision of the document.

3-7.1 ASME Performance Test Codes

ASME PTC 2, Definitions and Values
ASME PTC 4, Fired Steam Generators
ASME PTC 6, Steam Turbines
ASME PTC 11, Fans
ASME PTC 19.1, Test Uncertainty
ASME PTC 19.2, Pressure Measurement
ASME PTC 19.3, Temperature Measurement
ASME PTC 19.5, Flow Measurement — See also ASME MFC-3M–2004 with MFC-3Ma–2007 addenda, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle and Venturi
ASME PTC 19.10, Flue and Exhaust Gas Analyses
ASME PTC 38, Determining the Concentration of Particulate Matter in a Gas Stream

Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

3-7.2 ASTM Standard Methods

ASTM C25, Standard Test Methods for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime

ASTM D95, Standard Test Method for Water in Petroleum Products and Bituminous Materials by Distillation

ASTM D240, Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter

ASTM D482, Standard Test Method for Ash from Petroleum Products

ASTM D1298, Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method

ASTM D1552, Standard Test Method for Sulfur in Petroleum Products by High Temperature Combustion and IR Detection

ASTM D1826, Standard Test Method for Calorific (Heating) Value of Gases in Natural Gas Range by Continuous Recording Calorimeter

ASTM D1945, Standard Test Method for Analysis of Natural Gas by Gas Chromatography

ASTM D2013, Standard Practice for Preparing Coal Samples for Analysis

ASTM D2015, Standard Test Method for Gross Calorific Value of Coal and Coke by the Adiabatic Bomb Calorimeter

ASTM D2234, Standard Practice for Collection of a Gross Sample of Coal

ASTM D3173, Standard Test Method for Moisture in the Analysis Sample of Coal and Coke

ASTM D3174, Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal

ASTM D3177, Standard Test Methods for Total Sulfur in the Analysis Sample of Coal and Coke

ASTM D3178, Standard Test Methods for Carbon and Hydrogen in the Analysis Sample of Coal and Coke

ASTM D3179, Standard Test Methods for Nitrogen in the Analysis Sample of Coal and Coke

ASTM D3180, Standard Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases

ASTM D3228, Standard Test Method for Total Nitrogen in Lubricating Oils and Fuel Oils by Modified Kjeldahl Method

ASTM D3302, Standard Test Method for Total Moisture in Coal

ASTM D3588, Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuels

ASTM D4057, Standard Practice for Manual Sampling of Petroleum and Petroleum Products

ASTM D4239, Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion

ASTM D4809, Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)

ASTM D5142, Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures

ASTM D5287, Standard Practice for Automatic Sampling of Gaseous Fuels

ASTM D5291, Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants

ASTM D5373, Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke

ASTM D6316, Standard Test Method for Determination of Total, Combustible, and Carbonate Carbon in Solid Residues from Coal and Coke

ASTM E178, Standard Practice for Dealing with Outlying Observations

Publisher: American Society for Testing and Materials (ASTM International), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959 (www.astm.org)

3-7.3 GPA Standard

GPA 2166, Obtaining Natural Gas Samples for Analysis by Gas Chromatography

Publisher: Gas Processors Association (GPA), 6526 East 60th Street, Tulsa, OK 74145 (www.gpaglobal.org)

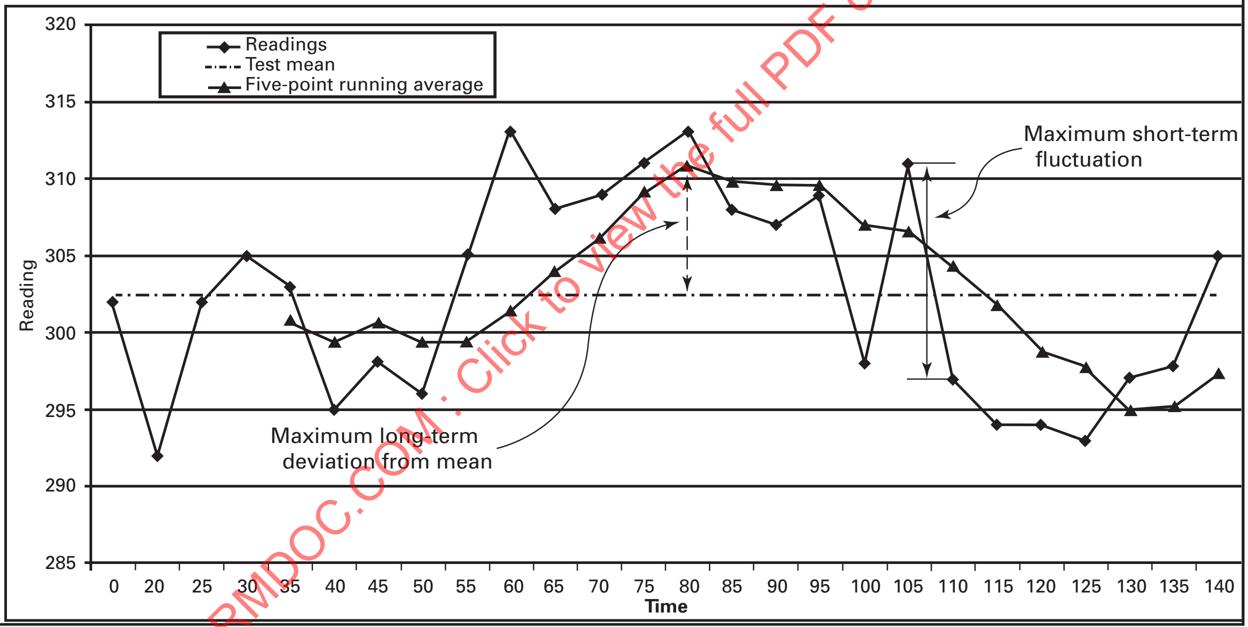
3-7.4 ISA Standard

ANSI/ISA-S51.1, Process Instrumentation Terminology

Publisher: The International Society of Automation (ISA), 67 T. W. Alexander Drive, P.O. Box 12277, Research Triangle Park, NC 27709 (www.isa.org)

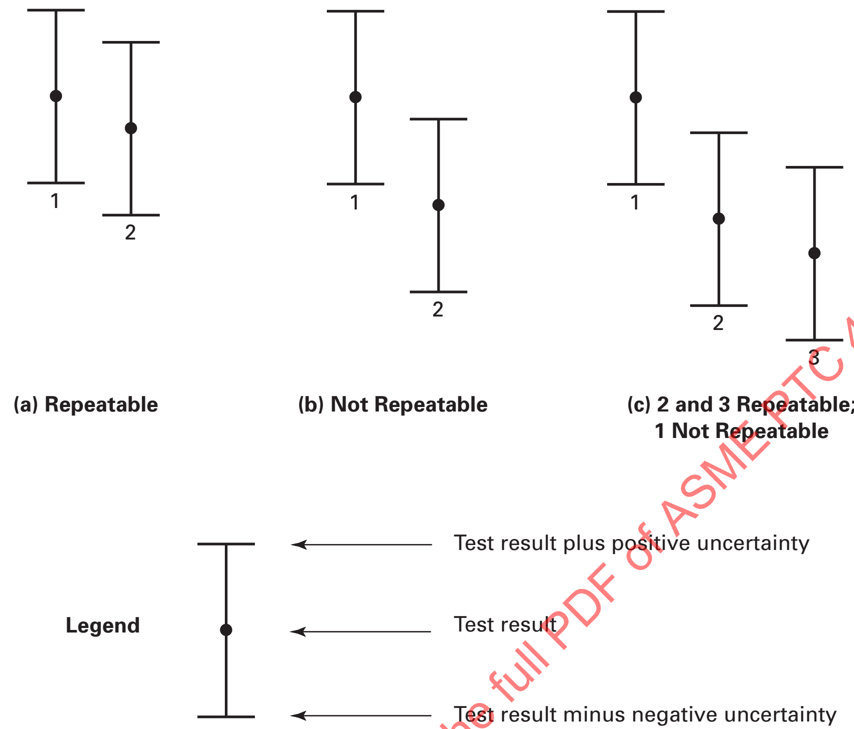
Fig. 3-3.1-1 Illustration of Short-Term (Point-to-Point) Fluctuation and Long-Term Deviation

Time	0	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140
Readings	302	292	302	305	303	295	298	296	305	313	308	309	311	313	308	307	309	298	311	297	294	294	293	297	298	305
Test mean	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4	302.4
5 pt running avg	…	…	…	…	300.8	299.4	300.6	299.4	299.4	301.4	304.0	306.2	309.2	310.8	309.8	309.6	309.6	307.0	306.6	304.4	301.8	298.8	297.8	295.0	295.2	297.4
Max LT dev.	…	…	…	…	1.6	3.0	1.8	3.0	3.0	1.0	1.6	3.8	6.8	**8.4**	7.4	7.2	7.2	4.6	4.2	2.0	0.6	3.6	4.6	7.4	7.2	5.0
Max ST flux	…	10	10	3	2	8	3	2	9	8	5	1	2	2	5	1	2	11	13	**14**	3	0	1	4	1	7



GENERAL NOTE: This Figure shows that the maximum short-term fluctuation (point-to-point) is 14 units (311 to 297) and the maximum long-term deviation (with a five-readings running average) is 8.4 units (310.8 to 302.4).

Fig. 3-3.5-1 Number of Runs and Repeatability Criteria



(a) Repeatable **(b) Not Repeatable** **(c) 2 and 3 Repeatable; 1 Not Repeatable**

GENERAL NOTE: Positive uncertainty and negative uncertainty are not usually equal magnitudes.

Table 3-2.1-1 Operating Parameter Deviations

Parameters	Short-Term Fluctuation (Point to Point)	Long-Term Deviation From Mean [Note (1)]
Air heater air inlet temperature	10°F (6°C)	See Note (2)
Air heater gas inlet temperature	10°F (6°C)	See Note (2)
Air heater inlet flue gas flow [Note (3)]		
Air heater inlet oxygen [Note (4)]		
Coal	1.0% O_2	0.5% O_2
Oil and gas	0.4% O_2	0.2% O_2
Unit steam flow [Note (5)]		
Coal	4.0%	3.0%
Oil and gas	2.0%	1.0%
Unit fuel flow [Note (6)]	2.0%	1.0%
Mill inlet air temperature [Note (7)]	10°F (6°C)	10°F (6°C)

NOTES:

(1) See Fig. 3-3.1-1.

(2) These are generally uncontrollable parameters. However, the parties may agree to some limit.

(3) In order to minimize fluctuations in flue gas flow, O_2 and either steam flow or fuel flow should be controlled within the limits indicated.

(4) Percentage values are absolute percent O_2.

(5) Applicable to steam generators. Feedwater flow and/or first stage pressure can be used as the indication of steam flow.

(6) Applicable primarily to combustion furnaces. For oil- and gas-fired steam generators, controlling fuel flow may be preferable to controlling steam flow.

(7) Indication of inconsistent fuel moisture and/or tempering airflow.

Section 4
Instruments and Methods of Measurement

4-1 INTRODUCTION

Various measurement techniques and apparatus are available for obtaining the data that comprises an air heater test. Several of the currently more-practical measurement methods and devices are presented in this Section. They are presented for guidance in defining the specific data acquisition, but in no particular order of preference. The relative uncertainty of each technique is presented and it is left to the lead test engineer to select the appropriate apparatus to meet the desired overall test uncertainty; see subsection 3-6.

The instrumentation system selected for the collection of data shall be durable and reliable in an environment that is often hot, dirty, and subject to vibration. All instruments shall be inspected and calibrated properly to achieve the uncertainty specified by the manufacturer.

Expected ranges of all data to be recorded shall be calculated prior to the test, based on expected equipment operating conditions, to ensure that the selected test instrumentation is suitable for the purpose intended. Appropriate sampling rates for each test plane shall be calculated, considering the rates, the size of the sampling lines, location, and response time of the instrumentation system.

4-2 DATA REQUIRED

Depending on test objectives, some or all of the following data will be needed to determine the performance of the air heater:

(a) temperature of the air entering and leaving each section of the air heater

(b) temperature of the flue gas entering and leaving each section of the air heater

(c) quantities of heated air leaving each section of the air heater

(d) quantity of flue gas entering and leaving the air heater

(e) inlet/outlet static pressure for each air stream

(f) outlet velocity pressure for each air stream

(g) flue gas (hot fluid) inlet/outlet static pressure

(h) flue gas (hot fluid) outlet velocity pressure

(i) specific humidity of inlet air

(j) concentration of oxygen in the flue gas entering and leaving the air heater

(k) quantity of fuel fired in the furnace

(l) ultimate analysis of the fuel fired

(m) quantity of atomizing steam or any other material added to the flue gas stream

(n) quantity of combustible matter in fly ash and other refuse stream locations

4-3 GRID

4-3.1 Measurement Location

Air and gas flowing through a duct generally have nonuniform flow, temperature, and (in the case of flue gas) composition, especially after an air heater. A multipoint measurement using a grid of sampling points is essential to determine the average value of each parameter accurately. After selecting a suitable location for the multipoint sampling grid, the flue or duct is subdivided into a number of elemental areas and, using a suitable probe and sampling system, the velocity, temperature, and gas constituents of interest are measured at a point in each elemental area. The total flow is then obtained by summing the contributions of each elemental area (perhaps, depending on the measurement and calculation technique, using different weighting factors for different areas). Average temperature and composition are calculated in accordance with subsection 4-4.

Many different techniques have been proposed for selecting the number of sampling points, establishing the size and geometry of the elemental areas, and summing or averaging (theoretically integrating) the individual readings from each elemental area. Options that have been proposed include the placing of points based on an assumed (log–linear, Legendre polynomial, or Chebyshev polynomial) distribution, the use of graphical or numerical techniques to integrate the individual readings, the use of equal elemental areas with simple arithmetic summing or averaging, and, in the case of flow measurement, the use of boundary-layer corrections to account for the thin layer of slow-moving fluid near a wall. As a general rule, accuracy of the measurement(s) can be increased by either increasing the number of points in the sampling plane or using more sophisticated mathematical techniques (e.g., interpolation polynomials, boundary layer corrections).

For velocity, temperature, and gas composition distributions encountered in large flues and ducts, it is more in line with the requirements of field testing, as well as more realistic in light of the varied distributions that actually occur in the field, to obtain the desired accuracy of measurement by specifying a relatively large number of sampling points at the center of equal areas, rather than by relying on assumed distributions or unsubstantiated assumptions regarding such things as boundary-layer effects. This Code requires the equal-area method with measurement at a relatively large number of points. For specific details on the use of Gaussian or Chebyshev measurement methodology, refer to ASME PTC 19.5.

4-3.1.1 Rectangular Flues and Ducts. Rectangular ducts shall be divided to form a grid with equal areas. Samples shall be taken at the centroid of each equal area. For ducts less than or equal to 324 ft^2, there should be from 9 to 36 sampling points and each equal area shall be no larger than 9 ft^2. For ducts greater than 324 ft^2, the number of points shall be increased above 36 and the equal areas may be increased to no more than 12 ft^2.

According to the systematic uncertainty models suggested in para. 7-5.3.2, the systematic uncertainty due to numerical integration decreases with the number of points; therefore, using more points has an impact on that component of the uncertainty.

There should be a minimum of three points spanning each dimension (height and width) of the duct cross section. The shape of the equal areas should be one of the following:

(a) If there is no significant stratification, or if the stratification in both directions are similar or unknown, the aspect ratios should be kept comparable (i.e., the long dimension of the duct is in the same direction as the long dimension of the equal areas), up to the equal areas being square. See Fig. 4-3.1.1-1.

(b) If there is severe stratification in one direction only, it is recommended that more points be added in that direction, without regard to the aspect ratio.

4-3.1.2 Circular Flues and Ducts. Circular ducts should be divided into equal areas of 9 ft^2 or less. There should be a minimum of nine sampling points. As noted above, increasing the number of sampling points reduces the systematic uncertainty due to numerical integration and a minimum number of 24 is recommended by the Code for large ducts. The number of sampling points may be increased to meet the 9 ft^2 minimum by dividing the cross section into four, six, or eight sectors. The location of each sampling point must be at the centroid of each equal area. The location of these sampling points may be determined by the method shown in Fig. 4-3.1.2-1, which uses 20 points and four sectors as an example.

4-3.2 Stratification

The distribution of gas composition, temperature, and velocity at the air heater inlet and exit measuring planes will be a function of the mixing and hydrodynamic processes upstream and downstream of the measuring location. It is likely that bends and/or dampers immediately upstream will be the overriding effect on velocity distribution. The following discussion applies to regenerative type air heaters, including rotating hood air heaters. This discussion also applies to tubular air heaters, although the magnitude of the outlet stratification may be less.

4-3.2.1 Air Inlets. At the air inlet the composition should be uniformly that of air, but temperatures will be a function of heating processes through the FD fan and air preheater coil if installed. The velocity distribution will be a function of mixing between the fan exit and the measuring plane. If an air preheater coil is in use, the velocity distribution of air at inlet and the internal fluid flow will influence the heat transfer and, therefore, the temperature distribution.

The combined effect of these complex processes cannot be calculated prior to a test, but it is likely that point-to-point variation will be small in relation to the mean temperature. However, the proportional effects on temperature might not be so small if hot air recirculation from air heater air exit to FD fan inlet is in operation.

4-3.2.2 Gas Inlets. The distribution of gas composition, temperature, and velocity will be a function of heat transfer and mixing processes in the combustion chamber and through the heat exchange system (superheaters and economizer) up to the air heater inlet. Also, ingress of ambient air in boilers operating under negative pressure will have an effect on the spatial distribution of all three quantities and particularly on flue gas composition. The closer the ingress point is to the measuring plane, the greater will be the effect on the distribution of gas composition.

These processes of ingress, heat transfer, and mixing will be very complex and also site and load oriented, and cannot be calculated prior to a test.

4-3.2.3 Air Heater Air Exits. As with the air inlet, the composition of exit air is considered to be uniformly that of standard air. The small effects of carryover of flue gas entrained in the rotor of a regenerative heater are not considered in this Code.

The velocity distribution will be a function of the distribution at air inlet, the hydrodynamics of transition ducting and bends between the heater matrix and measuring plane, and the influence of nonuniform fouling of the heat transfer surfaces.

The spatial temperature distribution will be a function of the same effects but with the additional influence of the inlet velocity on heat transfer and temperature distribution, together with the colder air that has bypassed the heat transfer surface though circumferential seals, alongside heater baskets, and integral cold air bypass.

The overriding effect on the range of values measured will, however, arise from the heat transfer process in the rotating heat transfer surface. At the exit from the heater matrix, the preheated air temperature will vary during the rotation, typically by 115°F (64°C) for an average temperature of 622°F (328°C), e.g., from 565°F to 680°F (296°C to 360°C) for larger air heaters. This rotational variation will be circumferentially linear with position around the matrix but will become distorted and the range reduced by the transition for semicircular to rectangular ducts and mixing effects up to the measuring plane. While this temperature range at matrix exit is calculable, the downstream mixing effects are not.

4-3.2.4 Gas Exits. The spatial distribution of gas composition will be more disturbed at gas exit than at gas inlet because of the presence of streams of air leaking across sealing surfaces and entrained air. These streams include radial leakage at both the hot and cold ends, together with air leaking around the rotor which will appear as cold end leakage. These are all localized flow streams that will mix into the main gas stream as it progresses through the ductwork.

Many of the points made above for air exit temperature distributions apply equally to the air heater gas exit but with the additional complication of the cooler air leakage streams.

As with the air exit plane, the overriding effect on the range of values measured will, however, arise from the heat transfer process in the rotating heat transfer surface. At the exit from the heater matrix, the undiluted gas temperature will vary during the rotation, typically by 99°F (55°C) for an average temperature of 286°F (141°C), e.g., from 235°F to 334°F (113°C to 168°C).

This rotational variation will be circumferentially linear in position around the matrix, but will become distorted and the range reduced by the transition for semicircular to rectangular and by mixing effects up to the measuring plane.

4-4 FLOW WEIGHTING

Duct layout around the air heater may prohibit locating the test planes at points of uniform, fully developed flow within the ducts. In such cases, it may be necessary to weight the individual data points with the flow at these points to compensate for the nonuniform flow pattern. This may be particularly important when large temperature stratifications (e.g., exit ducts of regenerative air heaters, cross-flow air preheaters, and downstream of steam or glycol air preheating coils) and/or large oxygen stratifications (e.g., exiting gas ducts of regenerative air preheaters) are anticipated.

Flow weighting requires the measurement of the velocity pressure and temperature of the fluid at the points in the ducts where the fluid is sampled for the individual point data. Two confirming data sets, including velocity pressures, temperatures, and static pressures, are required to verify repeatability of the velocity data. The collection of this data may be labor intensive and time consuming. Therefore, velocity pressure, temperature, and static pressure data collection in each duct, and at each test condition at which the air heater is to be tested, may be measured prior to testing and the velocity results applied to the individual tests. If the parties to the test agree that the flow-weighted average of the data varies noticeably from the arithmetic average of the data, the measured flow weighting data (recorded prior to the actual testing) will be applied to the data recorded during all tests for the affected ducts. Paragraph 7-5.3.3 describes a technique to determine when flow weighting should be applied, based on the pretest velocity and temperature (and oxygen) data. That paragraph also describes how to estimate the systematic uncertainty if flow weighting is used or if it is not used.

The flow-weighted average of a variable may be calculated from

$$X_{FW} = \frac{\sum_{i=1}^{n} Mr_i X_i}{\sum_{i=1}^{n} Mr_i} \text{ or } \frac{\sum_{i=1}^{n} v_i X_i}{\sum_{i=1}^{n} v_i} \tag{4-4-1}$$

where
Mr_i = mass flow rate in area associated with point i
n = total number of points
v_i = velocity in area associated with point i
X_{FW} = flow-weighted average of variable X (temperature, O_2, etc.)
X_i = value of the variable at point i

Flow Mr_i may be calculated from

$$Mr_i = Dn_i A_i v_i \tag{4-4-2}$$

where
A_i = area associated with point i
Dn_i = fluid density at point i
v_i = velocity at point i

Since

$$Dn_i \approx K_1[(P_B + P_{S,i})/(460 + T_i)] \tag{4-4-3}$$

where
K_1 = a constant, assuming an ideal gas, for a given fluid
P_B = barometric pressure, in. H_2O
$P_{S,i}$ = fluid static pressure at point i, in. H_2O (gage)
T_i = fluid temperature at point i, °F

and

$$v_i = K_2(\Delta P_i/Dn_i)^{1/2} \tag{4-4-4}$$

where
K_2 = a constant for the probe used to measure velocity pressure
ΔP_i = velocity pressure at point i

Equation (4-4-1) becomes

$$X_{\mathrm{Wgtd}} = \frac{K_1 K_2 \sum_{i=1}^{N} \{[\Delta P_i (P_B + P_{S,i})/(460 + T_i)]^{1/2} A_i X_i\}}{K_1 K_2 \sum_{i=1}^{N} \{[\Delta P_i (P_B + P_{S,i})/(460 + T_i)]^{1/2} A_i\}} \qquad (4\text{-}4\text{-}5)$$

Constant K_1 may be cancelled out of the summation since it is a function of unit conversion factors and the molecular weight of the fluid, which remain constant for a given test plane. Constant K_2 has been cancelled out of the summation, assuming that the same velocity pressure test probe (and therefore the probe correction factor) is used for all points at a given test plane. If multiple probes are used to record the velocity pressure data in a single duct, K_2 will not necessarily be constant and therefore should be moved within the summation.

4-5 TEMPERATURE MEASUREMENT

The primary application of temperature measurement in this Code is for combustion air and flue gas in large ducts. Secondary applications include the measurement of ambient air, dry bulb, and wet bulb temperatures, and when thermocouples are used with an ice bath for measuring the temperature of the ice bath.

For most temperature measurements, thermocouples are typically used. Other sensors include resistance temperature detectors (RTDs) and liquid-in-glass thermometers.

For a more complete discussion of temperature measurement, see ASME PTC 19.3.

4-5.1 Thermocouples

4-5.1.1 General Description. A thermocouple has two dissimilar electrical conductors called thermoelements, electrically insulated from each other except where joined together to form junctions. There are necessarily two junctions to each thermocouple, corresponding to the two extremities of the thermoelements. A thermocouple develops an emf that is a function of the difference in temperature of its measuring (hot) and reference (cold) junctions. If the temperature of the reference junction is known, the temperature of the measuring junction can be determined by measuring the emf generated in the circuit. The use of a thermocouple in temperature measurements, therefore, requires the use of an instrument capable of measuring emf.

The four most common thermocouple types are

(a) copper–constantan (Type T)
(b) iron–constantan (Type J)
(c) chromel–alumel (Type K)
(d) chromel–constantan (Type E)

The measuring junction of the thermocouple normally is enclosed in a sheath, and is ungrounded (i.e., the thermocouple junction is electrically insulated from the sheath by some type of refractory material, e.g., alumina, magnesia, or fiberglass). However, for the air inlet temperature measurement(s), "homemade" thermocouples (with exposed junctions) made from thermocouple wire (not extension wire) are sometimes used.

To minimize systematic uncertainty, thermocouples with continuous leads are used. To reduce cost, compatible (same type) thermocouple extension wires frequently are used. To minimize the increase in systematic uncertainty when doing this, the extension wire should be attached to the thermocouple before the pretest accuracy check and remain attached through the post-test accuracy check, and the accuracy check of the thermocouple includes both the thermocouple and its thermocouple extension wire.

Where a grid of thermocouples is used to measure temperature in a duct, the thermocouples should be read individually and not be grouped together to produce a single output.

4-5.1.2 Measuring Instruments

(a) Potentiometers. Potentiometers compare an unknown quantity against a known quantity or standard. Accurate weighting, for example, is often accomplished by direct comparison against standard weights using a mechanical balance. If the measured weights are too heavy for direct comparison, lever arms may be used to multiply the forces. The potentiometer serves a similar function in the measurement of voltage, the standard voltage being furnished by a standard cell, the "lever" being resistance ratios, and the galvanometer serving as the balance indicator. If a potentiometer is used, an ice bath should be used for the reference junction.

(b) Digital Thermometers. Digital thermometers are devices that read the emf from the measuring junction of a thermocouple and measure the ambient temperature, typically with a thermistor. With these two measurements and the standard thermocouple–emf relationships, digital thermocouples (both handheld devices and data acquisition systems) display/record the temperature at the measuring junction directly.

Where multiple thermocouples are connected to a data acquisition system that uses an isothermal bar for multiple inputs, extreme care must be taken to prevent temperature gradients between the inputs and the isothermal bar.

4-5.1.3 Accuracy Check. The preferred method of conducting accuracy checks of a thermocouple temperature measurement system is to evaluate the entire loop (thermocouple, wiring, potentiometer/digital thermometer/data acquisition system/etc.). Each accuracy check should consist of at least four points, and cover the entire range of measurements (i.e., at least one point must be below the lowest reading and at least one point must be above the highest reading). Note that while only four points are required for the accuracy check, in general, as the temperature spread between points decreases, the systematic uncertainty will also decrease.

An alternate method is to conduct separate accuracy checks of the thermocouple and the electronic system that displays/records the data. Both accuracy checks, the one for the thermocouple and the one for the electronics (digital thermometers/data acquisition systems/etc., and including any wiring not included with the thermocouple accuracy check), should consist of at least four points, and cover the entire range of measurements (i.e., at least one point must be below the lowest reading and at least one point must be above the highest reading). Note that while only four points are required for the accuracy check, in general, as the temperature spread between points decreases, the systematic uncertainty will also decrease.

An exception to the above is where potentiometers are used. Potentiometers do not require an accuracy check, but where they are used they should be set up in position not less than 3 hr before a test run for subjection to the ambient temperature and for stabilizing the standard cells. After stabilization, the potentiometer should be calibrated or "standardized" in accordance with the manufacturer's instructions.

Therefore, when setting the range of temperatures for the pretest accuracy check, take care when estimating the anticipated minimum and maximum temperatures, because if the average temperature from any thermocouple is outside its accuracy check range, that thermocouple should be considered to have failed.

Each thermocouple may have its own accuracy check, or two or more thermocouples from each spool may be selected for an accuracy check, the results averaged and used for all thermocouples from that spool. The accuracy check data from these selected thermocouples will be used to determine the systematic uncertainty and optionally to correct the measured temperatures for all thermocouples from the spool. If more than two thermocouples are selected to be checked, the data from each must be used in the calculations (i.e., none can be excluded). The accuracy check of the thermocouples (either every one or the selected representatives from a spool) may be done in a loop check (the preferred method) or stand alone (the alternate method). When the alternate method is used, the accuracy check of the remaining components of each loop, including electronic system, extension wire (if used), etc., should be performed.

4-5.2 Liquid-in-Glass Thermometers

4-5.2.1 General Description. Liquid-in-glass thermometers are primarily used for relative humidity and ice-bath measurements. They consist of a thin-walled glass bulb attached to a glass capillary stem closed at the opposite end, with the bulb and a portion of the stem filled with an expansive liquid, the remaining part of the stem being filled with the vapor of the liquid or a mixture of this vapor and an inert gas. Associated with the stem is a scale in temperature degrees, so arranged that when calibrated the reading corresponding to the end of the liquid column indicates the temperature of the bulb.

Partial-immersion thermometers are designed to indicate temperature correctly when used with the bulb and a specified part of the liquid column in the stem exposed to the temperature being measured, the remainder of the liquid column and the gas above the liquid exposed to a temperature that may or may not be different.

Where partial-immersion thermometers are used (e.g., in an ice bath), the thermometer should have a length and scale such that it can remain immersed in the fluid to its immersion line while being read.

Total-immersion thermometers are designed to indicate temperature correctly when used with the bulb and the entire liquid column in the stem exposed to the temperature being measured, the gas above the liquid exposed to a temperature that may or may not be different. Total-immersion thermometers should not be used.

Complete immersion thermometers are designed to indicate temperature correctly when used with the bulb, entire liquid column, and gas above the liquid exposed to the temperature being measured.

Thermometers should have etched stems, where the scale is marked directly on the stem by etching.

4-5.2.2 Accuracy Check. All thermometers used in the test should have a certified calibration. The calibration should consist of at least three points.

4-5.2.3 Inspection. Prior to use, each thermometer should be inspected to ensure that the fluid column has not separated. If the fluid has separated, it must be reunited or the thermometer must be replaced. For a mercury thermometer, the bulb only should be immersed in a dry ice/alcohol solution. For other fluids, centrifugal force may be used or with the thermometer in a vertical position, gently tap the stem above the separation.

4-5.3 RTDs

4-5.3.1 General Description. A resistance temperature detector (RTD) consists of a sensing element called a resistor, and two to four wires that are used to connect it to a resistance-measuring instrument. Most metals and some semiconductors change resistance with temperature in a known, repeatable manner. The resistor in an RTD is a pure metallic element (usually platinum, but nickel and copper are sometimes used) usually in the form of a coil of fine wire wrapped around a ceramic or glass core, and hermetically sealed within a capsule, which is enclosed in a metallic sheath. If only two wires were used, the measured resistance would include not only the resistance of the resistor, but also the lead wires. For this reason, three- or four-wire RTDs are used with a bridge circuit to measure the resistance of the resistor only.

4-5.3.2 Accuracy Check. Use the same methodology as described in para. 4-5.1.3.

4-5.4 Systematic Uncertainty

4-5.4.1 Thermometers. There are two components of the systematic uncertainty of a thermometer — its readability and its accuracy. The readability of the thermometer is the graduation interval divided by 2. The component of the systematic uncertainty due to accuracy is calculated from the errors at the calibration points and the interpolated error at the measured value. See Mandatory Appendix III for an example of these calculations.

4-5.4.2 Thermocouples and RTDs. There are several possible components of the total systematic uncertainty of a temperature measured with a thermocouple or RTD. These include, but are not limited to

(a) systematic uncertainty of the primary standard

(b) systematic uncertainty due to sensor installation, thermowell, pad welding, etc.

(c) temperature of the ice bath (thermocouples)

(d) uncalibrated lead wires

(e) potential sensor drift

(f) sensor systematic uncertainty due to interpolation between accuracy checkpoints (since the value of a measurement rarely coincides with a value from the calibration data)

(g) data acquisition system systematic uncertainty due to interpolation between accuracy checkpoints

Each component of the total systematic uncertainty could be positive only (causing the measured value to be higher than the “true” value), negative only (causing the measured value to be lower than the “true” value), or both positive and negative. When tabulating the values for each component of the total systematic uncertainty, two columns should be made, one for positive values and the other for negative values.

For thermocouples using potentiometers, accuracy check data consists of only data on the thermocouple itself (and wiring). For thermocouples using digital thermometers and RTDs, accuracy check data includes data on the sensor, wiring, and the device to display/record the temperature. (In the descriptions below and in Mandatory Appendix III, *sensor* is considered to be the thermocouple or RTD and any permanently attached wiring. *Electronics* are considered to be any lead wires, junctions, data acquisition/display equipment, or any other items in the loop excluding the *sensor*.)

4-5.4.3 Accuracy Checks. There are three ways to use the accuracy checks to determine the systematic uncertainty due to interpolation between accuracy checkpoints and to optionally correct the measured data, as follows:

(a) calculate a specific correction factor from the pretest loop (or sensor and separate electronics) accuracy check to be applied to each individual reading from each thermocouple/RTD or point (this is the preferred method)

(b) calculate a specific correction factor from the pretest loop (or sensor and separate electronics) accuracy check to be applied to the average reading (arithmetically or by weight) from each thermocouple/RTD or point

(c) no correction to the measured temperatures, and the pretest loop (or sensor and separate electronics) accuracy check data is used to determine the systematic uncertainty in temperature for that test plane

See Mandatory Appendix III for an example of these calculations.

4-5.5 Air and Flue Gas Measurements

In order to determine the average air or gas temperature in a large duct, multiple measurements must be taken. The duct is to be divided into several equal areas, and the temperature (and possibly velocity) is measured in the center of each elemental area in accordance with para. 4-3.1. If the air or gas velocities are “significantly” different across the duct, the temperature measurements must be weight averaged based on the mass flow (or velocity) at each point, which is calculated from the temperature and velocity at each point and the static pressure in the duct. Subsection 4-4 describes conditions when weight averaging is required. Even if weight averaging is not required, it is permissible if all parties agree to this. However, this may increase the overall systematic uncertainty due to the uncertainty in the flow measurements.

During a test run, where a fixed grid of temperature sensors (typically thermocouples) are continuously measuring temperatures, it is not uncommon for some sensors to fail. If a thermocouple in a fixed grid fails during a test, if it failed during the second half of the run (i.e., it made at least 50% of the number of readings as the sensors that worked during the entire test), the readings taken before the failure would be used, and the sensor is not considered to have “failed.” Table 4-5.5-1 sets upper limits on the number of sensors in any duct that may fail during a test run without voiding the test run. However, the uncertainty will be affected, and this may cause the run to be voided. If any sensors fail during a run, they should be replaced before the next test run, unless all parties agree to proceed without replacing them.

In order to have relatively equal representation of the temperature across the duct, it is important that any loss of measurements be in a random manner. If adjacent sensors fail, the systematic uncertainty of this measurement increases but the magnitude cannot be estimated. Figure 4-5.5-1 shows some examples of nonrandom combination of points. Should any of these failure patterns occur, the test should be aborted and restarted after replacing the faulty sensors.

In the flue gas ducts (inlet and outlet), in addition to measuring temperature, the O_2 concentration is also measured, at the same positions. If single-point traversing is performed, the probe consists of one tube for extracting a gas sample. The thermocouple may be secured to the outside of the tube, but more commonly it is run inside a second tube for protection. The measuring (hot) end of the thermocouple is at the same position as the end of the gas sampling tube. Where multiple gas sampling probes are installed and fixed in a single port, one tube usually contains all temperature sensors. Holes are drilled in the tube containing the temperature sensors at points corresponding to the ends of each gas sampling tube, and the measuring (hot) ends of the thermocouples are routed out of the holes.

4-5.6 Dry Bulb (Ambient) and Wet Bulb Temperature

For determination of specific humidity, the dry bulb temperature, wet bulb temperature, and barometric pressure are frequently used. These two temperatures are usually measured with "matched" thermometers that have similar characteristics. The bulb of the wet bulb thermometer should be covered by a braided, tubular cloth wick that has been saturated (but is not dripping) with distilled water.

4-5.7 Ice Bath Temperature

Where thermocouples are used with a potentiometer and ice bath, a partial immersion liquid-in-glass thermometer is required to be placed in the ice bath. The bulb of the thermometer should be close to the bottom of the ice bath.

4-6 PRESSURE MEASUREMENT

Total pressure is the sum of static pressure and velocity pressure. For the air heater test, the pressure readings required include

(a) air and gas side inlet/outlet static pressures

(b) air and gas side inlet/outlet velocity pressures

Additional information on pressure measurements and flow derived from pressure measurements can be found in ASME PTC 19.2, Pressure Measurement; ASME PTC 19.5, Flow Measurement; and ASME PTC 11, Fans.

4-6.1 Pressure Reading Instruments

Manometers or transducers are the practical instruments currently used for measuring pressures.

Precautions should be taken to protect the indicator from the effects of wind, sun, and radiant heat. Periodically during the test, probes, hoses, and indicators should be checked for leaks or plugging. Plugging can result from either particulate buildup in the probe or condensation in a portion of the system.

Indicators used for static or total pressure measurement may have one tap open to atmosphere. If the indicator is not located in the same atmosphere as the barometer, an additional measurement to determine the difference in pressure is required.

(a) Manometers. The manometers shall generally be vertical U-tubes or well type with a bore of $^5\!/_{16}$ in. (8 mm) or more and filled with oil or water. The spacing between the scale graduations shall be no more than $^1\!/_8$ in. (3 mm). The fluid density of the manometer shall be determined at site temperature. For low pressure readings, to enhance readability, inclined tube manometers should be used. In this type of manometer, one of the tubes is inclined and the sloping design of the tube stretches the graduations by an amount proportional to the angle of inclination of the tube. The inclined manometer is generally equipped with a bubble leveler and adjusting screws.

Manometers shall be selected such that the scale length and fluid density permit reading with an uncertainty of no greater than 0.5% of the measured pressure or pressure differential. The uncertainty can be caused by readability, temperature dependence of the density of the manometer fluid, capillarity effects, and the tilt of the instrument.

(b) Transducers. Pressure transducers are pressure-sensing devices that produce an electrical output proportional to the pressure applied. The pressure transducers utilize the variation in the properties of the sensor when it is subjected to strain or distortion. The transducing element can be a set of strain gages that rely on changes in electrical resistance when the length of a conductor (e.g., set of wires) is distorted under pressure. Similarly, the transducing element can be a semiconductor wafer or any other device that changes its electrical properties under pressure. The major sources of error in transducers are zero drift, hysteresis, temperature, and altitude dependence. The output from the transducer can be read on a meter or data logger. An in-situ pretest calibration of the pressure measuring system, or a pretest and posttest calibration, shall be required. For details on pressure transducers, refer to ASME PTC 19.2.

4-6.2 Systematic Uncertainty

An estimate of the systematic uncertainty of a pressure measurement is a combination of systematic uncertainty from the primary element, installation effects, and data acquisition. The typical potential instrumentation systematic uncertainty for a manometer is one-half of the graduation, while the typical potential instrumentation systematic uncertainty for a standard pressure transducer is ±0.1% of span or less.

The total systematic uncertainty of the pressure measuring systems includes the sensor, transmitter, and data acquisition system (if any). Corrections shall be made for any difference from calibrated conditions in density of manometer fluid, gas head, and change in length of graduated scale due to temperature.

4-6.3 Static Pressure

The static pressure is the pressure measured such that no effect is produced by the velocity of the flowing fluid. The static pressure can be used to determine the velocity pressure if the total pressure is known. The static pressure can also be used to determine pressure drop in air and gas ducts. When static pressure is used for pressure drop determinations, a differential measuring apparatus (e.g., two legs of the manometer) should be used rather than two separate instruments to minimize the uncertainty.

Static pressure shall be measured with wall taps or static pressure probes. The static pressure connection shall be installed to minimize errors from gas velocity impingement. This is accomplished by proper location of the tap on the duct wall(s) or by use of specially designed probes. When the duct walls are smooth and parallel with no flow interference, the static pressure wall tap on one of the walls is expected to provide a representative reading. Otherwise, the static pressure shall be taken as the arithmetic average of four wall tap stations equally spaced around the duct in the same plane and each read separately. This can also be accomplished by use of an averaging ring installed on the outside of the duct, and connected to the four wall taps and to a single pressure-sensing device. The cross-sectional area of this averaging ring shall be at least as large as the sum of the individual areas of the tapping points.

4-6.3.1 Pressure Wall Taps. As the fluid passes across the tap, the fluid streamlines are deflected into the hole — creating eddies within the tap. This distorts the true static pressure and results in a positive or negative pressure error. Large tap diameters and higher velocities give larger errors. The wall taps should therefore be small and have square edges. The taps shall be smooth, free from burrs and debris, and located such that there is no flow impingement or flow disturbances due to elbows or duct internals.

Wall taps are typically $\frac{3}{8}$ in. (9 mm) or $\frac{1}{2}$ in. (12 mm) diameter. If a single wall tap is being considered to measure static pressure, readings shall be taken from at least two wall taps in the same plane to determine if it is representative. If not, either hydraulic (piezometer ring) or arithmetic averaging of four taps, or a static pressure probe, shall be used. In all cases, the pressure sensing line shall be free of condensate.

4-6.3.2 Static Pressure Probes. The static pressure probes are generally required where wall taps do not provide representative readings due to flow distortions resulting from irregular shape of duct or from duct expansion joints. In such cases, the static pressure in the duct can be sensed with static pressure probes. A simple static pressure probe is in the form of a bent tube with a rounded nose pointed into the flow. A series of static taps are drilled along the stem. These taps are located diametrically opposed to each other to cancel out any airflow-induced errors. The static taps when connected to a pressure instrument (e.g., manometer) will provide the static pressure. Static pressure can also be measured with a pitot-static tube ("L" type). No calibration is required for the static pressure probe or the pitot-static tube.

In case the static pressure openings are prone to plugging, the Stauscheibe probe ("S" type) can be utilized. However, the "S" type will require calibration.

In cases where flow directions are unknown, both pitot-static and Stauscheibe probes are unsuitable and directional probes (like the Fechheimer tube) should be used for static pressure after calibration. Also see Mandatory Appendix V.

4-6.3.3 Readings for Static Pressure Measurements. The frequency of static pressure readings shall not coincide with the rotation of the air heater.

4-6.4 Velocity Pressure

Point values of pressure (velocity and total or static pressure) shall be measured using a probe that can be positioned at the appropriate points by insertion through one or more ports as required. A probe capable of measuring static pressure, total pressure, their differential, yaw angle, and pitch angle is preferred. A probe with only yaw-measuring capability can only be used if a preliminary test gives good evidence that the average of absolute values of pitch angle does not exceed 5 deg. A nondirectional probe may only be used where the preliminary test gives good evidence that the average of the absolute values of neither yaw angle nor pitch angle exceeds 5 deg. See Mandatory Appendix V for details of various probes used to measure velocity pressure.

Pressure measurements shall be made at each traverse point for each traverse plane. The indicated velocity pressure and either the total pressure or static pressure shall be measured. The remaining pressure can be determined arithmetically.

Total probe blockage shall not exceed 5% of the duct cross-sectional area.

The velocity pressure is the difference between the total pressure and the static pressure, and is expressed as

$$\frac{(\text{air density}) \times (\text{velocity})^2}{2g_c}, \text{ lbf/ft}^2 \text{ (Pa)}$$

where

g_c = mass conversion factor, e.g., 32.174 ft·lbm/lbf·sec^2 (1.000 m·kg/N·s^2)

The velocity pressure is measured by various instruments by conducting a velocity traverse of the duct. The velocity traverse consists of measurements taken at numerous locations in a plane perpendicular to the flow. A probe is inserted into the duct and measurements are made at a number of locations corresponding to the centers of equal areas.

Due to the highly disturbed flow at typical flue gas and air flow measurement locations, velocity measurement for purposes of flow weighting (see subsection 4-4), and/or measurement of mass flow rate, should include consideration for the direction of flow. Due to the errors associated with making measurements with probes unable to distinguish flow direction, probes capable of indicating gas direction and speed, hereinafter referred to as directional probes, are generally required. Only the component of velocity normal to the elemental area is pertinent to the calculation of flow. Measurement of this component cannot be accomplished by simply aligning a nondirectional probe parallel to the duct axis, since such probes only indicate the correct velocity pressure when aligned with the velocity vector. Errors are generally due to undeterminable effects on the static (and to a lesser degree, total) pressure sensing holes. Therefore, adequate flow measurements in a highly disturbed region can only be made by measuring speed and direction (i.e., yaw and pitch angles) at each sampling point and then calculating the component of velocity normal to the traverse plane.

4-6.5 Averaging of Fluctuating Pressure

Since pressures are seldom strictly steady, the pressure indicated on any instrument will fluctuate with time. To obtain a reading, either the instrument shall be damped or the readings shall be averaged in a suitable manner. Dampening can be accomplished with some type of pressure dampers or snubbers (e.g., porous plug type, orifice type) that can be installed between the process and the pressure instrument. Averaging can be accomplished mentally if the fluctuations are small and regular. If the fluctuations are large and irregular, more-sophisticated methods shall be used. It is possible to obtain a temporal average electronically when an electrical pressure transducer is the primary element. Even though the spatial average velocity is obtained from the square roots of the temporal average velocity pressures, it is not proper to take the square root of the raw data before temporal averaging, as this may introduce a systematic error into the average values. See ASME PTC 19.5, Section 6 for additional guidance.

4-6.6 Calculation of Velocity and Mass Flow From Velocity Pressure Measurements

In order to calculate mass flow at a point from data collected with a nondirectional probe, the following information is required:

Measure	Symbol	Units
Velocity pressure (measured)	P_{vm}	in. wg (kPa)
Static pressure (measured)	P_{sm}	in. wg (kPa)
Barometric pressure (measured)	P_b	in. Hg (kPa)
Dry bulb temperature (measured)	T_{dbm}	°R (K)
Probe (nondirectional) coefficient (from probe calibration, a constant or curve as function of *Re*)	K	. . .
Probe diameter (from probe geometry)	d_p	ft (m)
Duct cross-sectional area represented by this point (from duct geometry)	A_i	ft^2 (m^2)

If a directional probe is used, the following additional information is required:

Measure	Symbol	Units
Yaw angle (measured)	Ψ	deg
Pitch differential pressure (measured)	ΔP_{Φ}	in. wg (kPa)
Curve of pitch angle versus pitch pressure coefficient (from probe calibration)	Φ vs. C_{Φ}	. . .
Curve of velocity pressure coefficient versus pitch pressure coefficient (from probe calibration)	K_v vs. C_{Φ}	. . .
Curve of total pressure coefficient versus pitch pressure coefficient (from probe calibration)	K_t vs. C_{Φ}	. . .
Drag coefficient of probe section (from probe calibration)	C_D	. . .
Frontal area of probe exposed to calibration stream (from probe geometry)	S_p	ft^2 (m^2)
Cross-sectional area of calibration jet or wind tunnel (from calibration facility geometry)	C	ft^2 (m^2)

If the fluid being measured is air, the following additional information is required:

Measure	Symbol	Units
Humidity ratio (also referred to as mass fraction of water in dry air, *MFrWDA*; see Table 5-10.2-1)	W	. . .

If the fluid being measured is flue gas, the additional information below is required. Refer to para. 5-3.5 for determination of flue gas composition.

4-6.6.1 Calculation of Pitch Pressure Coefficient, C_Φ (Dimensionless)

$$\text{If } P_{\mathrm{vm}} \neq 0,\ C_\Phi = \Delta P_\Phi / P_{vm},\ \text{else } C_\Phi = 0$$

4-6.6.2 Determination of Pitch Angle, Φ (Degrees). Use the curve of the pitch angle, Φ, versus the pitch pressure coefficient, C_Φ, developed from the probe's calibration. This curve may be a function of a Reynolds number; if so, an iterative process is required. For the first iteration, assume a Reynolds number.

4-6.6.3 Determination of Velocity Pressure Coefficient, K_v (Dimensionless). Use the curve of the velocity pressure coefficient, K_v, versus the pitch pressure coefficient, C_Φ, developed from the probe's calibration. This curve may be a function of a Reynolds number; if so, an iterative process is required.

4-6.6.4 Determination of Total Pressure Coefficient, K_t (Dimensionless). Use the curve of the total pressure coefficient, K_t, versus the pitch pressure coefficient, C_Φ, developed from the probe's calibration. This curve may be a function of a Reynolds number; if so, an iterative process is required.

4-6.6.5 Calculation of Total Pressure, P_{tm} [in. wg (kPa)]

$$P_{tm} = P_{vm} + P_{sm}$$

4-6.6.6 Calculation of Absolute Static Pressure, P_{sam} [in. wg (kPa)]

$$P_{sam} = P_{sm} + P_b \times \text{conversion factor}$$

The conversion factor is 13.62 in. wg/in. Hg (1.0 kPa/kPa).

4-6.6.7 Calculation of Parameter Used to Correct Probe Calibration for Blockage, β (Dimensionless). To do this, the compressibility correction factor for velocity pressure $(1 - \epsilon_p)$ is required, but that requires β to be known, so an iterative process is required. For the first iteration, assume a value for $1 - \epsilon_p$.

$$\beta = \pm \frac{C_D(1 - \epsilon_p)}{4(1 - \epsilon_p) - 3}\left(\frac{S_p}{C}\right)$$

4-6.6.8 Calculation of Velocity Pressure Coefficient Corrected for Probe Blockage, K_{vc} (Dimensionless)

$$K_{vc} = K_v/(1 + \beta K_v)$$

4-6.6.9 Calculation of Molecular Weight, Mw, of Flue Gas and Air [lbm/mol (g/mol)]. The molecular weight of dry air is 28.963. The molecular weight of any dry gas, $MwDg$, including flue gas, shall be calculated from the average volume fractions, $(X)_x$, using

$$MwDg = 44.01\,(CO_2) + 28.01\,(CO) + 32.00\,(O_2) + 28.02\,(N_2) + \ldots$$

The molecular weight of moist gas, Mwg, shall be calculated from $MwDg$ and the humidity ratio, W.

$$Mwg = \frac{1 + W}{\dfrac{W}{18.02} + \dfrac{1}{MwDg}},\ \text{lbm/mol}$$

To determine the humidity ratio, W ($MFrWDA$), for air, see para. 5-3.4.2. To determine the humidity ratio, W ($MFrWDFg$), for flue gas, use the ratio of the total moisture in flue gas (see para. 5-3.5.8, $MqWFgz$) to the dry flue gas weight (see para. 5-3.5.10, $MqDFgz$).

4-6.6.10 Calculation of Specific Heat at Constant Pressure, c_p [Btu/lbm-°F (J/kg·K)]. Refer to subsection 5-9 for determination of specific heat.

4-6.6.11 Calculation of R {ft-lbf/(lbm-°R) [J/(kg·K)]}

$$R = R_0/Mw$$

where

R_0 = 1,545 ft-lbf/lbm-mol-°R (8.314462 J/mol·K)

4-6.6.12 Calculation of k (Dimensionless)

$$k = \frac{c_p}{c_p - R/J}$$

where

J = 778.2 ft-lb/Btu (1.0 J/J)

4-6.6.13 Calculation of Compressibility Correction Factor for Velocity Pressure, $1 - \epsilon_p$ (Dimensionless)

$$1 - \epsilon_p = 1 - (K_{vc}/2k)(P_{vm}/P_{sac})$$

If this doesn't match the assumed value of $1 - \epsilon_p$ used in para. 4-6.6.7, return to the step in para. 4-6.6.7.

Note that the instruments and methods of measurement specified in this Code are selected on the premise that only mild compressibility effects are present in the flow. The velocity, pressure, and temperature determination provided for in this Code are limited to situations in which the gas is moving with rate Mach number less than 0.4. This corresponds to a value of $K_{vjc}p_{vi}/p_{saj}$ of approximately 0.1 [see provision below eq. (V-8-9) in Mandatory Appendix V].

4-6.6.14 Calculation of Compressibility Correction Factor for Absolute Temperature, $1 - \epsilon_T$ (Dimensionless)

$$1 - \epsilon_T = 1 + 0.85(k - 1)/kK_{vc}P_{vm}/P_{sac}$$

4-6.6.15 Calculation of Absolute Temperature, T_m [°R (K)]

$$T_m = T_{dbm} + \text{conversion factor}$$

The conversion factor is 459.67 for U.S. Customary units (273.15 for SI units).

4-6.6.16 Calculation of Corrected Static Temperature, T_{sc} [°R (K)]

$$T_{sc} = T_m/(1 - \epsilon_T)$$

4-6.6.17 Calculation of Corrected Total Pressure, P_{tc} [in. wg (kPa)]

$$P_{tc} = K_t P_{tm}$$

4-6.6.18 Calculation of Corrected Static Pressure, P_{sc} [in. wg (kPa)]

$$P_{sc} = P_{tc} - K_v P_{vm}$$

4-6.6.19 Calculation of Corrected Velocity Pressure, P_{vc} [in. wg (kPa)]

$$P_{vc} = K_{vc}(1 - \epsilon_p)P_{vm}$$

4-6.6.20 Calculation of Corrected Absolute Static Pressure, P_{sac} [in. wg (kPa)]

$$P_{sac} = P_{sc} + P_b \times \text{conversion factor}$$

The conversion factor is 13.62 in. wg/in. Hg (1.0 kPa/kPa).

4-6.6.21 Calculation of Fluid Density, Dn_c [lbm/ft^3 (kg/m^3)]. For air see para. 5-3.4.10 (*DnA*) and for flue gas see para. 5-3.5.13 (*DnFg*), using the corrected static temperature (T_{sc}) and corrected absolute static pressure (P_{sac}).

4-6.6.22 Calculation of Fluid Velocity, V_c [ft/min (m/s)]

$$V_c = \cos(\Psi) \times \cos(\Phi) \times (P_{vc}/Dn_c)^{1/2} \times \text{conversion factor}$$

The conversion factor is 1,097 (lbm/ft·min^2·in. wg)$^{1/2}$ [(2 000)$^{1/2}$(m^2/s^2·Pa)$^{1/2}$].

4-6.6.23 Calculation of Fluid Viscosity, Vs [lbm/ft-sec (Pa·s)]. For this Code, the viscosity of air and flue gas is calculated from second-order curve fits developed from the ASME PTC 11 standard procedures. Viscosity is required to calculate a Reynolds number. The probe calibration factor, K (or $K^{1/2}$) is correlated versus a Reynolds number. The maximum viscosity error for these curve fits is approximately 2.5%. For a typical Fechheimer probe, the error in calculated fluid flow for a 5% error in viscosity is generally less than 0.05% when on the flat portion of the calibration range (typically Re from 10,000 to 50,000) and less than 0.1% at the ends of the calibration range. If the traverse data is out of the temperature range for these curve fits or the user already has a program based on the ASME PTC 11 procedures, it is recommended that those procedures be used.

For air and flue gas, the equation is

$$Vs = A + BT + CT^2 \tag{4-6-1}$$

where

A, B, C = coefficients obtained from Table 4-6.6.23-1
T = temperature, °F
Vs = viscosity

Two approaches for developing the curve fits for air and flue gas were taken. The major variable in determining the viscosity of air or flue gas is the quantity of moisture in the gas. As explained below, curve fits were developed for each with typical quantities of moisture and are referred to as "standard." The second method is to use the curve fit for dry air or flue gas and calculate the viscosity based on the "as-tested" amount of moisture in the gas. These two methods for both air and flue gas are discussed in more detail below.

(a) Air Standard. The curve fit for standard air was developed for a temperature range from 0°F to 1,000°F and a moisture content of 0.013 lbm/lbm dry air. This moisture content is a typical value for design. Table 4-6.6.23-1 shows the uncertainty for two ranges of moisture content in the air.

(b) Water Vapor. The curve fit for water vapor is required for the second method when it is desired to calculate the viscosity of air or flue gas for a specific water vapor content. Note that the range of temperatures for water vapor and flue gas is from 0°F to 1,500°F.

(c) Dry Air and Water Vapor. To calculate the viscosity of air with a specific water vapor, follow the two equations below.

$$VsA = \frac{\sqrt{MwDA} \times VsDA + \sqrt{MwWv} \times VsWv \times VFrWDA}{\left(\sqrt{MwDA} + \sqrt{MwWv} \times VFrWDA\right)}, \ \frac{\text{lbm}}{\text{ft-sec}} \ (\text{Pa·s}) \tag{4-6-2}$$

$$VFrWDA = MFrWDA \times \frac{MwDA}{MwWv}, \ \text{ft}^3/\text{ft}^3 \ (\text{m}^3/\text{m}^3) \tag{4-6-3}$$

where

$MFrWDA$ = mass fraction of water in dry air, lbm/lbm (kg/kg). Refer to para. 5-3.4.2.
$MwDA$ = molecular weight of dry air (28.965), lbm/mol (kg/mol)
$MwWv$ = molecular weight of water vapor (18.0153), lbm/mol (kg/mol)
$VFrWDA$ = volume fraction of water in dry air, ft^3/ft^3 (m^3/m^3)
VsA = viscosity of air, lbm/ft-sec (Pa·s)
$VsDA$ = viscosity of dry air, lbm/ft-sec (Pa·s), from Table 4-6.6.23-1

$VsWv$ = viscosity of water vapor, lbm/ft-sec (Pa·s), from Table 4-6.6.23-1

(d) Flue Gas, Standard. ASME PTC 11 provides a procedure for calculating the viscosity of flue gas based on each constituent in the flue gas. For this Code, the committee developed an average viscosity based on the average flue gas analysis of four different fuels with typical excess air values. The fuels were natural gas, oil, and two different coals. Considering that the test may be conducted at different excess levels and different fuels would produce different volumetric constituent quantities, the uncertainty was estimated to be 2.5%. If it is desired to use the ASME PTC 11 procedure, it is recommended to use the calculated flue gas constituents based on the measured flue gas O_2 and test or typical fuel analysis. See para. 5-3.4.

(e) Dry Flue Gas and Water Vapor. If a lower uncertainty than estimated for the standard flue gas is desired, the viscosity of flue gas may be calculated from the two equations below based on the dry flue gas coefficients and water vapor. It is recommended that the water vapor in flue gas be obtained from the combustion calculations using the test or a typical fuel analysis and measured excess air. The uncertainty of this procedure, considering the variations in the actual dry flue gas constituents and excess air at the time of the test, is estimated to be 1.5%.

$$VsFg = \frac{\sqrt{MwDFg} \times VsFg + \sqrt{MwWv} \times VsWv \times VFrWFg}{\left(\sqrt{MwFg} + \sqrt{MwWv} \times VFrWFg\right)}, \frac{\text{lbm}}{\text{ft-sec}} \text{ (Pa·s)} \tag{4-6-4}$$

$$VFrWFg = MFrWFg \times \frac{MwFg}{MwWv}, \text{ft}^3/\text{ft}^3 \text{ (m}^3/\text{m}^3\text{)} \tag{4-6-5}$$

where

$MFrWFg$ = mass fraction of water in the flue gas, lbm/lbm (kg/kg)

$MwDFg$ = molecular weight of dry flue gas. The molecular weight of the dry analysis of the four fuels used to develop the curve fit should be used (30.37), lbm/mol (kg/mol).

$MwWv$ = molecular weight of water vapor (18.0153), lbm/mol (kg/mol)

$VFrWFg$ = volume fraction of water in the flue gas, ft^3/ft^3 (m^3/m^3)

$VsDFg$ = viscosity of dry flue gas, lbm/ft-sec (Pa·s), from Table 4-6.6.23-1

$VsFg$ = viscosity of flue gas, lbm/ft-sec (Pa·s)

$VsWv$ = viscosity of water vapor, lbm/ft-sec (Pa·s), from Table 4-6.6.23-1

4-6.6.24 Calculation of Reynolds Number, *Re* (Dimensionless)

$$Re = Dn_j \times V_c \times d_p/(Vs \times \text{conversion factor})$$

The conversion factor is 60 sec/min (1.0 s/s).

NOTE: If this Reynolds number does not match the one used in paras. 4-6.6.2, 4-6.6.3, and 4-6.6.4, then return to para. 4-6.6.2 and repeat using this Reynolds number.

4-6.6.25 Calculation of Mass Flow, *m* [lbm/sec (kg/s)]

$$m = Dn_j \times V_c \times \text{area} \times \text{conversion factor}$$

The conversion factor is 60 sec/min (1.0 s/s).

4-7 FLOW MEASUREMENT

4-7.1 General

Numerous methods are employed in industry to determine the flow rate of solid, liquid, or gaseous streams. ASME PTC 11 is the preferred reference for air and flue gas. ASME PTC 19.5 and ASME MFC-3M/MFC-3Ma are the primary references for flow measurements of other fluids. ASME PTC 6, Steam Turbines, provides further information on flow measurement techniques, especially for water and steam. These sources include design, construction, location, and installation of flowmeters, the connecting piping, and computations of flow rates.

For multiple air heaters, the total gas flow can be calculated stoichiometrically more accurately than measured. The total gas mass flow entering air heaters is calculated stoichiometrically from input, *MrFg14*. See para. 5-3.5.9.

For air heaters of the same type, when the individual gas velocities (or flows) entering each individual air heater are measured, calculate the gas flow split between multiple air heaters based on the ratio of measured gas velocity pressures or mass flow rates calculated from velocity pressures and temperatures.

For multi-sector air heaters, see para. 5-4.1(b).

4-7.2 Air and Flue Gas

The total mass flow of air and flue gas crossing the steam generator boundary is calculated stoichiometrically. (This calculated flue gas flow normally can be used for the total flow entering the air heater; however, due to air infiltration, atmospheric tempering air, etc., this airflow cannot normally be used for the airflow through the air heater.) When there is more than one air heater or multiple flues/ducts, it may be necessary to measure the air or flue gas flow in addition to the temperature of the stream to account for an individual air or gas stream that crosses the steam generator boundary. The energy crossing the boundary in that air or gas stream then may be calculated. See Mandatory Appendix V.

4-7.2.1 Methods of Measurement. There are numerous methods for the measurement of air and gas flow (e.g., venturi, airfoil, velocity traverse, heat balance, etc.). If plant instrumentation is used, it should be calibrated. The flow may be calculated from velocity (as measured according to para. 4-6.4), the density of the fluid, and the duct cross-sectional area (see para. 4-6.6).

4-7.3 Liquid Fuel

The input–output method for efficiency determination requires the quantity of liquid fuel burned.

4-7.3.1 Method of Measurement. The quantity of fuel may be determined by flow measurement device, weigh tank, or volume tank. Refer to para. 4-7.4.1 for discussion of the use of flow nozzles and thin plate orifices. If a level change in a volume tank is utilized to determine the flow measurement, accurate density determination is required. ASTM D1298 provides procedures to determine API gravity and density. Recirculation of fuel between the point of measurement and point of firing shall be measured and accounted for in the flow calculation. Branch connections on the fuel piping shall be either blanked off or isolated with double valves.

4-7.4 Gaseous Fuel

For the input–output method, the quantity of gaseous fuel burned must be determined.

4-7.4.1 Method of Measurement. Measurement of the relatively large volumes of gaseous fuel normally encountered while testing steam generators requires the use of an orifice, flow nozzle, or turbine meter. The pressure drop shall be measured using a differential pressure gauge or differential pressure transmitter. Outputs from these devices can be read manually, via hand-held meters, or with data loggers. When gas flow is measured, the temperature and pressure used in the calculation of density are extremely important. Small variations can cause significant changes in the calculated gas density. In addition, the super-compressibility factor has a significant effect on the determination of gas density.

4-7.5 Solid Fuel and Sorbent Flow

For determination of fuel flow, measuring steam generator output and calculating fuel input and flow rate from fuel efficiency determined by the heat loss method is preferred. The accurate measurement of solid flow is difficult because of solid material variability.

4-7.5.1 Method of Measurement. Numerous methods are available to measure the flow of solids, e.g., gravimetric feeders, volumetric feeders, isokinetic particulate samples, weigh bins/timed weights, and impact meters. To reduce uncertainty of any of these methods below 5% to 10% requires extensive calibration against a reference. The calibration can involve the collection of the solid material into a container that can be weighted rather than placing weights on the belt. For example, the output of a gravimetric feeder can be directed to a container suspended by load cells, and the rate of feed indicated by the feeder can then be compared to the timed catch in the container.

It is even more difficult to assess the accuracy of volumetric feeders. This assessment requires assumptions about the volume of material passed per revolution and the density of the material. The rotor may not be full, the density may vary as a result of size distribution or other factors, and all these parameters may vary over time.

Calibrations of solid flow measurement devices should be conducted just prior to the testing and at frequent intervals to ensure the minimum systematic uncertainty.

4-7.6 Residue Splits

The amount of residue leaving the steam generator boundary is required to determine the sensible heat loss in the residue streams and the weighted average of unburned carbon (and CO_2 on units that utilize sorbent) in the residue. Typical locations where the residue is removed periodically or continuously are furnace bottom ash (bed drains), economizer or boiler hoppers, mechanical dust collector rejects, and fly ash leaving the unit. The parties to the test may agree to estimate the split. See below if the split is to be measured.

4-7.6.1 Method of Measurement. The calculated total residue mass flow rate is used since it is normally more accurate than a direct measurement. Therefore, the percent of the total residue that leaves each location must be determined. Several methods can be used to determine the split between the various locations.

(a) The mass flow rate should be measured at each location.

(b) The residue at one or more locations should be measured (usually the locations with the highest loading) and the quantity at the other locations should be calculated by difference. Where there is more than one unmeasured location, the split between these locations should be estimated.

(c) The residue percentage leaving each location may be estimated based on the typical results for the type of fuel and method of firing.

The parties to the test shall reach agreement on which streams are to be measured and values for any estimated splits prior to the test.

The fly ash concentration leaving the unit, determined in accordance with subsection 4-10, is used to calculate the residue mass flow rate leaving the unit. See para. 5-3.3.3 for calculating the mass flow rate from the grain loading.

The mass flow rate of residue discharged from hoppers or grates in a dry state may be determined from weigh bins/timed weights, e.g., the number of rotations of rotary feeders, screw speed, impact meters, etc. For considerations regarding calibration and sources of uncertainty, see subsection 4-13. Determining the mass flow rate of residue discharged from sluice systems is even more difficult than determining the dry state. Generally, the total discharge flow must be captured in bins or trucks, freestanding water drained off, and the bin or truck weighed and compared against the tare weight. Since residue is considered to leave the unit in a dry state, moisture content of the sample must be determined, and the measured wet mass flow rate corrected for moisture.

4-8 O_2 ANALYSIS

4-8.1 Electronic Analyzers

There are several different types of electronic gas analyzers for measuring the oxygen content of flue gas, including electrochemical, paramagnetic, and zirconia. Electrochemical analyzers use fuel cells to generate an electric current proportional to the amount of oxygen that reacts with a consumable electrode. Paramagnetic analyzers use the fact that oxygen is attracted by a magnetic field. Zirconia sensors use zirconium dioxide, which behaves as a solid electrolyte, generating a voltage proportional to the difference in the partial pressure of oxygen on the two sides of the cell. For details on the operation, calibration, factors affecting the accuracy of the analyzers, and typical systematic uncertainty values, see Nonmandatory Appendix E.

4-8.2 Chemical (Orsat)

Electronic analyzers are the preferred method for measuring oxygen in the flue gas. Orsats are still used in some circumstances, and are included in this Code for that reason. An Orsat is a test instrument with which the constituents of a combustion gas are manually measured through the use of gas-absorbing chemicals. The combustion gas constituents of typical interest are carbon dioxide, oxygen, and carbon monoxide. A systematic measurement of the change in volume of the gas is used to determine the constituents of a gas by the absorption method. A gas sample is passed through a series of gas-absorbing reagents to first remove the carbon dioxide, then oxygen, and finally carbon monoxide. The indicated decrease in volume of the gas sample is a measure of the constituent removed from the sample after exposure to a particular gas absorption chemical. See Nonmandatory Appendix F for a detailed description of using an Orsat.

4-8.3 Gas Sampling Techniques

The accuracy of any measured average gas analysis across a sampling plane is dependent on both the sampling technique and the instrument accuracy. This section describes typical sampling techniques that may be used, and the advantages and disadvantages of each technique.

4-8.3.1 Types of Samples. The following two types of samples can be collected:

(a) individual samples at each point

(b) a composite sample from the entire grid or from individual probes, each with multiple holes

4-8.3.2 Sampling Techniques. As point-to-point sampling techniques are time-consuming and labor-intensive, in many cases they are considered too cumbersome to complete. Moreover, because individual point sampling is completed over an extended period of several hours, during which time the boiler conditions might be varying noticeably, point-to-point sampling does not readily lend itself to the high-frequency sampling required for statistical analysis.

Nevertheless, point-to-point sampling is required in applications where there is a significant degree of stratification (composition and/or velocity) across the duct, or where it is impractical/impossible to have flow measurement and a means to control (equalize) the flow from each sample line to the mixing device.

As this sampling and analysis procedure takes some time, traverses must be made simultaneously at both the air heater inlet and outlet.

Apart from the use of velocity weighting to account for spatial variations in the local gas composition measured across the duct, additional minor corrections may be considered to account for the time-wise fluctuations in the average excess air level arriving at the air heater inlet during the duration of the traverse. The correction would be to continuously withdraw and analyze a sample of the flue gas at the air heater gas inlet from a separate single representative sampling point or to use the station instrument(s). In this manner, each individual gas sample and analysis can be referred to the corresponding instantaneous measurement from the fixed sampling probe and, if appropriate, corrected with respect to the time-averaged gas analysis measured from the single-point sample.

An advantage of this method is that there isn't any mixing device (bubbler or header), and there isn't a need for regulating the flow from multiple probes.

When sampling point-to-point and using electronic gas analyzers, after the system has been purged of gas from the previous point, sufficient measurements of the flue gas composition (O_2) shall be recorded (as frequently as practical, e.g., every 5 sec or 10 sec for manual readings) for a time period equal to two or more complete revolutions of the heater, to allow an average value to be calculated.

The other type of gas sample that can be collected is a bulk (or composite) sample. A composite sample is obtained by simultaneously collecting gas from all points in the sample plane in a mixing device. There are two types of multiple-inlet, sample-mixing devices used to create a composite sample — bubble jars and headers. A bubble jar is a clear vessel with multiple inlets and one outlet. The inlets' tubes extend down near the bottom of the vessel and the outlet is flush with the top of the jar. The bubble jar is partially filled with water, so that the inlet tubes are submerged. Headers are usually made from stainless steel pipe, 4 in. or 6 in. (10.12 cm or 15.25 cm) diameter by 12 in. to 18 in. (30.36 cm to 45.75 cm) long, with multiple inlets and a single outlet.

Composite sampling can only be used in situations where velocity weighting is deemed unnecessary and will produce errors when there are significant areas of low flow or recirculating flow across the sampling plane.

When considering composite sampling, at least one full point-to-point sampling traverse must be completed across both the gas inlet and outlet ducts, in order to determine if significant stratification exists. If composite sampling is used, the pretest point-to-point traverse data shall be used to obtain the spatial systematic uncertainty for the O_2 readings.

While bulk gaseous analysis using a sampling grid may be quick and convenient, care must be taken to ensure that this produces a sample that is truly representative of the spatial average gas composition, by maintaining equal flow through all inlets. If a bubble jar is used, in each of the sampling lines a small regulating "pinch" clamp, needle valve, rotometer with a valve, or provisions to vary the depth of the inlet tubes must be used. During sampling, these are adjusted to ensure that there is an even stream of bubbles (or indicated flow rate when using rotometers) from each submerged sampling tube in the "bubbler." If a header is used, a flow indication (i.e., rotometer) with a regulating valve on each inlet must be used.

4-8.3.3 Sample-Mixing Device. When using a sample-mixing device to create a composite sample, it can only be operated effectively by attempting to produce an equally balanced sampling rate across all of the sampling lines. This is generally achieved by a combination of the following:

(a) ensuring that each sampling probe and external length of sample tubing is the same diameter and length, and has the same number of bends and/or "T" pieces before the bubbler.

(b) ensuring that the sample mixing devices are large enough, with sufficient inlets to allow one inlet per sampling point.

(c) if using bubblers, ensuring that there is an adequate level of water in the bubbler and all bubbler tubes are submerged by the same amount (unless varying the depth of individual tubes is the method used to equalize the flows). If two bubblers are used in parallel, the depth of water in each bubbler shall be the same. Care shall be taken during the test to correct for possible variations between the water levels that might be caused by differences in the amount of condensed water vapor from the flue gas. The bubblers and inlet tubes shall be arranged to prevent drawback of water through the sampling lines when the sampling pump is switched off and there is suction pressure in the gas ducts.

(d) checking that there is no leakage in the sampling system before the tests. This can be achieved by starting the vacuum pump and blocking all sampling tubes at their corresponding probe connection. After the pressure at the pump suction has stabilized, isolate the suction of the vacuum pump. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check.

(e) as these sampling tubes may be prone to intermittent blockage during the test run, the operation of the bubblers or the headers shall be regularly checked during the test, readjusting the individual flow rates as appropriate. When testing a unit that has a high level of ash in the gas stream, the water in the bubbler(s) will sometimes get dirty, making it difficult to see the bubble streams from each inlet line.

Composite sampling, being a bulk sampling technique, can be sensitive to problems such as a leaking sample line or a high oxygen level at sampling points close to the wall due to local air ingress. Unlike point-to-point methods, the composite method does not provide a means of determining if such a problem is occurring and, consequently, a means of correcting the effect of any such "spurious" (or erroneous) samples.

4-8.3.4 Sampling Techniques. There are two principal gas-sampling techniques; see Table 4-8.3.4-1. These are the following:

(a) portable probe point-to-point traverse, using a sampling probe with a single inlet and manually moving it from point to point.

(b) fixed grid of sampling points uniformly arranged across the sampling plane. Four fixed-grid sampling arrangements are described in this section.

The alternative features, advantages, and disadvantages of each of these five sampling techniques are described in Mandatory Appendix II.

4-8.4 Preparation Methods

Almost all gas analyzers place some requirements on the gas to be analyzed. These may include requirements on dryness, temperature, and cleanliness. A fourth type of preparation that is usually required is some device to force the gas sample through the system.

(a) Sample Dryness. Most calculations require the gas concentration to be on a "dry" basis. This requires that the gas to be sampled is dried completely. The alternative is to ensure that no moisture is lost from the gas sample before it is analyzed and that the moisture concentration of the flue gas be measured or calculated from

the fuel and flue gas analysis. To convert from a wet basis to a dry basis, the following equation is used:

$$\% \text{ Dry}_{\text{VOL}} = \% \text{ Wet}_{\text{VOL}} \ / \ (1 - \% \text{ Moisture}_{\text{VOL}}/100)$$

Three general methods are used to remove moisture from a gas sample. First, the sample can be cooled, condensing most of the water vapor, followed by a desiccant filter to absorb the remaining water vapor. Second, a Peltier cooler can be used to cool the sample to below 0°F, condensing essentially all the moisture. Third, tubing can be used that allows water vapor to flow through it, due to a humidity gradient, but is impermeable to other gases.

(1) Method 1. The first method combines a condensing coil with a desiccant filter. A condensing coil alone submerged in an ice–water mixture cannot remove all the moisture. A desiccant filter alone would have to be extremely large to prevent it from becoming saturated during a test run.

The first step is to cool the sample gas by routing it through a coiled tube submerged in an ice bath, a mixture of ice and water maintained at 32°F (0°C). Typically $\frac{1}{4}$ in. or $\frac{3}{8}$ in. (6.35 mm or 9.52 mm) copper or stainless steel tubing is used. The gas inlet is at the top of the coil so that the flow helps push the condensate down the coil. As the water vapor condenses it can block the gas flow; therefore, either the coil must be periodically drained or, preferably, the coil can have a chamber at the bottom to collect water. By cooling the sample gas to 60°F (15.6°C), the amount of moisture remaining will be about 1.8% by volume. Even if the gas sample were cooled to 32°F (0°C), about 0.6% by volume moisture would remain in the sample gas; therefore, this device must be followed by a desiccant filter.

The next step is to use desiccant to absorb the remaining water vapor. Common desiccants include anhydrous calcium sulfate, calcium chloride, and silica gel. The desiccant is usually placed in a clear acrylic column with tube fittings on each end. To protect the desiccant from impurities, filters are usually placed just downstream of the inlet port. When the desiccant approaches saturation, it must be either discarded or regenerated. One regeneration method is to heat it in an oven to drive off the moisture it has absorbed. Another regeneration method is to have two chambers and use some dry gas off the "in-service" column to regenerate the other column. Some desiccant is "indicating," meaning that as it absorbs moisture it changes color, making it easy to determine when it needs to be changed and regenerated.

(2) Method 2. The second method is to cool the sample to a temperature at which essentially all the moisture will condense. This is done by routing the sample gas through a thermoelectric or Peltier cooler. These are solid-state heat pumps, where a DC current applied across two dissimilar materials causes a temperature differential. With these coolers the gas temperature is typically reduced below 0°F (−17.8°C), which results in a moisture content of about 0.14% by volume.

(3) Method 3. The third method is to pass the sample gas stream through a tube that absorbs water vapor from the internal gas stream and discharges water vapor to the gas on the tube's outside diameter. This flow of water vapor is driven by the humidity differential between the sample gas and the external gas; therefore, these devices must be supplied with a continuous stream of dry gas, usually air. One such type of tube is made from a copolymer of tetrafluoroethylene. With these devices, the gas temperature is typically reduced below 0°F (−17.8°C), which results in a moisture content of about 0.14% by volume.

