ASME PTC 47.1-2017

Cryogenic Air Separation Unit of an Integrated Gasification Combined Cycle Power Plant

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

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The American Society of Mechanical Engineers
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NOTICE

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

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

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

FOREWORD

ASME Performance Test Codes (PTCs) have been developed and have long existed for determining the performance of most major components used in electric power production facilities. A Performance Test Code has heretofore not existed to determine the overall performance of an integrated gasification combined cycle (IGCC) power generation plant. The ability to fire a wide range of fuels has been a key advantage of gas turbines over competing technologies. Until recently, the traditional fuels for gas turbines have been natural gas and liquid fuels. Today, future environmental concerns and future economic scenarios are causing power generation suppliers to develop gasification systems that can use solid and liquid fuels (e.g., coal, biomass, waste, heavy oils). Preparation of an alternative fuel suitable for a gas turbine includes removal of ash, contaminants, and erodents/corrodents. In response to these needs, the ASME Board on Performance Test Codes approved the formation of a committee (PTC 47) in 1993 with the charter of developing a Code for the determination of overall performance for IGCC power generation plants. The organizational meeting of the PTC 47 Committee was held in November 1993. The resulting committee included experienced and qualified users, manufacturers, and general interest category personnel.

The Committee has strived to develop an objective code that addresses the multiple needs for explicit testing methods and procedures, while attempting to provide maximum flexibility in recognition of the wide range of plant designs and the multiple needs for this Code.

This Code was approved by the PTC 47 Committee and the Performance Test Codes Standards Committee. It was approved as an American National Standard by the American National Standards Institute (ANSI) Board of Standards Review on December 14, 2017.

ASME PTC COMMITTEE
Performance Test Codes

(The following is the 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.

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

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

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 http://go.asme.org/PTCcommittee.

INTRODUCTION

ASME PTC 47 comprises five Performance Test Codes (PTCs) that describe testing procedures for an integrated gasification combined cycle (IGCC) power plant. ASME PTC 47, Integrated Gasification Combined Cycle Power Generation Plants, is used for testing the overall performance of an IGCC plant. If a plant passes the ASME PTC 47 test, no further testing is required. If a plant does not pass the ASME PTC 47 test, one or more secondary subsystems may be tested to isolate the problem(s), using the following PTCs:

(a) ASME PTC 47.1, Cryogenic Air Separation Unit of an Integrated Gasification Combined Cycle Power Plant, for testing the performance of the air separation unit (ASU)

NOTE: If the physical IGCC plant includes an ASU, the inclusion of the ASU within the overall test envelope is recommended, but not required.

(b) ASME PTC 47.2, Gasification Block of an Integrated Gasification Combined Cycle Power Plant, for testing the thermal performance of the gasification equipment

(c) ASME PTC 47.3, Syngas Conditioning Block of an Integrated Gasification Combined Cycle Power Plant, for testing the thermal performance of the syngas cleaning equipment

(d) ASME PTC 47.4, Power Block of an Integrated Gasification Combined Cycle Power Plant, for testing the thermal performance of the gas turbine combined cycle power block

It is recommended that the overall plant and various subsystems be tested separately rather than simultaneously to accommodate any boundary constraints and valve isolations and lineups that may be needed for subsystem testing. In highly integrated IGCC plants, the entire plant may need to be operating during a subsystem test, even if the only performance parameters being measured are those of the subsystem.

Test results can be used to determine the fulfillment of contract guarantees. Test results can also be used by a plant owner to compare plant performance to a design number, or to track plant performance changes over time. However, the results of a test conducted in accordance with this Code shall not provide a basis for comparing the thermoeconomic effectiveness of different plant designs.

APPLICATIONS AND LIMITATIONS. Air separation units that separate air into oxygen, nitrogen, and/or argon streams are included within the scope of this Code. Although primarily intended for application to cryogenic ASUs, the Code may also be used for noncryogenic processes such as adsorption-based systems. The Code applies to the following types of ASUs:

(a) Nonintegrated ASUs in which the primary product is oxygen for use in an oxygen-blown gasification system or nitrogen for use as a diluent in the power block's gas turbine. Air and nitrogen may also be produced for use within the general facility.

(b) Air-integrated ASUs that obtain all or a part of the required ASU compressed air supply from the power block's gas turbine or other source and in which the primary product is oxygen for use in an oxygen-blown gasification system or nitrogen for use as a diluent in the power block's gas turbine. Air and nitrogen may also be produced for use within the general facility.

(c) Nonintegrated ASUs in which the primary product is nitrogen for use in an air-blown gasification system. Air and nitrogen may also be produced for use within the general facility.

(d) Air-integrated ASUs that obtain all or a part of the required ASU compressed air supply from the power block's gas turbine or other source and in which the primary product is nitrogen for use in an air-blown gasification system. Air and nitrogen may also be produced for use within the general facility.

There are many types of cryogenic ASUs employing different combinations of product compression, product liquid pumping, and "cold box" processes. This Code provides procedures for the determination of ASU performance when electrically driven compressors and/or pumps are employed in any process configuration. While not specifically excluded, no explicit procedures are provided for determining the performance of equipment within the ASU test boundary driven by gas turbines, steam turbines, non-ASU process stream expanders, or other non-motor drivers. Other PTCs may be of use in determining the performance of non-motor-drive equipment in conjunction with the procedures described in this Code for analyzing ASU compression power performance.

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Section 1
Object and Scope

1-1 OBJECT

The object of this Code is to provide uniform test methods and procedures for conducting performance tests of air separation units (ASUs) supplying products to a gasification block and/or power block within an integrated gasification combined cycle (IGCC) facility. This Code provides test procedures that can yield results giving the highest level of accuracy consistent with engineering knowledge and practice.

1-1.1 Accuracy

The accuracy of a particular test may be affected by factors within the discretion of the operator. A test is considered an ASME Code test if the following conditions are met:

(a) Test procedures comply with the procedures and variations defined in this Code.

(b) The uncertainty of the test results does not exceed the uncertainty limit given in Table 1-3-1 and determined in Section 7 of this Code.

1-1.2 Performance Characteristics

This Code is used to determine the production rate and effectiveness of an ASU. The ASU effectiveness is defined as the power consumed per mass flow of pressurized product.

This Code provides procedures for the determination of the following performance characteristics:

(a) corrected net ASU power input

(b) corrected ASU production rate (mass flow of pressurized oxygen)

(c) corrected ASU effectiveness

These performance characteristics are typically required for comparing actual performance to guaranteed performance or to a reference, and for determining the performance of the equipment after modifications.

1-2 SCOPE

This Code applies to ASUs of any size, in either a single-train or multitrain configuration. It can be used to measure the performance of an ASU in its normal operating condition, with all equipment in a new, clean, and fully functional condition.

This Code provides methods and procedures explicitly for ASUs employing electric-motor-drive compression equipment, with or without the use of steam and/or electric power for internal regenerative processes. There is no intent to restrict the use of this Code for non-motor-driven compression equipment, nor for ASUs that use other heat inputs for internal regenerative processes, provided the explicit test procedures can be met.

(a) Test Conditions. To test a particular ASU, the following conditions shall be met:

(1) A means shall be available to determine, through either direct or indirect measurements, all of the electric power inputs entering the test boundary, as well as any electric power outputs leaving the test boundary.

(2) A means shall be available to determine, through either direct or indirect measurements, the purity and conditions of all of the pressurized flows entering or leaving the test boundary.

(3) A means shall be available to determine, through either direct or indirect measurements, all of the parameters to correct the results from the test to a base reference condition.

(4) The test uncertainties shall be less than or equal to the uncertainty limits specified in Table 1-3-1.

(b) Tests Outside the Scope of ASME PTC 47.1. Tests addressing performance-related issues other than those specified in (a) are outside the scope of this Code. These include, but are not limited to, the following:

(1) emissions tests

(2) operational demonstration tests pertaining to non-steady-state or off-design conditions

(3) liquid production tests conducted to determine the capability of producing liquefied products from the ASU at rates other than the specified design flows

(4) reliability tests conducted over extended periods of time beyond the required testing period

Table 1-3-1 Largest Expected Test Uncertainty

Measurement Result	Expected Uncertainty Limit, %
Power input	3
Production rate	3
Effectiveness	3
Specific power	3

GENERAL NOTE: The uncertainty limit will be affected by the number and choice of product streams.

1-3 TEST UNCERTAINTY

Many types of ASUs are available for use in IGCC facilities. The uncertainty levels achievable from testing in accordance with this Code depend on the type of ASU and its degree of integration with other blocks within the IGCC facility. Uncertainty limits have been established and are listed in Table 1-3-1.

The largest expected overall test uncertainties are given in Table 1-3-1. These values are not targets. A primary philosophy underlying this Code is that the lowest achievable uncertainty is in the best interest of all parties to the test. Deviations from the methods recommended in this Code are acceptable only if it can be demonstrated that they provide equal or lower uncertainty.

1-4 REFERENCES

The following is a list of publications referenced in this Code:

ANSI/IEEE Standard 120, Master Test Guide for Electrical Measurements in Power Circuits
Publisher: Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Lane, Piscataway, NJ 08854 (www.ieee.org)

ASME MFC-3M, Measurement of Fluid Flow in Pipes Using Orifice, Flow Nozzle, and Venturi
ASME PTC 1, General Instructions
ASME PTC 2, Definitions and Values
ASME PTC 19.1, Test Uncertainty
ASME PTC 19.2, Pressure Measurement
ASME PTC 19.3, Temperature Measurement
ASME PTC 19.5, Flow Measurement
ASME PTC 19.22, Digital Data Acquisition Systems
ASME PTC 47, Integrated Gasification Combined Cycle Power Generation Plants
Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

ASTM E1137/E1137M-08 (R2014), Standard Specification for Industrial Platinum Resistance Thermometers
ASTM Manual Series: MNL 12, Manual on the Use of Thermocouples in Temperature Measurement
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)

Dieck, R., *Measurement Uncertainty, Methods and Applications*, fourth edition, 2007
Publisher: International Society of Automation (ISA), 67 T. W. Alexander Drive, P.O. Box 12277, Research Triangle Park, NC 27709 (www.isa.org)

ITS-90, NIST Technical Note 1265, Guidelines for Realizing the International Temperature Scale of 1990
Publisher: National Institute of Standards and Technology (NIST), 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899 (www.nist.gov)

Section 2
Definitions and Description of Terms

2-1 INTRODUCTION

This Section contains technical definitions of terms used in this Code, and of symbols and subscripts used in the equations.

Note that ASME PTC 2 contains definitions of terms and values of physical constants and conversion factors common to equipment testing and analysis.

2-2 AIR SEPARATION UNIT EQUIPMENT DEFINITIONS

In addition to the definitions in ASME PTC 47, subsection 2-1, the following definitions specific to ASUs apply:

additive: a substance added to a process to cause a chemical or mechanical reaction.

air compressor: see *booster air compressor* or *main air compressor (MAC).*

air-integrated air separation unit: an air separation process unit that receives all or a part of the ASU air-feed requirement from a source external to the ASU block. An example is extraction of a portion of the compressed air from a gas turbine for supply to the ASU.

air pretreatment: the removal of water, carbon dioxide, and some hydrocarbon contaminants from the compressed air stream prior to processing in the cryogenic sections of the ASU. Pretreatment is usually based on a cyclical adsorption/desorption-based (molecular sieve–based), near-ambient-temperature process using heated dry nitrogen produced by the ASU for regeneration of the adsorbent.

air separation unit (ASU): a process unit that separates air-feed source(s) into primary gaseous product streams enriched in oxygen and/or nitrogen. Secondary product streams enriched in argon or liquid streams may also be produced.

ASU effectiveness: the net power consumed within the ASU test boundary divided by the total flow of pressurized product streams exiting the ASU test boundary.

auxiliary load: an electrical load within the ASU that is not consumed in the compression of air or product streams. Examples include cooling tower, pumps, mechanical chilling equipment, and power-producing expansion equipment.

booster air compressor: a compressor that takes a pressurized air stream as feed and compresses it to the operating pressure of the ASU. The compressor may supply all or a part of the air requirement of the ASU.

cold box: an enclosure containing cryogenic equipment that is part of the ASU.

main air compressor (MAC): a compressor or series of compressors that takes ambient air as feed and compresses it to the operating pressure of the ASU. The compressor(s) may supply all or a part of the air requirement of the ASU.

nonintegrated air separation unit: an ASU that uses an air separation process that is not air-integrated with the gas turbine or other sources of air, i.e., it has its own supply of feed air.

pressurized product: a product stream exiting the ASU test boundary for use in the IGCC facility that is above atmospheric pressure. Included are all streams that have been compressed or pumped inside the ASU test boundary as well as product streams withdrawn from the ASU at pressures above atmospheric without additional compression. The total flow of pressurized product streams represents the ASU production rate. The pressurized product may be gaseous oxygen (GOX), liquid oxygen (LOX), pumped liquid oxygen (PLOX), gaseous nitrogen, or liquid nitrogen (LIN).

product compressor(s): compressors that take oxygen or nitrogen products from the ASU and compress them to the pressures required by IGCC units.

product oxygen pump(s): pumps that take liquid oxygen from the ASU and pressurize it to the pressure required by IGCC units.

2-3 GENERAL DEFINITIONS

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.

base reference conditions: the values of all the external parameters, i.e., parameters outside the test boundary to which the test results are corrected.

bias error: see *systematic error, β*.

calibration: the process of comparing the response of an instrument to that of a standard instrument over some measurement range and adjusting the instrument to match the standard, if appropriate.

influence coefficient: the ratio of the change in a result to a unit change in a parameter.

instrument: a tool or device used to measure physical dimensions of length, thickness, width, weight, or any other value of a variable. These variables may include size, weight, pressure, temperature, fluid flow, voltage, electric current, density, viscosity, and power. Sensors are included that may not, by themselves, incorporate a display but instead transmit signals to remote devices for display, processing, or process control. Also included are items of ancillary equipment (e.g., an ammeter shunt) directly affecting the display of the primary instrument, and tools or fixtures used as the basis for determining part acceptability.

losses: energy other than the defined exit streams that exits the test boundary.

measurement error, δ: the true, unknown difference between the measured value and the true value.

parties to a test: those persons and companies interested in the results of a test.

precision: see *random error, ε*.

primary variables: those variables used in calculations of test results. Primary variables are further classified as follows:

Class 1 primary variables: those variables that have a relative influence coefficient of 0.2 or greater.

Class 2 primary variables: those variables that have a relative influence coefficient of less than 0.2.

Refer to ASME PTC 19.1 for the determination of relative sensitivity coefficients.

random error, ε: sometimes called precision; error due to limitations or repeatability of measurements that characterizes a member of a set of measurements. Random error varies in a random Gaussian-normal manner, from measurement to measurement.

random uncertainty, 2S: an estimate of the plus/minus limits of random error, with a defined level of confidence (usually 95%).

secondary variables: variables that are measured but do not enter into the calculation.

sensitivity: see *influence coefficient*.

serialize: to assign to an instrument a unique number that is then permanently inscribed on or to the instrument so that the instrument can be identified and tracked.

specific power performance (SPP): unit of product per unit of power consumed (e.g., Mg O_2/kW·h or short ton O_2/kW·h).

systematic error, β: sometimes called bias; the portion of the total measurement error, *δ*, that remains constant in repeated measurement of the true value in a test process, which characterizes every member of any set of measurements from the population.

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

test boundary: a control volume that identifies the energy streams required to calculate corrected results.

test reading: one recording of all required test instrumentation.

test run: a group of test readings.

traceable: term used to describe instruments for which records are available demonstrating that the instrument can be traced through a series of calibrations to an appropriate ultimate reference such as the National Institute of Standards and Technology (NIST).

uncertainty, U: ±*U* is the interval about the measurement or result that contains the true value for a given confidence level.

2-4 SYMBOLS

The following symbols are used in this Code:

AOD = additive correction factor to account for irregular or off-design condition, kW
E = ASU effectiveness, P/M, kW·h/short ton of pressurized oxygen
M = ASU production rate, mass flow of pressurized oxygen exiting test boundary, short ton/h
MCWIT = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference cooling water (or air) temperature
MDFR = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference flows
MDP = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference discharge pressure
MEFF = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference machine efficiency
MMC = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference moisture content
MSP = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference inlet pressure
MST = multiplicative correction factors to measured auxiliary power or individual compressor powers to correct to base reference inlet temperature
P = ASU power input, output, or net ASU power consumption, kW
SPP = M/P, ASU specific power performance, short ton of pressurized oxygen/kW·h

2-5 ABBREVIATIONS USED IN SUBSCRIPTS

The following abbreviations are used in subscripts in this Code:

A,i = a reference to ASU auxiliary power, where i is the identification for a discrete auxiliary power
amb = ambient atmospheric
C,i = a reference to an ASU compressor, where i is the identification for a discrete compression unit
corr = corrected result to base reference conditions
meas = measured or determined result prior to correcting to base reference conditions
P,i = a reference to an ASU pump, where i is the identification for a discrete pump

Section 3
Guiding Principles

3-1 INTRODUCTION

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

The Code recognizes that the ASU is a part of the larger IGCC facility and may be integrated with the gasification and power blocks. For the relatively short duration of the Code-specified test, base-load operation at the design rates of the ASU is the suggested mode of operation.

The Code recognizes that there are different types of ASU plants and different modes of operation that will have unique test goals, such as the following:

(a) The test can be run at a specified disposition that is set by independent or combined testing of the gasification and power blocks. An example of this goal would be a maximum output of one or more of the blocks within the IGCC facility.

(b) The test can be run at a specified production rate that is near the design value of interest. An example of this test goal would be an acceptance test in which the power consumption of the ASU is guaranteed at a specific set of product flow, purity, and pressure conditions.

Regardless of the test goal, the results of a Code test will be a corrected ASU effectiveness that is the corrected ASU power consumption divided by the amount of pressurized products supplied to the other blocks within the IGCC facility. The test shall be designed with the appropriate goal in mind to ensure that proper procedures are developed and that the appropriate operating mode during the test is followed.

3-2 TEST BOUNDARY AND REQUIRED MEASUREMENTS

The general methodology of the Code involves three steps: defining the test boundary, identifying energy streams related to the calculation of the test results, and conducting a pretest uncertainty analysis.

3-2.1 Test Boundary Definition

The ASU test boundary is a control volume that identifies the streams into and out of the system that must be measured to calculate the corrected test results. All input and output streams required for test calculations shall be determined with reference to the point at which they cross the test boundary. Streams internal to the ASU need not be determined unless they verify base operating conditions, relate functionally to conditions outside the boundary, or verify steady-state operation.

The test boundary usually encompasses all the equipment and systems considered to be a part of the ASU. However, if by-products are manufactured for use outside the IGCC facility, the ASU test boundary may be adjusted to exclude items such as storage systems, stand-alone liquefaction units, and gaseous product compressors not associated with the IGCC facility.

For a particular test, the specific test boundary shall be established by the parties to the test. Figure 3-2.1-1 shows the typical streams required for a generic ASU. Solid lines indicate the streams crossing the ASU test boundary for which mass flow rate, thermodynamic conditions, and chemical analysis have to be determined to calculate the results of an overall ASU performance test. The properties of streams indicated by dashed lines may be required for an overall energy and mass balance but may not have to be determined to calculate test results.

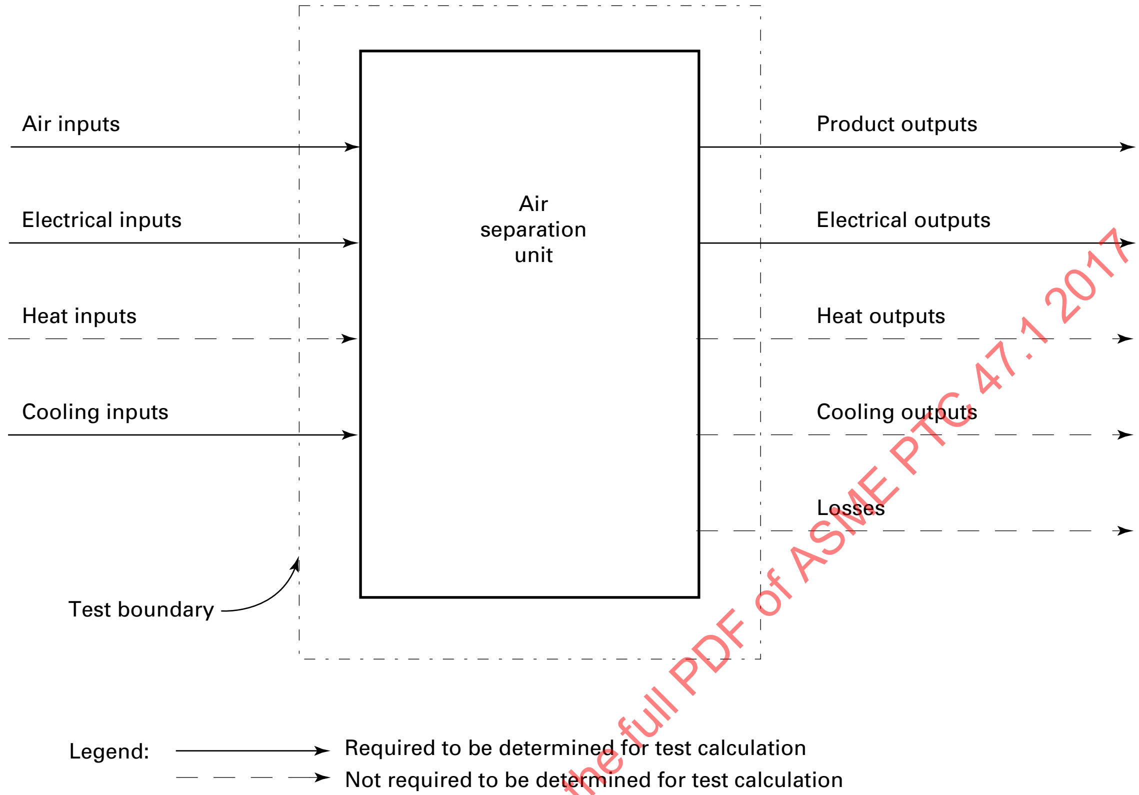
Figure 3-2.1-2 shows the test boundary of a nonintegrated ASU. Figure 3-2.1-3 shows the test boundary of an integrated ASU.

3-2.2 Required Measurements

In general, measurements or determinations are required for the following streams:

(a) *Ambient Air Input.* The total pressure, dry bulb temperature, relative humidity, and carbon dioxide and hydrocarbon content are required for ambient air where it enters the ASU air compression equipment.

