ASME PTC 50-2002

FUEL CELL POWER SYSTEMS PERFORMANCE

PERFORMANCE TEST CODES

An American National Standard

The American Society of
Mechanical Engineers

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Mechanical Engineers

AN AMERICAN NATIONAL STANDARD

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ASME PTC 50-2002

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FOREWORD

During the mid 1990s the importance of developing fuel cell standards was recognized. Fuel Cell power plants were in the early stages of commercialization. Potential applications included vehicular power, on-site power generation, and larger scale dispersal power generators. There was a growing demand to produce industry standards that would keep pace with the commercialization of this new technology.

ASME had a very active Fuel Cell Power Systems technical committee within the Advanced Energy Systems Division. Through its volunteer membership, it recommended the formation of a standards committee to work on developing a fuel cell standard. ASME Codes and Standard Directorate undertook this task. On October 14, 1996 the Board on Performance Test Codes voted to approve the formation of a performance test code committee, PTC 50.

This Committee had its first meeting on January 23-24, 1997. The membership consisted of some 18 fuel cell experts from Government, academia, manufacturers, and users of fuel cells. Ronald L. Bannister; Westinghouse Electric Corporation; retired, chaired the first meeting. He had been appointed by the Board on PTC as the Board Liaison member to the committee. He chaired and supervised the committee's activities until permanent officers were elected from the membership.

In the Fall 2001, the Committee issued a draft of the proposed Code to Industry for review and comment. The comments were addressed in February 2002 and the Committee by a letter ballot voted to approve the document on March 29, 2002. It was then approved and adopted by the Council as a standard practice of the Society by action of the Board on Performance Test Codes voted on May 6, 2002. It was also approved as an American National Standard by the ANSI Board of Standards Review on July 3, 2002.

NOTICE

All Performance Test Codes **MUST** adhere to the requirements of **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 this Supplement. It is expected that the Code user if fully cognizant of Parts I and III of PTC 1 and has read them prior to applying this Supplement.

ASME Performance Test Codes provide test procedures which 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. They specify procedures, instrumentation, equipment operating requirements, calculation methods, and uncertainty analysis.

When tests are 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 equipement. 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.

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FUEL CELL POWER SYSTEMS PERFORMANCE

INTRODUCTION

Fuel cells convert the energy of a fuel directly into electricity, eliminating the combustion stage that is characteristic of heat engines, and not requiring any moving parts. Instead, the fuel molecules (usually hydrogen often derived from hydrocarbon fuels) interact with the surface of an anode material to form reaction products, liberating electrons. The electrons flow through the electric load to the cathode where they react with an oxidant, typically oxygen from air. Ions migrate between the electrodes through the ionically conducting electrolyte to complete the circuit. The product of this electrochemical energy conversion process is water, but unlike heat engines, the process can take place at close to ambient temperature, or can also be conducted at higher temperatures, depending on the types of anode, electrolyte, and cathode materials.

Since fuel cells are not heat engines, the efficiency of a fuel cell system is not limited by the Carnot principle. It can, in fact, vary over a fairly wide range. When the current density of the fuel cell is very low, the energy conversion efficiency approaches the ratio of the *Free Energy of Combustion* of the fuel divided by the *Enthalpy of Combustion*. For methane this limit is 94%. However, such an operating mode would require a very large fuel cell and would be too expensive in most applications.

In practice, fuel cell systems are designed to operate at a power density reflecting the most economical trade-off of fuel and capital costs. At the design point of the system the power output of the system is specified by the manufacturer for certain standard conditions of fuel and air. It is the purpose of this Code to define in a commonly acceptable manner how the power output and the energy input should be measured and how the efficiency should be calculated.

Section 1 defines the objective and scope of this Code. Section 2 is dedicated to defining a fuel cell system and to definitions of terms. It also contains a brief discussion of the major types of fuel cells. In Section 3, methodology of establishing test protocol is outlined. Instrumentation for measuring the energy of the feed stream as well as of the exiting gases and liquids is given in Section 4, as is the instrumentation for measuring electric power. Section 5 describes how the efficiency of the systems shall be calculated from the measurements, and how corrections for nonstandard conditions shall be made.