(b) Sample Temperature. When analyzing gas on a wet basis, care must be exercised to ensure the temperature of the sample, from the probe to the analyzer, remains above the dew point; this prevents any moisture from condensing. If some moisture condenses, the measured gas concentrations will be higher than the true wet basis concentrations. Also the condensate can foul the system, which may plug the sample line and/or analyzer. This usually requires that the sample tubing be heat traced (i.e., running along the tubing is an electrical resistance heater, and both the tubing and the heater are insulated).

When analyzing gas on a dry basis, if the sample hasn't been sufficiently cooled during the moisture removal process, one of the two cooling systems mentioned above (running the sample through an ice bath or a Peltier chiller) must be used.

(c) Sample Cleanliness. Most analyzers require almost complete removal of particles larger than 1 μm. The use of both coarse and fine filters may be required in high-dust loading environments. Typical filter materials are felt, Teflon®, glass fiber, and quartz fiber. Sintered filters are typically installed on probe tips in high-temperature [above 600°F (315°C)] environments.

(d) Sample Pump. Many gas analyzers are equipped with an internal pump; however, these pumps are usually inadequate to overcome the pressure drops through a typical sampling system and, if sampling from a negative pressure duct, the draft. Therefore, an external sample pump is normally required. It should be sized appropriately to supply the flow-rate requirement of the analyzer and the pressure requirement of the entire sampling system (considering both the pressure drops through the probes, tubing, and equipment and the duct pressure, positive or negative). The pump must be designed such that no air in-leakage can occur and no contamination is introduced from pump-lubricating oils. Diaphragm and ejector type pumps that are oil free are recommended for the sampling system. When sampling from ducts where the gas pressure is below atmospheric pressure, one technique to reduce the head that the pump must supply is to run tubing from the discharge

of the gas analyzer back into the gas duct. With this setup, the pump must only supply sufficient head to overcome the system resistance. If this is done, be sure that there is no air in-leakage where the sample is returned to the gas duct, which could affect downstream readings.

4-9 HUMIDITY MEASUREMENT

4-9.1 General

The moisture in the air must be taken into consideration in the heat and material balance calculations.

4-9.2 Systematic Uncertainty for Humidity Measurement

When estimating the systematic uncertainty of a humidity measurement, test personnel should consider the following potential sources. Not all sources are listed, and some of those listed may not be applicable to all measurements.

(a) hygrometer
(b) wet/dry bulb thermometer type
(c) calibration
(d) drift
(e) thermometer nonlinearity
(f) parallax

4-9.3 Method of Measurement

The humidity of the inlet air to the unit shall be established. Since the specific humidity does not change with heat addition unless there is a moisture addition, the specific humidity of the combustion air leaving the air heater is the same as the specific humidity entering. To determine specific humidity, either dry-bulb and wet-bulb, or dry-bulb and relative humidity, are needed. Paragraph 5-3.4.2 addresses humidity ratio (pounds of moisture per pound of dry air) and specific humidity (pounds of moisture per pound of wet air). The moisture may be determined with the aid of a sling type psychrometer, hygrometer with temperature or similar device, and an observed barometric pressure reading.

4-10 FUEL, SORBENT, AND RESIDUE SAMPLING

4-10.1 General

The methods of sampling shall be agreed upon by all parties to the test and must be described in the test report. An appropriate uncertainty must be assigned for the method of sampling used for a test.

A representative sample of the fuel fired during the performance test should be obtained using the methods described in ASTM D2234, D4057, or D5287. Fuel oil and natural gas typically have more consistent composition than coal or other solid fuels, and therefore require fewer samples. If fuel properties may vary because of outside factors, e.g., changing source of fuel, a more rigorous sampling program will be required to ensure representative samples.

Methods used to determine variances, standard deviations, and random uncertainties for the samples obtained during the test are discussed below. The estimation of systematic uncertainties is also addressed.

4-10.2 Method of Solid Fuel and Sorbent Sampling

4-10.2.1 Sample Collection. ASTM D2234 provides guidance on sample collection. The "stopped belt cut" technique is the preferred or reference method. Zero sampling systematic uncertainty should be assigned if the stopped belt technique is used.

In many cases, however, stopped belt sampling is not practical; therefore, full-stream cut sampling should be used. Full-cut sampling consists of taking full-diverted cut of a moving stream. Figure 4-10.2.1-1 shows a typical "full-cut" sampling method.

A third method, "part-stream cut," is the most practical but may produce the greatest systematic uncertainty. A "thief" probe, as shown in Fig. 4-10.2.1-2, may be used for taking a part cut from a flowing stream.

A pretest run is recommended to identify and alleviate potential problems in the sampling techniques.

4-10.2.2 Sample Location. Fuel, sorbent (if applicable), and residue solids shall be sampled from a flowing stream as near to the steam generator as practical to ensure that samples are representative. If it is not possible or practical to sample near the steam generator, a time lag may be incurred between when the sample is taken and when it is actually injected or removed from the steam generator. This time lag must be determined based on estimated flow rates between the sample location and the steam generator. It is important that the time-lagged sample be representative of the actual material injected or removed from the steam generator.

Fuel or sorbent samples collected upstream of silos, tanks, and hoppers typically have larger systematic uncertainty compared to samples collected downstream of silos, tanks, and hoppers. Samplings from upstream of silos, tanks, and hoppers are classified as alternative procedures because of the possibility of samples not being representative of fuel fired during the test. Alternative procedures should not be used for acceptance tests. For other test purposes, if alternative procedures are used, the parties to the test shall assign appropriate systematic uncertainties.

4-10.2.3 Sample Interval. With one exception, the samples shall be collected at uniform, not random, intervals. The exception is when it is known that the collection sequence corresponds with "highs" or "lows" in the fines content. In that instance, random time intervals should be used. Each sample should be of the same weight. The elapsed time to collect all coal samples must equal the duration of the test run.

4-10.2.4 Sample Number. As a minimum, it is recommended to obtain (collect) a sample at the beginning and end of each test including once every hour during the test. Therefore, during a 4-hr test, five collections of samples will be exercised.

The number of individual samples collected will depend on the number of parallel streams. For example, if there are five parallel streams, a total of 20 individual samples will be collected.

The recommended minimum number of sample collections may be exceeded if the parties wish to increase accuracy of the fuel characteristics.

4-10.2.5 Sample Amount. For manual sampling of coal or sorbent, individual samples typically weighing from 2 lbm to 8 lbm (1 kg to 4 kg) are collected. For automatic sampling devices, much larger samples can be collected. Table 2 of ASTM D2234 provides information about sample size.

4-10.2.6 Parallel Streams. Parallel streams, e.g., coal feed with belt feeders, have the potential for variation from stream to stream because of different flow rates, particle sizes, and chemical composition. Therefore, unless the chemical constituents of the samples can be shown to be uniform, the samples must be taken from each of the parallel streams. If the flows for the parallel streams are unequal, the amount of samples of each parallel stream must be flow weighted. The flow for each of the parallel streams must be continuous throughout the test.

4-10.2.7 Sample Handling. Sampling must be carried out only under the supervision of qualified personnel. The procedure used must be developed and carefully implemented to ensure that representative samples are obtained, and to prevent contamination in sampling devices and storage containers. Samples collected outdoors must be protected from external environmental influences during collection. Airtight, noncorrosive storage containers prevent degradation of the sample until it is analyzed. Each sample should be sealed immediately after being taken. Samples should not be mixed in open air prior to analysis for moisture, because of the potential for moisture loss.

Samples must be properly labeled and described in terms of their significance to the test. The label should include, as a minimum, the date, time, location, and type of sample taken.

ASTM D2013 and D3302 should be followed in the preparation of coal samples. Sorbent analysis procedures are addressed by ASTM C25.

4-10.3 Methods of Liquid or Gas Sampling

For liquid fuels, a representative sample of the fuel fired during the performance test should be obtained using the method described in ASTM D4057. The type of sample vessel and procedure is illustrated for various cases and types of liquid fuels in the appropriate ASTM standard.

For gaseous fuels, a representative sample of the fuel fired during the performance test should be obtained using the methods described in ASTM D5287, or GPA 2166 should be consulted for the proper procedures and equipment for sampling gas.

4-10.4 Residue Sampling

Those fuels that contain ash necessitate a sample of the various streams leaving the unit containing the ash. These streams typically include fly ash and bottom ash. Obtaining representative samples from each of these streams is a difficult task. Fly ash may be collected in several hoppers as the flue gas makes its way to the stack. The heaviest particles fall out first, with the smaller particles being removed by mechanical forces resulting from the turning of the gas stream. Unfortunately, the carbon is not uniformly distributed throughout the particle size range. The relative distribution of the ash into the various hoppers is also not accurately known. The best method for obtaining a representative fly ash sample is to isokinetically sample the ash in the flue gas upstream of as many ash collection hoppers as possible. This usually means at the economizer outlet. This obtains a sample that has a representative cross section of particle size and carbon content. It also ensures that the sample is representative of the testing period.

The bottom ash also presents challenges, in the form of large chunks and poor distribution. A number of samples and several analyses of each sample may be required to obtain representative results. A single sample may contain a chunk of coal not typically found in other samples or may have no carbon content.

4-10.4.1 General. Fly ash may be sampled isokinetically as particulate by drawing a flue gas sample through a filter and weighing the amount of particulate gathered on the filter. The weight of the sample and the flue gas volume recorded during this process determine the particulate concentration in the flue gas stream. To avoid altering the concentration of the gas stream, the velocity of the stream entering the sample nozzle must equal the velocity of gas at that point in the duct. This process is known as isokinetic sampling. Multiple points are sampled in the testing plane to compensate for nonuniform velocity distributions and stratification of the particulate concentration.

4-10.4.2 Methods of Sampling Fly Ash. All apparatus and test procedures shall be in accordance with either ASME PTC 38 or U.S. EPA Reference Method 17 as described below.

(a) *ASME PTC 38.* The particulate sampling train generally consists of a nozzle, probe, filter, condenser, dry gas meter, orifice meter, and vacuum pump or aspirator. ASME PTC 38 illustrates different configurations of sampling trains and should be consulted for the type of train to be used on specific installations.

(b) U.S. EPA Method 17. The U.S. Environmental Protection Agency has established two methods for particulate sampling. Methods 5 and 17 are similar, except that Method 17 uses an in-flow filter, whereas Method 5 uses an external filter. Method 17 is preferred since all of the particulate catch remains in the filter holder. Method 5 requires an acetone wash of the probe assembly, which may not be suitable for analysis for carbon. Detailed procedures for these methods are contained in 40CFR60 Appendix A.

Isokinetic sampling of the flue gas is both the reference and the preferred method for sampling fly ash. The number of grid points on the traverse sampling plane must be in accordance with ASME PTC 38. The systematic uncertainty associated with this method is assumed to be zero. There is still an associated systematic uncertainty for the ash collected in the bottom ash, as well as any hoppers located upstream of the fly ash collection point. If multiple samples are analyzed using multiple analysis for the bottom ash, an estimate of the associated systematic uncertainty can be made from this information. The procedure should also be reviewed to determine if other sources of systematic uncertainty may also be present.

4-10.4.3 Methods of Sampling Bottom Ash. For a bottom ash sluice stream, the preferred method of sample collection is to take the sample with a multi-holed probe extending the width of the sluice stream. Pages 2-3, 2-4, and 2-5 of EPRI Report EA-3610 illustrate a multi-hole probe. Alternatively, a portion of the sluice stream may be diverted to a collection device where the ash is allowed to settle and a sample then taken.

4-10.4.4 Other Residue Streams. In some cases, the parties to the test may decide not to sample from a residue stream that does not contribute significantly to the energy loss. Possible examples of such streams are air heater disposal drains or vent lines, where the flow rate is negligible, or bottom ash drains, which may have insignificant sensible heat and unburned combustible losses. Alternatively, samples of bottom ash sluiced to a settling pond can yield a result that is no more certain than using an assumed value. If a solid stream is not sampled, the appropriate systematic uncertainty shall be assigned and the historical evidence documented in the final report.

4-10.5 Systematic Uncertainty

When the systematic uncertainty of a sampling procedure is estimated, the test engineer should consider the potential sources listed below. There may be other sources, and not all sources listed are applicable to all measurements.

(a) sampling location/geometry
(b) probe design
(c) stratification of flowing stream
(d) number and location of sample points
(e) ambient conditions at sample location
(f) fuel (solid, liquid, or gas)/sorbent variability
(g) solid fuel/sorbent size
(h) sample handling/storage
(i) duration of test
(j) quantity of sample obtained

An estimate of the systematic uncertainty from a sample is a combination of systematic uncertainties from sample acquisition, location, and stream consistency.

Sampling methods other than those recommended must be assigned higher systematic uncertainties.

Before conducting a performance test, it is mandatory that parties to the test make a pretest inspection of the sampling locations, identify the sampling methodology, and make the sampling probes available. Careful attention should be paid to areas where samples might not be representative. Sampling of coal and other solid materials from a moving stream can result in more of one size range of particles during collection. If systematic errors are present in the sampling system, the errors must be corrected or the parties must assign conservative (higher) systematic uncertainties.

4-10.6 Methods to Determine Average and Standard Deviation of the Mean

Three methods to determine the average and standard deviation of the mean for the fuel characteristics (i.e., moisture, ash, carbon, etc.) are available — individual, partial-composite, and full-composite.

4-10.6.1 Individual Method. An analysis sample is prepared from each individual sample, referred to as "increments" in the terminology of ASTM D2234. Each analysis sample is individually analyzed for the applicable constituents, heating value, carbon content, moisture, etc. The average value and standard deviation of the mean for each constituent are calculated using eqs. (5-2-1) and (5-2-3). This procedure must be used when there are no historical data available to estimate the random uncertainty of the samples.

4-10.6.2 Partial-Composite Method. Individual samples are collected as described in para. 4-10.6.1. The samples are collected in "sets," from which one set is individually analyzed for the variable constituents, e.g., ash and moisture (and sulfur if SO_2 reduction is to be considered). The average value and standard deviation of the mean for each variable constituent are calculated using eqs. (5-2-1) and (5-2-3).

The second set is thoroughly mixed (if they are from parallel streams) and analyzed for the composite constituents. The average value of each variable constituent is the measured value of the gross analysis sample. The standard deviation of the mean for the composite constituents is taken from valid historical data.

This is an alternative to analyzing individual samples, and is predicated on the availability of valid historical data. The objective is to reduce laboratory costs. The constituents are grouped into "composite" (e.g., carbon, hydrogen, and nitrogen) and "variable" (e.g., water, ash, and possibly sulfur) constituents.

The underlying premise for this alternative is that "composite" constituents for both the historical and test data are from the same statistical population. As the constituents are from the same population, a standard deviation of the mean derived from historical data may be used for the test uncertainty analysis. Paragraph 7-4.1.4 provides additional background for this alternative.

To simplify this discussion, coal constituents and terminology are used; sorbent constituents and terminology can be substituted as appropriate.

As coal is typically stored outdoors, the moisture content of as-fired coal may have greater variability than as-received coal. This increased variability may invalidate the premise that the historical as-received data and the test data are from the same statistical population. However, changes in moisture content do not affect constituents on a dry-and-ash-free basis. Where sulfur retention is an important consideration in the test, sulfur content should be included in the variable constituents. The variability of sulfur content is often relatively large.

This alternative is not suitable for residue samples. The composition of residue is affected by operating conditions within the steam generator. There is no simple way to ensure that historical and test data for residue would be from the same statistical population.

Historical data should satisfy the following criteria to be valid for estimating random uncertainty:

(a) the historical and test coal (sorbent) are from the same mine/quarry and seam

(b) historical data are the analyses of individual (not mixed) sample increments for the coal (sorbent)

(c) the historical and test samples are collected and prepared in accordance with ASTM D2234 and ASTM D2013

(d) the types of increments of the historical data and the test data are ASTM D2234 Type 1, Condition A (Stopped-Belt Cut) or Condition B (Full-Stream Cut), with systematic spacing

(e) the size of the historical samples is the same as the size of the samples collected during the test

If the historical samples were taken at a different location, an additional systematic uncertainty would likely have been introduced.

The historical analyses are converted to the dry-and ash-free (daf) basis by multiplying the as-received percentages (other than the variable constituents, ash and moisture) by

$$\frac{100}{100 - MpH2OF_i - MpAsF_i} \qquad (4\text{-}10\text{-}1)$$

where

$MpAsF_{\mathrm{i}}$ = ash content, %, of historical sample increment i

$MpH2OF_{\mathrm{i}}$ = moisture content, %, of historical sample increment i

For carbon content, the conversion equation is

$$MpCFdaf_i = MpCF_i\left(\frac{100}{100 - MpH2OF_i - MpAsF_i}\right) \qquad (4\text{-}10\text{-}2)$$

where

$MpAsF_{\mathrm{i}}$ = ash content of the fuel, %, as-fired basis (average of test analysis)

$MpCF_{\mathrm{i}}$ = carbon content of the fuel, %, as-fired basis

$MpCFdaf_{\mathrm{i}}$ = carbon content of the fuel, %, dry-and-ash-free basis

$MpH2OF_{\mathrm{i}}$ = moisture content of the fuel, %, as-fired basis (average of test analysis)

The conversion equations for heating value, hydrogen, nitrogen, sulfur, and oxygen are similar. ASTM D3180 addresses the conversion of analysis from one basis to another and should be used.

Using the dry-and-ash-free values of the individual historical samples, estimate the maximum probable standard deviation, s_{oj}, of each composite constituent. Use Appendix A2, Method of Estimating the Overall Variance for Increments, of ASTM D2234 to determine s_{oj}. The use of this appendix requires for each composite constituent 20 or more analyses of individual increments. If fewer than 20 are available, calculate the standard deviation, $STDDEV_j$, of each composite constituent using eq. (5-2-4).

The standard deviation of the mean for each composite constituent is the following for 20 or more analyses:

$$STDDEVMN_j = \frac{s_{oj}}{\sqrt{N}} \qquad (4\text{-}10\text{-}3)$$

For less than 20 use

$$STDDEVMN_j = \left(\frac{F_{n-1,\infty} \times STDDEV_j^2}{N}\right)^{1/2} \qquad (4\text{-}10\text{-}4)$$

where

$F_{n-1,\infty}$ = the upper 5% point of the F distribution for $n - 1$ and ∞ degrees of freedom. Table 4-10.6.2-1 provides selected values of the distribution.

n = number of sample increments in the historical data

= number of sample increments taken during the test

s_{oj} = maximum probable standard deviation of each composite constituent on dry-and-ash-free basis

The degrees of freedom of this standard deviation of the mean are infinite.

4-10.6.3 Full-Composite Method. This is also an alternative to analyzing individual samples. For full-composite samples, none of the constituents are classified as variable. This alternative may be applicable for sorbents and coal when historical data are available and changes in moisture or ash content are either very small or of minor concern.

A composite analysis sample is prepared from the (gross) samples taken during the test and analyzed for all constituents. The average value of each constituent is the measured value of the mixed analysis sample.

The criteria and calculations given above for partial-composite samples are applicable to full-composite samples except that the conversion factors of eqs. (4-10-1) and (4-10-2) are excluded.

4-11 FUEL, SORBENT, AND RESIDUE ANALYSIS

4-11.1 General

It is the intent of this Code that the samples be analyzed in accordance with the latest methods and procedures. The parties to the test should choose a laboratory by agreement.

4-11.2 Systematic Uncertainty for Fuel, Sorbent, and Residue Analysis

ASTM provides guidelines for typical lab-to-lab reproducibility. These values are listed in Tables 4-13-2, 4-13-3, 4-13-4, and 4-13-5 for use in estimating the systematic uncertainty of a sample analysis. In general, the systematic uncertainty is taken as one-half the reproducibility.

4-11.3 Methods of Fuel, Sorbent, and Residue Analysis

4-11.3.1 Solid Fuels. For solid fuel fired steam generators, the minimum fuel information required to determine efficiency is the ultimate analysis, proximate analysis, and the higher heating value. Tables 4-13-2, 4-13-3, and 4-13-4 identify the ASTM procedures to be used for analysis. ASTM D3180 defines the procedures for converting the analysis from one basis to another. The latest versions of these procedures shall be utilized. If ASTM adds a new or revised procedure that is agreeable to both parties to the test, that procedure may be used.

The determination of other solid fuel qualities, e.g., fusion temperature, free swelling index, grindability, ash chemistry, and fuel sizing, is important to judge the equivalence of the test fuel and the specified fuel, and may be required for other test objectives.

4-11.3.2 Sorbent and Other Additives. The minimum information needed to determine the sulfur capture and efficiency is the sorbent ultimate analysis (calcium, magnesium, moisture, and inert). The determination of other solid sorbent qualities, e.g., sorbent sizing, may be required, depending on the objectives of the particular test.

4-11.3.3 Liquid Fuel. For liquid fuel fired steam generators, the minimum fuel information needed to determine efficiency is the ultimate analysis and higher heating value of the fuel. The determination of other liquid fuel qualities, e.g., API gravity and density, may be required depending on the objectives of the test. The procedures for these determinations are found in ASTM D1298.

4-11.3.4 Gaseous Fuel. For gaseous fuel fired steam generators, the minimum fuel information needed to determine efficiency is the constituent volumetric analysis of the fuel. ASTM D1945 is used for this determination. This analysis is converted to an elemental mass analysis as detailed in para. 5-3.1.2. Higher heating value may be determined by a continuous online calorimeter as defined in ASTM D1826. The parties to the test shall agree on which method will be used.

4-11.3.5 Residue. Particulate residue samples shall be analyzed for total, combustible, and carbonate carbon content according to ASTM D6316. This test method comprises the use of any of several methods for determination of total carbon content. If the instrument method, ASTM D5373, is used to determine total carbon content, the instrument shall be capable of analyzing prepared residue samples of not less than 100 mg. Use of a loss on ignition (LOI) analysis is not permitted for the determination of unburned combustible loss, because several reactions may occur in the combustion process that reduce or increase the weight of the sample and that have no heating value.

The test for total carbon in the residue includes the determination of hydrogen, and the hydrogen result may be reported in addition to the carbon. This portion of the test is not mandatory for testing carbon in residue, and experience indicates that H_2 in fuel volatilizes readily and no significant quantity of H_2 exists in residue in the normal combustion process. This test may result in a hydrogen content measured on the order of 0.1% or less. Hydrogen quantities of this order of magnitude should be considered as zero in the combustion and efficiency calculations. A potential source for error in the determination of free hydrogen is that, as with carbon, this test method yields the total percentage of hydrogen in the residue as analyzed, and the results present the hydrogen present in the free moisture accompanying the sample as well as the hydrogen present as water of hydration of silicates or calcium oxide, $Ca(OH)_2$.

4-12 GENERAL MEASUREMENT REQUIREMENTS

This Code addresses the methodology to determine performance characteristics.

See Nonmandatory Appendix J, Tables J-1.2.4-3 through J-1.2.4-6, listing the parameters required to determine each of these performance characteristics for typical units as defined by the air heater system boundaries in Figs. 2-3.4-1 through 2-3.4-6.

4-13 DETERMINATION OF SYSTEMATIC UNCERTAINTY DUE TO MEASUREMENTS

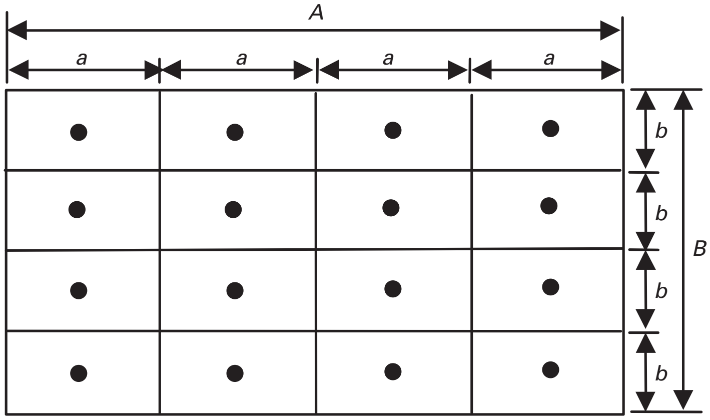
Estimating the systematic uncertainty is a key step in designing the test and selecting instrumentation. The total systematic uncertainty associated with a particular measurement is the result of several systematic uncertainties in the measurement system. The assignment of an appropriate systematic uncertainty value requires full knowledge of all components comprising the measurement system, the process being tested, and all other factors that may affect the systematic uncertainty of the measurement. The test engineer is in the best position to evaluate these factors, and can use Tables 4-13-1 through 4-13-5 as a tool to assist in assigning values for measurement systematic uncertainties. (Other sources that may be referenced for typical values of systematic uncertainty include ASME PTC 19.1, PTC 19.2, PTC 19.3, PTC 19.5, PTC 19.10, and MFC-3M/MFC-3Ma; appropriate ASTM standards; and instrument manufacturer specifications.) These tabulated systematic uncertainties, however, may not be representative of any specific measurement situation. It would be misleading for this Code to mandate specific values for systematic uncertainty; therefore, systematic uncertainty values must be agreed upon by parties to the test.

All factors that influence the measurement should be considered. Most factors will be two-sided, resulting in both positive and negative systematic uncertainties, which may or may not have the same magnitude. An example of equal-magnitude systematic uncertainties could be the systematic uncertainty associated with the primary standard of the temperature calibration equipment being ±0.25°F. An example of unequal-magnitude systematic uncertainties would be correcting readings using calibration data when the measured value is not equal distance between calibration points, which results in positive and negative systematic uncertainties of different magnitudes. Some factors, e.g., an air leak into a flue gas analyzer, should be considered and included as a one-sided systematic uncertainty, since a leak can only dilute the sample. (Obviously, all leaks should be found and repaired prior to the beginning of the test, although it is recognized that a small leak could occur during the test, or a very small leak may not be found prior to testing). All of the positive systematic uncertainties (and negative systematic uncertainties) must then be combined into a single positive systematic uncertainty value (and single negative systematic uncertainty value) for the parameter. Subsection 7-5 describes the process of combining the systematic uncertainties.

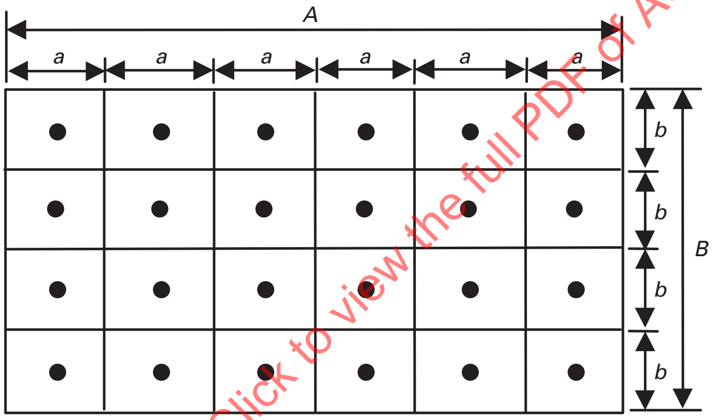
Many instruments include an accuracy specification. This accuracy is only a part of the potential systematic uncertainty of that instrument. Other factors, e.g., drift, vibration, and influence of other gases on oxygen analyzers, can influence the measurement. Often the reference accuracy of an instrument can be improved through calibration. After a calibration, the accuracy of the reference standard, the repeatability of the instrument, and potential systematic uncertainty due to measured values not coinciding with calibration points can be combined to estimate the positive and negative systematic uncertainties of the instrument.

For each parameter that is estimated rather than measured, the value for the parameter, the value of its positive systematic uncertainty, and the value of its negative systematic uncertainty shall be agreed upon by the parties to the test. The test engineer can usually arrive at reasonable values by considering that the probability is approximately 19:1 (95% confidence level) that the upper and lower limits will not be exceeded, and by noting that most processes are governed by well-known physical principles (e.g., radiant heat transfer occurs from a hotter object to a colder object; air can only leak into a sample train held under vacuum).

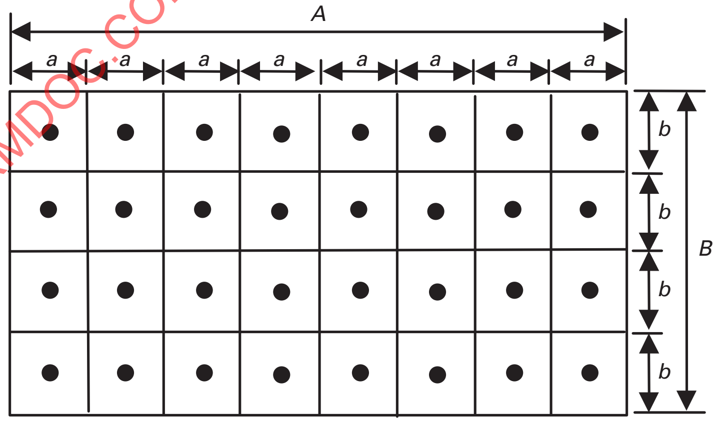
Fig. 4-3.1.1-1 Sampling Grid — Rectangular Duct



(a) Same Geometric Shape as Cross Section $\left(\frac{A}{B} = \frac{a}{b}\right)$

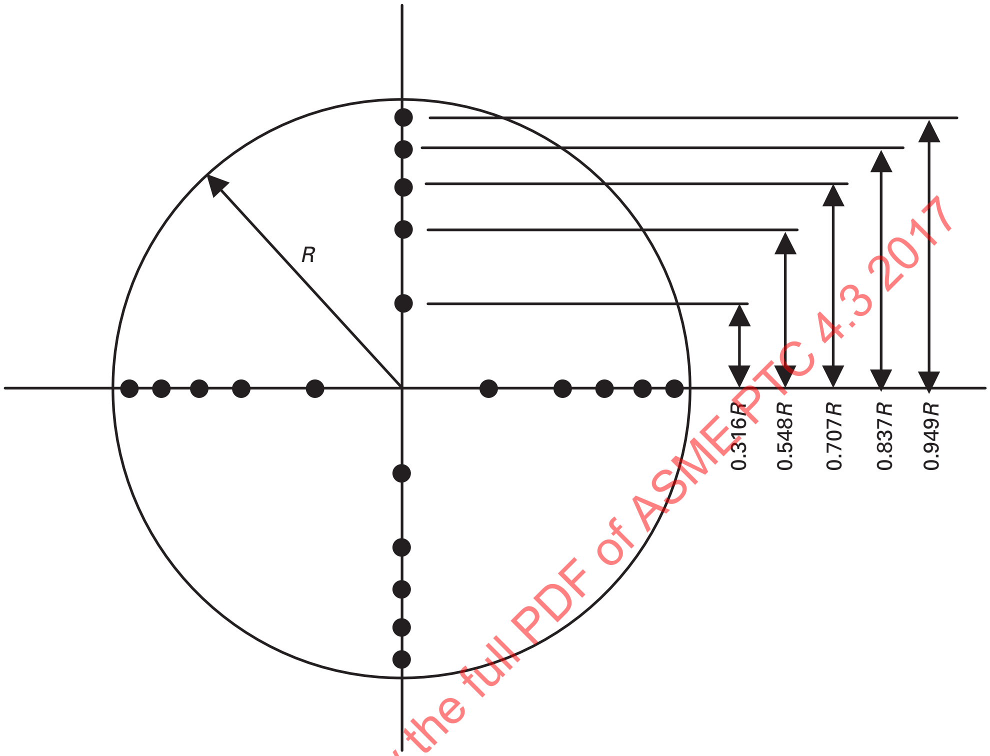


(b) More Nearly Square Than Illustration (a) $\left(\frac{A}{B} > \frac{a}{b} \text{ and } a > b\right)$



(c) Square ($a = b$)

Fig. 4-3.1.2-1 Sampling Grid — Circular Duct



Formula for determining location of sampling points in circular duct:

$$r_p = R\sqrt{\frac{p-0.5}{n}}$$

where

n = total number of points on a radius

p = sampling point number, where $p = 1$ to n. To be numbered from center of duct outward. All points on the same radius have the same number.

R = radius of duct

r_p = distance from center of duct to point p

GENERAL NOTES:

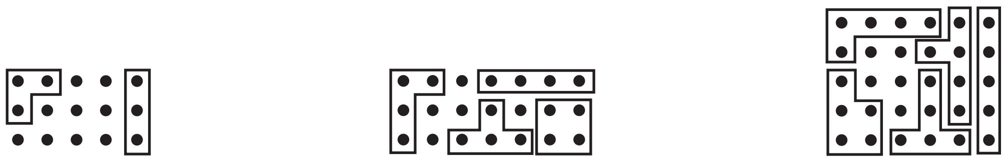
(a) Indicates points of location of sampling tube.

(b) r_p will be in the same units as R.

(c) Example: For $n = 5$, the distance to point 3 is

$$r_3 = R\sqrt{\frac{3-0.5}{5}} = R\sqrt{\frac{2.5}{5}} = R\sqrt{0.5} = 0.707R$$

Fig. 4-5.5-1 Examples of Nonrandom Failure Patterns

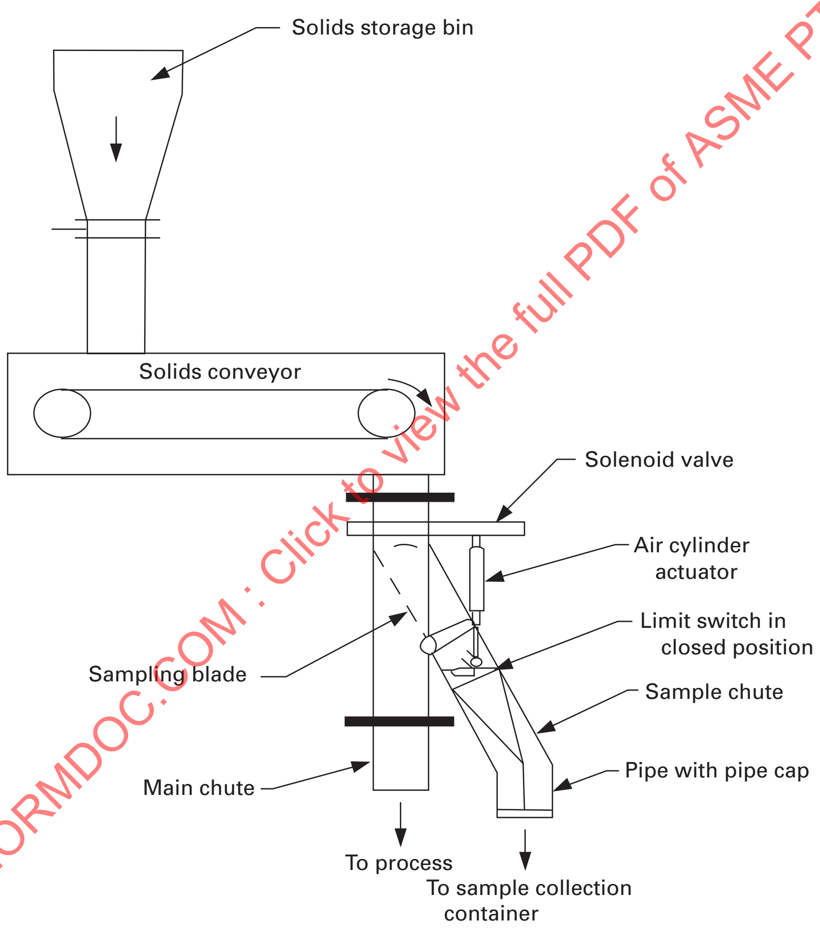


(a) Examples of Three Points in Nonrandom Patterns

(b) Examples of Four Points in Nonrandom Patterns

(c) Examples of Five Points in Nonrandom Patterns

Fig. 4-10.2.1-1 Full Stream Cut Solid Sampling Process



GENERAL NOTE: There are five steps for obtaining a sample.

Step 1. Close isolation gate on dust suppression system. This will eliminate fines removal.

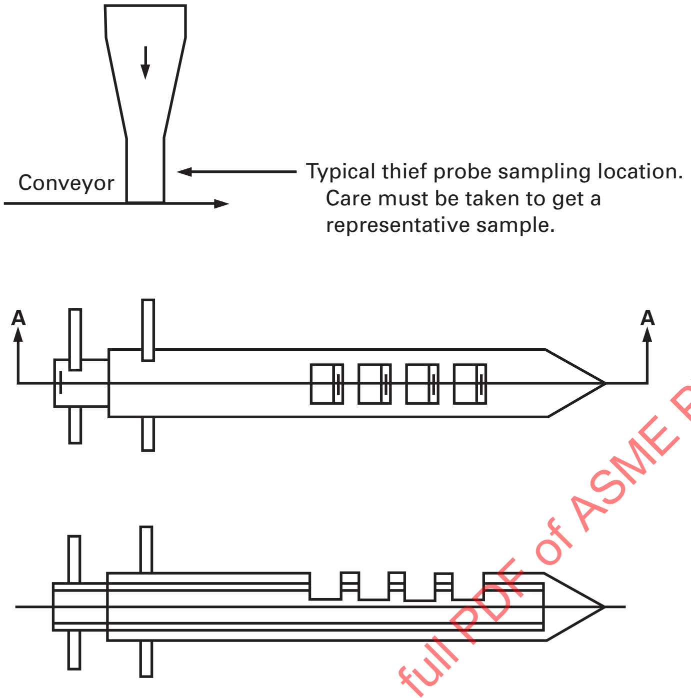
Step 2. Initiate sample diverter gate to sample position. This is done pneumatically.

Step 3. Adjust timer to obtain a proper sample size.

Step 4. Throw away the first sample.

Step 5. Collect 5-gal bucket and seal container. Prepare for riffling, crush, and size.

Fig. 4-10.2.1-2 Typical "Thief" Probe for Solids Sampling in a Solids Stream



Section A—A

GENERAL NOTE: Design consists of two concentric pipes with the same sample hole configuration. The probe is inserted into a flowing solids stream with the sample ports closed. (The inner tube rotates 180 deg relative to the outer tube from the sample position.) The inner tube is rotated to align the sample holes and is rotated back with the inner tube now full of material.

Table 4-5.5-1 Maximum Number of Sensor Failures

Number of Sensors in the Duct	Maximum Allowable Number of Failures
6–10	Any 1 point
11–15	Any 2 points
16–20	Any 3 random points
21–25	Any 4 random points
26–30	Any 5 random points
31–35	Any 6 random points
36 or more	Any 7 random points

Table 4-6.6.23-1 Air and Flue Gas Viscosity Curve-Fit Coefficients, lbm/ft-sec

Quantity	A	B	C	Temperature Range, °F	Uncertainty, %
Air, standard ($Wv = 0.013$)	1.08970E−05	1.76984E−08	−4.13800E−12	0 to 1,000	±0.5% for $Wv = 0.009–0.017$; otherwise ±1.0%
Air, dry	1.09831E−05	1.76963E−08	−4.11939E−12	0 to 1,000	±0.5%
Water vapor	5.50104E−06	1.43983E−08	−1.46824E−12	0 to 1,500	±0.1%
Flue gas, standard	1.02518E−05	1.63012E−08	−2.63308E−12	100 to 1,500	±2.5%
Flue gas, dry	1.07284E−05	1.64854E−08	−2.74740E−12	100 to 1,500	±1.5%

Table 4-8.3.4-1 Gas Sampling Techniques

		Type of Sample Collected		
Sampling Technique	Preference	Individual	Composite	Individual and Composite
Portable probes point-to-point	4	×	. . .	. . .
Fixed grid [Note (1)]				
Composite [Note (2)]	5	. . .	×	. . .
Point-to-point (single pump)	3	×	. . .	. . .
Point-to-point (dual pump)	2	×	. . .	. . .
Combination	1	. . .	. . .	×

NOTES:

(1) These options do not allow simultaneous velocity traverses.

(2) This option can only be used if flow weighting is not necessary.

Table 4-10.6.2-1 *F* Distribution

$n - 1$	F_{n-1}
1	3.8415
2	2.9957
3	2.6049
4	2.3719
5	2.2141
6	2.0896
7	2.0096
8	1.9384
9	1.8799
10	1.8307
12	1.7522
15	1.6664
20	1.5705
40	1.3940
120	1.2214
Infinity	1.0000

Table 4-13-1 Potential Instrumentation Systematic Uncertainty

Instrument	Systematic Uncertainty [Note (1)]
Data Acquisition	See Note (2)
Digital data logger	Per manufacturer’s specification
Plant control computer	±0.1%
Handheld temperature indicator	±0.25%
Handheld potentiometer (including reference junction)	±0.25%
Temperature	See Note (3)
Thermocouple	
NIST traceable calibration	See Note (4)
Premium grade, type E	
32°F to 600°F	±2°F
600°F to 1,600°F	±0.4%
Premium grade, type K	
32°F to 530°F	±2°F
530°F to 2,300°F	±0.4%
Standard grade, type E	
32°F to 600°F	±3°F
600°F to 1,600°F	±0.5%
Standard grade, type K	
32°F to 530°F	±4°F
530°F to 2,300°F	±0.8%
Resistance temperature device (RTD)	
NIST traceable calibration standard	See Note (4)
32°F	±0.03%
200°F	±0.08%
400°F	±0.13%
570°F	±0.18%
750°F	±0.23%
930°F	±0.28%
1,100°F	±0.33%
1,300°F	±0.38%
Temperature gauge	±2% of span
Mercury-in-glass thermometer	±0.5 graduation
Pressure	See Note (5)
Gauge	
Test	±0.25% of span
Standard	±1% of span
Manometer	±0.5 graduation
Transducer and transmitter	
High accuracy	±0.1% of span
Standard	±0.25% of span
Aneroid barometer	±0.05 in. Hg
Weather station	See Note (6)
Velocity	
Standard pitot tube	
Calibrated	±5% [see Notes (7) and (8)]
Uncalibrated	±8% [see Notes (7) and (8)]
S-type pitot tube	
Calibrated	±5% [see Notes (7) and (8)]
Uncalibrated	±8% [see Notes (7) and (8)]
Fechheimer three- or five-hole probe	
Calibrated	±2% [see Note (7)]
Uncalibrated	±4% [see Note (7)]
Hot wire anemometer	±10%
Turbometer	±2%

Table 4-13-1 Potential Instrumentation Systematic Uncertainty (Cont'd)

Instrument	Systematic Uncertainty [Note (1)]
Flow (Air and Gas)	
Multipoint pitot tube (within range)	
Calibrated and inspected (directional velocity probe)	±5%
Calibrated with S-type or standard	±10%
Uncalibrated and inspected	±8%
Uncalibrated and uninspected	±20%
Airfoil	
Calibrated	±5%
Uncalibrated	±20%
Flows (Steam and Water)	See Note (9)
Flow nozzle	
PTC 6 (with flow straighteners)	
Calibrated and inspected	±0.25%
Uncalibrated and inspected	±2.5%
Uncalibrated and uninspected	±5%
Pipe taps	
Calibrated and inspected	±0.50% steam ± 0.40% water
Uncalibrated and inspected	±2.2% steam ± 2.1% water
Uncalibrated and uninspected	New plant — see above Existing plant — variable
Venturi	
Throat taps	
Calibrated and inspected	±0.50% steam ± 0.40% water
Uncalibrated and inspected	±1.2% steam ± 1.1% water
Uncalibrated and uninspected	New plant — see above Existing plant — variable
Orifice	
Calibrated and inspected	±0.50% steam ± 0.40% water
Uncalibrated and inspected	±0.75% steam ± 0.70% water
Uncalibrated and uninspected	New plant — see above Existing plant — variable
Weir	±5%
Blowdown valve	±15%
Coriolis flowmeter (for liquid)	±0.1%
Liquid Fuel Flow (Calibrated)	
Flowmeter	
Positive displacement meter	±0.5%
Turbine meter	±0.5%
Orifice (uncalibrated)	±1.0%
Coriolis flowmeter	±0.1%
Weigh tank	±1%
Volume tank	±4%
Gaseous Fuel Flow	
Orifice	
Calibrated and inspected	±0.5%
Calibrated and uninspected	±2%
Uncalibrated and inspected	±0.75%
Turbometers	
Non-self-correcting	±1.0%
Self-correcting	±0.75%
Coriolis flowmeter	±0.35%

Table 4-13-1 Potential Instrumentation Systematic Uncertainty (Cont'd)

Instrument	Systematic Uncertainty [Note (1)]
Solid Fuel and Sorbent Flow	
Gravimetric feeders	
Calibrated with weigh tank	±2%
Calibrated with standard weights	±5%
Uncalibrated	±10%
Volumetric feeders	
Belt	
Calibrated with weigh tank	±5%
Uncalibrated	±15%
Screw, rotary valve, etc.	
Calibrated with weigh tank	±5%
Uncalibrated	±15%
Weigh bins	
Weigh scale	±5%
Strain gauges	±8%
Level	±10%
Impact meters	±10%
Residue Flow	
Isokinetic dust sampling	±10%
Weigh bins	
Weigh scale	±5%
Strain gauges	±8%
Level	±20%
Screw feeders, rotary valves, etc.	
Calibrated with weigh tank	±5%
Uncalibrated	±15%
Assumed split (bottom ash/fly ash)	10% of total ash
Solid Fuel and Sorbent Sampling	See Tables 4-13-2 and 4-13-3
Stopped belt	±0%
Full cut	≥1%
"Thief" probe	≥2%
Time-lagged	≥5%
Liquid and Gaseous Fuel Sampling	See Tables 4-13-4 and 4-13-5
Flue Gas Sampling	
Point-by-point traverse	See Section 7
Composite grid	See Section 7
Residue Sampling	
Isokinetic dust sampling	±5%
"Thief" probe	±200%
Bottom ash	±50% [see Note (10)]
Bed drain	±20%
Fuel Handling and Storage	
Limestone handling and storage	−10% / +5% of moisture value
Residue	0
Flue Gas Analysis	
Oxygen analyzer	
Continuous electronic analyzer	±1.0% of span
Orsat analyzer	±0.5 graduation
Portable chemical cell analyzer	±5% of reading ±2% of span
Calibrated on air	. . .
Calibrated on cal gas	. . .

Table 4-13-1 Potential Instrumentation Systematic Uncertainty (Cont'd)

Instrument	Systematic Uncertainty [Note (1)]
Electric Power	
Voltage or current	
Current transformer	±10%
Potential transformer	±10%
Handheld digital ammeter	±5%
Watts	
Wattmeter	±2%
Humidity	
Hygrometer	±2% RH
Sling psychrometer	±0.5 graduation
Weather station	See Note (6)

NOTES:

(1) All systematic uncertainties are percent of reading unless noted otherwise.

(2) For thermocouples, error may be introduced depending on the method of correcting for a reference junction. Also, the algorithm for conversion of thermocouple millivolts to temperature may introduce errors.

(3) See ASME PTC 19.3 for applicability.

(4) NIST traceable instruments have a systematic uncertainty equal to the accuracy of the calibration device. These systematic uncertainties do not include drift.

(5) See ASME PTC 19.2 for applicability.

(6) Must be corrected for elevation and distance from weather station.

(7) These systematic uncertainties include user-induced errors, e.g., probe location.

(8) These systematic uncertainty estimates are only applicable when it has been demonstrated that yaw and pitch angles do not exceed 5 deg.

(9) For the methodology to determine more accurate systematic uncertainty for steam and water flow, see ASME MFC-3M/MFC-3Ma and ASME PTC 19.5, where tables and equations of uncertainty in discharge coefficients and expansion factors are provided based on Reynolds number, beta ratio, pressure, and differential pressure.

(10) Bottom ash carbon content should be very low.

Table 4-13-2 Potential Systematic Uncertainty for Coal and Residue Properties

Coal Property	Analysis Procedure	Systematic Uncertainty	Comments
Sampling	ASTM D2234	±10% of ash content ±2% of other constituents	<5% ash ± 0.5%
Sample preparation	ASTM D2013	None	...
Air dry moisture	ASTM D3302	±0.31% bituminous ±0.33% subbituminous	...
Ash content	ASTM D3174	±0.15% bituminous with no carbonate ±0.25% subbituminous with carbonate ±0.5% for 12% ash with carbonate and pyrite	...
Proximate	ASTM D5142	Moisture = $0.12 + 0.017x$ Ash = $0.07 + 0.0115x$ VM = $0.31 + 0.0235x$	Automated method
Total moisture	ASTM D3173	±0.15% for fuels <5% moisture ±0.25% for fuels >5% moisture	...
Carbon	ASTM D5373	±1.25% (1 − %H_2O/100)	>100 mg sample
	ASTM D3178	±0.3% [Note (1)]	...
Hydrogen	ASTM D5373	±0.15% (1 − %H_2O/100)	>100 mg sample
	ASTM D3178	±0.07% [Note (1)]	...
Nitrogen	ASTM D5373	±0.09% (1 − %H_2O/100)	>100 mg sample method B
	ASTM D3179	$\pm 0.205x - 0.13$	...
Sulfur	ASTM D4239	±0.05% bituminous ±0.07% subbituminous	...
	ASTM D3177	±0.5% for fuels <2% sulfur ±0.1% for fuels >2% sulfur	...
Higher heating value	ASTM D2015	±54 Btu/lb dry basis — anthracite/bituminous ±70 Btu/lb dry basis — subbituminous/lignite	...
Converting analysis to different basis	ASTM D3180	None	...

GENERAL NOTE: All systematic uncertainties are absolute unless otherwise indicated.

NOTE:
(1) Estimated based on repeatability.

Table 4-13-3 Potential Systematic Uncertainty for Limestone Properties

Limestone Property	Analysis Procedure	Systematic Uncertainty	Comments
Limestone constituents	ASTM C25	Calcium oxide ±0.16%	Test method 31
		Magnesium oxide ±0.11%	Test method 31
		Free moisture ±10% of value	...
		Inert by difference ±5.0% of value	...
Sampling	See para. 4-7.5.1	±2.0% thief sample	...
		±5.0% other	...

GENERAL NOTES:
(a) All systematic uncertainties are absolute unless otherwise indicated.
(b) Free moisture, inerts, and sampling systematic uncertainty are suggested values.

Table 4-13-4 Potential Systematic Uncertainty for Fuel Oil Properties

Fuel Oil	Analysis Procedure	Systematic Uncertainty	Comments
Sampling	ASTM D4057	±0.5% for multiple samples ±1% for single sample ±2% for supplier analysis	. . .
API gravity	ASTM D1298	±0.25 API for opaque (heavy oil) ±0.15 API for transparent (distillate) ±5 API if estimated	. . .
Water content	ASTM D95	±0.1% for fuels <1% water ±5% of measured value for >1% water	. . .
Ash	ASTM D482	±0.003% for fuels < 0.08% ash ±0.012% for fuels 0.08% to 0.18% ash	. . .
Sulfur	ASTM D1552	S,% IR Iodate <0.5 0.07% 0.04% 0.5–1 0.11% 0.06% 1–2 0.14% 0.09% 2–3 0.19% 0.13% 3–4 0.22% 0.20% 4–5 0.25% 0.27%	. . .
Carbon	ASTM D5291	±(x + 48.48) 0.009	. . .
	ASTM D3178 [Note (1)]	±0.3% [Note (2)]	. . .
Hydrogen	ASTM D5291	±($x^{0.5}$) 0.1157	. . .
	ASTM D3178 [Note (1)]	±0.07% [Note (2)]	. . .
Nitrogen	ASTM D5291	±0.23	Reported to 0.00
	ASTM D3228	±0.095 $N^{0.5}$	. . .
Heating value	ASTM D240	86 Btu/lbm	. . .
	ASTM D4809	±49 Btu/lbm, all fuels ±51 Btu/lbm, nonvolatiles ±44 Btu/lbm, volatiles	. . .

GENERAL NOTE: All systematic uncertainties are absolute unless otherwise indicated.

NOTES:
(1) Modified for oil.
(2) Estimated based on repeatability.

Table 4-13-5 Potential Systematic Uncertainty for Natural Gas Properties

Natural Gas	Analysis Procedure	Systematic Uncertainty	Comments
Sampling	ASTM D287	±0.5% for multiple sample ±1.0% for single sample ±2.0% for supplier analysis Online analysis — use supplier specification for guidance	. . .
Gas constituents	ASTM D1945	Mole percent of constituent 0.0–0.1: ±0.01% 0.1–1.0: ±0.04% 1.0–5.0: ±0.05% 5.0–10.0: ±0.06% Over 10: ±0.08%	. . .
Higher heating value, calculated	ASTM D3588	None	Perturbed with fuel constituents
Higher heating value	ASTM D1826	0.3% to 0.55%	. . .

GENERAL NOTE: All systematic uncertainties are absolute unless otherwise indicated.

Section 5
Computation of Results

5-1 INTRODUCTION

This Section describes the data required and the computation procedures for determining the performance of air heaters covered by this Code. Since most air heater applications are in conjunction with fired steam generators, this Section includes the calculations necessary to determine steam generator efficiency and input from fuel by the energy-balance method. Since the air heater performance parameters are the key measured parameters for determining steam generator efficiency, this method will generally provide the lowest uncertainty compared to measuring fuel, air, and flue gas flows. Data acquisition principles, instruments, and methods of measurement are given in Sections 3 and 4. Derivations of certain equations are detailed in Nonmandatory Appendix H. The computation equations use acronyms for variables that consist of alphanumeric characters that may be used directly in computer programs without loss of interpretation. The format for these acronyms, definitions of letters or letter combinations, and a summary of developed acronyms are described in Section 2. The alphanumerical designations that identify the locations of gaseous and liquid streams in relation to the air heater components are listed in subsection 2-5 and shown schematically in Figs. 2-3.4-1 through 2-3.4-6.

Section 5 is generally arranged in the sequence required to compute air heater performance after completion of a test, beginning with determining input from fuel based upon steam generator efficiency. The test measurements recorded during a performance test must be reduced to average values before performance and uncertainty calculations are completed. Subsection 5-2 provides guidance for reducing test measurements to average values; it also presents the equations to determine the standard deviation of the mean for uncertainty analysis calculations. Subsection 5-3 presents the steam generator combustion and efficiency calculations. Subsection 5-4 presents equations for determining flue gas and airflows through the air heater(s). Subsection 5-5 presents the general air heater performance calculations. Subsection 5-6 provides the method to calculate air heater performance corrected to standard or design conditions. Subsection 5-7 presents the equations to determine the systematic component of the uncertainty and the remaining equations required to complete the test uncertainty analysis. Subsection 5-8 presents how to calculate corrected performance for noncondensing air preheater coils.

5-2 MEASUREMENT DATA REDUCTION

5-2.1 Calibration Corrections

When an instrument has been calibrated, the calibration correction should be applied prior to data reduction. An example is a pressure transducer for which an actual pressure versus output reading (e.g., mV output) has been determined statistically via laboratory measurements. Similarly, an error correlation versus mV determined for a thermocouple in a laboratory should be applied to the measured result prior to averaging.

In this same category is any dependent variable that is a result of multiple measurements. Measurement of fluid flow is a common example. The flow result is a square-root function of differential pressure, and an approximately linear function of temperature and pressure. The calculated result should be used in the data average. The random and systematic error of the instruments required to determine flow should be incorporated in the total random and systematic uncertainty of the measured flow parameter (refer to sensitivity coefficient in subsection 5-7).

5-2.2 Outliers

The first step in determining the average value for a measurement is to reject bad data points or outliers. Outliers are spurious data that are believed to be not valid, and should not be included as part of the calculations and uncertainty analyses. Causes of outliers are human errors in reading and writing values, and instrument errors resulting from electrical interference, etc. Several documents provide guidance and statistical methods for determining outliers; among them are ASME PTC 19.1 and ASTM E178. This Code does not recommend a particular statistical method for determining outliers. It is important to note that the use of statistical methods to determine outliers can produce unrealistic results, depending on the method and criteria used. Most outliers are obvious when all data recorded for a given parameter are compared. The rejection of outliers based on engineering judgment and/

or pretest agreements by the parties involved in the test is recommended. It is also recommended that the test engineer and all parties involved determine the likely cause of any outliers.

5-2.3 Averaging Test Measurement Data

The average value of a parameter measured during a performance test is determined before or after the rejection of outliers. The average value can provide important information that can be used to determine outliers. If the average value is calculated before determining outliers, it must be recalculated after all outliers are rejected.

Parameters measured during a performance test can vary with respect to time and spatial location. The majority can be averaged on the basis that the parameter has perturbations about a constant value. This includes any parameter measured at a single point to determine the value, e.g., air heater differential pressure, steam temperature, or steam pressure. During a steady-state performance test (as defined in Section 3), some single-point parameters may exhibit time dependency. However, for purposes of this Code, such parameters are assumed to have a constant value equal to the arithmetic average.

Some parameters measured during a test run must be considered with respect to space as well as time (i.e., parameters that are not uniform within a plane perpendicular to the direction of flow). This would include any measured parameter determined from more than one point at a given location. Air heater flue gas outlet temperature measurements using a point-by-point traverse (or a grid of thermocouples) is a typical example. Parameters that vary with space as well as time are averaged differently from parameters that vary only with time.

The average values of the parameters, along with their standard deviations of the mean and degrees of freedom, are used to calculate the overall random uncertainty.

5-2.3.1 Average Value for Spatially Uniform Parameters.[1] The average value of a parameter that is not expected to exhibit spatial variations is calculated by averaging readings taken over time.

For parameters modeled as constant in/over space (e.g., steam temperature or pressure, or air heater differential pressure), or values of a parameter at a fixed point in space (e.g., exit flue gas temperature at one point in the thermocouple grid), the equation used to calculate average values is

$$X_{AVG} = \frac{1}{n}(x_1 + x_2 + x_3 + \ldots + x_n) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{5-2-1}$$

where

n = number of times parameter x is measured
X_{AVG} = arithmetic average value of a measured parameter
x_i = value of measured parameter i at any point in time

5-2.3.2 Summary Data. It is common for data acquisition systems to print out (and store on electronic media) average values and standard deviations for measured parameters several times during a test period. These are called summary data. The total set of measurements for a test consists of m sets of measurements. Each set has n readings. The average value, $X_{AVG\ k}$, for set k is given by eq. (5-2-1) with the addition of a subscript to denote the set. The overall average value of such parameters is

$$X_{AVG} = \frac{1}{m}\sum_{k=1}^{m} X_{AVG\ k} \tag{5-2-2}$$

Summary data can only be used if individual measured parameter data and standard deviation information are available for each set of measurements. If this information is not available, the subsets should be treated as individual samples.

5-2.3.3 Average Value for Spatially Nonuniform Parameters. The average value of parameters having spatial variations can be determined by first calculating the average value of all the data for each defined point in a measurement grid. The average value of all points in the grid is then determined.

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[1] Some parameters measured at a single point in space may exhibit a time dependency, e.g., combustion air temperature due to ambient air temperature changes. This Code recommends using eq. (5-2-1) to calculate the average value of such parameters and increasing the number of readings to reduce the standard deviation of the mean. However, at the option of the parties to the test, a polynomial may be fitted to the data for a fixed point in space. If a curve fit is utilized, the user must

(a) statistically validate the model
(b) mathematically integrate the fitted curve to determine the average value of the parameter
(c) develop the method for calculating the variance of the average value for determining the standard deviation of the mean

5-2.4 Random Uncertainty

General guidelines for calculating the standard deviation of the mean for individual measurement parameters are given below. A more-detailed description of uncertainty analysis calculations along with derivations is included in Section 7. Section 7 should be reviewed prior to beginning any uncertainty calculations. The random component of uncertainty must be calculated using several steps. Each measured parameter has a standard deviation, standard deviation of the mean, and a certain number of degrees of freedom. There is also an overall standard deviation of the mean and number of degrees of freedom for all measurement parameters combined. These cannot be calculated until after the air heater performance computations shown in subsections 5-3 through 5-6 are completed. The calculations of the overall test standard deviation of the mean and the random component of uncertainty are presented in subsection 5-7.

The first step in determining the standard deviation of the mean and degrees of freedom for a measured parameter is to calculate the average value and standard deviation using the data recorded during a test. The average value, standard deviation, and degrees of freedom for a measured parameter are calculated differently for parameters that vary in both time and space and those parameters that vary only in time.

5-2.4.1 Random Uncertainty for Spatially Uniform Parameters. For multiple measurements of a parameter that is not expected to exhibit spatial variations, the standard deviation and standard deviation of the mean for the parameter are calculated from

$$STDDEVMN = \left(\frac{STDDEV^2}{n}\right)^{1/2} = \left[\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i - X_{AVG})^2\right]^{1/2} \tag{5-2-3}$$

$$STDDEV = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - X_{AVG})^2\right]^{1/2} \tag{5-2-4}$$

or

$$STDDEV = \left[(PSTDDEV)^2\,\frac{n}{n-1}\right]^{1/2} \tag{5-2-5}$$

where

n = number of times parameter is measured

$PSTDDEV$ = population standard deviation for a measured parameter

$STDDEV$ = standard deviation estimate from the sample measurements

$STDDEVMN$ = standard deviation of the mean for a measured parameter

X_{AVG} = arithmetic average value of a measured parameter

x_i = value of measured parameter *i* at any point in time

The equations are presented in the above format because some electronic calculators and spreadsheet programs calculate the population standard deviation, while others calculate the sample standard deviation. Some also calculate the standard deviation of the mean. It is important that the individual calculating the standard deviation of the mean used to determine random uncertainty understands the differences between population standard deviation, sample standard deviation, and standard deviation of the mean. With the use of a computer or scientific calculator, if the function for "sample standard deviation" is used with the measured values of the parameter, the result would be *STDDEV.* If the function for "population standard deviation" is used on these values, the result would be *PSTDDEV.* If the function for standard deviation for the mean or "standard error of the mean" is used, the result would be *STDDEVMN.* An understanding of the differences will help in the use of the correct functions and formulas.

The degrees of freedom for the standard deviation of the mean of a spatially uniform parameter is determined from eq. (5-2-6).

$$DEGFREE = n - 1 \tag{5-2-6}$$

where

$DEGFREE$ = number of degrees of freedom

5-2.4.2 Random Uncertainty for Spatially Nonuniform Parameters. The standard deviation of the mean (random uncertainty) and degrees of freedom for a parameter with spatial variations must be determined in a manner consistent with the integration methods discussed in subsection 7-4 for use of weighted or unweighted averages.

First, for each grid location, i, calculate the average, *STDDEV*, *STDDEVMN*, and *DEGFREE*. Then calculate the average of all the points in the grid.

The standard deviation of the mean for an integrated average parameter is

$$STDDEVMN = \frac{1}{m}\left[\sum_{i=1}^{m} STDDEVMN_i^2\right]^{1/2} \tag{5-2-7}$$

The associated degrees of freedom are

$$DEGFREE = \frac{STDDEVMN^4}{\displaystyle\sum_{i=1}^{m} \frac{STDDEVMN_i^4}{m^4 DEGFREE_i}} \tag{5-2-8}$$

where

$DEGFREE$ = degrees of freedom for the average parameter
$DEGFREE_i$ = degrees of freedom for the parameter at point i
m = number of grid points
$STDDEVMN$ = standard deviation of the mean for the average parameter
$STDDEVMN_i$ = standard deviation of the mean for the parameter at point i

The degrees of freedom must fall between minimum and maximum values based on the number of readings taken at each grid point and the number of grid points. The minimum possible degrees of freedom is the smaller of the following:

(a) number of points in the grid, m
(b) number of readings taken at each grid point minus 1, n −1

The maximum possible degrees of freedom is the product of the two items listed above.

Equations (5-2-7) and (5-2-8) are for unweighted averages and also for weighted averages when the weighting factors are measured simultaneously with the parameters so that the standard deviations of the mean at the grid points are calculated by using weighted parameters ($X_{FW} = F_i X_i$). This calculation should be used for weighted averages only when there are a large enough number of readings at each grid point to assure statistical significance.

If weighted averages are to be employed in performance calculations, with only a small number of simultaneous traverses (fewer than 6), giving only a small number of readings at each point, then the standard deviation of the mean of the weighted average is estimated using a single probe as described in subsection 7-4. This probe is arranged to simultaneously measure velocity and the parameter of interest (temperature or oxygen) at a fixed point. There are n readings at the single point. The readings are multiplied as follows:

$$X_{FW,i} = \left(\frac{V_i}{V_{\mathrm{AVG}}}\right) X_i \tag{5-2-9}$$

The sample standard deviation of X_{FW}, *STDDEV*, is calculated from eq. (5-2-4) or (5-2-5). The standard deviation of the mean for the weighted average parameter is

$$STDDEVMN_{FW} = \left(\frac{STDDEV^2}{n}\right)^{1/2} \tag{5-2-10}$$

where

FW = weighted average
n = number of readings at the single point

The standard deviation of the mean is determined from the standard deviation of the single point. If weighted averages are to be employed in performance calculations with weighting factors (velocities) determined separately from the weighted parameter, then the standard deviation of the mean of the weighted average parameter is calculated from

$$STDDEVMN = [STDDEVMN_{UW}{}^2 + (PARAVG_{UW} - PARAVG_{FW})^2\, STDDEVMN_V{}^2 / V_{\mathrm{AVG}}{}^2]^{1/2} \tag{5-2-11}$$

where

$PARAVG_{FW}$ = weighted average value of the parameter
$PARAVG_{UW}$ = unweighted average value of the parameter
$STDDEVMN_{UW}$ = standard deviation of the mean of the unweighted average

$STDDEVMN_V$ = standard deviation of the mean of the velocity
V_{AVG} = average velocity

If the velocity distribution is determined by a limited number of traverses, $STDDEVMN_V$ can be estimated from a large number of velocity readings taken over time at a single point, as described immediately above, with V_i used in place of $X_{FW,i}$.

5-3 COMBUSTION AND EFFICIENCY CALCULATIONS

This subsection deals with the calculations related to air heaters where flue gas is the heating fluid. The combustion calculations are taken from, and the same as, ASME PTC 4. This subsection is intended to be an abbreviated presentation of the required calculations. Refer to ASME PTC 4 for a more-comprehensive discussion.

The combustion calculations are based upon the following principles and follow in the general order of the calculation process:

(a) measure O_2
(b) calculate excess air and flue gas products stoichiometrically
(c) estimate UBC if not measured
(d) calculate sorbent reaction corrections if applicable
(e) calculate wet gas weight
(f) calculate flue gas *Mw* and density

Refer to Nonmandatory Appendix A for an example of the calculation forms. This subsection addresses the combustion and efficiency calculations.

Items that can be expressed on a unit of fuel basis (lbm/lbm fuel) can be normalized by using an input from fuel basis. The concept of mass per unit of fuel input is valuable when determining the impact of different fuels on combustion calculations. In the text, the primary units used in the calculations are lb/Btu (kg/J). For practical application such as on the calculation forms, lb/10,000 Btu (kg/10 MJ) is used as a convenient size with respect to the decimal place.

5-3.1 Fuel Properties

5-3.1.1 Heating Value of Fuel. Higher heating value, *HHVF*, refers to the "as-fired" higher heating value on a constant-pressure basis. For solid and liquid fuels, *HHVF* is determined in a bomb calorimeter, which is a constant-volume device. Since fuel is burned in a steam generator under essentially constant-pressure conditions, the bomb calorimeter values must be corrected to a constant-pressure basis

$$HHVF = HHVFcv + 2.644\ MpH2F, \text{ Btu/lbm (J/kg)} \tag{5-3-1}$$

where
$HHVFcv$ = higher heating value of the fuel on a constant-volume basis as determined from a bomb calorimeter
$MpH2F$ = mass percent of H_2 in the fuel

The user should ensure that the laboratory performing the fuel analysis has not made this correction. For gaseous fuels, the higher heating value is determined under constant-pressure conditions; therefore, the calorimeter values do not need correction.

The calculations throughout this Code utilize higher heating values expressed in units on a mass basis, Btu/lbm (J/kg). For gaseous fuels, the higher heating value, *HHVGF,* is normally expressed on a volume basis, Btu/scf ($J/N{\cdot}m^3$). For compatibility with the units used in the calculation procedure, the higher heating value must be converted to an energy per unit mass basis, Btu/lbm (J/kg), as follows:

$$HHVF = \frac{HHVGF}{DnGF}, \text{ Btu/lbm (J/kg)} \tag{5-3-2}$$

where
$DnGF$ = density of gas at the standard temperature and pressure conditions used for *HHVGF,* lbm/scf ($kg/N{\cdot}m^3$)

5-3.1.2 Chemical Analysis of Fuel. The calculations in this Code are based upon the ultimate analysis of the fuel expressed on a percent mass basis. The constituents considered are carbon (CF), hydrogen (H_2F), nitrogen (N_2F), sulfur (SF), oxygen (O_2F), water (H_2OF), and ash (AsF). The water in the fuel is on an "as fired" basis. Note that the hydrogen (or oxygen) does not include the hydrogen (or oxygen) in the water in the fuel. The total of the ultimate analysis must be 100%.

A gaseous fuel analysis expresses the individual hydrocarbon compounds and the other constituents on a volumetric percentage basis. For the combustion calculations in this Code, the gaseous fuel analysis is converted to a mass basis. The calculations follow the general logic below.

$$MpFk = 100\,\frac{MvFk}{MwGF}\text{, \% mass} \tag{5-3-3}$$

$$MwGF = \Sigma MvFk\text{, lbm/mol (kg/mol)} \tag{5-3-4}$$

$$MvFk = Mwk\,\Sigma\frac{VpGj\;Mokj}{100}\text{, lbm/mol fuel (kg/mol fuel)} \tag{5-3-5}$$

where

j = fuel components expressed on a by-volume or mole basis, e.g., CH_4 and C_2H_6

k = fuel constituents expressed on a mass basis. For this Code, these are C, H_2, N_2, S, O_2, and H_2O. For a gaseous fuel, it is assumed that water is in a vaporous state, and the acronym H_2Ov is used throughout the calculations.

$Mokj$ = moles of constituent k in component j. For example, for component $j = C_2H_6$ and $k = C$, $Mokj = 2$. For component $j = C_2H_6$ and $k = H_2$, $Mokj = 3$.

$MpFk$ = mass percentage of constituent k

$MvFk$ = mass of constituent k per unit volume of fuel, lbm/mol or lbm/ft^3 (kg/mol or kg/m^3)

$MwGF$ = molecular weight of the gaseous fuel, lbm/mol (kg/mol). This is the sum of each $MvFk$ value on a mass per unit mole (or volume) basis, lbm/mol (kg/mol).

Mwk = molecular weight of constituent k, lbm/mol (kg/mol)

$VpGj$ = as-fired fuel components (e.g., CH_4 and C_2H_6), percent by volume

5-3.2 Sorbent and Other Additive Properties

This section addresses solid and/or gaseous material other than fuel that is added to the gas side of the steam generator envelope. Additives can impact the efficiency and combustion process in the following ways:

(a) Additives may increase the quantity of residue and "sensible heat of residue" losses.

(b) Additives may introduce moisture that increases "moisture in flue gas" losses and alters the flue gas specific heat.

(c) Additives may undergo a chemical change and alter the flue gas composition or may alter the air requirement.

(d) Chemical reactions that are endothermic require heat, which is an additional loss.

(e) Chemical reactions that are exothermic add heat, which is an additional credit.

For an air heater test, the parameters associated with sorbent, e.g., sulfur capture and calcination fraction, may be estimated based on experience. Refer to ASME PTC 4 if these parameters are to be rigorously determined.

Since limestone is widely used for sulfur removal, this Code specifically addresses the impact of the addition of limestone on the efficiency and combustion calculations. The term *sorbent* is used throughout the Code to refer to any material added to the flue gas (within the steam generator envelope) that is not fuel. The calculations for limestone demonstrate the principles of calculation required for the effect of most additives on efficiency and combustion products. In addition to limestone, the calculations address hydrated lime, which consists of calcium hydroxide, $Ca(OH)_2$, and magnesium hydroxide, $Mg(OH)_2$, as a potential sorbent for reducing SO_2. When inert materials such as sand are added, the calculations below should be made as if limestone containing only inert material and moisture were used.

5-3.2.1 *MFrSb* — Mass Fraction of Sorbent, lbm/lbm Fuel (kg/kg Fuel). The mass fraction of sorbent is required for the reaction calculations. It may be determined from the measured sorbent rate or the estimated Ca/S molar ratio.

$$MFrSb = \frac{MrSb}{MrF}\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-6}$$

or

$$MFrSb = MoFrCaS\,\frac{MpSF}{MwS}\,\Sigma\frac{MwCak}{MpCak}\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-7}$$

and

$$MoFrCaS = MFrSb\,\frac{MwS}{MpSF}\,\Sigma\frac{MpCak}{MwCak}\text{, mol/mol} \tag{5-3-8}$$

where

$MoFrCaS$ = calcium-to-sulfur molar ratio
$MpCak$ = percent of calcium in sorbent in form of constituent k, % mass
$MpSF$ = percent sulfur in fuel
MrF = mass flow rate of fuel, lbm/hr (kg/s). Repeat efficiency calculation until the calculated MrF converges.
$MrSb$ = measured mass flow rate of sorbent, lbm/hr (kg/s)
$MwCak$ = molecular weight of calcium compound k, lbm/mol (kg/mol)
= 100.089 for $CaCO_3$, calcium carbonate (Cc)
= 74.096 for $Ca(OH)_2$, calcium hydroxide (Ch)
MwS = molecular weight of sulfur, 32.065 lbm/mol

5-3.2.2 *MFrSbk* — Mass of Constituents in Sorbent, lbm/lbm Fuel (kg/kg Fuel). The important constituents in the sorbent are the reactive products, the moisture, and the inerts. The mass of each constituent is converted to a mass/mass-from-fuel basis

$$MFrSbk = MFrSb\,\frac{MpSbk}{100}\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-9}$$

where

k = constituent in the sorbent
$MpSbk$ = percent of constituent k in the sorbent

The reactive constituents specifically addressed are

(a) $CaCO_3$, calcium carbonate (Cc)
(b) $MgCO_3$, magnesium carbonate (Mc)
(c) $Ca(OH)_2$, calcium hydroxide (Ch)
(d) $Mg(OH)_2$, magnesium hydroxide (Mh)

5-3.2.3 *MoFrClhk* — Calcination Fraction for Constituent *k*. The calcination fraction is the moles of CO_2 released per mole of constituent. Two constituents are addressed directly by this Code. Magnesium carbonate (Mc) calcines readily at partial pressures of CO_2 typical of combustion with air and normal operating temperatures of atmospheric fluidized bed steam generators, and thus the calcination fraction is normally considered to be 1.0. Not all of the $CaCO_3$ (Cc) is converted to CaO and CO_2, however. A value of 0.90 is recommended for this Code with an uncertainty of +0.05 and −0.10. For determination analytically, refer to ASME PTC 4.

5-3.2.4 *MFrSc* — Sulfur Capture/Retention Ratio, lbm/lbm (kg/kg). The sulfur capture/retention ratio is the mass of sulfur removed divided by the total mass of sulfur available. The sulfur capture/retention ratio is determined from the measured O_2 and SO_2. See ASME PTC 4. For this Code, use the expected or previously tested value with an appropriate uncertainty. If estimated, an uncertainty of ±0.05 lbm/lbm for the retention ratio is suggested.

5-3.2.5 *MqThAAd* — Additional Theoretical Air Due to Sulfur Capture/Retention. The sulfur/SO_2 that is captured/retained is converted to $CaSO_4$. The reaction

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4$$

requires an additional ½ mol of O_2 per mole of sulfur captured.

$$MqThAAd = \frac{0.02155\ MpSF\ MFrSc}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-10}$$

It is noted that this correction is included in the corrected theoretical air, *MqThACr*, below.