Figure 3-2.1-1 Generic ASU Test Boundary



(b) *Compressed Air Input.* The pressure, temperature, dry flow rate, water content (as liquid and vapor), and carbon dioxide and hydrocarbon content are required for any compressed-air streams entering the ASU test boundary.

(c) *Product Outputs (ASU Production Rate).* The pressure, temperature, total flow rate, and composition of compressed or pressurized product streams leaving the ASU test boundary are required. In general, streams vented at low pressure to the atmosphere are not required to be measured for ASU performance determination.

(d) *Electric Power (ASU Power Input).* The electric power input and any outputs crossing the ASU test boundary are required measurements. Points of measurement may include ASU step-down transformers, power meters located on specific items of equipment, or other locations as agreed to by the parties to the test.

Figure 3-2.1-2 Nonintegrated ASU Test Boundary

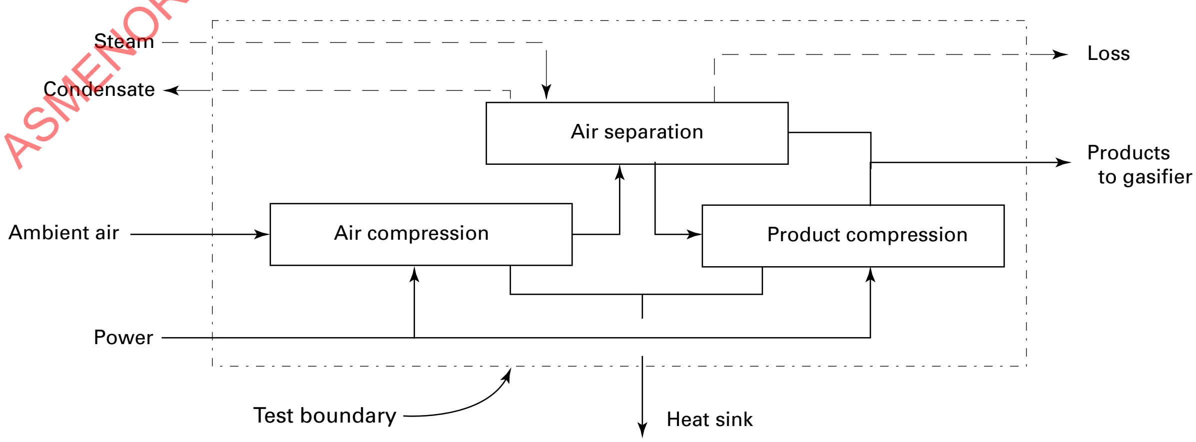
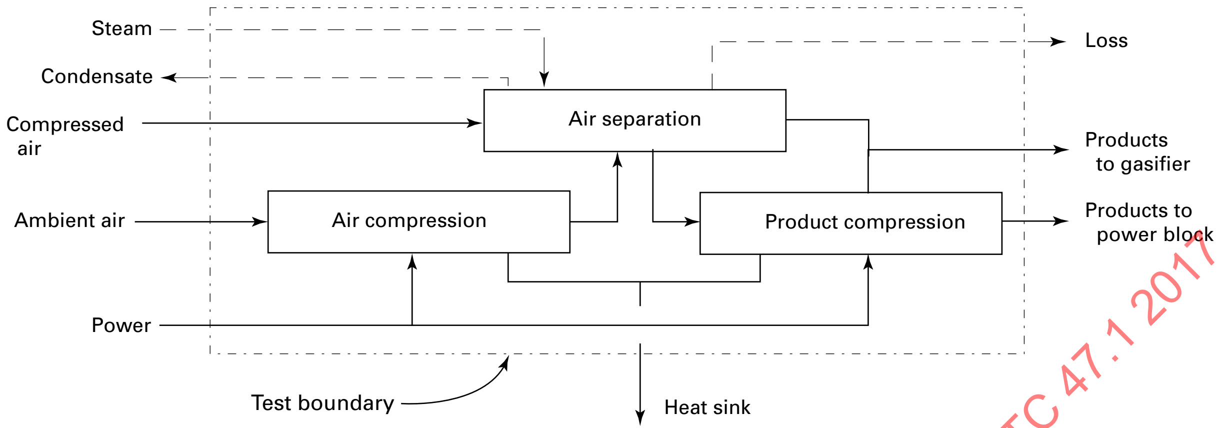


Figure 3-2.1-3 Integrated ASU Test Boundary



(e) *Heat-Sink Conditions.* Corrections to the power input are required for the differences between the design and the ASU test heat-sink conditions. For open-cycle cooling, the temperature and flow rate of the circulating water where it crosses the ASU test boundary are required. For air cooling, the ambient air total pressure, dry bulb temperature, and relative humidity are required. For evaporative cooling towers, the total ambient air pressure and wet bulb temperature are required.

(f) *Losses.* In general, losses will not be measured. Typical losses include water condensed as a result of cooling compressed-air streams, compressor-seal losses, purge and seal gases used within the ASU test boundary, and streams vented to the atmosphere.

3-2.3 Pretest Uncertainty Analysis

Once all energy streams have been identified, a pretest uncertainty analysis, as described in Section 7, shall be performed to identify the primary energy flows whose physical properties must be measured and input into the test results calculation. The pretest uncertainty analysis is also used to determine the level of measurement accuracy required for each measurement to maintain the agreed-on overall test uncertainty.

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

Other measurements may be required, such as those used in the application of correction factors for off-design ambient conditions to confirm test point stability, or those needed to ensure that the process does not exceed emissions or safety limits.

3-3 TEST PLAN

A detailed test plan should be prepared prior to conducting a Code test to document agreements on all issues affecting the conduct of the test and to provide detailed procedures for performing the test. The test plan should be approved, prior to the test, by authorized signatures of all parties to the test. It shall reflect any contract requirements that pertain to the test objectives and performance guarantees and provide any needed clarification of contract issues. The test plan should also include the schedule of test activities, responsibilities of the parties to the test, test procedures, and report of results.

3-3.1 Schedule of Test Activities

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

3-3.2 Responsibilities of Parties to the Test

The parties to the test shall agree on individual responsibilities required to prepare, conduct, analyze, and report the test in accordance with this Code. This includes agreement on the organization of test personnel and designation of a Test Coordinator who shall be responsible for executing the test in accordance with the test requirements and coordinating the setting of required operating conditions with the plant operations staff. Each of the parties to the test should designate a representative who shall observe the test and confirm that it was conducted in accordance with the test requirements. The representatives should have the authority to approve, if necessary, any agreed-on revisions to the test requirements during the test.

3-3.3 Test Procedures

The test plan shall include test procedures, such as the following, that provide details for the conduct of the test:

(a) objectives of the test and method of operation. The object of the test shall be agreed to by the parties to the test and shall be defined in writing before the test(s) commence.

(b) test acceptance criteria for test completion.

(c) base reference conditions.

(d) defined test boundaries identifying inputs and output and measurement locations.

(e) the intent of any contract or specification as to operating conditions and performance guarantees.

(f) completed pretest uncertainty analysis, with bias uncertainties established for each measurement.

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

(h) sample collection, handling, and analysis method, and frequency of sampling, for product purities.

(i) method of operating the plant.

(j) required operating disposition or accounting for all auxiliary power consumers and generators having a material effect on test results.

(k) required levels of equipment cleanliness and inspection procedures.

(l) procedures to account for performance degradation, if applicable.

(m) preliminary testing requirements.

(n) pretest stabilization criteria.

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

(p) number of test runs and duration of each run.

(q) test start and stop requirements.

(r) data acceptance and rejection criteria.

(s) allowable range of ambient and heat-sink conditions.

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

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

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

(w) test report format, contents, inclusions, and index.

3-4 TEST PREPARATIONS

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 method of testing. Descriptions, drawings, and/or photographs may be used to give a permanent, explicit record. Instrument location shall be predetermined, agreed to by the parties to the test, and described in detail in test records. Redundant, calibrated instruments should be provided for those instruments susceptible to in-service failure or breakage.

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 or 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 production rates or outputs under all specified operating conditions. Any actions taken shall be documented and immediately reported to all parties to the test.

All parties to the test shall be notified of the test schedule, as defined by prior agreement, to provide the necessary time for the parties to respond and to prepare personnel, equipment, or documentation. A test log shall be maintained and used to record any occurrences affecting the test. The log should document the time of the occurrence and the observed resultant effect. This log shall be part of the permanent record of the test. Necessary documentation for calculated or adjusted data shall be provided by the party conducting the test for independent verification of algorithms, constants, scaling, calibration corrections, offsets, base points, and conversions.

3-4.1 Requirements for Agreements

The parties to any test under this Code shall reach definite agreement on the specific objective of the test and method of operation. This agreement shall reflect the intent of any applicable contract or specification. Any specified or contract operating conditions or specified performance pertinent to the objective of the test shall be ascertained. Unless alternative test procedures are specified, full-scale test procedures shall be used. Omissions or ambiguities about any of the conditions shall be eliminated or their values or intent agreed on before the test is started. The cycle arrangement, operating conditions, and testing procedures shall be established during the agreement on test methods.

3-4.1.1 Engineering Phase Agreement. The following is a list of typical items on which agreement should be reached during the engineering phase of a new unit or modification of an existing unit:

(a) objective of the test and methods of operation

(b) the intent of any contract or specifications as to timing of the test, operating conditions, and guarantees, including the definition of effectiveness, the method of comparing test results with guarantees, and responsibility for the preparation of the test report(s)

(c) location of, and piping arrangement around, primary flow-measuring device(s) on which the test calculations are based

(d) location(s) and type of secondary flow-measuring devices and provisions for calibration, including temporary piping for in-place calibration, if required

(e) the number and location(s) of valves or other means required to ensure that no unaccounted-for flow enters or leaves the test cycle or bypasses any cycle component

(f) the means of measuring seal and leakage flows

(g) the number and location(s) of temperature wells and pressure connections

(h) the number and location(s) of duplicate instrument connections required to ensure correct measurements at critical points

(i) calibration and connection of instrument transformers to be used for measuring the electrical output

(j) where a plant computer is used for data acquisition, provisions for total-system in-place calibration of the station instrumentation and computer (Calibration should include comparison of known inputs to the output of the computer.)

(k) the method of determining gas quality, including the sampling technique, as required

(l) criteria for instrument recalibration after the test

3-4.1.2 Pretest Agreements. The following is a list of typical items on which agreement shall be reached prior to conducting the test:

(a) the object of the test

(b) the location and timing of the test

(c) test boundaries

(d) the procedure for determining the condition of the ASU system prior to the test, and requirements for pretest inspections

(e) the location, type, and calibration of instruments

(f) methods of measurement not established in (e)

(g) isolation of the system during the test

(h) the means for maintaining stable load and test conditions

(i) the operating conditions at which tests are to be conducted, including the position of manual and automatic valves

(j) the frequency of observations

(k) the number of copies of original data required

(l) the length of time for stable operation before starting a test run

(m) the number of test runs at the same test point

(n) the duration of operation at test load before readings are commenced

(o) the computer or data acquisition system to be used for test data acquisition and analysis, including calibration of the data acquisition system

(p) the organization of personnel, including designation of the engineer in responsible charge of the test

(q) the procedures and format for recording data

(r) the organization and training of test personnel and the responsibilities for the test

(s) procedures for calculating test results

(t) curves to correct for deviations from specified conditions

(u) corrections for deviation of test conditions from those specified

(v) curves to correct specified system conditions

(w) the method of comparing test results with specified performance

(x) the method of conducting test runs to determine the value of any correction factors
(y) the confidentiality of the test results
(z) pretest inspections
(aa) the methods for deviations from test arrangements and procedures
(bb) the methods to account for degradation

3-4.2 Test Apparatus

3-4.2.1 Location and Identification of Instruments. Transducers shall be located to minimize the effect of ambient conditions, e.g., temperature or temperature variations, on uncertainty. Care shall be used in routing lead wires to the data collection equipment to prevent electrical noise in the signal. Manual instruments shall be located so that they can be read with precision and convenience by the observer. All instruments shall be marked uniquely and unmistakably for identification. Calibration tables, charts, or mathematical relationships shall be readily available to all parties to the test. Observers recording data shall be instructed on the desired degree of precision of readings.

Test instruments are classified in Section 4. Instrumentation used for data collection shall be at least as accurate as instrumentation identified in the pretest uncertainty analysis. This instrumentation may be either permanent plant instrumentation or temporary test instrumentation.

Multiple instruments should be used as needed to reduce overall test uncertainty. The frequency of data collection is dependent on the particular measurement and the duration of the test. Automated data acquisition systems should be used to facilitate acquisition of sufficient data. All instruments shall be calibrated or adequately checked prior to and after the test.

3-4.2.2 Frequency and Timing of Observations. The timing of instrument observations shall be determined by an analysis of the time lag of both the instrument and the process so that a correct and meaningful mean value and departure from allowable operating conditions may be determined. Where steady-state conditions are required, sufficient observations shall be recorded to prove that steady-state conditions existed during the test. A sufficient number of observations shall be taken to reduce the random component of uncertainty to an acceptable level.

3-4.3 Test Personnel

There shall be a sufficient number of test personnel with the necessary expertise to support the execution of the test. Operations personnel shall be sufficiently familiar with the test operating requirements to operate the equipment according to the test plan.

3-4.4 Equipment Inspection and Cleanliness

All parties to the test shall have reasonable opportunity to examine the plant and agree that it is ready to test. The plant should be checked to ensure that equipment and subsystems are installed and operating in accordance with their design parameters. This Code covers testing of new and clean machinery. If testing is performed after the facility has been operated over a period of time, correction factors for machinery performance degradation and compressor inter- and after-cooler fouling shall be applied to the test results, or the machinery and equipment shall be cleaned to return it to new and clean conditions. Measurements internal to the ASU to determine the degree of machinery degradation and fouling are outside the scope of this Code.

3-4.5 Preliminary Testing

Preliminary test runs, with records, serve to determine if equipment is in suitable condition to test, to check instruments and methods of measurement, to check adequacy of organization and procedures, and to train personnel. All parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If such a preliminary test run complies with all the necessary requirements of the appropriate Code test, it may be used as an official test run within the meaning of this Code.

Preliminary testing should be conducted sufficiently in advance of the start of the overall performance test to allow time to calculate preliminary results, make final adjustments, and modify the test requirements and/or test equipment. Results from preliminary testing should be calculated and reviewed to identify any problems with the quantity and quality of the measured data. The parties to the test shall mutually agree before the test to any test modifications determined during the preliminary test. Reasons for a preliminary test run include the following:

(a) to determine whether the plant equipment is in suitable condition for the conduct of the test
(b) to make adjustments, the needs of which were not evident during the preparation of the test

(c) to check the operation of all instruments, controls, and data acquisition subsystems
(d) to ensure that the target uncertainty can be obtained by checking the complete system
(e) to ensure that the facility's operation can be maintained in a stable steady status of performance
(f) to ensure that sufficient power quantity and quality and utility flows and conditions are available so as to not require interruption of the test
(g) to ensure that process boundary inputs and outputs are not constrained other than those identified in the test requirements
(h) to familiarize test personnel with their assignments
(i) to retrieve sufficient data to tune the control system, if necessary

3-5 CONDUCT OF THE TEST

The parties to the test shall designate a person, hereafter called the Test Coordinator, to direct the test. Communication arrangements between all test personnel and all test parties and the Test Coordinator should be established. Complete written records of the test, including details that at the time may seem irrelevant, should be kept. Controls by ordinary operating (indicating, reporting, or integrating) instruments should be established, graphical logs prepared, and the test closely supervised to give assurance that the equipment under test is operating in substantial accord with the intended conditions. If it is a commercial test, accredited representatives of the purchaser and the manufacturer or supplier should be present at all times to assure themselves that the tests are being conducted in compliance with the Code and prior agreement.

3-5.1 Methods of Operation Prior to and During Tests

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

3-5.1.1 Valve Lineup/Cycle Isolation. A Cycle Isolation Checklist should be developed to the satisfaction of all parties to the test. The checklist should be divided into the following three categories:
(a) Manual Valve Checklist. This checklist shall note all of the manual valves that should be closed during normal operation so as not to affect the accuracy or results of the test. These valve positions should be checked before and after the test.
(b) Automatic Valve Checklist. This checklist shall note all of the automatic valves that should be closed during normal operation so as not to affect the accuracy or results of the test. These valve positions should be checked before, during, and after the test.
(c) Test Valve Isolation Checklist. This checklist is the list of those valves that should be closed during the performance test. These valves should be limited to those that must be closed to accurately measure the plant performance during the test. For example, valves connecting a source of stored product external to the test boundary limits should be closed. No valves that are normally open or closed should change position for the sole purpose of changing the maximum performance of the plant. The valves on the Test Valve Isolation Checklist should be closed prior to the preliminary test. The valves may need to be opened between test runs.

3-5.1.2 Operating Mode. The operating mode of the plant during the test should be consistent with the goal of the test. The corrections used in the general performance equation and the development of correction factors will be affected by the operating mode of the plant. If a specified corrected or measured flow is desired, the plant control system should be configured to maintain that flow during the test. The plant equipment should be operated in a manner consistent with the basis of design or guarantee, and in a manner that will permit correction from test operating conditions to base reference conditions.

3-5.1.3 Equipment Operation. All equipment systems shall be functional and operating properly, as agreed on by the parties to the test, before the performance test. Any equipment that is not functional before the test shall be repaired and proven operable before the performance test begins.

3-5.1.4 Proximity to Design Conditions. It is desirable to operate the plant during the test as closely as possible to the base reference performance conditions, and within the allowable design range of the plant and its equipment so as to limit the magnitude of correction factors. Excessive corrections to plant performance parameters can adversely affect overall test uncertainty. Limits of operation should be agreed to by the parties to the test prior to beginning a test run.

3-5.1.5 Stable Operation. Stable plant operation with respect to production rates, purities, and discharge pressures shall be achieved prior to the start of the test. Once steady-state operation is achieved, at least 1 h of stable operation shall be completed before commencing the test.

Stable operation has been achieved when all oxygen and nitrogen product streams have exceeded the required design purity, can be produced at flows that vary by no more than ±2.5%, and can be maintained throughout any disturbance from external conditions, such as changing ambient conditions, or system changes, such as reversals of the temperature swing adsorber beds.

3-5.1.6 Plant Output/Input. A test may be conducted at any product flow condition, as required to satisfy the goals of the test. Under this test condition, the power and utility supply to the plant shall not be constrained. If a test under constant power input is specified, the control system should be set up to change production rates to minimize fluctuation of total power demand.

3-5.1.7 Plant Thermal Energy. Thermal energy may be required to operate certain subsystems within the ASU test boundary limits, exclusive of mechanically driving significant power consumers. Thermal energy is considered a secondary measurement that is not included in the calculation of plant performance. If steam turbine drivers are used within the ASU boundary limits, the performance equations and measuring techniques shall be modified accordingly.

3-5.1.8 Fuel. Fuel may be required to operate certain subsystems within the ASU test boundary limits, exclusive of mechanically driving significant power consumers. Fuel is considered a secondary measurement that is not included in the calculation of plant performance. If gas turbine drivers or significant steam-generating equipment is used within the ASU boundary limits, the performance equations and measuring techniques shall be modified accordingly.

3-5.1.9 Online Cleaning. Online cleaning of equipment such as air compressors should be explicitly addressed and agreed to by the parties to the test.

3-5.2 Starting and Stopping Tests and Test Runs

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

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

3-5.2.1 Starting Criteria. Prior to starting each performance test, the following conditions shall be satisfied:

(a) Operation, configuration, and disposition for testing shall be reached in accordance with the agreed-on test requirements, including

(1) equipment operation and method of control
(2) unit configuration, including required process influx and efflux flows
(3) availability and quality of power and utilities within agreed-on limits
(4) plant operation within the bounds of the performance correction curves, algorithms, or programs
(5) equipment operation within allowable limits
(6) for a series of test runs, completion of internal adjustments required for repeatability

(b) Plant operation shall be stabilized for a sufficient period of time at test conditions (see para. 3-5.1.5).

(c) Data collection, including data acquisition system(s), should be functioning and test personnel should be in place and ready to collect samples or record data.

3-5.2.2 Stopping Criteria. Tests are normally stopped when the Test Coordinator is satisfied that the requirements for a complete test run have been satisfied. The Test Coordinator should verify that requirements for methods of operation during the test have been satisfied. The Test Coordinator may extend or terminate the test if the requirements have not been met. The Test Coordinator shall check data logging to ensure completeness.

3-5.3 Adjustments Prior to and During Tests

This subsection describes permissible and nonpermissible adjustments related to the test.

3-5.3.1 Permissible Adjustments During Stabilization Periods or Between Test Runs. Agreement should be reached before the test on acceptable adjustments prior to the test. Basically, any adjustments may be made to the equipment and/or operating conditions, but the requirements for determination of stable operation shall still apply. Typically, adjustments prior to tests are those required to correct malfunctioning controls or instrumentation or to optimize plant performance for the current operating conditions. Recalibration of suspect instrumentation or measurement loops is permissible. Tuning and/or optimization of component or plant performance is permissible. Adjustment to avoid corrections or to minimize the magnitude of performance corrections is permissible. Following any changes to operation of the system, reverification of stability is required.

3-5.3.2 Permissible Adjustments During Test Runs

(a) Permissible Deviations. The equipment tested should be operated to ensure its performance is bounded by the permissible fluctuations and permissible deviations specified.

(b) Readjustments. Once testing has started, readjustments to the equipment that can influence the results of the test require repetition of any test runs conducted prior to the readjustments. No adjustments should be permissible for the purpose of a test if they are inappropriate for reliable and continuous operation following a test under any and all of the specified outputs and operating conditions.

(c) Permissible Adjustments. Permissible adjustments during tests are those required to correct malfunctioning controls, to maintain equipment in safe operation, or to maintain plant stability.

3-5.3.3 Nonpermissible Adjustments. Any adjustments that would result in equipment being operated beyond the manufacturer's operating limits, design or safety limits, and/or specified operating limits are not permitted. Adjustments or recalibrations that would adversely affect the stability of a primary measurement during a test are also not permitted.

3-5.4 Duration, Number, and Evaluation of Test Runs

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

3-5.4.1 Duration of Test Runs. The duration of a test run shall be of sufficient length that the data reflects the average efficiency and/or performance of the plant. Typically, data is collected over a 2-h test run. The Test Coordinator and the parties to the test may determine that a longer run period is required.