Typically, this performance test code would be used for an independent verification of the performance of a particular fuel cell system by a customer or test agency. In the view of the members of the Committee, the described procedures are rigorous, and the test will require committing significant resources. For the casual user of fuel cells, it will suffice to determine the electric output of the system under steady state conditions, and to measure the fuel feed rate. As mentioned above, the efficiency of a fuel cell system varies significantly with power density. At power densities below the design point, the efficiency will usually increase, and it will decrease when the power output exceeds the design point. One of the characteristics of fuel cells is the ability to operate them over a wide power range, even exceeding the design point by 50% for a few minutes. Under dynamic operating conditions the efficiency of a fuel cell would be different than at the design point, and would probably be higher, since most loads contain significant segments of low-power operation and normal system control (e.g., for fuel flow) responds fairly quickly to these load conditions. Measuring the efficiency under dynamic conditions goes beyond the scope of the document.

SECTION 1
OBJECT AND SCOPE

1.1 OBJECT

This Code provides test procedures, methods, and definitions for the performance characterization of fuel cell power systems. Fuel cell power systems include all components required in the conversion of input fuel and oxidizer into output electrical and thermal energy. Performance characterization of fuel systems includes evaluating system energy inputs and electrical and thermal outputs to determine fuel-to-electrical energy conversion efficiency and where applicable, the overall thermal effectiveness. These efficiencies will be determined to an absolute uncertainty of less than ±2% at a 95% confidence level. (For example, for a calculated efficiency of 40%, the true value lies between 38% and 42%.)

1.2 SCOPE

This Code applies to all fuel cell power systems regardless of the electrical power output, thermal output, fuel cell type, fuel type, or system application.

Fuel cell power systems contain an assembly of electrochemical cells, which oxidize a fuel to generate direct current electricity. Balance-of-plant subsystems may include controls, thermal management, a fuel processor and a power conditioner. Some fuel cell power systems may contain additional power generating equipment such as steam generators, gas turbine generators, or micro-turbine generators. The net power output and all the fuel input to the system shall be taken into account in the performance test calculations.

This Code applies to the performance of overall fuel cell power systems. The Code addresses combined heat and power systems, that is, the generation of electricity and usable heat at specific thermal conditions. It does not address the performance of specific subsystems nor does it apply to energy storage systems, such as regenerative fuel cells or batteries. It also does not address emissions, reliability, safety issues, or endurance.

This Code contains methods and procedures for conducting and reporting fuel cell system testing, including instrumentation to be used, testing techniques, and methods for calculating and reporting results.

The Code defines the test boundary for fuel and oxidant input, secondary energy input and net electrical and thermal energy output. At these boundaries, this Code provides procedures for measuring temperature, pressure, input fuel flow and composition, electrical power, and thermal output.

The Code provides procedures for determination of electrical efficiency or heat rate and overall thermal effectiveness at rated or any other steady-state condition. The Code also provides the method to correct results from the test to reference conditions.

1.3 TEST UNCERTAINTY

In accordance with ASME PTC 19.1, procedures are provided for determining the uncertainty associated with the calculated performance parameters of this Code (energy input, electrical energy and thermal outputs, and electrical efficiency or heat rate). In the measurements made to determine performance parameters, there are systematic errors produced by the procedures and instrumentation recommended in this Code. A table of these systematic errors may be found in Section 4 of this Code.

Sample calculations of the uncertainties associated with the system performance parameters, which illustrate the effects of systematic errors and data, are presented in Mandatory Appendix I of this Code.

A pretest uncertainty analysis is recommended. The pretest analysis allows corrective action to be taken prior to the test, which will either decrease the uncertainty to an appropriate level consistent with the overall objective of the test or will reduce the cost of the test while still attaining the test uncertainty.

A post-test uncertainty analysis is mandatory. It will make use of empirical data to determine random measurement errors and test observations to establish whether or not the required uncertainty has been achieved.

This uncertainty procedure serves as a guide for pretest and post-test uncertainty calculations when the Code is used.

SECTION 2
DEFINITIONS AND DESCRIPTION OF TERMS

2.1 INTRODUCTION

Fuel cell power systems convert the energy of a fuel and an oxidant directly into electrical energy and heat using an electrochemical process. Fuel cell power systems consist of electrochemical reactors and the balance of plant. Electrochemical reactors convert the energy from chemical to electrical form. Balance-of-plant provides the required reactant and product flows, to and from the electrochemical reactors, and converts the power output to a usable form, such as AC power for a utility grid.