5-3.2.6 *MqCO2Sb* — Gas (CO_2) From Calcination of Sorbent, lbm/Btu (kg/J). When heat is added to calcium carbonate and magnesium carbonate, CO_2 is released. This increases the dry gas weight

$$MoCO2Sb = \Sigma MoFrClhk\,\frac{MFrSbk}{Mwk}\text{, mol/lbm fuel (mol/kg fuel)} \tag{5-3-11}$$

$$MFrCO2Sb = 44.0098\ MoCO2Sb\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-12}$$

$$MqCO2Sb = \frac{MFrCO2Sb}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-13}$$

where

k = constituents that contain carbonates, typically calcium carbonate (Cc) and magnesium carbonate (Mc)
MFrCO2Sb = mass fraction of gas (CO_2) from sorbent, lbm/lbm fuel (kg/kg fuel), where 44.0098 is the molecular weight of carbon dioxide
MoCO2Sb = moles of gas (CO_2) from sorbent, mol/lbm fuel (mol/kg fuel)
MoFrClhk = calcination fraction for constituent *k*, moles CO_2 released/mole of constituent
MqCO2Sb = mass of gas (CO_2) from sorbent on an input-from-fuel basis, lbm/Btu (kg/J)
Mwk = molecular weight of constituent *k*, lbm/mol (kg/mol)

5-3.2.7 *MqWSb* — Water From Sorbent, lbm/Btu (kg/J). The total moisture added due to sorbent is the sum of the moisture in the sorbent and the moisture released due to the dehydration of calcium hydroxide and magnesium hydroxide.

$$MoWSb = \frac{MFrH2OSb}{18.0153} + \Sigma\frac{MFrSbk}{Mwk}\text{, mol/lbm fuel (mol/kg fuel)} \tag{5-3-14}$$

$$MFrWSb = 18.0153\ MoWSb\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-15}$$

$$MqWSb = \frac{MFrWSb}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-16}$$

$$MrWSb = MFrWSb\ MrF\text{, lbm/hr (kg/s)} \tag{5-3-17}$$

where

k = constituents that contain water or hydroxides that are dehydrated, typically calcium hydroxide (Ch) and magnesium hydroxide (Mh). These constituents are considered to be 100% dehydrated in the combustion process.
MFrWSb = mass fraction of total water from sorbent, lbm/lbm fuel (kg/kg fuel)
MoWSb = total moles of water from sorbent, mol/lbm fuel (mol/kg fuel)
MqWSb = mass of total water from sorbent on an input-from-fuel basis, lbm/Btu (kg/J)
MrWSb = mass flow rate of total water from sorbent, lbm/hr (kg/s)

5-3.2.8 *MFrSsb* — Mass Fraction Spent Sorbent, lbm/lbm Fuel (kg/kg Fuel). Spent sorbent is the solid residue remaining from the sorbent after evaporation of the moisture in the sorbent, calcination/dehydration, and mass gain due to sulfation.

$$MFrSsb = MFrSb - MFrCO2Sb - MFrWSb + MFrSO3\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-18}$$

$$MFrSO3 = 0.025\ MFrSc\ MPSF\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-19}$$

$$MqSsb = \frac{MFrSsb}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-20}$$

$$MoO3ACr = \frac{MFrO3ACr}{MwO3}\text{, mol/mol} \tag{5-3-21}$$

$$MqO3ACr = \frac{MFrO3ACr}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-22}$$

$$MFrO3ACr = 0.6\ MFrSO3\text{, lbm/lbm (kg/kg)} \tag{5-3-23}$$

where

MFrO3ACr = mass fraction of oxygen from air required to form SO_3 in the sulfation process, lbm/lbm (kg/kg). The constant 0.6 is the molecular weight of O_3 divided by the molecular weight of SO_3.
MFrSO3 = mass fraction of SO_3 formed in the sulfation (sulfur capture) process, lbm/lbm fuel (kg/kg). The constant 0.025 is the molecular weight of sulfur divided by the molecular weight of SO_3 and divided by 100 to convert percent mass to mass fraction.
MoO3ACr = dry gas flow correction for the oxygen in air required to form SO_3, mol/mass fuel
MqO3ACr = dry gas flow correction for the O_3 in air required to form SO_3, lbm/Btu (kg/J)
MwO3 = molecular weight of O_3, 47.9982 mass/mol

5-3.3 *MpUbC* and *MpCb* — Unburned Carbon in Fuel and Carbon Burned, Percent Mass

The percent mass unburned carbon may be calculated from an estimated unburned carbon loss, *QpLUbC*, or calculated from either an estimated or measured unburned carbon in the residue, *MpCRs*. For estimated values, appropriate uncertainty values should be used.

5-3.3.1 Unburned Carbon in Fuel From Percent Unburned Carbon Loss

$$MpUbC = QpLUbC\,\frac{HHVF}{HHVCRs}\text{, \% mass} \tag{5-3-24}$$

where

$HHVCRs$ = heating value of carbon as it occurs in residue, 14,500 Btu/lbm (33 700 kJ/kg)

5-3.3.2 *MpCRs* — Unburned Carbon in the Residue, Percent. The unburned carbon in the residue, *MpCRs,* refers to the free carbon and is used to determine unburned carbon from fuel. The residue contains carbon in the form of carbonates as well as free carbon when limestone is utilized, and from fuels with a high carbonate content in the ash. The standard tests for carbon in the residue determine total carbon (*MpToCRs*). It is also necessary to determine the carbon dioxide content in the residue (*MpCO2Rs*), and correct the total carbon results to a free carbon basis (*MpCRs*). Refer to subsection 4-11 regarding the analysis methods to be specified. If the lab analysis is not clear whether total carbon (*MpToCRs*) or free carbon (*MpCRs*) is reported, it should be clarified. When sorbent with calcium carbonate is utilized, the CO_2 in residue is required to calculate the quantity of $CaCO_3$ in the residue and the calcination fraction of calcium carbonate in the sorbent.

$$MpCRs = MpToCRs - \frac{12.011}{44.0098}\,MpCO2Rs\text{, \% mass} \tag{5-3-25}$$

When residue is collected at more than one location, the weighted averages of carbon and carbon dioxide in residue are calculated from

$$MpCRs = \Sigma\,\frac{MpRsz\;MpCRsz}{100}\text{, \% mass} \tag{5-3-26}$$

$$MpCO2Rs = \Sigma\,\frac{MpRsz\;MpCO2Rsz}{100}\text{, \% mass} \tag{5-3-27}$$

5-3.3.3 *MFrRs* — Mass of Residue, lbm/lbm Fuel (kg/kg Fuel). The ash in fuel and spent sorbent are converted to a mass of residue per mass of fuel basis

$$MFrRs = \frac{MpAsF + 100\;MFrSsb}{100 - MpCRs}\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-28}$$

where

$MFrSsb$ = mass fraction of spent sorbent per mass of fuel, lbm/lbm fuel (kg/kg fuel)
$MpAsF$ = ash in fuel, % mass
$MpCRs$ = unburned carbon in the residue, % mass

5-3.3.4 *MpUbC* — Unburned Carbon in Fuel, Percent Mass. The unburned carbon in the residue is used to calculate the percent of the carbon in the fuel that is unburned

$$MpUbC = MpCRs\;MFrRs\text{, \% mass} \tag{5-3-29}$$

5-3.3.5 *MpCb* — Carbon Burned, Percent Mass. The actual percent mass carbon in the fuel that is burned is the difference between the carbon in the fuel from the ultimate analysis and the unburned carbon. The actual carbon burned (*MpCb*) is used in the stoichiometric combustion calculations in lieu of carbon in the fuel (*MpCF*)

$$MpCb = MpCF - MpUbC\text{, \% mass} \tag{5-3-30}$$

5-3.4 Combustion Air Properties

5-3.4.1 Physical Properties. The calculations and derivation of constants used in this Code are based upon a composition of dry air as follows:[2] 0.20946 O_2, 0.78102 N_2, 0.00916 Ar, 0.00033 CO_2 moles per mole of air (and other trace elements), yielding an average molecular weight of 28.9625. For simplification of the calculations, N_2 includes the argon and other trace elements and is referred to as atmospheric nitrogen (N_{2a}), having an equivalent molecular weight of 28.158.

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[2] Jones, F. E. The Air Density Equation and the Transfer of the Mass Unit. *Journal of Research of the National Bureau of Standards*. Vol. 83, No. 5, September–October 1978.

The following is a summary of the nominal properties of air used in this Code:
(a) volumetric basis: 20.95% oxygen, 79.05% nitrogen
(b) mass basis: 23.14% oxygen, 76.86% nitrogen

5-3.4.2 *MFrWDA* — Moisture in Air, lbm H_2O/lbm Dry Air (kg H_2O/kg Dry Air). The moisture in air is determined from measured inlet air wet-bulb and dry-bulb temperature, or dry-bulb temperature and relative humidity in conjunction with psychrometric charts, or calculated from vapor pressure as determined from Carrier's equation [eq. (5-3-32)] when wet-bulb temperature is measured or eq. (5-3-33) when relative humidity is measured.

$$MFrWDA = 0.622\,\frac{PpWvA}{Pb - PpWvA}\text{, lbm H}_2\text{O/lbm dry air (kg H}_2\text{O/kg dry air)} \tag{5-3-31}$$

$$PpWvA = PsWvTwb - \frac{(Pb - PsWvTwb)\,(Tdbz - Twbz)}{2830 - 1.44\;Twbz}\text{, psia} \tag{5-3-32}$$

$$PpWvA = 0.01\;Rhmz\;PsWvTdb\text{, psia} \tag{5-3-33}$$

$$PsWvTz = C1 + C2T + C3T^2 + C4T^3 + C5T^4 + C6T^5\text{, psia} \tag{5-3-34}$$

where
$C1$ = 0.019257
$C2$ = 1.289016E−3
$C3$ = 1.211220E−5
$C4$ = 4.534007E−7
$C5$ = 6.841880E−11
$C6$ = 2.197092E−11
Pb = barometric pressure, psia. To convert in. Hg to psia, divide by 2.0359.
$PpWvA$ = partial pressure of water vapor in air, psia. This may be calculated from relative humidity or wet- and dry-bulb temperatures.
$PsWvTz$ = saturation pressure of water vapor at wet-bulb temperature ($PsWvTwb$) or dry-bulb temperature ($PsWvTdb$), psia. The curve fit is valid for temperatures from 32°F to 140°F.
$Rhmz$ = relative humidity at location z
$Tdbz$ = temperature of air (dry-bulb) at location z, °F
$Twbz$ = temperature of air (wet-bulb) at location z, °F

5-3.4.3 *MqThACr* — Theoretical Air (Corrected), lbm/Btu (kg/J). Theoretical air is defined as the ideal minimum air required for the complete combustion of the fuel, i.e., carbon to CO_2, hydrogen to H_2O, and sulfur to SO_2. In the actual combustion process, small amounts of CO and nitrous oxides (NO_x) are formed and commonly measured. Also, small amounts of SO_3 and gaseous hydrocarbons are formed but less frequently measured. The impact of these minor species is negligible on the combustion calculations addressed by this Code.

$$MqThA = \frac{MFrThA}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-35}$$

$$MFrThA = 0.1151\;MpCF + 0.3429\;MpH2F + 0.0431\;MpSF - 0.0432\;MpO2F\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-36}$$

where fuel constituents *MpCF*, *MpH2F*, *MpSF*, and *MpO2F* are on a percent mass basis.

For typical fossil fuels, the value of calculated theoretical air is a good check on the reasonableness of the fuel analysis. Expressed on a lbm/million Btu (MBtu) basis ($MqThA \times 10^6$), a valid fuel analysis should fall within the following ranges of theoretical air:
(a) for coal (*VMmaf* > 30%), 735–775 lbm/MBtu
(b) for oil, 735–755 lbm/MBtu
(c) for natural gas, 715–735 lbm/MBtu

The theoretical airs for carbon and hydrogen, 816 and 516 lbm/MBtu, respectively, are the practical maximum and minimum values for hydrocarbon fuels.

For monitoring operation and analysis of combustion, the theoretical air required to produce the gaseous products of combustion is more meaningful than the ideal value defined above. In commercial applications, particularly for solid fuels, it is not feasible to burn the fuel completely. The gaseous products of combustion are the result of the fuel that is burned or gasified. When additives are used, secondary chemical reactions may also occur. For example, when CaO reacts with SO_2 in the flue gas to form $CaSO_4$ (a method of sulfur reduction), additional O_2 supplied from air is required. Therefore, for the purposes of the calculations in this Code, corrected theoretical air that accounts for the actual combustion process is used.

Corrected theoretical air is defined as the amount of air required to complete the combustion of the gasified fuel and support secondary chemical reactions with zero excess O_2. By definition, the theoretical products of combustion would have no CO or gaseous hydrocarbons.

$$MqThACr = \frac{MFrThACr}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-37}$$

$$\begin{aligned} MFrThACr = {} & 0.1151\ MpCb + 0.3429\ MpH2F + 0.0431\ MpSF\ (1 + 0.5\ MFrSc) \\ & - 0.0432\ MpO2F\text{, lbm/lbm fuel “as-fired”} \end{aligned} \tag{5-3-38}$$

$$MoThACr = \frac{MFrThACr}{28.9625}\text{, mol/mass fuel “as-fired”} \tag{5-3-39}$$

where

MFrSc = sulfur capture ratio, lbm/lbm. This item is normally assumed to be zero when the sulfur removal occurs external to the steam generator envelope. Refer to para. 5-3.4.4 for calculation.
MoThACr = theoretical air (corrected), mol/mass fuel as-fired
MpCb = *MpCF* − *MpUbC*
= carbon burned on a mass percentage basis
MqThACr = theoretical air (corrected), lbm/Btu. Note that when a sulfur removal process is employed, the excess air and combustion calculations are dependent upon where the sulfur removal occurs in relation to the flue gas composition measurements.

5-3.4.4 *XpA* — Excess Air, Percent Mass. Excess air is the actual quantity of air used, minus the theoretical air required, divided by the theoretical air, and expressed as a percentage.

$$XpA = 100\,\frac{MFrDA - MFrThACr}{MFrThACr} = 100\,\frac{MqDA - MqThACr}{MqThACr}\text{, \% mass} \tag{5-3-40}$$

In this Code, corrected theoretical air [eq. (5-3-37)] is used as the basis for calculating excess air. Defined as such, 0% O_2 in the flue gas corresponds to 0% excess air.

For efficiency and air heater leakage calculations, excess air must be determined at the air heater gas inlets (14A) and (14B), as well as air heater gas exits (15), (15A), and (15B). Refer to Figs. 2-3.4-1 through 2-3.4-6 and paras. 2-5.1 through 2-5.6 for boundary data identification numbers. Excess air is determined from the volumetric composition of the flue gas. O_2 is used as the basis for calculation of excess air in this Code.

5-3.4.5 O_2 Analysis on Dry Basis Where the Moisture in the Flue Gas Is Condensed (Such as When an Extractive Sampling System Is Used)

$$XpA = 100\,\frac{DVpO2\ (MoDPc + 0.7905\ MoThACr)}{MoThACr\ (20.95 - DVpO2)}\text{, \%} \tag{5-3-41}$$

$$MoDPc = \frac{MpCb}{1201.1} + (1 - MFrSc)\,\frac{MpSF}{3206.4} + \frac{MpN2F}{2801.34} + MoCO2Sb\text{, mol/mass fuel} \tag{5-3-42}$$

where

DVpO2 = oxygen concentration in the flue gas, percent by volume, dry basis
MFrSc = mass fraction of sulfur capture, lbm/lbm fuel (kg/kg fuel)
MoCO2Sb = moles of gas from sorbent, mol/lbm fuel (mol/kg). Refer to para. 5-3.2.6 for the calculation.
MoDPc = moles of dry products from the combustion of fuel (CO_2 from carbon burned), actual SO_2 produced (excluding sulfur retained due to SO_2 capture techniques), N_2 from fuel, and the dry gas from sorbent, CO_2, mol/mass fuel

5-3.4.6 Calculation of *DVpO2*, *DVpCO2*, *DVpSO2*, *DVpN2F*, and *DVpN2a* on a Dry Basis When Excess Air is Known

$$DVpO2 = \frac{0.2095\ MoThACr\ XpA}{MoDFg}\text{, \%} \tag{5-3-43}$$

$$DVpCO2 = \frac{\dfrac{MpCb}{12.011} + 100\ MoCO2Sb}{MoDFg}\text{, \%} \tag{5-3-44}$$

$$DVpSO2 = \frac{\frac{MpSF}{32.064}\left(1 - MFrSc\right)}{MoDFg}, \% \tag{5-3-45}$$

$$DVpN2F = \frac{MpN2F}{28.0134\ MoDFg}, \% \tag{5-3-46}$$

$$DVpN2a = 100 - DVpO2 - DVpCO2 - DVpSO2 - DVpN2F, \% \tag{5-3-47}$$

$$MoDFg = MoDPc + MoThACr\left(0.7905 + \frac{XpA}{100}\right) - MoO3ACr, \text{ mol/mass fuel} \tag{5-3-48}$$

where

$DVpCO2$ = carbon dioxide in the flue gas, %. Note that for comparison to an Orsat analysis, $DVpSO2$ must be added.

$DVpN2a$ = atmospheric nitrogen (refer to para. 5-3.4.1) in the flue gas, % volume

$DVpN2F$ = nitrogen from fuel in the flue gas, % volume. This term is shown separately from the atmospheric nitrogen from the air to note the technical distinction between the two. Since the quantity of nitrogen from the fuel is generally insignificant compared to the nitrogen in the air, calculation of this term is sometimes omitted.

$DVpSO2$ = sulfur dioxide in the flue gas, % volume

$MoDFg$ = moles of dry gas per lbm of fuel as-fired

$MoO3ACr$ = dry gas flow correction for the oxygen in air required to form SO_3, mol/mass fuel

5-3.4.7 O_2 Analysis on Wet Basis Where the Flue Gas Sample Includes Moisture (Such as In-Situ Monitors and Heated Extractive Systems)

$$XpA = 100\left\{\frac{VpO2\ [MoWPc + MoThACr\ (0.7905 + MoWA)]}{MoThACr\ [20.95 - VpO2\ (1 + MoWA)]}\right\}, \% \tag{5-3-49}$$

$$MoWA = 1.608\ MFrWDA, \text{ mol/mol dry air} \tag{5-3-50}$$

$$MoWPc = MoDPc + \frac{MpH2F}{201.59} + \frac{MpWF}{1801.53} + \frac{MFrWAdz}{18.0153} + MoWSb, \text{ mol/lbm fuel} \tag{5-3-51}$$

where

$MFrWAdz$ = additional moisture at location z, e.g., atomizing steam and soot-blowing steam, lbm/lbm fuel "as-fired." Measured values of steam and fuel flow are usually sufficiently accurate for this calculation.

$MFrWDA$ = moisture in air, lbm H_2O/lbm dry air

$MoWA$ = moles of moisture in air, mol H_2O/mol dry air

$MoWPc$ = $MoDPc$ plus moles of wet products from the combustion from fuel, plus the wet products from sorbent, plus any additional moisture, mol/mass fuel

$MoWSb$ = total water from sorbent, moles/lbm fuel. Refer to para. 5-3.2.7.

$MpWF$ = H_2O in fuel, % mass basis

$VpO2$ = oxygen concentration in the flue gas, percent by volume, wet basis

1.608 = molecular weight of dry air divided by the molecular weight of water

5-3.4.8 Calculation of *VpO2*, *VpCO2*, *VpSO2*, *VpH2O*, *VpN2F*, and *VpN2a* on a Wet Basis When Excess Air Is Known

$$VpO2 = \frac{0.2095\ MoThACr\ XpA}{MoFg}, \% \tag{5-3-52}$$

$$VpCO2 = \frac{\frac{MpCb}{12.011} + 100\ MoCO2Sb}{MoFg}, \% \tag{5-3-53}$$

$$VpSO2 = \frac{\frac{MpSF}{32.064}\left(1 - MFrSc\right)}{MoFg}, \% \tag{5-3-54}$$

$$VpH2O = \frac{\frac{MpH2F}{2.0159} + \frac{MpH2OF}{18.0153} + \frac{MFrWAdz}{0.180153} + 100\ MoWSb + (100 + XpA)\ MoThACr\ MoWA}{MoFg}, \% \tag{5-3-55}$$

$$VpN2F = \frac{MpN2F}{28.0134\ MoFg},\ \% \tag{5-3-56}$$

$$VpN2a = 100 - VpO2 - VpCO2 - VpSO2 - VpH2O - VpN2F,\ \% \tag{5-3-57}$$

$$MoFg = MoWPc + MoThACr\left[0.7905 + MoWA + \frac{XpA}{100}(1 + MoWA)\right] \tag{5-3-58}$$

where

MoFg = moles of wet gas per lbm fuel as-fired

5-3.4.9 *MqDAz* — Dry Air, lbm/Btu (kg/J). The quantity of dry air entering the steam generator ahead of location *z* is calculated from the excess air determined to be present at location *z* as follows:

$$MqDAz = MqThACr\left(1 + \frac{XpAz}{100}\right),\ \text{lbm/Btu (kg/J)} \tag{5-3-59}$$

$$MFrDAz = MFrThACr\left(1 + \frac{XpAz}{100}\right),\ \text{lbm/lbm fuel (kg/kg fuel)} \tag{5-3-60}$$

Note that this item is used to calculate flue gas flow. See subsection 5-4 for calculation of airflow leaving the air heaters.

5-3.4.10 *DnA* — Density of Air, lbm/ft^3 (kg/m^3). The density of wet air is calculated using the ideal gas relationship

$$DnA = \frac{C1\ (C2Pb + PAz)}{Rk\ (C3 + TAz)},\ \text{lbm/ft}^3\ (\text{kg/m}^3) \tag{5-3-61}$$

$$Rk = \frac{R}{Mwk},\ \frac{\text{ft·lbf}}{\text{lbm·°R}}\left(\frac{\text{J}}{\text{kg·K}}\right) \tag{5-3-62}$$

$$MwA = \frac{1 + MFrWDA}{\frac{1}{28.963} + \frac{MFrWDA}{18.0153}},\ \text{lbm/mol (kg/mol)} \tag{5-3-63}$$

where

C1 = 5.2023 lbf/ft (1.0 J/m^3)

C2 = 27.68 in. wg/psi (1.0 Pa/Pa)

C3 = 459.7°F (273.2°C)

MwA = molecular weight of wet air, lbm/mol (kg/mol)

PAz = static pressure of air at point *z*, in. wg (Pa)

Pb = barometric pressure, psia (Pa). To convert in. Hg to psia, divide by 2.0359.

R = universal molar gas constant, 1,545 ft·lbf/lbm-mol·°R (8 314.5 J/kg·mol·K)

Rk = specific gas constant for gas *k*, ft·lbf/lbm·°R (J/kg·K)

TAz = temperature of air at point *z*, °F (°C)

5-3.5 Flue Gas Products

Flue gas quantity is calculated stoichiometrically from the fuel analysis and excess air. Computations are not valid if significant quantities (in comparison to flue gas weight) of unburned hydrogen or other hydrocarbons are present in the flue gas.

The total gaseous products are referred to as *wet flue gas*. Solid products, e.g., ash from the fuel, unburned carbon, and spent sorbent, are considered separately and are not part of the wet flue gas mass. Wet flue gas is required for calculations such as air heater leakage, hot air quality control equipment energy losses, and draft loss corrections. The total gaseous products excluding moisture are referred to as *dry flue gas* and are used in the energy-balance efficiency calculations. The general logic of this section is that wet flue gas is the sum of the wet gas from fuel (fuel less ash, unburned carbon, and sulfur captured), combustion air, moisture in the combustion air, and any additional moisture, e.g., atomizing steam and moisture and gas added from the addition of sorbent. Dry flue gas is determined by subtracting all moisture from the wet flue gas.

5-3.5.1 *MqFgF* — Wet Gas From Fuel, lbm/Btu (kg/J)

$$MqFgF = \frac{100 - MpAsF - MpUbC - MFrSc\ MpSF}{100\ HHVF},\ \text{lbm/Btu (kg/J)} \tag{5-3-64}$$

where

$MFrSc$ = mass fraction of sulfur capture, lbm/lbm (kg/kg)

$MpAsF$ = ash in fuel, % mass

$MpSF$ = sulfur in fuel, % mass

$MpUbC$ = unburned carbon, % mass

5-3.5.2 *MqWF, MqWvF* — Moisture From H_2O (Water) in Fuel, lbm/Btu (kg/J)

$$MqWF = \frac{MpWF}{100\ HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-65}$$

where

$MpWF$ = water in the fuel, % mass

For gaseous fuels, moisture is assumed to be in a vaporous state. Water vapor from fuel (*MpWvF*) must be accounted for separately from liquid water for the energy-balance calculations.

5-3.5.3 *MqWH2F* — Moisture From the Combustion of Hydrogen in the Fuel, lbm/Btu (kg/J)

$$MqWH2F = \frac{8.937\ MpH2F}{100\ HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-66}$$

5-3.5.4 *MqCO2Sb* — Gas From Sorbent, lbm/Btu (kg/J)

$$MqCO2Sb = \frac{MFrCO2Sb}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-67}$$

5-3.5.5 *MqWSb* — Water From Sorbent, lbm/Btu (kg/J)

$$MqWSb = \frac{MFrWSb}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-68}$$

5-3.5.6 *MqWDAz* — Moisture in Dry Air, lbm/Btu (kg/J). Moisture in dry air is proportional to excess air and must be calculated for each location where excess air is determined.

$$MqWDAz = MFrWDA\ MqDAz\text{, lbm/Btu (kg/J)} \tag{5-3-69}$$

5-3.5.7 *MqWAdz* — Additional Moisture in Flue Gas, lbm/Btu (kg/J). This item accounts for any moisture added to the flue gas not accounted for above. Typical sources are atomizing steam and soot-blowing steam. Additional moisture measured on a mass flow basis is converted to a mass per mass of fuel basis for the stoichiometric calculations. For the initial calculations, either the measured or an estimated fuel rate is used. Where the quantity of additional moisture is small compared to the total moisture, this is usually sufficiently accurate. If the efficiency calculations are reiterated for other purposes, the mass fraction of additional moisture with respect to mass rate of fuel should also be corrected.

$$MqWAdz = \frac{MFrWAdz}{HHVF}\text{, lbm/Btu (kg/J)} \tag{5-3-70}$$

$$MFrWAdz = \frac{MrStz}{MrF}\text{, lbm/lbm fuel (kg/kg fuel)} \tag{5-3-71}$$

where

$MrStz$ = summation of the measured additional moisture sources entering the steam generator upstream of location z, lbm/hr

Moisture due to evaporation of water in the ash pit is considered negligible with regard to the mass flow rate of flue gas and ignored in this calculation. However, if measured, it should be included here.

5-3.5.8 *MqWFgz* — Total Moisture in Flue Gas, lbm/Btu (kg/J). The total moisture in flue gas at any location z is the sum of the individual sources.

$$MqWFgz = MqWF + MqWvF + MqWH2F + MqWSb + MqWAz + MqWAdz\text{, lbm/Btu (kg/J)} \tag{5-3-72}$$

5-3.5.9 *MqFgz* — Total Wet Flue Gas Weight, lbm/Btu (kg/J). The total wet gas weight at any location z is the sum of the dry air (less the dry gas flow correction for the oxygen in air required to form SO_3), moisture in air, wet gas from the fuel, gas from sorbent, water from sorbent, and any additional moisture

$$MqFgz = (MqDAz - MqO3ACr) + MqWAz + MqFgF + MqCO2Sb + MqWSb + MqWAdz\text{, lbm/Btu (kg/J)} \tag{5-3-73}$$

The mass flow rate of wet flue gas at any location z may be calculated from

$$\begin{aligned} MrFgz &= MqFgz\ QrF \\ &= MqFgz\ MrF\ HHVF\text{, lbm/hr (kg/s)} \end{aligned} \tag{5-3-74}$$

5-3.5.10 *MqDFgz* — Dry Flue Gas Weight, lbm/Btu (kg/J). The dry flue gas weight is the difference between the wet flue gas and the total moisture in flue gas at location z.

$$MqDFgz = MqFgz - MqWFgz\text{, lbm/Btu (kg/J)} \tag{5-3-75}$$

5-3.5.11 *MpWFgz* — Moisture in Flue Gas, Percent Mass. The percent moisture in wet flue gas is required for determining the flue gas enthalpy.

$$MpWFgz = 100\,\frac{MqWFgz}{MqFgz}\text{, \% mass} \tag{5-3-76}$$

5-3.5.12 *MpRsFg* — Residue (Solids) in Flue Gas, Percent Mass. The solids in flue gas add to the enthalpy of flue gas. When the mass of residue exceeds 15 lbm/MBtu input from fuel or when sorbent is utilized, the mass of solids in gas should be accounted for.

$$MpRsFgz = \frac{MpRsz\ MFrRs}{MqFgz\ HHVF}\text{, \% mass} \tag{5-3-77}$$

where

$MpRsz$ = total residue (solids) in the flue gas at location z, % wet gas

5-3.5.13 *DnFg* — Density of Wet Flue Gas, lbm/ft^3 (kg/m^3). The density of wet flue gas is calculated using the ideal gas relationship. Refer to para. 5-3.4 for calculation of the flue gas constituents on a volumetric basis and calculation of the density of air.

$$DnFgz = \frac{C1\ (C2Pb + PFgz)}{Rk\ (C3 + TFgz)}\text{, lbm/ft}^3\text{ (kg/m}^3\text{)} \tag{5-3-78}$$

$$Rk = \frac{R}{MwFg}\text{, }\frac{\text{ft·lbf}}{\text{lbm·°R}}\left(\frac{\text{J}}{\text{kg·K}}\right) \tag{5-3-79}$$

When the flue gas constituents have been calculated on a wet basis, the molecular weight of wet flue gas is calculated as follows:

$$\begin{aligned} MwFg = {} & 0.31999\ VpO2 + 0.4401\ VpCO2 + 0.64063\ VpSO2 + 0.28013\ VpN2F + 0.28158\ VpN2a \\ & + 0.18015\ VpH2O\text{, mass/mol} \end{aligned} \tag{5-3-80}$$

When the flue gas constituents have been calculated on a dry basis, the molecular weight of wet flue gas can be calculated as follows:

$$MwFg = (MwDFg + 0.18015\ DVpH2O)\,\frac{MoDFg}{MoFg}\text{, lbm/mol (kg/mol)} \tag{5-3-81}$$

$$\begin{aligned} MwDFg = {} & 0.31999\ DVpO2 + 0.4401\ DVpCO2 + 0.64063\ DVpSO2 \\ & + 0.28013\ DVpN2F + 0.28158\ DVpN2a\text{, mass/mol} \end{aligned} \tag{5-3-82}$$

$$DVpH2O = 100\,\frac{MoFg - MoDFg}{MoDFg}\text{, \% H}_2\text{O dry} \tag{5-3-83}$$

where

$C1$ = 5.2023 lbf/ft (1.0 J/m^3 Pa)
$C2$ = 27.68 in. wg/psi (1.0 Pa/Pa)
$C3$ = 459.7°F (273.2°C)
$MoDFg$ = moles dry gas. Refer to eq. (5-3-48) for calculation.
$MoFg$ = moles wet gas. Refer to eq. (5-3-58) for calculation.
$MwDFg$ = molecular weight of dry flue gas, lbm/mol (kg/mol)
$MwFg$ = molecular weight of wet flue gas, lbm/mol (kg/mol)
Pb = barometric pressure, psia (Pa). To convert in. Hg to psia, divide by 2.0359.

$PFgz$ = static pressure of flue gas at point z, in. wg (Pa)
R = universal molar gas constant, 1,545 ft·lbf/lbm-mol·°R (8 314.5 J/kg-mol·K)
Rk = specific gas constant for gas k, ft·lbf/lbm·°R (J/kg·K)
$TFgz$ = temperature of flue gas at point z, °F (°C)

5-3.6 *QrF* — Fuel Input, Btu/hr (W)

It is necessary to know the input from fuel in order to calculate air and gas mass flow rates. Fuel input may be calculated from the measured fuel flow and higher heating value or calculated from efficiency determined by the energy-balance method and measured output. For furnace applications that do not produce a steam output, it is necessary to use the measured fuel flow to determine input. For steam generator applications, where a measurable steam output is produced, determining fuel input from efficiency and output is the preferred method, especially for solid fuels where measuring the fuel flow is generally considered inaccurate. It is noted that for efficiency determined by the energy-balance method, the measured parameters around the air heater(s) are usually the most difficult data to obtain. Since accurate and comprehensive measurements around the air heater(s) are inherent to an air heater test, the additional instrumentation and input items required to calculate efficiency by the energy-balance method are minimal.

This subsection addresses calculation of the major efficiency losses and credits. Other minor losses may be assigned values.

The calculation of losses (and credits) falls into two categories in accordance with the method in which losses are measured and conveniently calculated. In the first category are losses that are a function of input from fuel and can be readily expressed in terms of loss per unit of input from fuel, i.e., expressed as a percentage of fuel input. Losses due to products of combustion (dry gas, water from fuel, etc.) are expressed in these units. In the second category are losses not related to fuel input, which are more readily calculated on an energy per unit of time basis, e.g., the loss due to surface radiation and convection. The losses in each category are grouped generally in order of significance and universal applicability, with applicability taking preference.

The logic for calculating losses (also applicable to credits) that are a function of fuel input is described below.

$$\begin{aligned} QpLk &= 100\ Mqk\ (HLvk - HRek) \\ &= 100\ Mqk\ MnCpk\ (TLvk - TRe),\ \% \end{aligned} \tag{5-3-84}$$

$$QpLk = 100\ \frac{\text{lbm constituent}}{\text{Btu fuel input}} \times \frac{\text{Btu}}{\text{lbm·°F}} \times \text{°F} = \frac{\text{Btu loss}}{\text{100 Btu input}},\ \% \tag{5-3-85}$$

where
$HLvk$ = enthalpy of constituent k at temperature $TLvk$, Btu/lbm (J/kg)
$HRek$ = enthalpy of constituent k at temperature TRe, Btu/lbm (J/kg). For water that enters the steam generator envelope as liquid and leaves the envelope as steam (water vapor), the ASME Steam Tables are used for enthalpy and are based on a 32°F reference temperature for enthalpy. The enthalpy of water at TRe is 45 Btu/lbm (105 kJ/kg). For all other constituents, the enthalpy is based upon the Code reference temperature of 77°F (25°C). Thus, the reference enthalpy is zero and does not appear in the loss/credit energy-balance equation as shown above.
$MnCpk$ = mean specific heat of constituent k between temperatures TRe and $TLvk$, Btu/lbm·°F (J/kg·K). Whenever practical, enthalpy is used in lieu of the mean specific heat and the difference in temperature.
Mqk = mass of constituent k per Btu input in fuel. This is the unit system used throughout this Code for items that are related to the fuel, e.g., air and gas quantities.
$QpLk$ = loss from constituent k, % of input from fuel, Btu/100 Btu input from fuel (J/100 J)
$TLvk$ = temperature of constituent k leaving the steam generator envelope, °F (°C)
TRe = reference temperature, °F (°C). The reference temperature is 77°F (25°C).

5-3.6.1 *QpLDFg* — Dry Gas Loss, Percent

$$QpLDFg = 100\ MqDFg\ HDFgLvCr,\ \% \tag{5-3-86}$$

where
$HDFgLvCr$ = enthalpy of dry gas at the temperature leaving the air heater(s), corrected for leakage (excluding leakage)
$MqDFg$ = dry gas mass flow entering the air heater(s) based on the excess air at location (14)

5-3.6.2 *QpLH2F, QpLWF, QpLWvF* — Water From Fuel Losses, Percent

$$QpLH2F = 100\ MqWH2F\ (HStLvCr - HWRe),\ \% \tag{5-3-87}$$

$$QpLWF = 100\ MqWF\ (HStLvCr - HWRe),\ \% \tag{5-3-88}$$

$$QpLWvF = 100\ MqWvF\ HWvLvCr,\ \% \tag{5-3-89}$$

where

HStLvCr = enthalpy of steam (water vapor) at 1 psia at temperature *TFgLvCr* or *TMnFgLvCr*. The enthalpy of steam (water vapor) does not vary significantly at the low partial pressures of water vapor in air or flue gas; thus, specifically calculating the actual partial pressure of water vapor is not warranted.

HWRe = enthalpy of water at the reference temperature *TRe*, Btu/lbm (J/kg)

HWvLvCr = enthalpy of water vapor at *TFgLvCr* or *TMnFgLvCr*, Btu/lbm (J/kg). The distinction of enthalpy of steam (*HSt*) versus the enthalpy of water vapor (*HWv*) is that *HSt* is the enthalpy of *vapor* with respect to *liquid* water at 32°F (0°C) as the reference in accordance with ASME Steam Tables, and includes the latent heat of vaporization of water, whereas *HWv* is the enthalpy of water *vapor* with respect to the enthalpy of water *vapor* at 77°F (25°C) as the reference (which is zero).

= $TRe - 32 = 45$, Btu/lbm

5-3.6.3 *QpLWA* — Moisture in Air Loss, Percent

$$QpLWA = 100\ MFrWDA\ MqDA\ HWvLvCr,\ \% \tag{5-3-90}$$

where

MqDA = mass of dry air corresponding to the excess air used for dry gas loss, lbm/Btu (kg/J)

5-3.6.4 *QpLUbC* — Unburned Carbon in Residue Loss, Percent. The major unburned combustible loss is due to unburned carbon in the residue. Other sources of unburned combustible loss include loss due to carbon monoxide, loss due to unburned hydrocarbons, loss due to pulverizer rejects, and loss due to unburned hydrogen in residue. These are normally minor losses and should be included in the other losses or unmeasured losses.

$$QpLUbC = MpUbC\ \frac{HHVCRs}{HHVF},\ \% \tag{5-3-91}$$

where

HHVCRs = heating value of carbon as it occurs in residue

= 14,500 Btu/lbm (33 700 kJ/kg)

For determination or estimation of *MpUbC*, see para. 5-3.3.1.

5-3.6.5 *QpLRs* — Sensible Heat of Residue Loss, Percent

$$QpLRs = \frac{MFrRs}{HHVF}\ \Sigma MpRsz\ HRsz,\ \% \tag{5-3-92}$$

where

HRsz = enthalpy of residue at location *z*, Btu/lbm (J/kg). For locations other than bottom ash, the residue can be assumed to be at gas temperature. For dry bottom ash, use 2,000°F (1 100°C) if not measured. For wet bottom ash, a typical enthalpy of 900 Btu/lbm (2 095 kJ/kg) is recommended.

MFrRs = mass of residue per mass of fuel

MpRsz = mass percent of residue at location *z*. The typical locations are bottom ash, economizer/air heater hopper, and fly ash leaving the air heater. Use the same residue split as used for determining *MpUbC* in para. 5-3.3.1.

5-3.6.6 *QpLOth* — Other Losses, Percent Basis. Other losses on a percent basis are generally small and it is recommended that the design value be used with an uncertainty of ±50%. The most typical other losses and typical values are CO (0.11% loss for 300 ppm), NO_x (0.03% loss for 250 ppm), and pulverizer rejects (0.02% loss for a 175°F mill outlet temperature). It is suggested to include the radiation loss to the ash pit with the other losses on a percent basis for simplicity. A typical value for the radiation loss to the ash pit is 0.03%.

5-3.6.7 *QrLSrc* — Surface Radiation and Convection Loss, Btu/hr (W). It is suggested that the contract value be used. For contracts with the efficiency calculated in accordance with ASME PTC 4.1, the ABMA radiation loss curve would have been used. It is suggested that if the ABMA radiation loss curve is used, the indicated loss be increased by a factor of 2.3 for coal-fired units. An uncertainty of ± 0.25% is recommended if the surface areas are not calculated in accordance with ASME PTC 4.

5-3.6.8 *QrLClh* — Calcination and Dehydration of Sorbent Loss, Btu/hr (W)

$$QrLClh = \Sigma MrSbk\ MFrClhk\ Hrk, \text{ Btu/hr (W)} \tag{5-3-93}$$

where

Hrk = heat of reaction for calcination of calcium or magnesium carbonate
= 766 Btu/lbm (1 782 kJ/kg) for $CaCO_3$ (Cc)
= 652 Btu/lbm (1 517 kJ/kg) for $MgCO_3$ (Mc)
= 636 Btu/lbm (1 480 kJ/kg) for $Ca(OH)_2$ (Ch)
= 625 Btu/lbm (1 455 kJ/kg) for $Mg(OH)_2$ (Mh)
$MFrClhk$ = mass fraction of calcination of constituent k. If not measured, use plant historical value or 0.90 for $CaCO_3$. Use 1.0 for all other constituents. An uncertainty of ±10% is recommended.
$MrSbk$ = mass flow rate of reactive constituents k, lbm/hr (kg/s)

5-3.6.9 *QrLWSb* — Water in Sorbent, Btu/hr (W)

$$QrLWSb = MrWSb\ (HStLvCr - HWRe), \text{ Btu/hr (W)} \tag{5-3-94}$$

5-3.6.10 *QrLOth* — Other Losses, Energy Basis. The most significant other loss on an energy input basis is the radiation loss to the ash pit. It may be estimated and included with the other losses on a percentage basis (see para. 5-3.6.6) or calculated in accordance with the following:

$$QrLAp = 10{,}000\ ApAf, \text{ Btu/hr (W)} \tag{5-3-95}$$

where

$ApAf$ = flat projected area of the hopper opening, ft^2 (m^2). The value of 10,000 above is the estimated radiation rate to the ash hopper. An uncertainty of ±50% is recommended.

5-3.6.11 *QpBDA* — Entering Dry Air Credit, Percent

$$QpBDA = 100\ MqDA\ HDAEn, \% \tag{5-3-96}$$

where

$HDAEn$ = enthalpy of dry air at the average air temperature entering the air heater(s).
$MqDA$ = total dry air entering the steam generator, corresponding to the excess air entering the air heater(s), lbm/Btu (kg/J)

5-3.6.12 *QpBWA* — Moisture in Entering Air Credit, Percent

$$QpBWA = 100\ MFrWDA\ MqDA\ HWvEn, \% \tag{5-3-97}$$

where

$HWvEn$ = enthalpy of water vapor at the average air temperature entering the air heater(s)

5-3.6.13 *QpBF* — Sensible Heat in Fuel Credit, Percent

$$QpBF = \frac{100}{HHVF} HFEn, \% \tag{5-3-98}$$

where

$HFEn$ = enthalpy of the fuel at the temperature of the fuel entering the steam generator envelope, Btu/lbm (J/kg)

5-3.6.14 *QpBSlf* — Sulfation Credit, Percent. Sulfation is the reaction of sulfur dioxide (SO_2) with calcium oxide (CaO) and oxygen to form calcium sulfate ($CaSO_4$). The reaction is exothermic.

$$QpBSlf = MFrSc \frac{MpSF}{HHVF} HrSlf, \% \tag{5-3-99}$$

where

$HrSlf$ = heat generated in the reaction of sulfur dioxide, oxygen, and calcium oxide to form calcium sulfate per pound of sulfur capture, 6,733 Btu/lbm (15 600 kJ/kg)

$MFrSc$ = mass fraction of sulfur capture, lbm/lbm (kg/kg). If not measured/calculated, use historical value. (An uncertainty of ±15% is recommended.)

5-3.6.15 *QpBOth* — Other Credits, Percent Basis. There are no typical other credits on a percent basis.

5-3.6.16 *QrBX* — Auxiliary Equipment Power Credit, Btu/hr (W). Typical auxiliary equipment includes pulverizers, gas recirculating fans, hot primary air fans, and boiler circulating pumps. If not measured, historical or expected credits [Btu/hr (W)] with an uncertainty of ±0.25% is recommended. Note that credits based on electrical input shall not be calculated for forced draft fans or primary air fans when the energy credit has been accounted for based on the fluid temperature rise across the fans.

$$QrBX = C1\ QX\ \frac{EX}{100}\text{, Btu/hr (W)} \tag{5-3-100}$$

where

$C1$ = 3,412 Btu/kW·h
EX = overall drive efficiency, %; includes motor efficiency, electric and hydraulic coupling efficiency, and gear efficiency
QX = average power, kW

5-3.6.17 *QrBSb* — Sensible Heat in Sorbent Credit, Btu/hr (W)

$$QrBSb = MrSb\ HSbEn\text{, Btu/hr (W)} \tag{5-3-101}$$

where

$HSbEn$ = enthalpy of the sorbent entering the steam generator envelope, Btu/lbm (J/kg)

5-3.6.18 *QrBOth* — Other Credits, Energy Basis. Other credits on an energy basis include additional moisture supplied from a source external to the steam generator, e.g., atomizing steam. Since the enthalpy of atomizing steam entering the steam generator envelope is typically approximately the same as the enthalpy of water vapor exiting the steam generator envelope, if applicable, this credit would generally be minimal (less than 0.05% on a percent basis).

5-3.6.19 *EF* — Efficiency: Energy-Balance Method. The following equation allows the direct solution of efficiency with losses and credits expressed on both a percent and energy basis:

$$EF = (100 - SmQpL + SmQpB)\left(\frac{QrO}{QrO + SmQrL - SmQrB}\right)\text{, \%} \tag{5-3-102}$$

where

$SmQpL$ and $SmQpB$ = sum of the losses and credits calculated on a percent input from fuel basis
$SmQrL$ and $SmQrB$ = sum of the losses and credits calculated on an energy basis, Btu/hr (W)

5-3.6.20 *QrF* and *MrF* — Fuel Input and Fuel Flow. Fuel input and fuel flow based upon efficiency and measured output are calculated as follows:

$$QrF = 100\left(\frac{QrO}{EF}\right)\text{, Btu/hr (W)} \tag{5-3-103}$$

$$MrF = 100\left(\frac{QrO}{EF\ HHVF}\right)\text{ lbm/hr (kg/s)} \tag{5-3-104}$$

5-4 AIR AND GAS MASS FLOW RATES

(a) Calculate total gas mass flow entering AHs stoichiometrically from input, *MrFg14*. See para. 5-3.5.9.

(b) When the individual gas velocities (or flows) entering each air heater are measured, calculate the gas flow split between multiple AHs based on the ratio of measured gas velocity pressures or mass flow rates calculated from velocity pressures and temperatures. The velocity pressure fraction of the flue gas entering air heater *n* is shown in the equation below.

$$VpFr14n = \frac{Am\ VpFg14nm}{Aam\ VpFg14a + Abm\ VpFg14b + \ldots + Azm\ VpFg14zm} \tag{5-4-1}$$

where

Am = area covered by Vp measurement nm
$VpFg14nm$ = flue gas velocity pressure at location nm

(c) Mass flow fractions are shown in the equation below.

$$MFrFg14n = \frac{MrFg14nm}{MrFg14Am + MrFg14Bm + \ldots + MrFg14zm}, \text{ lbm/lbm (kg/kg)} \tag{5-4-2}$$

where

$MFrFg14n$ = ratio of the measured mass flow rate of flue gas entering air heater n divided by the total measured flue gas mass flow rate entering the air heaters

5-4.1 Multiple AHs of the Same Type

(a) For bi-sector air heaters, calculate the airflow leaving each air heater, $MrA9n$, and total airflow leaving the air heaters, $MrA9$, by gas-side energy balance.

$$QFgAhn = MFrFg14n\ MrFg14\ (HFg14n - HFg15NLn), \text{ Btu/hr (W)} \tag{5-4-3}$$

$$QAAhn = QFgAhn = MrA9n\ (HA9n - HA8n), \text{ Btu/hr (W)} \tag{5-4-4}$$

$$MrA9n = \frac{QFgAhn}{HA9n - HA8n}, \text{ lbm/hr (kg/s)} \tag{5-4-5}$$

$$MrA9 = MrA9A + MrA9B + \ldots + MrA9n, \text{ lbm/hr (kg/s)} \tag{5-4-6}$$

where

$HA8n$ = enthalpy of air entering air heater n, Btu/lbm (J/kg)
$HA9n$ = enthalpy of air leaving air heater n, Btu/lbm (J/kg)
$HFg14n$ = enthalpy of flue gas entering air heater n, Btu/lbm (J/kg)
$HFg15NLn$ = enthalpy of flue gas leaving air heater n, excluding leakage, Btu/lbm (J/kg). When determining enthalpy, the moisture and residue in flue gas entering the air heater should be used.
$MrA9$ = total mass flow rate of air leaving the air heaters, lbm/hr (kg/s)
$MrA9n$ = mass flow rate of air leaving air heater n, lbm/hr (kg/s)
$QAAhn$ = energy absorbed by the air in air heater n, Btu/hr (W)
$QFgAhn$ = energy given up by the flue gas in air heater n, Btu/hr (W)

(b) For multi-sector air heaters, measure one airflow (usually the smaller or primary airflow). The flue gas mass flow entering the multi-sector air heater(s) is the total stoichiometric gas flow ($MrFg14$). The total airflow entering the air heater(s) is calculated by energy balance using $MrFg14$, and air and gas temperatures. The airflow stream not measured (usually the secondary airflow) is calculated by difference, i.e., subtracting the measured airflow from the total airflow. The average air temperature entering and leaving the multi-sector air heater(s) used for the energy balance is the mass-flow-weighted average temperature of the entering primary and secondary air streams (including consideration of the air leakage from the primary to secondary air stream); therefore, an iterative calculation procedure is necessary to converge on the final primary to secondary airflow splits used to calculate the average air temperatures entering and leaving. The following equations are for a tri-sector air heater and assume the primary airflow was measured, $MrA9Pm$. Note that the highest-pressure airflow stream(s) leaks air to the lower-pressure air. The manufacturer's estimated leakage rate is used in the equations.

$$QAPn = MrA9Pmn\ (HA9Pn - HA8Pn), \text{ Btu/hr (W)} \tag{5-4-7}$$

$$QASn = QFgAhn - QAPn, \text{ Btu/hr (W)} \tag{5-4-8}$$

$$MFrPAlSA = \frac{MrPAlSAEs\left(\dfrac{PDiA8PA8S}{PDiA8PA8SDs}\right)^{1/2}}{MrPAlFgEs + MrSAlFgEs}, \text{ lbm/lbm (kg/kg)} \tag{5-4-9}$$

$$MrAln = \frac{MpAln}{100}\ MpFg14n\ MrFg14, \text{ lbm/hr (kg/s)} \tag{5-4-10}$$

$$MrPAlSAn = MFrPAlSA\ MrAln, \text{ lbm/hr (kg/s)} \tag{5-4-11}$$

$$MrA9Sn = MrPAlSAn + \frac{QASn - MrPAlSAn\ (HA9Sn - HA8Pn)}{HA9Sn - HA8Sn}, \text{ lbm/hr (kg/s)} \tag{5-4-12}$$

where

$HA8Pn$ = enthalpy of primary air entering air heater n, Btu/lbm (J/kg)
$HA8Sn$ = enthalpy of secondary air entering air heater n, Btu/lbm (J/kg)
$HA9Pn$ = enthalpy of primary air leaving air heater n, Btu/lbm (J/kg)
$HA9Sn$ = enthalpy of secondary air leaving air heater n, Btu/lbm (J/kg)
$MFrPAlSA$ = ratio of primary air leakage to secondary air leakage divided by the total air-to-gas leakage, lbm/lbm (kg/kg)
$MrAln$ = mass flow rate of total air-to-gas leakage in air heater n, lbm/hr (kg/s)
$MrA9Pmn$ = measured primary airflow leaving air heater n, lbm/hr (kg/s)
$MrPAlSAEs$ = estimated mass flow rate of primary air to secondary air leakage, lbm/hr (kg/s)
$PDiA8PA8S$ = pressure differential between the entering primary air and entering secondary air, in. wg (Pa)
$PDiA8PA8SDs$ = design pressure differential between the entering primary air and entering secondary air, used to estimate $MrPAlSAEs$, in. wg (Pa)
$QAPn$ = energy absorbed by the primary air in air heater n, Btu/hr (W)
$QASn$ = energy absorbed by the secondary air in air heater n, Btu/hr (W)

5-4.2 Multiple AHs of Different Types (e.g., Primary and Secondary Air Heaters)

(a) If there is only one AH of each type (or if the multiple AHs of each type are considered as one AH), measure the airflow leaving one type (usually the smaller or primary airflow) and calculate the gas flow to that air heater type by energy balance.

$$QAPn = MrA9Pmn\ (HA9Pn - HA8Pn), \text{ Btu/hr (W)} \tag{5-4-13}$$

$$QFgPn = QAPn = MrFg14Pn\ (HFg14n - HFg15NLn), \text{ Btu/hr (W)} \tag{5-4-14}$$

$$MrFg14Pn = \frac{QAPn}{HFg14n - HFg15NLn}, \text{ lbm/hr (kg/s)} \tag{5-4-15}$$

where

$MrFg14Pn$ = mass flow rate of flue gas entering primary air heater n, lbm/hr (kg/s)
$QFgPn$ = energy given up by the flue gas in primary air heater n, Btu/hr (W)

Calculate the gas flow to the other air heater(s) by difference from total gas flow entering the air heaters. Calculate the secondary airflow by gas-side energy balance.

$$MrFg14S = MrFg14 - (MrFg14PA + MrFg14PB + \ldots + MrFg14Pn) \tag{5-4-16}$$

$$MrFg14Sn = MFrFg14Sn\ MrFg14S, \text{ lbm/hr (kg/s)} \tag{5-4-17}$$

$$QFgSn = MrFg14Sn\ (HFg14n - HFg15NLn), \text{ Btu/hr (W)} \tag{5-4-18}$$

$$QASn = QFgSn = MrA9Sn\ (HA9Sn - HA8Sn), \text{ Btu/hr (W)} \tag{5-4-19}$$

$$MrA9Sn = \frac{QFgSn}{HA9Sn - HA8Sn}, \text{ lbm/hr (kg/s)} \tag{5-4-20}$$

where

$MrFg14S$ = total mass flow rate of flue gas entering the secondary air heaters, lbm/hr (kg/s)
$QFgSn$ = energy given up by the flue gas in secondary air heater n, Btu/hr (W)

(b) If there is more than one AH of either or both types, and their performance is to be determined individually, the general procedure above is used but the stoichiometric gas flow ($MrFg14$) is divided to each air heater by one or more of the following:

(1) by energy balance if the airflow through that AH is measured

(2) by prorating the gas flow based on the ratio of measured gas velocity pressures or mass flow rates calculated from velocity pressures and temperatures

(3) by difference, i.e., total minus the gas flows calculated by (1) and/or (2)

For example, if there are two primary AHs and two secondary AHs, the airflow through the two primary AHs could be measured. The gas flow through the primary AHs could then be calculated by energy balance. The remaining gas flow could be proportioned by measuring the velocities entering the two secondary AHs.

5-5 FLUE GAS AIR HEATER CALCULATIONS

5-5.1 Performance Parameters

Conditions that affect the air heater performance and that should be given special consideration are

(a) quantity of air passing through the air heater

(b) temperature of air entering the air heater

(c) recirculating or bypassing of air to control cold-end temperature

(d) air that bypasses the air heater, e.g., boiler setting infiltration (tramp air, ingress air, etc., between the air heater air outlet and air heater gas inlet), sealing air, and, on pulverized coal-fired units, pulverizer tempering air

(e) hot side air heater leakage — condition of seals

(f) hot gas bypass — condition of seals

(g) quantity of gas (heating fluid) passing through the air heater

(h) temperature of gas (heating fluid) entering the air heater

(i) fouled, eroded, or corroded elements or tubes

(j) vapor quality of heating fluid

(k) heating fluid temperature control, including recirculation, dilution, and/or bypassing

5-5.2 *TMnA8* — Composite Entering Air Temperature

(a) Multiple Bi-Sector Air Heaters of the Same Type

$$\mathit{TMnA8} = \mathit{MFrA9A}\ \mathit{TA8A} + \mathit{MFrA9B}\ \mathit{TA8B} + \ldots + \mathit{MFrA9n}\ \mathit{TA8n} \qquad (5\text{-}5\text{-}1)$$

where the mass fraction of airflow leaving each air heater is determined as described in subsection 5-4.

(b) Multi-Sector Air Heaters. For multi-sector air heaters, the air leakage from high pressure air streams to lower pressure air streams must be accounted for.

$$\mathit{TMnA8n} = \frac{\mathit{TA8Pn}\ (\mathit{MrA9Pn} + \mathit{MrPAlSAn}) + \mathit{TA8Sn}\ (\mathit{MrA9Sn} - \mathit{MrPAlSAn})}{\mathit{MrA9Sn} + \mathit{MrA9Pn}} \qquad (5\text{-}5\text{-}2)$$

$$\mathit{MFrA9n} = \frac{\mathit{MrA9Pmn} + \mathit{MrA9Sn}}{\mathit{SmMrA9}}\text{, lbm/lbm (kg/kg)} \qquad (5\text{-}5\text{-}3)$$

$$\mathit{TMnA8} = \mathit{MFrA9A}\ \mathit{TMnA8A} + \mathit{MFrA9B}\ \mathit{TMnA8B} + \ldots + \mathit{MFrA9n}\ \mathit{TMnA8n}\text{, °F (°C)} \qquad (5\text{-}5\text{-}4)$$

where

SmMrA9 = sum of the measured primary airflows and calculated secondary airflows leaving the air heater

(c) Multiple Air Heaters of Different Types (e.g., Primary and Secondary Air Heaters)

$$\mathit{TMnA8} = \frac{\begin{pmatrix} \mathit{MrA9PmA}\ \mathit{TA8PA} + \mathit{MrA9SA}\ \mathit{TA8SA} + \mathit{MrA9PmB}\ \mathit{TA8PB} \\ + \mathit{MrA9SB}\ \mathit{TA8SB} + \ldots + \mathit{MrA9Pmn}\ \mathit{TA8Pn} + \mathit{MrA9Sn}\ \mathit{TA8Sn} \end{pmatrix}}{\mathit{SmMrA9}}\text{, °F (°C)} \qquad (5\text{-}5\text{-}5)$$

5-5.3 *TMnA9* — Composite Leaving Air Temperature

(a) Multiple Bi-Sector Air Heaters of the Same Type

$$\mathit{TMnA9} = \mathit{MFrA9A}\ \mathit{TA9A} + \mathit{MFrA9B}\ \mathit{TA9B} + \ldots + \mathit{MFrA9n}\ \mathit{TA9n}\text{, °F (°C)} \qquad (5\text{-}5\text{-}6)$$

(b) Multi-Sector Air Heaters

$$\mathit{TMnA9n} = \frac{\mathit{MrA9Sn}\ \mathit{TA9Sn} + \mathit{MrA9Pmn}\ \mathit{TA9Pn}}{\mathit{MrA9Sn} + \mathit{MrA9Pmn}} \qquad (5\text{-}5\text{-}7)$$

$$\mathit{TMnA9} = \mathit{MFrA9A}\ \mathit{TMnA9A} + \mathit{MFrA9B}\ \mathit{TMnA9B} + \ldots + \mathit{MFrA9n}\ \mathit{TMnA9n}\text{, °F (°C)} \qquad (5\text{-}5\text{-}8)$$

(c) Multiple Air Heaters of Different Types (e.g., Primary and Secondary Air Heaters)

$$TMnA9 = \frac{\left(\begin{array}{c} MrA9PmA\ TA9PA + MrA9SA\ TA9SA + MrA9PmB\ TA9PB \\ + MrA9SB\ TA9SB + \ldots + MrA9Pmn\ TA9Pn + MrA9Sn\ TA9Sn \end{array}\right)}{SmMrA9}, \text{°F (°C)} \qquad (5\text{-}5\text{-}9)$$

5-5.4 *TMnFg14* — Composite Entering Gas Temperature, °F (°C)

$$TMnFg14 = MFrFg14A\ TFg14A + MFrFg14B\ TFg14B + \ldots + MFrFg14n\ TFg14n, \text{°F (°C)} \qquad (5\text{-}5\text{-}10)$$

5-5.5 *EFFg* — Gas-Side Effectiveness

$$EFFg = \frac{TFg14 - TFg15NL}{TFg14 - TA8} \qquad (5\text{-}5\text{-}11)$$

5-5.6 *EFA* — Air-Side Effectiveness

$$EFA = \frac{TA9 - TA8}{TFg14 - TA8} \qquad (5\text{-}5\text{-}12)$$

5-5.7 *MpAl* — Percent Air Heater Leakage

$$MpAln = 100\left(\frac{MqFg15n - MqFg14n}{MqFg14n}\right), \% \qquad (5\text{-}5\text{-}13)$$

The wet gas weight entering each air heater, *MqFg14n*, and wet gas weight leaving each air heater, *MqFg15n*, are determined from the measured oxygen content in the flue gas, O_2, entering and leaving each air heater. The total air heater leakage is the sum of the weight-averaged leakages across each air heater.

5-5.8 *TFg15NL* — Gas Temperature Excluding Leakage

The air heater exit gas temperature excluding leakage, *TFg15NL*, represents the useful energy extracted from the gas as defined by the energy absorbed by the air. See Mandatory Appendix I for the energy-balance methodology.

$$TFg15NLn = TFg15n + \frac{MpAln}{100}\,\frac{CpAn}{CpFgn}\,(TA15n - TAln) \qquad (5\text{-}5\text{-}14)$$

where

CpAn = mean specific heat of air between the entering air temperature and the measured exit gas temperature, Btu/lbm·°F (J/kg·K)
CpFgn = mean specific heat of flue gas between the measured exit gas temperature and the exit gas temperature excluding leakage, Btu/lbm·°F (J/kg·K)
TAln = temperature of air heater leakage air, °F (°C). The leakage is made up of primary and secondary air streams at the average entering air temperature (*TAEn*), and air heater setting infiltration (ingress air) which is assumed to be at the same temperature (*TAEn*).
TA15n = air temperature at the measured air heater exit gas temperature
TFg15n = measured air heater exit gas, °F (°C)

For a bi-sector air heater, the leakage air temperature is the air temperature entering the air heater. For a multi-sector air heater, air passes from each entering air stream to the gas side. The weight-averaged AH leakage air temperature is estimated using the AH manufacturer's estimated split of the air-to-gas leakage from each entering air stream. For a tri-sector air heater, refer to the following equations:

$$TAln = MFrPAlFgEs\ TA8P + (1 - MFrPAlFgEs)\ TA8S, \text{°F (°C)} \qquad (5\text{-}5\text{-}15)$$

$$MFrPAlFgEs = \frac{MrPAlFgEs}{MrPAlFgEs + MrSAlFgEs}, \text{lbm/lbm (kg/kg)} \qquad (5\text{-}5\text{-}16)$$

where

MFrPAlFgEs = mass fraction of primary air-to-gas leakage, lbm primary air-to-gas leakage/lbm total air-to-gas leakage
MrPAlFgEs = estimated mass flow rate of primary air-to-gas leakage, lbm/hr (kg/s)
MrSAlFgEs = estimated mass flow rate of secondary air-to-gas leakage, lbm/hr (kg/s)

Equation (5-5-14) is the classic form for determining air heater exit gas temperature excluding leakage using measured temperatures and specific heats. It is noted that determining the specific heat of flue gas is iterative, since the exit gas temperature excluding leakage is not known initially. The exit gas temperature excluding leakage may be determined from the enthalpy of the exit gas temperature excluding leakage, which may be determined directly in accordance with the following equation:

$$HFg15NLn = HFg15n + \frac{MpAln}{100}\,(HA15n - HAln), \text{ Btu/lbm (J/kg)} \tag{5-5-17}$$

The *HAln* and *HA15n* are the enthalpy of air for the temperatures defined above, and *HFg15n* is the enthalpy of the measured flue gas at the temperature leaving the air heater, but using the moisture and residue content of the flue gas entering the air heater (the air leakage is treated as an additional stream to the gas mass flow rate entering the air heater in the equation above).

$$TFg15NL = MFrFg14A\ TFg15NLA + MFrFg14B\ TFg15NLB + \ldots + MFrFg14n\ TFg15NLn, \text{ °F (°C)} \tag{5-5-18}$$

5-5.9 Test *X*-Ratio

The ratio of the heat capacity of the air passing through the air heater to the heat capacity of the gas passing through the air heater is

$$Xr = \frac{MrA9\ CpA}{MrFg14\ CpFg} = \frac{TFg14 - TFg15NL}{TA9 - TA8} \tag{5-5-19}$$

The design *X*-ratio is obtained by using the above formula and entering the design data.

5-6 FLUE GAS AIR HEATER PERFORMANCE CORRECTED TO THE STANDARD OR DESIGN CONDITIONS

Test conditions may not correspond to the standard or design conditions. A method must be used to relate test and design conditions and to determine what standard of thermal performance will be used.

5-6.1 *TFg15NLCr* — Air Heater Exit Gas Temperature (Excluding Leakage) Corrected to Design Conditions

The exit gas temperature of each air heater is corrected in accordance with the equation below. The corrected temperatures of multiple air heaters may then be mass flow weighted using design air/gas flows to evaluate performance as a system.

$$TFg15NLCr = TFg15NL + TDiTA8 + TDiTFg14 + TDiMrFg14 + TDiXr \tag{5-6-1}$$

5-6.1.1 *TDiTA8* — Temperature Correction for Deviation From Design Entering Air Temperature

$$TDiTA8 = \frac{TA8Ds\ (TFg14 - TFg15NL) + TFg14\ (TFg15NL - TA8)}{TFg14 - TA8} - TFg15NL \tag{5-6-2}$$

where

TA8Ds = design entering air temperature

Each air heater must be corrected and then the corrected result mass flow weighted to obtain the final corrected result.

5-6.1.2 *TDiTFg14* — Temperature Correction for Deviation From Design Entering Gas Temperature

$$TDiTFg14 = \frac{TFg14Ds\ (TFg15NL - TA8) + TA8\ (TFg14 - TFg15NL)}{TFg14 - TA8} - TFg15NL \tag{5-6-3}$$

where

TFg14Ds = design entering gas temperature

Each air heater must be corrected and then the corrected result mass flow weighted to obtain the final corrected result.

5-6.1.3 *TDiMrFg14* — Temperature Correction for Deviation From Design Entering Flue Gas Mass Flow Rate. Correction to the measured gas temperature leaving the air heater for deviation from design entering flue gas mass flow rate may be made by the use of a design correction curve. This curve shall be provided by the manufacturer.

This correction curve is developed by varying the entering gas mass flow rate while holding the entering air, moisture in air, moisture in gas, and heat capacity ratio (*X*-ratio) constant at design conditions. The curve may be approximated using the procedure in Nonmandatory Appendix C. Each air heater must be corrected and then the corrected result mass flow weighted to obtain the final corrected result.

The correction curve is typically of the form of the exit gas temperature correction, *TDiMrFg14,* versus the entering flue mass flow rate, *MrFg14.*

Another format sometimes used is a correction factor, *FxFg,* versus the entering flue mass flow rate, *MrFg14.*

The exit gas temperature correction, *TDiMrFg14,* is calculated from the following equations:

$$TDiMrFg14 = TFg15Fg - TFg15NL \tag{5-6-4}$$

$$TFg15Fg = TFg14 - \frac{EFFg}{FxFg}(TFg14 - TA8) \tag{5-6-5}$$

$$FxFg = \frac{TFg14 - TFg15NL}{TFg14 - TFg15Fg} \tag{5-6-6}$$

where

$TFg15Fg$ = the exit gas temperature(s) calculated when developing the *FxFg* versus *MrFg14* correction curve

5-6.1.4 *TDiXr* — Temperature Correction for Deviation From Design *X*-Ratio (Heat Capacity Ratio). Correction to the measured gas temperature leaving the air heater for deviation from design *X*-ratio may be made by the use of a design correction curve. The heat capacity ratio not only accounts for the difference in the airflow/flue gas flow ratio between the test and design conditions, but also the difference in the specific heat of air and flue gas between the test and design conditions (see para. 5-5.9). This curve shall be provided by the manufacturer. This correction curve is developed by varying the *X*-ratio while holding the entering air, moisture in air, gas, moisture in gas, and gas mass flow rate constant at design conditions. The curve may be approximated using the procedure in Nonmandatory Appendix C. Each air heater must be corrected and then the corrected result mass flow weighted to obtain the final corrected result.

The correction curve is typically of the form of the exit gas temperature correction, *TDiXr,* versus the *X*-ratio, *Xr.*

Another format sometimes used is a correction factor, *FxXr,* versus the *X*-ratio, *Xr.*

The exit gas temperature correction, *TDiXr,* is calculated from the following equations:

$$TDiXr = TFg15Xr - TFg15NL \tag{5-6-7}$$

$$TFg15Xr = TFg14 - \frac{EFFg}{FxXr}(TFg14 - TA8) \tag{5-6-8}$$

$$FxXr = \frac{TFg14 - TFg15NL}{TFg14 - TFg15Xr} \tag{5-6-9}$$

where

$TFg15Xr$ = the exit gas temperature(s) calculated when developing the *FxXr* versus *Xr* correction curve

5-6.2 *TA9Cr* — Air Temperature Leaving the Air Heater, Corrected to Design Conditions

The air temperature leaving the air heater, corrected to design conditions, is calculated by energy balance based upon the design entering parameters and the air heater exit gas temperature corrected to design conditions. For multi-air-pass air heaters, this correction is limited to the composite air temperature of all the air passes. The correction for individual air passes may be approximated by the difference between the test composite exit air temperature and the corrected composite exit air temperature. The composite air temperature of each air heater is corrected in accordance with the equation below. The corrected temperatures of multiple air heaters may then be mass flow weighted using design air/gas flows to evaluate performance as a system.

$$HA9Cr = HA8Ds + \frac{MrFg14Ds\,(HFg14Ds - HFg15NLCr)}{MrA9Ds} \tag{5-6-10}$$

where

HA, HFg = enthalpies of air and flue gas, respectively, determined using the design moisture in air and design moisture and residue in the flue gas

$HA8Ds$ = enthalpy of entering air at design entering air temperature, *TA8Ds*

$HA9Cr$ = enthalpy of air leaving the air heater, corrected to design conditions (*TA9Cr* is determined from *HA9Cr*)

$HFg14Ds$ = enthalpy of flue gas entering at design entering gas temperature, $TFg14Ds$
$HFg15NLCr$ = enthalpy of flue gas leaving the air heater, excluding leakage, corrected to design conditions
$MrA9Ds$ = design mass flow rate of air leaving the air heater
$MrFg14Ds$ = design mass flow rate of flue gas entering the air heater

5-6.3 *MpAlCr* — Air Leakage Corrected for Deviation From Design Pressure Differential and From Design Entering Air Temperature

$$MpAlCr = 100\ MrAlCr\ /\ MrFg14Ds,\ \%$$

For a bi-sector air heater

$$MrAlCr = MrAl\left[\left(\frac{PDiSA8Fg15Ds}{PDiSA8Fg15}\right)\left(\frac{TA8S}{TA8SDs}\right)\right]^{1/2},\ \text{lbm/hr (kg/s)} \tag{5-6-11}$$

For a multi-sector air heater

$$MrAlCr = MrAl\left\{\left(\frac{MpPAlFg}{100}\right)\left[\left(\frac{PDiA8Fg15PDs}{PDiA8Fg15P}\right)\left(\frac{TA8P}{TA8PDs}\right)\right]^{1/2} + \left(\frac{100 - MpPAlFg}{100}\right)\left[\left(\frac{PDiA8Fg15SDs}{PDiA8Fg15S}\right)\left(\frac{TA8S}{TA8SDs}\right)\right]^{1/2}\right\},\ \text{lbm/hr (kg/s)} \tag{5-6-12}$$

where
$MpPAlFg$ = manufacturer's expected primary air-to-gas leakage, expressed as a percent of total air-to-gas leakage
$PDiA8Fg15P$ = static pressure difference between the primary air inlet at the duct connection flange and the gas outlet at the duct connection flange, in. wg (Pa)
$PDiA8Fg15PDs$ = design static pressure difference between the primary air inlet at the duct connection flange and the gas outlet at the duct connection flange, in. wg (Pa)
$PDiA8Fg15S$ = static pressure difference between the secondary air inlet at the duct connection flange and the gas outlet at the duct connection flange, in. wg (Pa)
$PDiA8Fg15SDs$ = design static pressure difference between the secondary air inlet at the duct connection flange and the gas outlet at the duct connection flange, in. wg (Pa)
$TA8P$ = measured entering primary air temperature (absolute), °R (K)
$TA8PDs$ = design entering primary air temperature (absolute), °R (K)
$TA8S$ = measured entering secondary air temperature (absolute), °R (K)
$TA8SDs$ = design entering secondary air temperature (absolute), °R (K)

5-6.4 *PDiFg14Fg15Cr* — Gas-Side Pressure Differential Corrected for Deviation From Design Gas Mass Flow Rate and Temperature, in. wg (Pa)

$$PDiFg14Fg15Cr = PDiFg14Fg15\left(\frac{MrFg14Ds}{MrFg14}\right)^{x}\left(\frac{TFg14Ds + TFg15Ds}{TFg14 + TFg15}\right),\ \text{in. wg (Pa)} \tag{5-6-13}$$

where
$MrFg14$ = measured/calculated mass flow rate of flue gas entering air heater, lbm/hr (kg/s)
$MrFg14Ds$ = design mass flow rate of flue gas entering air heater, lbm/hr (kg/s)
$PDiFg14Fg15$ = measured gas-side static pressure differential between the gas inlet duct connection flange and the gas outlet duct connection flange, in. wg (Pa)
$TFg14$ = measured entering gas temperature (absolute), °R (K)
$TFg14Ds$ = design entering gas temperature (absolute), °R (K)
$TFg15$ = measured exit gas temperature (absolute), °R (K)
$TFg15Ds$ = design exit gas temperature including leakage (absolute), °R (K)
x = power used for the mass flow ratio correction, which should be obtained from the air heater manufacturer. It is typically in the range of 1.7 to 1.8. The reason this is not 2.0 is that a significant portion of the air heater pressure drop is due to friction loss and the mass flow (Reynolds number) is typically in a range where the friction factor changes with mass flow.

5-6.5 *PDiA8A9Cr* — Air-Side Pressure Differential Corrected for Deviation From Design Air Mass Flow Rate and Temperature, in. wg (Pa)

$$PDiA8A9Cr = PDiA8A9\left(\frac{MrA9Ds}{MrA9}\right)^{x}\left(\frac{TA8Ds + TA9Ds}{TA8 + TA9}\right)\text{, in. wg (Pa)} \tag{5-6-14}$$

where

$MrA9$ = measured/calculated mass flow rate of air leaving the air heater, lbm/hr (kg/s)
$MrA9Ds$ = design mass flow rate of air leaving the air heater, lbm/hr (kg/s)
$PDiA8A9$ = air-side static pressure loss between the air inlet duct connection flange and the air outlet duct connection flange, in. wg (Pa)
$TA8$ = measured air temperature entering the air heater (absolute), °R (K)
$TA8Ds$ = design air temperature entering the air heater (absolute), °R (K)
$TA9$ = measured air temperature leaving the air heater (absolute), °R (K)
$TA9Ds$ = design air temperature leaving the air heater (absolute), °R (K)

5-7 UNCERTAINTY

Subsection 5-2 discussed calculation of the standard deviation of the mean and degrees of freedom for individual parameters. This subsection presents calculations for overall standard deviation of the mean and degrees of freedom for the test. This subsection also presents calculation methods for sensitivity coefficients and the random and systematic components of uncertainty. For post-test uncertainty calculations, all steam-generator performance calculations must be complete prior to the beginning of the uncertainty calculations presented in this subsection. The uncertainty calculations presented in this subsection, as well as those presented in para. 5-2.3, can be used for pretest as well as post-test uncertainty analysis.

The pretest uncertainty analysis can provide important information and reduce the effort required to calculate uncertainty after completion of a performance test. Refer to Section 7 for additional guidance on pretest uncertainty analysis. The majority of systematic uncertainty estimates can be made prior to starting a performance test. Standard deviation of the mean can be estimated based on preliminary observation of equipment operating conditions. Pretest estimates of the parameter standard deviation and degrees of freedom can be used to estimate the frequency and number of measurements required for a given variable during the test.

This subsection provides general guidelines for calculating the uncertainty associated with an air heater performance test. A more-detailed description of uncertainty analysis calculations along with derivations is included in Section 7, which should be reviewed prior to beginning any uncertainty calculations.

5-7.1 Sensitivity Coefficients

Sensitivity coefficients represent the absolute or relative effect of a measured parameter on the calculated air heater performance. Sensitivity coefficients can also be used for determining the effect of a parameter on an intermediate calculation, e.g., air heater exit gas temperature. Sensitivity coefficients are important for pretest uncertainty analysis to determine which parameters have the largest impact on the desired result (e.g. exit gas temperature, air heater leakage, pressure drop).

Sensitivity coefficients are calculated by arbitrarily perturbing the value of a parameter. The change in the value of a measured parameter can be calculated from

$$CHGPAR = \frac{PCHGPAR\ X_{AVG}}{100} \text{ or } \frac{PCHGPAR\ U}{100} \tag{5-7-1}$$

where

$CHGPAR$ = incremental change in the value of a measured parameter
$PCHGPAR$ = change in the value of a measured parameter, %. The recommended value of *PCHGPAR* is 1.0%. If the average value of the measured parameter is zero, enter any small incremental change.
U = integrated average value of a measured parameter. For development of sensitivity coefficients, care must be taken to use units that will not result in a numeric value of zero.
X_{AVG} = arithmetic average value of a measured parameter. For development of sensitivity coefficients, care must be taken to use units that will not result in a numeric value of zero.

Alternatively, e.g., when X_{AVG} is very small or zero, *CHGPAR* can be any convenient small increment of X_{AVG}.

Absolute sensitivity coefficients are calculated for each measured parameter from the following equation:

$$ASENSCO = \frac{RECALTGE - TGE}{CHGPAR} \tag{5-7-2}$$

where

$ASENSCO$ = absolute sensitivity coefficient for a measured parameter, corrected exit gas temperature excluding leakage, per measured parameter units
$RECALTGE$ = recalculated corrected exit gas temperature excluding leakage, using (X + *CHGPAR*) or (U + *CHGPAR*) in place of X (or U) while all other measured parameters are held fixed
TGE = corrected exit gas temperature excluding leakage (*TFg15NLCr*), calculated for the actual (measured) parameter

The above equation gives the sensitivity coefficient associated with the corrected exit gas temperature. However, this form of equation can be used for any calculated result, e.g., air heater leakage, pressure drop, etc., by substituting the result for *TGE* and *RECALTGE.*

Relative sensitivity coefficients are calculated for each measured parameter from the following equation:

$$RSENSCO = \frac{ASENSCO\ X_{AVG}}{TGE} \text{ or } \frac{ASENSCO\ U}{TGE} \tag{5-7-3}$$

where

$RSENSCO$ = relative sensitivity coefficient for a measured parameter, % change in result per % change in measured parameter
TGE = corrected exit gas temperature (or other desired uncertainty parameter, e.g., air heater leakage), calculated for the actual (measured) parameter

The above equation is shown for corrected exit gas temperature but can be used for other calculated results.