3-5.4.2 Number of Test Runs. A test run is a complete set of observations with the ASU at stable operating conditions. A test is the average of a series of test runs. This Code requires that a minimum of two valid test runs be used as the basis of the test and recommends that three test runs be conducted. Conducting multiple test runs

(a) provides a valid method of rejecting bad test runs.

(b) verifies the repeatability of the results. Results may not be repeatable due to variations in either test methodology (test variations) or the actual performance of the equipment being tested (process variations).

3-5.4.3 Evaluation of Test Runs. When comparing results from two test runs (X_1 and X_2) and their uncertainty intervals, the three cases shown in Figure 3-5.4.3-1 should be considered.

(a) Case I. A problem clearly exists when there is no overlap between uncertainty intervals. This situation may be due to uncertainty intervals being grossly underestimated, errors in the measurements, or abnormal fluctuations in the measurement values. Investigation to identify bad readings, overlooked or underestimated systematic uncertainty, and the like is necessary to resolve this discrepancy.

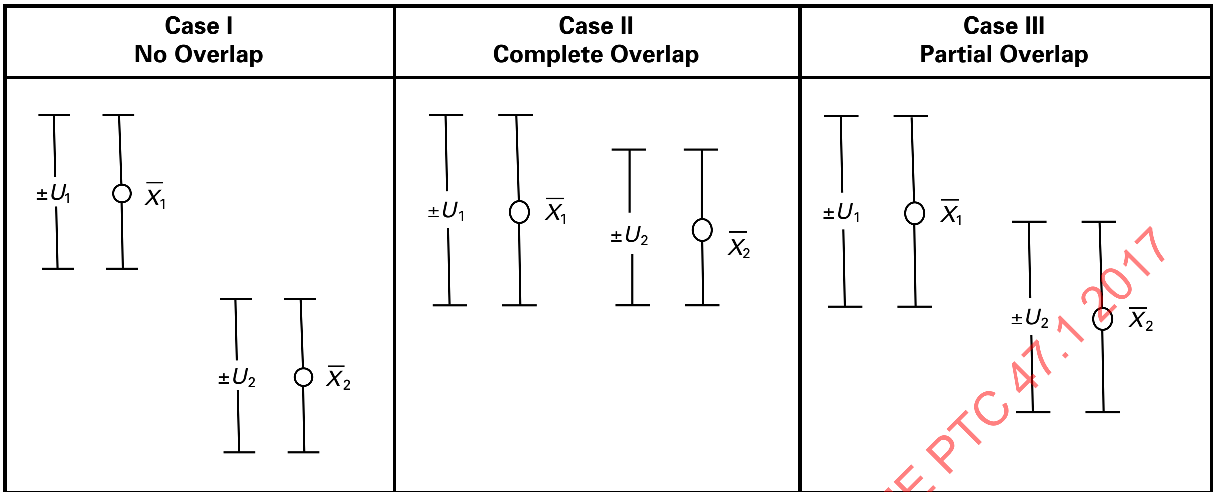
(b) Case II. When the uncertainty intervals completely overlap, as in this case, one can be confident that there has been a proper accounting of all major uncertainty components. The smaller uncertainty interval, $X_2 \pm U_2$, is wholly contained in the interval $X_1 \pm U_1$.

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

Should a run or set of runs be a Case I or Case III, the results from all of the runs should be reviewed in an attempt to explain the reason for excessive variation. Should no reason become obvious, the user of the Code should reevaluate the uncertainty band or conduct more test runs to calculate the precision component of uncertainty directly from the test results. Conducting additional tests may also validate the previous testing.

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

Figure 3-5.4.3-1 Uncertainty Intervals



3-5.5 Constancy of Test Conditions

The primary uncontrollable parameters affecting the steady-state test conditions are ambient and heat-sink conditions. Testing duration and schedules shall be such that changes in ambient conditions are minimized.

3-6 CALCULATION AND REPORTING OF RESULTS

The data taken during the test should be reviewed and rejected in part or in whole if it is not in compliance with the requirements for the constancy of test conditions. Each Code test shall include pretest and post-test uncertainty analyses, and the results of these analyses shall fall within Code requirements for the type of plant being tested.

3-6.1 Data Reduction

Following each test, when all test logs and records have been completed and assembled, the test data should be examined to ensure that the test data is within the limits of permissible deviations from specified operating conditions.

Adjustments of any kind should be agreed on by the parties to the test and explained in the test report. If adjustments cannot be agreed on, the test run(s) may have to be repeated. Inconsistencies in the test record or test result may require tests to be repeated in whole or in part to attain test objectives.

3-6.2 Rejection of Readings

Upon completion of the test or during the test itself, the test data shall be reviewed to determine if data from certain time periods should be rejected prior to calculation of test results. Refer to ASME PTC 19.1 for data-rejection criteria. A test log should be kept to note any plant upsets that cause test data to violate test parameter criteria.

An outlier analysis of spurious data should also be performed in accordance with ASME PTC 19.1 on all critical measurements after the test has ended. This analysis shall highlight any other time periods that should be rejected prior to calculating the test results. Caution should be used in rejecting test data.

3-6.3 Inconsistent Measurements

If any measurement influencing the result of a test is inconsistent with another measurement of the same parameter, although either or both of them may have been made strictly in accordance with the rules of the individual test Code, the cause of the inconsistency shall be identified and eliminated.

3-6.4 Invalid Test Runs

Should serious inconsistencies that affect the results be detected during a test run or during calculation of the results, the run shall be invalidated completely. A run that has been invalidated shall be repeated to attain the test objectives. The decision to reject a test run shall be the responsibility of the designated representatives of the parties to the test.

3-6.5 Test Records

3-6.5.1 Data Records and the Test Log. For all acceptance and other official tests, a complete set of data and a complete copy of the test log shall become the property of each of the parties to the test. The original test log and test data are the only evidence of actual test conditions and shall permit clear and legible reproduction. Copying data sheets by hand is not permitted. The completed data records shall include the date and time of day the observation was recorded. The observations shall be the actual readings without application of any instrument corrections.

The test log should constitute a complete record of events, including details that at the time may seem trivial or irrelevant. Erasures of or destruction or deletion of any data record, page of the test log, or recorded observation is not permitted. If an entry is corrected, the alteration shall be entered so that the original entry remains legible and an explanation for the change is included. For manual data collection, the test observations shall be entered on carefully prepared forms that constitute original data sheets authenticated by the observers' signatures. For automatic data collection, printed output or electronic files shall be authenticated by the Test Coordinator and other representatives of the parties to the test.

The parties to the test shall agree in advance to the method used for authenticating, reproducing, and distributing the data. Copies of the electronic data files shall be distributed to each of the parties to the test. The data files shall be in a format that is easily accessible to all parties. Data residing on a machine should not remain there unless a backup, permanent copy is made.

Parties to the test have the right to have copies of all data at the conclusion of the test. Data shall be distributed by the Test Coordinator and approved in a manner as agreed to prior to testing.

3-6.5.2 Analysis and Interpretation. During the conduct of a test, or during the subsequent analysis or interpretation of the observed data, an obvious inconsistency may be found. If this occurs, reasonable effort should be made to adjust or eliminate the inconsistency. Failing this, test runs should be repeated.

3-6.6 Test Report

A test report shall be written in accordance with Section 6 of this Code by the Test Coordinator and distributed within a time frame agreed to by all parties to the test. A preliminary report incorporating calculations and results may be required before the final test report is submitted for approval.

Section 4
Instruments and Methods of Measurement

4-1 GENERAL REQUIREMENTS

4-1.1 Introduction

This Section reviews the critical highlights of portions of the ASME PTC 19 series Code supplements that directly apply to this Code. This Section also contains details of the instrumentation requirements of this Code that are not specifically addressed in the referenced supplements. Such details include classification of data for the purpose of instrumentation selection and maintenance, field verification recommendations once instrumentation is removed from a laboratory, calibration requirements, electrical metering, and other information specific to an ASME PTC 47.1 test.

This Section presents the mandatory provisions for instrumentation used in the implementation of an ASME PTC 47.1 test. Using the philosophy of ASME Performance Test Codes, the minimum reasonably achievable uncertainty is the basis for the instrumentation requirements.

The Instruments and Apparatus Supplements to ASME Performance Test Codes (ASME PTC 19 series) outline the details concerning instrumentation and the governing requirements of instrumentation for ASME Code performance testing. Users of this Code should be familiar with the detailed requirements of ASME PTC 19.1, ASME PTC 19.2, ASME PTC 19.3, ASME PTC 19.5, and ASME PTC 19.22, as well as ASME MFC-3M for differential flowmeters.

If the instrumentation requirements in the ASME PTC 19 series Code supplements become more rigorous as they are updated, due to advances in the state of the art, their requirements will supersede those set forth in this Code.

4-1.2 Measurements

4-1.2.1 Measurement Designation. A measurement may be designated as either a parameter or a variable. The terms "parameter" and "variable" are often used interchangeably in the industry, and in some other ASME Codes. However, this Code distinguishes between the two.

A parameter is considered a direct measurement and is a physical quantity at a location that is determined by a single instrument, or by the average of several similar instruments. In the latter case, several instruments may be used to determine a parameter that has potential to display spatial gradient qualities, such as inlet air temperature. Similarly, multiple instruments may be used to determine a parameter simply for redundancy to reduce test uncertainty, such as using two temperature measurements of the fluid in a pipe in the same plane, where the temperature gradient is expected to be insignificant. Typical parameters measured in an ASME PTC 47.1 test are temperature, static and differential pressure flow, stream constituent concentrations (purity), power, voltage, and current.

A variable is considered an indirect measurement and is an unknown quantity in an algebraic equation that is determined by parameters. The performance equations in Section 5 contain the variables used to calculate the performance results, including corrected power consumption, corrected production rate, and gas purity. Typical variables in these equations are flow, pressure, temperature, correction factors, and electrical power. Each variable can be thought of as an intermediate result needed to determine the performance result.

Parameters are therefore the quantities measured directly to determine the value of the variables needed to calculate the performance results per the equations in Section 5. Examples of such parameters are temperature and pressure to determine the variable enthalpy; or temperature, pressure, and differential pressure to calculate the variable flow.

4-1.2.2 Measurement Classification. A parameter or variable is classified as primary or secondary, depending on its usage in the execution of this Code. Parameters and variables used in the calculation of test results are considered primary parameters and primary variables. Secondary parameters and secondary variables do not enter into the calculation of the results but are used to ensure that the required test condition was not violated.

Primary parameters and primary variables are further classified as Class 1 or Class 2, depending on their relative sensitivity coefficient to the results of the test. Class 1 primary parameters and Class 1 primary variables are those that have a relative sensitivity coefficient of 0.2% or greater. The primary parameters and primary variables that have a relative sensitivity coefficient of less than 0.2% are classified as Class 2 primary parameters and Class 2 primary variables.

4-1.3 Instrumentation

In general, measuring equipment should be selected to minimize test uncertainty. Critical parameters should be measured with instruments that have sufficient accuracy to ensure that target uncertainties will be achieved. Typical station recording instruments are designed for process control based on instrument reliability and for ease of use and maintenance, rather than for accuracy. Therefore, measurements made using station instruments may increase test uncertainty beyond agreed-on limits. Test instrumentation should be selected based on cost versus accuracy requirements to meet the requirements of this test Code.

All instruments shall be checked to verify that they are the specified type, properly installed, working as designed, and functioning over the range of the expected input.

4-1.3.1 Instrumentation Categorization. The instrumentation employed to measure a parameter will have different required type, accuracy, redundancy, and handling depending on the use of the measured parameter and how the measured parameter affects the performance result. This Code does not require high-accuracy instrumentation for secondary parameters. The instruments that measure secondary parameters may be permanently installed plant instrumentation.

This Code requires verification of instrumentation output prior to the test period. This verification can be performed by calibration. The instruments should also have redundant or other independent instruments that can be used to verify the integrity during the test period. Instrumentation is categorized as Class 1 or Class 2, depending on the instrumentation requirements defined by that parameter. Care shall be taken to ensure that the instrumentation meets the requirements set forth in this Code.

4-1.3.2 Class 1 Instrumentation. Class 1 instrumentation shall be used to determine Class 1 primary parameters. Class 1 instrumentation requires high accuracy, with precision laboratory calibration, and/or shall meet specific manufacturing and installation requirements, as specified in the ASME PTC 19 series Code supplements.

4-1.3.3 Class 2 Instrumentation. Class 2 instrumentation shall be used to determine Class 2 primary parameters. Class 2 instrumentation does not require laboratory calibration other than that performed in the factory for certification, but it does require field verification by techniques described in this Code.

4-1.3.4 Plant Instrumentation. It is acceptable to use plant instrumentation for primary parameters only if the plant instrumentation (including signal-conditioning equipment) can be demonstrated to meet the overall uncertainty requirements. In the case of flow measurement, all instrument measurements (process pressure, temperature, differential pressure, or pulses from metering devices) shall be made available, as plant conversions to flow are often not rigorous enough for the required uncertainty.

4-1.3.5 Redundant Instrumentation. Redundant instruments are two or more devices measuring the same parameter with respect to the same location. Where experience in the use of a particular model or type of instrument indicates that the uncertainty results would be unacceptable, and no other device is available, redundancy is recommended.

Other independent instruments in separate locations can also monitor instrument integrity. A sample case would be a constant-enthalpy process in which pressure and temperature at one point in a process line verify the pressure and temperature at another location in the line by comparing enthalpy.

4-1.4 Instrument Calibration

4-1.4.1 Definition of Calibration. Calibration is the set of operations that establishes, under specified conditions, the relationship between values indicated by a measuring instrument or measuring system, and the corresponding reference standard or known values derived from the reference standard. The result of a calibration permits the estimation of errors of indication of the measuring instrument or measuring system, or the assignment of values to marks on arbitrary scales. The result of a calibration is sometimes expressed as a calibration factor, or as a series of calibration factors in the form of a calibration curve. Calibrations performed in accordance with this Code are categorized as either laboratory calibrations or field calibrations.

4-1.4.1.1 Laboratory-Grade Calibration. A laboratory-grade calibration, as defined by this Code, is a calibration that is performed under controlled conditions with highly specialized measuring and test equipment that has been calibrated by approved sources and that remains traceable to the National Institute of Standards and Technology (NIST), another recognized international standard organization, or a natural physical (intrinsic) constant through unbroken comparisons having defined uncertainties. These calibrations shall be performed in strict compliance with established policy, requirements, and objectives of a laboratory quality assurance program. Laboratory calibration applications shall be employed on Class 1 instrumentation with the exception of fluid-metering devices that strictly adhere to specific manufacturing and installation requirements, as specified in the ASME PTC 19 series Code supplements.

4-1.4.1.2 Field Calibration. Field calibration, as defined by this Code, is a calibration that is performed under conditions that are less controlled, either with or without less rigorous measurement and test equipment, than under a laboratory-grade calibration. Field calibration measurement and test equipment requires calibration by approved sources that remain traceable to NIST, another recognized international standard organization, or a natural physical (intrinsic) constant through unbroken comparisons having defined uncertainties. Field calibration applications are commonly employed on instrumentation measuring secondary parameters and on Class 2 instrumentation that is identified as out-of-calibration during field verification.

4-1.4.2 Reference Standards. In general, all non-flow-metering Class 1 and Class 2 instrumentation used to measure primary (Class 1 and Class 2) parameters shall be calibrated against reference standards traceable to NIST, another recognized international standard organization, or recognized natural physical constants with values assigned or accepted by NIST. Instrumentation used to measure secondary variables need not be calibrated against a reference standard. These instruments may be calibrated against a calibrated instrument.

4-1.4.3 Environmental Conditions. Calibration of instruments used to measure primary parameters (Class 1 or Class 2) should be performed in a manner that replicates the conditions under which the instrument will be used to make the test measurements. As it is often not practical or possible to perform calibrations under replicated environmental conditions, additional elemental error sources shall be identified and estimated. Error source considerations shall be given to all process and ambient conditions that may affect the measurement system, including temperature, pressure, humidity, electromagnetic interference, and radiation.

4-1.4.4 Instrument Ranges and Calibration Points. The number of calibration points depends on the classification of the parameter the instrument will measure. The calibration should have points that bracket the expected measurement range. In some cases of flow measurement, it may be necessary to extrapolate a calibration. Field verifications shall be employed on all installed instrumentation prior to the test on all measured primary and secondary parameters.

(a) Class 1 Instrumentation. The instruments measuring Class 1 primary parameters should be laboratory-grade calibrated at two points more than the order of the calibration curve fit, whether it is necessary to apply the calibration data to the measured data or if the instrument is of the quality that the deviation between the laboratory calibration and the instrument reading is negligible in terms of affecting the test result. Flow metering that requires calibration should have a 20-point calibration. Instrument transformers do not require calibration at two points more than the order of the calibration curve fit.

Each instrument should also be calibrated such that the measuring point is approached in an increasing and a decreasing manner. This exercise minimizes the possibility of any hysteresis effects. Some instruments are built with a mechanism to alter the range once the instrument is installed. In this case, the instrument shall be calibrated at each range to be used during the test period.

Some devices cannot practically be calibrated over the entire operating range. For example, flow-measuring devices are often calibrated at flows lower than the operating range and the calibration data is extrapolated.

(b) Class 2 Instrumentation. If calibration for instruments measuring Class 2 primary parameters is to be curve fitted, the calibration should contain, as a minimum, one point more than the order of the calibration curve fit. If the instrument can be shown to typically have a hysteresis of less than the required accuracy, the measuring point need only be approached from one direction (either increasing or decreasing to the point).

4-1.4.5 Secondary Parameters. The instruments measuring secondary parameters shall undergo field verification as described in para. 4-1.5 and, if calibrated, need only be calibrated at one point in the expected operating range.

4-1.4.6 Timing of Calibration. Because of the variance in different types of instrumentation and their care, no mandate is made regarding the time interval between the initial laboratory calibration and the test period. Treatment of the device is much more important than the elapsed time since calibration. Instruments may be installed in the field but valved out of service, and/or they may, in many cases, be exposed to significant cycling. In these cases, the instrumentation is subject to vibration or other damage, and it shall undergo field verification.

All test instrumentation used to measure Class 1 primary parameters shall be laboratory-grade calibrated prior to the test and/or shall meet specific manufacturing and installation requirements, as specified in the ASME PTC 19 series Code supplements. The time between the calibration and the test period should be kept to a minimum to minimize calibration drift. Similarly, the time between the field verification and the test period should be kept to a minimum to minimize instrument drift. Test instrumentation used to measure Class 2 parameters and secondary parameters does not require laboratory calibration other than that performed in the factory for certification, but it does require field verification prior to the test.

Following a test, field verification shall be conducted on instruments measuring parameters where there is no redundancy or for which data is questionable. For the purposes of redundancy, plant instrumentation may be used in the field verification. If results indicate unacceptable drift or damage, then further investigation is required. Flow-element devices used to measure Class 1 primary parameters that do not have redundancy shall require field verification, including inspection, following the test. Flow-element devices used to measure Class 2 primary parameters need not undergo inspection following the test if the devices have not experienced conditions that would violate the test's integrity. Such conditions may include flushing, line blows, and chemical cleaning.

By nature, flow-measuring devices and current and potential transformers are not amenable to post-test calibration. In the case of flow-measuring devices used to measure Class 1 primary variables, the element may be inspected following the test rather than recalibrated. The inspection should include, as a minimum, a visual inspection for nicks, cuts, or other damage, and dimensional measurements (as required) in three planes. Flow elements used to measure Class 2 primary variables need not be inspected following the test if the devices have not experienced flushing, line blows, or chemical cleaning.

4-1.4.7 Calibration Drift. Calibration drift is defined as a shift in the calibration characteristics. When the field verification indicates the drift is less than the instrument accuracy, the drift is considered acceptable and the pretest calibration is used as the basis for determining the test results. Occasionally the instrument calibration drift is unacceptable. Should the calibration drift, combined with the reference standard accuracy as the square root of the sum of the squares, exceed the required accuracy of the instrument, it is unacceptable.

Calibration drift can result from instrument malfunction, transportation, installation, or removal of the test instrumentation. When a field verification of calibration indicates unacceptable drift to meet the uncertainty requirements of the test, further investigation is required.

A post-test laboratory calibration should be ordered, and engineering judgment shall be used when evaluating the field verifications to determine whether the initial or recalibration is correct. Below are some recommended field verification practices that lead to the application of good engineering judgment.

(a) When instrumentation is transported to the test site between the calibration and the test period, a single-point check prior to and following the test period can isolate when the drift may have occurred. For example, check the venting of the pressure transmitters, the load on the wattmeters, or the ice-point on the temperature instrument.

(b) In locations where redundant instrumentation is employed, calibration drift should be analyzed to determine which calibration data (the initial or recalibration) produces better agreement between redundant instruments.

4-1.4.8 Loop Calibration. All analog instruments used to measure primary parameters (Class 1 or Class 2) should be loop calibrated. Loop calibration involves the calibration of the instrument through the signal-conditioning equipment. This may be accomplished by calibrating instrumentation using the test signal-conditioning equipment either in a laboratory or on site during test setup before the instrument is connected to process. Alternatively, the signal-conditioning device may be calibrated separately from the instrument by applying a known signal to each channel using a precision signal generator. Where loop calibration is not practical, an uncertainty analysis shall be performed to ensure that the combined uncertainty of the measurement system meets the uncertainty requirements described in Table 1-3-1.

Instrumentation with digital output need be calibrated only through to the digital signal output. There is no further downstream signal-conditioning equipment as the conversion of the units of measure of the measured parameter has already been performed.

4-1.4.9 Quality Assurance Program. Each calibration laboratory shall have in place a quality assurance program that documents the following information:

(a) calibration procedures
(b) calibration technician training
(c) standard calibration records
(d) standard calibration schedule
(e) instrument calibration histories

The quality assurance program should be designed to ensure that the laboratory standards are calibrated as required and that properly trained technicians calibrate the equipment in the correct manner.

The parties to the test should be allowed access to the calibration facility for auditing. The quality assurance program should also be made available during such a visit.

4-1.5 Instrument Verification

Verification is a set of operations that establishes evidence, by calibration or inspection, that specified requirements have been met. It provides a means for checking that the deviations between values indicated by a measuring instrument and corresponding known values are consistently smaller than the limits of the permissible error defined in a standard, regulation, or specification particular to the management of the measuring device.

Field verification shall be performed on all installed instrumentation prior to the test on all secondary measured parameters. The verifications shall demonstrate that the instrumentation and systems are within acceptable limits of error as defined in para. 4-2.2. Verification techniques may include field calibration, nondestructive inspection, and comparison of redundant instruments.