There are a number of different types of fuel cells, and within each fuel cell type, designers have a variety of options for configuration of balance of plant systems. The basic type of fuel cell is defined by the chemistry of the materials used in the cell components. Section 2.2 below describes five of the most common fuel cell types currently being commercialized. Section 2.3 discusses the various components and subsystems that make up fuel cell balance of plant systems.

2.2 FUEL CELL TYPES

2.2.1 Classification of Fuel Cells. The most common classification of fuel cells is by the type of electrolyte used in the cells and includes:

(a) polymer electrolyte membrane, also referred to as proton exchange membrane (PEMFC)

(b) alkaline fuel cell (AFC)

(c) phosphoric acid fuel cell (PAFC)

(d) molten carbonate fuel cell (MCFC)

(e) solid oxide fuel cell (SOFC)

These fuel cells are listed in the order of approximate operating temperature, ranging from ~80°C for PEMFC,~100°C for AFC, ~200°C for PAFC, ~650°C for MCFC, and ~800°C to ~1000°C for SOFC. In addition to these fuel cell types, development is proceeding on other types of fuel cell power systems.

The operating temperature and useful life of a fuel cell are a result of the properties of materials used in the cell components (i.e., electrodes, electrolyte, interconnect, current collector, etc.). Aqueous electrolytes are limited to temperatures of about 200°C or lower because of their high water vapor pressure and/or rapid degradation at higher temperatures. The operating temperature also plays an important role in dictating the type of fuel that can be utilized in a fuel cell. The low-temperature fuel cells with aqueous electrolytes are, in most applications, restricted to hydrogen as a fuel. In high-temperature fuel cells, CO and even CH_4 can be used because of the inherently rapid electrode kinetics and the lesser need for high catalytic activity at high temperature.

2.2.2 Description of the Various Electrolyte Cells. The following descriptions indicate the range of systems currently available. They are not meant to restrict the scope of this Code in any way. This code can be applied for all fuel cell types some of which may not be listed here.

Alkaline Fuel Cell (AFC): the electrolyte in this fuel cell is an aqueous KOH solution, retained in a wicking matrix, and the cells typically operate at 100°C. A wide range of electro-catalysts has been used (e.g., Ni, Ag, metal oxides, spinels, and noble metals). The fuel supply is limited to nonreactive constituents except for hydrogen. CO is a poison, and CO_2 will react with the KOH to form K_2CO_3, thus altering the electrolyte. Even the small amount of CO_2 in air must be considered with the alkaline cell.

Fuel Cell Reformate: reformed fuel output (usually gaseous) from the fuel reformer. The fuel reformer is used to process the input hydrocarbon fuel into a fuel stream (the reformate) that matches the fuel cell stack parameters and meets the needs of the fuel cell system. Fuel Cell Reformate typically consists of the H_2, CO, H_2O results from a steam reforming process. For some fuel cell types, such as MCFC and SOFC, this is utilized directly in the fuel cell stack. For other fuel cell types, such as PEM, the stream is converted to a hydrogen rich gas, with minimal amounts of contaminants but sometimes containing nonreactive compounds such as nitrogen, carbon dioxide, or other nonreactive compounds that can pass through the anode in the unreacted state.