5-7.2 Random Uncertainty and Degrees of Freedom

The standard deviation of the mean (random uncertainty) of the calculated steam generator efficiency is obtained by combining the standard deviation of the mean of all measured parameters according to the root-sum-square rule.

$$STDDEVMN_R = \sum_{i=1}^{n}[(ASENSCO_i\ STDDEVMN_i)^2]^{1/2} \tag{5-7-4}$$

where

$ASENSCO_i$ = absolute sensitivity coefficient for measured parameter i
n = number of measured parameters
$STDDEVMN_i$ = standard deviation of the mean for measured parameter i
$STDDEVMN_R$ = overall random uncertainty (standard deviation of the mean) of result

The number of degrees of freedom for the overall test result is calculated from the following equation:

$$DEGFREE_R = \frac{STDDEV_R^4}{\displaystyle\sum_{i=1}^{n}\frac{(ASENSCO_i\ STDDEVMN_i)^4}{DEGFREE_i}} \tag{5-7-5}$$

where

$DEGFREE_i$ = degrees of freedom for measured parameter i
$DEGFREE_R$ = overall number of degrees of freedom for test

5-7.3 Random Component of Uncertainty

The random component of uncertainty, *URC,* is calculated from the standard deviation of the mean and degrees of freedom of the result using the following equation:

$$URC = STDTVAL\ STDDEVMN_R \tag{5-7-6}$$

5-7.4 Systematic Uncertainty

Systematic uncertainty calculations are estimated based on the method used to determine the values of a measured parameter. Recommended procedures for estimating systematic uncertainty are presented in Sections 4 and 7. Elementary systematic uncertainties for each measured parameter are combined according to the root-sum-square rule

$$SYS_i = \left(\sum_{j=1}^{m} SYS_j^2 \right)^{1/2} \tag{5-7-7}$$

where

m = number of components in the measurement system of parameter i

SYS_i = systematic uncertainty limit of measured parameter i. The units of systematic uncertainty are the same as the units of the measured parameter.

SYS_j = systematic uncertainty of individual components j used to determine the value of parameter i. The units of systematic uncertainty are the same as the units of the measured parameter.

NOTE: "Measure" and "measurement system" are used in a general sense and do not exclude estimation of parameters.

The degrees of freedom for systematic uncertainties shall be taken as 50, corresponding to a probable range of 10% in estimates of systematic uncertainty (see para. 7-5.5).

5-7.4.1 Systematic Uncertainties Associated With Spatially Nonuniform Parameters. The systematic uncertainties associated with spatially nonuniform parameters that vary in both space and time are discussed in detail in Sections 4 and 7. Section 7 presents models that can be used to estimate the systematic uncertainty associated with these types of parameters. These models use a variable called spatial distribution index (*SDI*). Spatial distribution index is calculated from the following equation:

$$SDI = \left[\frac{1}{n} \sum_{i=1}^{n} (z_i - Z)^2 \right]^{1/2} \tag{5-7-8}$$

The following equation is suggested for numerical integration:

$$SYSNI = \left[\frac{CS}{(n-1)^{1/2}} \right] SDI \tag{5-7-9}$$

where

CS = coefficient selected by the Code committee based on mathematical simulation as an estimate to achieve a 95% confidence level; listed in Table 7-5.3.2-1

n = number of points in the measurement grid

SDI = spatial distribution index

$SYSNI$ = systematic uncertainty from numerical integration

Z = integrated average value of z

z = time-averaged value of the measured parameter

It should be noted that although *SDI* is calculated identically to standard deviation, there is a significant statistical difference between the two variables.

5-7.4.2 Systematic Uncertainty of Result. The systematic uncertainty of a result is also calculated according to the root-sum-square rule

$$SYS_R = \left[\sum_{i=1}^{n} (ABSENCO_i \; SYS_i)^2 \right]^{1/2} \tag{5-7-10}$$

where

SYS_R = overall systematic uncertainty of the test result

The systematic uncertainty of the result can be positive and/or negative. If the positive and negative systematic uncertainties are not symmetrical, the positive and negative values must be calculated separately. The sign of the product $ABSENCO_i \; SYS_i$ determines whether the term is summed with the positive or negative systematic uncertainties.

5-7.5 Test Uncertainty

The test uncertainty is calculated from the overall random and systematic uncertainty components

$$UNC = STDTVAL\left[URC^2 + \left(\frac{SYS_R}{2}\right)^2\right]^{1/2} \tag{5-7-11}$$

where

$STDTVAL$ = two-tailed Student's t value evaluated for the degrees of freedom of the result ($DEGFREE_{UNC}$)

UNC = test uncertainty

The two-tailed Student's t value is based on the 95th percentile point distribution and the degrees of freedom of the result. Table 5-7.5-1 shows the Student's t value as a function of degrees of freedom. Interpolation in the table is done using reciprocal degrees of freedom.

A curve fit for t is

$$t = 1.959 + \frac{2.372}{DEGFREE} + \frac{3.121}{DEGFREE^2} + \frac{0.799}{DEGFREE^3} + \frac{4.446}{DEGFREE^4} \tag{5-7-12}$$

The number of degrees of freedom for the overall test result is calculated from the following equation:

$$DEGFREE_{UNC} = \frac{\left[\left(\frac{SYS_R}{2}\right)^2 + (URC)^2\right]^2}{\frac{URC^4}{DEGFREE_R} + \frac{\left(\frac{SYS_R}{2}\right)^4}{50}} \tag{5-7-13}$$

The total uncertainty must be calculated separately for both positive and negative ranges if the systematic uncertainties are not symmetrical.

5-8 AIR PREHEATER COILS

This Code is limited to air preheater coils utilizing noncondensing (single phase) steam, water, or other hot fluids. For condensable heating fluids, some degree of superheat must exist at the hot fluid exit for meaningful results, i.e., there must be no condensation for the energy-balance equations presented in this subsection to be applicable. The pretest agreements shall stipulate some arbitrary degree of superheat. A value on the order of 10°F (5°C) superheat is recommended by this Code.

5-8.1 Items to Be Measured

Measure the following:

(a) *MrA8* (airflow leaving). It is assumed that there is no air bypass, leakage, or ingress air. Therefore, $MrA8 = MrA7$. If the air preheater coil is tested in conjunction with the main combustion gas-to-air heat exchanger, the airflow entering the combustion gas air heater may be used for *MrA8*.

(b) *TA7* (air temperature entering), °F (°C)

(c) *TA8* (air temperature leaving), °F (°C)

(d) *PA7* (air pressure entering), in. wg (Pa)

(e) *PA8* (air pressure leaving), in. wg (Pa)

(f) *THFEn* (temperature of the hot fluid entering), °F (°C)

(g) *THFLv* (temperature of the hot fluid leaving), °F (°C)

(h) *PHFEn* (pressure of the hot fluid entering), psig (Pa)

(i) *PHFLv* (pressure of the hot fluid leaving), psig (Pa)

(j) *MrHF* (mass flow rate of the hot fluid), lbm/hr (kg/s). This item is optional, as it can normally be calculated by energy balance.

5-8.2 *TA8Cr* — Air Temperature Leaving the Air Heater, Corrected to Standard or Design Conditions

The air heater corrections to obtain the corrected air temperature are essentially the same as the corrections for the combustion gas-to-air heat exchanger to obtain the corrected exit gas temperature excluding leakage

$$TA8Cr = TA8 + TDiTA7 + TDiTHFEn + TDiMrA8 + TDiXr \tag{5-8-1}$$

Air preheating coils are usually designed for extremely cold temperatures compared to the time of testing. The primary purpose of correcting the air heater air outlet temperature is to determine their performance with the design entering cold air temperature. The major correction will be the *X*-ratio correction. It is necessary to obtain an *X*-ratio (and entering air mass flow rate) correction curve from the manufacturer. See paras. 5-8.2.4 and 5-8.2.5.

5-8.2.1 *EFA* — Air Heater Air-Side Effectiveness. It is a reasonable assumption that at constant mass flow, changes in temperature (i.e., changes in physical properties) have an insignificant effect on heat-exchanger effectiveness. The air-side effectiveness is used as the criterion for correcting the air heater outlet air temperature below for entering air temperature and entering hot-fluid temperature.

$$EFA = \frac{TA8 - TA7}{THFEn - TA7} \tag{5-8-2}$$

5-8.2.2 *TDiTA7* — Temperature Correction for Deviation From Design Entering Air Temperature. Based on the assumption that air-side effectiveness does not change substantially with deviations in entering air temperature and the relationships

$$EFA = \frac{TA8 - TA7}{THFEn - TA7} = \frac{TA8Cr - TA7}{THFEn - TA7Ds} \tag{5-8-3}$$

the temperature correction for entering air temperature can be reduced to the following:

$$TDiTA7 = (TA7Ds - TA7)\,(1 - EFA) \tag{5-8-4}$$

5-8.2.3 *TDiHFEn* — Temperature Correction for Deviation From Design Entering Hot Fluid Temperature. Based on the assumption that air-side effectiveness does not change substantially with deviations in entering hot fluid temperature and the relationships

$$EFA = \frac{TA8 - TA7}{THFEn - TA7} = \frac{TA8Cr - TA7}{THFEnDs - TA7} \tag{5-8-5}$$

the temperature correction for the hot fluid temperature entering can be reduced to the following:

$$TDiTHFEn = (THFEnDs - THFEn)\,(1 - EFA) \tag{5-8-6}$$

5-8.2.4 *TDiMrA8* — Temperature Correction for Deviation From Design Airflow. Correction to the measured air temperature leaving the air heater for deviation from design air mass flow rate may be made by the use of a design correction curve. This curve shall be provided by the manufacturer. This correction is developed by varying the air mass flow rate while holding the heat capacity ratio (*X*-ratio) constant.

5-8.2.5 *TDiXr* — Temperature Correction for Deviation From Design *X*-Ratio (Heat Capacity Ratio). When the heating fluid is a liquid, a noncondensable gas, or remains superheated vapor throughout the air preheating coil, correction to the air temperature may be made by the use of an *X*-ratio correction curve supplied by the manufacturer. The heat capacity ratio accounts for not only the difference in the airflow/hot fluid medium flow ratio between the test and design conditions, but also the difference in the specific heat of the two fluids between the test and design conditions. The correction curve is developed by varying the *X*-ratio while holding the air mass flow rate constant.

The *X*-ratio is defined by

$$Xr = \frac{MrA8\ CpA}{MrHF\ CpHF} = \frac{THFEn - THFLv}{TA8 - TA7} \tag{5-8-7}$$

If the hot fluid is condensable, the hot fluid leaving, *THFLv*, must be an agreed-upon temperature above saturation; 10°F (5°C) if not agreed upon by the parties to the test.

5-8.3 *PDiA7A8Cr* — Air-Side Pressure Differential Corrected for Deviation From Design Air Mass Flow Rate and Temperature

$$PDiA7A8Cr = PDiA7A8 \left(\frac{MrA8Ds}{MrA8}\right)^{x} \left(\frac{TA7Ds + TA8Ds}{TA7 + TA8}\right), \text{ in. wg (Pa)} \tag{5-8-8}$$

where

$PDiA7A8$ = air-side static pressure loss between the air inlet duct and air outlet duct connection flange, in. wg (Pa)

x = power used for the mass flow ratio, typically 2; however, it should be verified by the air heater manufacturer. It could be lower if a significant portion of the air preheater pressure drop is due to friction loss and the mass flow (Reynolds number) is in a range where the friction factor changes with mass flow.

5-9 ENTHALPY/SPECIFIC HEAT OF AIR, FLUE GAS, WATER VAPOR, AND RESIDUE

The specific energy (energy per unit mass) of many different flow streams is required for complete air heater test calculations. However, the most prominent requirement is for air and flue gas. For a complete reference on this subject, refer to subsection 5-19 in ASME PTC 4, which includes the constituents of all the gaseous products found in combustion of fossil fuels and the coefficients for a fifth-order curve fit for each constituent.

For convenience of hand calculations, we are presenting enthalpy of air, dry flue gas, and related substances based on second-order curve fits. These were developed from the same correlations as used in ASME PTC 4. U.S. Customary units of Btu/lbm are used for the curve fits. Compared to ASME PTC 4 higher-order correlations, the uncertainty of the enthalpy determined with these second-order curve fits is less than 0.1%. The higher-order correlations in ASME PTC 4 may be used in lieu of the curve fits presented in this Code.

The basic equation for the enthalpy of each substance is

$$H_n = A + B\,T + C\,T^2,\ \text{Btu/lbm (J/kg)}$$

where temperature, T, is in degrees Fahrenheit. The coefficients for the enthalpies covered are found in Table 5-9-1.

Frequently, changes in specific energy are calculated using the specific heat, C_p, and temperature difference. This Code recommends that the mean specific heat be determined based on the difference in enthalpy divided by the difference in temperature

$$MnCp = \frac{HLv - HEn}{TLv - TEn},\ \frac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{F}}$$

5-9.1 Enthalpy of Air

The enthalpy of air is a function of the mass of the mixture of dry air and water vapor in the air. To determine the enthalpy of dry air, use a water vapor content of zero.

$$HA = (1 - MFrWA)\,HDA + MFrWA\,HWv,\ \text{Btu/lbm (J/kg)} \tag{5-9-1}$$

$$MFrWA = \frac{MFrWDA}{1 + MFrWDA},\ \text{lbm Wv/lbm wet air (kg Wv/kg wet air)} \tag{5-9-2}$$

where

HA = enthalpy of wet air, Btu/lbm (J/kg)

HDA = enthalpy of dry air, Btu/lbm (J/kg)

HWv = enthalpy of water vapor, Btu/lbm (J/kg)

$MFrWA$ = mass fraction of water vapor in wet air, lbm Wv/lbm wet air (kg Wv/kg wet air)

$MFrWDA$ = mass fraction of water vapor in dry air, lbm Wv/lbm DA (kg Wv/kg DA). This is the standard method for expressing moisture in air.

5-9.2 Enthalpy of Flue Gas

Coefficients for dry flue gas are based on a flue gas composition of 15.3% CO_2, 3.5% O_2, 0.1% SO_2, and 81.1% atmospheric nitrogen by volume. The enthalpy of *dry* flue gas does not vary significantly for fossil fuels because atmospheric nitrogen is the predominant component. It varies from 80% for coal to approximately 88% for natural gas. The difference is predominantly CO_2 and O_2, which have similar heat capacity characteristics that are not significantly different from those of atmospheric nitrogen. For typical hydrocarbon fuels combusted with less than 300% excess air, the following coefficients are sufficiently accurate for most heat transfer calculations.

The enthalpy of dry flue gas may be determined based upon the actual flue gas composition during the test period if desired. For unusual fuels, e.g., manufactured gases, hydrogen, and/or combustion processes utilizing an oxidizing medium other than air, the enthalpy of dry flue gas shall be determined based upon the actual average composition of the actual flue gas. Refer to ASME PTC 4, para. 5-19.11.

Wet flue gas as defined by this Code is composed of the dry gaseous products of combustion and water vapor. Solid residue may also be entrained in the gas stream. It should be considered if sorbent is used or if greater than 15 lbm/MBtu. The enthalpy of wet flue gas accounts for the enthalpy of all these complements. If the enthalpy of dry flue gas is desired, the water and solid residue components are zero.

$$HFg = (1 - MFrWFg)\ HDFg + MFrWFg\ HWv + MFrRsFg\ HRs,\ \text{Btu/lbm (J/kg)} \tag{5-9-3}$$

where

$HDFg$ = enthalpy of dry flue gas, Btu/lbm (J/kg)
HFg = enthalpy of wet flue gas, Btu/lbm (J/kg)
HRs = enthalpy of residue, Btu/lbm (J/kg)
HWv = enthalpy of water vapor, Btu/lbm (J/kg)
$MFrRsFg$ = mass fraction of residue in wet gas, lbm Rs/lbm wet gas (kg/kg). Refer to para. 5-3.5.12 for calculation on a percentage basis. Divide by 100 to obtain the mass fraction.
$MFrWFg$ = mass fraction of water in wet gas, lbm H_2O/lbm wet gas (kg/kg). Refer to para. 5-3.5.11 for calculation on a percentage basis. Divide by 100 to obtain the mass fraction.

5-10 ACRONYMS AND SYMBOLS

5-10.1 Air Heater/Air Preheater Boundaries

7:	air entering air preheater coil
8:	air entering air heater
9:	air leaving air heater
14:	gas entering air heater
15:	gas leaving air heater
HF:	hot fluid entering or leaving air preheater coil

Note that acronyms in this Section are arranged in the following sequence: property > stream > location.

For example, in a multi-sector air heater, *MrSAlFg* refers to the mass flow of secondary air leakage to the flue gas stream. Similarly, *TA9* refers to the temperature of the air stream at location 9 (the air heater air outlet).

5-10.2 Computational Acronyms Used in Section 5

See Table 5-10.2-1.

5-10.3 Uncertainty Acronyms Used in Section 5

See Table 5-10.3-1.

Table 5-7.5-1 Two-Tailed Student's *t* Table for the 95% Confidence Level

Degrees of Freedom	*t*	Degrees of Freedom	*t*
1	12.706	16	2.120
2	4.303	17	2.110
3	3.182	18	2.101
4	2.776	19	2.093
5	2.571	20	2.086
6	2.447	21	2.080
7	2.365	22	2.074
8	2.306	23	2.069
9	2.262	24	2.064
10	2.228	25	2.060
11	2.201	26	2.056
12	2.179	27	2.052
13	2.160	28	2.048
14	2.145	29	2.045
15	2.131	30 or more	1.960

Table 5-9-1 Enthalpy Curve Fit Coefficients, Btu/lbm

Quantity	*A*	*B*	*C*	Temperature Range, °F
Dry air	−18.4743	0.239517	4.49169 E−06	0 to 250
Dry air	−17.6198	0.233660	1.44305 E−05	Over 250 to 1,000
Water vapor	−34.1850	0.442076	2.29150 E−05	0 to 250
Water vapor	−32.5905	0.431066	4.15202 E−05	Over 250 to 1,000
Water vapor	−28.7144	0.421885	4.68505 E−05	Over 1,000 to 1,500
Dry flue gas	−17.9132	0.231809	1.83275 E−05	100 to 800
Dry flue gas	−19.6351	0.235349	1.66272 E−05	Over 800 to 1,500
Residue	−13.7115	0.170656	8.16198 E−05	100 to 350
Residue	−16.3568	0.187639	5.44056 E−05	Over 350 to 900
Residue	−33.2975	0.219433	3.98828 E−05	Over 900 to 1,340
Residue	−17.5314	0.204644	2.24942 E−05	Over 1,340 to 1,500

Table 5-10.2-1 Computational Acronyms

Acronym	Description	Units
ApAf	Flat projected area of the ash hopper throat opening	ft^2 (m^2)
Ca(OH)2	Calcium hydroxide	mass/mol
CaCO3	Calcium carbonate	mass/mol
CpA	Specific heat of air	Btu/lbm·°F (J/kg°C)
CpFg	Specific heat of flue gas	Btu/lbm·°F (J/kg·K)
CpHf	Specific heat of the hot fluid to air preheater coils	Btu/lbm·°F (J/kg°C)
DnA	Density of air	lbm/ft^3 (kg/m^3)
DnFg	Density of wet flue gas	lbm/ft^3 (kg/m^3)
DnGF	Density of gaseous fuel	lbm/scf (kg/N·m^3)
DVpCO2	Carbon dioxide in the flue gas	% dry volume
DVpN2a	Atmospheric nitrogen in the flue gas	% dry volume
DVpN2F	Nitrogen from fuel in the flue gas	% dry volume
DVpO2	Oxygen concentration in the flue gas	% dry volume
DVpSO2	Sulfur dioxide in the flue gas	% dry volume
EF	Efficiency by the energy-balance method	% fuel input
EFA	Air-side effectiveness	Dimensionless
EFFg	Gas-side effectiveness	Dimensionless
EX	Overall drive efficiency; includes motor efficiency, electric and hydraulic coupling efficiency, and gear efficiency	%
FxFg	Correction factor for off design flue gas flow; from curve	Dimensionless
FxXr	Correction factor for off design *X*-ratio; from curve	Dimensionless
HA	Enthalpy of wet air	Btu/lbm (J/kg)
HA15	Enthalpy of air at the temperature *TFg15*	Btu/lbm (J/kg)
HA8Cr	Enthalpy of wet air entering the air heater, corrected to design conditions	Btu/lbm (J/kg)
HA8Ds	Enthalpy of entering air at design entering air temperature	Btu/lbm (J/kg)
HA9Cr	Enthalpy of air leaving the air heater corrected to design conditions	Btu/lbm (J/kg)
HAz	Enthalpy of air at location *z* (e.g., 7, 8, or 9)	Btu/lbm (J/kg)
HAzP	Enthalpy of primary air at location *z* (e.g., 7, 8, or 9)	Btu/lbm (J/kg)
HAzS	Enthalpy of secondary air at location *z* (e.g., 7, 8, or 9)	Btu/lbm (J/kg)
HDAEn	Enthalpy of dry air at the average entering air temperature	Btu/lbm (J/kg)
HDFgLvCr	Enthalpy of dry gas at the temperature leaving the air heater(s), excluding leakage	Btu/lbm (J/kg)
HFEn	Enthalpy of fuel at the entering temperature of fuel	Btu/lbm (J/kg)
HFg	Enthalpy of wet flue gas	Btu/lbm (J/kg)
HFg14Ds	Enthalpy of flue gas entering at design entering gas temperature	Btu/lbm (J/kg)
HFg15NL	Enthalpy of flue gas leaving the air heater, excluding leakage	Btu/lbm (J/kg)
HFg15NLCr	Enthalpy of flue gas leaving the air heater, excluding leakage, corrected to design conditions	Btu/lbm (J/kg)
HFgz	Enthalpy of flue gas at location *z* (e.g., 14 or 15)	Btu/lbm (J/kg)
HHVCRs	Higher heating value of carbon as it occurs in residue	Btu/lbm (kJ/kg)
HHVFcv	Higher heating value of the fuel on a constant volume basis	Btu/lbm (J/kg)
HLvk	Enthalpy of constituent *k* leaving	Btu/lbm (J/kg)
HRek	Enthalpy of constituent *k* at the reference temperature, *TRe*	Btu/lbm (J/kg)
Hrk	Heat of reaction for constituent *k*	Btu/lbm (J/kg)
HrSlf	Heat generated due to sulfation	Btu/lbm (kJ/kg)
HSbEn	Enthalpy of the sorbent entering	Btu/lbm (J/kg)
HStLvCr	Enthalpy of steam (per ASME Steam Tables) at the corrected exit gas temperature (*TFgLvCr* or *TMnFgLvCr*)	Btu/lbm (J/kg)
HWRe	Enthalpy of water (per ASME Steam Tables) at the reference temperature, *TRe*	Btu/lbm (J/kg)
HWvLvCr	Enthalpy of water vapor (per JANAF/NASA) at the corrected exit gas temperature (*TFgLvCr* or *TMnFgLvCr*)	Btu/lbm (J/kg)
MFrClhk	Mass fraction of calcination of constituent *k*	mass CO$_2$/mass constituent
MFrCO2Sb	Mass fraction of gas (CO$_2$) from sorbent	lbm/lbm fuel (kg/kg)
MFrFg14n	Ratio of the measured mass flow rate of the flue gas entering air heater *n* to the total measured mass flow rate entering the air heaters	lbm/lbm (kg/kg)
MFrH2OSb	Mass fraction of the water in sorbent	lbm/lbm fuel (kg/kg)
MFrO3ACr	Mass fraction of oxygen from air required to form SO$_3$ in the sulfation process	lbm/lbm (kg/kg)
MFrPAlFgEs	Estimated mass fraction of primary air-to-gas leakage	lbm (kg)
MFrPAlSAEs	Ratio of primary air leakage to secondary air leakage, divided by total air-to-gas leakage	lbm/lbm (kg/kg)
MFrRs	Mass fraction of residue	lbm/lbm fuel (kg/kg)

Table 5-10.2-1 Computational Acronyms (Cont'd)

Acronym	Description	Units
MFrRsFg	Mass fraction of residue in wet gas	lbm Rs/lbm wet gas (kg/kg)
MFrSb	Mass fraction of sorbent	lbm/lbm fuel (kg/kg)
MFrSbk	Mass fraction of constituent *k* in sorbent	lbm/lbm fuel (kg/kg)
MFrSc	Mass fraction of sulfur capture	lbm/lbm fuel (kg/kg)
MFrSO3	Mass fraction of SO_3 formed in the sulfation process	lbm/lbm fuel (kg/kg)
MFrSsb	Mass fraction of spent sorbent	lbm/lbm fuel (kg/kg)
MFrThA	Theoretical air, ideal	mass/mass fuel
MFrThACr	Mass of theoretical air (corrected for unburned carbon and O_3 required to form SO_3 in the sulfur capture process if sorbent is used)	mass/mass fuel
MFrWA	Mass fraction of moisture in wet air	lbm H_2O/lbm wet air (kg/kg)
MFrWAdz	Additional moisture at location *z*; mass fraction of fuel basis	mass/mass fuel
MFrWDA	Mass fraction of moisture in dry air. This is the standard method for expressing moisture in air (moisture in air or flue gas is also referred to as humidity ratio in Section 4 and the symbol is *W*).	mass H_2O/mass dry air
MFrWFg	Mass fraction of water in wet gas	lbm H_2O/lbm wet gas (kg/kg)
MFrWSb	Mass fraction of total water from sorbent per mass of fuel	mass/mass fuel
Mg(OH)2	Magnesium hydroxide	mass/mol
MgCO3	Magnesium carbonate	mass/mol
MnCpk	Mean specific heat of constituent *k*	Btu/lbm·°F (J/kg·K)
MoCO2Sb	Moles of gas (CO_2) from sorbent	mol/mass fuel
MoDFg	Moles of dry gas	mol/mass fuel
MoDPc	Moles of dry products from the combustion of fuel	mol/mass fuel
MoFg	Moles of wet gas per mass fuel	mol/mass fuel
MoFrCaS	Calcium-to-sulfur molar ratio	mol/mol
MoFrClhk	Calcination fraction for constituent *k*	mol CO_2/mol constituent
Mokj	Moles of constituent *k* in fuel component *j*	mol/mass fuel
MoO3ACr	Dry gas flow correction for oxygen in air required to form SO_3	mol/mass fuel
MoThACr	Moles of theoretical air (corrected for unburned carbon and O_3 required to form SO_3 in the sulfur capture process if sorbent is used)	mol/mass fuel as-fired
MoWA	Moles of moisture in air	mol H_2O/mol dry air
MoWPc	*MoDPc* plus moles H_2O from fuel, sorbent, and any additional H_2O	mol/mass fuel
MoWSb	Total moles of water from sorbent	mol/mass fuel
MpAl	Air to gas air heater leakage, percent of entering gas mass flow rate	% mass
MpAlCr	Air to gas leakage, corrected to design conditions	% mass
MpAsF	Percent ash in fuel	% mass
MpCak	Percent of calcium in sorbent in form of constituent *k*	% mass
MpCb	Percent carbon burned	% mass
MpCF	Percent carbon in fuel	% mass
MpCO2Rs	Percent carbon dioxide in residue	% mass
MpCRs	Percent unburned carbon in the residue	% mass
MpFk	Mass percentage of constituent *k* in fuel	% mass
MpH2F	Percent hydrogen in fuel	% mass
MpO2F	Percent oxygen in fuel	% mass
MpPAlFgEs	Manufacturer's expected primary air-to-gas leakage, adjusted for pressure drop between the entering primary air and exiting flue gas	% of total leakage
MpRsFg	Percent residue (solids) in flue gas	% mass
MpSF	Percent sulfur in fuel	% mass
MpToCRs	Percent total carbon in residue; includes CO_2	% mass
MpUbC	Percent unburned carbon in fuel	% mass
MpWF	Percent water in fuel	% mass
MpWFgz	Percent moisture in flue gas at location *z*	% mass
MqCO2Sb	Mass of gas (CO_2) from calcination of sorbent on an input from fuel basis	lbm/Btu (kg/J)
MqDA	Mass of dry air on an input from fuel basis	lbm/Btu (kg/J)
MqDAz	Mass dry air at location *z* on an input from fuel basis	lbm/Btu (kg/J)
MqDFgz	Mass dry flue gas at location *z* on an input from fuel basis	lbm/Btu (kg/J)
MqFgF	Wet gas from fuel on an input from fuel basis	lbm/Btu (kg/J)
MqFgz	Total wet flue gas weight at location *z* on an input from fuel basis	lbm/Btu (kg/J)
Mqk	Mass of constituent *k* per unit input in fuel	lbm/Btu (kg/J)
MqO3ACr	Dry gas flow correction for the O_3 in air required to form SO_3 on an input from fuel basis	lbm/Btu (kg/J)
MqThA	Typical value of theoretical air for fuel (ideal) on an input from fuel basis	lbm/Btu (kg/J)

Table 5-10.2-1 Computational Acronyms (Cont'd)

Acronym	Description	Units
MqThAAd	Additional theoretical air due to sulfur capture/retention on an input from fuel basis	lbm/Btu (kg/J)
MqThACr	Theoretical air on input from fuel basis (corrected for unburned carbon and O$_3$ required to form SO$_3$ in the sulfur capture process if sorbent is used)	lbm/Btu (kg/J)
MqWAdz	Additional moisture at location *z* on an input from fuel basis	lbm/Btu (kg/J)
MqWAz	Moisture in air on an input from fuel basis	lbm/Btu (kg/J)
MqWF	Moisture from H$_2$O (water) in fuel on an input from fuel basis	lbm/Btu (kg/J)
MqWFgz	Total moisture in flue gas on an input from fuel basis	lbm/Btu (kg/J)
MqWH2F	Moisture from the combustion of hydrogen in the fuel on an input from fuel basis	lbm/Btu (kg/J)
MqWSb	Mass of total water from sorbent on an input from fuel basis	lbm/Btu (kg/J)
MqWvF	Moisture from H$_2$O (water vapor) in fuel on an input from fuel basis	lbm/Btu (kg/J)
MrA	Mass flow rate of wet air, general	lbm/hr (kg/s)
MrA9Ds	Design mass flow rate of air leaving the air heater	lbm/hr (kg/s)
MrA9Pm	Measured primary airflow leaving the air heater	lbm/hr (kg/s)
MrAl	Mass flow rate of total air-to-gas leakage in air heater	lbm/hr (kg/s)
MrAz	Mass flow rate of wet air at location *z*	lbm/hr (kg/s)
MrAzDs	Design mass flow rate of wet air at location *z*	lbm/hr (kg/s)
MrF	Mass flow rate of fuel	lbm/hr (kg/s)
MrFg14Ds	Design mass flow rate of flue gas entering the air heater	lbm/hr (kg/s)
MrFg14S	Total mass flow rate of flue gas entering the secondary air heaters	lbm/hr (kg/s)
MrFgz	Mass flow rate of wet flue gas at location *z*	lbm/hr (kg/s)
MrFgzDs	Design mass flow rate of wet flue gas at location *z*	lbm/hr (kg/s)
MrHF	Mass flow rate of the hot fluid entering air preheat coils	lbm/hr (kg/s)
MrPAlFgEs	Estimated mass flow rate of primary air-to-gas leakage	lbm/hr (kg/s)
MrPAlSAEs	Estimated mass flow rate of primary air to secondary air leakage	lbm/hr (kg/s)
MrSAlFgEs	Estimated mass flow rate of secondary air-to-gas leakage	lbm/hr (kg/s)
MrSb	Measured mass flow rate of sorbent	lbm/hr (kg/s)
MrSbk	Mass flow rate of reactive sorbent constituent *k*	lbm/hr (kg/s)
MrStz	Summation of the measured additional moisture sources	lbm/hr (kg/s)
MrWSb	Mass flow rate of total water from sorbent	lbm/hr (kg/s)
MvFk	Mass of constituent *k* per unit volume of fuel	lbm/mol fuel or lbm/ft^3 fuel (kg/mol or kg/m^3)
MwA	Molecular weight of wet air	mass/mol
MwCak	Molecular weight of calcium compound *k*	mass/mol
MwDFg	Molecular weight of dry flue gas	mass/mol
MwFg	Molecular weight of wet flue gas	mass/mol
MwGF	Molecular weight of the gaseous fuel	mass/mol
Mwk	Molecular weight of constituent *k*	mass/mol
MwO3	Molecular weight of O$_3$	mass/mol
MwS	Molecular weight of sulfur	mass/mol
PAz	Static pressure of air at location *z* (e.g., 7, 8, or 9)	in. wg (Pa)
Pb	Barometric pressure	psia (Pa)
PDiA	Pressure differential, air (air resistance)	in. wg (Pa)
PDiA8A9	Air-side static pressure loss between the air inlet duct connection flange and the air outlet duct connection flange	in. wg (Pa)
PDiA8A9Cr	Air-side pressure differential, corrected for deviation from design air mass flow rate and temperature	in. wg (Pa)
PDiA8Fg15P	Static pressure difference between the primary air inlet at the duct connection flange and the gas outlet at the duct connection flange	in. wg (Pa)
PDiA8Fg15PDs	Design static pressure difference between the primary air inlet at the duct connection flange and the gas outlet at the duct connection flange	in. wg (Pa)
PDiA8Fg15S	Static pressure difference between the secondary air inlet at the duct connection flange and the gas outlet at the duct connection flange	in. wg (Pa)
PDiA8Fg15SDs	Design static pressure difference between the secondary air inlet at the duct connection flange and the gas outlet at the duct connection flange	in. wg (Pa)
PDiA8PA8S	Static pressure difference between entering primary air and entering secondary air	in. wg (Pa)
PDiA8PA8SDs	Design static pressure difference between entering primary air and entering secondary air	in. wg (Pa)
PDiA8PA9P	Static pressure difference between entering primary air and leaving primary air	in. wg (Pa)
PDiA8SA9S	Static pressure difference between entering secondary air and leaving secondary air	in. wg (Pa)
PDiFg14Fg15	Measured gas-side static pressure differential between the gas inlet duct connection flange and the gas outlet duct connection flange	in. wg (Pa)

Table 5-10.2-1 Computational Acronyms (Cont'd)

Acronym	Description	Units
PDiFg14Fg15Cr	Gas-side pressure differential, corrected for deviation from design gas mass flow rate and temperature	in. wg (Pa)
PFgz	Static pressure of flue gas at point *z*	in. wg (Pa)
PHFEn	Pressure of the hot fluid entering air preheater coils	psig (Pa)
PHFLv	Pressure of the hot fluid leaving air preheater coils	psig (Pa)
PpWvA	Partial pressure of water vapor in air	psia (Pa)
PsWvTdb	Dry-bulb temperature	°F (°C)
PsWvTwb	Wet-bulb temperature	°F (°C)
PsWvTz	Saturation pressure of water vapor at wet-bulb temperature	psia (Pa)
QAAh	Energy absorbed by the air leaving air heater	Btu/hr (W)
QAP	Energy absorbed by the primary air leaving air heater	Btu/hr (W)
QAS	Energy absorbed by the secondary air leaving air heater	Btu/hr (W)
QFgAh	Energy given up by the flue gas entering air heater	Btu/hr (W)
QFgP	Energy given up by the flue gas entering primary air heater	Btu/hr (W)
QFgS	Energy given up by the flue gas entering secondary air heater	Btu/hr (W)
QpBDA	Credit due to entering dry air	% fuel input
QpBF	Credit due to sensible heat in fuel	% fuel input
QpBOth	Other credits	% fuel input
QpBSlf	Credit due to sulfation	% fuel input
QpBWA	Credit due to moisture in entering air	% fuel input
QpLDFg	Loss due to dry gas	% fuel input
QpLH2F	Loss due to water formed from combustion of H_2 in fuel	% fuel input
QpLk	Loss from constituent *k*	% fuel input
QpLOth	Other losses	% fuel input
QpLRs	Sensible heat of residue loss	% fuel input
QpLUbC	Loss due to unburned carbon in residue	% fuel input
QpLWA	Loss due to moisture in air	% fuel input
QpLWF	Loss due to water in fuel	% fuel input
QpLWvF	Loss due to water vapor in gaseous fuel	% fuel input
QrBSb	Sensible heat in sorbent credit	Btu/hr (W)
QrBX	Credit due to auxiliary equipment power	Btu/hr (W)
QrF	Fuel input	Btu/hr (W)
QrLClh	Loss due to calcination and dehydration of sorbent	Btu/hr (W)
QrLOth	Other losses, energy basis	Btu/hr (W)
QrLSrc	Loss due to surface radiation and convection	Btu/hr (W)
QrLWSb	Loss due to water in sorbent	Btu/hr (W)
QrO	Total steam generator heat output	Btu/hr (J/h)
QX	Energy input to the drives	kW·h (J)
R	Universal molar gas constant	ft·lbf/mol·°R (J/kg·mol·K)
Rhmz	Relative humidity at location *z*	%
Rk	Specific gas constant for gas *k*	ft/°R (J kg/K)
SmQpB	Sum of the heat credits on a percent input from fuel basis	% fuel input or Btu/hr (W)
SmQpL	Sum of the heat losses on a percent input from fuel basis	% fuel input or Btu/hr (W)
SmQrB	Sum of credits on an energy basis	Btu/hr (J/h)
SmQrL	Sum of losses on an energy basis	Btu/hr (J/h)
TA8Cr	Air temperature leaving the air preheater coil, corrected to design conditions [Note (1)]	°F (°C)
TA8Ds	Design air temperature entering the air heater [Note (1)]	°F (°C)
TA8P	Measured air temperature entering primary air heater [Note (1)]	°F (°C)
TA8PDs	Design air temperature entering primary air heater [Note (1)]	°F (°C)
TA8S	Measured air temperature entering secondary air heater [Note (1)]	°F (°C)
TA8SDs	Design air temperature entering secondary air heater [Note (1)]	°F (°C)
TA9Cr	Air temperature leaving the air heater, corrected to design conditions [Note (1)]	°F (°C)
TA9Ds	Design air temperature leaving the air heater [Note (1)]	°F (°C)
TACr	Temperature of wet air, corrected to design conditions	°F (°C)
TAl	Temperature of air heater leakage air	°F (°C)
TAz	Temperature of air at point *z* (e.g., 7, 8, or 9)	°F (°C)
TAzDs	Design temperature of wet air at location *z* (e.g., 7, 8, or 9)	°F (°C)
Tdbz	Temperature of air (dry bulb) at location *z*	°F (°C)
Twbz	Temperature of air (wet bulb) at location *z*	°F (°C)
TDiMr8A	Temperature correction for design airflow	°F (°C)
TDiMrFg14	Temperature correction for deviation from design entering flue gas mass flow	°F (°C)

Table 5-10.2-1 Computational Acronyms (Cont'd)

Acronym	Description	Units
TDiTA8	Temperature correction for deviation from design entering air temperature	°F (°C)
TDiTFg14	Temperature correction for deviation from design entering gas temperature	°F (°C)
TDiTHFEn	Temperature correction for entering hot fluid temperature APH coils	°F (°C)
TDiXr	Temperature correction for deviation from design *X*-ratio	°F (°C)
TFg14Ds	Design entering gas temperature [Note (1)]	°F (°C)
TFg15Ds	Design exit gas temperature including leakage (absolute)	°F (°C)
TFg15NL	Air heater exit gas temperature, excluding leakage	°F (°C)
TFg15NLCr	Air heater exit gas temperature, excluding leakage, corrected to design conditions	°F (°C)
TFgz	Temperature of wet flue gas at location *z* (e.g., 14 or 15)	°F (°C)
TFgzDs	Design temperature of wet flue gas at location *z* (e.g., 14 or 15)	°F (°C)
THFEn	Temperature of the hot fluid entering air preheater coils	°F (°C)
THFEnDs	Design temperature of the hot fluid entering air preheater coils	°F (°C)
THFLv	Temperature of the hot fluid leaving air preheater coils	°F (°C)
TLvk	Temperature of constituent *k* leaving the envelope	°F (°C)
TMnA8	Composite air temperature entering the air heater	°F (°C)
TMnA9	Composite air temperature leaving the air heater	°F (°C)
TMnFg14	Composite gas temperature entering the air heater	°F (°C)
TRe	Reference temperature	°F (°C)
VpCO2	Carbon dioxide in the flue gas	% volume
VpGj	As-fired gaseous fuel components (e.g., CH_4 or C_2H_6)	% volume
VpN2a	Atmospheric nitrogen in the flue gas	% volume
VpN2F	Nitrogen from fuel in the flue gas	% volume
VpO2	Oxygen concentration in the flue gas	% volume
VpSO2	Sulfur dioxide in the flue gas	% volume
XpA	Excess air	% mass
Xr	Test air heater *X*-ratio	Dimensionless

NOTE:

(1) Acronym may be used in absolute units [°R (K)] in some equations, as noted in the text.

Table 5-10.3-1 Uncertainty Acronyms

Acronym	Description
ASENSCO	Absolute sensitivity coefficient
CHGPAR	Incremental change in value of measured parameter
CS	Coefficient selected by the Code committee, based on mathematical simulation, as an estimate to achieve a 95% confidence level; listed in Table 7-5.3.2-1
DEGFREE	Number of degrees of freedom
$DEGFREE_{UNC}$	Number of degrees of freedom for the overall test result
m	Number of sets of data or grid points
n	Number of times parameter is measured
PARAVG	Average value of a parameter
PCHGPAR	Percent change in value of measured parameter
PSTDDEV	Population standard deviation
RECALTGE	Recalculated corrected exit gas temperature, excluding leakage
RSENSCO	Relative sensitivity coefficient
SDI	Spatial distribution index
STDDEV	Standard deviation of the sample
STDDEVMN	Standard deviation of the mean
STDTVAL	Two-tailed Student's *t* value
SYS	Systematic uncertainty
SYS_R	Overall systematic uncertainty
SYSNI	Systematic uncertainty for numerical integration
TGE	Corrected exit gas temperature excluding leakage
U	Integrated average value of measured parameter
UNC	Test uncertainty
URC	Random component of uncertainty
V	Velocity
X_i	Value of a measured parameter at time *i*
Z	Summation, integrated average value of *z*
z	Time-averaged value of the measured parameter
Subscripts	
AVG	Average
FW	Weighted (average)
i	Index of summation, a specific point
R	Random uncertainty or pertaining to result *R*, as noted in the text
UW	Unweighted (average)
V	Pertaining to velocity
Superscript	
—	Average

Section 6
Report of Results

6-1 GENERAL REQUIREMENTS

The test report for a performance test shall incorporate the following general requirements:

(a) executive summary (see subsection 6-2)

(b) introduction (see subsection 6-3)

(c) calculation and results (see subsection 6-4)

(d) instrumentation (see subsection 6-5)

(e) conclusions (see subsection 6-6)

(f) appendices (see subsection 6-7)

This outline is a recommended report format. Other formats agreed to by all parties of the test are acceptable.

6-2 EXECUTIVE SUMMARY

The executive summary is brief and should contain the following:

(a) general information about the air heater and the test, e.g., the type of air heater and operating configuration, and the test objective

(b) date and time of the test

(c) summary of the results of the test, including uncertainty and conclusions reached

(d) comparison with the contract guarantee, if any

(e) any agreements among the parties to the test to allow any deviations from the test requirements

6-3 INTRODUCTION

This section of the test report includes the following:

(a) authorization for the tests, their object, contractual obligations and guarantees, stipulated agreements, by whom the test is directed, and the representative parties to the test

(b) any additional general information about the fan and the test not included in the executive summary, e.g.,

(1) an historical perspective, if appropriate

(2) an equipment diagram showing the test boundary

(3) description of the equipment tested and any other auxiliary apparatus, the operation of which may influence the test result

(c) a listing of the representatives of the parties to the test

(d) any pretest agreements that were not tabulated in the executive summary

(e) the organization of the test personnel

(f) test goal per Sections 3 and 5 of this Code

6-4 CALCULATIONS AND RESULTS

The following should be included in detail:

(a) method of the test and operating conditions

(b) tabular summary of measurements and observations, including the reduced data necessary to calculate the results and a summary of additional operating conditions not part of such reduced data

(c) step-by-step calculation of test results from the reduced data, including the probable uncertainty

(d) any calculations showing elimination of data for outlier reason or for any other reason

(e) comparison of repeatability of test runs

(f) correction factors to be applied because of deviations, if any, of test conditions from standard or design conditions

(g) primary measurement uncertainties, including method of application

(h) the test performances stated under the following headings:

(1) test results computed on the basis of the test operating conditions, instrument calibrations only having been applied

(2) test results corrected to standard or design conditions if test operating conditions have deviated from those specified

(i) tabular and graphical presentation of the test results

(j) discussion and details of the test results uncertainties

(k) discussion of the test, its results and conclusions

(l) tabular summary of pretest uncertainty analysis

(m) tabular summary of pretest velocity traverse

6-5 INSTRUMENTATION

(a) tabulation of instrumentation used, including make, model number, etc.

(b) description of the instrumentation location

(c) means of data collection for each data point, e.g., temporary data acquisition system printout, plant control computer printout, or manual data sheet, and any identifying tag number and/or address of each

(d) identification of the instrument that was used as backup

(e) description of data acquisition system(s) used

(f) summary of pretest and post-test calibration

6-6 CONCLUSIONS

6-7 APPENDICES

Appendices to the test report should include

(a) copies of original data sheets and/or data acquisition system(s) printouts

(b) copies of operator logs or other recording of operating activity during each test

(c) instrumentation calibration results from laboratories, certification from manufacturers

Section 7
Uncertainty Analysis

7-1 INTRODUCTION

Every measurement includes an error that results in a difference between the measured value and the true value. The difference between the measured value and the true value is the total measurement error. Since the true value is unknown, the total error in a measurement cannot be known and only its limits can be estimated. The total measurement error consists of two components, systematic error and random error, which are illustrated in Fig. 7-1-1. Accurate measurement requires minimizing both systematic and random errors. Error and uncertainty are similar in many respects. There are many types and sources of error, but when a number is assigned to error, it becomes an uncertainty. The term *accuracy* is often used interchangeably with *uncertainty* but the two are not synonymous since high accuracy implies low uncertainty.

7-1.1 Random Error

Random error is defined in this context as the portion of the total measurement error that varies randomly from measurement to measurement of the same value. Usually, random uncertainties are associated with variability in time, whereas systematic uncertainties are considered fixed in time, as shown in Fig. 7-1.1-1. The total random error in a measurement is usually the sum of the contributions of several elemental random error sources. Variability in space (e.g., temperature stratification or nonuniform gas velocities in a flue gas duct) is treated as random uncertainty in this Code. Random errors may also arise from uncontrolled test conditions, nonrepeatability in the measurement system, environmental conditions, data reduction techniques, and measurement methods.

7-1.2 Systematic Error

Systematic error is the portion of the total measurement error that remains constant in repeated measurements of the true value. The total systematic error in a measurement is usually the sum of the contributions of several individual systematic errors. Systematic errors include those that are known and can be calibrated out, those that are negligible and are ignored, and those that are unknown and whose limits must be estimated. Systematic errors may arise from imperfect calibration corrections, data acquisition systems, data reduction techniques, etc. The nonnegligible systematic errors that remain after calibration contribute to the systematic uncertainty of the measurement.

7-2 UNCERTAINTY

Since every observation or measurement is the combination of the true value of the parameter plus the total measurement error, there is an inherent uncertainty in the use of measurements to represent the true value. The total uncertainty in a measurement is the combination of uncertainty due to systematic error and uncertainty due to random error.

7-2.1 Uncertainty Due to Random Error

Since random error introduces variation or scatter in repeated measurements of the same parameter, the uncertainty due to random error may be estimated by taking multiple measurements and inspection of the measurement scatter. The population standard deviation is a measure of the scatter about the true population mean caused by random error. An estimate of the population standard deviation of the mean is the standard deviation of a data sample, which is determined by

$$S_x = \left(\frac{S_x^2}{n}\right)^{1/2} = \frac{\left[\frac{1}{n-1}\sum_{1}^{n}(x_i - \bar{x})^2\right]^{1/2}}{n^{1/2}} \qquad \text{(7-2-1)}$$

where

n = number of measurements made
s_x = sample standard deviation
$\bar{x}$ = mean of the individual measurements given by

$$\bar{x} = \frac{\sum_{1}^{n} x_i}{n} \qquad \text{(7-2-2)}$$

Averaging multiple measurements and using this average in lieu of any individual measurement reduces the random uncertainty. This indicates that the mean of several samples is a better measure of the true population mean than one sample.

7-2.2 Uncertainty Due to Systematic Error

Since systematic error is defined as constant for repeated measurements of the same parameter utilizing the same technique and with a constant true value, and since systematic error cannot be quantified absolutely, the uncertainty due to systematic error must be estimated. The systematic uncertainty estimate should be based on engineering judgment and analysis of elemental systematic errors. Every effort must be made to identify and account for all elemental systematic errors.

7-3 FUNDAMENTAL CONCEPTS

7-3.1 Benefits of Uncertainty Analysis

Uncertainty analysis is a procedure by which the accuracy of test results can be quantified. Because it is required that the parties to the test agree to the quality of the test (measured by test uncertainty), pretest and post-test uncertainty analyses are an indispensable part of a meaningful performance test.

Additional discussion on uncertainty is available in ASME PTC 19.1 and ASME PTC 4.

The benefits of performing an uncertainty analysis are illustrated by the following statements:

(a) The uncertainty of a test result is a measure of the quality of the test value. A band representing the test result plus or minus the uncertainty will include the true value with a stated probability.

(b) Uncertainty analysis is the best procedure to estimate the error limit in a set of measurements or test results.

(c) Uncertainty analysis performed while a test is being planned (using nominal or estimated values for primary measurement uncertainties) identifies potential measurement problems and promotes designing a cost-effective test.

(d) Uncertainty analysis performed after a test is run allows the test engineer to determine those parameters and measurements that were the greatest contributors to testing error.

(e) A performance test code based on a specified uncertainty level is much easier to adapt to new measurement technology than a code tied to certain types of instruments.

This Code allows the parties to an air heater test to choose among many options for test instruments and methods of performance assessment. Uncertainty analysis helps the parties to the test make these choices.

7-3.2 Uncertainty Analysis Principles

This paragraph reviews fundamental concepts of uncertainty analysis.

It is an accepted principle that all measurements have errors. It follows, therefore, that any results calculated from measured data, e.g., air heater performance parameters, including cross-leakage and correction for off-design conditions, also contain errors, resulting not only from the errors in the data but also from approximations in the calculation procedure. The methods of uncertainty analysis require the engineer to first determine estimates of the error (uncertainty) of the basic measurements and data reduction procedures, and then to propagate those uncertainties into the uncertainty of the result.

Note the following definitions:

(a) Error is the difference between the true value of a parameter and the measured or calculated value of the parameter. Error is unknown because the true value is unknown. Obviously, if the error were known, the test results could be based on the true value, not the measured or calculated value.

(b) Uncertainty is the estimated error limit of a measurement or result.

(c) Coverage is the percentage of observations (measurements) that can be expected to differ from the true value by no more than the uncertainty. Stated another way, a typical value, say 95% coverage, means that the true value will be bounded by the measured value plus or minus the uncertainty with 95% confidence, with the corollary that there is a 5% (1 in 20) risk that the true value lies outside this band. The concept of coverage is necessary in uncertainty analysis, since the uncertainty is only an estimated error limit. In some cases uncertainty can be calculated by statistical analysis; however, engineering judgment sometimes must be used to estimate the systematic uncertainties. Engineering judgment must be made within the concept of the confidence interval.

The calculated average value of a parameter plus or minus the uncertainty thus defines a band in which the true value of the parameter is expected to lie with stated coverage.

If the magnitude and sign of a systematic error are known, they must be handled as a correction to the measured value, with the corrected value used to calculate the test result. Systematic uncertainty estimates considered in uncertainty analysis attempt to cover those systematic errors whose magnitudes are unknown. Examples of systematic errors that are intended to be included in uncertainty analysis are the systematic error resulting from using an uncalibrated measuring device, drift in calibration of a measuring device, the systematic error arising from the deteriorated condition of a previously calibrated measuring device, errors resulting from calculation procedure approximations, and the potential errors made in estimating values for unmeasured parameters.

It is not always easy to classify a specific uncertainty as systematic or random. Usually random uncertainties are associated with variability in time, whereas systematic uncertainties are considered fixed in time. Variability in space (e.g., temperature or gas constituent stratification, or nonuniform gas velocity in a flue gas duct) has been treated as random or systematic uncertainty in different works.

This Code treats spatial variability as a potential source of systematic uncertainty.

A complete uncertainty analysis requires determining values for both random and systematic uncertainty in the basic measurements, their propagation into the calculated results, and their combination into the overall uncertainty of the results. Uncertainty analysis can be performed before a test is run (pretest analysis) and/or after a test is run (post-test analysis).

7-3.3 Averaging

Instruments used in air heater performance testing measure parameters such as temperature and concentration of certain constituents in a gas stream. Most instruments are capable of sensing the value of a parameter only at a single point or within a limited region of space and at discrete instants or over limited "windows" of time. It is well known that gas temperature and composition vary in space (stratification) and time (unsteadiness). It should be realized that these variations are primarily due to the physical processes (including mixing) in the vicinity of an air heater, rather than experimental error.

In a performance test, engineers sample several points in space and time, and then use averages of the data to calculate test results. The averages are the best available estimates, and the differences between the average value of a parameter and its instantaneous and/or local values are used to estimate the uncertainty in the measurements and in any results calculated from them.

The average value is the familiar arithmetic average

$$\bar{x} = \frac{1}{n}\sum_{1}^{n} x_i \qquad \text{(7-3-1)}$$

7-4 PROCEDURES FOR DETERMINING RANDOM UNCERTAINTY

This subsection contains equations and procedures for calculating the standard deviation. The required post-test uncertainty analysis uses actual data from the performance test. The required pretest uncertainty analysis uses expected values for the parameter averages and estimates for the standard deviations. The equations and procedures of this subsection are aimed at a post-test uncertainty analysis, for which actual test data are available.

Process parameters, e.g., exit gas temperature and oxygen, naturally exhibit perturbations about their true (or average) values. These perturbations are the *real variations* of the parameters. For a set of measurements of the process parameters, the instrumentation system superimposes further perturbations on the average values of the parameters. These instrumentation-based perturbations are assumed to be independent random variables with a normal distribution.

The random uncertainty of an instrument is sometimes called the *reproducibility* of the instrument.

Reproducibility includes hysteresis, deadband, and repeatability; reference ISA standard ANSI/ISA-S51.1. The instrumentation variance is often estimated from published data because testing of a specific instrument for its random uncertainty can rarely be justified.

For a post-test uncertainty analysis, the instrumentation variances are not specifically required, because they are already imbedded in the data. Knowledge of instrumentation variances may be needed when instrumentation alternatives are compared in a pretest uncertainty analysis. In most instances, an instrument's variance is small enough, relative to the real variance of the parameter, that the instrumentation variance may be ignored. If the instrumentation variance is less than one-fifth of the real variance of a measured parameter, the instrumentation random error can be ignored.

7-4.1 Standard Deviation of Individual Parameters

The standard deviation of an individual parameter depends on the type of parameter (integrated-average or constant-value) and the method used to measure the parameter. Some of the methods are as follows:

(a) multiple measurements made over time at a single location, e.g., differential pressure

(b) multiple measurements made at several locations in a given plane, e.g., flue gas temperature, flue gas constituents, and air temperature at air heater inlet

(c) the sum of averaged measurements, e.g., total coal flow rate when multiple weigh feeders are used

(d) measurements on samples taken in multiple increments, e.g., fuel and sorbent characteristics

(e) multiple sets of measurements at weigh bins or tanks to determine the average flow rates, e.g., solid residue flow rates

(f) a single measurement

(g) the sum of single measurements

7-4.1.1 Multiple Measurements at a Single Point. For multiple measurements of a constant value parameter made over time at a single location, the population standard deviation of the mean cannot be measured. Therefore, the sample standard deviation of the mean [eq. (7-4-1)] is used as an indicator of variability and a basis for calculating uncertainty for random variations.

$$S_{\bar{x}} = \left(\frac{S_x^2}{n}\right)^{1/2} = \frac{\left[\dfrac{1}{n-1}\displaystyle\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2}}{n^{1/2}} \qquad \text{(7-4-1)}$$

$$s_x = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2} \qquad \text{(7-4-2)}$$

where

s_x = sample standard deviation

The number of degrees of freedom is

$$\nu_x = n - 1 \qquad \text{(7-4-3)}$$

7-4.1.2 Integrated Average Parameters (Unweighted Averages). Examples of integrated average parameters are flue gas temperature and oxygen content. Multiple measurements are made over time at each of several points in a grid. The measurements over time at each point are averaged to determine the value of the parameter at the point in accordance with eq. (7-3-1).

The sample standard deviations, sample standard deviations of the mean, and degrees of freedom are calculated *at each grid point* as if the parameter exhibited a constant value, i.e., by eqs. (7-4-1) and (7-4-2).

The standard deviation of the integrated average parameter is

$$S_{\bar{\bar{x}}} = \frac{1}{m}\left[\sum_{i=1}^{m}(S_{\bar{x}_i})^2\right]^{1/2} \tag{7-4-4}$$

The associated degrees of freedom are

$$\nu = \frac{S_{\bar{\bar{x}}}^4}{\sum_{i=1}^{m}\left[\frac{S_{\bar{x}}^4}{m^4\nu_i}\right]} \tag{7-4-5}$$

where

m = number of grid points

$S_{\bar{x}_i}$ = standard deviation of the mean for the parameter at point i [from eq. (7-4-1)]

v_i = degrees of freedom of $S_{\bar{x}_i}$, which is the number of readings at point i minus 1

If fewer than six measurements from each grid point are collected during a test run, e.g., when individual grid point measurements of O_2 and/or temperature are made using manual point-by-point traverses, the standard deviation of the integrated average parameter shall be determined by multiple measurements at a single representative point in the test plane. Plant instrumentation may be used to determine the standard deviation of the integrated average parameter, provided that the instrumentation is in a representative location. Any dead bands or "exception reporting" that the plant's data collection/archiving system may use shall be removed and/or reduced to the satisfaction of all parties to the test. It is not necessary to flow weight the point(s) used to determine random uncertainty.

7-4.1.3 Integrated Average Parameters (Weighted Averages). Parameters such as flue gas temperature or oxygen are sometimes calculated as weighted averages. The weighting factor is the fluid velocity fraction evaluated at the same point as the parameter measurement. Calculation (or estimation) of the standard deviation for a flow-weighted integrated average depends on the available data for the velocity distribution.

(a) Velocity Measured Simultaneously With the Parameter, With Several Complete Traverses. The number of readings at each point in the grid must be large enough to assure statistical significance. Six or more readings are generally required. In this case, the standard deviation and degrees of freedom are calculated using eqs. (7-4-1) through (7-4-5) as appropriate, with the parameter $x_{j,i}$ being the weighted value. For temperature (for example),

$$x_{ji} = \left(\frac{V_{j,i}}{\bar{V}}\right) T_{j,i} \tag{7-4-6}$$

where

i = point in space

j = time

$\bar{V}$ = space- and time-averaged velocity

(b) Velocity Measured Simultaneously With the Parameter, With a Small Number of Complete Traverses. In this case, the standard deviation is estimated from a large number of readings taken at a single point. Instruments must be provided to simultaneously measure the velocity and the parameter at a single fixed point. The point should be selected so that the expected values of velocity and the parameter are approximately the average values. Plant instrumentation may be used if it meets the criteria outlined in Section 4. Data should be recorded with a frequency comparable to that for other data.

The instantaneous values from the point are multiplied to give a variable x_j

$$x_j = \left(\frac{V_j}{\bar{V}}\right) T_j \tag{7-4-7}$$

The sample standard deviation for x is calculated from eq. (7-4-2).

(c) Velocity Measured Separately From the Parameter. The standard deviation of the mean for the weighted *average parameter* is

$$S_{\bar{\bar{P}},FW} = \left[S^2_{\bar{\bar{P}},UW} + (\bar{P}_{UW} - \bar{P}_W)^2\,\frac{S^2_{\bar{\bar{v}}}}{\bar{\bar{V}}^2}\right]^{1/2} \tag{7-4-8}$$

where

FW = the weighted average

P = the parameter (temperature or oxygen)

$S_{\bar{P}}$ = calculated as described in para. 7-4.1.2

UW = the unweighted average

Ideally, the standard deviation of velocity is evaluated from multiple readings over time at each point in the velocity measuring grid. If such readings are not available, the standard deviation of velocity is estimated from historical data.

7-4.1.4 Measurements on Samples Taken in Multiple Increments. Samples of material streams are obtained and analyzed to determine the chemical compositions of the streams. These streams may be gaseous (e.g., flue gas) or solid (e.g., coal, sorbent, and residue). Usually, these samples are obtained in increments, i.e., a finite sample is taken at periodic intervals. The sample locations may be separated in space, as in sampling multiple coal feeders or multiple points in a flue gas duct cross section, as well as in time. It should be noted that in this Code, solids composition is treated as a constant value parameter and flue gas composition is treated as a spatially nonuniform parameter. A second major difference between solid streams and gaseous streams is that the gaseous samples are usually analyzed "online" during the test while solid samples are usually analyzed in a laboratory at a later time.

There are two alternative means for determining the average properties of material samples taken in increments; therefore, there are two means for determining the standard deviation. The first method for determining the average properties uses a separate analysis of each individual sample. The average value for all samples (the value to be used in the performance calculations) is then determined as the mean of all of the individual sample results. In the second method, the individual samples are mixed together into a composite sample and an analysis is made of the composite sample. While there may be replicated analyses of the composite sample, there is still only one sample for analysis.

Often, a combination of both methods is the most cost-effective approach. Some constituents can be determined from a single analysis of a gross sample, while other constituents are determined from analysis of individual samples. For example, when the steam generator fires coal from a single seam, the moisture and ash can be highly variable while the other constituents, expressed on a moisture-and-ash-free basis, are relatively constant. In this case, as-fired moisture and ash, and their standard deviations, should be determined from analysis of several individual samples, while the average values for the other constituents (on a moisture-and-ash-free basis) can be determined from a single analysis of a mixed gross sample. The following paragraphs describe determination of random uncertainty in these two cases:

(a) *Increments Individually Analyzed*. If each incremental sample is properly mixed, reduced, and divided separately, the average value of a constituent is the mean of the analysis measurements. The standard deviation and degrees of freedom are determined from eqs. (7-4-2) and (7-4-4).

(b) *Increments Mixed Prior to Analysis*. If the sample increments are mixed prior to analysis, the various increments are mechanically averaged (an example is the "ganging" of several flue gas sampling lines into a mixing chamber or bubbler prior to analysis). If proper procedures have been followed in mixing and reducing the gross sample, the results of the analysis of the mixed sample may be considered a proper average. As there is only one set of results, the standard deviation cannot be calculated from statistics and must therefore be estimated.[1] It is often possible to obtain accurate estimates using historical data or, sometimes, limited measurements, for determining random uncertainty.

(c) *Estimates From Historical Data*. Cases where this method can be used include those where past test data are available or when fuel or sorbent used during the test has been obtained from a source whose characteristics have been previously established. One criterion for a proper estimate is that the historical data and the test data are taken from the same measurement population. If this is the case, the data have the same *population* mean, μ, and the same *population* standard deviation, σ. Moisture-and-ash-free constituents for coal mined from a single seam should satisfy this condition, so that historical data from the same seam can be used to estimate the random uncertainty for the test data.

Suppose that historical data on a particular parameter (e.g., carbon content) are available. The historical data are based on n_H observations and have sample standard deviation.

The standard deviation can be conservatively estimated by

$$S_{\bar{x}} = \frac{S_{X,H}}{\sqrt{N}} \tag{7-4-9}$$

where

N = number of individual samples that were mixed

The degrees of freedom for this estimate is n_{H-1}.

(d) *Estimates From Limited Measurements*. To illustrate this approach, consider the random uncertainty of flue gas oxygen concentration, O_2. While samples are typically taken from several grid points in a duct cross section, seldom are the individual point samples analyzed; instead, samples are mixed and passed to a single analyzer. As flue gas oxygen concentration is a spatially nonuniform parameter, the mixing simulates the integrated-averaging process. If equal extraction rates are taken from each grid point, the process most closely matches multiple midpoint averaging. The point-to-point variation in O_2, although not revealed by the composite sample, is considered a systematic uncertainty due to numerical integration by this Code.

Even though the point-to-point variation is not considered as random error, the variation over time at each point does contribute to random error. Information on this variation is revealed only in the composite sample. It is assumed that several composite samples are taken and analyzed over time. The standard deviation and degrees of freedom should be calculated from eqs. (7-4-2)

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[1] It should be noted that *multiple analyses* of the same gross sample can give the standard deviation of the analytical instruments and procedures but give *no information* about the real variation in the material properties or the sampling variation. In most cases, these latter two sources of variability dominate the standard deviation of material properties.

and (7-4-4) and the results for the mixed samples as if the parameter (e.g., spatially averaged oxygen concentration) was a constant-value parameter.[2]

7-4.1.5 A Single Measurement or the Sum of Single Measurements. For parameters determined by a single measurement or the sum of single measurements, the standard deviation is the square root of the estimate of the instrumentation variance. The magnitude of the standard deviation is likely to be small enough so that it can be neglected. The spatial and time variations of such parameters should be considered as systematic uncertainties, with appropriate estimates made for their magnitude. The problem of uncertainty of single measurements was considered extensively by Kline and McClintock.

7-4.2 Standard Deviation and Degrees of Freedom of Intermediate Results

Frequently, a parameter used as if it were measured data is actually calculated from more primary measurements. Two examples are fluid flow rate, which is often determined from differential pressure and measurements, and enthalpy, which is determined from temperature (and sometimes pressure) measurements. There are two possibilities for calculating the standard deviation of these intermediate results. One is to use the "propagation of error" formula, eq. (7-6-1), together with the equation(s) relating the intermediate result to the primary measurements. This is not as difficult as it appears, because the equations connecting the intermediate results to the data are usually simple. The second option is to transform the data into the intermediate result prior to averaging and then calculate the standard deviation of the result. Specific cases are described below.

7-4.2.1 Parameters of the Form $z = C\sqrt{x}$. The measurements, x_i, should first be converted to z_i.Then the average and the sample variance of z can be calculated from the z_i. Differential pressure flowmeters exhibit this type of parameter relationship.

7-4.2.2 Parameters of the Form $z = a_0 + a_1\bar{x} + a_2\bar{x}^2 + \ldots + a_n\bar{x}^n$. Equation (7-6-1) is applicable to functions of one variable; in this case the variable is $\bar{x}$. The sensitivity coefficient for $\bar{x}$ is

$$ {}_z\Theta_x = \frac{\partial z}{\partial \bar{x}} = a_1 + 2a_2\bar{x} + \ldots + na_n x^{-n-1} \qquad (7\text{-}4\text{-}10)$$

The standard deviation of the mean is

$$ S_{\bar{z}} = ({}_z\Theta_x)\left(S_{\bar{x}}^2\right) \qquad (7\text{-}4\text{-}11)$$

The degrees of freedom for z are the same as for x.

The most common occurrence of this form of equation in steam generator performance testing is an enthalpy–temperature relationship.

7-4.3 Standard Deviation and Degrees of Freedom of Test Results

If the test result is a measured parameter, e.g., the temperature of the flue gas exiting the steam generator, then the standard deviation and degrees of freedom of the result are just the values for the parameter itself. If the test result must be computed from the measured data, e.g., corrected exit gas temperature, then the standard deviation and degrees of freedom of the result must be calculated from their values for the individual parameters.

7-4.3.1 Combining Standard Deviations. The standard deviation of a calculated result is obtained by combining the standard deviations of all of the parameters that affect the result according to the root-sum-square rule

$$ S_{\bar{R}} = \left[\sum_{i=1}^{k}\left({}_R\Theta_{x_i} S_{\bar{x}_i}\right)^2\right]^{1/2} \qquad (7\text{-}4\text{-}12)$$

where

${}_R\Theta_{x_i}$ = $\partial R/\partial x_i$
= sensitivity coefficient of parameter x_i on result R
k = total number of parameters that are used to calculate R

7-4.3.2 Combining Degrees of Freedom. The degrees of freedom of the standard deviation of R are computed by

$$ v_{S_R} = \frac{S_{\bar{R}}^4}{\displaystyle\sum_{i=1}^{k}\frac{\left({}_R\Theta_{x_i} S_{\bar{x}_i}\right)^4}{v_{x_i}}} \qquad (7\text{-}4\text{-}13)$$

7-5 GUIDANCE FOR DETERMINING SYSTEMATIC UNCERTAINTY

Systematic uncertainty is a "built-in" component of the error. The systematic error is what remains after all reasonable attempts to eliminate it (e.g., calibrating instruments) have been made. An essential characteristic of systematic uncertainty is that it cannot be determined directly from the test data. It is always necessary to estimate systematic uncertainty. Sometimes, models based on the test data or observations of conditions during the test can be used in making estimates, but they remain estimates nevertheless. A second essential fact concerning systematic uncertainty is that its value(s) is unique to the measurement system employed in a specific test and to the process and ambient conditions during the test.

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[2] While it may be argued that the standard deviation and degrees of freedom are better than those calculated by eqs. (7-4-2) and (7-4-4) because of several points sampled, it is impossible to determine these "better" values after samples are mixed.

This subsection gives certain mandatory rules for making estimates of the systematic error and for mathematical manipulation of them. These estimates are called systematic uncertainty. This subsection also provides guidance and some models for estimating values of systematic uncertainties. Users of this Code are free to adopt, modify, or reject any models for systematic uncertainty set forth in this subsection, provided that the parties to the test agree to do so and that they agree on an appropriate substitute.

7-5.1 General Rules

Systematic uncertainties used in this Code have the following characteristics:

(a) Systematic uncertainties shall be agreed upon by the parties to the test.

(b) Systematic uncertainties should be estimated at a 95% confidence level; the maximum conceivable values of systematic uncertainty should not be used.

(c) Systematic uncertainty estimates may be one-sided or nonsymmetrical if the physical process so suggests and the parties to the test agree that such estimates are the best available. If nonsymmetrical or one-sided systematic uncertainties are used, then the technique given in ASME PTC 19.1 should be used to propagate the parameter uncertainties into the test result.

Although the actual systematic uncertainty in any measurement or result is a fixed value, we do not know the value. The plus and minus range that would contain about 95% of the possible estimates of the systematic error is what is used as the systematic uncertainty estimate. This Code specifies that systematic uncertainty estimates shall be combined by using the root-sum-square principle.

Generally, the same systematic uncertainties will be used for both pretest and post-test uncertainty analyses. Observations of conditions during the test may indicate that it is allowable to decrease one or more systematic uncertainties, or that it is advisable to increase one or more systematic uncertainties. This shall be permitted if all parties to the test agree.

7-5.2 Systematic Uncertainties Due to Instrumentation

There are a number of sources of instrumentation systematic uncertainty in any measurement — primary element, primary sensor, transducer, amplifier, analog/digital converter, recording device, and environmental effects. ISA standard ANSI/ISA-S51.1 may be consulted for general information about instrumentation systematic uncertainty.

Section 4 gives guidance for estimating systematic uncertainties due to specific instrumentation systems. This Section provides general guidelines and rules for combining these elemental systematic uncertainties.

7-5.2.1 Combining Systematic Uncertainties From Several Components. If an instrument system has several components and each has a separate systematic uncertainty, the combined systematic uncertainty of the measurement is

$$B = (B_1^2 + B_2^2 + \ldots + B_{m)}^2)^{1/2} \tag{7-5-1}$$

where subscripts 1, 2, ..., m represent the various components of the system. Because this root-sum-square rule is used, systematic uncertainties whose estimated magnitude is less than one-fifth of the largest in a specific loop may be ignored in calculating the systematic uncertainty of the parameter.

7-5.2.2 Multiple Measurements With a Single Instrument. For multiple measurements at a single location with a single instrument (e.g., measuring the temperature at several points in a flue gas duct cross section with the same thermocouple system), the instrumentation systematic uncertainty of the average value of the parameter is equal to the instrumentation systematic uncertainty of a single measurement.

$$B_{\bar{x}} = B_x \tag{7-5-2}$$

7-5.2.3 Multiple Measurements With Multiple Instruments at Several Locations. The most common example is the use of a fixed grid of thermocouples to measure (average) flue gas temperature. Two different situations may be present.

The first situation is when all instrument loops (each thermocouple plus lead wire, data logger, etc., constitutes one loop) are judged to have the same systematic uncertainty. This would occur when all of the instrument loops are calibrated in place against the same standard. In this case, the instrument systematic uncertainty in the *average* parameter (temperature) is equal to the instrument systematic uncertainty for any one of the loops.

$$B_{\bar{x}} = B_{x_i} \text{ (any } i\text{)} \tag{7-5-3A}$$

The second situation is when different loops are judged to have different systematic uncertainties. This would occur if different independent calibrations are used or for a variety of other reasons. In this case, the instrument systematic uncertainty for the average parameter is the *average* of the systematic uncertainties for each loop.

$$B_{\bar{x}} = \frac{1}{N}\sum_{i=1}^{N} B_{x_i} \tag{7-5-3B}$$

7-5.3 Systematic Uncertainty in Spatially Nonuniform Parameters

Certain parameters in a steam generator performance test, namely flue gas and air temperatures at the air heater envelope boundaries and flue gas composition, should be evaluated as flow-weighted integrated average values (refer to subsection 4-4 and para. 7-5.3.3). In practice, integrated averages are approximated by sampling at a finite number of points and using a numerical approximation to the necessary integral. In addition to this approximation, the parties to the test may agree to forego measurement of the velocity and omit the flow weighting. In certain cases, e.g., flue gas composition, the samples may be mixed and mechanically averaged prior to analysis. Each of these approximations may introduce an error, which this Code treats as systematic uncertainty. These systematic uncertainties are in addition to instrumentation systematic uncertainties discussed in para. 7-5.2.

If measurements are made at only a few points (sometimes as few as one or two), then the methods suggested below for estimating these systematic uncertainties cannot be used. Likewise, these methods cannot be used for multipoint samples that are mixed prior to analysis. In both cases, the systematic uncertainty in integrated averages must be estimated and assigned by agreement between parties to the test. Experience and data from previous tests on similar units can serve as the basis for a model. Systematic uncertainty estimates must be large enough to account for the indeterminate errors present in small samples.

7-5.3.1 Spatial Distribution Index. This Code follows the recommendations of ASME PTC 4 and employs the spatial distribution index (SDI) as a measure of spatial variability.

Spatial distribution index is calculated from the following equation:

$$SDI = \left[\frac{1}{m}\sum_{j=1}^{m}(z_j - \bar{z})^2\right]^{1/2} \qquad (7\text{-}5\text{-}4)$$

where

m = number of points in the measurement grid. In the case of a single stream (e.g., flue gas) divided between two or more ducts, *SDI* is calculated for each duct.

$\bar{z}$ = arithmetic average of the time-averaged value of the points in the sample grid

z_j = time-averaged value of each point in a sample grid

The *SDI* is very similar to the standard deviation arithmetically but has a different statistical significance.

7-5.3.2 Systematic Uncertainty Due to Numerical Integration. The recommended systematic uncertainty is

$$B_n = \left[\frac{C_S}{(m-1)^{1/2}}\right] SDI \qquad (7\text{-}5\text{-}5)$$

where

C_S = coefficient selected by the Code committee based on numerical simulation as an estimate to achieve a 95% confidence level; coefficients are listed in Table 7-5.3.2-1. C_S should be interpolated between grid sizes listed.

m = number of points in the measurement grid

7-5.3.3 Systematic Uncertainty Associated With Flow Weighting. Although the theoretically proper averages for some parameters, e.g., flue gas temperature and oxygen content, are flow weighted, it is often not advisable to use flow weighting in a performance test because the errors associated with velocity determination may be greater than the error made by not flow weighting. There are, therefore, two different types of systematic error associated with flow weighting, as follows:

If flow weighting is used in the performance calculations, then there is a systematic error due to the systematic uncertainty in the velocity data used for weighting.

If flow weighting is not used in the performance calculations, then there is a (systematic uncertainty) error of method. This error is equal to the difference between the (true) weighted average and the unweighted average actually used in the calculations.

It is clear that only one of these two types of errors can be present in any one data set (either the average is weighted or it is not). This Code treats either type as flow weighting systematic uncertainty.

Whether flow weighting is required or not is primarily dependent upon the relationship of the measured parameter, *x* (typically temperature or flue gas constituent), and the velocity, *v*, spatially within the traverse plane. If the tendency is for high values of *x* to coincide with high values of velocity and low values of *x* to coincide with low values of velocity, then flow weighting is clearly required. Based on a similar argument, if the tendency is for low values of *x* to coincide with the high values of velocity and high values of *x* to coincide with low values of velocity, then flow weighting is clearly required. Conversely, if there is no strong relationship between the measured parameter, *x*, and the measured velocity, *v*, then, considering the added uncertainty of the velocity measurement, flow weighting would not be required.

The relationship between the measured parameter, *x*, and velocity, *v*, at each point in the grid can be evaluated by the correlation coefficient (also referred to as the Pearson correlation coefficient), *R*

$$R = \frac{\Sigma_i^n (x_i - \bar{x})\,(v_i - \bar{v})}{(n-1)\, S_x S_v} \qquad (7\text{-}5\text{-}6)$$

where

n = the number of equal areas within the traverse plane

R = correlation coefficient between the quantity, *x*, and the velocity, *v*, spatially at a traverse plane. The correlation coefficient is a built-in function for many programs. In Microsoft Excel® and

Lotus 1-2-3®, the function CORREL may be used to calculate the correlation coefficient. The PEARSON function may also be used in Excel®.