Elemental error sources arising from the methods of measurement shall be evaluated during the field verification to identify the uncertainty sources beyond those contained in the calibration or manufacturer's specification, data acquisition, and data reduction, that may significantly affect the assessment of the verification. Some common examples include vibration effects, mounting position effects, electromagnetic effects, external temperature and humidity effects, and, in some cases, static temperature effects. The errors may be of either a systematic or random nature, depending on their effect on the measurement.

4-2 PRESSURE MEASUREMENT

4-2.1 Introduction

This subsection presents requirements and guidance for the measurement of pressure. Electronic pressure measurement equipment should be used for primary measurements to minimize systematic and random error.

Pressure transmitters are the recommended pressure measurement devices. Application, installation, and pressure standards are described in detail in ASME PTC 19.2. The following types of pressure transmitters are expected to be used in applying this test Code:

(a) absolute pressure transmitters
(b) gauge pressure transmitters
(c) differential pressure transmitters

Electronic pressure measurement equipment is preferred due to inherent compensation procedures for sensitivity, zero balance, and thermal effect on sensitivity and on zero. Deadweight gauges, manometers, and other measurement devices that meet the uncertainty requirements of para. 4-2.2 may be used. The uncertainty of the pressure measurement shall consider effects including, but not limited to, ambient temperature, resolution, repeatability, linearity, hysteresis, vibration, power supply, stability, mounting position, radio frequency interference (RFI), static pressure, water leg, warm-up time, data acquisition, spatial variation, and primary element quality.

The piping between the process and secondary element must accurately transfer the pressure to obtain accurate measurements. Possible sources of error include pressure transfer, leaks, friction loss, trapped fluid (i.e., gas in a liquid line or liquid in a gas line), and density variations between legs.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from devices that produce electromagnetic force (EMF) such as motors, generators, electrical conduit, cable trays, and electrical service panels.

Prior to calibration, the pressure transducer range may be altered to match the process. However, the sensitivity to ambient temperature fluctuation may increase as the range is altered.

A calibration of at least five points is required. Additional points increase the accuracy but are not required. During calibration, the measuring point should be approached from an increasing and a decreasing manner to minimize the hysteresis effects.

Some pressure transducers have the capability of changing the range once the transmitter is installed. The transmitters shall be calibrated at each range to be used during the test period.

The readings from all static pressure transmitters and any differential pressure transmitters with taps at different elevations (such as on vertical flow elements) shall be adjusted to account for elevation head in water legs. This adjustment shall be applied automatically at the transmitter or in the control system or data acquisition system, or manually by the user after the raw data is collected. Care shall be taken to ensure that this adjustment is applied properly, particularly at low static pressures, and that it is applied only once.

4-2.2 Required Uncertainty

The required uncertainty will depend on the type of parameters and variables being measured. Class 1 primary parameters and Class 1 primary variables shall be measured with 0.1%-accuracy-class pressure transmitters or equivalents that have a total uncertainty of ±0.3% or better of calibrated span. Pressure transmitters should be temperature compensated. If temperature compensation is not available, the ambient temperature at the measurement location during the test period shall be compared with the temperature during calibration to determine if the decrease in accuracy is acceptable.

Class 2 primary parameters and Class 2 primary variables shall be measured with 0.25%-accuracy-class pressure transmitters or equivalents that have a total uncertainty of ±0.50% or better of calibrated span. These pressure transmitters do not need to be temperature compensated.

Secondary variables can be measured with any type of pressure transmitter or equivalent device.

4-2.3 Recommended Pressure Measurement Devices

4-2.3.1 Absolute Pressure Transmitters

(a) Application. Absolute pressure transmitters measure pressure referenced to absolute zero pressure. Absolute pressure transmitters should be used on all measurement locations with a pressure equal to or less than atmospheric. Absolute pressure transmitters may also be used to measure pressures above atmospheric pressure.

(b) Calibration. Absolute pressure transmitters can be calibrated using one of two methods. The first method involves connecting the test instrument to a device that develops an accurate vacuum at desired levels. Such a device can be a deadweight gauge in a bell jar referenced to zero pressure or a divider piston mechanism with the low side referenced to zero pressure.

The second method uses a suction-and-bleed control mechanism to develop and hold a constant vacuum in a chamber. The test instrument and the calibration standard are both connected to the chamber. The chamber shall be maintained at constant vacuum during the calibration of the instrument. Other devices can be used to calibrate absolute pressure transmitters provided that the same level of care is taken.

4-2.3.2 Gauge Pressure Transmitters

(a) Application. Gauge pressure transmitters measure pressure referenced to atmospheric pressure. To obtain absolute pressure, the test site atmospheric pressure shall be added to the gauge pressure. This test site atmospheric pressure should be measured by an absolute pressure transmitter. Gauge pressure transmitters may be used only on measurement locations with pressures higher than atmospheric. Gauge pressure transmitters are preferred over absolute pressure transmitters in measurement locations above atmospheric pressure because they are easier to calibrate.

(b) Calibration. Gauge pressure transmitters can be calibrated by an accurate deadweight gauge. The pressure generated by the deadweight gauge shall be corrected for local gravity, air buoyancy, piston surface tension, piston area deflection, actual mass of weights, actual piston area, and working medium temperature. If these corrections are not used, the pressure generated by the deadweight gauge may be inaccurate. The actual piston area and mass of weights are determined each time the deadweight gauge is calibrated. Other devices can be used to calibrate gauge pressure transmitters provided that the same level of care is taken.

4-2.3.3 Differential Pressure Transmitters

(a) Application. Differential pressure transmitters are used where flow is determined by a differential pressure meter, or where pressure drops in a duct or pipe shall be determined. Differential pressure devices may also be used in distillation column pressure-drop measurements.

(b) Calibration. Differential pressure transmitters used to measure Class 1 primary parameters and Class 1 primary variables shall be calibrated at line static pressure unless information is available detailing the effect of line static pressure on the instrument accuracy that demonstrates compliance with the uncertainty requirements of para. 4-2.2. Calibrations at line static pressure are performed by applying the actual expected process pressure to the instrument as it is being calibrated. Calibrations at line static pressure can be accomplished by one of the following three methods:

(1) two highly accurate deadweight gauges
(2) a deadweight gauge and divider combination
(3) one deadweight gauge and one differential pressure standard

Differential pressure transmitters used to measure Class 2 primary parameters and Class 2 primary variables or secondary parameters and secondary variables do not require calibration at line static pressure and can be calibrated using one accurate deadweight gauge connected to the "high" side of the instrument.

If line static pressure is not used, the span shall be corrected for high line static pressure shift unless the instrument is internally compensated for the effect. Once the instrument is installed in the field, the differential pressure from the source should be equalized and a zero value read. This zero bias shall be subtracted from the test-measured differential pressure. Other devices can be used to calibrate differential pressure transmitters provided that the same level of care is taken.

4-2.4 Absolute Pressure Measurements

4-2.4.1 Introduction. Absolute pressure measurements are pressure measurements that are below or above atmospheric pressure. Absolute pressure transmitters are recommended for these measurements. The typical absolute pressure measurement is for ambient pressure.

For vacuum pressure measurements, differential pressure transmitters may be used with the "low" side of the transmitter connected to the source to effectively result in a negative gauge that is subtracted from atmospheric pressure to obtain an absolute value. This method may be used but is not recommended for Class 1 primary parameters and Class 1 primary variables since these measurements are typically small and the difference of two larger numbers may result in error.

4-2.4.2 Installation. Absolute pressure transmitters used for absolute pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting hardware should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing that is large enough to avoid friction effects and prevent blockage.

(f) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 60 cm (2 ft) horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form so the downward slope will be completely full of liquid.

The water leg is the condensed liquid or water in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head shall be subtracted from the pressure measurement. The static head is calculated in eq. (4-2.4.2-1).

$$p_{\text{stat}} = \rho(g/g_c)h \tag{4-2.4.2-1}$$

where

g = local gravitational acceleration, ≈ 9.81 m/s^2 (32.17 ft/sec^2)

g_c = gravitational conversion factor, 1.00 (kg-m)/N-s^2) [32.17 (lbm-ft)/(lbf-sec^2)

h = sensing line vertical height, m (ft)

p_{stat} = static head, Pa (lbf/ft^2)

ρ = density of liquid in sensing line, kg/m^3 (lbm/ft^3)

All vacuum measurement sensing lines shall slope continuously upward from the source to the instrument. A purge system that isolates the purge gas during measurement of the process should be used. A continuous purge system may be used; however, it shall be regulated to have no influence on the reading. Prior to the test period, readings from all purged instrumentation should be taken successively with the purge on and with the purge off to prove that the purge air has no influence.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check shall be conducted. For vacuum measurements, the leak check is performed by isolating first the purge system and then the source. If the sensing line has no leaks, the instrument reading will not change. For nonvacuum measurements, the leak check should be performed using a leak detection fluid on the impulse tubing fittings.

Ambient pressure transmitters should be installed in the same general area and elevation of the gauge pressure transmitters and should be protected from air currents that could influence the measurements.

4-2.5 Gauge Pressure Measurements

4-2.5.1 Introduction. Gauge pressure measurements are pressure measurements that are at or above atmospheric pressure. These measurements may be made with gauge or absolute pressure transmitters. Gauge pressure transmitters are recommended since they are easier to calibrate and to check in situ than absolute pressure transmitters.

4-2.5.2 Installation. Gauge pressure transmitters used for gauge pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting hardware should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing that is large enough to avoid friction effects and prevent blockage.

(f) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 60 cm (2 ft) horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form so the downward slope will be completely full of liquid.

The water leg is the condensed liquid or water in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head must be subtracted from the pressure measurement. The static head is calculated in eq. (4-2.4.2-1).

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check shall be conducted. The leak check should be performed using a leak detection fluid on the impulse tubing fittings.

4-2.6 Differential Pressure Measurements

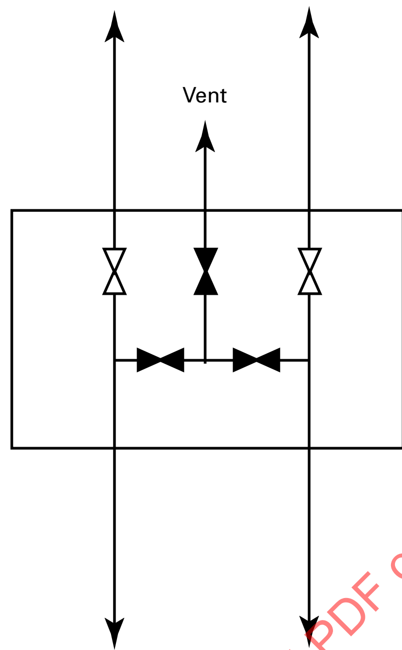
4-2.6.1 Introduction. Differential pressure measurements are used to determine the difference in static pressure between pressure taps in a primary device. Differential pressure transmitters are recommended for these measurements. Typical differential pressure measurements include the differential pressure of a flow element or pressure loss in a pipe or duct. The differential pressure transmitter measures this pressure difference or pressure drop, which is used to calculate the fluid flow.

4-2.6.2 Installation. Differential pressure transmitters used for differential pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting hardware should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

Figure 4-2.6.2-1 Five-Way Manifold



(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Ensure that both impulse legs are at the same temperature.

(f) When using a sealing fluid, fill both impulse legs to the same level.

(g) Use impulse tubing that is large enough to avoid friction effects and prevent blockage.

(h) Keep corrosive or high-temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 60 cm (2 ft) horizontally from the source before the downward slope begins. This horizontal length will allow condensation to form so the downward slope will be completely full of liquid.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing lines upstream of the instrument. The instrument sensing lines should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing lines of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

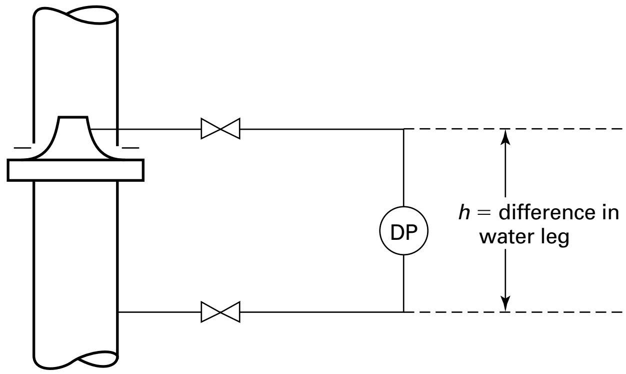
Differential pressure transmitters should be installed using a five-way manifold, as shown in Figure 4-2.6.2-1. This manifold is recommended rather than a three-way manifold because the five-way manifold eliminates the possibility of leakage past the equalizing valve. The vent valve acts as a telltale for leakage detection past the equalizing valves.

Once transmitters are connected to process, a leak check shall be conducted. The leak check should be performed using a leak-detection fluid on the impulse tubing fittings.

When a differential pressure meter is installed on a flow element that is located in a vertical steam or water line, the measurement shall be corrected for the difference in sensing line height and fluid head change unless the upper sensing line is installed against a steam or water line inside the insulation down to where the lower sensing line protrudes from the insulation. The correction for the noninsulated case is shown in Figure 4-2.6.2-2.

For differential pressure transmitters on flow devices, the transmitter output is often an extracted square root value unless the square root is applied in the plant control system. Care should be taken to ensure that the square root is applied only once.

Figure 4-2.6.2-2 Water Leg Correction for Flow Measurement



GENERAL NOTE:

For upward flow: $\Delta p_{true} = \Delta p_{meas} + \left(D_{amb} - D_{pipe}\right)\left(g/g_c\right)h$

For downward flow: $\Delta p_{true} = \Delta p_{meas} - \left(D_{amb} - D_{pipe}\right)\left(g/g_c\right)h$

where

D_{amb} = fluid density at ambient conditions, kg/m^3 (lbm/ft^3)
D_{pipe} = fluid density at conditions within pipe, kg/m^3 (lbm/ft^3)
g = local gravitational force per unit mass, ≈ 9.81 m/s^2 (32.17 ft/sec^2)
g_c = gravitational dimensional constant, 1.00 (kg-m)/(N-s^2) [32.17 (lbm-ft)/(lbf-sec^2)]
h = difference in water leg, m (ft)
Δp_{meas} = measured pressure difference, Pa (lbf/ft^2)
Δp_{true} = true pressure difference, Pa (lbf/ft^2)

4-3 TEMPERATURE MEASUREMENT

4-3.1 Introduction

This subsection presents requirements and guidance for the measurement of temperature. Recommended temperature measurement devices and the calibration and application of temperature measurement devices are discussed. Electronic temperature measurement equipment should be used for primary measurements to minimize systematic and random errors. Application, installation, and standards are more completely described in ASME PTC 19.3.

The uncertainty of the temperature measurement shall consider effects including, but not limited to, stability, environment, self-heating, parasitic resistance, parasitic voltages, resolution, repeatability, hysteresis, vibration, warm-up time, immersion or conduction, radiation, dynamic and spatial variation, and data acquisition.

Thermocouples, resistance temperature detectors, and thermistors are the recommended temperature measurement devices. Economic, application, and uncertainty considerations should be used in the selection of the most appropriate temperature measurement device.

Since temperature measurement technology will change over time, this Code does not limit the use of other temperature measurement devices that are not currently available or not currently reliable. If such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from EMF-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

4-3.2 Required Uncertainty

The required uncertainty will depend on the type of parameters and variables being measured. Refer to paras. 4-1.2.2 and 4-1.3.1 for discussion on measurement classification and instrumentation categorization.

Class 1 primary parameters and Class 1 primary variables shall be measured with temperature measurement devices that have an instrument systematic uncertainty of no more than ±0.28°C (0.50°F) for temperatures lower than 93°C (200°F) and no more than ±0.5°C (1.0°F) for temperatures higher than 93°C (200°F).

Class 2 primary parameters and Class 2 primary variables shall be measured with temperature measurement devices that have an instrument systematic uncertainty of no more than ±1.7°C (3.0°F).

Secondary variables should be measured with temperature measurement devices that have an instrument systematic uncertainty of no more than ±2.8°C (5.0°F).

4-3.3 Recommended Temperature Measurement Devices

4-3.3.1 Thermocouples. Thermocouples may be used to measure temperature of any fluid above 93°C (200°F). The maximum temperature is dependent on the type of thermocouple and sheath material used.

Thermocouples may be used for measurements below 93°C (200°F) if caution is used. The thermocouple is a differential-type device. The thermocouple measures the difference between the measurement location in question and a reference temperature. The greater this difference, the higher the EMF from the thermocouple. Therefore, below 93°C (200°F) the EMF becomes low and is subject to induced noise, causing increased systematic uncertainty and inaccuracy.

Measurement errors associated with thermocouples typically derive from the following primary sources:

(a) junction connection
(b) shunt impedance
(c) galvanic action
(d) thermal shunting
(e) noise and leakage currents
(f) thermocouple specifications

The homogeneity of the thermocouple wire is an important factor in accurate measurement. The EMF developed by a thermocouple made from homogeneous wires is a function of the temperature difference between the measurement and the reference junction. However, if the wires are not homogeneous in a region where a temperature gradient exists, extraneous EMF will develop, and the output of the thermocouple will depend on factors in addition to the temperature difference at the two junctions. See ASME PTC 19.3.

The elements of a thermocouple shall be electrically isolated from each other, from ground, and from conductors on which they may be mounted, except at the measuring junction. When a thermocouple is mounted along a conductor, such as a pipe or metal structure, special care should be exercised to ensure good electrical insulation between the thermocouple wires and the conductor to prevent stray currents in the conductor from entering the thermocouple circuit and vitiating the readings. Stray currents may further be reduced with the use of guarded integrating analog-to-digital (A/D) techniques. Further, to reduce the possibility of magnetically induced noise, the thermocouple wires should be constructed in a twisted uniform manner.

Thermocouples are susceptible to drift after cycling. Cycling is the act of exposing the thermocouple to the process temperature and then removing to ambient conditions. The number of times a thermocouple is cycled should be kept to a minimum.

Thermocouples can effectively be used in high-vibration areas such as main or high-pressure inlets to the steam turbine. High-vibration measurement locations may not be conducive to other measurement devices. This Code recommends that the highest EMF per degree be used in all applications. The NIST ITS-90 Thermocouple Database has technical information about thermocouples.

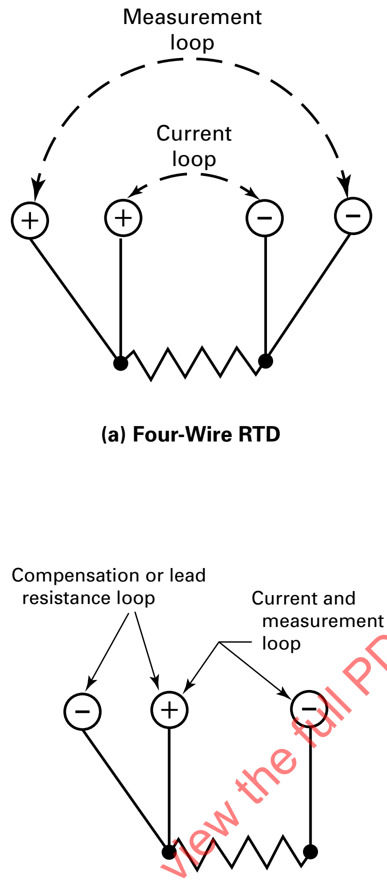
4-3.3.1.1 Class 1 Primary Parameters. Thermocouples used to measure Class 1 primary parameters shall have continuous leads from the measuring junction to the connection on the reference junction. These high-accuracy thermocouples shall have a reference junction at 0°C (32°F) or an ambient reference junction that is well insulated and calibrated.

4-3.3.1.2 Class 2 Primary Parameters. Thermocouples used to measure Class 2 primary parameters can have junctions in the sensing wire. The junction of the two sensing wires shall be maintained at the same temperature. The reference junction may be at ambient temperature provided that the ambient is measured and the measurement is compensated for changes in the reference junction temperature.

4-3.3.1.3 Thermocouple Signal Measurement. Many instruments are used today to measure the output voltage. The use of each of these instruments in a system to determine temperature requires that they meet the uncertainty requirements for the parameter. It is recommended that the thermocouple signal conversion use ITS-90 software compensation techniques.

4-3.3.2 Resistance Temperature Detectors. Resistance temperature detectors (RTDs) may be used in testing from any low temperature to the highest temperature, depending on the mechanical configuration and manufacturing methods. RTDs can measure from −270°C to 850°C (−454°F to 1,562°F). ASTM E1137/E1137M-08 (R2014) provides standard specifications for industrial platinum resistance thermometers and includes requirements for manufacture, pressure, vibration, and mechanical shock to improve the performance and longevity of these devices.

Figure 4-3.3.2.1-1 Three- and Four-Wire RTDs



(a) Four-Wire RTD

(b) Three-Wire RTD

Measurement errors associated with RTDs typically derive from the following primary sources:

(a) self-heating
(b) environment
(c) thermal shunting
(d) thermal EMF
(e) stability
(f) immersion

Although RTDs are considered to be more linear devices than thermocouples, due to manufacturing technology, RTDs are more susceptible to vibrational applications. As such, care should be taken in the specification and application of RTDs, with consideration for the effect on the devices' stability. Field verification techniques should be used to demonstrate that the stability is within the uncertainty requirements of para. 4-3.2.

4-3.3.2.1 Class 1 Primary Parameters. Class 1 primary parameters shall be measured with a Grade A four-wire platinum RTD as shown in Figure 4-3.3.2.1-1, illustration (a) if it can be shown to meet the uncertainty as required in para. 4-3.2.

4-3.3.2.2 Class 2 Primary Parameters. Class 2 primary parameters shall be measured with Grade A three-wire platinum RTDs as shown in Figure 4-3.3.2.1-1, illustration (b) if they can be shown to meet the uncertainty as required in para. 4-3.2. The four-wire technique is preferred to minimize effects associated with lead-wire resistance due to dissimilar lead wires.

4-3.3.2.3 RTD Signal Measurement. Many instruments are used to measure the output resistance. The use of each of these instruments in a system to determine temperature requires that they meet the uncertainty requirements for the parameter. It is recommended that the RTD signal conversion use the Callendar–Van Dusen equation for curve fitting. The values for the coefficients α, β, and δ should be taken from the calibration coefficients. RTD calibrations should be done in accordance with the methods detailed in ITS-90, Section 4.6.