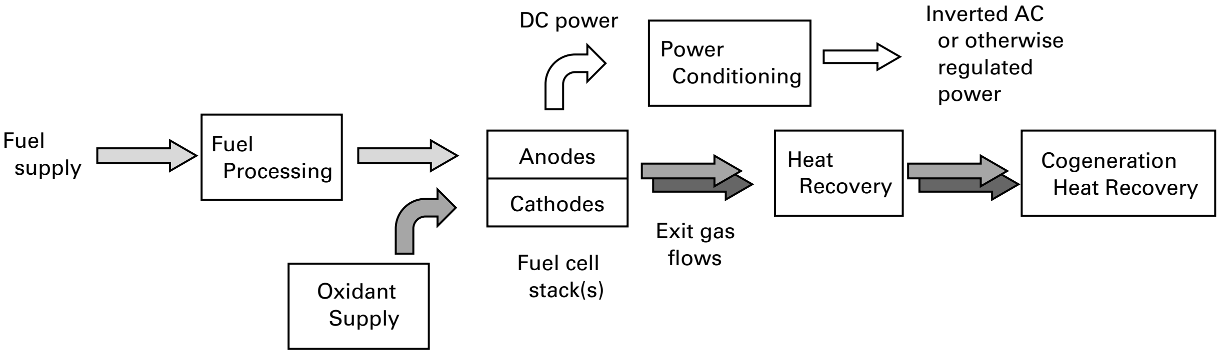


FIG. 2.1 GENERIC FUEL CELL POWER SYSTEM DIAGRAM

Molten Carbonate Fuel Cell (MCFC): the electrolyte in this fuel cell is usually a combination of alkali carbonates retained in a ceramic wicking matrix. The fuel cell operates at 600°C to 700°C where the alkali carbonates form a highly conductive molten salt. At the high operating temperatures in MCFCs, Ni (anode) and nickel oxide (cathode) are adequate catalysts for the cell reactions. MCFC systems can be run at ambient or elevated pressures. Hydrocarbon fuels can be utilized with hydrogen generating reforming subsystems in the balance-of-plant, or utilizing the high temperature of the cells to promote reforming within the cell stacks.

Phosphoric Acid Fuel Cell (PAFC): aqueous phosphoric acid is used for the electrolyte in this fuel cell, which operates at 150°C to 220°C. The system can be run at ambient or elevated pressures, and on hydrogen or hydrocarbon fuels. On hydrocarbon fuels the fuel processing system includes provisions for hydrogen generation. Typical processes for hydrogen generation include steam reforming, partial oxidation or auto thermal reforming. PAFC are significantly less sensitive to CO than PEMFC or AFC, so CO removal subsystems are less elaborate.

Polymer Electrolyte Membrane Fuel Cells: also referred to as *Proton Exchange Membrane Fuel Cell (PEMFC)*; the electrolyte in this fuel cell is an ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymers) that is an excellent hydrogen ion conductor. PEMFC systems typically operate at less than 120°C, because of temperature limitations of the polymer electrolyte. The low operating temperature confers a degree of flexibility on the system (e.g.,startup times will be shorter than for higher temperature systems), but also means the cell catalysts are more sensitive to CO poisoning than other systems. PEMFC systems can be configured to run on hydrogen fuel or hydrocarbon fuels, in which case the fuel processing system includes provisions for hydrogen generation. Typical processes for hydrogen generation include steam reforming, partial oxidation or auto thermal reforming and CO removal (shift reactors and/or selective oxidation reactors). PEMFC systems may be designed to run at atmospheric pressure or higher pressures, depending on application requirements.

Solid Oxide Fuel Cell (SOFC): the electrolyte in this fuel cell is a solid, nonporous metal oxide, usually Y_2O_3 stabilized ZrO_2. The cell operates at 800°C to 1000°C where ionic conduction of oxygen ions across the electolyte takes place.

2.3 FUEL CELL POWER SYSTEMS

A generic fuel cell power system block diagram is shown in Fig. 2.1. A fuel cell combines fuel (usually hydrogen derived from hydrocarbon fuels) and oxygen (usually from air) to produce DC power, water, and heat. In cases where CO and CH_4 are reacted in the cell to produce hydrogen, CO_2 is also a product. These reactions must be carried out at a suitable temperature and pressure for fuel cell operation. A system must be built around the fuel cells to supply air and clean fuel, convert the power to a more usable form such as grid quality AC power, and remove the depleted reactants and heat that are produced by the reactions in the cells. The components of that system are typically as follows:

(a) Cogeneration Heat Recovery. Consists of equipment to export thermal energy for use outside the fuel cell system.

(b) Fuel Supply. Can be as simple as a hookup to a filtered, regulated natural gas source, or can include a gas compressor.

(c) Fuel Cell Stack. Consists of the fuel cell stack or stacks that produce the DC power.

(d) Fuel Processing. Involves a variety of processes, depending on the fuel cell types. If the fuel cell is running on bottled hydrogen, fuel processing is minimal. Typically a fuel cell power system will be run on common hydrocarbon fuels, such as natural gas. Fuel processing usually involves cleaning to remove possible fuel cell poisons (e.g., sulfur compounds used in natural gas odorants). It can include reforming of the gas to produce hydrogen (in "externally reformed" systems) or this function can occur inside the stacks in some types of fuel cells. The fuel processor may also include other equipment, such as shift reactors, CO oxidizer reactors, higher hydrocarbon removal, etc.