S_v = standard deviation of the velocity
S_x = standard deviation of parameter x
$\bar{v}$ = average value of the velocity v
v_i = velocity at point i coincident with point x_i
$\bar{x}$ = average value of the measured parameter x
x_i = value of measured parameter (temperature or gas composition) at point i within the traverse plane

The arithmetic average of a quantity x is calculated from

$$\bar{x} = \frac{\sum_{i}^{n} x_i}{n} \tag{7-5-7}$$

A velocity-weighted average is normally calculated from

$$\bar{z} = \frac{\sum_{i}^{n} x_i v_i}{\sum_{i}^{n} v_i} \tag{7-5-8}$$

where

n = number of areas
v_i = coincident area velocity
$\bar{x}$ = arithmetic average of quantity x
x_i = traverse area quantity (temperature or gas concentration)
$\bar{z}$ = velocity weighted average value of x for the traverse

The weighted average and straight arithmetic average are related to the correlation coefficient, R, as follows (refer to Nonmandatory Appendix B for the derivation):

$$\bar{z} = \bar{x}\left(1 + \frac{(n-1)}{n} R V_x V_v\right) \tag{7-5-9}$$

where

V_v = ratio of standard deviation/arithmetic average of velocity, known as coefficient of variation
$= \dfrac{S_v}{\bar{v}}$
V_x = ratio of standard deviation/arithmetic average of quantity x, known as coefficient of variation
$= \dfrac{S_x}{\bar{x}}$

R will lie between +1 and −1, and can easily be calculated by the spreadsheet function CORREL. If R is unity or large (approaching +1 or −1), there is a strong correlation between the measured parameter and velocity, indicating that the difference between the arithmetic mean and the velocity weighted mean will be large and flow weighting is required. If R is zero or small, there is not a strong correlation between the measured parameter and velocity, indicating that the difference between the arithmetic mean and the velocity weighted mean will be the same or small and flow weighting is not required.

The parties to the test should agree upon whether or not flow weighting is required for each measurement location. This Code recommends that flow weighting is not required if R is less than ±0.3, with the following additional considerations:

(a) For the AH gas inlet and air outlet, the difference in the average temperature and flow weighted temperature should not be more than 3°F (1.7°C).

(b) For the AH gas outlet and air inlet, the difference in the average temperature and flow weighted temperature should not be more than 2°F (1.1°C).

(c) The difference between the average O_2 and flow weighted O_2 should not be more than 0.05 pts of O_2.

For example calculations applying the above principles using typical test data, see Nonmandatory Appendix B.

7-5.3.3.1 Flow Weighting Systematic Uncertainty When Flow Weighting Is Used. This Code only addresses flow weighting when the velocity for flow weighting is measured simultaneously with the parameter being weighted (temperature or oxygen content). It is assumed that the velocity data are deemed sufficiently valid (see subsection 4-4 for rules regarding use of velocity data for flow weighting).

Where the velocity is measured simultaneously with the parameter being averaged, the flow weighting systematic uncertainty estimate is

$$B_{FW} = (\bar{P}_{UW} - \bar{P}_{FW})\,\frac{B_v}{\bar{V}} \tag{7-5-10}$$

where

B_v = systematic uncertainty for velocity measurement
FW = weighted average
$\bar{P}$ = the (integrated) average parameter (temperature or oxygen concentration)
UW = unweighted average
$\bar{V}$ = average velocity

7-5.3.3.2 Flow Weighting Systematic Uncertainty When Flow Weighting Is Not Used. This option applies when the criteria above indicate that flow weighting is not required and/or the quality of the velocity data is suspect.

If velocity data is not suspect, use eq. (7-5-10) to determine the systematic uncertainty due to not flow weighting. If velocity data was not collected in conjunction with the measured parameter(s) during the test, use the data from the preliminary traverses. If the velocity data is suspect, the parties to the test should agree upon the systematic uncertainty due to not flow weighting.

7-5.3.4 Combined Systematic Uncertainty for Integrated Averages. The combined systematic uncertainty for integrated average values is

$$B_{IA} = (B_I^2 + B_n^2 + B_{FW}^2)^{1/2} \tag{7-5-11}$$

where

FW = flow weighting
i = instrument
n = spatial distribution

7-5.4 Systematic Uncertainty Due to Assumed Values for Unmeasured Parameters

Examples of unmeasured parameters associated with an air heater performance test include the residue splits, estimated unburned carbon loss, and sulfur retention.

The midpoint between reasonable “limiting” values of an assumed parameter normally should be used as the value of the parameter in performance calculations. Half the difference between the “limiting” values is normally used as a systematic uncertainty in uncertainty analyses. If, e.g., the bottom ash flow rate was taken as a percentage of the total ash produced in a pulverized coal-fired boiler, the percentage would be an assumed parameter. It would be the midpoint between the “limiting” values set, of course, by judgment and agreed to by the parties to the test.

In some cases, unsymmetrical systematic uncertainties may be used if physical considerations imply it. For example, an ash split cannot be 10% ± 15%, as a negative 5% is not possible. Likewise, systematic uncertainty due to air infiltration into an oxygen sampling system cannot be positive (the true value can be lower than the measurement but not higher).

7-5.5 Degrees of Freedom for Systematic Uncertainty Estimates

As discussed previously, the systematic uncertainty is an estimate of the limits of the possible values of the unknown, fixed errors that remain after calibration. In a given experiment, these errors remain fixed, but we do not know their values. All that we know is our 95% confidence estimate of the range that we think covers the possible error values. There will always be some uncertainty in the estimate of the range. The ISO Guide and ASME PTC 19.1 give a methodology for handling this uncertainty.

If the uncertainty in the systematic uncertainty estimate, B, is expressed as ΔB, then the ISO Guide recommends the following approximation for the degrees of freedom for B:

$$V_B \approx \frac{1}{2}\left(\frac{\Delta B}{B}\right)^{-2} \tag{7-5-12}$$

For example, if we think that there is as much as a ±10% uncertainty, ΔB, in our estimate of B, then the degrees of freedom for B would be 50. The more certain we are in our systematic uncertainty estimate, the larger the degrees of freedom will be. Conversely, more uncertain estimates for B will yield smaller degrees of freedom.

The degrees of freedom expression for the systematic uncertainty, eq. (7-5-8), applies to all of the systematic uncertainty estimates discussed in subsection 7-5. In the most general case for doing an uncertainty analysis, the degrees of freedom for each systematic uncertainty would have to be estimated.

7-5.6 Systematic Uncertainty for Test Results

The total systematic uncertainty for a result calculated from the measured and assumed parameters is

$$B_R = \left[\sum_{i=1}^{k}\left({}_R\Theta_{x_i} B_{x_i}\right)^2\right]^{1/2} \tag{7-5-13}$$

This expression assumes that none of the parameters have systematic uncertainties that arise from common sources. If separate pressures, temperatures, etc., have the same systematic errors, e.g., those arising from a calibration standard, then these correlated systematic uncertainties must be taken into account in the evaluation of B_R. See ASME PTC 19.1 for the more general form of eq. (7-5-13). Also, if asymmetric systematic uncertainties are present, the techniques in ASME PTC 19.1 should be used.

The degrees of freedom for B_R are determined as

$$V_{B_R} = \frac{(B_R)^4}{\sum_{i=1}^{k}\frac{({}_R\Theta_{x_i} B_{x_i})^4}{v_{B_{xi}}}} \tag{7-5-14}$$

7-6 UNCERTAINTY OF TEST RESULTS

7-6.1 Propagation of Uncertainties

After values for both random and systematic uncertainties have been determined, it is necessary to determine the uncertainty in any results calculated from the data. This process is called *propagation of uncertainties*. Because random and systematic uncertainties are different types of quantities, it is customary to propagate them separately and combine them as the final step in an uncertainty calculation. The calculation procedure is straightforward, if somewhat tedious. Assume that a result, R, is calculated by

$$R = f(m_1, m_2, m_3 \ldots)$$

where

$m_1, m_2, m_3 \ldots$ = independent measured quantities. In this context, the term independent means that the value of each measured quantity is not influenced by a change in another.

Each of the quantities m has both random and systematic uncertainty. For either type of uncertainty, the basic propagation equation is

$$e_R = \left[\left(\frac{\partial f}{\partial m_1} e_{m1}\right)^2 + \left(\frac{\partial f}{\partial m_2} e_{m2}\right)^2 + \left(\frac{\partial f}{\partial m_3} e_{m3}\right)^2 + \ldots\right]^{1/2} \tag{7-6-1}$$

where

e = either the random uncertainty or the systematic uncertainty

The root-sum-square addition of errors is theoretically correct for random uncertainty and is assumed to be proper for systematic uncertainty as well.

The propagation equation can be written in the following dimensionless form:

$$\frac{e_R}{R} = \left\{\sum_{1}^{N_m}\left[\left(\frac{m_i}{R}\frac{\partial f}{\partial m_i}\right)\left(\frac{e_{m_i}}{m_i}\right)\right]^2\right\}^{1/2} \tag{7-6-2}$$

where

e_R/R = proportional uncertainty (random or systematic uncertainty) in the result, R, and can be expressed as a percentage

N_m = number of measurements employed to calculate the result, R

The coefficients $\left(\frac{m_i}{R}\frac{\partial f}{\partial m_i}\right)$ are termed the *relative sensitivity coefficients*.

Since the calculation procedure is often complicated, it is not always possible to evaluate algebraically the required partial derivatives. These derivatives can be conveniently estimated by a numerical perturbation technique

$$\frac{\partial f}{\partial m_i} \approx \frac{\left[\begin{array}{l} f(m_1, \ldots, m_i + \delta m_i, \ldots, m_{N_v}) \\ \quad - f(m_1, \ldots, m_i, \ldots, m_M) \end{array}\right]}{\delta m_i} \tag{7-6-3}$$

One at a time, each parameter (m_i) is changed by a small amount (δm_i, typically 0.1% to 1% or, if the functional relationship is nonlinear, the uncertainty for each parameter can be used) and the result is recalculated with the perturbed parameter replacing the nominal value. All other parameters are held constant for the recalculation. The difference between the result with the perturbed value and the nominal result, divided by the perturbation, estimates the partial derivative. Since this procedure requires recalculation of the result many times (one recalculation for each independent measurement), an automated calculation procedure is essential.

7-6.2 Combined Uncertainty of Calculated Result

The standard deviation and the systematic uncertainty of a test result are combined into the test uncertainty according to

$$U_R = t_{v,0.025}\left[\left(\frac{B_R}{2}\right)^2 + S_{\bar{R}}^2\right]^{1/2} \tag{7-6-4}$$

where

$t_{v0.025}$ = percentile point of Student's t distribution for $v = v_R$ degrees of freedom and a 95% confidence limit, and is taken from Table 5-7.5-1 or eq. (5-7-12)

The degrees of freedom result, v_R, is obtained from the expression

$$v_R = \frac{\left[\left(\frac{B_R}{2}\right)^2 + S_{\bar{R}}^2\right]^2}{\frac{S_{\bar{R}}^4}{v_{S_R}} + \frac{\left(\frac{B_R}{2}\right)^4}{v_{B_R}}} \tag{7-6-5}$$

For most engineering applications, the value of v_R will be relatively large (≥9) based on all of the error sources that influence it; therefore, for most applications the degrees of freedom for the result can be taken as 2 for 95% confidence estimates, and the uncertainty in the result is determined as

$$U_R = 2\left[\left(\frac{B_R}{2}\right)^2 + S_{\bar{R}}^2\right]^{1/2} \tag{7-6-6}$$

or

$$U_R = \left[B_R^2 + (2S_{\bar{R}})^2\right]^{1/2} \tag{7-6-7}$$

In the test report, the uncertainty, U_R, shall be stated along with the values of S_R and B_R. If the large sample approximation is used, the report shall state that v_R was taken as a large value so that Student's t is approximately 2.

7-7 GENERAL LIST OF SYMBOLS FOR SECTION 7

The following symbols are generally used throughout Section 7. Some symbols are used only in a specific paragraph and are defined or redefined locally.

B = systematic uncertainty

C_S = coefficient selected by the Code committee based on mathematical simulation as an estimate to achieve a 95% confidence level

e = either the random uncertainty or the systematic uncertainty

$f()$ = (mathematical) function

m = number of grid points or number of different measurement locations

n = number of data points used in calculating standard deviation

$\bar{P}$ = integrated average parameter

R = Pearson correlation coefficient, or a result (such as efficiency, output), depending upon context

$S_{\bar{R}}$ = standard deviation of a calculated result

S_x = sample standard deviation (S_x^2 is the sample variance)

$S_{\bar{x}}$ = standard deviation of the mean

SDI = spatial distribution index

t = Student's t statistic

U = uncertainty

V = velocity, or coefficient of variation, depending upon context

v = any parameter

x = any parameter

y = any parameter

Z = arithmetic average of the time-averaged value of the measured parameters

z = time-averaged value of the measured parameter, or any parameter, depending upon context

$\delta()$ = small change of ()

${}_R\Theta_x$ = sensitivity coefficient for parameter x on result R (${}_R\Theta_x = \partial R/\partial x$)

ν = degrees of freedom

$\sum_{b}^{a}()_i$ = sum of $()_i$ from $i = a$ to $i = b$

7-7.1 Subscripts

B = systematic uncertainty

FW = weighted average

I = instrument, instrumentation

i = index of summation, a specific point

j = index of summation, a specific point

k = index of summation, a specific point

n = pertaining to numerical integration

R = pertaining to result R

UW = unweighted average

V = pertaining to velocity

x = pertaining to parameter x

7-7.2 Superscript

— = average

Fig. 7-1-1 Types of Errors in Measurements

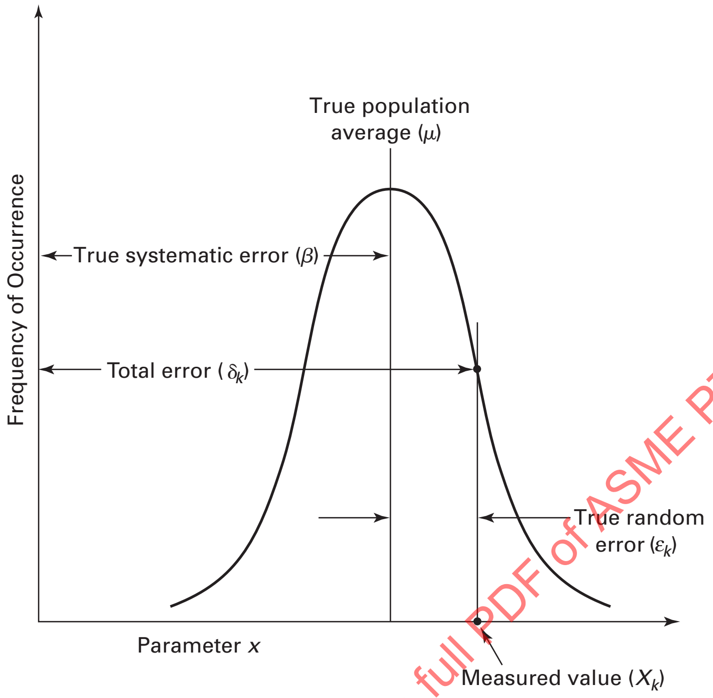


Fig. 7-1.1-1 Time Dependence of Errors

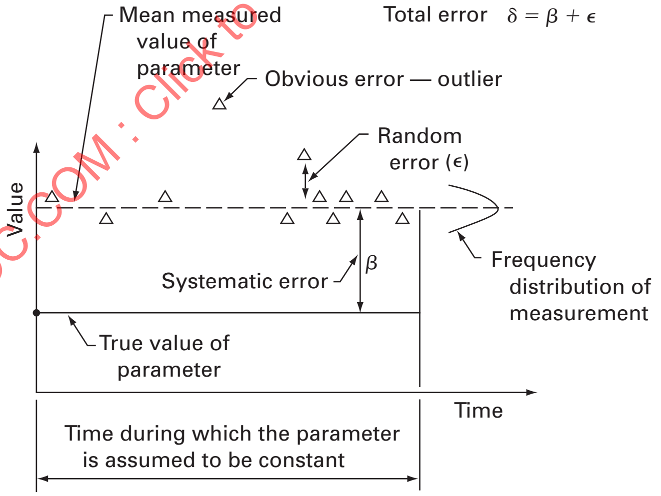


Table 7-5.3.2-1 Systematic Uncertainty Coefficients Due to Numerical Integration

Quantity	Number of Grid Points		
	9 or Less	10 to 23	24 or More
Measurement Location	C_S	C_S	C_S
Air temperature entering air heater			
Air preheater coil out of service	1.0	1.0	1.0
Air preheater coil in service	1.7	1.6	1.0
Air temperature leaving air heater	1.7	1.6	1.0
Gas temperature entering air heater	1.7	1.6	1.0
Gas temperature leaving air heater	1.7	1.6	1.0
O_2 entering air heater	1.7	1.6	1.0
O_2 leaving air heater	1.7	1.6	1.0

MANDATORY APPENDIX I
AIR HEATER EXIT GAS TEMPERATURE EXCLUDING LEAKAGE, *TFg15NL*

I-1 GENERAL

There is a common misconception that the calculation of the air heater exit gas temperature excluding leakage, *TFg15NL*, is based upon air leaking directly from the air inlet to the gas outlet. The purpose of this Appendix is to derive the air heater exit gas temperature excluding leakage by energy balance. The derivation demonstrates that the calculated exit gas temperature excluding leakage is not affected by the path(s) of the leakage.

Figure I-1-1 is a schematic of an air heater. The boundary around the air heater equipment is shown. The purpose of this heat exchanger is to cool the gas entering the air heater at *TFg14* by heating cold air entering the air heater at *TA8.* When used in a steam generator application, this process improves efficiency by decreasing the exit gas temperature. There is also an advantage to the combustion process by increasing the air temperature to improve combustion, as well as, in some applications, e.g., pulverized coal, provide drying of the fuel. The heat transferred to the air, *QA*, is represented by the following energy equation (acronyms are defined in Mandatory Appendix 5):

$$\begin{aligned} QA &= MrA9\,(HA9 - HA8) \\ &= MrFg14\,(HFg14 - HFg15NL), \text{ Btu/hr (W)} \end{aligned} \tag{I-1}$$

It is important to recognize that the useful heat transfer is defined by the heat added to the air leaving the air heater. Maybe that is the reason air heaters are called air heaters.

While Fig. I-1-1 is labeled "ideal air heater," some air heater types approach an ideal air heater in that the air heater leakage is minimal.

I-2 BI-SECTOR AIR HEATER

Figure I-2-1 is a schematic showing the boundary of the same air heater as shown in Fig. I-1-1, except leakage between the air and gas sides is depicted. Leakage is shown as entering from the entering air. Since the excess air entering and leaving the air heater is measured, the only exception to this concept would be if there were leakage in the flues between the air heater and the measurement points and/or leakage in the air heater housing/casing itself (ingress air). For purposes of the energy balance calculations, if ingress air is present, the temperature is assumed to be the same as the entering air stream(s).

The leakage air mixes with the gas inside the boundary and exits at the same temperature as the gas.

This schematic depicts leakage within the air heater boundary on both the hot and cold sides of the air heater.

Leakage on the cold side of the air heater boundary has no impact on air heater thermal performance.

Leakage on the hot side of the air heater impacts (decreases) air heater thermal performance but is within the air heater boundary. A nominal amount of hot-side leakage is expected, attributable to the equipment design characteristics and therefore not correctable for purposes of an air heater compliance code.

Note that the useful energy transferred is still expressed by the energy added to the air and expressed by the same air energy equation as in Fig. I-1-1.

$$QA = MrA9\,(HA9 - HA8) \tag{I-2}$$

For simplicity of explanation and calculations, the leakage air stream can be considered separately from the gas stream as shown in Fig. I-2-2.

Consider the energy transfer in the following streams:

Heat transferred to air leaving the air heater (useful heat transfer)

$$QA = MrA9\,(HA9 - HA8) \tag{I-3}$$

Heat transferred to air leakage, *QAl*

$$QAl = MrAl\,(HA15 - HA8) \tag{I-4}$$

Heat transferred to gas

$$QFg = MrFg14\,(HFg14 - HFg15) \tag{I-5}$$

or the useful energy transferred is

$$QA = QFg - QAl = QFgNL \tag{I-6}$$

where *QFgNL* is the useful energy extracted from the gas and from eq. (I-1) is

$$QFgNL = MrFg14\,(HFg14 - HFg15NL) \tag{I-7}$$

Combining eqs. (I-4), (I-5), and (I-7),

$$MrFg14\ (HFg14 - HFg15NL) = MrFg14 \times (HFg14 - HFg15) - MrAl\ (HA15 - HA8) \tag{I-8}$$

Expressing leakage as a percentage of the entering flue gas,

$$MpAl = 100\,\frac{MrAl}{MrFg14}$$

Then

$$MrAl = \frac{MpAl}{100}\,MrFg14 \tag{I-9}$$

Equation (I-8) can be reduced to

$$HFg15NL = HFg15 + \frac{MpAl}{100}\,(HA15 - HA8) \tag{I-10}$$

The gas temperature leaving the air heater, excluding leakage (corrected for leakage), *TFg15NL*, can be calculated from *HFg15NL*. Equation (I-10) can also be expressed in terms of temperature and specific heat

$$CpFg\ (TFg15NL - TFg15) = \frac{MpAl}{100}\,CpA \times (TA15 - TA8) \tag{I-11}$$

which reduces to the more familiar equation for *TFg15NL*

$$TFg15NL = TFg15 + \frac{MpAl}{100}\,\frac{CpA}{CpFg} \times (TA15 - TA8) \tag{I-12}$$

I-3 TRI-SECTOR AIR HEATER

Figure I-3-1 shows the leakage streams for a tri-sector air heater. As with the bi-sector air heater, all leakage occurs within the air heater boundary. It can be shown that eq. (I-10) or eq. (I-12) is applicable for calculating *TFg15NL* with one exception. Both the primary air and secondary air leak into the gas leaving the boundary. Thus, the weighted average temperature of the entering air streams must be used to calculate the exit gas temperature excluding leakage.

$$TAl = \frac{MrAlP}{MrAl}\,TA8P + \frac{MrAlS}{MrAl}\,TA8S \tag{I-13}$$

where *TAl* is the weighted average leakage temperature and should be substituted for *TA8* in eq. (I-12) [and the equivalent enthalpy, *HAl*, in eq. (I-10)].

It is not deemed practical to try to measure this split, as the uncertainty is estimated to be greater than the manufacturer's predicted split. Therefore, for this Code, the air heater vendors predicted split between the primary air-to-gas and secondary air-to-gas air leakage shall be used to calculate the average air leakage temperature, *TAl*.

One other feature unique to multi-sector air heaters is that there will be air leakage from the higher pressure air stream to the lower pressure air stream(s). This should be accounted for when calculating the energy balance between the air and gas streams. As with the air-to-gas splits, the manufacturer's estimated primary air to secondary air should be used as a base and adjusted by the ratio of measured total air-to-gas leakage divided by the predicted total air-to-gas leakage.

Fig. I-1-1 Ideal Air Heater — No Leakage

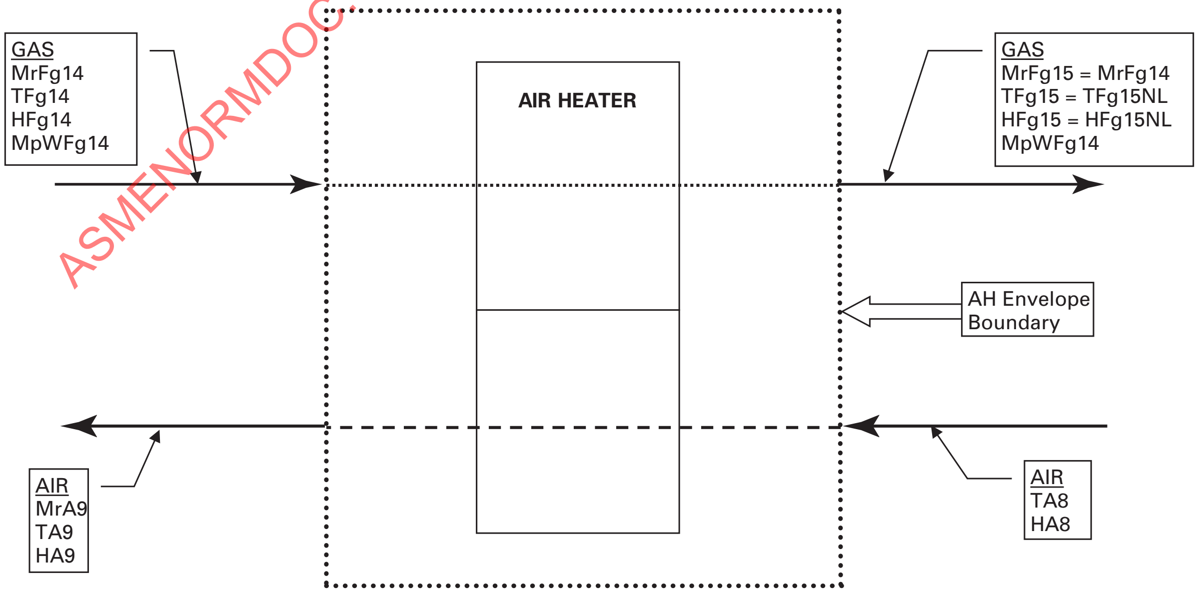


Fig. I-2-1 Air Heater With Leakage

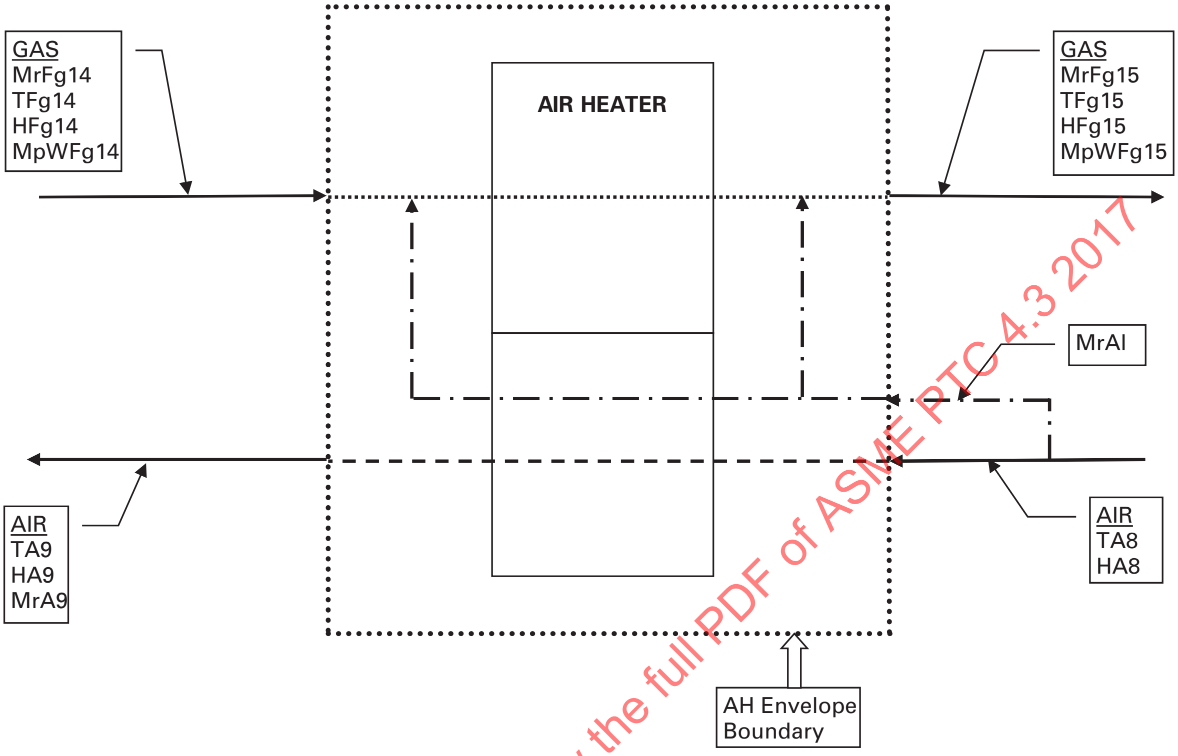


Fig. I-2-2 Air/Gas Flow Schematic — Air Heater With Leakage

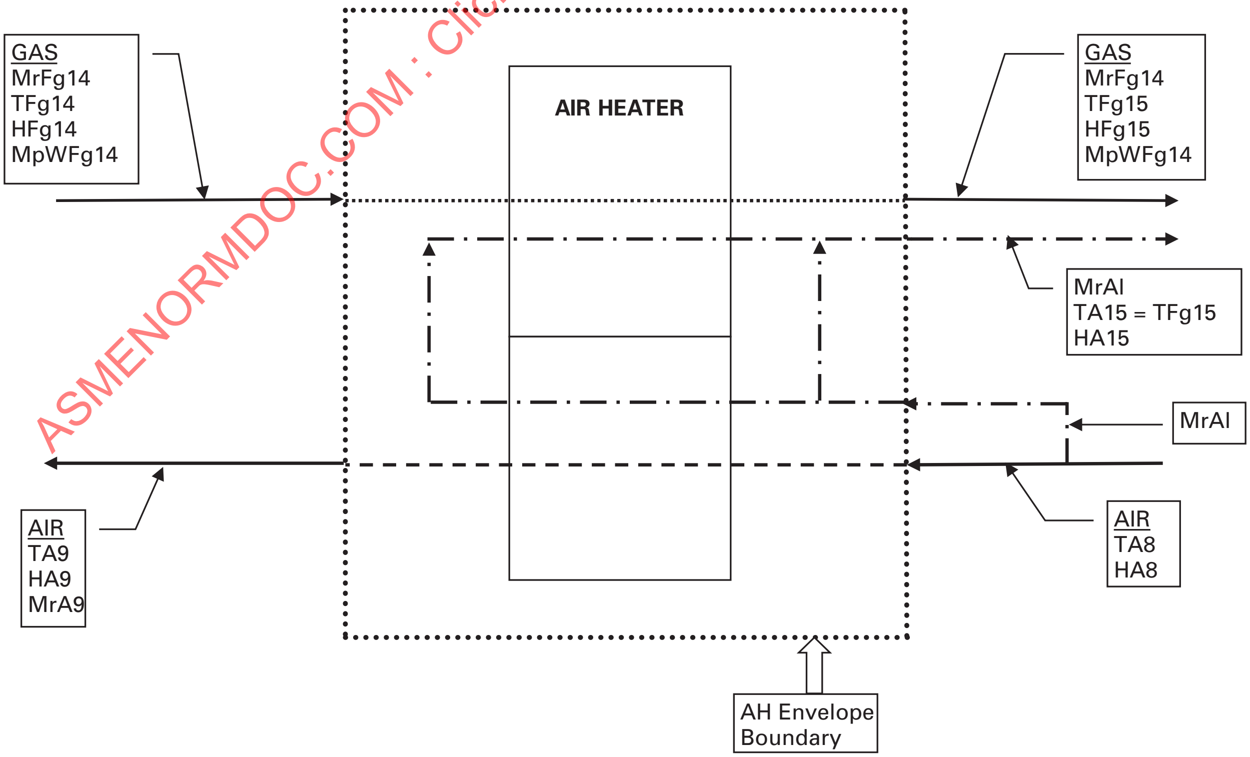
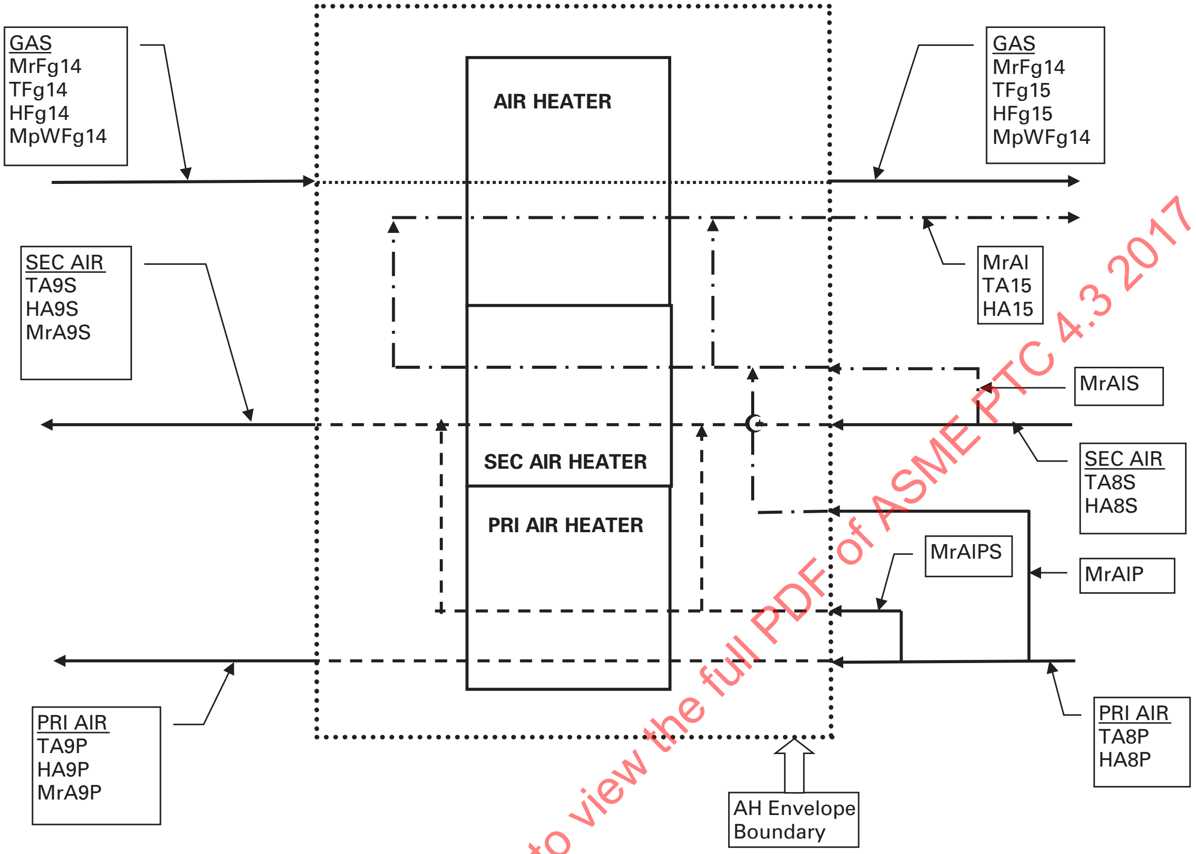


Fig. I-3-1 Tri-Sector Air Heater



MANDATORY APPENDIX II
SAMPLING SYSTEMS

II-1 PORTABLE PROBES POINT-TO-POINT SAMPLING

The gas sampling probes (one or more at the inlet and one or more at the outlet) are each normally inserted to the deepest point in a port. After the system has been purged of gas from the previous point, sufficient measurements of the flue gas composition (O_2) shall be recorded (as frequently as practical, e.g., every 5 or 10 sec for manual recording of electronic analyzers) for a time period equal to two or more complete revolutions of the heater (or at least two readings when using an Orsat). Then the probe is moved to the next test port and the procedure repeated.

The minimum time for the sampling lines to be adequately purged of gas withdrawn from the previous sampling position shall be determined by experiment at the start of the test. For test planes where the static pressure is above atmospheric pressure, insert the probe into the flue gas stream. When the indicated gas composition stabilizes, withdraw the probe from the gas stream, and record the time required for the indicated gas composition to change from the stable reading to near ambient (20.9% for O_2). For test planes where the static pressure is below atmospheric pressure, connect the sample tubing at the probe end and insert the probe into the gas stream. The time taken for the indicated gas composition of the sampled gas to change from ambient to within 0.2% points of the expected reading shall be recorded. The recorded time shall then be multiplied by a factor of 1.5 to determine the minimum time before sample analysis can commence.

At each traverse point, simultaneous measurements are taken of gas composition, gas temperature, and, optionally, velocity head. If the velocity head readings are taken, the weighted mean average gas composition across the sampling plane can be computed. This is the only sampling technique that allows for simultaneous gas sampling and velocity measurements.

Prior to the start of each test run, a leak check shall be performed of the entire system. With the probe out of the duct, start the vacuum pump and seal the probe's tip. After the pressure at the pump suction has stabilized, isolate the suction of the vacuum pump. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check.

Since this method requires sample collection simultaneously from both the air heater inlet and outlet gas streams, on balanced draft units care must be taken to ensure that leakage from the gas inlet does not affect the readings at the gas outlet. First, only open one test port per probe at a time and when replacing caps ensure that they are leak tight. Second, continuously block any gaps between the probe and the port. Third, the inlet and outlet traverses shall be offset. (For example, both the inlet and outlet traverses always work from left to right, and when they reach the right end, they move to the left end and continue from there. However, the inlet traverse starts at the left side, and the outlet traverse starts in the middle and works to the right.)

With portable probe point-to-point sampling, since the probes are moved manually to each position, in addition to potential air ingress, care must be taken to ensure repeatability of the probe's position from one traverse to another.

II-2 FIXED GRID SAMPLING TECHNIQUES

Fixed grid sampling techniques are generally used for their combined advantages of reduced labor requirements and minimal potential for air ingress on balanced draft units. Such fixed grids can be arranged to provide either a bulk (composite) gas sample for analysis or individual samples from each sampling probe that can be analyzed separately to replicate the readings achieved by a portable probe point-to-point analysis, or both. Another advantage is that some fixed-grid sampling techniques allow individual point samples to be collected much faster than portable probe point-to-point traverses.

One disadvantage of fixed grids is that they do not allow for simultaneous measurements of gas composition and velocity. Another disadvantage is that some thermocouples on the probes of a fixed grid may fail during a test. Since these thermocouples are usually not readily replaceable during a test run, if the minimum number are not functional throughout the test run, the test run shall be aborted (see para. 4-5.5).

II-2.1 Fixed Grid — Composite Sampling

Where stratification of the gas analysis and/or velocity is not excessive, fixed sampling grids are commonly combined with sample mixing devices to obtain bulk (composite) gas samples for continuous monitoring throughout the test, as shown in Figs. II-2.1-1 and II-2.1-2. These bulk-sampling techniques are particularly convenient whenever air heater tests are integrated with a full boiler test. Moreover, the speed at which such continuous bulk gas sampling may be analyzed facilitates the multiple, repeated measurements that are required to complete a statistical analysis of the readings.

To ensure the system is leak-free, before inserting the probes into the duct they shall be thoroughly inspected for leaks. Prior to the start of each test run, a leak check shall be performed of the entire system. At each sample tube, disconnect the tubing and plug each, ensure that all pinch clamps/valves are open, and start the vacuum pump. After the pressure at the pump suction has stabilized, isolate the suction of the vacuum pump. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check. See Nonmandatory Appendix D.

II-2.2 Fixed Grid — Point-to-Point (Single Pump) Sampling

Fixed grid — point-to-point (single pump) sampling is very similar to portable probe point-to-point sampling. However, instead of using a portable probe, fixed probes are placed in the duct, and the sampling system is connected to each point one at a time. See Fig. II-2.2-1.

An advantage of this method is less potential for air ingress on balanced draft units (affecting the readings) with this point-to-point method, compared to the "portable probe point-to-point" traverse. Another advantage is that the sample position is repeatable from one traverse to another.

To ensure the system is leak-free, before inserting the probes into the duct they shall be thoroughly inspected for leaks. Prior to the start of each test run, a leak check shall be performed. With the sampling tubing disconnected at the probe, start the vacuum pump and seal the tubing at the end. After the pressure at the pump suction has stabilized, isolate the suction of the vacuum pump. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check.

The minimum time for the sampling lines to be adequately purged of gas withdrawn from the previous sampling position shall be determined by experiment at the start of the test. For test planes where the static pressure is above atmospheric pressure, connect the sample tubing to a probe. When the indicated gas composition stabilizes, temporarily disconnect the sample tubing at the probe end, and record the time required for the indicated gas composition to change from the stable reading to near ambient (20.9% for O_2). For test planes where the static pressure is below atmospheric pressure, with the gas analysis equipment indicating ambient composition, connect the sample tubing at the probe end. The time required for the indicated gas composition of the sampled gas to change from ambient to within 0.2% points of the expected reading shall be recorded. The recorded time shall then be multiplied by a factor of 1.5 to determine the minimum time before sample analysis can commence.

II-2.3 Fixed Grid — Point-to-Point (Dual Pump) Sampling

A better sampling system would combine the convenience and speed of fixed-grid — composite sampling with the accuracy and analytical capabilities of point-to-point sampling.

Figure II-2.3-1 shows a simplified diagram of one such fixed sampling grid, designed to allow fast withdrawal and analysis of gas samples. Note the use of multiple, paired valves (which are typically ball valves and can be automated) to select individual sample tubes. In the period immediately before sampling begins, all of the sampling valves upstream of vacuum pump 2 will be closed, while all of the side-stream valves would be open, with vacuum pump 1 drawing samples through all of the lines in parallel. This ensures that each of the long lengths of individual lines from the sampling plane is continuously flushed with the flue gas to be analyzed, thus reducing the response time whenever that line is sampled. However, this system, compared to the previous system, requires an additional pump, additional valves equal to twice the number of sample points, as well as a person or automated system to perform valve sequencing.

In order to sample an individual point, the appropriate pair of valves are operated (sampling valve is opened and side-stream valve is closed) for the required time (first for flushing and then for collecting data), before reversing the valve positions and moving to the next sample point. This arrangement allows for the detailed analytical capabilities of point-to-point sampling with faster traverse times than the aforementioned methods.

To ensure the system is leak-free, before inserting the probes into the duct they shall be thoroughly inspected for leaks. Prior to the start of each test run, a leak check shall be performed. With all side-stream valves closed and all sample tubing disconnected at each probe, start the vacuum pump and seal the ends of all tubing. After the pressure at the pump suction has stabilized, isolate the suction of the vacuum pump. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check.

The minimum time for the sampling lines to be adequately purged of gas withdrawn from the previous sampling position shall be determined by experiment at the start of the test. First, determine which sample point has the longest tubing run between its sample valve and the gas preparation equipment. Second, start the pumps and place the valves in position for sampling that point. Third, when the indicated gas composition stabilizes, record this reading. Fourth, close the sample valve, open the side-stream valve, disconnect the tubing on the downstream side of the sampling valve, and allow time for the indicated gas composition to change from the stable reading to near ambient (20.9% for O_2). Fifth, reconnect the sample tubing to the downstream side of the sampling valve, open the sampling valve, and close the side-stream valve. Measure the time required for the indicated gas composition to change from ambient to within 0.2% points of the previously recorded reading. This measured time shall then be multiplied by a factor of 1.5 to determine the minimum time before sample analysis can commence.

II-2.4 Fixed Grid — Combination Sampling

Finally, Fig. II-2.4-1 shows a complementary system that combines the features of the bulk (composite) gas sampling with the capability to obtain individual point-to-point samples using a second gas analyzer. However, this system, compared to the previous system, requires an additional gas analyzer and set of gas preparation equipment.

To ensure the system is leak-free, before inserting the probes into the duct they shall be thoroughly inspected for leaks. Prior to the start of each test run, a leak check shall be performed of both the point-to-point and the composite subsystems. To check the point-to-point subsystem, start with all side-stream valves closed and all sample tubing disconnected at each probe, start vacuum pump 2, and seal the ends of all tubing. After the pressure at the suction of pump 2 has stabilized, isolate the pump suction. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check. To check the composite subsystem, continue with all side-stream valves closed, open the outlet valve at the sample mixing device, open the mixing device inlet valves (if the mixing device has these valves in addition to the side-stream valves), and start vacuum pump 1. After the pressure at the pump suction has stabilized, isolate the pump suction. If the system pressure increases more than 0.1 in. Hg in 2 min, locate the leak, repair it, and repeat the leak check.

The minimum time for the point-to-point subsystem sampling lines to be adequately purged of gas withdrawn from the previous sampling position shall be determined by experiment at the start of the test. First, determine which sample point has the longest tubing run between its sample valve and the gas preparation equipment. Second, start the pumps and place the valves in position for sampling that point. Third, when the indicated gas composition stabilizes, record this reading. Fourth, close the sample valve, open the side-stream valve, disconnect the tubing on the downstream side of the sampling valve, and allow time for the indicated gas composition to change from the stable reading to near ambient (20.9% for O_2). Fifth, reconnect the sample tubing to the downstream side of the sampling valve, open the sampling valve, and close the side-stream valve. Measure the time required for the indicated gas composition to change from ambient to within 0.2% points of the previously recorded reading. This measured time shall then be multiplied by a factor of 1.5 to determine the minimum time before sample analysis can commence.

Fig. II-2.1-1 Fixed Grid — Composite Setup

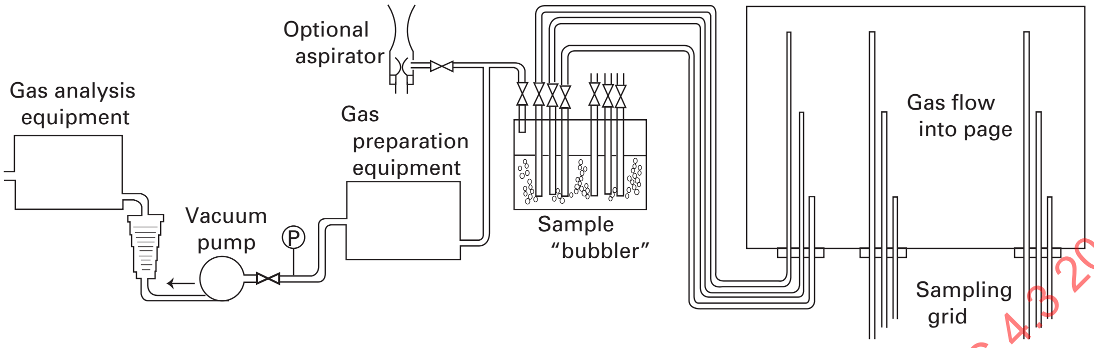


Fig. II-2.1-2 Boiler Testing Composite Gas Sample Flow Path

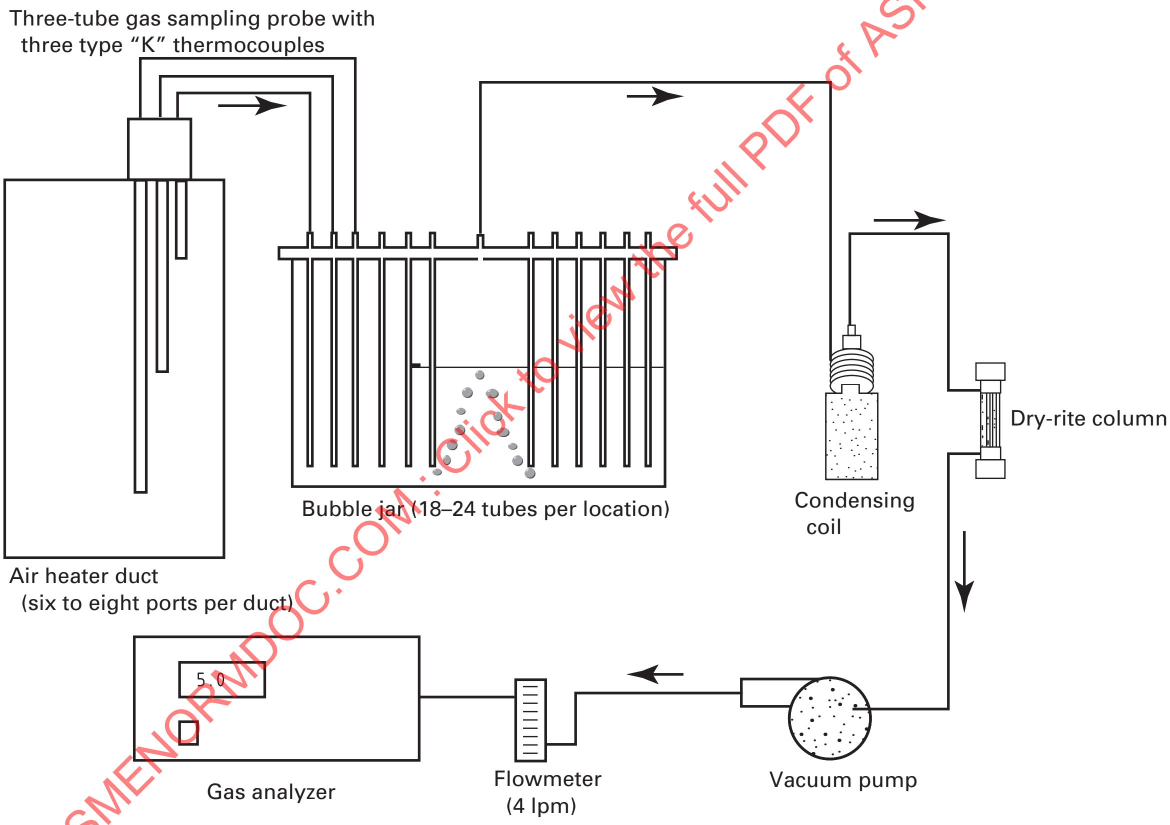


Fig. II-2.2-1 Fixed Grid — Point-to-Point (Single Pump) Setup

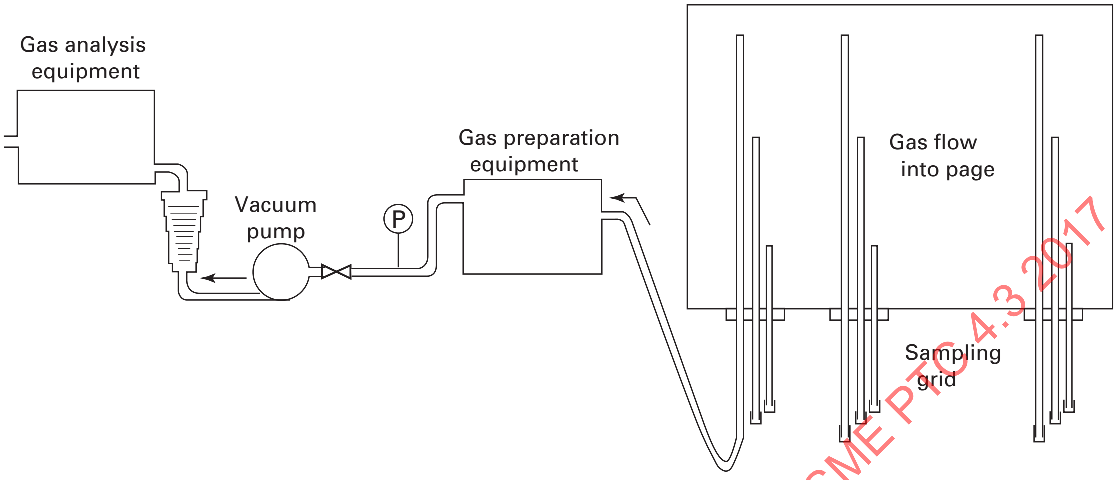


Fig. II-2.3-1 Fixed Grid — Point-to-Point (Dual Pump) Setup

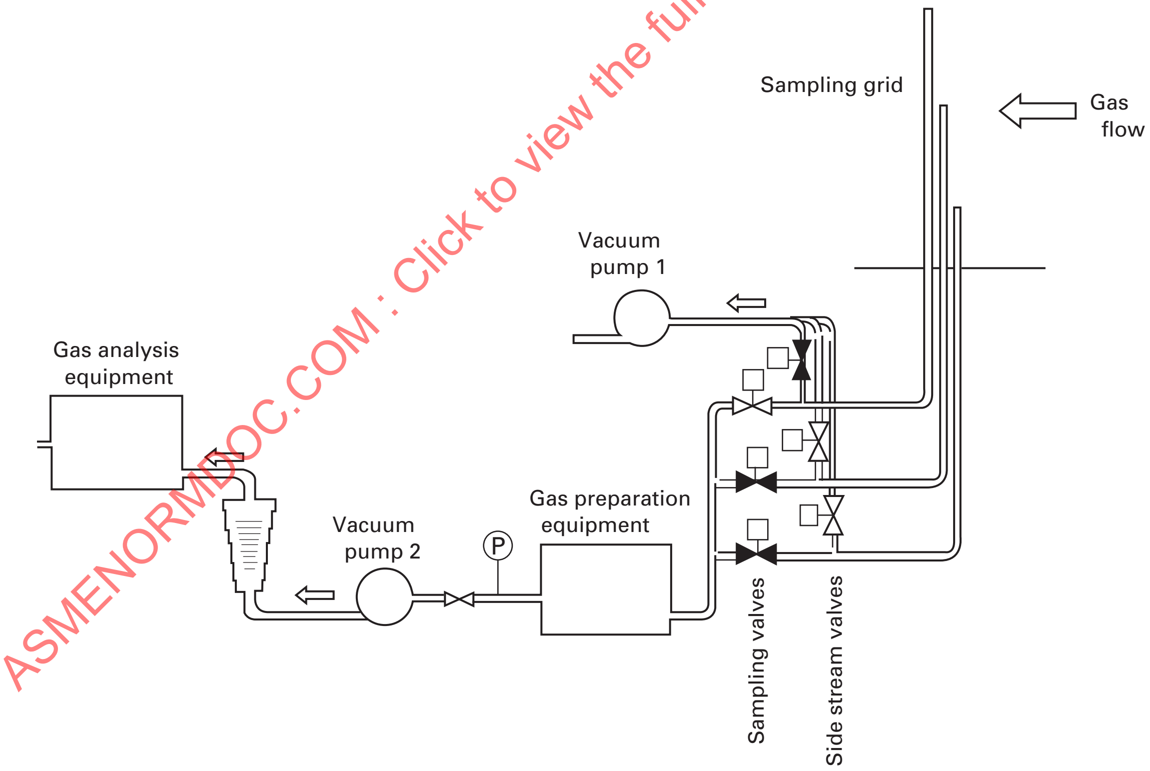
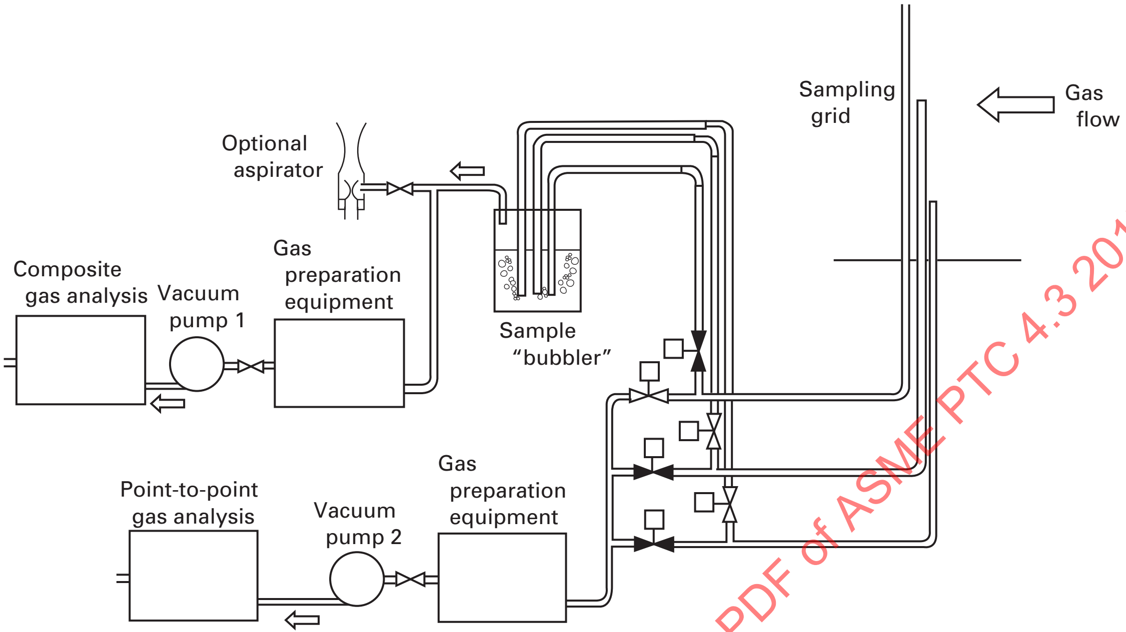


Fig. II-2.4-1 Fixed Grid — Combination Setup



MANDATORY APPENDIX III
SAMPLE CALCULATIONS FOR TEMPERATURE MEASUREMENTS

III-1 THERMOMETER (DEGREES FAHRENHEIT)

For example, given a thermometer whose smallest divisions are 0.2°F, with a reading of 100°F, and the following calibration data:

Standard Temperature, °F	Thermometer Reading, °F	Error, °F
32	32.5	+0.5
90	89.9	−0.1
140	139.5	−0.5

The readability is one-half of 0.2°F, or 0.1°F.

III-1.1 Procedures When Not Correcting the Reading

If the reading is not to be corrected, then 100°F will be used in the calculations. To calculate the positive and negative components of the systematic uncertainty, see the following steps and Table III-1.1-1:

Step 1: Calculate the error at the calibration point below the measured value. At 89.9°F, the error is the indicated temperature minus the standard temperature, 89.9°F − 90.0°F, or −0.1°F. This indicates the measured temperature could be 0.1°F too low.

Step 2: Calculate the error at the calibration point above the measured value. At 139.5°F, the error is the indicated temperature minus the standard temperature, 139.5°F − 140.0°F, or −0.5°F. This indicates the measured temperature could be 0.5°F too low.

(a) Positive Systematic Uncertainty. The positive systematic uncertainty

(1) if both errors are positive, is the larger of the two errors

(2) if only one error is positive, is that value

(3) if both errors are negative, is 0

For this example, the positive systematic uncertainty is +0.0°F, since both errors have negative values.

(b) Negative Systematic Uncertainty. The negative systematic uncertainty

(1) if both errors are negative, is the one with the larger magnitude

(2) if only one error is negative, is that value

(3) if both errors are positive, is 0

For this example, the negative systematic uncertainty is −0.5°F, since it has the larger magnitude of the two negative errors.

III-1.2 Procedures When Correcting the Reading

If the reading is to be corrected, then to calculate the corrected value and the positive and negative components of the systematic uncertainty, see the following steps and Table III-1.2-1:

Step 1: Calculate the error at the calibration point below the measured value. At 89.9°F, the error is the indicated temperature minus the standard temperature, 89.9°F − 90.0°F, or −0.1°F. This indicates the measured temperature could be 0.1°F too low.

Step 2: Calculate the error at the calibration point above the measured value. At 139.5°F, the error is the indicated temperature minus the standard temperature, 139.5°F − 140.0°F, or −0.5°F. This indicates the measured temperature could be 0.5°F too low.

Step 3: Calculate the error at the measured value by straight-line interpolation.

$$\frac{-0.1}{89.9}, \frac{x}{100}, \frac{-0.5}{139.5}$$

$$\begin{aligned} x &= \frac{[(-0.5) - (-0.1)]\,(100 - 89.9)}{139.5 - 89.9} + (-0.1) \\ &= -0.18°\text{F} \end{aligned}$$

This indicates the measured temperature could be 0.18°F too low.

Step 4: Calculate the corrected reading by measured reading minus the error at the measured value.

$$100°\text{F} - (-0.18) = 100.18°\text{F}$$

Step 5: Calculate the first span by taking the "error at the calibration point below the measured value" minus the "error at the measured value."

$$-0.1°\text{F} - (-0.18°\text{F}) = +0.08°\text{F}$$

Step 6: Calculate the second span by taking the "error at the calibration point above the measured value" minus the "error at the measured value."

$$-0.5°\text{F} - (-0.18°\text{F}) = -0.32°\text{F}$$

Step 7: The positive systematic uncertainty is one-half of the span with the positive value.

$$\frac{1}{2}\,(+0.08) = +0.04$$

Step 8: The negative systematic uncertainty is one-half of the span with the negative value.

$$\frac{1}{2}(-0.32) = -0.16$$

III-2 THERMOCOUPLES AND RESISTANCE TEMPERATURE DEVICES (DEGREES FAHRENHEIT)

The accuracy check of a temperature measurement using thermocouples or RTDs may be done by an accuracy check of the entire loop or by separate accuracy checks of two or more segments of the loop. Each segment of a loop could include one or more components (e.g., the sensor, the lead wire, and the electronics). An example of a loop with multiple segments (and therefore multiple accuracy checks) would be if the thermocouple has a stand-alone accuracy check, the lead wire has a stand-alone accuracy check, and the electronics has a stand-alone accuracy check. Another example would be where the thermocouple and lead wire have a stand-alone accuracy check and the electronics has a stand-alone accuracy check.

III-2.1 Combining Multiple Segments With Accuracy Checks

Where the measurement system has more than one segment, each with its own accuracy check, the correction to be applied to the reading and the systematic uncertainties are combined as follows:

(a) The overall correction is determined by calculating a correction (by interpolating between the calibration data below and above the indicated reading) for each segment and then summing the corrections.

(b) The overall systematic uncertainty for the reading is determined.

(1) For a loop with only one segment, do the following:

(-a) Calculate the correction at the accuracy checkpoints below and above the indicated temperature.

(-b) Subtract the correction at the accuracy checkpoint below the indicated reading from the correction at the indicated reading. If it is a negative value, it is a negative systematic uncertainty; if it is a positive value, it is a positive systematic uncertainty.

(-c) Subtract the correction at the accuracy checkpoint above the indicated reading from the correction at the indicated reading. If it is a negative value, it is a negative systematic uncertainty; if it is a positive value, it is a positive systematic uncertainty.

(-d) If both calculated systematic uncertainties are zero (i.e., the corrections at the accuracy checkpoints below and above the indicated reading are the same), use 0.1°F (0.05°C) for the positive and negative systematic uncertainty for an RTD, and 0.2°F (0.1°C) for the positive and negative systematic uncertainty for a thermocouple.

NOTE: If the segment does not have a unique accuracy check (i.e., an accuracy check was performed on a selected number of components and that data is used to represent all similar components), see the next paragraph for a discussion of how to determine the correction and systematic uncertainty.

(2) For a loop with multiple segments, repeat the four steps above for each segment.

(c) Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement system to obtain the overall positive (and negative) systematic uncertainty.

III-2.2 Combining Multiple Segments With Representative Accuracy Checks

Each segment of a measurement (either the entire loop or the two or more segments of the measurement) could have a specific accuracy check (i.e., every thermocouple in a grid has a unique accuracy check). Each segment of a measurement could also have two or more segments that use representative accuracy check data from two or more representatives of all of the segments of that section of every measurement. Where a segment uses two or more representative accuracy checks, the corrections to be applied to the reading and the systematic uncertainties are combined as follows:

(a) The overall correction is determined by calculating a correction for each representative and then averaging the corrections.

(b) The overall systematic uncertainty for a segment with representative accuracy checks is determined.

(1) For each representative of the segment, do the following:

(-a) Calculate the correction at the accuracy checkpoints below and above the indicated temperature.

(-b) Subtract the correction at the accuracy checkpoint below the indicated reading from the correction at the indicated reading. If it is a negative value, it is a negative systematic uncertainty; if it is a positive value, it is a positive systematic uncertainty.

(-c) Subtract the correction at the accuracy checkpoint above the indicated reading from the correction at the indicated reading. If it is a negative value, it is a negative systematic uncertainty; if it is a positive value, it is a positive systematic uncertainty.

(-d) If both calculated systematic uncertainties are zero (i.e., the corrections at the accuracy checkpoint below and above the indicated reading are the same), use 0.1°F (0.05°C) for the positive and negative systematic uncertainty for an RTD, and 0.2°F (0.1°C) for the positive and negative systematic uncertainty for a thermocouple.

(2) Combine the positive (then negative) systematic uncertainties by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties, to one less than the number of positive (then negative) systematic uncertainties.

III-2.3 Using Accuracy Check Data

There are three ways to use the accuracy checks to determine sensor and data acquisition system systematic uncertainty due to interpolation between accuracy checkpoints and to optionally correct the measured data.

III-2.3.1 Method 1 — Correct Each Reading At Each Point

III-2.3.1.1 Method 1 Procedure. In the first (and preferred) method, accuracy check data is used to correct each reading at each point. The corrected readings at each point are then arithmetically averaged (over time) to determine the average corrected temperature for each point. The average corrected temperatures for each point are then averaged (algebraically or weight, by mass flow) to determine the temperature at the location.

III-2.3.1.1.1 Steps for Each Point at a Particular Location

(a) For each reading at the point, for each segment of the measurement system at the point, the steps below should be performed.

(1) For each accuracy check for a segment [either individual component(s) or for each representative component(s)], perform the following:

Step 1: Determine the correction at the accuracy check's data set below the reading.

Step 2: Determine the correction at the accuracy check's data set above the reading.

Step 3: Determine the correction at the reading by interpolating between the accuracy check data below and above the reading.

Step 4: Subtract the correction at the accuracy check's data set below the reading from the correction at the reading.

Step 5: Subtract the correction at the accuracy check's data set above the reading from the correction at the reading.

Step 6: The positive systematic uncertainty is the positive value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F (0.1°C) for the positive systematic uncertainty for a thermocouple.

Step 7: The negative systematic uncertainty is the negative value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

(2) Average the corrections from all accuracy checks.

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to z, where

(-a) z equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) z equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

(b) For each reading at the point, sum the corrections from each segment of the measurement system.

(c) For each reading at the point, calculate the corrected reading by summing the reading and the sum of the corrections.

(d) Average all corrected readings at this point.

III-2.3.1.1.2 Averaging. Average all averages of corrected readings, from all points at this location.

III-2.3.1.1.3 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each reading, by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to one less than the number of readings (from all points).

III-2.3.1.1.4 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty.

III-2.3.1.2 Method 1 Example. There are nine measurement points at this location. The sensors at the first six points were all from one spool, and the sensors at the other three points were from another spool. Both spools had accuracy checks performed on three randomly selected sensors with extension wire. An accuracy check was also performed on the common data acquisition system reading all sensors.

Results of the representative sensor (three each) accuracy checks are shown in Table III-2.3.1.2-1. Results of the electronics pretest accuracy check are shown in Table III-2.3.1.2-2.

The first set of readings (corrected for the ice-bath temperature) at the nine points at this location are 652°F, 649°F, 654°F, 646°F, 648°F, 661°F, 645°F, 659°F, and 643°F.

The second set of readings (corrected for the ice-bath temperature) at eight points at this location are 648°F, 657°F, 654°F, 652°F, 646°F, 659°F, 647°F, and 655°F; the sensor at point nine failed before the second reading.

III-2.3.1.2.1 Steps for Each Point at a Particular Location. The calculations for point #1, reading #1 are shown below (the data for all points and readings are in Tables III-2.3.1.2.1-1, III-2.3.1.2.1-2, and III-2.3.1.2.1-3).

(a) Thermocouple Segment. The calculations for the thermocouple segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) Step 1. Determine the correction at the accuracy check's data set below the reading.

(-1) Representative Thermocouple #1. Calculate the correction at the calibration point below the measured value. At 602.0°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.0°F = −3.0°F. This indicates the measured temperature could be 3.0°F too high.

(-2) Representative Thermocouple #2. Calculate the correction at the calibration point below the measured value. At 601.5°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 601.5°F = −2.5°F. This indicates the measured temperature could be 2.5°F too high.

(-3) Representative Thermocouple #3. Calculate the correction at the calibration point below the measured value. At 602.2°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.2°F = −3.2°F. This indicates the measured temperature could be 3.2°F too high.

(-b) Step 2. Determine the correction at the accuracy check's data set above the reading.

(-1) Representative Thermocouple #1. Calculate the correction at the calibration point above the measured value. At 805.5°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.5°F = −4.5°F. This indicates the measured temperature could be 4.5°F too high.

(-2) Representative Thermocouple #2. Calculate the correction at the calibration point above the measured value. At 805.0°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.0°F = −4.0°F. This indicates the measured temperature could be 4.0°F too high.

(-3) Representative Thermocouple #3. Calculate the correction at the calibration point above the measured value. At 805.7°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.7°F = −4.7°F. This indicates the measured temperature could be 4.7°F too high.

(-c) Step 3. Determine the correction at the reading by interpolating between the accuracy check data below and above the reading.

The intermediate sensor correction (from the sensor accuracy check) for spool #1, representative sensor #1, at point #1's first reading of 652°F is

$$\frac{-3.0}{602}, \frac{x}{652}, \frac{-4.5}{805.5}$$

$$\begin{aligned} x &= \frac{[(-4.5) - (-3.0)] \times (652 - 602)}{805.5 - 602} + (-3.0) \\ &= -3.37\text{°F} \end{aligned}$$

The intermediate sensor correction (from the sensor accuracy check) for spool #1, representative sensor #2, at point #1's first reading of 652°F is

$$\frac{-2.5}{601.5}, \frac{x}{652}, \frac{-4.0}{805}$$

$$\begin{aligned} x &= \frac{[(-40) - (-2.5)] \times (652 - 601.5)}{805 - 601.5} + (-2.5) \\ &= -2.87\text{°F} \end{aligned}$$

The intermediate sensor correction (from the sensor accuracy check) for spool #1, representative sensor #3, at point #1's first reading of 652°F is

$$\frac{-3.2}{602.2}, \frac{x}{652}, \frac{-4.7}{805.7}$$

$$\begin{aligned} x &= \frac{[(-4.7) - (-3.2)] \times (652 - 602.2)}{805.7 - 602.2} + (-3.2) \\ &= -3.57\text{°F} \end{aligned}$$

(-d) Step 4. Subtract the correction at the accuracy check's data set below the reading from the correction at the reading.

(-1) For representative thermocouple #1, −3.37 − (−3.0) = −0.37°F.

(-2) For representative thermocouple #2, −2.87 − (−2.5) = −0.37°F.

(-3) For representative thermocouple #3, −3.57 − (−3.2) = −0.37°F.

(-e) Step 5. Subtract the correction at the accuracy check's data set above the reading from the correction at the reading.

(-1) For representative thermocouple #1, −3.37 − (−4.5) = +1.13°F.

(-2) For representative thermocouple #2, −2.87 − (−4.0) = +1.13°F.

(-3) For representative thermocouple #3, −3.57 − (−4.7) = +1.13°F.

(-f) Step 6. The positive systematic uncertainty is the positive value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F

(0.1°C) for the positive systematic uncertainty for a thermocouple.

(-1) For representative thermocouple #1, the value is +1.13°F.

(-2) For representative thermocouple #2, the value is +1.13°F.

(-3) For representative thermocouple #3, the value is +1.13°F.

(-g) Step 7. The negative systematic uncertainty is the negative value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

(-1) For representative thermocouple #1, the value is −0.37°F.

(-2) For representative thermocouple #2, the value is −0.37°F.

(-3) For representative thermocouple #3, the value is −0.37°F.

(2) Average the corrections from all accuracy checks.

$$[(-3.37) + (-2.87) + (-3.57)]/3 = -3.27$$

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to *z*, where

(-a) *z* equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) *z* equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

The sensor positive systematic uncertainty is

$$\sqrt{[(1.13)^2 + (1.13)^2 + (1.13)^2]/(3 - 1)} = +1.38°\text{F}$$

The sensor negative systematic uncertainty is

$$\sqrt{[(-0.37)^2 + (-0.37)^2 + (-0.37)^2]/(3 - 1)} = -0.45°\text{F}$$

(b) Electronics Segment. The calculations for the electronics segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) Step 1. Determine the correction at the accuracy check's data set below the reading. Calculate the correction at the calibration point below the measured value. At 602.0°F, the correction is the standard temperature minus the indicated temperature, 600.0°F − 600.3°F = −0.3°F. This indicates the measured temperature could be 0.3°F too high.

(-b) Step 2. Determine the correction at the accuracy check's data set above the reading. Calculate the correction at the calibration point above the measured value. At 805.5°F, the correction is the standard temperature minus the indicated temperature, 800.0°F − 799.8°F = +0.2°F. This indicates the measured temperature could be 0.2°F too low.

(-c) Step 3. Determine the correction at the reading by interpolating between the accuracy check data below and above the reading.

The intermediate sensor correction (from the sensor accuracy check) for the electronics, at point #1's first reading of 652°F is

$$\frac{-0.3}{600.3}, \frac{x}{652}, \frac{+0.2}{799.8}$$

$$\begin{aligned} x &= \frac{[(0.2) - (-0.3)] \times (652 - 600.3)}{799.8 - 600.3} + (-0.3) \\ &= -0.17°\text{F} \end{aligned}$$

(-d) Step 4. Subtract the correction at the accuracy check's data set below the reading from the correction at the reading.

$$-0.17 - (-0.30) = +0.13°\text{F}$$

(-e) Step 5. Subtract the correction at the accuracy check's data set above the reading from the correction at the reading.

For representative thermocouple #1,

$$-0.17 - (+0.20) = -0.37°\text{F}$$

(-f) Step 6. The positive systematic uncertainty is the positive value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F (0.1°C) for the positive systematic uncertainty for a thermocouple.

For electronics, the value is +0.13°F.

(-g) Step 7. The negative systematic uncertainty is the negative value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

For electronics, the value is −0.37°F.

(2) Average the corrections from all accuracy checks. The result is −0.17.

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to z, where

(-a) z equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1.

(-b) z equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1.

The sensor positive systematic uncertainty is

$$\sqrt{(0.13)^2/1} = +0.13°\text{F}$$

The sensor negative systematic uncertainty is

$$\sqrt{(-0.37)^2/1} = -0.37°\text{F}$$

(c) Sum the corrections from each segment of the measurement system.

$$-3.27 + (-0.17) = -3.44°\text{F}$$

(d) Calculate the corrected reading by summing the reading and the sum of the corrections.

$$652.0 + (-3.44) = 648.56°\text{F}$$

(e) Average all corrected readings at this point.

$$(648.56 + 644.58)/2 = 646.57°\text{F}$$

III-2.3.1.2.2 Averaging. Average all averages of corrected readings, from all points at this location.

$$\begin{aligned}&(646.57 + 649.55 + 650.55 + 645.58 + 643.59 + 656.53 + 647.43\\&\quad + 658.47 + 644.42)/9 = 649.19°\text{F}\end{aligned}$$

III-2.3.1.2.3 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each reading, by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties, to one less than the number of readings (from all points).

(a) For segment #1 — thermocouples — the positive systematic uncertainty is

$$\begin{aligned}&\{[(1.38)^2 + (1.41)^2 + (1.37)^2 + (1.44)^2 + (1.42)^2 + (1.31)^2\\&+ (0.05)^2 + (0.06)^2 + (0.05)^2 + (1.42)^2 + (1.34)^2 + (1.37)^2\\&+ (1.38)^2 + (1.44)^2 + (1.32)^2 + (0.05)^2 + (0.06)^2]/(17 - 1)\}^{0.5}\\&= +1.20°\text{F}\end{aligned}$$

The negative systematic uncertainty for segment #1 is

$$\begin{aligned}&\{[(-0.45)^2 + (-0.42)^2 + (-0.47)^2 + (-0.40)^2 + (-0.42)^2\\&+ (-0.53)^2 + (-0.16)^2 + (-0.15)^2 + (-0.16)^2 + (-0.42)^2\\&+ (-0.50)^2 + (-0.47)^2 + (-0.45)^2 + (-0.40)^2 + (-0.51)^2\\&+ (-0.16)^2 + (-0.15)^2]/(17 - 1)\}^{0.5} = -0.40°\text{F}\end{aligned}$$

(b) For segment #2 — electronics — the positive systematic uncertainty is

$$\begin{aligned}&\{[(0.13)^2 + (0.12)^2 + (0.13)^2 + (0.11)^2 + (0.12)^2 + (0.15)^2\\&+ (0.11)^2 + (0.15)^2 + (0.11)^2 + (0.12)^2 + (0.14)^2 + (0.13)^2\\&+ (0.13)^2 + (0.11)^2 + (0.15)^2 + (0.12)^2 + (0.14)^2]/(17 - 1)\}^{0.5}\\&= +0.13°\text{F}\end{aligned}$$

The negative systematic uncertainty is

$$\begin{aligned}&\{[(-0.37)^2 + (-0.38)^2 + (-0.37)^2 + (-0.39)^2 + (-0.38)^2\\&+ (-0.35)^2 + (-0.39)^2 + (-0.35)^2 + (-0.39)^2 + (-0.38)^2\\&+ (-0.36)^2 + (-0.37)^2 + (-0.37)^2 + (-0.39)^2 + (-0.35)^2\\&+ (-0.38)^2 + (-0.36)^2]/(17 - 1)\}^{0.5} = -0.38°\text{F}\end{aligned}$$

III-2.3.1.2.4 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty. See Table III-2.3.1.2.4-1.

III-2.3.2 Method 2 — Correct the Averaged Readings

III-2.3.2.1 Method 2 Procedure. In the second method, accuracy check data is used to correct the arithmetically averaged readings (over time) at each point to determine a corrected temperature for each point. Then the corrected temperatures (across the grid) are averaged (arithmetic or weight, by mass flow) to determine the temperature at the location. The systematic uncertainties are either

(a) calculated from the accuracy check data below and above each point's average reading and the interpolated correction at each point's temperature or

(b) a value the parties mutually agree upon (permissible for electronics/data acquisition system's systematic uncertainties only)

III-2.3.2.1.1 Steps for Each Point at a Particular Location

(a) Arithmetically average the readings (over time) at the point.

(b) For each segment of the measurement system at the point, the steps below should be performed.

(1) For each accuracy check for a segment [either individual component(s) or for each representative component(s)], perform the following:

Step 1: Determine the correction at the accuracy check's data set below the point's average reading.

Step 2: Determine the correction at the accuracy check's data set above the point's average reading.

Step 3: Determine the correction at the average reading, by interpolating between the accuracy check data below and above the average reading.

Step 4: Subtract the correction at the accuracy check's data set below the point's average reading from the correction at the average reading.

Step 5: Subtract the correction at the accuracy check's data set above the point's average reading from the correction at the average reading.

Step 6: The positive systematic uncertainty is the positive value from Steps 4 and 5. Unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F (0.1°C) for the positive systematic uncertainty for a thermocouple.

Step 7: The negative systematic uncertainty is the negative value from Steps 4 and 5. Unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

(2) Average the corrections from all accuracy checks.

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to *z*, where

(-a) *z* equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) *z* equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

(c) For each reading at the point, sum the corrections from each segment of the measurement system.

(d) For each reading at the point, calculate the corrected average for this point by summing the average (over time) indicated reading and the sum of the corrections.

III-2.3.2.1.2 Averaging. The temperature at this location is the average (arithmetic or weight, by mass flow) of the corrected averages at each point.