4-3.3.3 Thermistors. Thermistors are constructed with ceramic-like semiconducting material that acts as a thermally sensitive variable resistor. This device may be used on any measurement below 149°C (300°F). Above this temperature, the signal is low and susceptible to error from current-induced noise. Although positive temperature coefficient (TC) units are available, most thermistors have a negative TC; that is, unlike an RTD, their resistance decreases with increasing temperature. The negative TC is large enough to allow the thermistor circuit to detect minute changes in temperature that could not be observed with an RTD or thermocouple circuit. As such, the thermistor is the most sensitive, whereas the thermocouple is the most versatile and the RTD is the most stable.

Measurement errors associated with thermistors typically derive from the following primary sources:

(a) self-heating
(b) environment
(c) thermal shunting
(d) decalibration
(e) stability
(f) immersion

The four-wire resistance measurement is not required for thermistors as it is for RTDs due to the thermistors' high resistivity. Thus, the measurement lead resistance produces error magnitudes less than the equivalent RTD error. Thermistors are generally more fragile than RTDs and thermocouples and shall be carefully mounted and handled in accordance with the manufacturer's specifications to avoid crushing or bond separation.

4-3.3.3.1 Thermistor Signal Measurement. Many instruments can be used to measure the output resistance. The use of each of these instruments in a system to determine temperature requires that they meet the uncertainty requirements for the parameter. It is recommended that the thermistor signal conversion use the Steinhart-Hart equation for curve fitting. The values for the coefficients A, B, and C should be taken from the calibration coefficients. Thermistor calibrations should be done in accordance with the methods detailed in ITS-90, Section 4.6.

4-3.4 Calibration of Primary Parameter Temperature Measurement Devices

This Code recommends that primary (Class 1 or Class 2) parameter instrumentation used in the measurement of temperature have a suitable calibration history (three or four sets of calibration data). The calibration history should include the temperature level the device experienced between calibrations. A device that is stable after being used at low temperatures may not be stable at higher temperatures. Hence, the calibration history of the device should be evaluated to demonstrate the required stability of the parameter.

During the calibration of any thermocouple, the reference junction shall be held constant, preferably at the ice point, with an electronic reference junction or isothermal reference junction, or in an ice bath. The calibration shall be made by an acceptable method, with the standard being traceable to a recognized national standards laboratory such as NIST. The calibration shall be conducted over the temperature range in which the instrument is used.

See ASME PTC 19.3 for a more detailed discussion of calibration methods.

4-3.5 Temperature Scale

ITS-90 is recognized and maintained by NIST to provide a standard scale of temperature for use by science and industry in the United States.

Temperatures on the ITS-90 can be expressed in terms of international kelvins (K), represented by the symbol T_{90}, or in terms of international Celsius (°C), represented by the symbol t_{90}.

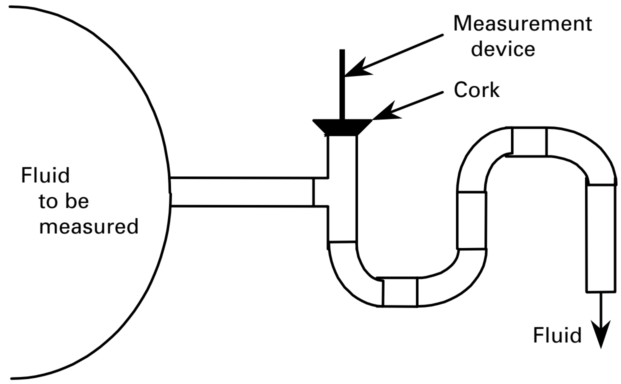
$$t_{90} = T_{90} - 273.15 \tag{4-3.5-1}$$

Fahrenheit temperature (°F), t_f, is obtained from the conversion formula

$$t_f = (9/5)t_{90} + 32 \tag{4-3.5-2}$$

Temperatures on the ITS-90 are defined in terms of equilibrium states of pure substances (defining points), interpolating instruments, and equations that relate the measured property to T_{90}. The defining equilibrium states and the values of temperature assigned to them are listed in ITS-90 and ASTM Manual Series: MNL 12.

Figure 4-3.6.2-1 Flow-Through Well



4-3.6 Typical Applications

4-3.6.1 Temperature Measurement of Fluid in a Pipe or Vessel. Temperature measurement of a fluid in a pipe or vessel is accomplished by installing a thermowell. The thermowell can be installed into a system by a threaded, socket weld, or flanged connection and has a bore extending to near the tip to facilitate the immersion of a temperature measurement device.

The bore should be sized to allow adequate clearance between the temperature measurement device and the well. The bottom of the bore of the thermowell should be the same shape as the tip of the temperature measurement device. Tubes and wells should be as thin as possible and consistent with safe stress and other ASME Code requirements, and the inner diameters of the wells should be clean, dry, and free from corrosion or oxide. The bore should be cleaned with high-pressure air prior to insertion of the device.

The thermowell should be installed so that the tip protrudes through the boundary layer of the fluid to be measured. Unless limited by design considerations, the temperature sensor shall be immersed in the fluid at least 75 mm (3 in.) but not less than one-quarter of the pipe diameter. If the pipe diameter is less than 100 mm (4 in.), the temperature sensor shall be arranged axially in the pipe, by inserting it in an elbow or tee. If such fittings are not available, the piping should be modified to render this possible. The thermowell should be located in an area where the fluid is well mixed and has no potential gradients. If the location is near the discharge of a plant component, the thermowell should be downstream of the discharge location, such as downstream of an elbow in the pipe, to ensure adequate mixing.

If more than one thermowell is installed in a given pipe location, the second thermowell should be installed on the opposite side of the pipe and not directly downstream of the first thermowell.

When the temperature measurement device is installed, it should be "spring-loaded" to ensure positive thermal contact between the temperature measurement device and the thermowell.

For Class 1 primary parameter measurements, the portion of the thermowell or lag section protruding outside the pipe or vessel should be insulated, along with the device itself, to minimize conduction losses. The locations at which Class 1 primary temperature measurements are taken for use in determining enthalpy shall be as close as possible to the points at which the corresponding pressures are to be measured.

4-3.6.2 Temperature Measurement of Low-Pressure Fluid in a Pipe or Vessel. As an alternate to installing a thermowell in a pipe, if the fluid is at low pressure, either the temperature measurement device can be installed directly into the pipe or vessel or "flow-through wells" may be used.

The temperature measurement device can be installed directly into the fluid using a bore-through-type compression fitting. The fitting should be of proper size to clamp onto the device. A plastic or Teflon-type ferrule is recommended so that the device can be removed easily and used elsewhere. The device shall protrude through the boundary layer of the fluid. Care shall be used so that the device does not protrude into the fluid enough to cause vibration of the device from the flowing fluid.

A flow-through well is shown in Figure 4-3.6.2-1. This arrangement is applicable only for water in a cooling system where the fluid is not hazardous and can be disposed of without great cost. The principle is to allow the fluid to flow out of the pipe or vessel, over the tip of the temperature measurement device.

4-3.6.3 Temperature Measurement in a Duct. Measurement of the fluid temperature in a duct requires several measurement points to minimize the uncertainty effects of temperature gradients. Typically, the duct pressures are low or negative so that thermowells or protection tubes are not needed. A long sheathed thermocouple or an unsheathed thermocouple attached to a rod will suffice.

The required number of measurement points is determined experimentally or by experience from the magnitude of the temperature variations at the desired measurement cross section and the required maximum uncertainty of the value of the average temperature. The total uncertainty of the average temperature is affected by the uncertainty of the individual measurements, the number of points used in the averaging process, the velocity profile, the temperature gradients, and the time variation of the readings. The parties to the test should locate the measurement plane at a point of uniform temperatures and velocities to the extent practical. Points should be located every 0.8 m^2 (9 ft^2), with a minimum of 4 points and a maximum of 36 points.

ASME PTC 19.1 describes the method of calculating the uncertainty of the average of multiple measurements that vary with time.

For circular ducts, the points should be installed in two diameters 90 deg from each other, as shown in Figure 4-3.6.3-1, which also shows the method of calculating the measurement point spacing. The point spacing is based on locating the measurement points at the centroid of equal areas.

For square or rectangular ducts, the same concept of locating the measurement points at centroids of equal areas should be used. The measurement points should be laid out in a rectangular pattern that takes into account the horizontal and vertical temperature gradients at the measurement cross section. The direction with the highest temperature gradient should have the closer point spacing.

4-3.6.4 Temperature Measurement of Inlet Air. Measurement of the inlet air temperature of the air crossing the test boundary at the inlet varies spatially. The number and location of temperature measurement devices should be determined such that the overall measurement uncertainty of the average inlet air temperature measurement devices will be less than 0.5°C (1°F). Due to the shape of the inlet system, measuring the temperature downstream provides a better chance for mixing and a more representative distribution of the temperature profile results. Spatial variation effects are considered errors of method and contributors to the systematic uncertainty in the measurement system. ASME PTC 19.1 should be consulted for the determination of the uncertainty associated with spatial variation.

4-4 HUMIDITY MEASUREMENT

4-4.1 Introduction

This subsection presents requirements and guidance for the measurement of humidity. Recommended humidity measurement devices, and calibration and application of humidity measurement devices are also discussed. Electronic humidity measurement equipment should be used for primary measurements to minimize systematic and random errors.

The uncertainty of humidity measurement equipment shall consider effects including, but not limited to, resolution, stability, environment, temperature measurement errors, pressure measurement errors, warm-up time, spatial variation, nonlinearity, repeatability, analog output, and data acquisition.

Since humidity measurement technology will change over time, this Code does not limit the use of other humidity measurement devices that are not currently available or reliable. If such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

Measurements to determine moisture content shall be made in proximity with measurements of ambient dry bulb temperature to provide the basis for determination of air properties.

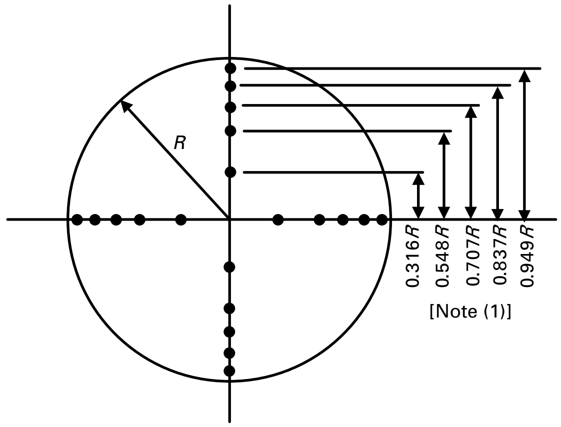
All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from EMF-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

4-4.2 Required Uncertainty

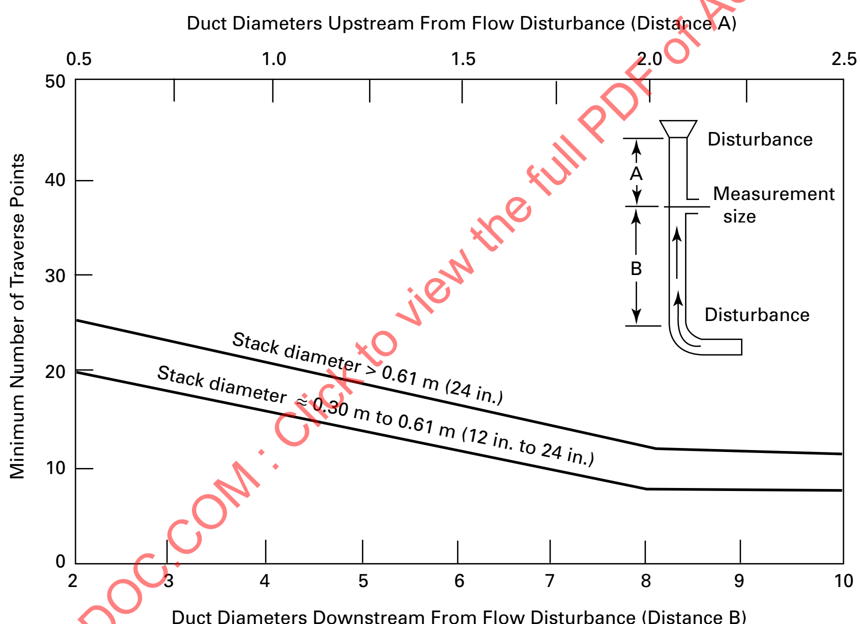
The required uncertainty will depend on the type of parameters and variables being measured. Class 1 primary parameters and Class 1 primary variables shall be measured with humidity measurement devices that determine specific humidity to an uncertainty of no more than ±0.001 g water vapor/g dry air (0.001 lbm water vapor/lbm dry air). Class 2 primary parameters and Class 2 primary variables shall be measured with humidity measurement devices that determine specific humidity to an uncertainty of no more than ±0.002 g water vapor/g dry air (0.002 lbm water vapor/lbm dry air).

Secondary variables can be measured with any type of humidity measurement device.

Figure 4-3.6.3-1 Duct Measurement Points



Cross Section of Circular Gas Passage



NOTE: (1) Dots indicate location of sample points. To calculate the distance from sampling point to center of pipe, use the following equation:

$$r_p = R\sqrt{\frac{2(2p-1)}{n}}$$

where

n = total number of points, = $\pi R^2/A_{cmax}$, rounded to the next multiple of 4, but no fewer than 4 and no more than 36
A_{cmax} = maximum area per centroid, = 0.8 m^2 (9 ft^2)
p = sampling point number, numbered from the center outward; all four points on the same circumference have the same number
R = radius of duct (in the same units as r_p), m (ft)
r_p = distance from center of duct to point p, m (ft)

For example, with 20 total points, the radius of point r_3 is

$r_3 = R \times \{[2 \times (2 \times 3 - 1)]/20\}^{0.5}$
$= R \times (0.5)^{0.5}$
$= 0.707R$

4-4.3 Recommended Humidity Measurement Devices

Relative humidity transmitters and wet bulb and dry bulb psychrometers are the recommended humidity measurement devices. Economic, application, and uncertainty considerations should be used in the selection of the most appropriate humidity measurement device.

4-4.3.1 Relative Humidity Transmitters

(a) General. Relative humidity transmitters employ specifically selected hydrophilic materials. As the humidity changes at the ambient temperature, the material exchanges enough moisture to regain equilibrium, and corresponding measurable changes occur in the electrical resistance or capacitance of the device. Commercially available relative humidity transmitters use sensors with a wide variety of hygroscopic substances, including electrolytes and substantially insoluble materials. Relative humidity transmitters are commonly employed for the direct measurement of parameters, including relative humidity and dry bulb temperature, and use a thin polymer film as the sensor to absorb water molecules. These instruments are often microprocessor based, and from the parameters of relative humidity and dry bulb temperature, variables including dew-point temperature, absolute humidity, mixing ratio, wet bulb temperature, and enthalpy may be calculated. In cases where the instruments output moisture-indicating parameters or variables that are used in the calculation of the test results (primary parameter or primary variable), the instrument's internal calculation formulas and basis shall be verified to demonstrate compliance with the uncertainty requirements detailed in para. 4-4.2. Relative humidity transmitters typically provide accuracy specifications that include nonlinearity and repeatability over relative humidity (RH) conditions (i.e., ±2% RH from 0% RH to 90% RH, and ±3% RH from 90% RH to 100% RH).

The application of relative humidity transmitters is highly sensitive to temperature equilibrium, as a small difference between the measured object and the sensor causes an error. This error is greatest when the sensor is colder or warmer than the surroundings and the humidity is high.

The sensor location should be selected to minimize sensor contamination. Air should circulate freely around the sensor. A rapid airflow is recommended as it ensures that the sensor and the surroundings are at temperature equilibrium. The installation orientation should be in accordance with the device manufacturer's specifications.

(b) Measurement Errors. Measurement errors associated with hygrometers typically derive from the following primary sources:

(1) sensor contamination
(2) analog output
(3) installation location
(4) temperature equilibrium
(5) accuracy
(6) resolution

(c) Calibration. Relative humidity transmitters shall be calibrated using one of two methods. The first method involves calibrating against high-quality, certified humidity standards to achieve the maximum achievable accuracy. The second method calibrates with certified salt solutions that may include lithium chloride (LiCl), magnesium chloride ($MgCl_2$), sodium chloride (NaCl), and potassium sulfate (K_2SO_4). During calibration, the temperatures of the sensor and of the measured object shall be in equilibrium to minimize the error associated with the temperature equilibrium. Further, when using the second method, the equilibrium humidity of the salt solution shall be corrected for the solution's temperature using Greenspan's calibration corrections or equivalent.

Relative humidity transmitters shall be calibrated to meet the uncertainty requirements in specific humidity as described in para. 4-4.2. This shall be demonstrated with the application of an uncertainty analysis, with consideration for the uncertainty associated with other measured parameters, including barometric pressure and ambient dry bulb temperature or wet bulb temperature.

4-4.3.2 Wet Bulb and Dry Bulb Psychrometers

(a) General. Wet bulb and dry bulb psychrometers consist of two temperature sensors and use the temperature effects caused by latent heat exchange. The temperature sensors shall be shielded from solar and other sources of radiation and shall have a constant airflow across the sensing element.

Sling psychrometers are susceptible to the effects of radiation from the surroundings and to other errors such as those resulting from faulty capillary action. When using a sling psychrometer, it is important that the instrument is whirled for a sufficient number of times until the wet bulb temperature reaches a steady minimum value. Once this occurs, it is imperative that the temperature be read quickly, with consideration for inertial effects on the temperature element in the case of a liquid-in-glass thermometer to minimize observation errors. The use of an average from at least three observations is advisable.

Although not required, a mechanically aspirated psychrometer is recommended. If a psychrometer is used, a wick should not be placed over the dry bulb temperature sensor (as is required for measurement of wet bulb temperature). If the air velocity across the sensing element is greater than 7.6 m/s (1,500 ft/min), shielding of the sensing element is required to minimize stagnation effects.

The thermodynamic wet bulb temperature is the air temperature that results when air is adiabatically cooled to saturation. Wet bulb temperature can be inferred by a properly designed mechanically aspirated psychrometer. The process by which a psychrometer operates is not adiabatic saturation, but one of simultaneous heat and mass transfer from the wet bulb sensing element. The resulting temperature achieved by a psychrometer is sufficiently close to the thermodynamic wet bulb temperature over most of the range of conditions. However, a psychrometer should not be used for temperatures below 5°C (40°F) or when the relative humidity is less than 15%. Within the allowable range of use, a properly designed psychrometer can provide a determination of wet bulb temperature with an uncertainty of approximately ±0.14°C (0.25°F) [based on a temperature sensor uncertainty of ±0.08°C (0.15°F)].

A mechanically aspirated psychrometer should incorporate the following features:

(1) The sensing element is shielded from direct sunlight and any other surface that is at a temperature other than the dry bulb temperature. If the measurement is to be made in direct sunlight, the sensor shall be enclosed by a double-wall shield that permits the air to be drawn across the sensor and between the walls.

(2) The sensing element is suspended in the air stream and is not in contact with the shield walls.

(3) The sensing element is snugly covered by a clean cotton wick that is kept wetted from a reservoir of distilled water. The length of the wick shall be sufficient to minimize the sensing-element stem conduction effects and to ensure that it is properly wetted.

(4) The air velocity across the sensing element is maintained constant in the range of 240 m/min to 360 m/min (800 ft/min to 1,200 ft/min).

(5) Air is drawn across the sensing element in such a manner that it is not heated by the fan motor or other sources of heat. The psychrometer should be located at least 1.5 m (5 ft) above ground level and should not be located within 1.5 m (5 ft) of vegetation or surface water.

(b) Measurement Errors. Measurement errors associated with wet bulb and dry bulb psychrometers typically derive from the following primary sources:

(1) temperature sensor

(2) installation location

(3) radiation

(4) conduction

(c) Calibration. The temperature sensors of wet bulb and dry bulb psychrometers shall be calibrated in accordance with para. 4-3.4 and shall meet the uncertainty requirements for specific humidity as described in para. 4-4.2. The uncertainty shall be demonstrated with the application of an uncertainty analysis, with consideration for the errors associated with other measured parameters including barometric pressure.

4-5 FLOW MEASUREMENT

4-5.1 Introduction

This subsection presents the requirements and guidance for flow measurements of air, product gases, steam, and water. Generally, differential pressure devices provide a high level of accuracy, with standard calculations, at a reasonable cost. Other devices may be used, depending on the application. Compliance with the requirements of ASME MFC-3M for differential flowmeters and of ASME PTC 19.5 for other types of flowmeters is required. New designs or alternate measurement devices may be used as long as the device accuracy is consistent with the uncertainty requirements for the test results consistent with this test Code.

4-5.2 Water and Steam

4-5.2.1 General. Water flows can be measured more accurately than steam flows. Whenever possible, it is best to configure the tests so that water flows are measured and used to calculate steam flows. The usual method of determining flow is with a differential pressure meter, using two independent differential pressure instruments and two sets of taps.

4-5.2.2 Primary Flow Measurements. A flow section channel that meets the requirements of ASME MFC-3M for differential flowmeters and of ASME PTC 19.5 for other types of flowmeters is recommended for Class 1 primary flow measurements.

4-5.2.3 Other Flow-Measuring Devices. Other flow-measuring devices may be used if they are consistent with the accuracy required by this test Code. These devices can be used for Class 2 flow measurements and for secondary flow measurements.

4-5.2.4 Water Flow Characteristics. Flow measurements shall not be undertaken unless the flow is steady or fluctuates only slightly with time. Fluctuations in the flow shall be suppressed before the beginning of a test by careful adjustment of flow and level controls or by introducing a combination of conductance, such as pump recirculation, and resistance, such as throttling the pump discharge, in the line between the pulsation sources and the flow-measuring device. Hydraulic damping devices on instruments do not eliminate errors due to pulsations and, therefore, should not be used.

In passing through the flow-measuring device, the water should not flash into steam. The minimum throat static pressure shall be higher than the saturation pressure corresponding to the temperature of the flowing water by at least 20% of the throat velocity head to avoid cavitation.

4-5.2.5 Steam Flow Characteristics. In passing through the flow-measuring device, the steam shall remain superheated. For steam lines with desuperheaters, the flow section should be installed ahead of desuperheaters, and the total flow shall be determined from the sum of steam flow and the desuperheater water flow.

4-5.2.6 Secondary Measurements. The calculation of steam flow through a nozzle, an orifice, or a venturi should be based on upstream conditions of pressure, temperature, and viscosity. To avoid the disturbing influence of a thermowell located upstream of a primary element, downstream measurements of pressure and temperature should be used to determine the enthalpy of the steam, which is assumed to be constant throughout a well-insulated flow measurement section. Based on this enthalpy and the upstream pressure, the desired upstream properties can be computed from the ASME Steam Tables.