(e) Heat Recovery. Systems in fuel cell power systems usually consist of fairly conventional heat exchange equipment, which is used to extract waste heat (typically from the system exhaust stream) to provide reactant pre-heat and steam generation.

(f) Oxidant Supply. Usually consists of a means of providing fresh air to the system, typically with a blower or compressor.

(g) Power Conditioning. Involves conversion of the DC power output from the electrochemical fuel cells to useful power. This usually involves inversion to produce AC power suitable for the intended purpose, but it can also include the production of regulated DC or "chopped" DC.

2.4 GENERAL FUEL CELL NOMENCLATURE

Some of the common terms used to describe fuel cell power system components are as follows:

(a) Fuel Cells. Individual electrochemical cells that produce a voltage (typically 0.5 V to 1 V each) when provided with a supply of fuel and oxidant. Fuel cells consist of an anode (where fuel is consumed and electrons are liberated), a cathode (where oxidant is consumed and electrons are captured), and an electrolyte that provides a path for transfer of ions between the anode and cathode reaction sites.

(b) Fuel Cell Stacks. Consist of a group of individual fuel cells that are physically held together in a stack or a bundle, are fed fuel and oxidant flows together, and whose electrical output is combined. Fuel cell stacks may be configured individually, combined into multistack modules, or they may be configured as part of a fully self-contained power system.

(c) Balance of Plant (BOP). Used to refer to all components in a fuel cell power system besides the electrochemical fuel cell stacks. The BOP can include fuel processing equipment, heat recovery equipment, power conversion equipment, control equipment, etc.

2.5 GENERAL DEFINITIONS

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. Also, the specified secondary heat inputs and outputs are base reference conditions.

bias error: see *systematic error.*

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

calibration drift: see para. 4.1.3.6.

calibration shift: see para. 4.1.3.6.

consistent liquid or gaseous fuels: fuels with a heating value that varies less than one percent over the course of a performance test.

electric efficiency: the ratio of the electrical energy output to the energy supplied to the power system expressed as a percentage. It is inversely related to heat rate.

emissions: nuisance discharges from power plant systems which are regulated by authorities having jurisdiction, such as air pollutants, waste streams and noise.

heat input: the flow of fuel(s) multiplied by the high or low heating value of the fuel(s).

heat rate [kJ/kW·h or Btu/(kW·h)]: heat input per unit of power output, based on either the low or high heating value of the fuel.

heat sink: the reservoir to which the heat rejected by the system is transferred. For a cooling pond, river, lake, or ocean cooling system, the reservoir is the body of water. For an evaporative or dry air-cooled heat exchanger system, the reservoir is the ambient air.

high heating value (HHV): the heat of combustion, per unit quantity of fuel, when all combustion product water is condensed to liquid water and all associated heat is recovered. This is the highest possible heat of combustion of a particular fuel at specified conditions and is typically the heating value paid for by the fuel buyer.

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 include: size, weight, pressure, temperature, fluid flow, voltage, electric current, density, viscosity, and power. Sensors are included which may not, by themselves, incorporate a display but transmit signals to remote computer type devices for display, processing or process control. Also, included are items of ancillary equipment directly affecting the display of the primary instrument (e.g., ammeter shunt), and tools or fixtures used as the basis for determining part acceptability.

low heating value (LHV): the heat of combustion, per unit quantity of fuel when all combustion product water is assumed to remain as vapor. This is the lowest possible heat of combustion of a particular fuel at specified conditions and when used in calculations results in the highest values of power plant efficiency.

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

net power: the electrical power leaving the test boundary minus any electrical power entering the test boundary.

parasitic power: energy produced by the power plant and used within the fuel cell system.

precision error: see *random error.*

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

(a) *Class 1.* Primary variables are those that have a relative sensitivity coefficient of 0.2 or greater.

(b) *Class 2.* Primary variables are those that have a relative sensitivity coefficient of less than 0.2.