III-2.3.2.1.3 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each point, by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties, to one less than the number of points.

III-2.3.2.1.4 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty.

III-2.3.2.2 Method 2 Example. There are nine measurement points at this location. The sensors at the first six points were all from one spool, and the sensors at the other three points were from another spool. Both spools had accuracy checks performed on three randomly selected sensors with extension wire. An accuracy check was also performed on the common data acquisition system reading all sensors.

Results of the representative sensor (three each) accuracy checks are shown in Table III-2.3.2.2-1.

Results of the electronics pretest accuracy check are shown in Table III-2.3.2.2-2.

III-2.3.2.2.1 Steps for Each Point at a Particular Location

(a) Arithmetically average the readings (over time) at the point. The data for all points and readings are in Tables III-2.3.2.2.1-1, III-2.3.2.2.1-2, and III-2.3.2.2.1-3. The arithmetic average (over time) of the temperatures at point #1 is 650°F.

(b) *Thermocouple Segment.* The calculations for the thermocouple segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) *Step 1.* Determine the correction at the accuracy check's data set below the point's average reading.

(-1) *Representative Thermocouple #1.* Calculate the correction at the calibration point below the measured value. At 602.0°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.0°F = −3.0°F. This indicates the measured temperature could be 3.0°F too high.

(-2) *Representative Thermocouple #2.* Calculate the correction at the calibration point below the measured value. At 601.5°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 601.5°F = −2.5°F. This indicates the measured temperature could be 2.5°F too high.

(-3) *Representative Thermocouple #3.* Calculate the correction at the calibration point below the measured value. At 602.2°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.2°F = −3.2°F. This indicates the measured temperature could be 3.2°F too high.

(-b) *Step 2.* Determine the correction at the accuracy check's data set above the point's average reading.

(-1) *Representative Thermocouple #1.* Calculate the correction at the calibration point above the measured value. At 805.5°F, the correction is the standard

temperature minus the indicated temperature, 801.0°F − 805.5°F = −4.5°F. This indicates the measured temperature could be 4.5°F too high.

(-2) Representative Thermocouple #2. Calculate the correction at the calibration point above the measured value. At 805.0°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.0°F = −4.0°F. This indicates the measured temperature could be 4.0°F too high.

(-3) Representative Thermocouple #3. Calculate the correction at the calibration point above the measured value. At 805.7°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.7°F = −4.7°F. This indicates the measured temperature could be 4.7°F too high.

(-c) Step 3. Determine the correction at the average reading by interpolating between the accuracy check data below and above the average reading.

(-1) For representative thermocouple #1,

$$\frac{-3.0}{602.0}, \frac{x}{650}, \frac{-4.5}{805.5}$$

$$x = \frac{[(-4.5) - (-3.0)]\,(650 - 602.0)}{805.5 - 602.0} - 3.0$$
$$= -3.35\text{°F}$$

(-2) For representative thermocouple #2,

$$\frac{-2.5}{601.5}, \frac{x}{650}, \frac{-4.0}{805.0}$$

$$x = \frac{[(-4.0) - (-2.5)]\,(650 - 601.5)}{805.0 - 601.5} - 2.5$$
$$= -2.86\text{°F}$$

(-3) For representative thermocouple #3,

$$\frac{-3.2}{602.2}, \frac{x}{650}, \frac{-4.7}{805.7}$$

$$x = \frac{[(-4.7) - (-3.2)]\,(650 - 602.2)}{805.7 - 602.2} - 3.2$$
$$= -3.55\text{°F}$$

(-d) Step 4. Subtract the correction at the accuracy check's data set below the point's average reading from the correction at the average reading.

(-1) For representative thermocouple #1,

$$-3.35 - (-3.0) = -0.35\text{°F}$$

(-2) For representative thermocouple #2,

$$-2.86 - (-2.5) = -0.36\text{°F}$$

(-3) For representative thermocouple #3,

$$-3.55 - (-3.2) = -0.35\text{°F}$$

(-e) Step 5. Subtract the correction at the accuracy check's data set above the point's average reading from the correction at the average reading.

(-1) For representative thermocouple #1,

$$-3.35 - (-4.5) = +1.15\text{°F}$$

(-2) For representative thermocouple #2,

$$-2.86 - (-4.0) = +1.14\text{°F}$$

(-3) For representative thermocouple #3,

$$-3.55 - (-4.7) = +1.15\text{°F}$$

(-f) Step 6. The positive systematic uncertainty is the positive value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F (0.1°C) for the positive systematic uncertainty for a thermocouple.

(-1) For representative thermocouple #1, the value is +1.15°F.

(-2) For representative thermocouple #2, the value is +1.14°F.

(-3) For representative thermocouple #3, the value is +1.15°F.

(-g) Step 7. The negative systematic uncertainty is the negative value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

(-1) For representative thermocouple #1, the value is −0.35°F.

(-2) For representative thermocouple #2, the value is −0.36°F.

(-3) For representative thermocouple #3, the value is −0.35°F.

(2) Average the corrections from all accuracy checks.

$$[(-3.35) + (-2.86) + (-3.55)]/3 = -3.25$$

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to *z*, where

(-a) *z* equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) *z* equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

The sensor positive systematic uncertainty is

$$\sqrt{[(1.15)^2 + (1.14)^2 + (1.15)^2]/(3-1)} = +1.40°\text{F}$$

The sensor negative systematic uncertainty is

$$\sqrt{[(-0.35)^2 + (-0.36)^2 + (-0.35)^2)]/(3-1)} = -0.43°\text{F}$$

(c) Electronics Segment. The calculations for the electronics segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) Step 1. Determine the correction at the accuracy check's data set below the point's average reading. Calculate the correction at the calibration point below the measured value. At 600.3°F, the correction is the standard temperature minus the indicated temperature, 600.0°F – 600.3°F = –0.3°F. This indicates the measured temperature could be 0.3°F too high.

(-b) Step 2. Determine the correction at the accuracy check's data set above the point's average reading. Calculate the correction at the calibration point above the measured value. At 799.8°F, the correction is the standard temperature minus the indicated temperature, 800.0°F – 799.8°F = +0.2°F. This indicates the measured temperature could be 0.2°F too low.

(-c) Step 3. Determine the correction at the average reading by interpolating between the accuracy check data below and above the average reading.

$$\frac{-0.3}{600.3}, \frac{x}{650}, \frac{+0.2}{799.8}$$

$$x = \frac{[(0.2) - (-0.3)]\,(650 - 600.3)}{799.8 - 600.3} - 0.3$$
$$= -0.18°\text{F}$$

(-d) Step 4. Subtract the correction at the accuracy check's data set below the point's average reading from the correction at the average reading.

$$-0.18 - (-0.3) = +0.12°\text{F}$$

(-e) Step 5. Subtract the correction at the accuracy check's data set above the point's average reading from the correction at the average reading.

$$-0.18 - (0.2) = -0.38°\text{F}$$

(-f) Step 6. The positive systematic uncertainty is the positive value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the positive systematic uncertainty for an RTD and 0.2°F (0.1°C) for the positive systematic uncertainty for a thermocouple.

For the electronics, the value is +0.12°F.

(-g) Step 7. The negative systematic uncertainty is the negative value from Steps 4 and 5. Therefore, unless the accuracy check data has identical corrections above and below the measured value (in which case the differences will both be zero), use 0.1°F (0.05°C) for the negative systematic uncertainty for an RTD and 0.2°F (0.1°C) for the negative systematic uncertainty for a thermocouple.

For the electronics, the value is –0.38°F.

(2) Average the corrections from all accuracy checks. The result is –0.18°F.

(3) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to *z*, where

(-a) *z* equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) *z* equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

The sensor positive systematic uncertainty is

$$\sqrt{(0.12)^2/1} = +0.12°\text{F}$$

The sensor negative systematic uncertainty is

$$\sqrt{(-0.38)^2/1} = -0.38°\text{F}$$

(d) Sum the corrections from each segment of the measurement system.

$$-3.25 + (-0.18) = -3.43°\text{F}$$

(e) Calculate the corrected average for this point by summing the average (over time) indicated reading and the sum of the corrections.

$$650 + (-3.43) = 646.57°\text{F}$$

III-2.3.2.2.2 Averaging. The temperature at this location is the average (arithmetic or weight, by mass flow) of the corrected averages at each point.

$$(646.57 + 649.55 + 650.55 + 645.57 + 643.59 + 656.52 + 647.42 + 658.46 + 644.42)\ /\ 9 = 649.18°\text{F}$$

III-2.3.2.2.3 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each point, by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties, to one less than the number of points.

(a) For segment #1 — thermocouples — the positive systematic uncertainty is

$$\sqrt{\begin{array}{l}[(1.40)^2 + (1.38)^2 + (1.37)^2 + (1.41)^2 + (1.43)^2 \\ + (1.31)^2 + (0.05)^2 + (0.06)^2 + (0.05)^2]/(9 - 1)\end{array}} = +1.20°\text{F}$$

The negative systematic uncertainty for segment #1 is

$$\sqrt{\begin{array}{l}[(-0.43)^2 + (-0.46)^2 + (-0.47)^2 + (-0.42)^2 \\ + (-0.41)^2 + (-0.53)^2 + (-0.16)^2 + (-0.15)^2 \\ + (-0.16)^2]/(9 - 1)\end{array}} = -0.41°\text{F}$$

(b) For segment #2 — electronics — the positive systematic uncertainty is

$$\sqrt{\begin{array}{l}[(0.12)^2 + (0.13)^2 + (0.13)^2 + (0.12)^2 + (0.12)^2 \\ + (0.15)^2 + (0.11)^2 + (0.14)^2 + (0.11)^2]/(9 - 1)\end{array}} = +0.13°\text{F}$$

The negative systematic uncertainty is

$$\sqrt{\begin{array}{l}[(-0.38)^2 + (-0.37)^2 + (-0.37)^2 + (-0.38)^2 \\ + (-0.38)^2 + (-0.35)^2 + (-0.39)^2 + (-0.36)^2 \\ + (-0.39)^2]/(9 - 1)\end{array}} = -0.40°\text{F}$$

III-2.3.2.2.4 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty. See Table III-2.3.2.2.4-1.

III-2.3.3 Method 3 — Measured Values Are Not Corrected. In the third method, the measured values are not corrected. The temperatures at each point are arithmetically averaged (over time) and then the average temperatures at each point are averaged (arithmetic or weight, by mass flow) to get the temperature at the location. The sensor and data acquisition system's systematic uncertainties are either

(a) calculated from the accuracy check data below and above each point's average reading or

(b) a value the parties mutually agree upon (permissible for electronics/data acquisition system's systematic uncertainties only)

III-2.3.3.1 Method 3 Procedure

III-2.3.3.1.1 Steps for Each Point at a Particular Location

(a) Arithmetically average the readings (over time) at each point at the location.

(b) The temperature at this location is the average (arithmetic or weight, by mass flow) of the average values at each point.

(c) For each segment of the measurement system at the point, the steps below should be performed.

(1) For each accuracy check for a segment [either individual component(s) or for each representative component(s)], perform the following:

Step 1: Determine the corrections at the accuracy check's data set below the location's average reading.

Step 2: Determine the corrections at the accuracy check's data set above the location's average reading.

Step 3: The positive systematic uncertainty is the larger negative correction (or zero if both are positive numbers).

Step 4: The negative systematic uncertainty is the larger positive correction (or zero if both are negative numbers).

(2) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to z, where

(-a) z equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) z equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

III-2.3.3.1.2 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each point by dividing the root sum square of the positive (then negative) systematic uncertainties by one less than the number of points.

III-2.3.3.1.3 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty.

III-2.3.3.2 Method 3 Example. There are nine measurement points at this location. The sensors at the first six points were all from one spool, and the sensors at the other three points were from another spool. Both spools had accuracy checks performed on three randomly selected sensors with extension wire. An accuracy check was also performed on the common data acquisition system reading all sensors.

Results of the representative sensor (three each) accuracy checks are shown in Table III-2.3.3.2-1.

Results of the electronics pretest accuracy check are shown in Table III-2.3.3.2-2.

III-2.3.3.2.1 Steps for Each Point at a Particular Location

(a) Arithmetically average the readings (over time) at each point at the location. The data for all points and readings are in Table III-2.3.3.2.1-1 and Table 2.3.3.2.1-2. The arithmetic average (over time) readings (corrected for the ice-bath temperature) at the nine points at this location are 650°F, 653°F, 654°F, 649°F, 647°F, 660°F, 646°F, 657°F, and 643°F.

(b) The temperature at this location is the average (arithmetic or weight, by mass flow) of the average values at each point.

The arithmetic average temperature at this location is the average of the nine points, or 651°F. (For this example it is assumed that weight averaging by mass flow between points was not required.)

If the readings are not to be corrected, then 651°F will be used in the calculations. To calculate the positive and negative components of the systematic uncertainty for each point, see the steps below.

(c) Thermocouple Segment. The calculations for the thermocouple segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) Step 1. Determine the correction at the accuracy check's data set below the location's average reading.

(-1) Representative Thermocouple #1. Calculate the correction at the calibration point below the measured value. At 602.0°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.0°F = −3.0°F. This indicates the measured temperature could be 3.0°F too high.

(-2) Representative Thermocouple #2. Calculate the correction at the calibration point below the measured value. At 601.5°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 601.5°F = −2.5°F. This indicates the measured temperature could be 2.5°F too high.

(-3) Representative Thermocouple #3. Calculate the correction at the calibration point below the measured value. At 602.2°F, the correction is the standard temperature minus the indicated temperature, 599.0°F − 602.2°F = −3.2°F. This indicates the measured temperature could be 3.2°F too high.

(-b) Step 2. Determine the correction at the accuracy check's data set above the location's average reading.

(-1) Representative Thermocouple #1. Calculate the correction at the calibration point above the measured value. At 805.5°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.5°F = −4.5°F. This indicates the measured temperature could be 4.5°F too high.

(-2) Representative Thermocouple #2. Calculate the correction at the calibration point above the measured value. At 805.0°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.0°F = −4.0°F. This indicates the measured temperature could be 4.0°F too high.

(-3) Representative Thermocouple #3. Calculate the correction at the calibration point above the measured value. At 805.7°F, the correction is the standard temperature minus the indicated temperature, 801.0°F − 805.7°F = −4.7°F. This indicates the measured temperature could be 4.7°F too high.

(-c) Step 3. The positive systematic uncertainty is the larger negative correction (or zero if both are positive numbers).

(-1) Representative Thermocouple #1. For this example, the positive systematic uncertainty is +4.5°F, since it is the larger of the two negative corrections (−3.0°F and −4.5°F).

(-2) Representative Thermocouple #2. For this example, the positive systematic uncertainty is +4.0°F, since it is the larger of the two negative corrections (−2.5°F and −4.0°F).

(-3) Representative Thermocouple #3. For this example, the positive systematic uncertainty is +4.7°F, since it is the larger of the two negative corrections (−3.2°F and −4.7°F).

(-d) Step 4. The negative systematic uncertainty is the larger positive correction (or zero if both are negative numbers).

(-1) Representative Thermocouple #1. For this example, the negative systematic uncertainty is −0.0°F, since both corrections have negative values (−3.0°F and −4.5°F).

(-2) Representative Thermocouple #2. For this example, the negative systematic uncertainty is −0.0°F, since both corrections have negative values (−2.5°F and −4.0°F).

(-3) Representative Thermocouple #3. For this example, the negative systematic uncertainty is −0.0°F, since both corrections have negative values (−3.2°F and −4.7°F).

(2) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to z, where

(-a) z equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) z equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1.

The thermocouple positive systematic uncertainty is

$$\sqrt{[(4.5)^2 + (4.0)^2 + (4.7)^2]/(3 - 1)} = +5.40°\text{F}$$

The thermocouple negative systematic uncertainty is

$$\sqrt{[(0.0)^2 + (0.0)^2 + (0.0)^2]/(3 - 1)} = -0.0°\text{F}$$

(d) Electronics Segment. The calculations for the electronics segment of the measurement system at the point are as follows:

(1) For each accuracy check for this segment [either individual component(s) or for each representative component(s)], perform the following:

(-a) Step 1. Determine the correction at the accuracy check's data set below the location's average reading.

Calculate the correction at the calibration point below the measured value. At 600.3°F, the correction is the standard temperature minus the indicated temperature, 600.0°F − 600.3°F = −0.3°F. This indicates the measured temperature could be 0.3°F too high.

(-b) Step 2. Determine the correction at the accuracy check's data set above the location's average reading.

Calculate the correction at the calibration point above the measured value. At 799.8°F, the correction is the standard temperature minus the indicated temperature, 800.0°F − 799.8°F = +0.2°F. This indicates the measured temperature could be 0.2°F too low.

(-c) Step 3. The positive systematic uncertainty is the larger negative correction (or zero if both are positive numbers).

For this example, the positive systematic uncertainty is +0.3°F, since it is the only negative correction (−0.3°F and +0.2°F).

(-d) Step 4. The negative systematic uncertainty is the larger positive correction (or zero if both are negative numbers).

For this example, the negative systematic uncertainty is −0.2°F, since it is the only positive correction (−0.3°F and +0.2°F).

(2) Combine the positive (then negative) systematic uncertainties from each accuracy check by calculating the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties to z, where

(-a) z equals one less than the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is greater than 1

(-b) z equals the number of positive (then negative) systematic uncertainties if the number of positive (then negative) systematic uncertainties is 1

The thermocouple positive systematic uncertainty is

$$\sqrt{(0.3)^2/1} = +0.3°\text{F}$$

The thermocouple negative systematic uncertainty is

$$\sqrt{(-0.2)^2/1} = -0.2°\text{F}$$

III-2.3.3.2.2 Combining. For each segment, combine the positive (then negative) systematic uncertainties from each point by dividing the root sum square of the positive (then negative) systematic uncertainties by one less than the number of points.

(a) The calculations for segment #1 thermocouples are as follows:

The sensor positive systematic uncertainty is

$$\sqrt{[6(5.40)^2 + 3(0.0)^2]/(9 - 1)} = +4.68°\text{F}$$

The sensor negative systematic uncertainty is

$$\sqrt{[6(-0.00)^2 + 3(-2.14)^2]/(9 - 1)} = -1.31°\text{F}$$

(b) The calculations for segment #2 electronics are as follows:

The electronics positive systematic uncertainty is

$$\sqrt{[9(0.30)^2]/(9 - 1)} = +0.32°\text{F}$$

The electronics negative systematic uncertainty is

$$\sqrt{[9(-0.20)^2]/(9 - 1)} = -0.21°\text{F}$$

III-2.3.3.2.3 Overall Uncertainty. Combine (square root of the ratio of the sum of the squares to one less than the number of values) the positive (and negative) systematic uncertainty for each segment with the other components of the measurement to obtain the overall positive (and negative) systematic uncertainty. See Table III-2.3.3.2.3-1.

Table III-1.1-1 Systematic Uncertainty Worksheet — Uncorrected Reading

Measured Parameter: Temperature/Thermometer Uncorrected Reading, °F **Worksheet No.**________

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive		3 Negative	
			Percent of Reading	°F	Percent of Reading	°F
a	Readability	Characteristic of data acquisition system		+0.1		–0.1
b	Accuracy			+0.0		–0.5
c						
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +0.1	3A	3B –0.51

Table III-1.2-1 Systematic Uncertainty Worksheet — Corrected Reading

Measured Parameter: Temperature/Thermometer Uncorrected Reading, °F **Worksheet No.**________

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive		3 Negative	
			Percent of Reading	°F	Percent of Reading	°F
a	Readability	Characteristic of data acquisition system		+0.1		–0.1
b	Accuracy			+0.04		–0.16
c						
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +0.11	3A	3B –0.19

Table III-2.3.1.2-1 Representative Sensor Accuracy Check Results for Method 1

True Temperature, °F	Sensor Reading, °F	Correction, °F	Error, °F
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #1			
32.0	32.0	0.0	0.0
199.0	200.0	−1.0	1.0
399.0	401.0	−2.0	2.0
599.0	602.0	−3.0	3.0
801.0	805.5	−4.5	4.5
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.4	−0.4	0.4
399.0	400.5	−1.5	1.5
599.0	601.5	−2.5	2.5
801.0	805.0	−4.0	4.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	200.1	−1.1	1.1
399.0	401.2	−2.2	2.2
599.0	602.2	−3.2	3.2
801.0	805.7	−4.7	4.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #1			
32.0	32.0	0.0	0.0
199.0	199.1	−0.1	0.1
399.0	397.9	1.1	−1.1
599.0	597.5	1.5	−1.5
801.0	799.3	1.7	−1.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.5	−0.5	0.5
399.0	397.5	1.5	−1.5
599.0	597.2	1.8	−1.8
801.0	799.0	2.0	−2.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	198.8	0.2	−0.2
399.0	398.2	0.8	−0.8
599.0	597.6	1.4	−1.4
801.0	799.5	1.5	−1.5

Table III-2.3.1.2-2 Electronics Pretest Accuracy Check Results for Method 1 (As-Left Calibration)

True Temperature, °F	Electronics Reading, °F	Correction, °F	Error, °F
32.0	32.6	−0.6	0.6
200.0	200.5	−0.5	0.5
400.0	400.4	−0.4	0.4
600.0	600.3	−0.3	0.3
800.0	799.8	0.2	−0.2

Table III-2.3.1.2.1-1 Calculation of Systematic Uncertainty From Thermocouple Calibration for Method 1 (Segment #1)

Point in Duct	Sensor Used From Spool #	Reading at Each Point	Step 1: Correction at Calibration Point Below Point Average	Step 3: Interpolated Correction at Point Average	Step 2: Correction at Calibration Point Above Point Average	Step 4: Span Correction Below Average (Step 3 Minus Step 1)	Step 5: Span Correction Above Average (Step 3 Minus Step 2)	Step 6: Positive Systematic Uncertainty	Step 7: Negative Systematic Uncertainty
First Set of Readings for Representative Thermocouple #1									
1	1	652	−3.0	−3.37	−4.5	−0.37	1.13	1.13	−0.37
2	1	649	−3.0	−3.35	−4.5	−0.35	1.15	1.15	−0.35
3	1	654	−3.0	−3.38	−4.5	−0.38	1.12	1.12	−0.38
4	1	646	−3.0	−3.32	−4.5	−0.32	1.18	1.18	−0.32
5	1	648	−3.0	−3.34	−4.5	−0.34	1.16	1.16	−0.34
6	1	661	−3.0	−3.43	−4.5	−0.43	1.07	1.07	−0.43
7	2	645	1.5	1.55	1.7	0.05	−0.15	0.05	−0.15
8	2	659	1.5	1.56	1.7	0.06	−0.14	0.06	−0.14
9	2	643	1.5	1.55	1.7	0.05	−0.15	0.05	−0.15
Second Set of Readings for Representative Thermocouple #1									
1	1	648	−3.0	−3.34	−4.5	−0.34	1.16	1.16	−0.34
2	1	657	−3.0	−3.41	−4.5	−0.41	1.09	1.09	−0.41
3	1	654	−3.0	−3.38	−4.5	−0.38	1.12	1.12	−0.38
4	1	652	−3.0	−3.37	−4.5	−0.37	1.13	1.13	−0.37
5	1	646	−3.0	−3.32	−4.5	−0.32	1.18	1.18	−0.32
6	1	659	−3.0	−3.42	−4.5	−0.42	1.08	1.08	−0.42
7	2	647	1.5	1.55	1.7	0.05	−0.15	0.05	−0.15
8	2	655	1.5	1.56	1.7	0.06	−0.14	0.06	−0.14
9	2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
First Set of Readings for Representative Thermocouple #2									
1	1	652	−2.5	−2.87	−4.0	−0.37	1.13	1.13	−0.37
2	1	649	−2.5	−2.85	−4.0	−0.35	1.15	1.15	−0.35
3	1	654	−2.5	−2.89	−4.0	−0.39	1.11	1.11	−0.39
4	1	646	−2.5	−2.83	−4.0	−0.33	1.17	1.17	−0.33
5	1	648	−2.5	−2.84	−4.0	−0.34	1.16	1.16	−0.34
6	1	661	−2.5	−2.94	−4.0	−0.44	1.06	1.06	−0.44
7	2	645	1.8	1.85	2.0	0.05	−0.15	0.05	−0.15
8	2	659	1.8	1.86	2.0	0.06	−0.14	0.06	−0.14
9	2	643	1.8	1.85	2.0	0.05	−0.15	0.05	−0.15
Second Set of Readings for Representative Thermocouple #2									
1	1	648	−2.5	−2.84	−4.0	−0.34	1.16	1.16	−0.34
2	1	657	−2.5	−2.91	−4.0	−0.41	1.09	1.09	−0.41
3	1	654	−2.5	−2.89	−4.0	−0.39	1.11	1.11	−0.39
4	1	652	−2.5	−2.87	−4.0	−0.37	1.13	1.13	−0.37
5	1	646	−2.5	−2.83	−4.0	−0.33	1.17	1.17	−0.33
6	1	659	−2.5	−2.92	−4.0	−0.42	1.08	1.08	−0.42
7	2	647	1.8	1.85	2.0	0.05	−0.15	0.05	−0.15
8	2	655	1.8	1.86	2.0	0.06	−0.14	0.06	−0.14
9	2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
First Set of Readings for Representative Thermocouple #3									
1	1	652	−3.2	−3.57	−4.7	−0.37	1.13	1.13	−0.37
2	1	649	−3.2	−3.54	−4.7	−0.34	1.16	1.16	−0.34
3	1	654	−3.2	−3.58	−4.7	−0.38	1.12	1.12	−0.38
4	1	646	−3.2	−3.52	−4.7	−0.32	1.18	1.18	−0.32
5	1	648	−3.2	−3.54	−4.7	−0.34	1.16	1.16	−0.34
6	1	661	−3.2	−3.63	−4.7	−0.43	1.07	1.07	−0.43
7	2	645	1.4	1.42	1.5	0.02	−0.08	0.02	−0.08
8	2	659	1.4	1.43	1.5	0.03	−0.07	0.03	−0.07
9	2	643	1.4	1.42	1.5	0.02	−0.08	0.02	−0.08

Table III-2.3.1.2.1-1 Calculation of Systematic Uncertainty From Thermocouple Calibration for Method 1 (Segment #1) (Cont'd)

Point in Duct	Sensor Used From Spool #	Reading at Each Point	Step 1: Correction at Calibration Point Below Point Average	Step 3: Interpolated Correction at Point Average	Step 2: Correction at Calibration Point Above Point Average	Step 4: Span Correction Below Average (Step 3 Minus Step 1)	Step 5: Span Correction Above Average (Step 3 Minus Step 2)	Step 6: Positive Systematic Uncertainty	Step 7: Negative Systematic Uncertainty
Second Set of Readings for Representative Thermocouple #3									
1	1	648	−3.2	−3.54	−4.7	−0.34	1.16	1.16	−0.34
2	1	657	−3.2	−3.60	−4.7	−0.40	1.10	1.10	−0.40
3	1	654	−3.2	−3.58	−4.7	−0.38	1.12	1.12	−0.38
4	1	652	−3.2	−3.57	−4.7	−0.37	1.13	1.13	−0.37
5	1	646	−3.2	−3.52	−4.7	−0.32	1.18	1.18	−0.32
6	1	659	−3.2	−3.62	−4.7	−0.42	1.08	1.08	−0.42
7	2	647	1.4	1.42	1.5	0.02	−0.08	0.02	−0.08
8	2	655	1.4	1.43	1.5	0.03	−0.07	0.03	−0.07
9	2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

GENERAL NOTES:

(a) The average thermocouple correction at each point for each set of readings is determined from the above data. See para. III-2.3.1.2.1(a)(2).

Point in Duct	Average Correction for First Reading	Average Correction for Second Reading
1	−3.27	−3.24
2	−3.25	−3.31
3	−3.28	−3.28
4	−3.22	−3.27
5	−3.24	−3.22
6	−3.33	−3.32
7	1.61	1.61
8	1.62	1.62
9	1.61	. . .

(b) The average positive and negative thermocouple systematic uncertainties at each point for each reading are also determined from the above data. See para. III-2.3.1.2.1(a)(3).

Point in Duct	Average Positive Systematic Uncertainty for First Reading	Average Negative Systematic Uncertainty for First Reading	Average Positive Systematic Uncertainty for Second Reading	Average Negative Systematic Uncertainty for Second Reading
1	1.38	−0.45	1.42	−0.42
2	1.41	−0.42	1.34	−0.50
3	1.37	−0.47	1.37	−0.47
4	1.44	−0.40	1.38	−0.45
5	1.42	−0.42	1.44	−0.40
6	1.31	−0.53	1.32	−0.51
7	0.05	−0.16	0.05	−0.16
8	0.06	−0.15	0.06	−0.15
9	0.05	−0.16	. . .	. . .

The systematic uncertainties for thermocouples (see para. III-2.3.1.2.3) are +1.20, −0.40.

Table III-2.3.1.2.1-2 Calculation of Systematic Uncertainty From Electronics Calibration for Method 1 (Segment #2)

Point in Duct	Reading at Each Point	Step 1: Correction at Calibration Point Below Point Average	Step 3: Interpolated Correction at Point Average	Step 2: Correction at Calibration Point Above Point Average	Step 4: Span Correction Below Average (Step 3 Minus Step 1)	Step 5: Span Correction Above Average (Step 3 Minus Step 2)	Step 6: Positive Systematic Uncertainty	Step 7: Negative Systematic Uncertainty	Average Electronics Correction [Note (1)]	Average Electronics Systematic Uncertainty [Note (2)]	
										Positive	Negative
First Set of Readings											
1	652	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
2	649	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
3	654	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
4	646	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39
5	648	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
6	661	−0.3	−0.15	0.2	0.15	−0.35	0.15	−0.35	−0.15	0.15	−0.35
7	645	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39
8	659	−0.3	−0.15	0.2	0.15	−0.35	0.15	−0.35	−0.15	0.15	−0.35
9	643	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39
Second Set of Readings											
1	648	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
2	657	−0.3	−0.16	0.2	0.14	−0.36	0.14	−0.36	−0.16	0.14	−0.36
3	654	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
4	652	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
5	646	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39
6	659	−0.3	−0.15	0.2	0.15	−0.35	0.15	−0.35	−0.15	0.15	−0.35
7	647	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
8	655	−0.3	−0.16	0.2	0.14	−0.36	0.14	−0.36	−0.16	0.14	−0.36
9	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

GENERAL NOTE: The systematic uncertainties for electronics (see para. III-2.3.1.2.3) are +0.13 and −0.38.

NOTES:

(1) See para. III-2.3.1.2.1(b)(2).

(2) See para. III-2.3.1.2.1(b)(3).

Table III-2.3.1.2.1-3 Calculation of Combined Corrections and Corrected Readings for Method 1 (Segment #2)

	First Set of Readings		Second Set of Readings		
Point in Duct	Average Thermocouple and Electronics Correction [Note (1)]	Corrected Reading [Note (2)]	Average Thermocouple and Electronics Correction [Note (1)]	Corrected Reading [Note (2)]	Average Corrected Reading [Note (3)]
1	−3.44	648.56	−3.42	644.58	646.57
2	−3.43	645.57	−3.47	653.53	649.55
3	−3.45	650.55	−3.45	650.55	650.55
4	−3.41	642.59	−3.44	648.56	645.58
5	−3.42	644.58	−3.41	642.59	643.59
6	−3.48	657.52	−3.47	655.53	656.53
7	1.42	646.42	1.43	648.43	647.43
8	1.47	660.47	1.46	656.46	658.47
9	1.42	644.42	. . .	. . .	644.42
			Duct average temperature (see para. III-2.3.1.2.2) =		649.19

NOTES:

(1) See para. III-2.3.1.2.1(c).

(2) See para. III-2.3.1.2.1(d).

(3) See para. III-2.3.1.2.1(e).

Table III-2.3.1.2.4-1 Systematic Uncertainty Worksheet for Method 1 — Air/Gas Temperature

Measured Parameter: Temperature/Thermometer Uncorrected Reading, °F

Worksheet No. ______

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive Percent of Reading	2 Positive °F	3 Negative Percent of Reading	3 Negative °F
a	Thermocouple installation	Assumed by parties to test		+0.0		–0.25
b	Sensor	Calculated from test and accuracy check data		+1.2		–0.40
c	Electronics	Calculated from test and accuracy check data		+0.13		–0.38
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +1.21	3A	3B –0.61

Table III-2.3.2.2-1 Representative Sensor Accuracy Check Results for Method 2

True Temperature, °F	Sensor Reading, °F	Correction, °F	Error, °F
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #1			
32.0	32.0	0.0	0.0
199.0	200.0	−1.0	1.0
399.0	401.0	−2.0	2.0
599.0	602.0	−3.0	3.0
801.0	805.5	−4.5	4.5
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.4	−0.4	0.4
399.0	400.5	−1.5	1.5
599.0	601.5	−2.5	2.5
801.0	805.0	−4.0	4.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	200.1	−1.1	1.1
399.0	401.2	−2.2	2.2
599.0	602.2	−3.2	3.2
801.0	805.7	−4.7	4.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #1			
32.0	32.0	0.0	0.0
199.0	199.1	−0.1	0.1
399.0	397.9	1.1	−1.1
599.0	597.5	1.5	−1.5
801.0	799.3	1.7	−1.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.5	−0.5	0.5
399.0	397.5	1.5	−1.5
599.0	597.2	1.8	−1.8
801.0	799.0	2.0	−2.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	198.8	0.2	−0.2
399.0	398.2	0.8	−0.8
599.0	597.6	1.4	−1.4
801.0	799.5	1.5	−1.5

Table III-2.3.2.2-2 Electronics Pretest Accuracy Check Results for Method 2 (As-Left Calibration)

True Temperature, °F	Electronics Reading, °F	Correction, °F	Error, °F
32.0	32.6	−0.6	0.6
200.0	200.5	−0.5	0.5
400.0	400.4	−0.4	0.4
600.0	600.3	−0.3	0.3
800.0	799.8	0.2	−0.2

Table III-2.3.2.2.1-1 Calculation of Systematic Uncertainty From Thermocouple Calibration for Method 2 (Segment #1)

Point in Duct	Sensor Used From Spool #	Average (Over Time) of All Readings at This Point [Note (1)]	Step 1: Correction at Calibration Point Below Point Average	Step 3: Interpolated Correction at Point Average	Step 2: Correction at Calibration Point Above Point Average	Step 4: Span Correction Below Average (Step 3 Minus Step 1)	Step 5: Span Correction Above Average (Step 3 Minus Step 2)	Step 6: Positive Systematic Uncertainty	Step 7: Negative Systematic Uncertainty
Representative Thermocouple #1									
1	1	650	−3.0	−3.35	−4.5	−0.35	1.15	1.15	−0.35
2	1	653	−3.0	−3.38	−4.5	−0.38	1.12	1.12	−0.38
3	1	654	−3.0	−3.38	−4.5	−0.38	1.12	1.12	−0.38
4	1	649	−3.0	−3.35	−4.5	−0.35	1.15	1.15	−0.35
5	1	647	−3.0	−3.33	−4.5	−0.33	1.17	1.17	−0.33
6	1	660	−3.0	−3.43	−4.5	−0.43	1.07	1.07	−0.43
7	2	646	1.5	1.55	1.7	0.05	−0.15	0.05	−0.15
8	2	657	1.5	1.56	1.7	0.06	−0.14	0.06	−0.14
9	2	643	1.5	1.55	1.7	0.05	−0.15	0.05	−0.15
Representative Thermocouple #2									
1	1	650	−2.5	−2.86	−4.0	−0.36	1.14	1.14	−0.36
2	1	653	−2.5	−2.88	−4.0	−0.38	1.12	1.12	−0.38
3	1	654	−2.5	−2.89	−4.0	−0.39	1.11	1.11	−0.39
4	1	649	−2.5	−2.85	−4.0	−0.35	1.15	1.15	−0.35
5	1	647	−2.5	−2.84	−4.0	−0.34	1.16	1.16	−0.34
6	1	660	−2.5	−2.93	−4.0	−0.43	1.07	1.07	−0.43
7	2	646	1.8	1.85	2.0	0.05	−0.15	0.05	−0.15
8	2	657	1.8	1.86	2.0	0.06	−0.14	0.06	−0.14
9	2	643	1.8	1.85	2.0	0.05	−0.15	0.05	−0.15
Representative Thermocouple #3									
1	1	650	−3.2	−3.55	−4.7	−0.35	1.15	1.15	−0.35
2	1	653	−3.2	−3.57	−4.7	−0.37	1.13	1.13	−0.37
3	1	654	−3.2	−3.58	−4.7	−0.38	1.12	1.12	−0.38
4	1	649	−3.2	−3.54	−4.7	−0.34	1.16	1.16	−0.34
5	1	647	−3.2	−3.53	−4.7	−0.33	1.17	1.17	−0.33
6	1	660	−3.2	−3.63	−4.7	−0.43	1.07	1.07	−0.43
7	2	646	1.4	1.42	1.5	0.02	−0.08	0.02	−0.08
8	2	657	1.4	1.43	1.5	0.03	−0.07	0.03	−0.07
9	2	643	1.4	1.42	1.5	0.02	−0.08	0.02	−0.08

GENERAL NOTES:

(a) The average thermocouple correction is determined from the above data. See para. III-2.3.2.2.1(b)(2).

Point in Duct	Average Correction
1	−3.25
2	−3.28
3	−3.28
4	−3.25
5	−3.23
6	−3.33
7	1.61
8	1.62
9	1.61

Table III-2.3.2.2.1-1 Calculation of Systematic Uncertainty From Thermocouple Calibration for Method 2 (Segment #1) (Cont'd)

GENERAL NOTES (Cont'd):

(b) The average positive and negative thermocouple systematic uncertainties at each point are also determined from the above data. See para. III-2.3.2.2.1(b)(3).

Point in Duct	Average Positive Systematic Uncertainty	Average Negative Systematic Uncertainty
1	1.40	−0.43
2	1.38	−0.46
3	1.37	−0.47
4	1.41	−0.42
5	1.43	−0.41
6	1.31	−0.53
7	0.05	−0.16
8	0.06	−0.15
9	0.05	−0.16

The systematic uncertainties for thermocouples (see para. III-2.3.2.2.3) are +1.20, −0.41.

NOTE:

(1) See para. III-2.3.2.2.1(a).

Table III-2.3.2.2.1-2 Calculation of Systematic Uncertainty From Electronics Calibration for Method 2 (Segment #2)

Point in Duct	Average (Over Time) of All Readings at This Point [Note (1)]	Step 1: Correction at Calibration Point Below Point Average	Step 3: Interpolated Correction at Point Average	Step 2: Correction at Calibration Point Above Point Average	Step 4: Span Correction Below Average (Step 3 Minus Step 1)	Step 5: Span Correction Above Average (Step 3 Minus Step 2)	Step 6: Positive Systematic Uncertainty	Step 7: Negative Systematic Uncertainty	Average Electronics Correction [Note (2)]	Average Electronics Systematic Uncertainty [Note (3)]	
										Positive	Negative
1	650	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
2	653	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
3	654	−0.3	−0.17	0.2	0.13	−0.37	0.13	−0.37	−0.17	0.13	−0.37
4	649	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
5	647	−0.3	−0.18	0.2	0.12	−0.38	0.12	−0.38	−0.18	0.12	−0.38
6	660	−0.3	−0.15	0.2	0.15	−0.35	0.15	−0.35	−0.15	0.15	−0.35
7	646	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39
8	657	−0.3	−0.16	0.2	0.14	−0.36	0.14	−0.36	−0.16	0.14	−0.36
9	643	−0.3	−0.19	0.2	0.11	−0.39	0.11	−0.39	−0.19	0.11	−0.39

GENERAL NOTE: The systematic uncertainties for electronics (see para. III-2.3.2.2.3) are +0.13 and −0.40.

NOTES:

(1) See para. III-2.3.2.2.1(a).

(2) See para. III-2.3.2.2.1(c)(2).

(3) See para. III-2.3.2.2.1(c)(3).

Table III-2.3.2.2.1-3 Calculation of Combined Corrections and Corrected Readings for Method 2 (Segment #2)

Point in Duct	Average Thermocouple and Electronics Correction [Note (1)]	Corrected Reading [Note (2)]
1	−3.43	646.57
2	−3.45	649.55
3	−3.45	650.55
4	−3.43	645.57
5	−3.41	643.59
6	−3.48	656.52
7	1.42	647.42
8	1.46	658.46
9	1.42	644.42

GENERAL NOTE: The duct average temperature (see para. III-2.3.2.2.2) is 649.18.

NOTES:
(1) See para. III-2.3.2.2.1(d).
(2) See para. III-2.3.2.2.1(e).

Table III-2.3.2.2.4-1 Systematic Uncertainty Worksheet for Method 2 — Air/Gas Temperature

Measured Parameter: Temperature/Thermometer Uncorrected Reading, °F **Worksheet No.** ________

1		**Source of Systematic Uncertainty**	**2**	**Positive**	**3**	**Negative**
	Measured Parameter for Individual Systematic Uncertainty		**Percent of Reading**	**°F**	**Percent of Reading**	**°F**
a	Thermocouple installation	Assumed by parties to test		+0.0		–0.25
b	Sensor	Calculated from test and accuracy check data		+1.2		–0.41
c	Electronics	Calculated from test and accuracy check data		+0.13		–0.40
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +1.21	3A	3B –0.62

Table III-2.3.3.2-1 Representative Sensor Accuracy Check Results for Method 3

True Temperature, °F	Sensor Reading, °F	Correction, °F	Error, °F
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #1			
32.0	32.0	0.0	0.0
199.0	200.0	−1.0	1.0
399.0	401.0	−2.0	2.0
599.0	602.0	−3.0	3.0
801.0	805.5	−4.5	4.5
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.4	−0.4	0.4
399.0	400.5	−1.5	1.5
599.0	601.5	−2.5	2.5
801.0	805.0	−4.0	4.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #1, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	200.1	−1.1	1.1
399.0	401.2	−2.2	2.2
599.0	602.2	−3.2	3.2
801.0	805.7	−4.7	4.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #1			
32.0	32.0	0.0	0.0
199.0	199.1	−0.1	0.1
399.0	397.9	1.1	−1.1
599.0	597.5	1.5	−1.5
801.0	799.3	1.7	−1.7
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #2			
32.0	31.9	0.1	−0.1
199.0	199.5	−0.5	0.5
399.0	397.5	1.5	−1.5
599.0	597.2	1.8	−1.8
801.0	799.0	2.0	−2.0
Pretest Sensor and Extension Wire Accuracy Check, Spool #2, Sensor #3			
32.0	32.1	−0.1	0.1
199.0	198.8	0.2	−0.2
399.0	398.2	0.8	−0.8
599.0	597.6	1.4	−1.4
801.0	799.5	1.5	−1.5

Table III-2.3.3.2-2 Electronics Pretest Accuracy Check Results for Method 3 (As-Left Calibration)

True Temperature, °F	Electronics Reading, °F	Correction, °F	Error, °F
32.0	32.6	−0.6	0.6
200.0	200.5	−0.5	0.5
400.0	400.4	−0.4	0.4
600.0	600.3	−0.3	0.3
800.0	799.8	0.2	−0.2

Table III-2.3.3.2.1-1 Calculation of Systematic Uncertainty From Thermocouple Calibration for Method 3 (Segment #1)

Point in Duct	Sensor Used From Spool #	Average (Over Time) of All Readings at This Point [Note (1)]	Step 1: Correction at Calibration Point Below Measured Value	Step 2: Correction at Calibration Point Above Measured Value	Step 3: Positive Systematic Error	Step 4: Negative Systematic Error
Representative Thermocouple #1						
1	1	650	−3.00	−4.50	4.50	0.00
2	1	653	−3.00	−4.50	4.50	0.00
3	1	654	−3.00	−4.50	4.50	0.00
4	1	649	−3.00	−4.50	4.50	0.00
5	1	647	−3.00	−4.50	4.50	0.00
6	1	660	−3.00	−4.50	4.50	0.00
7	2	646	1.50	1.70	0.00	−1.70
8	2	657	1.50	1.70	0.00	−1.70
9	2	643	1.50	1.70	0.00	−1.70
Representative Thermocouple #2						
1	1	650	−2.50	−4.00	4.00	0.00
2	1	653	−2.50	−4.00	4.00	0.00
3	1	654	−2.50	−4.00	4.00	0.00
4	1	649	−2.50	−4.00	4.00	0.00
5	1	647	−2.50	−4.00	4.00	0.00
6	1	660	−2.50	−4.00	4.00	0.00
7	2	646	1.80	2.00	0.00	−2.00
8	2	657	1.80	2.00	0.00	−2.00
9	2	643	1.80	2.00	0.00	−2.00
Representative Thermocouple #3						
1	1	650	−3.20	−4.7	4.70	0.00
2	1	653	−3.20	−4.7	4.70	0.00
3	1	654	−3.20	−4.7	4.70	0.00
4	1	649	−3.20	−4.7	4.70	0.00
5	1	647	−3.20	−4.7	4.70	0.00
6	1	660	−3.20	−4.7	4.70	0.00
7	2	646	1.40	1.5	0.00	−1.50
8	2	657	1.40	1.5	0.00	−1.50
9	2	643	1.40	1.5	0.00	−1.50

GENERAL NOTE: The average positive and negative thermocouple systematic uncertainties at each point are determined from the above data. See para. III-2.3.3.2.1(c)(2).

Point in Duct	Average Positive Systematic Uncertainty	Average Negative Systematic Uncertainty
1	5.40	0.00
2	5.40	0.00
3	5.40	0.00
4	5.40	0.00
5	5.40	0.00
6	5.40	0.00
7	0.00	−2.14
8	0.00	−2.14
9	0.00	−2.14

The systematic uncertainties for thermocouples [see para. III-2.3.3.2.2(a)] are +4.68, −1.31.

NOTE:

(1) The duct average temperature is 651.0°F. See paras. III-2.3.3.2.1(a) and (b).

Table III-2.3.3.2.1-2 Calculation of Systematic Uncertainty From Electronics Calibration for Method 3 (Segment #2)

Point in Duct	Sensor Used From Spool #	Average (Over Time) of All Readings at This Point [Note (1)]	Step 1: Correction at Calibration Point Below Measured Value	Step 2: Correction at Calibration Point Above Point Average Measured Value	Step 3: Positive Systematic Error	Step 4: Negative Systematic Error
1	1	650	−0.30	0.20	0.30	−0.20
2	1	653	−0.30	0.20	0.30	−0.20
3	1	654	−0.30	0.20	0.30	−0.20
4	1	649	−0.30	0.20	0.30	−0.20
5	1	647	−0.30	0.20	0.30	−0.20
6	1	660	−0.30	0.20	0.30	−0.20
7	2	646	−0.30	0.20	0.30	−0.20
8	2	657	−0.30	0.20	0.30	−0.20
9	2	643	−0.30	0.20	0.30	−0.20

GENERAL NOTE: The average positive and negative electronics systematic uncertainties at each point are determined from the above data. See para. III-2.3.3.2.1(d)(2).

Point in Duct	Average Positive Systematic Uncertainty	Average Negative Systematic Uncertainty
1	0.30	−0.20
2	0.30	−0.20
3	0.30	−0.20
4	0.30	−0.20
5	0.30	−0.20
6	0.30	−0.20
7	0.30	−0.20
8	0.30	−0.20
9	0.30	−0.20

The systematic uncertainties for electronics [see para. III-2.3.3.2.2(b)] are +0.32, −0.21.

NOTE:
(1) The duct average temperature is 651°F. See paras. III-2.3.3.2.1(a) and (b).

Table III-2.3.3.2.3-1 Systematic Uncertainty Worksheet for Method 3 — Air/Gas Temperature

Measured Parameter: Temperature/Thermometer Uncorrected Reading, °F

Worksheet No. ________

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive Percent of Reading	Positive °F	3 Negative Percent of Reading	Negative °F
a	Thermocouple installation	Assumed by parties to test		+0.0		−0.25
b	Sensor	Calculated from test and accuracy check data		+4.68		−1.31
c	Electronics	Calculated from test and accuracy check data		+0.32		−0.21
d						
e						
	Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$		2A	2B +4.69	3A	3B −1.35

MANDATORY APPENDIX IV
SAMPLE CALCULATIONS FOR OXYGEN MEASUREMENTS

IV-1 INTRODUCTION

Three methods are used for the initial accuracy check and subsequent accuracy checks to determine instrument systematic uncertainty and to optionally correct the measured data.

In method 1, calculate and apply a specific correction to each measured value, and calculate a positive and negative systematic uncertainty for each reading. For each reading between accuracy checks, calculate a correction to be applied to the reading, and calculate a corresponding positive and negative systematic uncertainty. Average the corrected readings, and combine the positive and negative systematic uncertainties by the square root of the ratio of the sum of the squares to one less than the number of readings. This is the preferred method.

In method 2, calculate and apply a single correction to all measured readings between accuracy checks. If there is more than one corrected average for a duct, weight average the averages based on the number of readings in each average. For each average between accuracy checks, calculate a corresponding positive and negative systematic uncertainty. Combine the positive and negative systematic uncertainties by the square root of the ratio of the sum of the squares to one less than the number of readings.

In method 3, the measured values are not adjusted. The positive (and negative) instrument systematic uncertainties are the square root of the result of the sum of the squares of the negative (and positive) corrections divided by the number of negative (and positive) corrections, from all accuracy checks (the initial accuracy check, the post-test accuracy check, and any mid-test accuracy checks), within the range between the smallest reading and the largest reading.

IV-2 METHOD 1 — CORRECT INDIVIDUAL READINGS

IV-2.1 Procedure

In the first method, all measured values are individually corrected. For each reading, an intermediate correction is determined based on that reading's value and the data from the prior accuracy check, and another intermediate correction is determined based on that reading's value and the data from the subsequent accuracy check. The final correction, to be applied to the reading, is calculated by interpolating between those two intermediate corrections based on the time the reading was taken and the times of the accuracy checks.

The unadjusted positive (and negative) instrument systematic uncertainty for each reading is the square root of the ratio of the sum of the squares of each reading's negative (and positive) corrections to the number of negative (and positive) corrections. The adjusted positive instrument systematic uncertainty for each reading is the sum of the reading's unadjusted positive systematic uncertainty and the reading's correction; if that is a positive value, it is divided by 2 and otherwise it is 0. The adjusted negative instrument systematic uncertainty for each reading is the reading's correction minus the reading's unadjusted negative systematic uncertainty; if that is a negative value, it is divided by 2 and otherwise it is 0. The instrument's positive (and negative) systematic uncertainty for the test run is calculated by the square root of the ratio of the sum of the squares of each reading's positive (and negative) systematic uncertainty to 1 minus the number of readings.

IV-2.2 Example

Given the following data:

The results of the initial accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
06:30	0.1% O_2	0.0	+0.1
	5.0% O_2	4.8	+0.2
	10.0% O_2	10.1	−0.1

The results of the mid-test accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
10:00	0.1% O_2	0.2	−0.1
	5.0% O_2	5.1	−0.1
	10.0% O_2	10.4	−0.4

The results of the post-test accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
11:30	0.1% O_2	0.4	−0.3
	5.0% O_2	5.2	−0.2
	10.0% O_2	10.3	−0.3

The readings taken between the pretest and mid-test accuracy checks are

Time	Reading	Time	Reading	Time	Reading
8:35	4.6	9:03	4.1	9:31	4.7
8:37	4.5	9:05	4.2	9:33	4.9
8:39	4.1	9:07	3.8	9:35	4.1
8:41	4.3	9:09	5.1	9:37	3.6
8:43	4.7	9:11	5.2	9:39	3.9
8:45	4.5	9:13	4.4	9:41	3.9
8:47	5.1	9:15	3.8	9:43	5.1
8:49	5.1	9:17	4.2	9:45	4.7
8:51	4.5	9:19	4.5	9:47	4.9
8:53	3.8	9:21	5.2	9:49	4.8
8:55	4.2	9:23	3.9	9:51	4.6
8:57	3.6	9:25	3.7	9:53	5.3
8:59	4.1	9:27	5.2		
9:01	4.2	9:29	4.2		

The readings taken between the mid-test and post-test accuracy checks are

Time	Reading	Time	Reading	Time	Reading
10:15	3.8	10:37	3.8	10:59	3.8
10:17	5.2	10:39	5.2	11:01	4.2
10:19	5.0	10:41	4.6	11:03	5.6
10:21	5.7	10:43	4.1	11:05	5.2
10:23	5.6	10:45	4.5	11:07	3.8
10:25	5.1	10:47	4.8	11:09	3.8
10:27	3.8	10:49	4.3	11:11	4.8
10:29	3.9	10:51	5.1	11:13	4.2
10:31	5.7	10:53	4.5	11:15	5.6
10:33	3.9	10:55	4.9	11:17	3.7
10:35	3.8	10:57	4.6		

For the first reading (4.6%) at 8:35, the first intermediate correction (from the initial accuracy check) at 4.6% is

$$\frac{+0.1}{0.0}, \frac{x}{4.6}, \frac{+0.2}{4.8}$$

$$\begin{aligned} x &= \frac{(0.2 - 0.1)\ (4.6 - 0.0)}{4.8 - 0.0} + 0.1 \\ &= +0.20 \end{aligned}$$

The second intermediate correction (from the mid-test accuracy check) at 4.6% is

$$\frac{-0.1}{0.2}, \frac{x}{4.6}, \frac{-0.1}{5.1}$$

$$\begin{aligned} x &= \frac{[(-0.1) - (-0.1)]\ (4.6 - 0.2)}{5.1 - 0.2} + (-0.1) \\ &= -0.10 \end{aligned}$$

The correction to be applied to the reading, by interpolating between the times of the accuracy checks and the time of the reading, is

$$\frac{0.20}{6:30}, \frac{x}{8:35}, \frac{-0.1}{10:00}$$

$$\begin{aligned} x &= \frac{[(-0.1) - (0.2)]\ (8:35 - 6:30)}{10:00 - 6:30} + (-0.1) \\ &= +0.02 \end{aligned}$$

This results in a corrected reading at 8:35 of 4.6% + 0.02% = 4.62%.

The positive and negative systematic uncertainties are calculated as follows:

From the pretest accuracy check, below the reading of 4.6% the correction is +0.1, and above the reading of 4.6% the correction is +0.2. From the mid-test accuracy check, below the reading of 4.6% the correction is −0.1, and above the reading of 4.6% the correction is −0.1.

The unadjusted positive (and negative) instrument systematic uncertainty for each reading is the square root of the ratio of the sum of the squares of each reading's negative (and positive) corrections to the number of negative (and positive) corrections. The two corrections from the accuracy check data before the reading, below and above the reading's value, are +0.1 and +0.2. The two corrections from the accuracy check data after the reading, below and above the reading's value, are −0.1 and −0.1.

Therefore, the unadjusted positive systematic uncertainty is

$$\sqrt{[(-0.1)^2 + (-0.1)^2]/2} = 0.10$$

and the unadjusted negative systematic uncertainty is

$$\sqrt{[(0.1)^2 + (0.2)^2]/2} = 0.16$$

The adjusted positive instrument systematic uncertainty for each reading is the sum of the reading's unadjusted positive systematic uncertainty and the reading's correction; if that is a positive value, it is divided by 2 and otherwise it is 0.

The adjusted positive systematic uncertainty is [0.1 + (+0.02)]/2 = 0.06%.

The adjusted negative instrument systematic uncertainty for each reading is the reading's correction minus the reading's unadjusted negative systematic uncertainty; if that is a negative value, it is divided by 2 and otherwise it is 0.

The adjusted negative systematic uncertainty is [+0.02 − (+0.16)]/2 = −0.07%.

The data for the other readings are in Table IV-2.2-1.

The average of the corrected readings is 4.40%. The positive systematic uncertainty is the square root of the results of the sum of the squares of the individual positive systematic uncertainties divided by 71 minus 1 (0.04%). The negative systematic uncertainty is the square root of the results of the sum of the squares of the individual negative systematic uncertainties divided by 71 minus 1 (0.10%).

See Table IV-2.2-2.

IV-3 METHOD 2 — SINGLE CORRECTION FOR ALL DATA COLLECTED BETWEEN ACCURACY CHECKS

IV-3.1 Procedure

In the second method, all values at a location (with one or more points) measured with the same gas analyzer, taken between consecutive accuracy checks, are adjusted by the same correction. Using this method, the readings are adjusted based on an assumed linear drift of the instrument. The systematic uncertainty is the square root of the sum of the squares of the corrections calculated at the lowest reading, the highest reading, and the midrange accuracy check gas, using the accuracy check data both before and after the data collection times.

IV-3.1.1 Readings. For all readings taken between the first and second accuracy check of the analyzer,

(a) average (arithmetic or weight, by mass flow) all readings

(b) calculate the average clock time of the readings [time of the first reading + (time between first and last readings/2)]

(c) calculate the loop correction from the accuracy check data before the average clock time, at the average reading

(d) calculate the loop correction from the accuracy check data after the average clock time, at the average reading

(e) calculate the correction to be applied to each reading by interpolating between the two above corrections, based on the time of each accuracy check and the average clock time of the readings

(f) add the correction to the average reading

IV-3.1.2 Loop Systematic Uncertainties. Estimate the positive and negative loop systematic uncertainties by the square root of the sum of the squares of the corrections calculated at the lowest reading, the highest reading, and the mid-range accuracy check gas, using the accuracy check data both before and after the data collection times. Repeat the above steps for data collected between the second and third accuracy checks, then for data collected between the third and fourth accuracy checks, etc.

IV-3.1.3 Corrected Averages. Average (by number of readings in each group or weight, by mass flow) all corrected averages for this duct.

IV-3.1.4 Averages. Average (arithmetic or weight, by mass flow) the averages at each point in this location.

IV-3.1.5 Systematic Uncertainties. Combine the positive (then negative) systematic uncertainties of each by the square root of the ratio of the sum of the squares of the positive (then negative) systematic uncertainties for each analyzer/time period, to the number of analyzers/time periods minus 1.

IV-3.2 Example

Given the following data:

The results of the initial accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
06:30	0.1% O_2	0.0	+0.1
	5% O_2	4.8	+0.2
	10% O_2	10.1	–0.1

The results of the mid-test accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
10:00	0.1% O_2	0.2	–0.1
	5% O_2	5.1	–0.1
	10% O_2	10.4	–0.4

The results of the post-test accuracy check are

Time	Calibrated Gas	Instrument Reading	Correction
11:30	0.1% O_2	0.4	–0.3
	5% O_2	5.2	–0.2
	10% O_2	10.3	–0.3

The readings taken between the pretest and mid-test accuracy checks are

Time	Reading	Time	Reading	Time	Reading
8:35	4.6	9:03	4.1	9:31	4.7
8:37	4.5	9:05	4.2	9:33	4.9
8:39	4.1	9:07	3.8	9:35	4.1
8:41	4.3	9:09	5.1	9:37	3.6
8:43	4.7	9:11	5.2	9:39	3.9
8:45	4.5	9:13	4.4	9:41	3.9
8:47	5.1	9:15	3.8	9:43	5.1
8:49	5.1	9:17	4.2	9:45	4.7
8:51	4.5	9:19	4.5	9:47	4.9
8:53	3.8	9:21	5.2	9:49	4.8
8:55	4.2	9:23	3.9	9:51	4.6
8:57	3.6	9:25	3.7	9:53	5.3
8:59	4.1	9:27	5.2		
9:01	4.2	9:29	4.2		

The readings taken between the mid-test and post-test accuracy checks are

Time	Reading	Time	Reading	Time	Reading
10:15	3.8	10:37	3.8	10:59	3.8
10:17	5.2	10:39	5.2	11:01	4.2
10:19	5.0	10:41	4.6	11:03	5.6
10:21	5.7	10:43	4.1	11:05	5.2
10:23	5.6	10:45	4.5	11:07	3.8
10:25	5.1	10:47	4.8	11:09	3.8
10:27	3.8	10:49	4.3	11:11	4.8
10:29	3.9	10:51	5.1	11:13	4.2
10:31	5.7	10:53	4.5	11:15	5.6
10:33	3.9	10:55	4.9	11:17	3.7
10:35	3.8	10:57	4.6		

The average of the 40 readings taken between the initial accuracy check and the mid-test accuracy check is 4.43% O_2. The average of the 32 readings taken between the mid-test accuracy check and the post-test accuracy check is 4.58% O_2.

(a) For the first time period (between the initial accuracy check and the mid-test accuracy check), the first intermediate correction (from the initial accuracy check) at 4.43% is

$$\frac{+0.1}{0.0}, \frac{x}{4.43}, \frac{+0.2}{4.8}$$

$$x = \frac{(0.2 - 0.1)\ (4.43 - 0.0)}{4.8 - 0.0} + 0.1$$
$$= +0.19$$

The second intermediate correction (from the mid-test accuracy check) at 4.43% is

$$\frac{-0.1}{0.2}, \frac{x}{4.43}, \frac{-0.1}{5.1}$$

$$x = \frac{[(-0.1) - (-0.1)]\ (4.43 - 0.2)}{5.1 - 0.2} + (-0.1)$$
$$= -0.10$$

The correction to be applied to the reading, by interpolating between the times of the accuracy checks and the time of the reading, is

$$\frac{0.19}{6{:}30}, \frac{x}{8{:}35 + (9{:}53 - 8{:}35)/2}, \frac{-0.1}{10{:}00}$$

$$x = \frac{[(-0.1) - (0.19)]\ (9{:}14 - 6{:}30)}{10{:}00 - 6{:}30} + 0.19$$
$$= -0.04$$

The average reading (4.43%) between the initial accuracy check and the mid-test accuracy check will be adjusted by adding −0.04% points, resulting in a corrected average of 4.39%.

Calculate the positive and negative systematic uncertainty for the data in the first time period as follows:

The correction from the initial accuracy check at the lowest reading (3.6%) is

$$\frac{+0.1}{0.0}, \frac{x}{3.6}, \frac{+0.2}{4.8}$$

$$x = \frac{(0.2 - 0.1)\ (3.6 - 0.0)}{4.8 - 0.0} + 0.1$$
$$= +0.175$$

The correction from the initial accuracy check at the mid-range calibration gas reading (4.8%) is +0.2.

The correction from the initial accuracy check at the highest reading (5.3%) is

$$\frac{+0.2}{4.8}, \frac{x}{5.3}, \frac{-0.1}{10.1}$$

$$x = \frac{[(-0.1) - (0.2)]\ (5.3 - 4.8)}{10.1 - 4.8} + 0.2$$
$$= +0.17$$

The correction from the mid-test accuracy check at the lowest reading (3.6%) is

$$\frac{-0.1}{0.2}, \frac{x}{3.6}, \frac{-0.1}{5.1}$$

$$x = \frac{[(-0.1) - (-0.1)]\ (3.6 - 0.2)}{5.1 - 0.2} + (-0.1)$$
$$= -0.10$$

The correction from the mid-test accuracy check at the mid-range calibration gas reading (5.1%) is -0.10.

The correction from the mid-test accuracy check at the highest reading (5.3%) is

$$\frac{-0.1}{5.1}, \frac{x}{5.3}, \frac{-0.4}{10.4}$$

$$x = \frac{[(-0.4) - (-0.1)]\ (5.3 - 5.1)}{10.4 - 5.1} + (-0.1)$$
$$= -0.11$$

The square root of the result of the sum of the squares of the negative corrections divided by the number of errors is $\sqrt{(-0.1)^2 + (-0.1)^2 + (-0.11)^2/3} = 0.10\%$ point. Since the average of this data has a *negative* correction of −0.04, the positive systematic uncertainty is reduced by that amount, so the positive systematic uncertainty for this set of readings is 0.10 − 0.04 = 0.06%.

The square root of the result of the sum of the squares of the positive corrections divided by the number of errors is $\sqrt{(0.175)^2 + (0.2)^2 + (0.17)^2/3} = 0.18\%$ point. Since the average of this data has a *negative* correction of −0.04, the negative systematic uncertainty is unchanged, so 0.18% is the negative systematic uncertainty for this set of readings.

(b) For the second time period (between the mid-test accuracy check and the post-test accuracy check), the first intermediate correction (from the mid-test accuracy check) at 4.58% is

$$\frac{-0.1}{0.2}, \frac{x}{4.58}, \frac{-0.1}{5.1}$$

$$x = \frac{[(-0.1) - (-0.1)]\ (4.58 - 0.2)}{5.1 - 0.2} + (-0.1)$$
$$= -0.10$$

The second intermediate correction (from the post-test accuracy check) at 4.58% is

$$\frac{-0.3}{0.4}, \frac{x}{4.58}, \frac{-0.2}{5.2}$$

$$x = \frac{[(-0.2) - (-0.3)]\ (4.58 - 0.4)}{5.2 - 0.4} + (-0.3)$$
$$= -0.21$$

The correction to be applied to the reading, by interpolating between the times of the accuracy checks and the time of the reading, is

$$\frac{-0.1}{10{:}00}, \frac{x}{10{:}15 + (11{:}17 - 10{:}15)/2}, \frac{-0.21}{11{:}30}$$

$$x = \frac{[(-0.21) - (-0.1)]\ (10{:}46 - 10{:}00)}{11{:}30 - 10{:}00} + (-0.1)$$
$$= -0.16$$

The average reading (4.58%) between the mid-test accuracy check and the post-test accuracy check will be adjusted by adding −0.16% points, resulting in a corrected average of 4.42%.

The overall corrected average is (40 readings × 4.39% + 32 readings × 4.42%)/72 readings = 4.40%.

Calculate the positive and negative systematic uncertainty for the data in the second time period as follows:

The correction from the mid-test accuracy check at the lowest reading (3.7%) is

$$\frac{-0.1}{0.2}, \frac{x}{3.7}, \frac{-0.1}{5.1}$$

$$x = \frac{[(-0.1) - (-0.1)]\ (3.7 - 0.2)}{5.1 - 0.2} + (-0.1)$$
$$= -0.10$$

The correction from the mid-test accuracy check at the mid-range calibration gas reading (5.1%) is −0.10.

The correction from the mid-test accuracy check at the highest reading (5.7%) is

$$\frac{-0.1}{5.1}, \frac{x}{5.7}, \frac{-0.4}{10.4}$$

$$x = \frac{[(-0.4) - (-0.1)]\ (5.7 - 5.1)}{10.4 - 5.1} + (-0.1)$$
$$= -0.13$$

The correction from the post-test accuracy check at the lowest reading (3.7%) is

$$\frac{-0.3}{0.4}, \frac{x}{3.7}, \frac{-0.2}{5.2}$$

$$x = \frac{[(-0.2) - (-0.3)]\ (3.7 - 0.4)}{5.2 - 0.4} + (-0.3)$$
$$= -0.23$$

The correction from the post-test accuracy check at the mid-range calibration gas reading (5.2%) is −0.20.

The correction from the post-test accuracy check at the highest reading (5.7%) is

$$\frac{-0.2}{5.2}, \frac{x}{5.7}, \frac{-0.3}{10.3}$$

$$x = \frac{[(-0.3) - (-0.2)]\ (5.7 - 5.2)}{10.3 - 5.2} + (-0.2)$$
$$= -0.21$$

The square root of the result of the sum of the squares of the negative corrections divided by the number of negative corrections is $\{[(-0.1)^2 + (-0.1)^2 + (-0.13)^2 + (-0.23)^2 + (-0.2)^2 + (-0.21)^2]/6\}^{1/2} = 0.17\%$ point. Since the average of this data has a *negative* correction of −0.16, the positive systematic uncertainty is reduced by that amount, so the positive systematic uncertainty for this set of readings is 0.01.

There are no positive corrections, so the negative systematic uncertainty is 0. Since the average of this data has a *negative* correction of −0.16, the negative systematic uncertainty is unchanged, so the negative systematic uncertainty for this set of readings is 0.

The overall positive systematic uncertainty is

$$\sqrt{[40\ (0.06)^2 + 32\ (0.01)^2]/(72 - 1)} = 0.05\%$$

The overall negative systematic uncertainty is

$$\sqrt{[40\ (0.18)^2 + 32\ (0.0)^2]/(72 - 1)} = 0.14\%$$

See Table IV-3.2-1.

IV-4 METHOD 3 — MEASURED VALUES NOT CORRECTED

IV-4.1 Procedure

In the third method, the measured values are not adjusted. The positive (and negative) instrument systematic uncertainties are the square root of the result of the sum of the squares of the negative (and positive) corrections divided by the number of negative (and positive) corrections, from all accuracy checks (the initial accuracy check, the post-test accuracy check, and any mid-test accuracy checks), within the range between the smallest reading and the largest reading. For each accuracy check, a correction must be calculated at the minimum reading, the maximum reading, and the mid-range calibration gas reading (if used).

IV-4.2 Example

Given the following data:

The results of the initial accuracy check are

Calibrated Gas	Instrument Reading	Correction
0.1% O_2	0.0	+0.1
5.0% O_2	4.8	+0.2
10.0% O_2	10.1	−0.1

The results of the mid-test accuracy check are

Calibrated Gas	Instrument Reading	Correction
0.1% O_2	0.2	−0.1
5.0% O_2	5.1	−0.1
10.0% O_2	10.4	−0.4

The results of the post-test accuracy check are

Calibrated Gas	Instrument Reading	Correction
0.1% O_2	0.4	−0.3
5.0% O_2	5.2	−0.2
10.0% O_2	10.3	−0.3

During the test, the average value was 4.50%. The smallest measured value was 3.6% and the largest value was 5.7%.

The correction from the initial accuracy check at the lowest reading (3.6%) is

$$\frac{+0.1}{0.0}, \frac{x}{3.6}, \frac{+0.2}{4.8}$$

$$\begin{aligned} x &= \frac{(0.2 - 0.1)\,(3.6 - 0.0)}{4.8 - 0.0} + 0.1 \\ &= +0.175 \end{aligned}$$

The correction from the initial accuracy check at the mid-range calibration gas reading (4.8%) is +0.2.

The correction from the initial accuracy check at the highest reading (5.7%) is

$$\frac{+0.2}{4.8}, \frac{x}{5.7}, \frac{-0.1}{10.1}$$

$$\begin{aligned} x &= \frac{[(-0.1) - (0.2)]\,(5.7 - 4.8)}{10.1 - 4.8} + 0.2 \\ &= +0.15 \end{aligned}$$

The correction from the mid-test accuracy check at the lowest reading (3.6%) is

$$\frac{-0.1}{0.2}, \frac{x}{3.6}, \frac{-0.1}{5.1}$$

$$\begin{aligned} x &= \frac{[(-0.1) - (-0.1)]\,(3.6 - 0.2)}{5.1 - 0.2} + (-0.1) \\ &= -0.10 \end{aligned}$$

The correction from the mid-test accuracy check at the mid-range calibration gas reading (5.1%) is −0.10.

The correction from the mid-test accuracy check at the highest reading (5.7%) is

$$\frac{-0.1}{5.1}, \frac{x}{5.7}, \frac{-0.4}{10.4}$$

$$\begin{aligned} x &= \frac{[(-0.4) - (-0.1)]\,(5.7 - 5.1)}{10.4 - 5.1} + (-0.1) \\ &= -0.13 \end{aligned}$$

The correction from the post-test accuracy check at the lowest reading (3.6%) is

$$\frac{-0.3}{0.4}, \frac{x}{3.6}, \frac{-0.2}{5.2}$$

$$\begin{aligned} x &= \frac{[(-0.2) - (-0.3)]\,(3.6 - 0.4)}{5.2 - 0.4} + (-0.3) \\ &= -0.23 \end{aligned}$$

The correction from the post-test accuracy check at the mid-range calibration gas reading (5.2%) is −0.20.

The correction from the post-test accuracy check at the highest reading (5.7%) is

$$\frac{-0.2}{5.2}, \frac{x}{5.7}, \frac{-0.3}{10.3}$$

$$\begin{aligned} x &= \frac{[(-0.3) - (-0.2)]\,(5.7 - 5.2)}{10.3 - 5.2} + (-0.2) \\ &= -0.21 \end{aligned}$$

The square root of the result of the sum of the squares of the negative corrections divided by the number of corrections is $\{[(-0.1)^2 + (-0.1)^2 + (-0.13)^2 + (-0.23)^2 + (-0.2)^2 + (-0.21)^2]/6\}^{1/2} = 0.17\%$ point, so that is the instrument's positive systematic uncertainty.

The square root of the result of the sum of the squares of the positive corrections divided by the number of corrections is $\sqrt{[(0.175)^2 + (0.2)^2 + (0.15)^2]/3} = 0.18\%$ point, so that is the instrument's negative systematic uncertainty.

See Table IV-4.2-1.

For the purpose of pretest uncertainty analysis, the O_2 analyzer's systematic uncertainty can be determined from the OEM literature, past experience, or a value of approximately ±0.2%.