4-5.3 Gas Flow Measurements

4-5.3.1 General. Gas flows may be measured using a number of devices, depending on the application. The usual method of determining flow is with a differential pressure meter, using two independent differential pressure instruments and two sets of taps.

4-5.3.2 Primary Flow Measurements. A flow section that meets the requirements of ASME MFC-3M for differential flowmeters and of ASME PTC 19.5 for other types of flowmeters is recommended for Class 1 primary flow measurements. The flow section should be calibrated for Class 1 primary measurements.

4-5.3.3 Other Flow-Measuring Devices. Other flow-measuring devices consistent with the accuracy required by this test Code may be used. These devices can be used for Class 2 flow measurements and for secondary flow measurements. An evaluation of the accuracy and impact on the uncertainty of the test results should be considered in selecting other measurement devices.

4-6 GAS PURITY MEASUREMENTS

4-6.1 Introduction

This subsection presents the requirements and guidance for measuring gas purity in air and ASU product gases. Any gas purity measurement method consistent with this test Code may be used. Gas chromatographs are typically used to measure gas purity, but new measurement devices may be used as long as the device accuracy is consistent with the uncertainty requirements of this test Code. Gas purity may be measured with a number of different devices and processes.

(a) Chemiluminescent analyzers are used to determine the concentrations of nitrogen oxides NO and NO_x.

(b) Fourier transform infrared spectrometry (FTIR) can detect all contaminant species of interest rapidly and simultaneously, with detection limits in the parts-per-billion (ppb) range.

(c) Gas chromatography is used to analyze mixtures of gaseous or volatile liquid compounds.

(d) Mass spectrometry is commonly used for gas analysis, even in standard operations monitoring.

(e) Nondispersive infrared photometer (NDIR) measurements can detect from 0 parts per million (ppm) to 10 ppm CO or 0 ppm to 5 ppm CO_2 impurities.

(f) Paramagnetic sensors can measure oxygen concentrations as low as 0% to 1%.

(g) Plasma detectors exploit the principle of electroluminescence without the aid of lamps in an electromagnetic field.

(h) A thermal conductivity detector (TCD) is a bulk property detector and a chemical-specific detector commonly used in the analysis of the permanent gases argon, oxygen, nitrogen, and carbon dioxide.

(i) A trace oxygen sensor (galvanic fuel cell) can measure oxygen concentrations as low as 0 ppm to 10 ppm. Measurements can be affected by the temperature and pressure of the sample. Measuring devices shall have pressure and temperature compensation to account for ambient and sample conditions. Careful attention to the sensor requirements and installation requirements will reduce the measurement uncertainty. The measuring devices shall be protected from sample gases beyond the calibrated range of the instrument.

In some cases, contaminant gases may affect the reading of the instrument. The potential for contaminants to enter into the process or sample gas streams should be evaluated.

Installed ASU gas purity measurement devices are typically used to measure gas purity during a Code test. Temporary measurement devices may be used where gas purity has a significant impact on the test uncertainty. The instrumentation shall be inspected to ensure that the installation requirements are met and the gas sample lines are installed correctly. The instruments shall be calibrated before testing with appropriate concentrations of reference gas within the expected range of measurement. Some gas purity measurement devices have the capability of recording measurements in a variety of scales. The calibration shall be performed on all scales expected for use during the test.

The data from the instruments shall be collected by a data acquisition device. The measurements should be collected at intervals of at least 5 min or at the most frequent interval consistent with the device. The frequency of the data collection and the expected operating variations should be evaluated to determine their impacts on the test uncertainty. If a plant control system is used to record the purity data, any deadbands shall be removed to allow recording of actual instrument data.

4-6.2 Required Uncertainty

The required uncertainty depends on the type of parameters and the variables being measured.

(a) Class 1 primary parameters and Class 1 primary variables shall be measured with gas purity measurement devices that determine the concentration of a specific gas to an uncertainty of no more than ±0.25%.

(b) Class 2 primary parameters and Class 2 primary variables shall be measured with gas purity measurement devices that determine the concentration of a specific gas to an uncertainty of no more than ±1.0%.

(c) Secondary variables can be measured with any type of gas purity measurement device.

4-6.3 Gas Purity Measurement Devices

A gas chromatograph is the standard measurement device typically used for the analysis of a wide range of gases. As the state of the art changes in the industry, instrumentation may be introduced that meets the Code requirements for gas purity measurement accuracy and that is more economical. This Code does not specify specific instrument technology but, rather, identifies the uncertainty expected for a Code-level test.

4-7 SPEED MEASUREMENTS

If required as a test measurement, shaft speed is normally measured from the shaft connected to the compressor. The shaft speed may also be measured by standard speed sensors used in the compressor control system. For compressors connected to alternating-current (AC) electric motors, the line frequency measured at the generator terminals may be used instead of shaft speed since the shaft speed is directly coupled to the line frequency. The chosen method shall meet the uncertainty requirement in this Code.

4-8 ELECTRICAL MEASUREMENTS

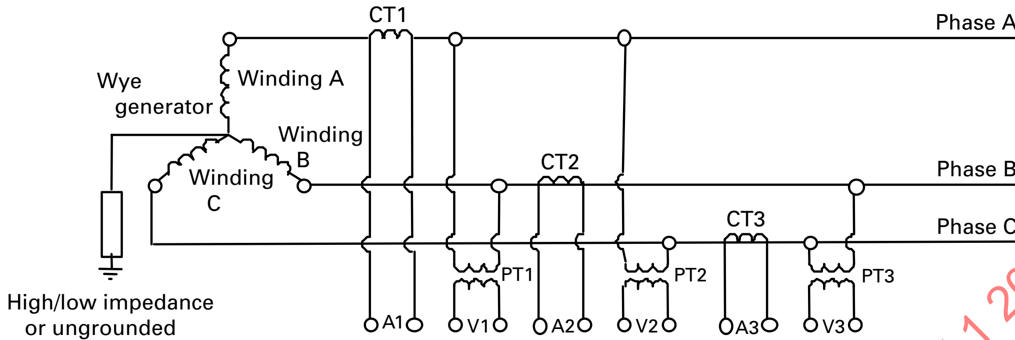
4-8.1 Introduction

This subsection presents requirements and guidance for the measurement of electrical power. Power measurements should be conducted using sufficient instrumentation to ensure that no additional uncertainty is introduced due to the metering method under all conditions of the test. AC power measurements are typically used for most test power calculations. If direct-current (DC) power measurements are required for a test, ANSI/IEEE Standard 120-1989 shall be referenced for measurement requirements not included in this subsection or for any additionally required instruction.

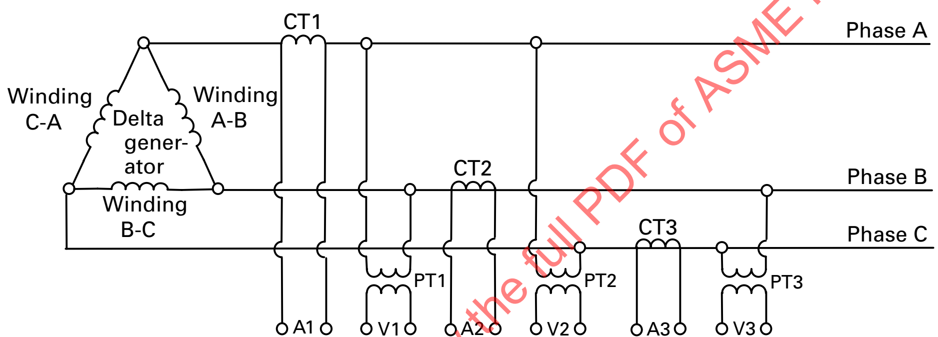
4-8.2 Polyphase AC Electrical Measurement System Connections

The connection of the primary elements for measurement of polyphase AC power systems is subject to required uncertainty and the degree of unbalance between phases. Many different connections can be used for measuring polyphase AC; however, the connections covered in this Code are for three-wire-type systems and are recommended for

Figure 4-8.2-1 Three-Wire Metering Systems



(a) Wye Generator Connections to Three Wattmeters or One Three-Element Watt-Hour Meter



(b) Delta Generator Connections to Three Wattmeters or One Three-Element Watt-Hour Meter

meeting the uncertainty requirements of this Code. Figure 4-8.2-1 shows the connections for wye generators and delta generators using three wattmeters or one three-element watt-hour meter.

4-8.3 Electrical Metering Equipment

Wattmeters are the electrical metering equipment typically used to measure electrical energy. Watt-hour meters may also be used for power measurements. Single- or polyphase metering equipment may be used. However, if polyphase equipment is used, the output from each phase shall be available, or the meter shall be calibrated for three-phase measurements.

4-8.3.1 Wattmeters. Wattmeters measure instantaneous active power. The instantaneous active power shall be measured frequently during a test run and averaged over the test-run period to determine average power (kW) during the test. Should the total active electrical energy (kW·h) be desired, the average power shall be multiplied by the test duration in hours.

Wattmeters measuring a Class 1 primary variable shall have a systematic uncertainty equal to or less than 0.2% of reading. Metering with an uncertainty equal to or less than 0.5% of reading may be used for the measurement of Class 2 primary variables. There is no metering accuracy requirement for measurement of secondary variables. The output from the wattmeters shall be sampled with a frequency high enough to attain an acceptable precision. This is a function of the variation of the power measured. A general guideline is a frequency of not less than once each minute.

4-8.3.2 Watt-Hour Meters. Watt-hour meters measure active energy (kW·h) during a test period. The measurement of kilowatt-hours must be divided by the test duration in hours to determine average active power (kW) during the test period.

Watt-hour meters measuring a Class 1 primary variable shall have an uncertainty equal to or less than 0.2% of reading. Metering with an uncertainty equal to or less than 0.5% of reading may be used for measurement of Class 2 primary variables. There are no metering accuracy requirements for measurement of secondary variables.

The resolution of watt-hour meter output is often so low that high inaccuracies can occur over a typical test period. Often watt-hour meters will have an analog or digital output with a higher resolution that may be used to increase the accuracy. Some watt-hour meters also have a pulse-type output that may be summed over time to determine an accurate total energy during the test period. For disk-type watt-hour meters with no external output, the disk revolutions can be counted during a test to increase resolution.

4-8.3.3 Wattmeter and Watt-Hour Meter Calibration. Wattmeters and watt-hour meters, collectively referred to as power meters, are calibrated by applying power through the test power meter and a wattmeter or watt-hour meter standard simultaneously. This comparison should be conducted at a minimum of five power levels across the expected power range. The difference between the test and standard instruments for each power level should be calculated and applied to the power measurement data from the test. For test points between the calibration power levels, a curve fit or linear interpolation should be used. The selected power levels should be approached in an increasing and a decreasing manner. The calibration data at each power level should be averaged to minimize any hysteresis effect. Should polyphase metering equipment be used, the output of each phase shall be available or the meter shall be calibrated with all three phases simultaneously.

When calibrating watt-hour meters, the output from the wattmeter standard should be measured with a frequency high enough to reduce the systematic error during calibration, to minimize the total uncertainty of the calibration process.

Wattmeters should be calibrated at the electrical line frequency of the equipment under test, i.e., do not calibrate a meter at 60 Hz and use it on 50-Hz equipment.

Wattmeter standards should have power flow through them prior to calibration to ensure that the device reaches operating temperature. The standard should be checked for zero reading each day prior to calibration.

4-8.4 Instrument Transformers

Instrument transformers include potential transformers, which measure voltage from a conductor to a reference, and current transformers, which measure current in a conductor.

4-8.4.1 Potential Transformers. Potential transformers measure either phase-to-phase voltage or phase-to-neutral voltage. The potential transformers serve to convert the line or primary voltage (typically high voltage) to a lower or secondary voltage that is safe for metering (typically 120 V for phase-to-phase systems and 69 V for phase-to-neutral systems). For this reason, the secondary voltage measured by the potential transformer shall be multiplied by a turns ratio to calculate the primary voltage.

Potential transformers are available in several metering accuracy classes. For the measurement of Class 1 primary variables, Class 2 primary variables, or secondary variables, Accuracy Class 0.3 potential transformers (0.3% permissible error) shall be used. In the case of Class 1 primary variable measurement, potential transformers shall be calibrated for turns ratio and phase angle and operated within their rated burden range.

4-8.4.2 Current Transformers. Current transformers measure current in a given phase. Current transformers serve to convert line or primary current to a lower or secondary metering current. For this reason, the secondary current measured by the current transformer shall be multiplied by a turns ratio to calculate the primary current.

Current transformers are available in several metering accuracy classes. For the measurement of Class 1 primary variables, Class 2 primary variables, or secondary variables, Accuracy Class 0.3 current transformers (0.3% permissible error) shall be used. In the case of Class 1 primary variable measurement, current transformers shall be calibrated for turns ratio and phase angle and operated within their rated burden range.

4-8.5 Calculation of Corrected Average Power or Corrected Total Energy

The calculation method for average power or total energy should be performed in accordance with ANSI/IEEE Standard 120 for the specific type of measuring system used.

4-8.6 Measurement of Auxiliary Electrical Load

A separate transformer and associated load metering may be available to measure specific ASU auxiliary loads. Permanent station instrumentation can be used for measuring the electrical load to specific subcomponents, where the electrical load is measured and displayed either as active power or as voltage and current. If real power (kW) is not measured, the auxiliary power is calculated as described in Section 5.

4-8.7 Measurement of Step-Up and Step-Down Transformers

The power losses of step-up and step-down transformers may be required for a test or a test correction. Since the power loss for a step-up/step-down transformer is difficult to measure in the field, it may be necessary to use the results of the transformer's factory performance tests. Normally the factory tests for determining the power loss are conducted at 0% and 100% of the rated load of the transformer and at various voltages. To calculate the transformer power loss, the measurements of the voltage and current at the high side of the transformer shall be recorded.

4-9 DATA COLLECTION AND HANDLING

4-9.1 Introduction

This subsection presents requirements and guidance regarding the acquisition and handling of test data. It also presents the fundamental elements that are essential to the makeup of an overall data acquisition and handling system.

This Code recognizes that technologies and methods in data acquisition and handling will continue to change and improve over time. If new technologies and methods become available and are shown to meet the required standards stated within this Code, they may be used.

4-9.1.1 Data Acquisition System. The purpose of a data acquisition system is to collect data and store it in a form suitable for processing or presentation. Systems may be as simple as a person manually recording data to as complex as a digital computer-based system. Regardless of the complexity of the system, a data acquisition system shall be capable of recording, sampling, and storing the data within the requirements of the test and target uncertainty set by this Code.

4-9.1.2 Manual System. In some cases, it may be necessary or advantageous to record data manually. It should be recognized that this type of system introduces additional uncertainty in the form of human error, and such uncertainty should be accounted for accordingly. Further, due to the limited sampling rate, manual systems may require longer periods of time or additional personnel for a sufficient number of samples to be taken. The time duration of the test should be selected with this in mind, allowing for enough time to gather the number of samples required by the test. Data collection sheets should be prepared prior to the test. The data collection sheets should identify the test site location, date, time, and type of data collected, and should delineate the sampling time required for the measurements. Sampling times should be clocked using a digital stopwatch or other sufficient timing device. If it becomes necessary to edit data sheets during the testing, all edits shall be made using black ink, and all errors shall be marked through with a single line and initialed and dated by the editor.

4-9.2 Data Management

4-9.2.1 Automated Collected Data. All automated collected data should be recorded in its uncorrected, uncalculated state on both permanent and removable media to permit post-test data correction for application of any necessary calibration corrections. Immediately after the test and prior to leaving the test site, copies of the automated collected data should be distributed to the parties to the test to secure against the chance of such data being accidentally lost, damaged, or modified. Similar steps should be taken with any corrected or calculated results from the test.

4-9.2.2 Manually Collected Data. All manually collected data recorded on data collection sheets shall be reviewed for completeness and correctness. Immediately after the test and prior to leaving the test site, copies of the data collection sheets should be made and distributed to the parties to the test to eliminate the chance of such data being accidentally lost, damaged, or modified.

4-9.2.3 Data Calculation System. The data calculation system should have the capability to average each input collected during the test and calculate the test results based on the average values. The system should also calculate the standard deviation of each instrument. The system should also have the ability to plot the test data and readings from each instrument over time, to highlight trends and outlying data.

4-9.3 Data Acquisition System Selection

4-9.3.1 Data Acquisition System Requirements. Prior to selection of a data acquisition system, it is necessary to have the test procedure in place that dictates the requirements of the system. The test procedure should clearly dictate the type of measurements to be made, the number of data points needed, the length of the test, the number of samples required, and the frequency of data collection to meet the target test uncertainty set by this Code. This information will serve as a guide in the selection of equipment and system design.

Each measurement loop shall be designed with the ability to be loop calibrated and to be checked for continuity and power supply problems. To prevent signal degradation due to noise, each instrument cable should be designed with a shield around the conductor, and the shield should be grounded on one end to drain any stray induced currents.

4-9.3.2 Temporary Automated Data Acquisition System. This Code encourages the use of temporary automated data acquisition systems for testing purposes. These systems can be carefully calibrated and their proper operation confirmed in the laboratory before they are transported to the testing area, thus providing traceability and control of the complete system. Instruments are limited in their exposure to the elements and avoid the problems associated with construction and ordinary plant maintenance.

Site layout and ambient conditions shall be considered when determining the type and application of temporary systems. Instruments and cabling shall be selected to withstand or minimize the impact of any stresses, interference, or ambient conditions to which they may be exposed.

4-9.3.3 Existing Plant Measurement and Control System. This Code allows the use of the ASU control system or the plant measurement and control system for Code testing. However, the system shall meet the requirements set forth in this Code. The limitations and restrictions of these systems should be considered when deciding whether to use them for performance testing.

Most distributed plant control systems apply threshold or deadband restraints on data signals. This results in data that is only the report of the change in a parameter that exceeds a set threshold value. All threshold values shall be set low enough so that all data signals sent to the distributed control system during a test are reported and stored.

Most plant systems do not calculate flows in accordance with this Code, but rather estimate such rates based on simplified relationships, such as the assumption of a constant discharge coefficient or expansion factor. A plant system indication of flow shall not be used in the execution of this Code, unless the fundamental input parameters are also logged and the calculated flow is confirmed to be in accordance with this Code and ASME MFC-3M for differential flowmeters and ASME PTC 19.5 for other types of flowmeters.

4-10 LOSSES

4-10.1 Gearbox Losses

Gearbox losses shall be determined for applications that require load gears for speed reduction between the driver rotor and the compressor rotor. Gearbox losses are typically determined from data provided by the gearbox manufacturer. Gearbox losses can vary greatly, but they are typically on the order of 1% to 2% of shaft output.

4-10.2 Fixed Losses

Fixed losses remain relatively constant across the range of operating conditions and may include mechanical losses and losses from shaft-driven accessories. The value for these losses should be provided by the manufacturer.

4-10.3 Variable Losses

Variable losses include minor streams for heat rejection, overboard air or gas leakages, and radiated heat. The algorithms for determining these losses should be provided by the manufacturer.

Section 5
Calculations and Results

5-1 FUNDAMENTAL EQUATIONS

The fundamental performance equations [eqs. (5-1-1) through (5-1-6)] are applicable to any type of ASU covered by this Code. See Table 5-1-1 for correction factors. See subsection 2-4 for nomenclature.

Corrected net ASU power input, P_{corr}, is expressed as

$$P_{corr} = P_{A,corr} + P_{C,corr} \tag{5-1-1}$$

$$\begin{aligned} P_{A,corr} = & \sum [(P_{A,meas}) + (AOD_{A,i}) \times (MDFR_{A,i}) \times (MMC_{A,i}) \\ & \times (MST_{A,i}) \times (MSP_{A,i}) \times (MDP_{A,i}) \times (MCWIT_{A,i})] \end{aligned} \tag{5-1-2}$$

where $i = 1, 2, \ldots, n_A$

$$\begin{aligned} P_{C,corr} = & \sum [(P_{C,meas}) + (AOD_{C,i}) \times (MDFR_{C,i}) \times (MMC_{C,i}) \\ & \times (MST_{C,i}) \times (MSP_{C,i}) \times (MDP_{C,i}) \times (MCWIT_{C,i})] \end{aligned} \tag{5-1-3}$$

where $i = 1, 2, \ldots, n_C$

Corrected ASU production rate, M_{corr}, is expressed as

$$M_{corr} = (M_{O2meas} + M_{LPO2meas} + AOD_{MO2}) \times (MST_{amb}) \times (MSP_{amb}) \tag{5-1-4}$$

Table 5-1-1 Summary of Additive and Multiplicative Correction Factors in Fundamental Performance Equations

Correction Factor: To ASU Auxiliary Power [Note (1)]	Correction Factor: To Individual ASU Compressor Powers [Note (2)]	Operating Condition or Uncontrollable External Condition Requiring Correction
Additive		
$AOD_{A,i}$	$AOD_{C,i}$	Irregular or off-design operation
Multiplicative		
$MDFR_{A,j}$	$MDFR_{C,j}$	Dry flow rate [Note (3)]
$MMC_{A,j}$	$MMC_{C,j}$	Moisture content [Note (3)]
$MST_{A,j}$	$MST_{C,j}$	Suction temperature [Note (4)]
$MSP_{A,j}$	$MSP_{C,j}$	Suction pressure [Note (5)]
$MDP_{A,j}$	$MDP_{C,j}$	Discharge pressure [Note (6)]
$MCWIT_{A,j}$	$MCWIT_{C,j}$	Cooling-water inlet temperature [Note (3)]

GENERAL NOTE: Individual equipment units may have different correction factors to account for deviations from the base reference condition.

NOTES:
(1) A subscript "A,j" indicates that the correction is for an auxiliary component within the ASU; $j = 1, 2, \ldots n_A$.
(2) A subscript "C,j" indicates that the correction is for a compressor within the ASU; $j = 1, 2, \ldots n_C$.
(3) Measured at the test boundary inlet to the equipment.
(4) Measured at the test boundary inlet to the equipment or derived from cooling medium temperature.
(5) Measured at the test boundary inlet to the equipment, derived from ambient pressure measurement, or derived from external air supply pressure to the ASU.
(6) Measured at the test boundary discharge of the equipment.

For ASU plants that have nitrogen as the main product, the ASU production rate is based on nitrogen flow instead of oxygen flow.