Table IV-2.2-1 Data for Other Readings — O_2 Example

		Correction at				Correction Factor at				Correction			
		Prior	Latter			Prior		Latter		Prior		Latter	
Time	Measured Reading	Accuracy Check	Accuracy Check	Time of Reading	Corrected Reading [Note (1)]	Below Reading	Above Reading	Below Reading	Above Reading	Below Reading	Above Reading	Below Reading	Above Reading
8:35	4.6	0.196	−0.100	0.020	4.62	0.196	0.211	−0.100	−0.072	0.100	0.200	−0.100	−0.100
8:37	4.5	0.194	−0.100	0.016	4.52	0.194	0.217	−0.100	−0.066	0.100	0.200	−0.100	−0.100
8:39	4.1	0.185	−0.100	0.010	4.11	0.185	0.240	−0.100	−0.043	0.100	0.200	−0.100	−0.100
8:41	4.3	0.190	−0.100	0.009	4.31	0.190	0.228	−0.100	−0.055	0.100	0.200	−0.100	−0.100
8:43	4.7	0.198	−0.100	0.009	4.71	0.198	0.206	−0.100	−0.077	0.100	0.200	−0.100	−0.100
8:45	4.5	0.194	−0.100	0.005	4.51	0.194	0.217	−0.100	−0.066	0.100	0.200	−0.100	−0.100
8:47	5.1	0.183	−0.100	0.002	5.10	0.206	0.183	−0.100	−0.100	0.200	−0.100	−0.100	−0.100
8:49	5.1	0.183	−0.100	−0.004	5.10	0.206	0.183	−0.100	−0.100	0.200	−0.100	−0.100	−0.100
8:51	4.5	0.194	−0.100	0.003	4.50	0.194	0.217	−0.100	−0.066	0.100	0.200	−0.100	−0.100
8:53	3.8	0.179	−0.100	−0.011	3.79	0.179	0.257	−0.100	−0.026	0.100	0.200	−0.100	−0.100
8:55	4.2	0.188	−0.100	−0.011	4.19	0.188	0.234	−0.100	−0.049	0.100	0.200	−0.100	−0.100
8:57	3.6	0.175	−0.100	−0.018	3.58	0.175	0.268	−0.100	−0.015	0.100	0.200	−0.100	−0.100
8:59	4.1	0.185	−0.100	−0.017	4.08	0.185	0.240	−0.100	−0.043	0.100	0.200	−0.100	−0.100
9:01	4.2	0.188	−0.100	−0.019	4.18	0.188	0.234	−0.100	−0.049	0.100	0.200	−0.100	−0.100
9:03	4.1	0.185	−0.100	−0.023	4.08	0.185	0.240	−0.100	−0.043	0.100	0.200	−0.100	−0.100
9:05	4.2	0.188	−0.100	−0.025	4.18	0.188	0.234	−0.100	−0.049	0.100	0.200	−0.100	−0.100
9:07	3.8	0.179	−0.100	−0.030	3.77	0.179	0.257	−0.100	−0.026	0.100	0.200	−0.100	−0.100
9:09	5.1	0.183	−0.100	−0.031	5.07	0.206	0.183	−0.100	−0.100	0.200	−0.100	−0.100	−0.100
9:11	5.2	0.177	−0.106	−0.040	5.16	0.208	0.177	−0.100	−0.106	0.200	−0.100	−0.100	−0.400
9:13	4.4	0.192	−0.100	−0.035	4.37	0.192	0.223	−0.100	−0.060	0.100	0.200	−0.100	−0.100
9:15	3.8	0.179	−0.100	−0.040	3.76	0.179	0.257	−0.100	−0.026	0.100	0.200	−0.100	−0.100
9:17	4.2	0.188	−0.100	−0.041	4.16	0.188	0.234	−0.100	−0.049	0.100	0.200	−0.100	−0.100
9:19	4.5	0.194	−0.100	−0.043	4.46	0.194	0.217	−0.100	−0.066	0.100	0.200	−0.100	−0.100
9:21	5.2	0.177	−0.106	−0.053	5.15	0.208	0.177	−0.100	−0.106	0.200	−0.100	−0.100	−0.400
9:23	3.9	0.181	−0.100	−0.050	3.85	0.181	0.251	−0.100	−0.032	0.100	0.200	−0.100	−0.100
9:25	3.7	0.177	−0.100	−0.054	3.65	0.177	0.262	−0.100	−0.021	0.100	0.200	−0.100	−0.100
9:27	5.2	0.177	−0.106	−0.062	5.14	0.208	0.177	−0.100	−0.106	0.200	−0.100	−0.100	−0.400
9:29	4.2	0.188	−0.100	−0.057	4.14	0.188	0.234	−0.100	−0.049	0.100	0.200	−0.100	−0.100
9:31	4.7	0.198	−0.100	−0.059	4.64	0.198	0.206	−0.100	−0.077	0.100	0.200	−0.100	−0.100
9:33	4.9	0.194	−0.100	−0.062	4.84	0.202	0.194	−0.100	−0.089	0.200	−0.100	−0.100	−0.100
9:35	4.1	0.185	−0.100	−0.066	4.03	0.185	0.240	−0.100	−0.043	0.100	0.200	−0.100	−0.100
9:37	3.6	0.175	−0.100	−0.070	3.53	0.175	0.268	−0.100	−0.015	0.100	0.200	−0.100	−0.100
9:39	3.9	0.181	−0.100	−0.072	3.83	0.181	0.251	−0.100	−0.032	0.100	0.200	−0.100	−0.100
9:41	3.9	0.181	−0.100	−0.075	3.83	0.181	0.251	−0.100	−0.032	0.100	0.200	−0.100	−0.100
9:43	5.1	0.183	−0.100	−0.077	5.02	0.206	0.183	−0.100	−0.100	0.200	−0.100	−0.100	−0.100
9:45	4.7	0.198	−0.100	−0.079	4.62	0.198	0.206	−0.100	−0.077	0.100	0.200	−0.100	−0.100
9:47	4.9	0.194	−0.100	−0.082	4.82	0.202	0.194	−0.100	−0.089	0.200	−0.100	−0.100	−0.100
9:49	4.8	0.200	−0.100	−0.084	4.72	0.200	0.200	−0.100	−0.083	0.100	0.200	−0.100	−0.100
9:51	4.6	0.196	−0.100	−0.087	4.51	0.196	0.211	−0.100	−0.072	0.100	0.200	−0.100	−0.100
9:53	5.3	0.172	−0.111	−0.102	5.20	0.210	0.172	−0.100	−0.111	0.200	−0.100	−0.100	−0.400

Table IV-2.2-1 Data for Other Readings — O_2 Example

Positive Systematic Uncertainty (Unadjusted for Reading Correction)						Negative Systematic Uncertainty (Unadjusted for Reading Correction)						Systematic Uncertainty	
Prior		Latter		No. of Neg. Corr.	Sq. Root (Sum Sq./ No. of Readings)	Prior		Latter		No. of Pos. Corr.	Sq. Root (Sum Sq./ No. of Readings)	Positive [Note (2)]	Negative [Note (3)]
Below Reading	Above Reading	Below Reading	Above Reading			Below Reading	Above Reading	Below Reading	Above Reading				
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.060	−0.069
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.058	−0.071
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.055	−0.074
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.055	−0.075
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.055	−0.075
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.053	−0.077
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.049	−0.101
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.048	−0.102
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.049	−0.081
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.045	−0.085
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.045	−0.085
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.041	−0.088
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.042	−0.088
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.041	−0.089
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.039	−0.091
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.038	−0.092
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.035	−0.094
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.035	−0.116
0.000	−0.100	−0.100	−0.400	3	0.245	0.200	0.000	0.000	0.000	1	0.200	0.103	−0.120
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.033	−0.097
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.030	−0.099
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.030	−0.100
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.029	−0.101
0.000	−0.100	−0.100	−0.400	3	0.245	0.200	0.000	0.000	0.000	1	0.200	0.096	−0.127
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.025	−0.104
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.023	−0.106
0.000	−0.100	−0.100	−0.400	3	0.245	0.200	0.000	0.000	0.000	1	0.200	0.092	−0.131
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.022	−0.108
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.021	−0.109
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.019	−0.131
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.017	−0.112
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.015	−0.114
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.014	−0.115
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.013	−0.117
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.012	−0.139
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.011	−0.119
0.000	−0.100	−0.100	−0.100	3	0.100	0.200	0.000	0.000	0.000	1	0.200	0.009	−0.141
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.008	−0.121
0.000	0.000	−0.100	−0.100	2	0.100	0.100	0.200	0.000	0.000	2	0.158	0.007	−0.123
0.000	−0.100	−0.100	−0.400	3	0.245	0.200	0.000	0.000	0.000	1	0.200	0.072	−0.151

Table IV-2.2-1 Data for Other Readings — O_2 Example (Cont'd)

Time	Measured Reading	Correction at			Corrected Reading [Note (1)]	Correction Factor at				Correction			
		Prior Accuracy Check	Latter Accuracy Check	Time of Reading		Prior		Latter		Prior		Latter	
						Below Reading	Above Reading	Below Reading	Above Reading	Below Reading	Above Reading	Below Reading	Above Reading
10:15	3.8	−0.100	−0.229	−0.122	3.68	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
10:17	5.2	−0.106	−0.200	−0.124	5.08	*−0.100*	*−0.106*	*−0.200*	*−0.200*	−0.100	−0.400	−0.300	−0.200
10:19	5.0	−0.100	−0.204	−0.122	4.88	*−0.100*	*−0.094*	*−0.204*	*−0.196*	−0.100	−0.100	−0.300	−0.200
10:21	5.7	−0.134	−0.210	−0.152	5.55	*−0.100*	*−0.134*	*−0.190*	*−0.210*	−0.100	−0.400	−0.200	−0.300
10:23	5.6	−0.128	−0.208	−0.148	5.45	*−0.100*	*−0.128*	*−0.192*	*−0.208*	−0.100	−0.400	−0.200	−0.300
10:25	5.1	−0.100	−0.202	−0.128	4.97	*−0.100*	*−0.100*	*−0.202*	*−0.198*	−0.100	−0.100	−0.300	−0.200
10:27	3.8	−0.100	−0.229	−0.139	3.66	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
10:29	3.9	−0.100	−0.227	−0.141	3.76	*−0.100*	*−0.032*	*−0.227*	*−0.175*	−0.100	−0.100	−0.300	−0.200
10:31	5.7	−0.134	−0.210	−0.160	5.54	*−0.100*	*−0.134*	*−0.190*	*−0.210*	−0.100	−0.400	−0.200	−0.300
10:33	3.9	−0.100	−0.227	−0.147	3.75	*−0.100*	*−0.032*	*−0.227*	*−0.175*	−0.100	−0.100	−0.300	−0.200
10:35	3.8	−0.100	−0.229	−0.150	3.65	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
10:37	3.8	−0.100	−0.229	−0.153	3.65	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
10:39	5.2	−0.106	−0.200	−0.147	5.05	*−0.100*	*−0.106*	*−0.200*	*−0.200*	−0.100	−0.400	−0.300	−0.200
10:41	4.6	−0.100	−0.213	−0.151	4.45	*−0.100*	*−0.072*	*−0.213*	*−0.188*	−0.100	−0.100	−0.300	−0.200
10:43	4.1	−0.100	−0.223	−0.159	3.94	*−0.100*	*−0.043*	*−0.223*	*−0.178*	−0.100	−0.100	−0.300	−0.200
10:45	4.5	−0.100	−0.215	−0.158	4.34	*−0.100*	*−0.066*	*−0.215*	*−0.186*	−0.100	−0.100	−0.300	−0.200
10:47	4.8	−0.100	−0.208	−0.156	4.64	*−0.100*	*−0.083*	*−0.208*	*−0.192*	−0.100	−0.100	−0.300	−0.200
10:49	4.3	−0.100	−0.219	−0.165	4.14	*−0.100*	*−0.055*	*−0.219*	*−0.182*	−0.100	−0.100	−0.300	−0.200
10:51	5.1	−0.100	−0.202	−0.158	4.94	*−0.100*	*−0.100*	*−0.202*	*−0.198*	−0.100	−0.100	−0.300	−0.200
10:53	4.5	−0.100	−0.215	−0.168	4.33	*−0.100*	*−0.066*	*−0.215*	*−0.186*	−0.100	−0.100	−0.300	−0.200
10:55	4.9	−0.100	−0.206	−0.165	4.74	*−0.100*	*−0.089*	*−0.206*	*−0.194*	−0.100	−0.100	−0.300	−0.200
10:57	4.6	−0.100	−0.213	−0.172	4.43	*−0.100*	*−0.072*	*−0.213*	*−0.188*	−0.100	−0.100	−0.300	−0.200
10:59	3.8	−0.100	−0.229	−0.185	3.62	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
11:01	4.2	−0.100	−0.221	−0.182	4.02	*−0.100*	*−0.049*	*−0.221*	*−0.180*	−0.100	−0.100	−0.300	−0.200
11:03	5.6	−0.128	−0.208	−0.184	5.42	*−0.100*	*−0.128*	*−0.192*	*−0.208*	−0.100	−0.400	−0.200	−0.300
11:05	5.2	−0.106	−0.200	−0.174	5.03	*−0.100*	*−0.106*	*−0.200*	*−0.200*	−0.100	−0.400	−0.300	−0.200
11:07	3.8	−0.100	−0.229	−0.196	3.60	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
11:09	3.8	−0.100	−0.229	−0.199	3.60	*−0.100*	*−0.026*	*−0.229*	*−0.173*	−0.100	−0.100	−0.300	−0.200
11:11	4.8	−0.100	−0.208	−0.185	4.62	*−0.100*	*−0.083*	*−0.208*	*−0.192*	−0.100	−0.100	−0.300	−0.200
11:13	4.2	−0.100	−0.221	−0.198	4.00	*−0.100*	*−0.049*	*−0.221*	*−0.180*	−0.100	−0.100	−0.300	−0.200
11:15	5.6	−0.128	−0.208	−0.195	5.41	*−0.100*	*−0.128*	*−0.192*	*−0.208*	−0.100	−0.400	−0.200	−0.300
11:17	3.7	−0.100	−0.231	−0.212	3.49	*−0.100*	*−0.021*	*−0.231*	*−0.171*	−0.100	−0.100	−0.300	−0.200

NOTES:

(1) The average corrected reading is 4.40%.

(2) The average positive systematic uncertainty is +0.04% points.

(3) The average negative systematic uncertainty is −0.10% points.

Table IV-2.2-1 Data for Other Readings — O_2 Example (Cont'd)

Positive Systematic Uncertainty (Unadjusted for Reading Correction)						Negative Systematic Uncertainty (Unadjusted for Reading Correction)						Systematic Uncertainty	
Prior		Latter		No. of Neg. Corr.	Sq. Root (Sum Sq./ No. of Readings)	Prior		Latter		No. of Pos. Corr.	Sq. Root (Sum Sq./ No. of Readings)		
Below Reading	Above Reading	Below Reading	Above Reading			Below Reading	Above Reading	Below Reading	Above Reading			Positive [Note (2)]	Negative [Note (3)]
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.036	−0.061
−0.100	−0.400	−0.300	−0.200	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.075	−0.062
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.036	−0.061
−0.100	−0.400	−0.200	−0.300	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.061	−0.076
−0.100	−0.400	−0.200	−0.300	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.063	−0.074
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.033	−0.064
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.028	−0.070
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.027	−0.071
−0.100	−0.400	−0.200	−0.300	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.057	−0.080
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.024	−0.074
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.022	−0.075
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.021	−0.077
−0.100	−0.400	−0.300	−0.200	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.064	−0.074
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.022	−0.076
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.018	−0.080
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.018	−0.079
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.019	−0.078
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.015	−0.083
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.018	−0.079
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.013	−0.084
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.015	−0.083
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.011	−0.086
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.005	−0.093
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.006	−0.091
−0.100	−0.400	−0.200	−0.300	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.045	−0.092
−0.100	−0.400	−0.300	−0.200	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.050	−0.087
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.000	−0.098
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.000	−0.100
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.005	−0.093
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.000	−0.099
−0.100	−0.400	−0.200	−0.300	4	0.274	0.000	0.000	0.000	0.000	0	0.000	0.040	−0.098
−0.100	−0.100	−0.300	−0.200	4	0.194	0.000	0.000	0.000	0.000	0	0.000	0.000	−0.106

Table IV-2.2-2 Estimate of Systematic Uncertainty for Method 1

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive		3 Negative	
			Percent of Reading	Percent Points	Percent of Reading	Percent Points
a	Readability	Characteristic of data acquisition system		+0.05		−0.05
b	Accuracy	Calculated from test and accuracy check data		+0.04		−0.10
c						
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +0.06	3A	3B −0.11

Table IV-3.2-1 Estimate of Systematic Uncertainty for Method 2

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive		3 Negative	
			Percent of Reading	Percent Points	Percent of Reading	Percent Points
a	Readability	Characteristic of data acquisition system		+0.05		–0.05
b	Accuracy	Calculated from test and accuracy check data		+0.05		–0.14
c						
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +0.07	3A	3B –0.15

Table IV-4.2-1 Estimate of Systematic Uncertainty for Method 3

1	Measured Parameter for Individual Systematic Uncertainty	Source of Systematic Uncertainty	2 Positive		3 Negative	
			Percent of Reading	Percent Points	Percent of Reading	Percent Points
a	Readability	Characteristic of data acquisition system		+0.05		–0.05
b	Accuracy	Calculated from test and accuracy check data		+0.17		–0.18
c						
d						
e						
Total systematic uncertainty $(a^2 + b^2 + c^2 + \ldots)^{0.5}$			2A	2B +0.18	3A	3B –0.19

MANDATORY APPENDIX V
NONDIRECTIONAL AND DIRECTIONAL FLOW PROBES

V-1 INTRODUCTION

Nondirectional probes include Pitot-static tubes and Stauscheibe tubes. The most common type of directional probe is the Fechheimer. For additional information on flow probes, see ASME PTC 11, Fans.

V-2 PITOT-STATIC TUBES

Pitot-static tubes are also called "L" type pitots due to their shape. The Pitot-static tube consists of a tube within a tube, bent at a 90-deg angle toward the sensing head (see Fig. V-2-1 and Fig. V-2-2). The shapes of the sensing head include hemispherical, tapered, ellipsoidal, and modified ellipsoidal. At the head of the probe, the inner tube is open to the flow and senses the total (static plus velocity) pressure of the flow stream. Downstream of the head but before the bend, the outer tube has several holes through which the static pressure of the flow stream is transmitted to the annular area between the two tubes.

V-3 STAUSCHEIBE TUBE

Stauscheibe tubes are also called "S" type or forward–reverse tubes.

The type "S" consists of two stainless steel tubes with impact holes oriented at 180-deg angles to one another (see Fig. V-3-1). One hole faces upstream for the measurement of total pressure (P_T); the other is aligned in a downstream direction for static pressure (P_S) measurement. The difference between these two pressures ($P_T - P_S$) approximately equals 142% of the velocity pressure (P_V) of the fluid. P_V approximation must be corrected to true value through proper calibration to the particular flow situation.

V-4 THREE-HOLE FECHHEIMER

A three-hole version of the Fechheimer probe, also called a three-hole cylindrical yaw probe, can be used to determine total pressure (and therefore indicated velocity pressure), as well as the static pressure and yaw (see Fig. V-4-1).

V-5 FIVE-HOLE FECHHEIMER

A five-hole probe is generally required to determine pitch angles, as well as the various pressures and yaw angles [see Fig. V-5-1, illustrations (a) through (c)]. Probes with wedge shapes (see Fig. V-5-2) where the holes are located on flat surfaces are slightly preferred over probes with spherical shapes throughout, because they are easier to null-balance (see para. V-7.5).

V-6 PROBE CALIBRATION

All probes except pitot-static tubes shall be calibrated. Pitot-static tubes are considered primary instruments and need not be calibrated, provided they are maintained in as-new condition. The calibration procedures specified in this paragraph apply to pressure measurement only. Calibration of probes for direction sensing is usually carried out simultaneously with calibration for pressure. See para. V-7.3 for calibration procedures for direction sensing.

Probe calibration may be carried out in a free stream nozzle jet or a closed wind tunnel (see Figs. V-6-1 through V-6-3). Preferably, the probe blockage should be as small as possible and shall be less than 5% of the cross-sectional area. The flow should be adjusted to produce equally spaced calibration points. For two- and three-hole probes, a minimum of eight points between the expected minimum and maximum nominal velocity is required. For five-hole probes, calibration points are required at a minimum of three points, with one point near the expected minimum nominal velocity, one point near the expected maximum nominal velocity, and the other points equally spaced between these two.

The calibration reference may be a standard pitot-static tube (preferred) or a previously calibrated reference probe of another type. The blockage of the reference probe should be as small as possible. In no case shall the blockage of the reference probe exceed 5% of the cross-sectional area.

The reference probe and test probe shall each be mounted so that they can be placed in the stream alternately, and their positions in the stream will be the same and firmly held, or the test probe and the reference probe can be placed side by side if it can be demonstrated that there is no difference in flow conditions between the two locations, the total blockage does not exceed 5%, and there is no interference between the test probe and reference probe. When calibrating directional probes, the probe shall be aligned with the stream to eliminate yaw according to the null-balance principle described in para. V-7.5. Any offset of the null position with respect to jet or tunnel axis shall be recorded. Positive yaw angles are associated with probe rotation clockwise to achieve null-balance position, and negative yaw angles with counterclockwise rotation. Static pressure indication shall be from the appropriate static pressure hole(s) of the reference probe and test probe, and not from wall taps (wind tunnel), nor shall it be assumed equal to ambient pressure (free jet). The test probe and reference probe shall be connected to appropriate indicators so that the indicated static pressure, p_{si}, indicated total pressure, p_{it}, and indicated velocity pressure, p_{vi}, can each be recorded for each probe. The static pressure hole that is used to obtain indicated velocity pressure during the calibration should be noted and the same hole used for subsequent tests.

Probe calibration shall be expressed in terms of a probe total pressure coefficient, K_t, and a probe velocity coefficient, K_v. The probe total pressure coefficient is calculated from the calibration data by

$$K_t = \frac{(p_{ti})_{ref}}{(p_{ti})_{test}} \tag{V-6-1}$$

The probe velocity pressure coefficient is calculated from the test data by

$$K_v = \frac{\left[\dfrac{(K_v)_{ref}}{1 + (K_v)_{ref}\,\beta_{ref}}\right]\left[\dfrac{(p_{v1})_{ref}}{(p_{v1})_{test}}\right]}{1 - \left[\dfrac{\beta_{test}\,(K_v)_{ref}}{1 + (K_v)_{ref}\,\beta_{ref}}\right]\left[\dfrac{(p_{v1})_{ref}}{(p_{v1})_{test}}\right]} \tag{V-6-2}$$

where

$$\beta = \pm\frac{C_D(1 - \epsilon_p)}{4(1 - \epsilon_p) - 3}\left(\frac{S_p}{C}\right) \tag{V-6-3}$$

and

$$1 - \epsilon_p = 1 - \left[\frac{(K_v)_{ref}}{2k}\right]\left[\frac{(p_{vi})_{ref}}{(p_{sa})_{ref}}\right] \tag{V-6-4}$$

NOTE: It is recognized that CD is usually not known to a high degree of accuracy. Lacking specific information, $CD \approx 1.2$ for probes of cylindrical shape. For a closed wind tunnel, β will be positive; for a free jet, β will be negative.

The equation for K_v includes a correction for probe blockage (see ASME PTC 11). If the reference probe is a pitot-static tube, $K_{v,ref} = 1.0$, and the blockage of both the reference probe and test probe is negligible ($Sp/C < 0.005$), the equation for K_v assumes the simplified form

$$K_v = \frac{(p_{vi})_{ref}}{(p_{vi})_{test}} \tag{V-6-5}$$

Generally, the probe total pressure coefficient and probe velocity pressure coefficient are functions of Reynolds number, Re_p, for nondirectional and three-hole probes, and functions of pitch pressure coefficient, C_Φ, and Reynolds number for five-hole probes. For probes of highly angular shape, e.g., the prismatic five-hole probe shown in Fig. V-5-2, the coefficients may be expected to be independent of Reynolds number for values of Reynolds number above roughly 10^4. For such probes, Reynolds number effects on the coefficients may be ignored.

Calibrated probes should be handled with care because large scratches or nicks near the pressure taps will invalidate the calibration. Probe recalibration should be performed on a regular basis but shall be performed if damage near the sensing holes is noted.

V-7 YAW AND PITCH

Refer to Fig. V-7-1 for an illustration of the yaw and pitch planes with regard to the direction of fluid flow. Refer to Fig. V-7-2 as well as Fig. V-4-1 and Fig. V-7-3 with regard to the devices for indicating yaw and pitch angles.

V-7.1 Instruments

Yaw angle shall be measured using a directional probe equipped with a suitable indicating device. Pitch shall be determined from directional probe calibration. A five-hole probe is preferred as noted in section V-5. A three-hole probe may be suitable in some cases (see Fig. V-4-1 and Fig. V-7-3).

V-7.2 Accuracy

The yaw- and pitch-measuring systems shall have demonstrated accuracies of ±2 deg.

V-7.3 Calibration

A reference line shall be scribed along the probe axis prior to calibration for pressure response. This reference line is typically aligned with, or 180 deg from, the total pressure-sensing hole. The scribe is used as a reference position for installation of a yaw angle-measuring device. The relationship of the reference line to null-balance position shall be known as determined in section V-6. The probe is then equipped with a protractor scale that can be checked against any high-quality protractor used as a reference. As noted below, the protractor arrangement is only used to measure yaw.

Calibration for pitch can be performed in a free-stream nozzle jet or in a wind tunnel and is usually completed during calibrations outlined in section V-6. The facility should be equipped to allow the test probe to be positioned at various pitch angles. The mounting apparatus should firmly hold the test probe at each location along the pitch arc. Probe sensing-head location should remain in the same position within the flow stream as the probe pitch angle is varied.

The probe shall be precision aligned at various pitch angles, null-balanced, and the pressure difference across the taps for the fourth and fifth holes recorded, along with pressures and pressure differences required in section V-6 and any null-balance offset. Pressure data shall be recorded at pitch angles from −30 deg to +30 deg in 5-deg increments at each of three nominal velocities as described in section V-6. The calibration facility flow should be set at one nominal velocity and data recorded at each required pitch angle before proceeding to subsequent nominal velocities and repeating. Alternatively, the nominal velocity can be set at required values for each probe pitch position to develop the data set.

Calibration functions, which represent pitch angle and probe coefficient(s) as a function of pitch pressure coefficient, C_Φ (defined as pitch pressure difference/indicated velocity pressure), and Reynolds number may be derived. For probes of highly angular shape, e.g., the prismatic five-hole probe, the pitch-angle/pitch-pressure coefficient relationship may be expected to be independent of Reynolds number for values of Reynolds number above roughly 10^4. For such probes, Reynolds number effects may be ignored (see Figs. V-7.3-1 through V-7.3-3).

V-7.4 Number of Readings

Pressure measurements shall be made at each traverse point for each traverse plane. The indicated velocity pressure and either the total pressure or static pressure shall be measured. The remaining pressure can be determined arithmetically. Where required, yaw and pitch angles shall be determined at each traverse point for each traverse plane.

Pressures can be obtained at two or more locations, simultaneously, by using two or more probes as appropriate. This would require two or more probes and two or more probe crews, but it would significantly reduce the total elapsed time required for a test.

V-7.5 Operation

In operation, a five-hole probe is inserted in the proper port to the proper depth for each traverse point. The probe should be rigid enough over its inserted length to avoid any droop outside the traverse plane by more than 30% of the largest elemental area dimension. The reference line on the probe should be used to orient the probe in such a way that when the total pressure hole is pointing upstream perpendicular to the measuring plane, the indicated yaw angle is zero. The probe is then rotated about its own axis until a null balance is obtained across the taps of the static pressure holes. The angle of probe rotation from the zero yaw reference direction is measured with an appropriate indicator and is reported as the yaw angle. Without changing the angularity of the probe, the pressure difference across the taps for the fourth and fifth holes shall also be recorded, and used with the indicated velocity pressure and pitch pressure coefficient to determine pitch angle. Measurements of indicated velocity pressure and static pressure, or indicated velocity pressure and total pressure, as outlined in para. V-7.4, shall be recorded with the probe in the proper null-balance position. (Note that a null balance can be obtained at four different positions, but only one is correct. Incorrect null positions usually correspond to negative velocity pressures.)

When a directional probe cannot be nulled, velocity pressure shall be recorded as zero. A three-hole probe is operated in a similar manner, except that the pitch pressure difference is omitted.

V-8 CORRECTION OF TRAVERSE DATA

Difficulties arise in using traverse data in calculations, as these data usually must be corrected for probe calibration and possibly for blockage and compressibility as well. The probe calibration coefficients, K_t and K_v, are sometimes functions of the probe Reynolds number, Re_p, which is determined by actual gas velocity, V, density, ρ, and viscosity, μ, at the probe location. They are also slightly dependent upon specific heat ratio, k. As these four quantities are determined only from the measurements themselves, an iteration procedure may be necessary. Such a procedure would be as follows:

(a) Select provisional values of K_{tj}, K_{vj}, and k (see para. V-8.1).

(b) Correct the traverse readings for calibration and, if necessary, probe blockage and compressibility (see para. V-8.2).

(c) Proceed with calculations.

(d) After determining gas viscosity (see para. 4-6.6.23), densities (see para. 5-3.4.10 or 5-3.5.13), and velocities (see para. 4-6.6.22) at all points in a traverse plane, calculate Reynolds number (see para. 4-6.6.24) at all points, and determine new values of K_{tj} and K_{vj}.

(e) If new values of K_{tj} and K_{vj} are significantly different from the old values, the process must be repeated.

The probe calibration coefficients are also a function of pitch pressure coefficient, C_Φ; however, this dependency does not affect the iteration process.

V-8.1 Guideline for Initial Estimation of Probe Coefficient

To begin calculations, initial values of K_{tj} and K_{vj} must be selected. The selection of an appropriate value makes the calculation procedure converge more rapidly, often making iteration unnecessary. The following are guidelines to help the initial selection of K_{tj} and K_{vj}:

(a) For pitot-static probe, K_{tj} and $K_{vj} = 1.0$ and need not be changed.

(b) For other probes, the K_{tj} and K_{vj} versus Re_p curves should be relatively flat in the range of interest; hence, any reasonable first estimates of K_{tj} and K_{vj} should

produce satisfactory results. The following ideas are suggested:

(1) Select the values of K_{tj} and K_{vj} at the middle of the range of calibration data.

(2) Use an average K_{tj} and K_{vj} value based on the calibration data.

(3) Estimate Re_p from standard or design fan conditions, and use corresponding K_{tj} and K_{vj} values.

(4) Estimate Re_p from a typical point in the traverse data, and use the corresponding K_{tj} and K_{vj} values.

V-8.2 Correction for Probe Coefficient and Probe Blockage

Measured values from traverse are t_i, p_{vi}, and p_{si} or p_{ti}. The remaining pressures can be calculated from $p_{ti} = p_{si} + p_{vi}$. Corrected values (subscript j) at each point shall be obtained from the measured values (subscript i) at that point and probe coefficients, K_{tj} and K_{vj}, using

$$p_{tj} = K_{tj}\, p_{ti} \qquad \text{(V-8-1)}$$

$$K_{vjc} = \frac{K_{vj}}{1 + \beta_j K_{vj}} \qquad \text{(V-8-2)}$$

$$\begin{aligned} p_{sj} &= K_{tj}\, p_{ti} - K_{vjc}\, p_{vi} \qquad \text{(V-8-3)} \\ &= K_{vjc}\, p_{si} - (K_{vjc} - K_{tj})\, p_{ti} \end{aligned}$$

$$p_{saj} = p_{sj} + C_{13}\, p_b \qquad \text{(V-8-4)}$$

where
C_{13} = 13.62 in. wg/in. Hg (1.0 Pa/Pa)

$$p_{vj} = K_{vjc}\,(1 - \epsilon_p)\, p_{vi} \qquad \text{(V-8-5)}$$

$$T_{sj} = T_i/(1 + \epsilon_T) \qquad \text{(V-8-6)}$$

where
$T_i = t_i + C_1$
$= t_i +$ 459.7°F (273.15°C)

β_j is used to correct for probe blockage and is calculated by

$$\beta_j = \frac{C_D\,(1 - \epsilon_p)}{4\,(1 - \epsilon_p) - 3}\left(\frac{S_{pj}}{A}\right) \qquad \text{(V-8-7)}$$

In these equations, $(1 - \epsilon_p)$ and $(1 + \epsilon_T)$ are compressibility corrections and are calculated by

$$1 - \epsilon_p = 1 - \frac{1}{2k}\left(\frac{K_{vjc}\, p_{vi}}{p_{saj}}\right) \qquad \text{(V-8-8)}$$

and

$$1 + \epsilon_T = 1 + 0.85\left(\frac{k - 1}{k}\right)\left(\frac{K_{vjc}\, p_{vi}}{p_{saj}}\right) \qquad \text{(V-8-9)}$$

provided that $K_{vjc}\, p_{vi}/p_{saj}$ does not exceed 0.1 (see para. 4-6.6.13).

NOTE: The recovery factor of the temperature sensor is assumed to be 0.85 (see Aerodynamic Measurements, MIT Gas Turbine Lab Report, 1953, edited by R. C. Dean).

Fig. V-2-1 Pitot-Static Probe

Fig. V-2-2 Pitot-Static Probe Head

Fig. V-3-1 Pitot–Stauscheibe Tube or “S” Type Pitot

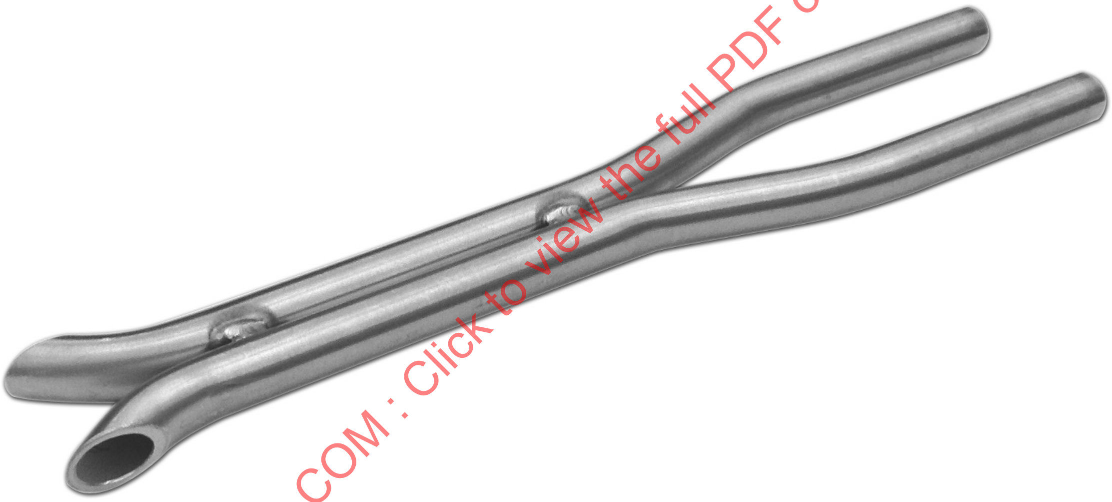


Fig. V-4-1 Fechheimer Probe

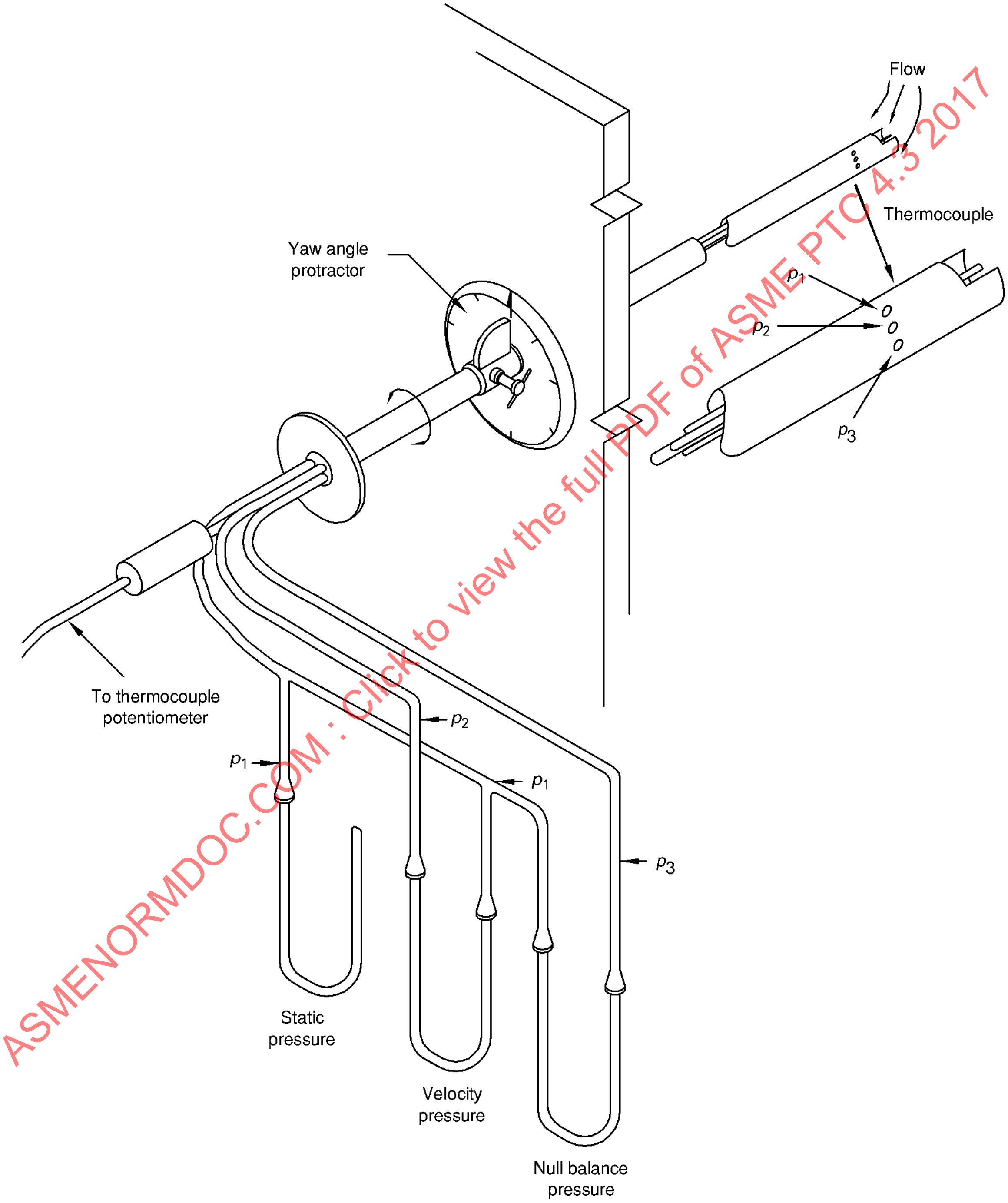


Fig. V-5-1 Five-Hole Probe Tips

(a)

(b)

(c)

Fig. V-5-2 Prism Probe Cutaway

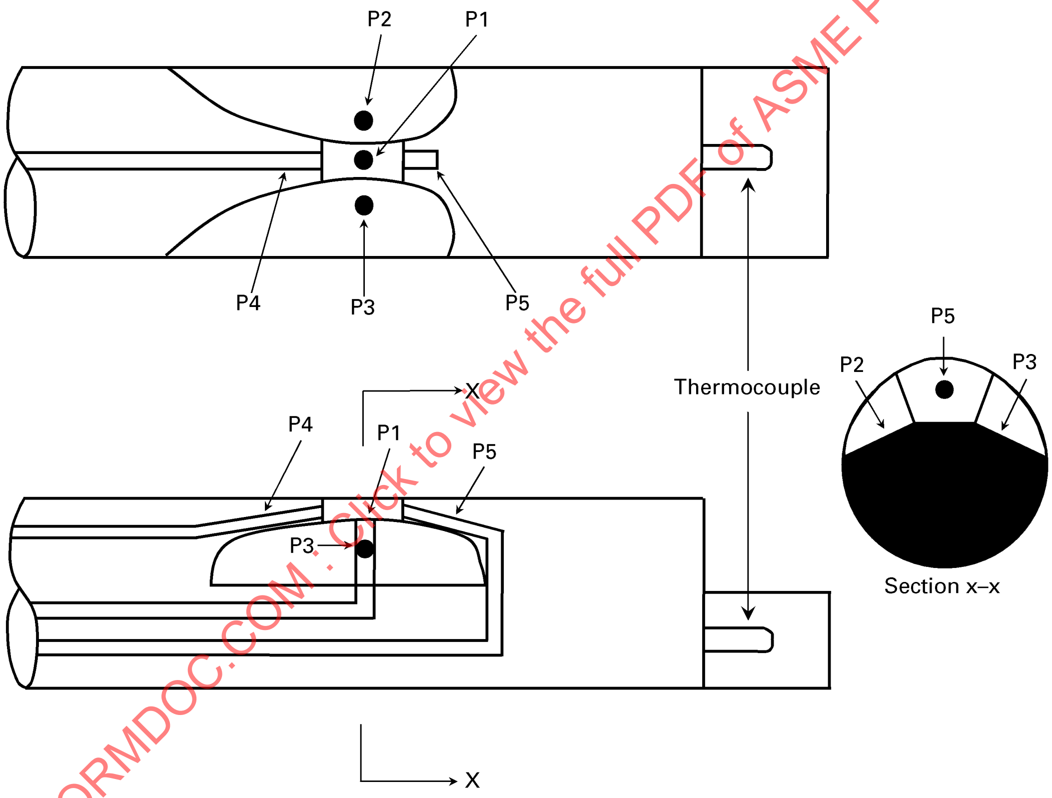


Fig. V-6-1 Free Stream Nozzle Jet

Fig. V-6-2 Wind Tunnel

Fig. V-6-3 Free Stream

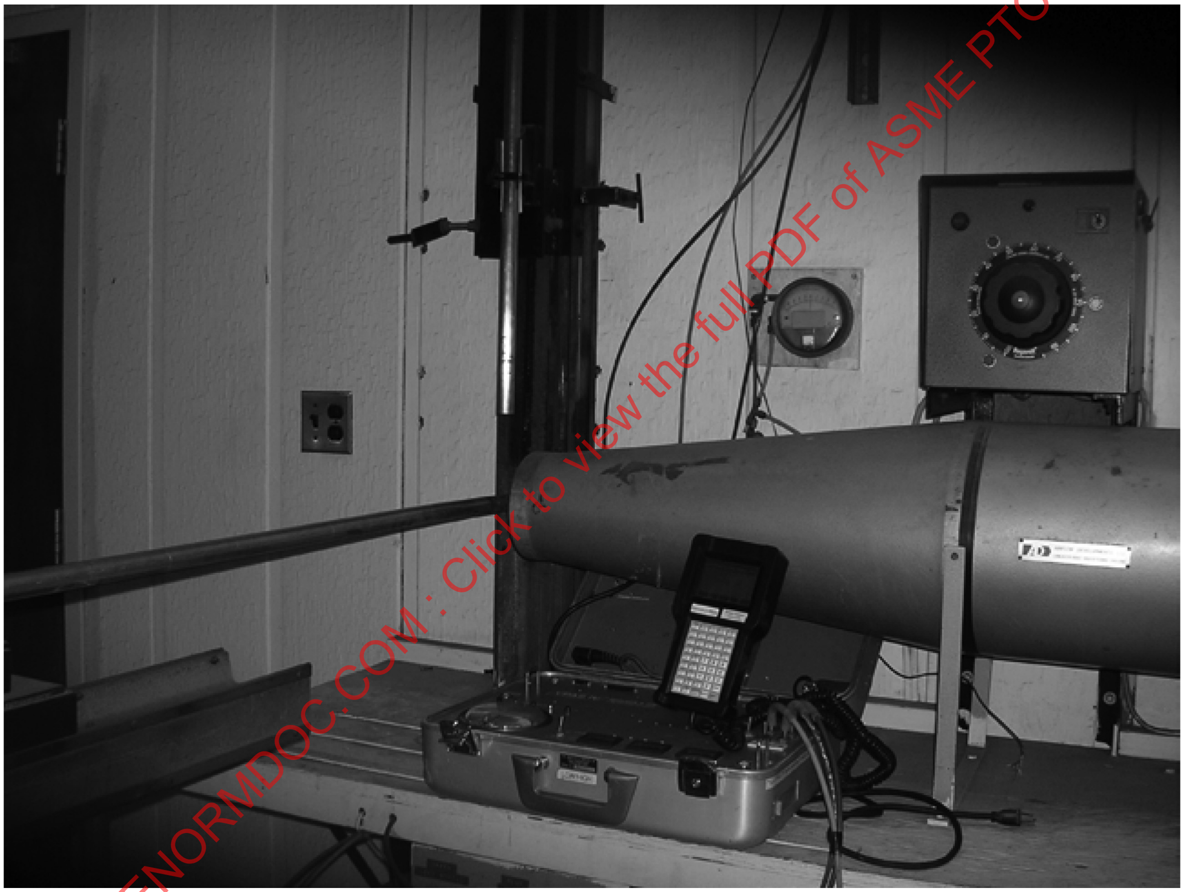


Fig. V-7-1 Yaw and Pitch Planes

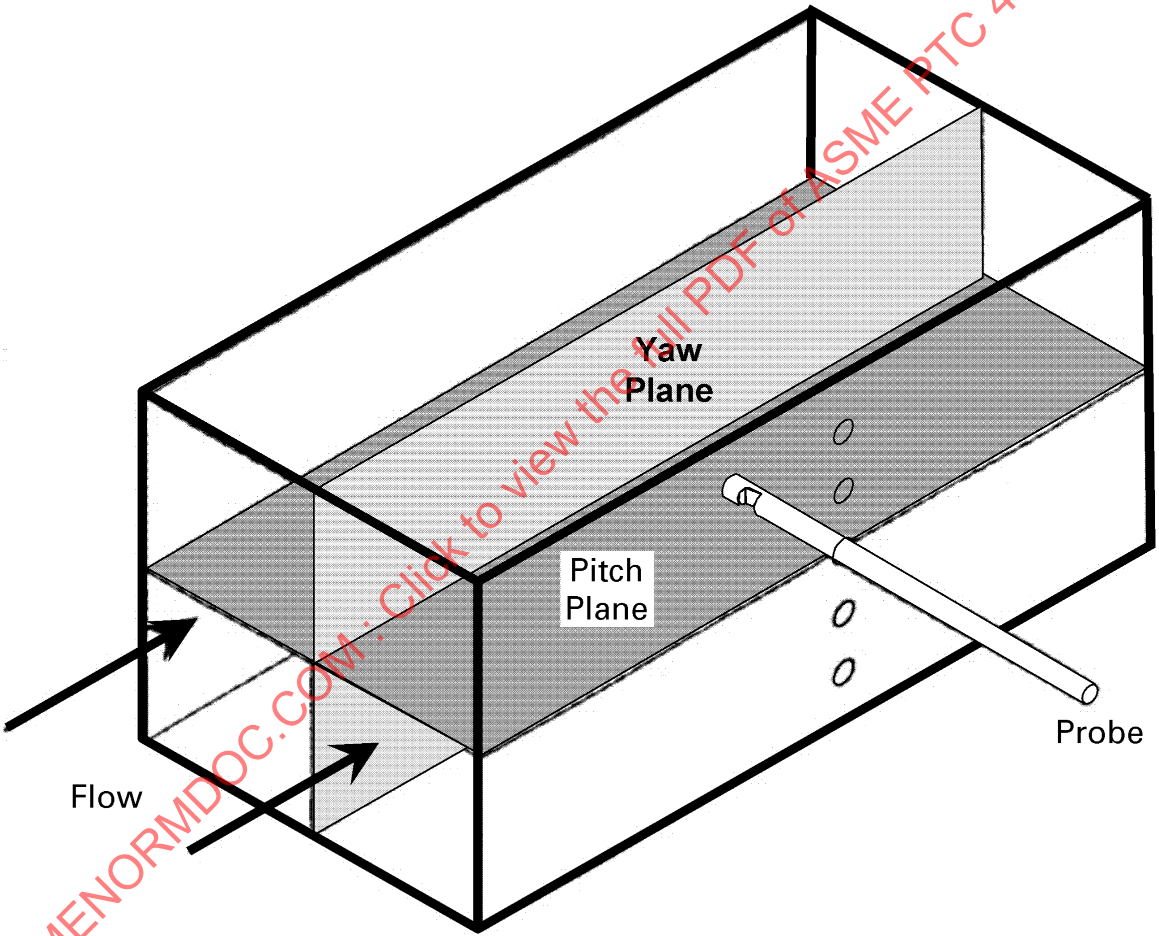


Fig. V-7-2 Yaw and PItch Convention

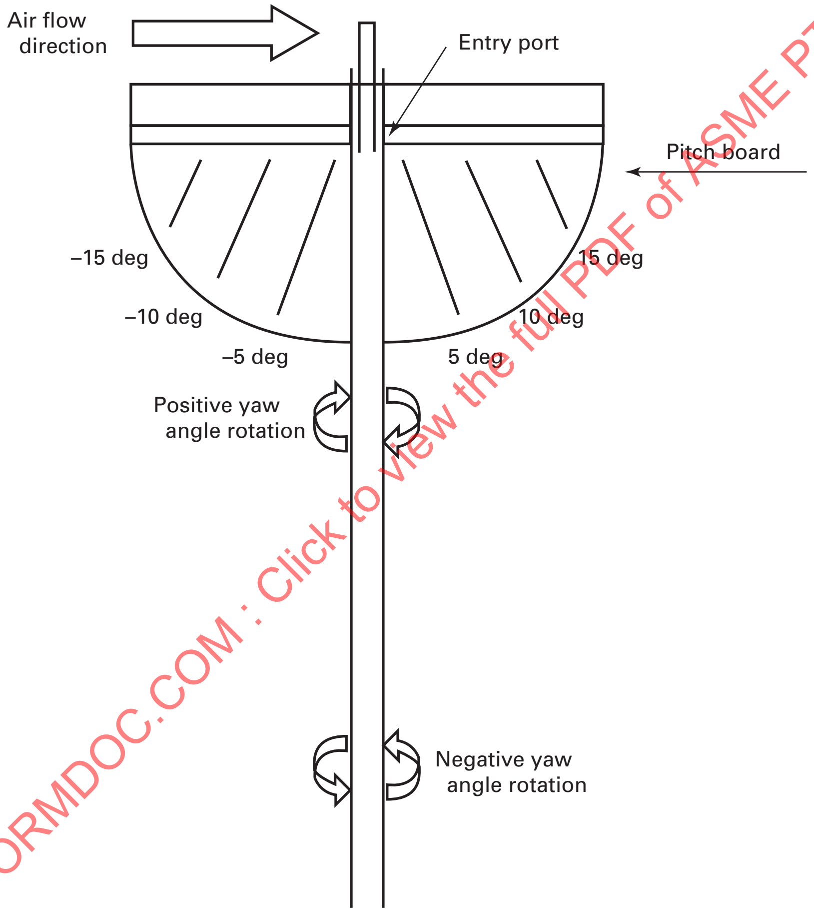


Fig. V-7-3 Five-Hole Probe

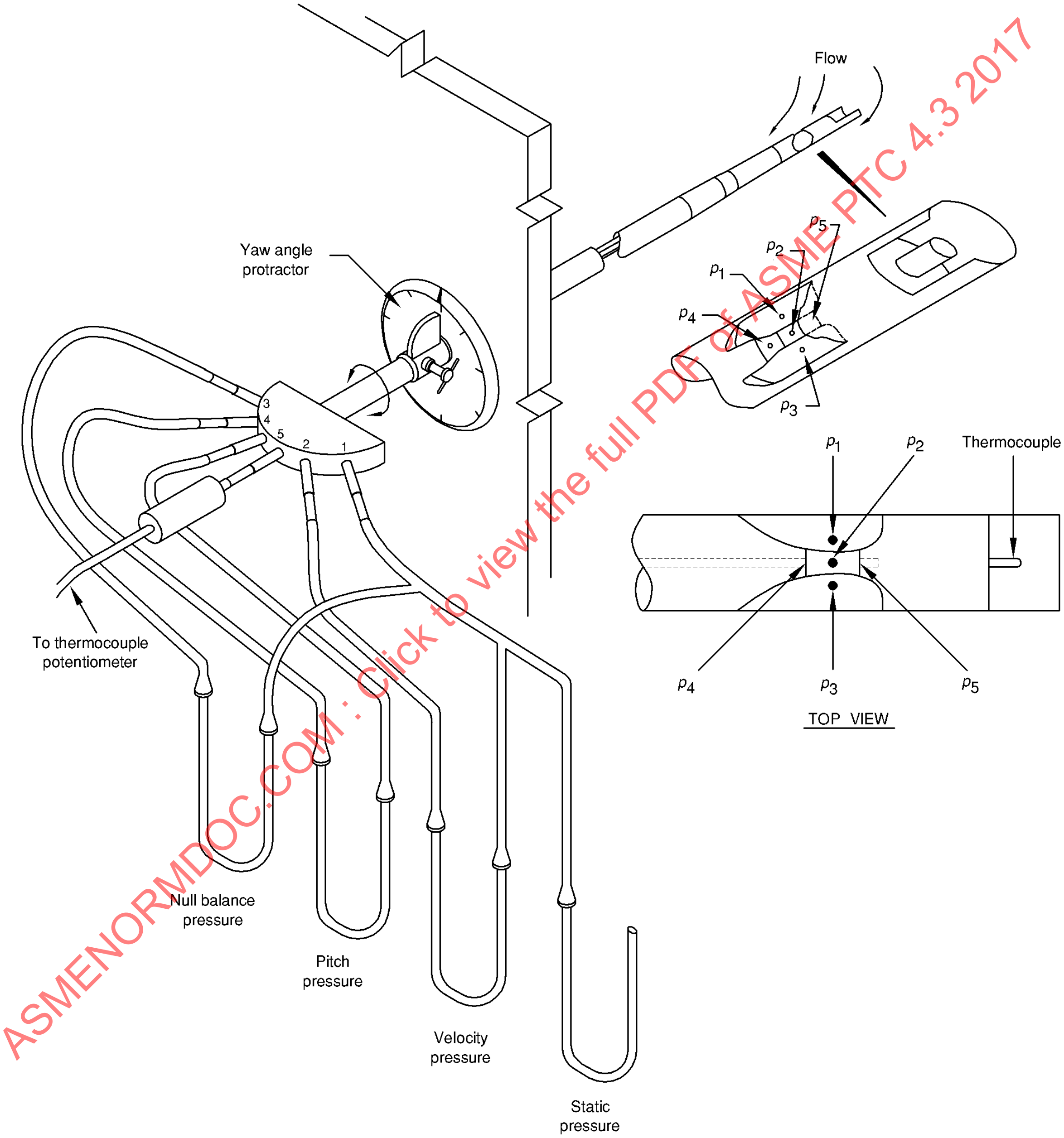


Fig. V-7.3-1 Pitch Angle, Φ, Versus Pitch Coefficient, C_{Φ}

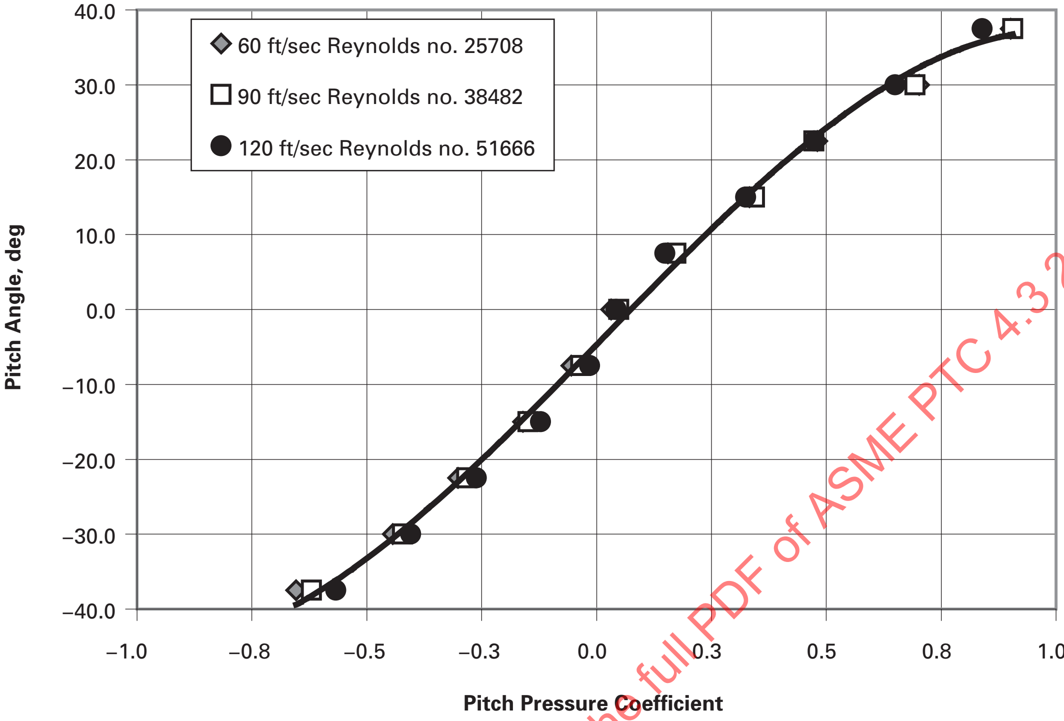


Fig. V-7.3-2 Velocity Pressure Coefficient, K_v, Versus Pitch Pressure Coefficient, C_{Φ}

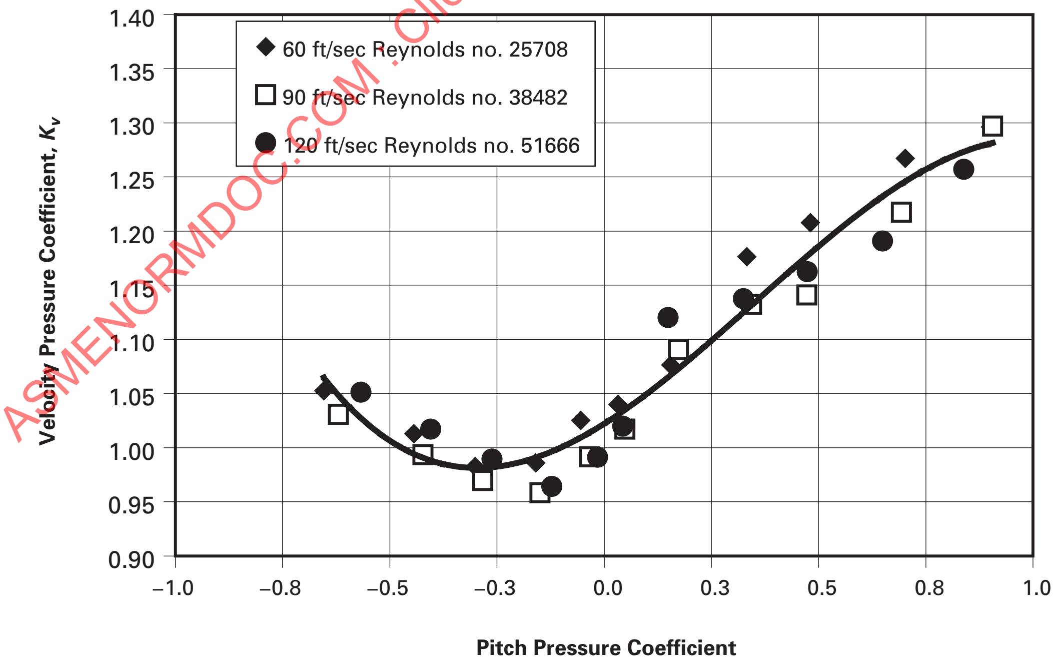
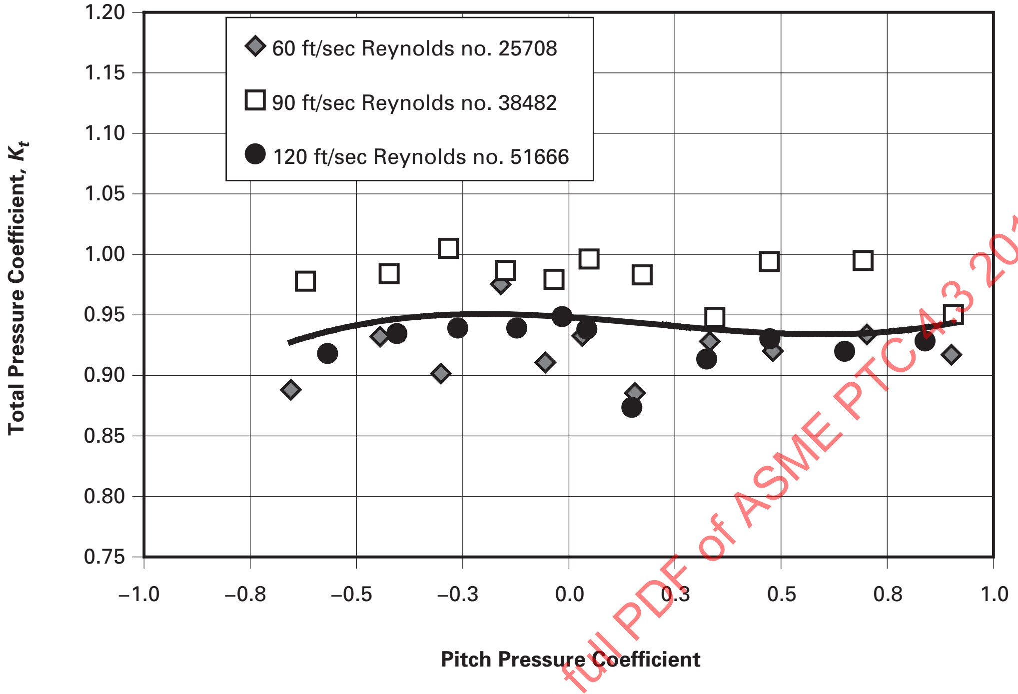


Fig. V-7.3-3 Total Pressure Coefficient, K_t, Versus Pitch Pressure Coefficient, C_Φ



NONMANDATORY APPENDIX A
SAMPLE CALCULATIONS

A-1 INTRODUCTION

The forms in this Appendix show an example of the calculations for two tri-sector air heaters in parallel. The calculation forms for this Code generally show the input data required and calculated results, as opposed to the detailed step-by-step calculations required.

In the interest of space on the forms and convenient numbers to work with, the units used on the forms are abbreviated and are some multiple of the basic mass/mass or mass/unit of heat input. Some of the more frequently used abbreviations are described below.

(a) lbm/lbm. Pound mass of one constituent per pound mass of another constituent or total. For example, lbm ash/lbm fuel is the mass fraction of ash in the fuel.

(b) lbm/100 lbm. Pound mass of one constituent per 100 lb mass of another constituent or total. For example, lbm ash/100 lbm fuel is the same as percent ash in fuel.

(c) lbm/10 kBtu. Pound mass per 10,000 Btu input from fuel. These are convenient units to use for the combustion calculations.

(d) lb/10 kB. Abbreviation for lbm/10 kBtu.

(e) klbm/hr. 1,000 pound mass per hour.

A-2 INPUT DATA SHEETS

The required input is shown on Input Data Sheets 1 through 4 (Tables A-2-1 through A-2-4).

Data Sheets 1 and 2 show the detailed average values and uncertainty input required.

Data Sheet 3 shows the input and uncertainty data required for the combustion and unit efficiency calculations. It is noted that the preferred method for determining input from fuel is to perform the efficiency calculations by the energy-balance method. The most critical data for performing these calculations is the air heater data. However, the Code also allows measuring fuel flow (this is only recommended for oil- and gas-fired units and the flow must be measured with minimum uncertainty for acceptable uncertainty of the air heater performance result).

Data Sheet 4 shows the standard or design values for the air heater(s). Included is curve-fit data for the *X*-ratio and entering gas mass-flow corrections.

It is preferred that the unit output be calculated and the required input data obtained. See Output — U.S. Units (Input and Calculation Sheet) in this Appendix. Note that Data Sheet 3 provides for entering output directly in lieu of measuring the data required to calculate output.

A-3 INTEGRATED UNCERTAINTY INPUT SHEETS

The major task of testing an air heater consists of obtaining air and flue gas temperature, velocity, pressure, and flue gas oxygen content over large flue and duct areas. Two of the major uncertainties associated with these measurements are the systematic uncertainty related to spatial variations (numerical integration) and the systematic uncertainty related to velocity or flow weighting the measured parameters. These sheets (see Table A-3-1 and Table A-3-2) provide a format for determining the total systematic uncertainty for these measurements on a unit basis.

An example systematic uncertainty worksheet for air temperature follows the integrated uncertainty input sheets (see Table A-3-3). These sheets are developed for most measurements and referenced in most of the uncertainty worksheets by worksheet number, abbreviated “Sys. Unc. Sht. No.,” e.g., 1A, 1C, and 4B. Also reference ASME PTC 4 for uncertainty calculations.

A-4 OUTPUT — U.S. UNITS (INPUT AND CALCULATION SHEET)

The input data — flow, temperature and pressure — are shown in three columns in Table A-4-1. Superheater spray flow can be measured or calculated by heat balance.

A-5 COMBUSTION AND EFFICIENCY CALCULATIONS

The input data is shown at the top of the first sheet in Table A-5-1. If sorbent is utilized, the inputs shown would have to be calculated separately. The combustion and efficiency calculations from Item 50 through Item 69 are tutorial in that the Item numbers and calculations are shown.

A-6 CORRECTED AIR HEATER PERFORMANCE CALCULATION SHEETS

In Table A-6-1, sheet 1 summarizes the measured data for each air heater. Sheet 2 shows the standard or design data utilized for the correction calculations. Sheet 3 shows the intermediate results of the calculated values required for the air heater performance corrections and the corrected results of the key performance parameters.

A-7 AIR HEATER PERFORMANCE UNCERTAINTY WORKSHEETS

The sheets in Tables A-7-1 through A-7-6 show the detailed inputs and calculations required to determine the uncertainty of any selected parameter. The example shown is for determining the uncertainty of the AH exit gas temperature excluding leakage. Sheets are numbered 1A and 2A through 1F and 2F. Sheets 1A and 2A show the measured values, standard deviation, and systematic uncertainty values to be used for each measured parameter (refer to the description of the input forms). Sheets 1B and 2B show the recalculated result for an incremental change for each measured parameter, and the calculation of the random uncertainty and positive and negative systematic uncertainty of the result for each parameter. The uncertainties for each parameter are totaled on Sheet 2F and a summary of the total uncertainty results is displayed. The detailed calculations required for each column are shown in the title block of each sheet. The uncertainty parameter investigated is shown in Item [20] on Sheets 2A through 2F.

Table A-2-1 Input Data Sheet 1

AIR HEATER INPUT DATA	Average Value	Standard Deviation	Total Positive Systematic Uncertainty		Total Negative Systematic Uncertainty		No. of Readings	Sys Unc Sht No.
			%	Unit	%	Unit		
Air Heater ID	A							
Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi	1							
TEMPERATURES								
Air Ent AH (Secondary)	93.5	0.17	0.14	0.75	0.14	0.70	20.95	1A
Air Lvg AH (Secondary)	639.3	0.03	0.14	1.48	0.14	1.81	16.28	1A
Air Ent AH (Primary)	114.8	0.20	0.14	0.59	0.14	0.59	14.80	1A
Air Lvg AH (Primary)	617.1	0.16	0.14	8.25	0.14	8.25	4.30	1A
Gas Ent AH (Secondary)	712.3	0.33	0.14	4.63	0.14	4.59	20.23	1B
Gas Lvg AH (Secondary)	283.6	0.02	0.14	4.57	0.14	4.47	19.40	1B
Gas Ent AH (Primary)	0.0	0.00	0.14	0.00	0.14	0.00	0.00	1B
Gas Lvg AH (Primary)	0.0	0.00	0.14	0.00	0.14	0.00	0.00	1B
GAS AND AIR WEIGHTS								
Flue Gas Flow Ent AH (Meas)	2,941.6	6.63	5.00	0.05	5.00	0.05	2	4D
Air Flow Lvg Sec AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Ent Sec AH (Meas - Bisector)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Pri AH (Meas)	373.8	0.06	5.00	0.05	5.00	0.05	2	4D
MISCELLANEOUS								
O_2 Ent AH, % Vol Dry=0 Wet=1 0	3.26	0.02	0.00	0.15	0.00	0.15	20.49	5A
O_2 Lvg AH, % Vol Dry=0 Wet=1 0	4.14	0.02	0.00	0.32	0.00	0.32	20.70	5B
PRESSURE DROP								
DP Secondary Air, in. wg	4.26	0.23	0.00	0.27	0.00	0.27	32	2C
DP Primary Air, in. wg	4.17	0.14	0.00	0.27	0.00	0.27	30	2C
DP Flue Gas (Secondary)	5.84	0.08	0.00	0.27	0.00	0.27	32	2C
DP Flue Gas (Primary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Secondary Air Ent to Flue Gas Lvg, in. wg	18.10	0.21	0.00	0.27	0.00	0.27	32	2C
DP Primary Air Ent to Flue Gas Lvg, in. wg	44.00	0.16	0.00	0.27	0.00	0.27	30	2C
Air Heater ID	B							
Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi	1							
TEMPERATURES								
Air Ent AH (Secondary)	93.1	0.16	0.14	0.6	0.14	0.7	20.95	1A
Air Lvg AH (Secondary)	641.6	0.06	0.14	1.3	0.14	1.7	16.28	1A
Air Ent AH (Primary)	117.6	0.20	0.14	0.7	0.14	0.7	14.80	1A
Air Lvg AH (Primary)	623.7	0.14	0.14	8.4	0.14	8.4	4.30	1A
Gas Ent AH (Secondary)	717.6	0.28	0.14	4.3	0.14	4.2	20.23	1B
Gas Lvg AH (Secondary)	284.7	0.01	0.14	4.5	0.14	4.3	19.40	1B
Gas Ent AH (Primary)	0.0	0.00	0.00	0.0	0.00	0.0	0.00	
Gas Lvg AH (Primary)	0.0	0.00	0.00	0.0	0.00	0.0	0.00	
GAS AND AIR WEIGHTS								
Flue Gas Flow Ent AH (Meas)	3,106.6	20.14	5.00	0.05	5.00	0.05	2	4D
Air Flow Lvg Sec AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Ent Sec AH (Meas - Bisector)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Pri AH (Meas)	385.8	0.05	5.00	0.05	5.00	0.05	2	4D
MISCELLANEOUS								
O_2 Ent AH, % Vol	3.49	0.02	0.00	0.2	0.00	0.2	20.49	5A
O_2 Lvg AH, % Vol	3.96	0.01	0.00	0.2	0.00	0.2	20.70	5B
PRESSURE DROP								
DP Secondary Air, in. wg	3.87	0.38	0.00	0.27	0.00	0.27	32	2C
DP Primary Air, in. wg	4.22	0.16	0.00	0.27	0.00	0.27	30	2C
DP Flue Gas (Secondary)	5.00	0.18	0.00	0.27	0.00	0.27	32	2C
DP Flue Gas (Primary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Secondary Air Ent to Flue Gas Lvg, in. wg	16.87	0.41	0.00	0.27	0.00	0.27	32	2C
DP Primary Air Ent to Flue Gas Lvg, in. wg	43.17	0.21	0.00	0.27	0.00	0.27	30	2C

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Date Test	1-Sep-2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date Calc	1-Dec-2011

Table A-2-2 Input Data Sheet 2

AIR HEATER INPUT DATA	Average Value	Standard Deviation	Total Positive Systematic Uncertainty %	Total Positive Systematic Uncertainty Unit	Total Negative Systematic Uncertainty %	Total Negative Systematic Uncertainty Unit	No. of Readings	Sys Unc Sht No.
Air Heater ID	C							
Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi	0							
TEMPERATURES								
Air Ent AH (Secondary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Lvg AH (Secondary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Ent AH (Primary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Lvg AH (Primary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Gas Ent AH (Secondary)	0.0	0.00	0.14	1.16	0.14	1.16	0.00	1B
Gas Lvg AH (Secondary)	0.0	0.00	0.14	1.16	0.14	1.16	0.00	1B
Gas Ent AH (Primary)	0.0	0.00	0.14	0.00	0.14	0.00	0.00	
Gas Lvg AH (Primary)	0.0	0.00	0.14	0.00	0.14	0.00	0.00	
GAS AND AIR WEIGHTS								
Flue Gas Flow Ent AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Sec AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Ent Sec AH (Meas - Bisector)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Pri AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
MISCELLANEOUS								
O_2 Ent AH, % Vol	0.00	0.00	0.00	0.15	0.00	0.15	0.00	5A
O_2 Lvg AH, % Vol	0.00	0.00	0.00	0.15	0.00	0.15	0.00	5B
PRESSURE DROP								
DP Secondary Air, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Primary Air, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Flue Gas (Secondary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Flue Gas (Primary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Secondary Air Ent to Flue Gas Lvg, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Primary Air Ent to Flue Gas Lvg, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
Air Heater ID	D							
Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi	0							
TEMPERATURES								
Air Ent AH (Secondary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Lvg AH (Secondary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Ent AH (Primary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Air Lvg AH (Primary)	0.0	0.00	0.14	0.58	0.14	0.58	0.00	1A
Gas Ent AH (Secondary)	0.0	0.00	0.14	0.58	0.14	1.16	0.00	1B
Gas Lvg AH (Secondary)	0.0	0.00	0.14	0.58	0.14	1.16	0.00	1B
Gas Ent AH (Primary)	0.0	0.00	0.00	0.00	0.00	0.00	0.00	
Gas Lvg AH (Primary)	0.0	0.00	0.00	0.00	0.00	0.00	0.00	
GAS AND AIR WEIGHTS								
Flue Gas Flow Ent AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Sec AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Ent Sec AH (Meas - Bisector)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
Air Flow Lvg Pri AH (Meas)	0.0	0.00	5.00	0.05	5.00	0.05	0	4D
MISCELLANEOUS								
O_2 Ent AH, % Vol	0.00	0.00	0.00	0.15	0.00	0.15	0.00	5A
O_2 Lvg AH, % Vol	0.00	0.00	0.00	0.15	0.00	0.15	0.00	5B
PRESSURE DROP								
DP Secondary Air, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Primary Air, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Flue Gas (Secondary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Flue Gas (Primary)	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Secondary Air Ent to Flue Gas Lvg, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C
DP Primary Air Ent to Flue Gas Lvg, in. wg	0.00	0.00	0.00	0.27	0.00	0.27	0	2C

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Date Test	1-Sep-2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date Calc	1-Dec-2011

Table A-2-3 Input Data Sheet 3

COMB. AND EFFICIENCY INPUT	Average Value	Standard Deviation	Total Positive Systematic Uncertainty		Total Negative Systematic Uncertainty		No. of Readings	Sys Unc Sht No.
			%	Unit	%	Unit		
Fuel Temperature	86.4	0.30	0.00	7.07	0.00	7.07	120	INPT
Moisture in Air (enter value or meas below)	0.016	0					0	
Barometric Pressure, in. Hg	29.92	0	0.00	0.11	0.00	0.11	2	4B
Dry Bulb Temperature, °F	98.0	1.25	0.14	0.58	0.14	0.58	4	1A
Wet Bulb Temperature, °F	74.6	0.40	0.00	0.00	0.00	0.00	4	1A
Relative Humidity, %	0.0	0	0.00	0.00	0.00	0.00	0	4A
Additional Moisture, lbm/100 lbm Fuel	0.0	0.0	0.0	0.0	0.0	0.0	0	
Residue Entering AH, % Total	75.0	0.0	0.0	0.0	0.0	0.0	0	
Output, 10^6 Btu/hr (enter only if not meas)	5,615.000	0.0	3.0	0.0	3.0	0.0	0	
Fuel Rate (meas), klbm/hr (in lieu of output)	0	0.0	0.0	0.0	0.0	0.0	0	
Fuel Type 0=Coal 1=Oil 2=Gas 3=Wood 4=Other		0						
Fuel Analysis, % Mass								
Carbon	63.580	0.10	0.32	0.00	0.32	0.00	2	6B
Sulfur	0.945	0.01	0.11	0.00	0.11	0.00	2	6C
Hydrogen	3.230	0.00	0.12	0.00	0.12	0.00	2	6D
Water	13.600	0.57	2.02	0.00	2.25	0.00	2	6E
Water Vapor	0.000	0.40	0.00	0.00	0.00	0.00	2	
Nitrogen	0.825	0.01	0.14	0.00	0.14	0.00	2	6G
Oxygen	13.115	0.45	0.12	0.00	0.12	0.00	2	6D
Ash	4.705	0.04	2.02	0.00	2.25	0.00	2	6E
Volatile Matter, % (for coal enthalpy)	40.8	3.04	0.00	0.00	0.00	0.00	2	5C
Fixed Carbon, % (for coal enthalpy)	41.0	3.61	0.00	0.00	0.00	0.00	2	5D
API for Oil Fuels (for enthalpy)	0.0	0.00	0.00	0.00	0.00	0.00	1	5A
Higher Heating Value (HHV), Btu/lb	10,621	18.14	2.00	54.00	2.24	54.00	2	6A
Unburned Carbon Loss, % Fuel Input	0.60	0.00	0.00	0.30	0.00	0.30	0	INPT
Auxiliary Equipment Power, kW	0.00	0.00	1.50	0.00	1.50	0.00	0	INPT
Motor Efficiency	0.00	0.00	0.00	1.00	0.00	1.00	0	INPT
Surface Radiation and Convection Loss, % (use if area not calculated)	0.39	0.00	0.00	0.20	0.00	0.10	0	INPT
Flat Projected Surface Area, 10^3 sq ft	0.00	0.00	0.00	0.00	0.00	0.00	0	
Average Velocity of Air Near Surface, ft/sec	0.00	0.00	0.00	0.00	0.00	1.00	0	
Average Surface Temperature, °F	0.00	0.00	0.00	0.00	0.00	0.00	0	
Average Ambient Temperature Near Surface, °F	0.00	0.00	0.00	0.00	0.00	0.00	0	
Sorbent Rate, klbm/hr (enter '0' if no sorbent)	0.00	0.00	0.00	0.00	0.00	0.00	0	
Ca/S Molar Ratio (estimate if flow not meas)	0.00	0.00	0.00	0.00	0.00	0.00	0	
Calcination Fraction	0.00	0.00	0.00	0.00	0.00	0.00	0	
Sulfur Capture, lbm/lbm Sulfur	0.00	0.00	0.00	0.00	0.00	0.00	0	
Sorbent Temperature, °F	0.00	0.00	0.00	0.00	0.00	0.00	0	
Sorbent Analysis, % Mass								
$CaCO_3$	0.00	0.00	0.00	0.00	0.00	0.00	0	
$Ca(OH)_2$	0.00	0.00	0.00	0.00	0.00	0.00	0	
$MgCO_3$	0.00	0.00	0.00	0.00	0.00	0.00	0	
$Mg(OH)_2$	0.00	0.00	0.00	0.00	0.00	0.00	0	
H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0	
Inert	0.00	0.00	0.00	0.00	0.00	0.00	0	
Tempering Air Flow (air bypassing AH)	258.34	3.43	5.00	5.00	5.00	5.00	10	
Tempering Air Temperature	116.20	2.00	5.00	5.00	5.00	5.00	10	
Expected Pri Air to Gas Leakage, % Total Lkg	84.39		0.00	1.00	0.00	10.00		
Expected Pri Air to Sec Air Leakage, % Total Lkg	0.32		0.00	10.00	0.00	0.00		
Other Losses, % Basis	0.15		0.00	0.15	0.00	0.15		
Other Losses, 10^6 Btu/hr Basis	0.00		0.00	0.00	0.00	0.00		
Other Credits, % Basis	0.00		0.00	0.00	0.00	0.00		
Other Credits, 10^6 Btu/hr Basis	0.00		0.00	0.00	0.00	0.00		

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Date Test	1-Sep-2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	0
		Calc By	tch	Date Calc	1-Dec-2011

Table A-2-4 Input Data Sheet 4

AIR HEATER DESIGN DATA				
Temperatures				
Air Ent AH (Secondary)	85.0			
Air Lvg AH (Secondary)	652.0			
Air Ent AH (Primary)	106.0			
Air Lvg AH (Primary)	631.0			
Gas Ent AH (Secondary)	720.0			
Gas Lvg AH (Secondary)	268.0			
Gas Lvg AH Excl Lkg (Secondary)	277.0			
Gas Ent AH (Primary)	0.0			
Gas Lvg AH (Primary)	0.0			
Gas Lvg AH Excl Lkg (Primary)	0.0			
Flows and Curve Fit Constants				
Flue Gas Flow Ent AH (Secondary)	5,665			
Flue Gas Flow Ent AH (Primary)				
Temp Corr Curve Fit Constants for Ent Gas Flow (Secondary AH)	4.76240E-02	-2.77472E-01	1.09520E-03	-8.54943E-06
Temp Corr Curve Fit Constants for Ent Gas Flow (Primary AH)	0	0	0	0
Air Flow Lvg AH (Secondary)	3,985			
Air Flow Lvg AH (Primary)	828.6			
Standard or Design Heat Capacity Ratio (Secondary)	0.80742			
Temp Corr Curve Fit Constants for X-Ratio (Secondary AH)	-695.0774	1,581.889	-1,153.407	322.8411
Standard or Design Heat Capacity Ratio (Primary)	0			
Temp Corr Curve Fit Constants for X-Ratio (Primary AH)	0	0	0	0
Miscellaneous				
Moisture in Air, lbm/lbm dry air	0.016			
Moisture in Flue Gas Ent AH, %	5.21			
Residue in Flue Gas Ent AH, % Total Solids	0			
For Estimated Pri Air Leakage, see Input Sheet 3				
PRESSURE DROP				
DP Secondary Air, in. wg	2.85			
DP Primary Air, in. wg	1.80			
DP Flue Gas (Secondary)	3.35			
DP Flue Gas (Primary)	0.00			
DP Secondary Air Ent to Flue Gas Lvg, in. wg	17.4			
DP Primary Air Ent to Flue Gas Lvg, in. wg	51.6			
Exponent for Gas Flow Ratio Correction	1.8			
Exponent for Air Flow Ratio Correction	1.8			

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Date Test	1-Sep-2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date Calc	1-Dec-2011

Table A-3-1 Integrated Uncertainty Input Sheet 1

Item No.			Sys Unc Sht No.	Air Heater ID A	 B	 C	 D
	COMB. CALCULATIONS — CMBSTNa						
1	Gas Temp Ent AH, °F (Sec / Pri)			712.3	717.6	0.0	0.0
2	No. Points per Flue, m			40	38	0	0
3	Spatial Distribution Index (SDI)			16.6	11.9	0.0	0.0
4	Tave Flow Weighted	Vel Data Avail	Yes	710.2	715.2	0.0	0.0
5	Correlation Coefficient 'R'			-0.181	0.269	0.000	0.000
6	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	712.3	717.6	0.0	0.0
7	Sample Standard Deviation for Grid			0.333	0.281	0.000	0.000
8	Sys Unc, Integrated Average, °F			2.66	1.95	0.00	0.00
9	Pos Sys Unc, Flow Weighting, °F			3.61	3.69	0.00	0.00
10	Neg Sys Unc, Flow Weighting, °F			3.56	3.57	0.00	0.00
11	Number of Readings	20.2		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
12	Total Instrument Sys Unc, °F		1B	1.158		1.158	
13	Total Combined Positive Sys Unc for Int Ave, °F			4.627	4.330	0.000	0.000
14	Total Combined Negative Sys Unc for Int Ave, °F			4.588	4.233	0.000	0.000
15	Gas Temp Lvg AH, °F (Sec / Pri)			283.6	284.7	0	0
16	No. Points per Flue, m			40	40	0	0
17	Spatial Distribution Index (SDI)			26.6	25.8	0	0
18	Tave Flow Weighted	Vel Data Avail	Yes	284.8	285.8	0	0
19	Correlation Coefficient 'R'			-0.167	-0.246	0.000	0.000
20	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	283.6	284.7	0.0	0.0
21	Sample Standard Deviation for Grid			0.016	0.014	0.000	0.000
22	Sys Unc, Integrated Average, °F			4.26	4.12	0.00	0.00
23	Pos Sys Unc, Flow Weighting, °F			1.16	1.45	0.00	0.00
24	Neg Sys Unc, Flow Weighting, °F			0.67	0.64	0.00	0.00
25	Number of Readings	19.4		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
26	Total Instrument Sys Unc, °F		1B	1.158		1.158	
27	Total Combined Positive Sys Unc for Int Ave, °F			4.568	4.521	0.000	0.000
28	Total Combined Negative Sys Unc for Int Ave, °F			4.467	4.331	0.000	0.000
29	Air Temp Ent Sec AH	APH Coil 0=No 1=Yes	0	93.5	93.1	0	0
30	No. Points per Flue, m			40	40	0	0
31	Spatial Distribution Index (SDI)			2.0	0.6	0	0
32	Tave Flow Weighted	Vel Data Avail	No	92.1	91.2	0	0
33	Correlation Coefficient 'R'			0.080	-0.241	0.000	0.000
34	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	93.5	93.1	0.0	0.0
35	Sample Standard Deviation for Grid			0.171	0.163	0.000	0.000
36	Sys Unc, Integrated Average, °F			0.3191	0.0898	0.0000	0.0000
37	Pos Sys Unc, Flow Weighting, °F			0.348	-0.046	0.0	0.0
38	Neg Sys Unc, Flow Weighting, °F			0.207	0.387	0.0	0.0
39	Number of Readings	21.0		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
40	Total Instrument Sys Unc, °F		1A	0.583		0.583	
41	Total Combined Positive Sys Unc for Int Ave, °F			0.750	0.592	0.000	0.000
42	Total Combined Negative Sys Unc for Int Ave, °F			0.696	0.706	0.000	0.000
43	Air Temp Lvg Secondary AH			639.3	641.6	0	0
44	No. Points per Flue, m			40	40	0	0
45	Spatial Distribution Index (SDI)			7.6	4.9	0	0
46	Tave Flow Weighted	Vel Data Avail	Yes	638.4	639.2	0	0
47	Correlation Coefficient 'R'			0.088	0.288	0.000	0.000
48	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	639.3	641.6	0.0	0.0
49	Sample Standard Deviation for Grid			0.030	0.055	0.000	0.000
50	Sys Unc, Integrated Average, °F			1.21	0.78	0.00	0.00
51	Pos Sys Unc, Flow Weighting, °F			0.62	0.93	0.00	0.00
52	Neg Sys Unc, Flow Weighting, °F			1.21	1.40	0.00	0.00
53	Number of Readings	16.3		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
54	Total Instrument Sys Unc, °F		1A	0.583		0.583	
55	Total Combined Positive Sys Unc for Int Ave, °F			1.483	1.342	0.000	0.000
56	Total Combined Negative Sys Unc for Int Ave, °F			1.809	1.705	0.000	0.000

PLANT NAME	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
REMARKS:	PTC 4.3 EXAMPLE CASE	Load	MCR	Test Date	09/01/10
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date Calc	12/01/11
		Sheet 1 of 2			

Table A-3-2 Integrated Uncertainty Input Sheet 2

Item No.			Sys Unc Sht No.	Air Heater ID A	B	C	D
	COMB. CALCULATIONS - CMBSTNa						
61	O_2 in Flue Gas Ent AH, % (Sec / Pri)			3.26	3.49	0.00	0.00
62	No. Points per Flue, m			40	38	0	0
63	Spatial Distribution Index (SDI)			0.07	0.06	0.00	0.00
64	Ave O_2 Flow Weighted	Vel Data Avail	Yes	3.26	3.46	0.00	0.00
65	Correlation Coefficient 'R'			-0.196	0.050	0.00	0.00
66	Ave O_2 Selected	Enter 0=Ave 1=Flow Wtd	0	3.26	3.49	0.00	0.00
67	Sample Standard Deviation for Grid			0.016	0.016	0.000	0.000
68	Sys Unc, Integrated Average, Unit Meas			0.012	0.009	0.000	0.000
69	Pos Sys Unc, Flow Weighting, Unit Meas			0.000	0.054	0.000	0.000
70	Neg Sys Unc, Flow Weighting, Unit Meas			0.000	0.001	0.000	0.000
71	Number of Readings	20.5		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
72	Total Instrument Sys Unc, Unit Meas		5A	0.150		0.150	
73	Total Combined Positive Sys Unc for Int Ave, Unit Meas			0.150	0.160	0.000	0.000
74	Total Combined Negative Sys Unc for Int Ave, Unit Meas			0.150	0.160	0.000	0.000
75	O_2 in Flue Gas Lvg AH, % (Sec / Pri)			4.14	3.96	0.00	0.00
76	No. Points per Flue, m			40	40	0	0
77	Spatial Distribution Index (SDI)			0.07	0.06	0.00	0.00
78	Ave O_2 Flow Weighted	Vel Data Avail	Yes	4.09	3.95	0.00	0.00
79	Correlation Coefficient 'R'			-0.125	-0.096	0.00	0.00
80	Ave O_2 Selected	Enter 0=Ave 1=Flow Wtd	0	4.14	3.96	0.00	0.00
81	Sample Standard Deviation for Grid			0.016	0.014	0.000	0.000
82	Sys Unc, Integrated Average, Unit Meas			0.012	0.010	0.000	0.000
83	Pos Sys Unc, Flow Weighting, Unit Meas			0.281	0.050	0.000	0.000
84	Neg Sys Unc, Flow Weighting, Unit Meas			0.281	0.050	0.000	0.000
85	Number of Readings	20.7		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
86	Total Instrument Sys Unc, Unit Meas		5B	0.150		0.150	
87	Total Combined Positive Sys Unc for Int Ave, Unit Meas			0.319	0.158	0.000	0.000
88	Total Combined Negative Sys Unc for Int Ave, Unit Meas			0.319	0.158	0.000	0.000
89	Air Temp Ent Pri AH	APH Coil 0=No 1=Yes	0	114.8	117.6	0	0
90	No. Points per Flue, m			30	26	0	0
91	Spatial Distribution Index (SDI)			0.47	0.36	0.00	0.00
92	Tave Flow Weighted	Vel Data Avail	No	116.4	117.3	0	0
93	Correlation Coefficient 'R'			-0.112	0.128	0.000	0.000
94	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	114.8	117.6	0.0	0.0
95	Sample Standard Deviation for Grid			0.205	0.200	0.000	0.000
96	Sys Unc, Integrated Average, °F			0.088	0.073	0.000	0.000
97	Pos Sys Unc, Flow Weighting, °F			0.043	0.379	0.000	0.000
98	Neg Sys Unc, Flow Weighting, °F			0.026	0.277	0.000	0.000
99	Number of Readings	14.8		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
100	Total Instrument Sys Unc, °F		1A	0.583		0.583	
101	Total Combined Positive Sys Unc for Int Ave, °F			0.591	0.699	0.000	0.000
102	Total Combined Negative Sys Unc for Int Ave, °F			0.591	0.699	0.000	0.000
103	Air Temp Lvg Primary AH			617.1	623.7	0	0
104	No. Points per Flue, m			15	15	6	0
105	Spatial Distribution Index (SDI)			19.02	19.27	0.00	0.00
106	Tave Flow Weighted	Vel Data Avail	Yes	616.2	622.8	0	0
107	Correlation Coefficient 'R'			-0.098	-0.248	0.000	0.000
108	Tave Selected	Enter 0=Ave 1=Flow Wtd	0	617.1	623.7	0.00	0.00
109	Sample Standard Deviation for Grid			0.156	0.142	0.000	0.000
110	Sys Unc, Integrated Average, °F			8.205	8.312	0.000	0.000
111	Pos Sys Unc, Flow Weighting, °F			0.673	0.743	0.000	0.000
112	Neg Sys Unc, Flow Weighting, °F			1.371	1.443	0.000	0.000
113	Number of Readings	4.3		Pos Sys Unc, Unit Meas		Neg Sys Unc, Unit Meas	
114	Total Instrument Sys Unc, °F		1A	0.583		0.583	
115	Total Combined Positive Sys Unc for Int Ave, °F			8.253	8.365	0.000	0.000
116	Total Combined Negative Sys Unc for Int Ave, °F			8.253	8.365	0.000	0.000

PLANT NAME	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
REMARKS:	PTC 4.3 EXAMPLE CASE	Load	MCR	Test Date	09/01/10
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date Calc	12/01/11
		Sheet 2 of 2			

Table A-3-3 Systematic Uncertainty Worksheet

Measured Parameter: Air Temperature, °F **Worksheet No:** 1A

Estimate of Systematic Uncertainty

1	Measured Parameter		2 Positive		3 Negative	
	Individual Sys Unc	Source of Sys Unc	Percent of Reading	Unit of Meas	Percent of Reading	Unit of Meas
a	TC or RTD type	Calibrated		0.50		0.50
b	Calibration	Included in item a				
c	Lead wires	Negligible		0.3		0.3
d	Ice bath	Negligible				
e	Thermowell location/geometry	N/A				
f	Pad weld (insulated/uninsulated)	N/A				
g	Stratification of flowing liquid	Calculated separately				
h	Sys unc of instrument system	Estimated	0.1		0.1	
i	Drift	Estimated	0.1		0.1	
j						
k						
l						
m						
n						
o						

Total Systematic Uncertainty $(a^2 + b^2 + c^2 + \dots)^{1/2}$	2A	2B	3A	3B
	0.14	0.58	0.14	0.58

PLANT NAME	ASME PTC 4.3 MASTER FORM			UNIT NO	1
TEST NO.	1	DATE	1-Sep-10	LOAD	MCR
TIME START	9:00	TIME END	11:00	CALC BY	tch
REMARKS:	PTC 4.3 EXAMPLE CASE			CALC DATE	1-Dec-11
	TRI-SECTOR AH				

Table A-4-1 Output — U.S. Units (Input and Calculation Sheet)

Enter Steam Table Vers: 0=1967 1=1997	1					
	PARAMETER	Flow, *W*, klbm/hr	Temperature, *T*	Pressure, *P*	Enthalpy, *H*, Btu/lbm	Absorption, *Q*, 10^6 Btu/hr [W × (H − H1)/1,000]
1	FEEDWATER (Excluding SH Spray)	4,375.267	404.2	2,616.9	382.41	
2	SH SPRAY WATER: Ent 1 to Calc HB	0	404.2	2,616.9	382.41	0.00
3	Ent SH-1 Attemperator	4,375.267	740.5	2,557.8	1,229.91	
4	Lvg SH-1 Attemperator	4,393.567	735.1	2,557.8	1,222.49	
5	SH-1 Spray Water Flow	18.300				
6	Ent SH-2 Attemperator	4,393.567	806.4	2,521.0	1,305.69	
7	Lvg SH-2 Attemperator	4,445.367	782.7	2,521.0	1,282.19	
8	SH-2 Spray Water Flow	51.800	W6 × (H6 − H7) / (H7 − H2) or W7 × (H6 − H7) / (H6 − H2)			
	INTERNAL EXTRACTION FLOWS					
9	Blowdown / Drum	0.000		2,586.1	743.37	0.00
10	Sat Steam Extraction	0.000	0.0	0.0	1,080.09	0.00
11	Sootblowing Steam	0.000	0.0	0.0	0.00	0.00
12	SH Steam Extraction 1	0.000	0.0	2,557.8	0.00	0.00
13	SH Steam Extraction 2	0.000	0.0	0.0	0.00	0.00
14	Atomizing Steam	0.000	0.0	0.0	0.00	0.00
	AUXILIARY EXTRACTION FLOWS					
15	Aux Steam 1	0.000	0.0	0.0		
16	Aux Steam 2	0.000	0.0	0.0		
17						
18	MAIN STEAM	4,445.367	1,004.8	2,463.3	1,462.23	4,800.17
19	HIGH PRESS STEAM OUTPUT	Q18 + Q2 + Q9 through Q17				4,800.17
	REHEAT UNITS					
20	REHEAT OUTLET		1,011.3	580.3	1,524.35	
21	COLD REHEAT ENT ATTEMPERATOR	0.000	647.4	600.9	1,318.51	
22	RH SPRAY WATER	0.000	399.2	1,000.0	375.11	
23	COLD REHEAT EXTRACTION FLOW	0.000				
24	TURB SEAL FLOW & SHAFT LKG, %	1.750				
	FW HEATER NO. 1					
25	FW Ent: 0=FW 1=FW+Spray 0	4,375.267	403.2	2,616.9	381.33	
26	FW Leaving		482.4	596.2	467.45	
27	Extraction Steam		644.5	596.2	1,317.06	
28	Drain		418.7	596.2	395.76	
29	FW HEATER NO. 1 FLOW	408.989	W25 × (H26 − H25) / (H27 − H28)			
	FW HEATER NO. 2					
30	FW Entering	4,375.267	0.0	0.0	0.00	
31	FW Leaving		0.0	0.0	0.00	
32	Extraction Steam		0.0	0.0	0.00	
33	Drain		0.0	0.0	0.00	
34	FW HEATER NO. 2 FLOW	0.000	[W30 × (H31 − H30) − W29 × (H28 − H33)] / (H32 − H33)			
35	COLD REHEAT FLOW	3,958.599	W18 × (1.0 − 0.01 × W24) − W23 − W29 − W34			
36	REHEAT OUTPUT	W35 × (H20 − H21) + W22 × (H20 − H22)				814.84
37	TOTAL OUTPUT	Q19 + Q36				5,615.00

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Test Date	09/01/10
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc Date	12/01/11

Table A-5-1 Combustion and Efficiency Calculations

	INPUT CONDITIONS — BY TEST OR SPECIFICATION — Enter data in lightly shaded cells				
1	Average entering air temperature, °F	97.6		**Sorbent Input Parameters**	
2	Fuel temperature, °F	86.4	26	Sorbent rate, klbm/hr (enter '0' if sorbent not used)	0.000
3	Average AH exit gas temperature, °F	284.2	27	Ca/S molar ratio (enter sorbent rate or est Ca/S ratio)	0.000
4	Moisture in air, lbm/lbm dry air	0.0160	28	Calcination fraction	0.000
5	Additional moisture, lbm/100 lbm fuel	0	29	Sulfur capture, lbm/lbm sulfur	0.000
6	Residue entering AH, % total	75	31	Sorbent temperature, °F	0.0
7	Output, 10^6 Btu/hr	5,615.000		**Sorbent Analysis, % Mass**	
			32	$CaCO_3$	0.00
9	**Fuel Type 0=Coal 1=Oil 2=Gas 3=Wood 4=Other**	0	33	$Ca(OH)_2$	0.00
	Fuel Analysis, % Mass (for Gas, see Gaseous Fuels Form)		34	$MgCO_3$	0.00
11	Carbon	63.580	35	$Mg(OH)_2$	0.00
12	Sulfur	0.945	36	H_2O	0.00
13	Hydrogen	3.230	37	Inert	0.00
14	Water	13.600	38	Total	0.00
15	Water vapor	0.000		**Corrections for Sorbent**	
16	Nitrogen	0.825	40	Additional theoretical air, lbm/10,000 Btu	0.000
17	Oxygen	13.115	41	CO_2 from sorbent, lbm/10,000 Btu	0.000
18	Ash	4.705	42	H_2O from sorbent, lbm/10,000 Btu	0.000
19	**Total**	100.000	43	Spent sorbent, lbm/10,000 Btu	0.000
			44	Dry air/gas flow correction for O_3 in SO_3, lbm/10,000 Btu	0.000
21	Higher heating value (HHV), Btu/lbm	10,621.475			
22	Unburned carbon loss, % fuel input	0.600	46	Theoretical air, lbm/100 lbm fuel	784.92
23	Unburned carbon, % of fuel	0.440	47	Water from fuel, lbm/100 lbm fuel	42.47
			48	Theoretical air, lbm/10,000 Btu	7.438

	COMBUSTION GAS CALCULATIONS, Quantity per 10,000 Btu Fuel Input					
50	Theoretical air (corrected), lbm/10,000 Btu	[48] + [40] − [23] × 1,151 / [21]				*7.390*
51	Residue from fuel, lbm/10,000 Btu	([18] + [23]) × 100 / [21]				*0.048*
52	Total residue, lbm/10,000 Btu	[51] + [43]				*0.048*
53			A	Leaving Econ	B	Leaving Air Heater
54	O_2, % O2 Dry=0 Wet=1	0		3.38		4.05
55	Excess air, % by weight — calculated			*19.0*		*23.6*
56	Gas from dry air, lbm/10,000 Btu	(1 + [55]/100) × [50] − [44]		*8.793*		*9.136*
57	H_2O from air, lbm/10,000 Btu	[56] × [4]	*0.141*	*0.141*	*0.146*	*0.146*
58	Additional moisture, lbm/10,000 Btu	[5] × 100 / [21]	*0.000*	*0.000*	*0.000*	*0.000*
59	H_2O from fuel, lbm/10,000 Btu	[47] × 100 / [21]	*0.400*		*0.400*	
60	Wet gas from fuel, lbm/10,000 Btu	(100 − [18] − [23]) × 100 / [21]		*0.893*		*0.893*
61	CO_2 from sorbent, lbm/10,000 Btu	[41]		*0.000*		*0.000*
62	H_2O from sorbent, lbm/10,000 Btu	[42]	*0.000*	*0.000*	*0.000*	*0.000*
63	Total wet gas, lbm/10,000 Btu	Summation [56] through [62]		*9.827*		*10.175*
64	Water in wet gas, lbm/10,000 Btu	Summation [57] + [58] + [59] + [62]	*0.541*	*0.541*	*0.546*	*0.546*
65	Dry gas, lbm/10,000 Btu	[63] − [64]		*9.286*		*9.629*
66	H_2O in gas, % by weight	100 × [64] / [63]		*5.50*		*5.37*
67	Residue, % by weight (zero if <0.125 lbm/10 kB)	[6] × [52] / [63]		*0.00*		*0.00*
68	Air heater leakage, % entering gas weight	100 × ([63 Lvg] − [63 Ent]) / [63 Ent]				*3.54*
69	Exit gas temperature excluding leakage, °F	[3] + [68]/100 × ([3]− [TAI]) × CpA / CpG	CpA | CpG	*0.245*	*0.254*	*290.04*
	COMBUSTION PRODUCTS, % Volume (Dry Basis)					
70	O_2			*3.38*		*4.05*
71	CO_2			*16.49*		*15.86*
72	SO_2, ppm			*924*		*889*
73	N_2			*80.04*		*80.00*
74	Gas density, lbm/ft^3 @ 60°F and 29.92 in. Hg			*0.0784*		*0.08*
75	Dry volume to wet volume conversion factor					*0.909*

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Test Date	09/01/10
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc Date	12/01/11
		Sheet 1 of 2			

Table A-5-1 Combustion and Efficiency Calculations (Cont'd)

	EFFICIENCY CALCULATIONS, Percent Input From Fuel								
	Losses, % — Enter Calculated Results in Column [B]							A 10^6 Btu/hr	B %
80	Dry gas, %		[65A] × HDFg / 100			HDFg	50.9		*4.73*
81	Water from fuel, as fired %	Enthalpy of steam at 1 psia, T=[69]	H1=(3.958E−5 × T + 0.4329) × T + 1,062.2				*1,191.1*		
82		Enthalpy of water at T=77°F	H2=77 − 32				*45.0*		
83			([59] − [15]) × ([81] − [82]) / 100						*4.58*
84	Water vapor from fuel		[15] × HWv[69] / [21]						*0.00*
85	Moisture in air, %		[57A] × HWv[69] / 100			HWv [69]	9.2		*0.14*
86	Unburned carbon, %		[22] or [23] × 14,500 / [21]						*0.60*
87	Sensible heat of residue	Temp bottom ash	*2,000*	HRs bot	515.7	HRs [69]	42.7		*0.08*
88									
89	Unmeasured or other losses, % basis								*0.15*
90	Summation of losses, % basis		Summation [80] through [89]						*10.27*
	Losses, 10^6 Btu/hr — Enter in Column [A]								
93	Surface radiation and convection							*24.4*	
94	Sorbent calcination/dehydration							*0.0*	
95	Water from sorbent							*0.0*	
96									
97	Other losses, 10^6 Btu/hr basis							*0.0*	
98	Summation of losses, 10^6 Btu/hr basis		Summation [93] through [97]					*24.4*	
	Credits, % — Enter Calculated Results in Column [B]								
101	Entering dry air		[56A] × HDA[1] / 100			HDA [1]	*5.0*		*0.44*
102	Moisture in air		[57A] × HWv[1] / 100			HWv [1]	*9.2*		*0.01*
103	Sensible heat in fuel		100 × HF[2] / [21]			H Fuel [2]	*3.9*		*0.04*
104	Sulfation								*0.00*
105									
106	Other credits, % basis								*0.00*
107	Summation of credits, %		Summation [101] through [106]						*0.49*
	Credits, 10^6 Btu/hr — Enter in Column [A]								
110	Auxiliary equipment power		3,412 × QX × EX / 100	QX (kW)	0.0	EX (%)	0.00	*0.0*	
111	Sensible heat from sorbent							*0.0*	
112									
113	Other credits, 10^6 Btu/hr basis							*0.0*	
114	Summation of credits, 10^6 Btu/hr basis		Summation [110] through [113]					*0.0*	
115	**Fuel Efficiency, %**		(100 − [90] + [107])×[7] / ([7] +[98] − [114])						*89.82*
	KEY PERFORMANCE PARAMETERS					Entering Air Heater		Leaving Air Heater	
118	Input from fuel, 1,000,000 Btu/hr		100 × [7] / [115]						*6,251.0*
119	Fuel rate, 1,000 lbm/hr		1,000 × [118] / [21]						*588.5*
120	Wet gas weight, 1,000 lbm/hr		[63] × [118] / 10				*6,142.9*		*6,360.3*
121	Air weight (wet), 1,000 lbm/hr		(1 + [4]) × (1 + [55]/100) × [50]				*5,584.629*		*5,802.1*
Name of Plant		ASME PTC 4.3 MASTER FORM				Unit No.	1	Test No.	1
Remarks		PTC 4.3 EXAMPLE CASE				Load	MCR	Test Date	09/01/10
		TRI-SECTOR AH				Time 1	9:00	Time 2	11:00
						Calc By	tch	Calc Date	12/01/11
						Sheet 2 of 2			

Table A-6-1 Corrected Air Heater Performance Calculation Sheet

		Column		**A**	**B**	**C**	**D**
		Air Heater ID		A / RIGHT	B / LEFT		
		Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi		1	1	0	0
		INPUT DATA					
		Temperatures, °F					
1	TA8S	Air Ent AH (Secondary)		93.47	93.08		
2	HA8S	Enthalpy Air		4.01	4.01		
3	TA9S	Air Lvg AH (Secondary)		639.33	641.60		
4	HA9S	Enthalpy Air		139.57	140.15		
5	TA8P	Air Ent AH (Primary)		114.77	117.64	0.00	0.00
6	HA8P	Enthalpy Air		9.20	9.90		
7	TA9P	Air Lvg AH (Primary)		617.08	623.68	0.00	0.00
8	HA9P	Enthalpy Air		133.89	135.58		
9	TFg14S	Gas Ent AH (Secondary)		712.31	717.59		
10	HFg14S	Enthalpy Gas		164.17	165.54		
11	TFg15S	Gas Lvg AH (Secondary)		283.61	284.74		
12	HFg15S	Enthalpy Gas		51.74	52.01		
13	HA15S	Enthalpy Air		50.51	50.78		
14	TFg14P	Gas Ent AH (Primary)				0.00	0.00
15	HFg14P	Enthalpy Air					
16	TFg15P	Gas Lvg AH (Primary)				0.00	0.00
17	HFg15P	Enthalpy Gas					
18	HA15P	Enthalpy Air					
		Gas and Air Weights, klbm/hr					
19	MrFg14Sm	Flue Gas Flow Ent Sec AH (Meas)		2,941.560	3,106.559	0.000	0.000
20	MrFg14Pm	Flue Gas Flow Ent Pri AH (Meas)				0.000	0.000
21	MrFg14	Total Ent Flue Gas Flow (Calc)		6,142.881			
22	MrA9Sm	Air Flow Lvg Sec AH (Meas)		0.000	0.000	0.000	0.000
23	MrA8Sm	Air Flow Ent Sec AH (Meas - Bisector)		0.000	0.000	0.000	0.000
24	MrA9Pm	Air Flow Lvg Pri AH (Meas)		373.809	385.758	0.000	0.000
		Miscellaneous					
25	VpO214	O_2 Ent AH, % by vol 0=Dry 1=Wet	0	3.264	3.492	0.000	0.000
26	VpO215	O_2 Lvg AH, % by vol 0=Dry 1=Wet	0	4.138	3.960	0.000	0.000
27	MFrWDA	Moisture in Air, lbm/lbm Dry Air		0.0160			
28	MpWFg14	Moisture in Flue Gas Ent AH, %		5.50			
29	MpRsFg14	Residue in Flue Gas Ent AH, %		0.00			
30	MrA5	Tempering Air Flow (air that bypasses the AH)		0.00			
31	TA5	Tempering Air Temperature		0.00			
		Pressure Drop					
32	PDiA8S	DP Secondary Air, in. wg		4.26	3.87		
33	PDiA8P	DP Primary Air, in. wg				4.17	4.22
34	PDiG14S	DP Flue Gas (Secondary)		5.84	5.00		
35	PDiG14P	DP Flue Gas (Primary)				0.00	0.00
36	PDiA8Fg15S	DP Secondary Air Ent to Flue Gas Lvg, in. wg Estimated		20.10	18.87		
37	PDiA8Fg15P	DP Primary Air Ent to Flue Gas Lvg, in. wg Estimated				51.00	50.22
Name of Plant		ASME PTC 4.3 MASTER FORM		Unit No.	1	Test No.	1
Remarks		PTC 4.3 EXAMPLE CASE		Load	MCR	Date	9/1/2010
		TRI-SECTOR AH		Time 1	9:00	Time 2	11:00
				Calc By	tch	Date	12/1/2011
				Sheet 1 of 3			

Table A-6-1 Corrected Air Heater Performance Calculation Sheet (Cont'd)

		Column		**A**	**B**	**C**	**D**
		Air Heater ID		A / RIGHT	B / LEFT		
		Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi		1	1	0	0
		DESIGN VALUES					
		Temperatures, °F					
38	TA8SDs	Air Ent AH (Secondary)		85.0			
39	TA9SDs	Air Lvg AH (Secondary)		652.0			
40	TA8PDs	Air Ent AH (Primary)		106.0			
41	TA9PDs	Air Lvg AH (Primary)		631.0			
42	TFg14SDs	Gas Ent AH (Secondary)		720.0			
	TFg15SDs	Gas Lvg AH (Secondary)		268.0			
43	TFg15SNLDs	Gas Lvg AH Excl Lkg (Secondary)		277.0			
44	TFg14PDs	Gas Ent AH (Primary)		0.0			
	TFg15PDs	Gas Lvg AH (Primary)		0.0			
45	TFg15PNLDs	Gas Lvg AH Excl Lkg (Primary)		0.0			
		Flows and Curve Fit Constants					
46	MrFg14SDs	Flue Gas Flow Ent AH (Secondary)		5,665.000			
	MrFg14PDs	Flue Gas Flow Ent AH (Primary)		0.000			
47	TDiMrFgSCf	Temp Corr Curve Fit for Ent Gas Flow (Secondary AH)		0.04762401	-0.2774723	0.0010952	-8.5494E-06
48	TDiMrFgPCf	Temp Corr Curve Fit for Ent Gas Flow (Primary AH)		0	0	0	0
49	MrA9SDs	Air Flow Lvg Sec AH		3,985.000			
50	MrA9PDs	Air Flow Lvg Pri AH		828.600			
56	XrSDs	Design Heat Capacity Ratio (Secondary)		0.8074			
57	TDiXrSCf	Temp Corr Curve Fit Constants for Heat Capacity Ratio (Secondary)		-695.0774	1,581.889	-1,153.407	322.8411
58	XrPDs	Design Heat Capacity Ratio (Primary)		0.0000			
59	TDiXrPCf	Temp Corr Curve Fit Constants for Heat Capacity Ratio (Primary)		0	0	0	0
		Miscellaneous					
51	MFrWDADs	Moisture in Air, lbm/lbm Dry Air		0.016			
52	MpWFg14Ds	Moisture in Flue Gas Ent AH, %		5.21			
53	MpRsFg14Ds	Residue in Flue Gas Ent AH, %		0.00			
54	MpPAIFg	Exp Pri Air to Gas Leakage, % of Total Air to Gas Lkg		84.39			
55	MpPAISA	Exp Pri Air to Sec Air Lkg, % of Total Air to Gas Lkg		0.32			
		Pressure Drop					
60	PDiA8SDs	DP Secondary Air, in. wg		2.85			
61	PDiA8PDs	DP Primary Air, in. wg		1.80			
62	PDiG14SDs	DP Flue Gas (Secondary)	Estimated	3.35			
63	PDiG14PDs	DP Flue Gas (Primary)	Estimated	0.00			
64	PDiA8Fg15SDs	DP Secondary Air Ent to Flue Gas Lvg, in. wg	Estimated	19.48			
65	PDiA8Fg15PDs	DP Primary Air Ent to Flue Gas Lvg, in. wg	Estimated	50.61			
66	ExpFg	Exponent for Gas Flow Ratio Correction		1.80			
67	ExpA	Exponent for Air Flow Ratio Correction		1.80			
Name of Plant		ASME PTC 4.3 MASTER FORM		Unit No.	1	Test No.	1
Remarks		PTC 4.3 EXAMPLE CASE		Load	MCR	Date	9/1/2010
		TRI-SECTOR AH		Time 1	9:00	Time 2	11:00
				Calc By	tch	Date	12/1/2011
				Sheet 2 of 3			

Table A-6-1 Corrected Air Heater Performance Calculation Sheet (Cont'd)

		Column		**A**	**B**	**C**	**D**
		Air Heater ID		A / RIGHT	B / LEFT		
		Air Heater Type 0=No AH 1=Sec/Tri 2=Pri/Bi		1	1	0	0
		CALCULATIONS					
		Air Heater Leakage					
	XpA14	Excess Air Ent AH, %		18.21	19.73	0	0
	XpA15	Excess Air Lvg AH, %		24.29	23.00	0	0
	MqFg14	Wet Gas Weight Ent AH, lb/10 kB		9.77	9.88	0	0
	MqFg15	Wet Gas Weight Lvg AH, lb/10 kB		10.22	10.13	0	0
	MpAl	AH Leakage, % Ent Gas Wt		4.67	2.48	0	0
		Air Heater Exit Gas Temp Excl Lkg					
68	Tal	Ave Air Leakage Temp		111.44	113.81		
69	Hal	Enthalpy		8.39	8.96		
70	HFg15NL	Enthalpy Gas Lvg AH Excl Lkg		53.70	53.04		
71	TFg15NL	Gas Temp Lvg AH Excl Lkg		291.34	288.82		
73	MpFg14	Gas Ent AH, % Mass		48.64	51.36		
74	MrPAISA	Pri Air to Sec Air Lkg, klbm/hr		0.45	0.25		
75	QFgAh	Heat Absorbed by Gas, 10^6 Btu/hr		330,035.40	354,940.87		
76	QPA	Heat Absorbed by Pri Air, 10^6 Btu/hr		46,612.69	48,481.11		
77	QSA	Heat Absorbed by Sec Air, 10^6 Btu/hr		283,422.71	306,459.76		
78	MrA9S	Secondary Air Lvg AH, klbm/hr		2,090.80	2,249.52		
79	TMnA8	Ave Air Temp Ent AH		96.70	96.68		
80	TMnA9	Ave Air Temp Lvg AH		635.95	638.98		
82	Xr	Test Heat Capacity Ratio (X-Ratio)		0.7807	0.7906		
83	XrDs	Design Heat Capacity Ratio (X-Ratio)		0.8074	0.8074		
84	MpDiMrFg14	Ent Gas Flow, % Difference from Design		8.21	8.67		
		CORRECTED EXIT GAS TEMPERATURE, °F					
87	TDiA8Cr	Entering Air Temperature		-5.76	-5.55		
88	TDiG14Cr	Entering Gas Temperature		2.46	0.76		
89	TDiMrFg14Cr	Entering Gas Mass Flow		-2.16	-2.28		
90	TDiXrCr	Heat Capacity Ratio		-9.66	-5.99		
91	TFg15NLCr	Corrected Exit Gas Temperature		276.22	275.76		
92	TA9Cr	Corrected Exit Air Temperature, Wtd Ave		638.83	639.37		
93	TMnFg15NLCr	Average Corrected Exit Gas Temperature, °F		275.99			
94	TMnA9Cr	Corrected Exit Air Temperature, Wtd Ave		639.11		0.00	
95	SmMrAl	Total AH Leakage, klbm/hr		217.74			
96	MpAlAv	Total AH Leakage, %		3.54			
		CORRECTED PRESSURE DROP					
98	PDiG14SCr	Flue Gas Sec AH, in. wg		5.28	4.09		
99	PDiG14PCr	Flue Gas Pri AH, in. wg				0.00	0.00
100	PDiA8SCr	Air Sec AH, in. wg		3.92	3.11		
101	PDiA8PCr	Air Pri AH, in. wg				5.03	4.78
102	PDiG14SCrAv	Average Flue Gas, in. wg Sec | Pri		4.68		0.00	
103	PDiA8SCrAv	Average Air, in. wg Sec | Pri		3.51		4.91	
		CORRECTED AH LEAKAGE					
105	MrAlCr	AH Leakage, klbm/hr		139.77	79.47	0.00	0.00
106	MpAlCr	AH Leakage, %		4.68	2.52	0.00	0.00
107	SmMrAlCr	Total AH Leakage, klbm/hr		219.24			
108	MpAlCrAv	Total AH Leakage, %		3.57			

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Date	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Date	12/1/2011
		Sheet 3 of 3			

Table A-7-1 Air Heater Performance Uncertainty Worksheets: A

Worksheet No. 1A

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form)		4 Total Negative Systematic Uncert (Item [3] on SYS Form)		5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, $[2]^2 / [5]^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
					%	Unit	%	Unit					
a	Output	5,615.000	0.000		3.00	0.00	3.00	0.00	0.00	7.670	63.34	1.00	56.15
b	Fuel Temperature	86.38	0.304	INPT	0.00	7.07	0.00	7.07	120.00	0.028	119.00	1.00	0.86
c	Moisture in Air (User Value)	0.016	0.000						0.00	0.000	0.00	1.00	0.00
d	Barometric Pressure, in. Hg	29.92	0.000	4B	0.00	0.11	0.00	0.11	2.00	0.000	1.00	1.00	0.30
e	Dry Bulb Temperature,°F	97.98	1.250	1A	0.14	0.58	0.14	0.58	4.00	0.625	3.00	1.00	0.98
f	Wet Bulb Temperature, °F	74.58	0.403	1A	0.00	0.00	0.00	0.00	4.00	0.202	3.00	1.00	0.75
g	Relative Humidity, %	0.00	0.000	4A	0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
h	Additional Moisture, lbm/100 lbm fuel	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
i	Residue Entering AH, % Total	75.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.75
j	Fuel Rate (Meas), klbm/hr	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
k	Carbon	63.6	0.099	6B	0.32	0.00	0.32	0.00	2.00	0.070	1.00	1.00	0.64
l	Sulfur	0.95	0.007	6C	0.11	0.00	0.11	0.00	2.00	0.005	1.00	1.00	0.01
m	Hydrogen	3.23	0.000	6D	0.12	0.00	0.12	0.00	2.00	0.000	1.00	1.00	0.03
n	Water	13.6	0.566	6E	2.02	0.00	2.25	0.00	2.00	0.400	1.00	1.00	0.14
o	Water Vapor	0.00	0.403		0.00	0.00	0.00	0.00	2.00	0.285	1.00	1.00	0.00
p	Nitrogen	0.83	0.007	6G	0.14	0.00	0.14	0.00	2.00	0.005	1.00	1.00	0.01
q	Oxygen	13.1	0.445	6D	0.12	0.00	0.12	0.00	2.00	0.315	1.00	1.00	0.13
r	Ash	4.71	0.035	6E	2.02	0.00	2.25	0.00	2.00	0.025	1.00	1.00	0.05
s	Volatile Matter, %	40.75	3.041	5C	0.00	0.00	0.00	0.00	2.00	2.150	1.00	1.00	0.41
t	Fixed Carbon, %	41.0	3.606	5D	0.00	0.00	0.00	0.00	2.00	2.550	1.00	1.00	0.41
u	API for Oil Fuels	0.00	0.000	5A	0.00	0.00	0.00	0.00	1.00	0.000	0.00	1.00	0.00
v	Higher Heating Value (HHV), Btu/lbm	10,621.5	18.137	6A	2.00	54.00	2.24	54.00	2.00	12.825	1.00	1.00	106.22
w	Unburned Carbon Loss, %	0.60	0.000	INPT	0.00	0.30	0.00	0.30	0.00	0.000	0.00	1.00	0.01
x													
y	Auxiliary Equipment Power, kW	0.00	0.000	INPT	1.50	0.00	1.50	0.00	0.00	0.000	0.00	1.00	0.00
z	Motor Efficiency, %	0.00	0.000	INPT	0.00	1.00	0.00	1.00	0.00	0.000	0.00	1.00	0.00
aa													
ab													
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2A

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, $([11] \times [6])^4 / [7]$	15 Positive Sys Unc of Result $[11] \times \{([1] \times [3A] / 100)^2 + [3B]^2\}^{1/2}$	16 Negative Sys Unc of Result $[11] \times \{([1] \times [4A] / 100)^2 + [4B]^2\}^{1/2}$
a	Output	275.669	-0.0056	-0.1144	-0.0431	0.0000	-0.95	-0.95
b	Fuel Temperature	275.986	0.0014	0.0004	0.0000	0.0000	0.01	0.01
c	Moisture in Air (User Value)	275.980	-30.1980	-0.0018	0.0000	0.0000	0.00	0.00
d	Barometric Pressure, in. Hg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
e	Dry Bulb Temperature, °F	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
f	Wet Bulb Temperature, °F	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
g	Relative Humidity, %	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
h	Additional Moisture, lbm/100 lbm fuel	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
i	Residue Entering AH, % Total	275.986	0.0008	0.0002	0.0000	0.0000	0.00	0.00
j	Fuel Rate (Meas), klbm/hr	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k	Carbon	275.707	-0.4384	-0.1010	-0.0307	0.0000	-0.09	-0.09
l	Sulfur	275.984	-0.1647	-0.0006	-0.0008	0.0000	0.00	0.00
m	Hydrogen	275.932	-1.6455	-0.0193	0.0000	0.0000	-0.01	-0.01
n	Water	275.980	-0.0405	-0.0020	-0.0162	0.0000	-0.01	-0.01
o	Water Vapor	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	Nitrogen	275.985	-0.0041	0.0000	0.0000	0.0000	0.00	0.00
q	Oxygen	276.006	0.1615	0.0077	0.0509	0.0000	0.00	0.00
r	Ash	275.987	0.0284	0.0005	0.0007	0.0000	0.00	0.00
s	Volatile Matter, %	275.985	0.0001	0.0000	0.0003	0.0000	0.00	0.00
t	Fixed Carbon, %	275.985	0.0001	0.0000	0.0001	0.0000	0.00	0.00
u	API for Oil Fuels	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
v	Higher Heating Value (HHV), Btu/lb	276.334	0.0033	0.1264	0.0421	0.0000	0.72	0.80
w	Unburned Carbon Loss, %	275.985	-0.0100	0.0000	0.0000	0.0000	0.00	0.00
x								
y	Auxiliary Equipment Power, kW	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
z	Motor Efficiency, %	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa								
ab								
ac								

20	Corrected Average Exit Gas Temperature, °F	From Item [133] on AH Calc Form	See UNCERT2F
21	Standard Deviation of Result	$([13a]^2 + [13b]^2 + \ldots)^{1/2}$	0.0074
22	Overall Degrees of Freedom	$[21]^4 / ([14a] + [14b] + \ldots)$	0.0000
23	Student's *t* Value	From Table 5-7.5-1 in Code	
24	Random Component of Uncertainty	[21] × [23]	
25	Positive Systematic Uncertainty of Result	$([15a]^2 + [15b]^2 + \ldots)^{1/2}$	1.4238
26	Negative Systematic Uncertainty of Result	$([16a]^2 + [16b]^2 + \ldots)^{1/2}$	1.5455
27	Positive Total Uncertainty	$([24]^2 + [25]^2)^{1/2}$	
28	Negative Total Uncertainty	$([24]^2 + [26]^2)^{1/2}$	

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

Table A-7-2 Air Heater Performance Uncertainty Worksheets: B

Worksheet No. 1B

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form)		4 Total Negative Systematic Uncert (Item [3] on SYS Form)		5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, $[2]^2 / [5]^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
					%	Unit	%	Unit					
a	Surf Rad & Conv Loss, %									0.000	0.00	1.00	0.00
b	Flat Proj Surf Area, 10^3 sq ft									0.000	0.00	1.00	0.00
c	Ave Vel of Air Near Surf, ft/sec	0.39	0.000	INPT	0.00	0.20	0.00	0.10	0.00	0.000	0.00	1.00	0.00
d	Average Surface Temperature,°F	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
e	Ave Amb Temp Near Surface, °F	0.00	0.000		0.00	0.00	0.00	1.00	0.00	0.000	0.00	1.00	0.00
f													
g	Sorbent Rate, klbm/hr	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
h	Ca/S Molar Ratio (estimated)									0.000	0.00	1.00	0.00
i	Calcination Fraction	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
j	Sulfur Capture, lbm/lbm sulfur	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
k	Sorbent Temperature, °F	0.0	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
l													
m	$CaCO_3$									0.000	0.00	1.00	0.00
n	$Ca(OH)_2$									0.000	0.00	1.00	0.00
o	$MgCO_3$	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
p	$Mg(OH)_2$	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
q	H_2O	0.0	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
r	Inert	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
s													
t	Tempering Air Flow	0.0	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
u	Tempering Air Temperature									0.000	0.00	1.00	0.00
v	Exp Pri Air to Gas Leakage, %	258.3	3.430		5.00	5.00	5.00	5.00	10.00	0.000	0.00	1.00	2.58
w	Exp Pri Air to Sec Air Lkg, %	116.20	2.000		5.00	5.00	5.00	5.00	10.00	0.000	0.00	1.00	1.16
x													
y	Other Losses, % Basis	0.32			0.00	10.00	0.00	0.00		0.000	0.00	1.00	0.00
z	Other Losses, 10^6 Btu/hr Basis									0.000	0.00	1.00	0.00
aa	Other Credits, % Basis	0.15			0.00	0.15	0.00	0.15		0.000	0.00	1.00	0.00
ab	Other Credits, 10^6 Btu/hr Basis	0.00			0.00	0.00	0.00	0.00		0.000	0.00	1.00	0.00
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2B

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, $([11] \times [6])^4 / [7]$	15 Positive Sys Unc of Result $[11] \times \{([1] \times [3A] / 100)^2 + [3B]^2\}^{1/2}$	16 Negative Sys Unc of Result $[11] \times \{([1] \times [4A] / 100)^2 + [4B]^2\}^{1/2}$
a	Surf Rad & Conv Loss, %	275.984	0.0000	0.0000	0.0000	0.0000	0.00	0.00
b	Flat Proj Surf Area, 10^3 sq ft	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
c	Ave Vel of Air Near Surf, ft/sec	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
d	Average Surface Temperature, °F	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
e	Ave Amb Temp Near Surface, °F	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
f								
g	Sorbent Rate, klbm/hr	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
h	Ca/S Molar Ratio (estimated)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
i	Calcination Fraction	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
j	Sulfur Capture, lbm/lbm Sulfur	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k	Sorbent Temperature, °F	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
l								
m	$CaCO_3$	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
n	$Ca(OH)_2$	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
o	$MgCO_3$	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	$Mg(OH)_2$	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
q	H_2O	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
r	Inert	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
s								
t	Tempering Air Flow	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
u	Tempering Air Temperature	275.986	0.0000	0.0000	0.0000	0.0000	0.00	0.00
v	Exp Pri Air to Gas Leakage, %	275.983	-0.0008	-0.0008	0.0000	0.0000	-0.01	-0.01
w	Exp Pri Air to Sec Air Lkg, %	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
x								
y	Other Losses, % Basis	275.985	-0.1655	-0.0002	0.0000	0.0000	-1.65	0.00
z	Other Losses, 10^6 Btu/hr Basis	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa	Other Credits, % Basis	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ab	Other Credits, 10^6 Btu/hr Basis	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ac								

20	Corrected Average Exit Gas Temperature,°F	From Item [133] on AH Calc Form	See UNCERT2F
21	Standard Deviation of Result	$([13a]^2 + [13b]^2 + \dots)^{1/2}$	0.0074
22	Overall Degrees of Freedom	$[21]^4 / ([14a] + [14b] + \dots)$	0.0000
23	Student's *t* Value	From Table 5-7.5-1 in Code	
24	Random Component of Uncertainty	[21] × [23]	
25	Positive Systematic Uncertainty of Result	$([15a]^2 + [15b]^2 + \dots)^{1/2}$	1.4238
26	Negative Systematic Uncertainty of Result	$([16a]^2 + [16b]^2 + \dots)^{1/2}$	1.5455
27	Positive Total Uncertainty	$([24]^2 + [25]^2)^{1/2}$	
28	Negative Total Uncertainty	$([24]^2 + [26]^2)^{1/2}$	

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

Table A-7-3 Air Heater Performance Uncertainty Worksheets: C

Worksheet No. 1C

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form) %	Unit	4 Total Negative Systematic Uncert (Item [3] on SYS Form) %	Unit	5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, $[2]^2/[5]^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
a	**AH A**												
b	**TEMPERATURES**												
c	Air Ent AH (Secondary)	93.5	0.171	1A	0.14	0.75	0.14	0.70	20.95	0.037	19.95	1.00	0.93
d	Air Lvg AH (Secondary)	639.3	0.030	1A	0.14	1.48	0.14	1.81	16.28	0.007	15.28	1.00	6.39
e	Air Ent AH (Primary)	114.8	0.205	1A	0.14	0.59	0.14	0.59	14.80	0.053	13.80	1.00	1.15
f	Air Lvg AH (Primary)	617.1	0.156	1A	0.14	8.25	0.14	8.25	4.30	0.075	3.30	1.00	6.17
g	Gas Ent AH (Secondary)	712.3	0.333	1B	0.14	4.63	0.14	4.59	20.23	0.074	19.23	1.00	7.12
h	Gas Lvg AH (Secondary)	283.6	0.016	1B	0.14	4.57	0.14	4.47	19.40	0.004	18.40	1.00	2.84
i	Gas Ent AH (Primary)	0.0	0.000	1B	0.14	0.00	0.14	0.00	0.00	0.000	0.00	1.00	0.00
j	Gas Lvg AH (Primary)	0.0	0.000	1B	0.14	0.00	0.14	0.00	0.00	0.000	0.00	1.00	0.00
k													
l	**GAS AND AIR WEIGHTS**												
m	Flue Gas Flow Ent AH (Meas)	2,941.6	6.631	4D	5.00	0.05	5.00	0.05	2.00	4.689	1.00	1.00	29.42
n	Air Flow Lvg Sec AH (Meas)	0.0	0.004	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
o	Air Flow Ent Sec AH (Meas — Bi)	0.0	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
p	Air Flow Lvg Pri AH (Meas)	373.8	0.056	4D	5.00	0.05	5.00	0.05	2.00	0.039	1.00	1.00	3.74
q													
r	**MISCELLANEOUS**												
s	O_2 Ent AH, % Vol	3.26	0.016	5A	0.00	0.15	0.00	0.15	20.49	0.004	19.49	1.00	0.03
t	O_2 Lvg AH, % Vol	4.14	0.016	5B	0.00	0.32	0.00	0.32	20.70	0.004	19.70	1.00	0.04
u													
v	**PRESSURE DROP**												
w	DP Secondary Air, in. wg	4.26	0.225	2C	0.00	0.27	0.00	0.27	32.00	0.040	31.00	1.00	0.04
x	DP Primary Air, in. wg	4.17	0.142	2C	0.00	0.27	0.00	0.27	30.00	0.026	29.00	1.00	0.04
y	DP Flue Gas (Secondary), in. wg	5.84	0.081	2C	0.00	0.27	0.00	0.27	32.00	0.014	31.00	1.00	0.06
z	DP Flue Gas (Primary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	32.00	0.071	31.00	1.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	32.00	0.071	31.00	1.00	0.00
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2C

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, $([11] \times [6])^4 / [7]$	15 Positive Sys Unc of Result $[11] \times \{([1] \times [3A] / 100)^2 + [3B]^2\}^{1/2}$	16 Negative Sys Unc of Result $[11] \times \{([1] \times [4A] / 100)^2 + [4B]^2\}^{1/2}$
a	**AH A**							
b	**TEMPERATURES**							
c	Air Ent AH (Secondary)	275.874	-0.1190	-0.0403	-0.0045	0.0000	-0.09	-0.08
d	Air Lvg AH (Secondary)	274.590	-0.2182	-0.5055	-0.0016	0.0000	-0.38	-0.44
e	Air Ent AH (Primary)	276.024	0.0336	0.0140	0.0018	0.0000	0.02	0.02
f	Air Lvg AH (Primary)	275.743	-0.0392	-0.0877	-0.0030	0.0000	-0.33	-0.33
g	Gas Ent AH (Secondary)	277.184	0.1683	0.4345	0.0125	0.0000	0.80	0.79
h	Gas Lvg AH (Secondary)	276.465	0.1691	0.1737	0.0006	0.0000	0.78	0.76
i	Gas Ent AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
j	Gas Lvg AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k								
l	**GAS AND AIR WEIGHTS**							
m	Flue Gas Flow Ent AH (Meas)	275.987	0.0001	0.0006	0.0003	0.0000	0.01	0.01
n	Air Flow Lvg Sec AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
o	Air Flow Ent Sec AH (Meas – Bi)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	Air Flow Lvg Pri AH (Meas)	276.002	0.0046	0.0062	0.0002	0.0000	0.09	0.09
q								
r	**MISCELLANEOUS**							
s	O_2 Ent AH, % Vol	275.911	-2.2709	-0.0269	-0.0081	0.0000	-0.34	-0.34
t	O_2 Lvg AH, % Vol	276.049	1.5292	0.0229	0.0055	0.0000	0.49	0.49
u								
v	**PRESSURE DROP**							
w	DP Secondary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
x	DP Primary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
y	DP Flue Gas (Secondary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
z	DP Flue Gas (Primary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ac								

20	Corrected Average Exit Gas Temperature,°F	From Item [133] on AH Calc Form	See UNCERT2F
21	Standard Deviation of Result	$([13a]^2 + [13b]^2 + \ldots)^{1/2}$	0.0003
22	Overall Degrees of Freedom	$[21]^4 / ([14a] + [14b] + \ldots)$	0.0000
23	Student's t Value	From Table 5-7.5-1 in Code	
24	Random Component of Uncertainty	[21] × [23]	
25	Positive Systematic Uncertainty of Result	$([15a]^2 + [15b]^2 + \ldots)^{1/2}$	1.8569
26	Negative Systematic Uncertainty of Result	$([16a]^2 + [16b]^2 + \ldots)^{1/2}$	1.8706
27	Positive Total Uncertainty	$([24]^2 + [25]^2)^{1/2}$	
28	Negative Total Uncertainty	$([24]^2 + [26]^2)^{1/2}$	

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

Table A-7-4 Air Heater Performance Uncertainty Worksheets: D

Worksheet No. 1D

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form)		4 Total Negative Systematic Uncert (Item [3] on SYS Form)		5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, [2]^2/ [5]$^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
					%	Unit	%	Unit					
a	**AH B**												
b	**TEMPERATURES**												
c	Air Ent AH (Secondary)	93.1	0.163	1A	0.14	0.59	0.14	0.71	20.952	0.036	19.95	1.00	0.93
d	Air Lvg AH (Secondary)	641.6	0.055	1A	0.14	1.34	0.14	1.70	16.283	0.014	15.28	1.00	6.42
e	Air Ent AH (Primary)	117.6	0.200	1A	0.14	0.70	0.14	0.70	14.799	0.052	13.80	1.00	1.18
f	Air Lvg AH (Primary)	623.7	0.142	1A	0.14	8.37	0.14	8.37	4.304	0.068	3.30	1.00	6.24
g	Gas Ent AH (Secondary)	717.6	0.281	1B	0.14	4.33	0.14	4.23	20.226	0.062	19.23	1.00	7.18
h	Gas Lvg AH (Secondary)	284.7	0.014	1B	0.14	4.52	0.14	4.33	19.404	0.003	18.40	1.00	2.85
i	Gas Ent AH (Primary)	0.0	0.000		0.00	0.00	0.00	0.00	0.000	0.000	0.00	1.00	0.00
j	Gas Lvg AH (Primary)	0.0	0.000		0.00	0.00	0.00	0.00	0.000	0.000	0.00	1.00	0.00
k													
l	**GAS AND AIR WEIGHTS**												
m	Flue Gas Flow Ent AH (Meas)	3,106.6	20.144	4D	5.00	0.05	5.00	0.05	2.000	14.244	1.00	1.00	31.07
n	Air Flow Lvg Sec AH (Meas)	0.0	0.000	4D	5.00	0.05	5.00	0.05	0.000	0.000	0.00	1.00	0.00
o	Air Flow Ent Sec AH (Meas– Bi)	0.0	0.000	4D	5.00	0.05	5.00	0.05	0.000	0.000	0.00	1.00	0.00
p	Air Flow Lvg Pri AH (Meas)	385.8	0.053	4D	5.00	0.05	5.00	0.05	2.000	0.038	1.00	1.00	3.86
q													
r	**MISCELLANEOUS**												
s	O_2 Ent AH, % Vol	3.492	0.016	5A	0.00	0.16	0.00	0.16	20.490	0.003	19.49	1.00	0.03
t	O_2 Lvg AH, % Vol	3.960	0.014	5B	0.00	0.16	0.00	0.16	20.696	0.003	19.70	1.00	0.04
u													
v	**PRESSURE DROP**												
w	DP Secondary Air, in. wg	3.87	0.381	2C	0.00	0.27	0.00	0.27	32.000	0.067	31.00	1.00	0.04
x	DP Primary Air, in. wg	4.22	0.157	2C	0.00	0.27	0.00	0.27	30.000	0.029	29.00	1.00	0.04
y	DP Flue Gas (Secondary), in. wg	5.00	0.180	2C	0.00	0.27	0.00	0.27	32.000	0.032	31.00	1.00	0.05
z	DP Flue Gas (Primary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.000	0.000	0.00	1.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	32.000	0.071	31.00	1.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	32.000	0.071	31.00	10.00	0.00
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2D

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, ([11] × [6])^4/ [7]	15 Positive Sys Unc of Result [11] × {([1] × [3A] / 100)^2 + [3B]^2}$^{1/2}$	16 Negative Sys Unc of Result [11] × {([1] × [4A] / 100)^2 + [4B]^2}$^{1/2}$
a	**AH B**							
b	**TEMPERATURES**							
c	Air Ent AH (Secondary)	275.867	-0.1267	-0.0427	-0.0045	0.0000	-0.08	-0.09
d	Air Lvg AH (Secondary)	274.517	-0.2288	-0.5320	-0.0031	0.0000	-0.37	-0.44
e	Air Ent AH (Primary)	276.028	0.0364	0.0155	0.0019	0.0000	0.03	0.03
f	Air Lvg AH (Primary)	275.739	-0.0394	-0.0891	-0.0027	0.0000	-0.33	-0.33
g	Gas Ent AH (Secondary)	277.231	0.1737	0.4515	0.0108	0.0000	0.77	0.76
h	Gas Lvg AH (Secondary)	276.496	0.1794	0.1851	0.0006	0.0000	0.81	0.78
i	Gas Ent AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
j	Gas Lvg AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k								
l	**GAS AND AIR WEIGHTS**							
m	Flue Gas Flow Ent AH (Meas)	275.983	-0.0001	-0.0006	-0.0008	0.0000	-0.01	-0.01
n	Air Flow Lvg Sec AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
o	Air Flow Ent Sec AH (Meas – Bi)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	Air Flow Lvg Pri AH (Meas)	276.002	0.0044	0.0061	0.0002	0.0000	0.08	0.08
q								
r	**MISCELLANEOUS**							
s	O_2 Ent AH, % Vol	275.901	-2.4167	-0.0306	-0.0084	0.0000	-0.39	-0.39
t	O_2 Lvg AH, % Vol	276.048	1.5898	0.0228	0.0050	0.0000	0.25	0.25
u								
v	**PRESSURE DROP**							
w	DP Secondary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
x	DP Primary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
y	DP Flue Gas (Secondary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
z	DP Flue Gas (Primary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ac								

20	Corrected Average Exit Gas Temperature,°F	From Item [133] on AH Calc Form	See UNCERT2F
21	Standard Deviation of Result	([13a]^2+ [13b]^2+ ...)$^{1/2}$	0.0003
22	Overall Degrees of Freedom	[21]^4 / ([14a] + [14b] + ...)	0.0000
23	Student's *t* Value	From Table 5-7.5-1 in Code	
24	Random Component of Uncertainty	[21] × [23]	
25	Positive Systematic Uncertainty of Result	([15a]^2+ [15b]^2+ ...)$^{1/2}$	1.7332
26	Negative Systematic Uncertainty of Result	([16a]^2+ [16b]^2+ ...)$^{1/2}$	1.7139
27	Positive Total Uncertainty	([24]^2+ [25]^2)$^{1/2}$	
28	Negative Total Uncertainty	([24]^2+ [26]^2)$^{1/2}$	

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

Table A-7-5 Air Heater Performance Uncertainty Worksheets: E

Worksheet No. 1E

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form)		4 Total Negative Systematic Uncert (Item [3] on SYS Form)		5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, $[2]^2 / [5]^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
					%	Unit	%	Unit					
a	**AH C**												
b	**TEMPERATURES**												
c	Air Ent AH (Secondary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
d	Air Lvg AH (Secondary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
e	Air Ent AH (Primary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
f	Air Lvg AH (Primary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
g	Gas Ent AH (Secondary)	0.00	0.000	1B	0.14	1.16	0.14	1.16	0.00	0.000	0.00	1.00	0.00
h	Gas Lvg AH (Secondary)	0.00	0.000	1B	0.14	1.16	0.14	1.16	0.00	0.000	0.00	1.00	0.00
i	Gas Ent AH (Primary)	0.00	0.000		0.14	0.00	0.14	0.00	0.00	0.000	0.00	1.00	0.00
j	Gas Lvg AH (Primary)	0.00	0.000		0.14	0.00	0.14	0.00	0.00	0.000	0.00	1.00	0.00
k													
l	**GAS AND AIR WEIGHTS**												
m	Flue Gas Flow Ent AH (Meas)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
n	Air Flow Lvg Sec AH (Meas)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
o	Air Flow Ent Sec AH (Meas — Bi)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
p	Air Flow Lvg Pri AH (Meas)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
q													
r	**MISCELLANEOUS**												
s	O_2 Ent AH, % Vol	0.00	0.000	5A	0.00	0.15	0.00	0.15	0.00	0.000	0.00	1.00	0.00
t	O_2 Lvg AH, % Vol	0.00	0.000	5B	0.00	0.15	0.00	0.15	0.00	0.000	0.00	1.00	0.00
u													
v	**PRESSURE DROP**												
w	DP Secondary Air, in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
x	DP Primary Air, in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
y	DP Flue Gas (Secondary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
z	DP Flue Gas (Primary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2E

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, $([11] \times [6])^4 / [7]$	15 Positive Sys Unc of Result $[11] \times \{([1] \times [3A] / 100)^2 + [3B]^2\}^{1/2}$	16 Negative Sys Unc of Result $[11] \times \{([1] \times [4A] / 100)^2 + [4B]^2\}^{1/2}$
a	**AH C**							
b	**TEMPERATURES**							
c	Air Ent AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
d	Air Lvg AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
e	Air Ent AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
f	Air Lvg AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
g	Gas Ent AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
h	Gas Lvg AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
i	Gas Ent AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
j	Gas Lvg AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k								
l	**GAS AND AIR WEIGHTS**							
m	Flue Gas Flow Ent AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
n	Air Flow Lvg Sec AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
o	Air Flow Ent Sec AH (Meas – Bi)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	Air Flow Lvg Pri AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
q								
r	**MISCELLANEOUS**							
s	O_2 Ent AH, % Vol	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
t	O_2 Lvg AH, % Vol	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
u								
v	**PRESSURE DROP**							
w	DP Secondary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
x	DP Primary Air, in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
y	DP Flue Gas (Secondary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
z	DP Flue Gas (Primary), in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ac								

20	Corrected Average Exit Gas Temperature, °F	From Item [133] on AH Calc Form	See UNCERT2F
21	Standard Deviation of Result	$([13a]^2 + [13b]^2 + \ldots)^{1/2}$	0.0000
22	Overall Degrees of Freedom	$[21]^4 / ([14a] + [14b] + \ldots)$	0.0000
23	Student's *t* Value	From Table 5-7.5-1 in Code	
24	Random Component of Uncertainty	[21] × [23]	
25	Positive Systematic Uncertainty of Result	$([15a]^2 + [15b]^2 + \ldots)^{1/2}$	0.0000
26	Negative Systematic Uncertainty of Result	$([16a]^2 + [16b]^2 + \ldots)^{1/2}$	0.0000
27	Positive Total Uncertainty	$([24]^2 + [25]^2)^{1/2}$	
28	Negative Total Uncertainty	$([24]^2 + [26]^2)^{1/2}$	

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

Table A-7-6 Air Heater Performance Uncertainty Worksheets: F

Worksheet No. 1F

	Measured Parameter (from DATA)	1 Average Value (Item [2] on MEAS Form)	2 Standard Deviation (Item [3] on MEAS Form)	Sys Uncert Sheet No.	3 Total Positive Systematic Uncert (Item [2] on SYS Form)		4 Total Negative Systematic Uncert (Item [3] on SYS Form)		5 No. of Readings (MEAS Form)	6 Standard Dev of Mean, $[2]^2 / [5]^{1/2}$	7 Degrees of Freedom, [5] – 1	8 Percent Change	9 Incremental Change,* [8] × [1] / 100
					%	Unit	%	Unit					
a	**AH D**												
b	**TEMPERATURES**												
c	Air Ent AH (Secondary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
d	Air Lvg AH (Secondary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
e	Air Ent AH (Primary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
f	Air Lvg AH (Primary)	0.00	0.000	1A	0.14	0.58	0.14	0.58	0.00	0.000	0.00	1.00	0.00
g	Gas Ent AH (Secondary)	0.00	0.000	1B	0.14	0.58	0.14	1.16	0.00	0.000	0.00	1.00	0.00
h	Gas Lvg AH (Secondary)	0.0	0.000	1B	0.14	0.58	0.14	1.16	0.00	0.000	0.00	1.00	0.00
i	Gas Ent AH (Primary)	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
j	Gas Lvg AH (Primary)	0.00	0.000		0.00	0.00	0.00	0.00	0.00	0.000	0.00	1.00	0.00
k													
l	**GAS AND AIR WEIGHTS**												
m	Flue Gas Flow Ent AH (Meas)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
n	Air Flow Lvg Sec AH (Meas)	0.0	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
o	Air Flow Ent Sec AH (Meas — Bi)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
p	Air Flow Lvg Pri AH (Meas)	0.00	0.000	4D	5.00	0.05	5.00	0.05	0.00	0.000	0.00	1.00	0.00
q													
r	**MISCELLANEOUS**												
s	O$_2$ Ent AH, % Vol	0.00	0.000	5A	0.00	0.15	0.00	0.15	0.00	0.000	0.00	1.00	0.00
t	O$_2$ Lvg AH, % Vol	0.00	0.000	5B	0.00	0.15	0.00	0.15	0.00	0.000	0.00	1.00	0.00
u													
v	**PRESSURE DROP**												
w	DP Secondary Air, in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
x	DP Primary Air, in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
y	DP Flue Gas (Secondary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
z	DP Flue Gas (Primary), in. wg	0.00	0.000	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0.00	0.400	2C	0.00	0.27	0.00	0.27	0.00	0.000	0.00	1.00	0.00
ac													

This worksheet is set up for constant-value parameters. See Section 5 of the Code for calculation of average value, degrees of freedom, and systematic uncertainty for integrated average value parameters.

*The value used for incremental change can be any increment of the average value. The recommended increment is 1.0% (0.01 times the average value). If the average value of the measured parameter is zero, use any small incremental change. It is important to note that the incremental change must be in the same units as the average value.

Worksheet No. 2F

	Measured Parameter	10 Recalc Corr Exit Gas Temp (See Item [20])	11 Absolute Sensitivity Coefficient, ([10] – [20]) / [9]	12 Relative Sensitivity Coefficient, [11] × [1] / [20]	13 Random Unc of Result Calculation, [11] × [6]	14 Overall Deg of Freedom Contribution, $([11] \times [6])^4 / [7]$	15 Positive Sys Unc of Result $[11] \times \{([1] \times [3A] / 100)^2 + [3B]^2\}^{1/2}$	16 Negative Sys Unc of Result $[11] \times \{([1] \times [4A] / 100)^2 + [4B]^2\}^{1/2}$
a	**AH D**							
b	**TEMPERATURES**							
c	Air Ent AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
d	Air Lvg AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
e	Air Ent AH (Primary)	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
f	Air Lvg AH (Primary)	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
g	Gas Ent AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
h	Gas Lvg AH (Secondary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
i	Gas Ent AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
j	Gas Lvg AH (Primary)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
k								
l	**GAS AND AIR WEIGHTS**							
m	Flue Gas Flow Ent AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
n	Air Flow Lvg Sec AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
o	Air Flow Ent Sec AH (Meas – Bi)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
p	Air Flow Lvg Pri AH (Meas)	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
q								
r	**MISCELLANEOUS**							
s	O$_2$ Ent AH, % Vol	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
t	O$_2$ Lvg AH, % Vol	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
u								
v	**PRESSURE DROP**							
w	DP Secondary Air, in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
x	DP Primary Air, in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
y	DP Flue Gas (Secondary), in. wg	275.985	0.0000	0.0000	0.0000	0.0000	0.00	0.00
z	DP Flue Gas (Primary), in. wg	0.000	0.0000	0.0000	0.0000	0.0000	0.00	0.00
aa	DP Sec Air Ent to Flue Gas Lvg, in. wg	0	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ab	DP Pri Air Ent to Flue Gas Lvg, in. wg	0	0.0000	0.0000	0.0000	0.0000	0.00	0.00
ac								

20	Corrected Average Exit Gas Temperature,°F	From Item [133] on AH Calc Form	275.985
21	Standard Deviation of Result	$([13a]^2 + [13b]^2 + \ldots)^{1/2}$	0.09
22	Overall Degrees of Freedom	$[21]^4 / ([14a] + [14b] + \ldots)$	5.9
23	Student's *t* Value	From Table 5-7.5-1 in Code	2.46
24	Random Component of Uncertainty	[21] × [23]	0.22
25	Positive Systematic Uncertainty of Result	$([15a]^2 + [15b]^2 + \ldots)^{1/2}$	2.22
26	Negative Systematic Uncertainty of Result	$([16a]^2 + [16b]^2 + \ldots)^{1/2}$	2.25
27	Positive Total Uncertainty	$([24]^2 + [25]^2)^{1/2}$	2.23
28	Negative Total Uncertainty	$([24]^2 + [26]^2)^{1/2}$	2.26

Name of Plant	ASME PTC 4.3 MASTER FORM	Unit No.	1	Test No.	1
Remarks	PTC 4.3 EXAMPLE CASE	Load	MCR	Load	9/1/2010
	TRI-SECTOR AH	Time 1	9:00	Time 2	11:00
		Calc By	tch	Calc By	12/1/2011

NONMANDATORY APPENDIX B
DERIVATION OF EQUATION FOR COEFFICIENT OF CORRELATION

B-1 AVERAGE VALUES OF TEMPERATURES AND GAS CONCENTRATIONS IN DUCTS, AND THE NEED FOR FLOW WEIGHTING

In boiler ducts where the transverse distribution of mass flow, temperature, and gas concentration is complex, the respective average values are used to define the stream conditions. Ideally, the average should represent conditions that would exist if the duct stream became completely mixed. The average values are obtained by carrying out coincident velocity, temperature, and gas concentration traverses (usually at the centers of equal areas) and producing a "weighted average" that is defined for an instantaneous traverse as

$$Z = \frac{\sum_i^n x_i w_i}{\sum_i^n w_i} \qquad \text{(B-1.1)}$$

where

n = number of area

w_i = coincident area mass flow

x_i = traverse area quantity (temperature or gas concentration)

Z = weighted average value of x for the traverse

This is often replaced by a "velocity-weighted average" and this step is recommended by ASME PTC 4 in para. 4-3.4.

$$Z = \frac{\sum_i^n x_i v_i}{\sum_i^n v_i} \qquad \text{(B-1.2)}$$

where

v_i = area velocity

The arithmetic spatial average, $\bar{x}$, of quantity x is defined as

$$\bar{x} = \frac{\sum_i^n x_i}{n} \qquad \text{(B-1.3)}$$

and the arithmetic spatial average velocity as

$$\bar{v} = \frac{\sum_i^n v_i}{n} \qquad \text{(B-1.4)}$$

In order to calculate the difference between Z and $\bar{x}$, we need to develop an equation that is based on cross-products of the variations of i-th values of the velocity and quantity x about their respective arithmetic averages.

Substituting

$$x_i = (x_i - \bar{x}) + \bar{x} \qquad \text{(B-1.5)}$$

$$v_i = (v_i - \bar{v}) + \bar{v} \qquad \text{(B-1.6)}$$

into eq. (B-1.2) and rearranging gives

$$Z = \frac{1}{\sum_i^n v_i}\left[\sum_i^n (v_i - \bar{v})(x_i - \bar{x}) + n\bar{v}\bar{x} + \bar{x}\sum_i^n (v_i - \bar{v}) + \bar{v}\sum_i^n (x_i - \bar{x})\right] \qquad \text{(B-1.7)}$$

By definition,

$$\sum_i^n (v_i - \bar{v}) = \sum_i^n (x_i - \bar{x}) = 0$$

Taking this into account, substituting $\sum_i^n v_i = n\bar{v}$ from eq. (B-1.4) into eq. (B-1.7), and rearranging, we get

$$Z = \bar{x}\left[1 + \frac{\sum_i^n (v_i - \bar{v})(x_i - \bar{x})}{n\,\bar{v}\,\bar{x}}\right] \qquad \text{(B-1.8)}$$

The velocity-weighted spatial average Z is therefore equivalent to the arithmetic average plus a term that is a function of the variation of both quantity x and velocity across the duct.

Using the spatial root average variation of v and x as estimators of the population spatial deviation, we define

$$s_x = \sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n - 1}} \qquad \text{(B-1.9)}$$

$$s_v = \sqrt{\frac{\sum_i^n (v_i - \bar{v})^2}{n - 1}} \qquad \text{(B-1.10)}$$

$$V_x = \frac{s_x}{\bar{x}} \qquad \text{(B-1.11)}$$

$$V_v = \frac{s_v}{\bar{v}} \qquad \text{(B-1.12)}$$

where

V_x, V_v = ratios between standard deviation and average of the respective coefficients of spatial variation

Substituting into eq. (B-1.8) from eqs. (B-1.9) through (B-1.12) and rearranging, we get

$$Z = \bar{x}\left(1 + \frac{n-1}{n} RV_xV_v\right) \qquad \text{(B-1.13)}$$

where

R = coefficient of correlation between velocity and quantity x in space across the duct

$$= \frac{\sum_i^n (v_i - \bar{v})(x_i - \bar{x})}{\sqrt{\left[\sum_i^n (v_i - \bar{v})^2\right]\left[\sum_i^n (x_i - \bar{x})^2\right]}} \qquad \text{(B-1.14)}$$

R can take values between ±1, e.g., +1 when 100% correlation exists across the duct and high values of both velocity and x coincide, and −1 when high values and low values are coincident. R will be zero when there is no dependence between v and x across the traverse plane.

If R is zero, then eq. (B-1.13) shows that the velocity-weighted average will equal the arithmetic average.

The following table is an example of the calculations based on actual traverse results:

Oxygen, % [Note (1)]			Temperature, °F [Note (2)]			(Velocity Head)$^{1/2}$ [Note (3)]		
6.26	4.55	3.92	636	683	712	0.87	0.71	0.81
5.91	4.68	3.75	640	683	717	0.92	0.74	0.74
5.31	4.30	3.71	649	679	721	0.95	0.77	0.77
4.59	3.95	4.00	655	671	721	1.05	0.87	0.63
3.79	3.40	3.94	655	659	715	1.10	0.97	0.55
3.45	3.62	4.35	648	645	710	0.87	0.77	0.50

NOTES:

(1) Average value is 4.304, coefficient variation is 0.188, and R correlation is 0.139.

(2) Average value is 677.7, coefficient variation is 0.046, and R correlation is −0.709.

(3) Average value is 0.81 and coefficient variation is 0.196.

Velocity-weighted oxygen from eq. (B-1.2) = 4.325%.

Velocity-weighted oxygen from eq. (B-1.13) = 4.325%.

Velocity-weighted temperature from eq. (B-1.2) = 673.67°F.

Velocity-weighted temperature from eq. (B-1.13) = 673.67°F.

These results show that eq. (B-1.13) will give precisely the same result as eq. (B-1.2).

If there is no correlation between velocity and x, then R is zero and eq. (B-1.13) shows that the velocity-weighted and the arithmetic average will be the same irrespective of the spatial distributions of velocity and quantity x, i.e., temperature or oxygen concentration.

If there is a high degree of correlation between velocity and x, then R approaches unity and the difference between the velocity-weighted and the arithmetic average will be at a maximum. The actual difference will then depend on the separate spatial distributions of velocity and temperature or oxygen at the measuring plane.

In the limiting case, if one of the quantities does not vary in space (i.e., its spatial standard deviation is zero), the velocity-weighted mean and arithmetic mean will be the same.

In most station ductwork, particularly downstream of bends or changes in section, there is unlikely to be significant correlation between gas concentration or temperature and velocity, because the velocity will be a function of the immediate upstream aerodynamics while temperature and gas composition will be a function of some of the mixing processes that have taken place further upstream.

Analysis of some 56 coincident traverse results gave the following:

Measure	Result
Average velocity coefficient of variation	0.203
Average oxygen coefficient of variation	0.250
Average temperature coefficient of variation	0.051
Average velocity/oxygen absolute correlation coefficients	0.290
Average velocity/temperature absolute correlation coefficients	0.407

Based on these average values, eq. (B-1.13) for a 30-point traverse (n = 30) predicts the following:

(a) For oxygen traverses, the difference between velocity-weighted and arithmetic-average oxygen will be (29/30 × 0.29 × 0.203 × 0.25 × 100)% = ±1.42% of the oxygen level (i.e., at 3% oxygen concentration, the difference will be ±0.04% oxygen). If there was 100% correlation (i.e., R = 1) between oxygen and velocity for the average spatial variations, the difference between arithmetic and weighted average would be ±4.8% of the oxygen value, or ±0.1% oxygen if the oxygen were 3%.

(b) For temperature traverses, the difference between velocity-weighted and arithmetic-average temperature will be (29/30 × 0.407 × 0.203 × 0.051 × 100)% = ±0.41% of the temperature level (i.e., at 680°F, the difference will be ±2.8°F). If there was 100% correlation (i.e., R = 1) between temperature and velocity for the average spatial variations, the difference between arithmetic and weighted average would be ±1% of the temperature value, or ±6.8°F if the temperature were 680°F.

Preliminary traverses of coincident velocity and/or temperature are mandatory in this Code. The decision whether or not velocity weighting is necessary should