Corrected ASU effectiveness, E_{corr}, is expressed as

$$E_{corr} = P_{corr}/M_{corr} \tag{5-1-5}$$

Corrected ASU specific power performance, SPP_{corr}, is expressed as

$$SPP_{corr} = M_{corr}/P_{corr} \tag{5-1-6}$$

The correction factors that are not applicable to the specific type of unit being tested, or to the test objectives, are set to unity or zero, depending on whether they are multiplicative or additive correction factors, respectively.

5-2 POWER TERMS IN THE FUNDAMENTAL EQUATIONS

An ASU may be composed of any number of compressors and expanders. Each compressor may have individual correction factors based on the percentage of power that is dependent on ambient air temperature, cooling water temperature, or suction and discharge conditions. The fundamental equations are developed to allow for the measurement and correction of power consumption at each machine. A test based on the measurement of total ASU power is not precluded by the fundamental equations, provided suitable overall correction factors can be derived for a given ASU. For the purposes of this Code, it is suggested that the manufacturer's correction curves be referenced to conditions at typical test boundaries. Suggested test boundaries for both nonintegrated and integrated ASUs are shown in Figures 5-2-1 and 5-2-2, and typically include

(a) ambient conditions at the inlet to the air compressor
(b) utility or air supply conditions at or near the ASU equipment items or ASU battery limit
(c) product conditions at the discharge of compression equipment or at the ASU battery limit

The figures show typical components that could be used in various designs, but not all components would necessarily be used in any specific ASU.

Auxiliary loads may be zero if all utilities are supplied to the test boundary, or may consist of electric loads to operate cooling towers, air coolers, and electric heaters. Auxiliary electrical production such as from expanders should be included in net auxiliary power. Auxiliary power may be included or excluded as agreed to by the parties to the test.

5-3 DISCUSSION OF APPLICATION OF CORRECTION FACTORS

The fundamental equation for ASU power consumption is constructed to allow for individual correction factors to be applied to each production rate, power user, or power producer in the plant. The appropriate information in the form of correction formulas or plots shall be requested from the supplier of the ASU and/or the suppliers of the equipment contained within the ASU test boundary.

The additive correction factors AOD_{MO2} and AOD_{MLPO2} allow correction of the production rate within the ASU. The additive correction factor $AOD_{A,i}$ allows correction of the auxiliary power within the ASU. An example is the on–off use of supplemental refrigeration that may be required during off-design operation and testing of the ASU. The additive correction factor $AOD_{C,i}$ allows correction of the individual compressor power within the ASU.

The multiplicative correction factors listed in Table 5-1-1 are used to correct ASU auxiliary power or ASU compressor power.

5-3.1 Dry Flow Factors, $MDFR_{A,j}$ and $MDFR_{C,j}$

The dry flow factors correct the measured power consumption for changes in flow from the base reference conditions.

5-3.2 Moisture Content Factors, MMC_{MO2}, MMC_{LPO2}, $MMC_{A,j}$, and $MMC_{C,j}$

The moisture content factors correct the measured power consumption for changes in water content. This factor could be used to adjust the production rate or auxiliary power for the difference in humidity of ambient air compared to the base reference conditions. It also permits adjusting air compressor power measurements for deviations in moisture content. Correction factors for air compressors may have to be derived as functions of both humidity and cooling water inlet temperature. Ambient humidity determines how much water vapor is taken into the suction of the air compressor, while cooling water temperature determines how much water is condensed in the intercooling steps between stages of compression. Moisture content corrections may need to be applied to one or more of the compressed product streams. An example is a stream used to regenerate the air pretreatment section of the ASU prior to being compressed and delivered as a pressurized product at the ASU test boundary.

Figure 5-2-1 Typical Nonintegrated ASU Test Boundary

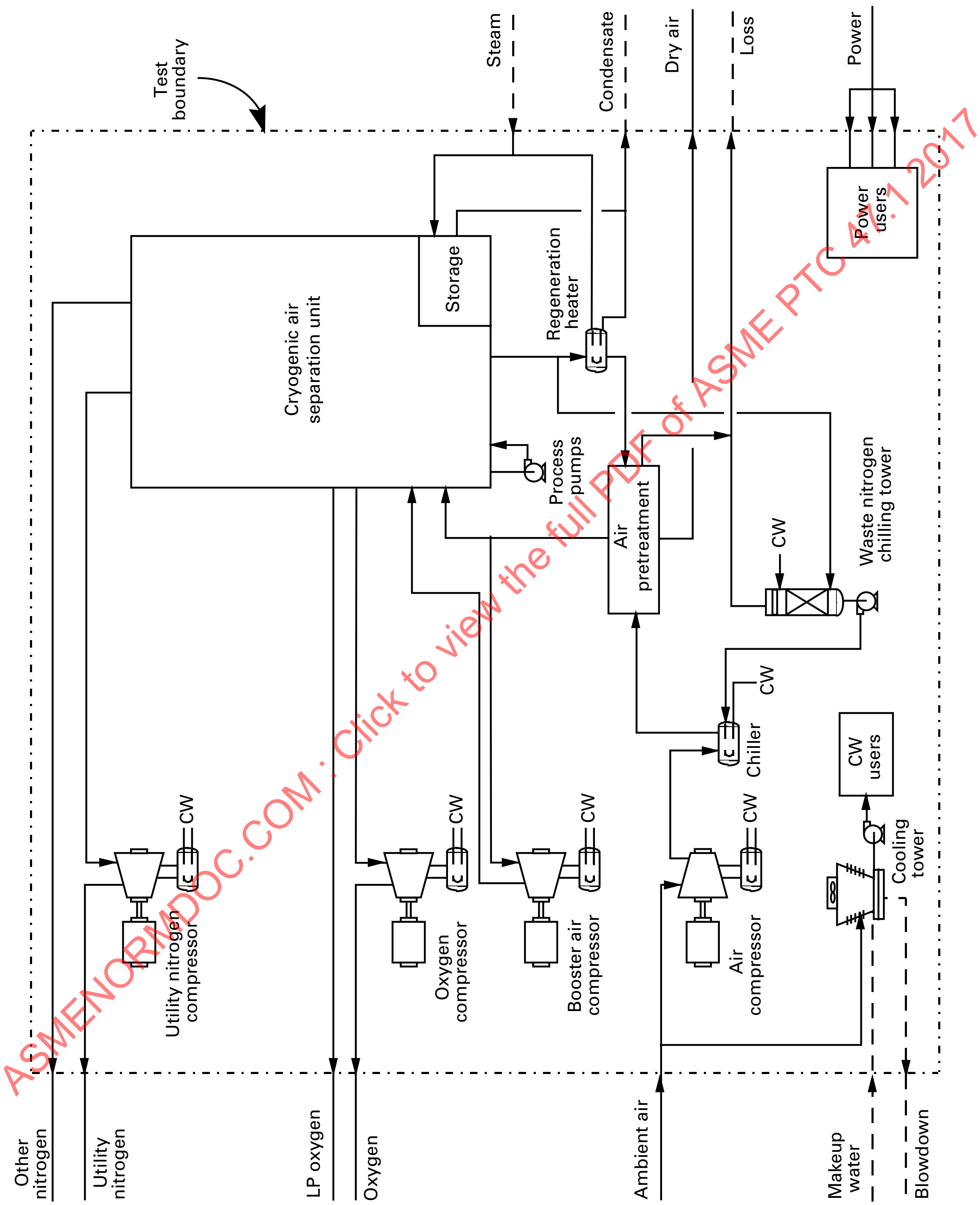
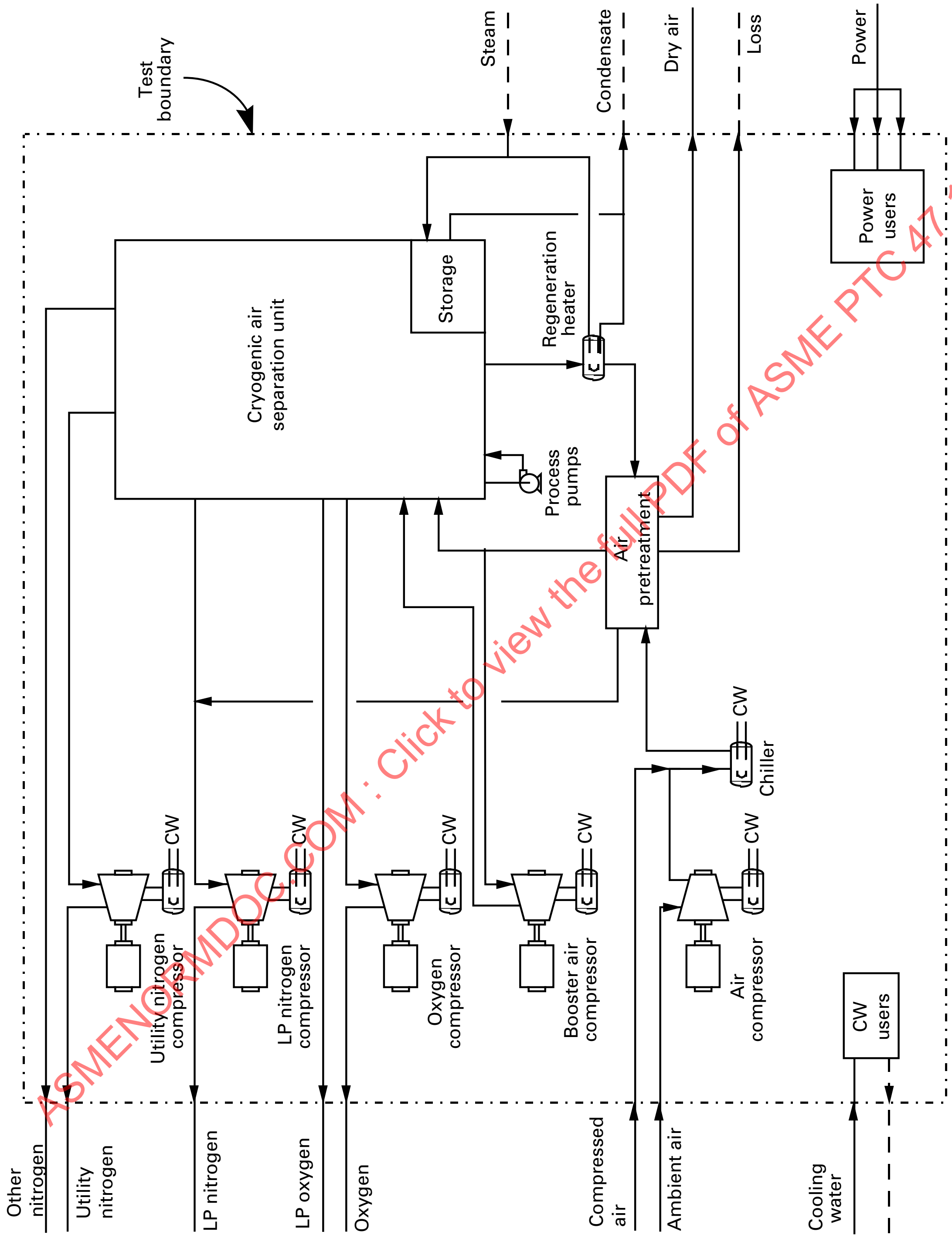


Figure 5-2-2 Typical Integrated ASU Test Boundary



5-3.3 Suction Temperature Factors, MST_{MO2}, MST_{LPO2}, $MST_{A,j}$, and $MST_{C,j}$

Correction factors are required to compensate for changes in suction temperatures to the ASU compressors. For air compression, the factor usually corresponds to changes in the ambient air temperature. For product compressors, the factor is usually linked to changes in cooling water inlet temperature or the performance of chilling equipment internal to the ASU test boundary. Chilling equipment factors may be dependent on flows and ambient conditions or the performance of mechanical chilling units at conditions other than the base reference point. For production rate or auxiliary loads such as cooling towers or air coolers, the factor is dependent on ambient air conditions.

5-3.4 Suction Pressure Factors, MSP_{MO2}, MSP_{LPO2}, $MSP_{A,j}$, and $MSP_{C,j}$

Correction factors are required to compensate for changes in suction pressures to the ASU compressors. For air compression, the factor usually corresponds to changes in the ambient air pressure less an allowance for inlet filtration. For product compressors, the factor is usually linked to changes in air compressor discharge pressure or air supply pressure from a source originating outside the ASU test boundary. For production rate or auxiliary loads such as cooling towers, the factor is dependent on ambient air pressure.

5-3.5 Discharge Pressure Factors, $MDP_{A,j}$ and $MDP_{C,j}$

Correction factors are required to compensate for changes in discharge pressures from the ASU compressors. For air compression, the factor usually corresponds to changes in the discharge pressure linked to matching the supply pressure of air from a source originating outside the ASU test boundary. For product compressors, the factor is usually linked to changes in discharge pressure resulting from the supply of product to users downstream of the ASU test boundary.

5-3.6 Cooling Water Factors, $MCWIT_{A,j}$ and $MCWIT_{C,j}$

Correction factors are required to compensate for changes in cooling water temperature to the ASU compressors. For air compression, the factor may account for inlet temperature deviations to compression stages following intercoolers as well as for flow deviations resulting from changes in the amount of water condensed in interstage intercoolers. For product compressors, the factor is usually linked to changes in interstage suction temperatures, but may also encompass flow changes if the compressed stream contains moisture. For auxiliary loads such as mechanical chillers, the factor may account for condenser pressure and resulting performance changes.

5-4 MODEL FUNCTIONAL REQUIREMENTS

The main functional requirements of the model are completeness, flexibility, and accuracy.

5-4.1 Completeness

The model shall be able to predict changes in the power block performance in response to changes in the test boundary conditions. These include ambient conditions such as temperature, pressure, and humidity; process steam and water flow conditions; and secondary thermal and electrical inputs and outputs.

5-4.2 Flexibility

The normal range of the model is expected to be at base load with the expected variation of ambient conditions and the expected variation of streams that cross the test boundary. Inputs to and outputs from the model should include the measured terms listed in Table 5-1-1.

5-4.3 Accuracy

The methods and calculations used to develop the power block plant model, including property methods, convergence techniques, and engineering models, shall be of sufficient accuracy to satisfy the needs of the acceptance test. For the primary purpose of correcting plant performance to reference conditions, consistency and relative accuracy of the calculations are more important than absolute accuracy, meaning that the ability to accurately predict changes in performance due to a change (Δ) in a test boundary condition is more important than matching the actual plant production rate and power input at a given set of conditions. The final results should be accurate enough to meet the uncertainty levels defined in Table 1-3-1.

5-4.4 Model Validation

Model validation is desirable, but the proprietary nature of comprehensive plant models may preclude complete validation. Normally the uncertainties of correction factors, curves, and models cannot be ascertained because of the proprietary nature of such information. This aspect of uncertainty is not included in Table 1-3-1.

The basic ASU model is typically provided by the ASU supplier to cover expected performance over a range of conditions. The individual component performance used in the comprehensive plant model shall be verified to match the equipment supplier's expected performance for the component. If the equipment supplier supplies performance curves or data, the model should be adjusted to allow comparison of the plant-model-predicted performance against the equipment supplier's curve or data. The comparison should be made at the rating point and the extremes of the equipment-supplier-predicted performance.

The limit of the model's use and accuracy is restricted to the limit of the components used as inputs to the plant model.

(a) Comparison With Measured Data. As much as practicable prior to the test, the model results should be compared with measured data from the plant. This comparison allows model refinement and tuning to match the actual operation of the plant as closely as possible.

Where possible, selected plant boundary parameters should be adjusted so that changes in the model's calculated dependent variables match the changes in the measured plant values. The parties to the test should agree to such adjustments. The agreement may be included in the test plan. Adjustable model parameters should be limited to equipment characteristics, such as compressor efficiency, heat-exchanger heat-transfer coefficients, and correlation coefficients that affect the model outputs over a range of conditions in the same way as at test conditions. Directly measured variables should not be adjusted.

(b) Extremes and End Points. Ideally, the test will be conducted at the reference conditions to minimize the amount and size of corrections to the measured performance. If the model is used for test corrections, the model will in effect be interpolating within the valid range of the model rather than extrapolating beyond it.

(c) Limits. It is important during the development, testing, and tuning of the ASU model to identify the limits of the model, i.e., those operating regions where the accuracy of the model is reduced or is unacceptable for the purposes of testing. The model cannot be used for testing plant operation beyond the validated limits.

5-5 DEGRADATION

The corrected results from subsection 5-1 represent the performance of the ASU at the specified reference conditions at the time of the performance test. If required by the contractor or the parties to the test, an additional correction for performance degradation may be applied.

Section 6
Report of Results

6-1 GENERAL REQUIREMENTS

At a minimum, the test report should include the following distinctive sections:

(a) Executive Summary (see subsection 6-2) containing

(1) a brief description of the object, result, and conclusions reached

(2) signature of the test director(s)

(3) signature of the reviewer(s)

(4) approval signature(s)

(b) Introduction (see subsection 6-3) containing

(1) authorization for the tests, the object of the tests, contractual obligations and guarantees, stipulated agreements, the name of the person directing the test, and the representative parties to the test

(2) description of the equipment tested and any other auxiliary apparatus, the operation of which may influence the test results

(3) method of test, giving arrangement of testing equipment, instruments used and their locations, operating conditions, and a complete description of methods of measurement not prescribed by this Code

(c) Calculations and Results (see subsection 6-4) containing

(1) a summary of measurements and observations

(2) methods of calculation from observed data, and calculation of probable uncertainty

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

(4) primary measurement uncertainties, including method of application

(5) the test performances stated under the following headings:

(-a) test results computed on the basis of the test operating conditions, instrument calibrations only having been applied

(-b) test results corrected to specified conditions if test operating conditions have deviated from those specified

(6) tabular and graphical presentation of the test results

(d) Instrumentation (see subsection 6-5)

(e) Conclusions (see subsection 6-6) containing

(1) discussion and details of the test results and uncertainties

(2) discussion of the test, its results, and conclusions

(f) Appendices (see subsection 6-7) containing

(1) further description and illustrations to clarify the circumstances, equipment, and methodology of the test

(2) description of methods of calibrations of instruments

(3) outline of details of calculations, including a sample set of computations, descriptions, and statements depicting special testing apparatus

(4) result of preliminary inspections and trials

(5) any supporting information required to make the report a complete, self-contained document of the entire undertaking

This outline is a recommended report format. Other formats are acceptable; however, a report of an overall plant performance test should contain all the information described in subsections 6-2 through 6-7.

6-2 EXECUTIVE SUMMARY

The Executive Summary is a brief synopsis of the full report and contains only the most essential information in a concise format. The following items should be contained in the Executive Summary:

(a) general information about the plant and the test, such as the plant type and operating configuration, and the test objectives

(b) date and time of the test

(c) summary of the results of the test, including uncertainty
(d) comparison with the contract guarantees
(e) any agreements among the parties to the test that allow any major deviations from the test requirements, e.g., if the test requirements call for three test runs and all parties agree that two are sufficient

6-3 INTRODUCTION

The Introduction to the test report gives general background information necessary for the reader to understand the circumstances leading up to, and the reasons for, the test. This section of the test report includes the following topics:
(a) any additional general information about the plant and the test not included in the Executive Summary
(b) an historical perspective, if appropriate
(c) a diagram(s) showing the test boundary and streams (refer to the diagrams for specific plant type or test goal)
(d) a list of the representatives of the parties to the test and their involvement and responsibilities in the testing process
(e) any pretest agreements that were not listed in the Executive Summary
(f) the organization of the test personnel, including number and type of personnel supplied by each organization and the tasks each organization was responsible for during the test
(g) test goals per Sections 3 and 5

6-4 CALCULATIONS AND RESULTS

The goal of the Calculations and Results section of the test report is to lay out all calculation procedures used in the analysis phase of the test. By using the detailed description and sample calculations, the reader should be able to understand and reproduce any results contained in the report. The following should be included in detail:
(a) the format of the general performance equation that is used, based on the test goals and applicable corrections
(b) tabulation of the reduced data necessary to calculate the results, and a summary of additional operating conditions that are not part of such reduced data
(c) step-by-step calculation of test results from the reduced data (Refer to Nonmandatory Appendices A and B for examples of step-by-step calculations for each plant type and test goal.)
(d) detailed calculation of primary flows from applicable data, including intermediate results, if required
(e) detailed calculations of stream properties, i.e., density, purity, enthalpy, and heating value (Values of constituent properties used in the detailed calculations shall be shown.)
(f) any calculations showing elimination of data for outlier reason, or for any other reason
(g) comparison of the repeatability of test runs

6-5 INSTRUMENTATION

The Instrumentation section of the test report contains a detailed description of all instrumentation used during the test and their accuracy, and how each measurement made conforms to the Code requirements. The following shall be included:
(a) tabulation of instrumentation used for the primary and secondary measurements, including make and model number
(b) description of the instrumentation location
(c) means of data collection for each data set, such as temporary data acquisition system printout, plant control computer printout, or manual data sheets, and any identifying tag number and/or address of each document
(d) identification of the instrument used as backup
(e) description of data acquisition system(s) used; summary of pretest and post-test calibration

6-6 CONCLUSIONS

The Conclusions section of the test report should include
(a) a more detailed discussion of the test results, if required
(b) recommended changes to future test procedures due to "lessons learned"

6-7 APPENDICES

Appendices to the test report should include
(a) the test requirements

(b) copies of original data sheets and/or data acquisition system(s) printouts
(c) copies of operator logs or other recording of operating activity during each test
(d) copies of signed isolation checklists and valve lineup sheets, and other documents and disposition
(e) results of laboratory fuel analysis
(f) instrumentation calibration results from laboratories; certification from manufacturers

Section 7
Uncertainty Analysis

7-1 INTRODUCTION

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

Test uncertainty is an estimate of the limit of error of a test result. It is the interval about the test result that contains the true value within a level of confidence. This Code uses a 95% confidence interval for uncertainty calculations. The primary technical reference for uncertainty calculations is ASME PTC 19.1, which provides general procedures for determining the uncertainties in individual test measurements for both random errors and systematic errors, and for tracking the propagation of these errors into the uncertainty of a test result.

Pretest and post-test uncertainty analyses are indispensable parts of a performance test.

7-1.1 Pretest Uncertainty Analysis

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

7-1.2 Post-Test Uncertainty Analysis

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

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

Test results should be reported using the following form: $R \pm U_R$.

7-2 OBJECTIVE OF UNCERTAINTY ANALYSIS

The objective of a test uncertainty analysis is to estimate the limit of error of the test results.

This Code does not cover or discuss test tolerances; test tolerances are defined as contractual agreements regarding an acceptable range of test results.

7-3 DETERMINATION OF OVERALL UNCERTAINTY

There are two types of uncertainty that comprise the total uncertainty, as follows:

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

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

Table 7-5-1 Format of Uncertainty Calculations

Measured Parameter	Sensitivity Coefficient, θ_i	Systematic Uncertainty (95% CI), $\pm\left(b_{\overline{X}_i}\right)$	Systematic Uncertainty Contribution, $\left(\theta_i b_{\overline{X}_i}\right)^2$	Random Uncertainty (95% CI), $\pm\left(s_{\overline{X}_i}\right)$	Random Uncertainty Contribution, $\left(\theta_i s_{\overline{X}_i}\right)^2$
Ambient air pressure	%/%	%	...	%	...
Dry bulb ambient air temperature	%/°F	°F	...	°F	...
Other parameters	%	%	...	%	...
Correlated Uncertainties					
Sum of squares				...	...
Square root of sum of squares				%	%
Combined expanded uncertainty of the results, $U_{R,95}$					%

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

7-4 SOURCES OF ERROR

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

(a) *calibration error:* a residual error not removed by the calibration process

(b) *installation error:* an error resulting from nonideal instrumentation installation

(c) *data acquisition error:* an error typically resulting from analog-to-digital conversion

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

(e) *sampling error:* an error introduced from sampling techniques

(f) *correction methodology error:* an error introduced by using a correction formula

(g) *interpolation error:* an error resulting from curve fitting or from the shape of a curve between discrete formulation points

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

7-5 CALCULATION OF UNCERTAINTY

The elements of uncertainty calculations for a complete test can be presented in tabular form, with columns as shown in Table 7-5-1. Typical stream measurements for an IGCC ASU are listed in Table 7-5-2, but they are not all used in all configurations.

The test uncertainty associated with each measured parameter includes the effects of its sensitivity, systematic uncertainty, and random uncertainty. Each systematic and random uncertainty entry in the table is specified at a 95% confidence interval, as is the overall combined expanded uncertainty of the results.

The parameters used to calculate the uncertainty are as follows:

(a) *Measured parameter*: the fluid or energy stream parameter that crosses the test boundary, required for test calculation (see table 7-5-2 for the list of measured parameters.)

(b) *Sensitivity coefficient,* Θ_I: the percent change in corrected result caused by a unit change in the measured parameter

(c) *Systematic uncertainty,* $B_{\overline{X}_I}$: inherent systematic error for the type of measurement

(d) *Systematic uncertainty contribution,* $\left(\Theta_I B_{\overline{X}_I}\right)^2$: the square of the product of sensitivity and systematic uncertainty

(e) *Random uncertainty,* $S_{\overline{X}_I}$: the standard deviation of the mean statistically determined from multiple measurements of the same variable

(f) *Random uncertainty contribution,* $\left(\Theta_I S_{\overline{X}_I}\right)^2$: the square of the product of sensitivity and the standard deviation

Table 7-5-2 Measured Parameters Needed for Uncertainty Calculations

Measured Parameter	Power Input Uncertainty	Production Rate Uncertainty	Effectiveness Uncertainty	Specific Power Uncertainty
Ambient air pressure	X	...	X	X
Dry bulb ambient air temperature	X	...	X	X
Wet bulb ambient air temperature	X	...	X	X
Cooling water supply temperature	X	...	X	X
Air supply pressure	X	...	X	X
Air supply flow (wet)	X	...	X	X
Product airflow (dry, CO_2 free)	X	...	...	X
Air supply dew point	X	...	X	...
Air supply water content	...	...	X	...
Oxygen discharge flow	X	X	X	X
Oxygen purity	X	X	X	X
Oxygen discharge pressure	X	...	...	...
Oxygen compressor power	X	...	X	X
Gaseous oxygen discharge flow	X	X	X	X
Gaseous oxygen purity	X	X	X	X
Air compressor power	X	...	X	X
Utility nitrogen discharge flow	X	X	X	X
LP nitrogen discharge flow	...	X	...	...
Inlet filter/silencer pressure drop	X	...	X	X

The overall uncertainty of a measurement, $U_{\overline{X}}$, is the root-sum-square (RSS) total of overall systematic and random uncertainties

$$U_{\overline{X}} = \sqrt{\left(b_{\overline{x}}^2 + s_{\overline{x}}^2\right)} \tag{7-5-1}$$

The uncertainty of the result is calculated from the overall test random and systematic uncertainty terms. Each systematic and random uncertainty entry in Table 7-5-1 is specified at a 95% confidence interval, so the overall combined expanded uncertainty of the result, U_r, at 95% confidence is calculated from the sum of systematic and random uncertainty contributions

$$U_R = \sqrt{\left(b_R^2 + s_R^2\right)} \tag{7-5-2}$$

where

b_R = the systematic uncertainty of the result, the sum of systematic uncertainty contributions
s_R = the random uncertainty of the result, the sum of random uncertainty contributions
U_R = overall uncertainty of the result

The expanded uncertainty at 95% confidence is given by

$$U_{R,95} = 2U_R \tag{7-5-3}$$

Table 7-5-2 shows the measured parameters used to calculate uncertainty for each of the four test criteria using the calculation procedures shown in Table 7-5-1.

7-6 SENSITIVITY COEFFICIENTS

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

(a) Partial Differential Form

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

where

R = the corrected test result
X_{avg} = the average value of the measured parameter
∂R = the change (partial differential) in the corrected test result
∂X = the change (partial differential) in the measured parameter

(b) Finite Difference Form

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

where R and X_{avg} are as defined in (a) and

ΔR = the change (finite difference) in the corrected test result
ΔX = the change (finite difference) in the measured parameter, typically $0.01X_{avg}$

7-7 SYSTEMATIC UNCERTAINTY

Identification of the systematic error is an important step in the uncertainty analysis. Failure to identify a significant systematic error will lead to underestimating the accuracy of the test. The process requires a thorough understanding of the test objectives and methods of the test. Published data, calibration information, and engineering judgment should be used to eliminate or understand systematic errors in measurements.

Systematic uncertainty of a measurement is identified as b_X. The individual systematic uncertainties can be combined into the systematic uncertainty of the result, b_R. The systematic uncertainty of the result can be calculated according to the SRSS rule as follows:

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

where

b_R = the systematic uncertainty of the result
b_{X_i} = the systematic uncertainty of the result of a measured parameter i
n = the number of measured parameters
θ_i = the relative sensitivity coefficient for measured parameter i

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

7-8 RANDOM STANDARD UNCERTAINTY FOR SPATIALLY UNIFORM PARAMETERS

The standard deviation, s_X, is a measurement of the dispersion of the sample measurements; the standard deviation of the mean, $s_{\overline{X}}$; and a characteristic degree of freedom, $\nu = N - 1$. Test measurements need to be reduced to average values and the standard deviation calculated before the performance and uncertainty calculations can be executed. The random standard uncertainty is calculated using the sample standard deviation. For a result, R, calculated from many measured parameters, there is a combined standard uncertainty for the result, s_R, for the combined measurement parameters.

(a) Sample Mean. The mean, $\overline{X}$, for the sample is calculated from

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

where

N = the number of readings for each set

X_i = the average value for measurement set i

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

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

where

M = the number of sets of measurements

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

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

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

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

where

N = the number of times the parameter is measured

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

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

where

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

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

(1) The absolute random standard uncertainty is determined using the following equation:

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

where

l = counter for correlated sources of systematic error

θ_i = absolute sensitivity coefficient

(2) The relative random standard uncertainty of a result is determined using the following equation:

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

where l is as defined for eq. (7-8-5) and

θ'_i = the relative sensitivity coefficient

7-9 RANDOM STANDARD UNCERTAINTY FOR SPATIALLY NONUNIFORM PARAMETERS

The spatial contribution to the systematic standard uncertainty, b_{spatial}, for a given parameter is calculated as follows:

$$b_{\text{spatial}} = \frac{s_{\text{spatial}}}{\sqrt{J}} \tag{7-9-1}$$

$$s_{\text{spatial}} = \sqrt{\frac{\sum_{i=1}^{J}(\overline{X}_i - \overline{\overline{X}})}{J-1}} \tag{7-9-2}$$

where

J = number of sensors (i.e., spatial measurement locations)

s_{spatial} = standard deviation of the multiple-sensor time-averaged values

$\overline{\overline{X}}$ = grand average for all averaged measurands

$\overline{X}_i$ = average for the sampled measurand i

7-10 CORRELATED SYSTEMATIC STANDARD UNCERTAINTY

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

$$b_R = \sum_{i=1}^{l}(\theta_i b_i)^2 + 2\sum_{i=1}^{l-1}\sum_{k=i+1}^{l}\theta_i\theta_k b_{ik} \tag{7-10-1}$$

NONMANDATORY APPENDIX A
SAMPLE CALCULATION

A-1 ASU DESCRIPTION AND UNIT DISPOSITION

The ASU operates at elevated pressure and supplies compressed products to both the gasification and power blocks. All of the incoming air feed is processed into oxygen or nitrogen product streams; the only losses are from compressor seals and purges. The ASU receives a portion of its air supply at pressure from the power block's gas turbine. All utilities to operate the ASU (electric power, steam, and cooling water) are supplied from the IGCC facility's utility section. The air pretreatment and distillation sections of the ASU neither consume nor generate power. A motor-driven air compressor supplements the airflow to the ASU. The discharge pressure matches the pressure of the air supplied from the power block's gas turbine, and the flow is controlled based on the oxygen demand of the gasification block and supply of a pressurized dry air stream to the IGCC facility. There are two oxygen products that flow to the gasification block: a small pressurized but uncompressed stream used in the gas treatment section, and a compressed stream that constitutes most of the total oxygen generated that is fed to the gasifier. A high-purity stream of utility nitrogen is compressed for use within the IGCC facility, most of which is dedicated to the gasification block. The remainder of the nitrogen available from the ASU is compressed and sent to the power block for injection into the gas turbine.

The operating disposition of the ASU is to supply the required amount of oxygen products to the gasification unit such that sufficient fuel gas can be produced to fully load the power block's gas turbine. All remaining nitrogen after deduction of the utility nitrogen and compressed dry air supplies will be compressed and sent to the power block's gas turbine for power augmentation and fuel gas dilution for nitrogen oxide (NO_x) control. The ASU's air compressor flow is adjusted to provide sufficient air to supply the required amount of oxygen products.

The performance test goal is to measure the performance of the ASU at full IGCC power output based on the prevailing ambient conditions.

A-2 TEST BOUNDARY DESCRIPTION

The test boundary diagram is shown in Figure A-2-1.

(a) Power consumers that are individually determined include
- *(1)* air compressor
- *(2)* oxygen compressor
- *(3)* utility nitrogen compressor
- *(4)* LP nitrogen compressor
- *(5)* facility power

(b) Streams that require flow and pressure determinations include
- *(1)* compressed air supply
- *(2)* oxygen
- *(3)* utility nitrogen
- *(4)* LP nitrogen

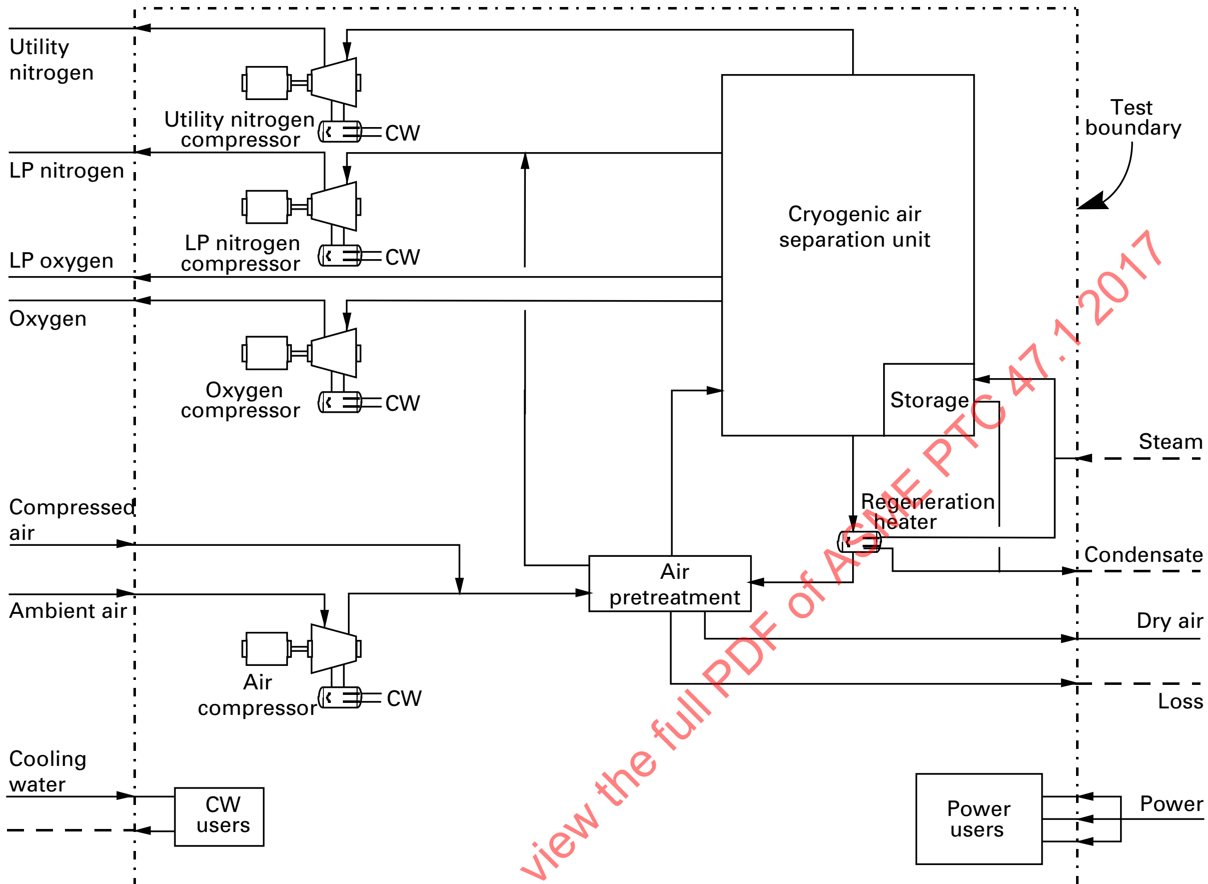
(c) Streams that require flow determinations include
- *(1)* LP oxygen
- *(2)* dry air

(d) Ambient air pressure, temperature, and water content need to be determined for air compressor performance determination. Cooling water supply temperature needs to be determined for compressor power performance determinations. Ambient air pressure and temperature need to be determined for production rate performance determination.

A-3 REFERENCE AND MEASURED CONDITIONS

Table A-3-1 contains reference data and measured test data that are the basis for determining the performance of the ASU.

Figure A-2-1 Example Case Flow Diagram



A-4 CORRECTED SPECIFIC POWER

During the test, the ASU is operated to supply the oxygen, LP oxygen, dry air, and utility nitrogen flows demanded from the gasification and power block to maintain full power output from the power block. The remaining residual nitrogen is compressed and sent to the power block at the demanded pressure. Since the product flow and pressures will be different from those of the reference case, the power consumption of each compressor will be corrected back to the reference conditions using the multiplicative correction factors. The LP O_2 discharge pressure should be kept at its design point and will not require correction.

If the measured data is sufficiently close to the reference case, then correction of individual compressor efficiencies for operation significantly off the design points is not required. The only auxiliary power consumer within the ASU test boundary is a small facility consumption that does not require correction. The test equation for this specific ASU and test is

$$E_{\mathrm{ASUcorr}} = P_{\mathrm{ASUcorr}} / M_{\mathrm{ref}}$$

$$\begin{aligned} P_{\mathrm{ASUcorr}} = & (P_{\mathrm{ASUC1meas}})(\mathrm{MDFR}_{\mathrm{ASUC1}}\mathrm{MMC}_{\mathrm{ASUC1}}\mathrm{MST}_{\mathrm{ASUC1}}\mathrm{MSP}_{\mathrm{ASUC1}}\mathrm{MDP}_{\mathrm{ASUC1}}\mathrm{MCWIT}_{\mathrm{ASUC1}}\mathrm{MEFF}_{\mathrm{ASUC1}}) \\ & + (P_{\mathrm{ASUC2meas}})(\mathrm{MDFR}_{\mathrm{ASUC2}}\mathrm{MMC}_{\mathrm{ASUC2}}\mathrm{MST}_{\mathrm{ASUC2}}\mathrm{MSP}_{\mathrm{ASUC2}}\mathrm{MDP}_{\mathrm{ASUC2}}\mathrm{MCWIT}_{\mathrm{ASUC2}}\mathrm{MEFF}_{\mathrm{ASUC2}}) \\ & + (P_{\mathrm{ASUC3meas}})(\mathrm{MDFR}_{\mathrm{ASUC3}}\mathrm{MMC}_{\mathrm{ASUC3}}\mathrm{MST}_{\mathrm{ASUC3}}\mathrm{MSP}_{\mathrm{ASUC3}}\mathrm{MDP}_{\mathrm{ASUC3}}\mathrm{MCWIT}_{\mathrm{ASUC3}}\mathrm{MEFF}_{\mathrm{ASUC3}}) \\ & + (P_{\mathrm{ASUC4meas}})(\mathrm{MDFR}_{\mathrm{ASUC4}}\mathrm{MMC}_{\mathrm{ASUC4}}\mathrm{MST}_{\mathrm{ASUC4}}\mathrm{MSP}_{\mathrm{ASUC4}}\mathrm{MDP}_{\mathrm{ASUC4}}\mathrm{MCWIT}_{\mathrm{ASUC4}}\mathrm{MEFF}_{\mathrm{ASUC4}}) \end{aligned}$$

where

$\mathrm{MCWIT}_{\mathrm{ASUC}n}$ = multiplicative correction factors to individual compressor powers to correct to base reference cooling water temperature

$\mathrm{MDFR}_{\mathrm{ASUC}n}$ = multiplicative correction factors to individual compressor powers to correct to base reference dry flows

Table A-3-1 Reference and Measured Data

Measured Parameters	Reference Value	Test Value
Ambient Conditions		
Ambient air pressure	14.696 psia	14.600 psia
Dry bulb ambient air temperature	59.0°F	65.0°F
Wet bulb ambient air temperature	51.0°F	57.0°F
Relative humidity	60%	62%
Ambient air water content	0.00634 lb/lb dry air	0.00858 lb/lb dry air
Main Air Compressor		
Motor efficiency	98.36%	98.36%
Motor losses	1.64%	1.64%
Inlet filter/silencer pressure drop	0.1 psi	0.1 psi
Air compressor discharge pressure	181.0 psi	176.0 psi
Airflow (dry)	641,346 lb/hr	655,911 lb/hr
Gas power	97.28% of total	97.28% of total
Power to first stage	23.89%	23.89%
Intercooler approach temperature(s)	10°F	10°F
Oxygen Compressor		
Motor losses	2.44%	2.44%
Suction pressure vs. air supply pressure	56.07 psia	53.51 psia
Discharge pressure	600 psia	605 psia
Gas power	96.2% of total	96.2% of total
Power to first stage	24.7%	24.7%
Suction temperature	83°F	87°F
Intercooler approach temperature(s)	10°F	10°F
Utility Nitrogen Compressor		
Motor losses	4.31%	4.31%
Suction pressure vs. air supply pressure	171.88 psia	166.62 psia
Discharge pressure	650.0 psia	660.0 psia
Gas power	95.6% of total	95.6% of total
Power to first stage	47.5%	47.5%
Suction temperature	83°F	87°F
Intercooler approach temperature(s)	10°F	10°F
LP Nitrogen Compressor		
Motor losses	1.87%	1.87%
Suction pressure vs. air supply pressure	53.0 psia	50.5 psia
LP nitrogen compressor discharge pressure	300.0 psia	305.0 psia
Gas power	96.65% of total	96.65% of total
Power to first stage	31.93%	31.93%
Intercooler approach temperature(s)	10°F	10°F
Suction temperature	83°F	87°F
Facility auxiliary power	64 kW	64 kW

MDP_{ASUCn} = multiplicative correction factors to individual compressor powers to correct to base reference discharge pressure
$MEFF_{ASUCn}$ = multiplicative correction factors to individual compressor powers to correct for deviations from base reference conditions
MMC_{ASUCn} = multiplicative correction factors to individual compressor powers to correct to base reference moisture content
MSP_{ASUCn} = multiplicative correction factors to individual compressor powers to correct to base reference inlet (suction) pressure
MST_{ASUCn} = multiplicative correction factors to individual compressor powers to correct to base reference inlet (suction) temperature

The subscripts are defined as follows:
$C1$ = air compressor
$C2$ = oxygen compressor
$C3$ = utility nitrogen compressor
$C4$ = LP nitrogen compressor

A-4.1 Corrections to Specific Power

Tables A-4.1-1 through A-4.1-4 contain the basis for determining discrete correction factors, values for the discrete correction factors, and the four individual corrected compressor powers for the ASU. MEFF was set equal to 1.0 in this example for all compressors because they were operated sufficiently close to the reference conditions.

Note that the algorithms used to determine individual correction factors are for the purpose of demonstrating the example case; they cannot be used for other performance test cases.

A-4.2 Corrected Specific Power Performance

Fundamental performance results for the sample case are summarized in Table A-4.2-1.

A-5 CORRECTED ASU EFFECTIVENESS

Corrected ASU effectiveness is calculated from the performance results described in para. A-4.2 as shown in Table A-5-1.

A-6 CORRECTED OXYGEN PRODUCTION RATE

The corrected oxygen production rate is calculated using eq. (5-1-4), which is repeated here:

$$M_{corr} = (M_{O2meas} + M_{LPO2meas} + AOD_{MO2}) \times (MST_{amb}) \times (MSP_{amb}) \tag{5-1-4}$$

In this example, correction AOD_{MO2} was set equal to zero because the ASU operated sufficiently close to the reference conditions. The only two factors affecting the oxygen production rate are ambient pressure and ambient temperature, which determine the mass flow of inlet air to the ASU.

The correction curves for ambient pressure and temperature in this example are shown in Figures A-6-1 and A-6-2, respectively, and their empirical equations are shown below.

$$MSP_{amb} = 1/(0.1192 + 0.0947 \times P_{amb} - 0.0024 \times P_{amb}{}^2) \tag{A-6-1}$$

$$MST_{amb} = 1/(1.0849 - 0.0009 \times T_{amb} - 8.44 \times 10^{-6} \times T_{amb}{}^2) \tag{A-6-2}$$

where
P_{amb} = ambient pressure, psia
T_{amb} = ambient temperature, °F

Performance results for this sample case are summarized in Table A-6-1.