Refer to ASME PTC 19.1 for calculations of relative sensitivity coefficients.

random error (ε)*:* sometimes called *precision error;* the true random error, which characterizes a member of a set of measurements. (varies in a random, Gaussian (normal) manner, from measurement to measurement).

rated power: the power output of the power system when operating at specified control and ambient conditions.

secondary energy inputs: energy streams, exclusive of the heating value of main fuel supply crossing into the power plant boundary to support fuel cell systems.

secondary outputs: any useful nonelectrical energy output stream which is used by an external process.

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

secondary thermal energy inputs: the additional heat inputs to the test boundary which must be accounted, such as cycle makeup and process condensate return.

sensitivity: see *influence coefficient.*

serialize: means an instrument has been assigned a unique number and that number has been permanently inscribed on or to the instrument so that it can be identified and tracked.

shaft work: mechanical energy crossing the power plant boundary for accomplishing useful work.

specified corrected net power test: a test run at a specified corrected net power that is near to the design value of interest; for example, an acceptance test where heat rate is guaranteed at a specific load and partial-load tests for development of heat-rate curve conditions.

specified net power test: a test run at a specified net power regardless of ambient or other external conditions. An example of this test goal is acceptance test on a power system with an output guarantee over a range of ambient temperatures.

specific fuel consumption [$ft^3/(kW\cdot h)$, or $lbm/(kW\cdot h)$, or $kg/kW\cdot h$]*:* fuel consumption rate per unit of power output.

standard atmospheric conditions: 14.696 psia (101.325 kPa), 59°F (288.15 K), and relative humidity of 60%.

standard temperature and pressure (STP): 101.325 kPa (14.696 psia), 59°F (288.15 K).

systematic error (β)*:* sometimes called *bias;* the true systematic or fixed error, which characterizes every member of any set of measurements from the population. The constant component of the total measurement error *(δ)*.

test boundary: 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 taken while the fuel cell power system is operating at steady state at a specified operating condition.

thermal effectiveness: percentage of input energy captured for useful purpose which includes conversion to electric energy, shaft work, and thermal energy recovery for external uses.

thermal efficiency: the ratio of the energy output (electrical and shaft) to the energy supplied to the power system, expressed as a percentage. In most fuel cell systems shaft work is not produced. For these systems thermal efficiency is synonymous with electrical efficiency. Thermal efficiency differs from thermal effectiveness in that it does not include utilized heat output. In mathematical terms:

$$\text{thermal efficiency} = (E_n + W)/QI_{\text{total}}$$

where

E_n = net electrical energy output
QI_{total} = total energy into the system
W = shaft work

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

uncertainty (U): $\pm U$ is the interval about the measurement or result that contains the true value for a given confidence level.

SECTION 3
GUIDING PRINCIPLES

3.1 INTRODUCTION

This Section provides guidance on the conduct of the power system testing, and outlines the steps required to plan, conduct, and evaluate a Code test of fuel cell power system performance. The Subsections discuss the following:

(a) agreements
(b) test boundary
(c) test plan
(d) preparation for test
(e) operation of the test
(f) calculation and reporting of results
(g) records

3.2 AGREEMENTS

The parties to the test shall agree in writing on the object, scope, and plan for the test. The parties are normally the customer/owner and the fuel cell system supplier, and may include an independent contractor (e.g., a testing agency, architect engineers, etc.).

3.3 TEST BOUNDARY

The test boundary and the pertinent material and energy streams that cross the test boundary are to be determined and agreed upon during the preparations for the performance test. Different fuel cell technologies will yield unique balance of plant (BOP) systems, but in every system fuel and an oxidant will cross the boundary into the unit and electrical energy and at least one heat and waste stream will cross the boundary out of the unit. Each unique fuel cell system can have numerous additional streams into and out of the system. These streams of material and energy into and out of power system need to be identified, quantified as to significant energy content, and measured if significant to evaluate the system performance. Figures 3.1 and 3.2 illustrate typical fuel cell power system boundaries, and possible material and energy streams into and out of the system.

3.4 TEST PLAN

A test plan, including detailed test procedures, shall be written by the fuel cell system supplier or his agent prior to conducting the performance test. The test plan shall identify the operational conditions and associated state-point values, the pertinent control system set points, the minimum test time at a condition, and the significant data to be taken. Additional test operating conditions, such as part-load, shall be defined and identified along with the expected sequence for testing them.

The test plan shall be approved, prior to the testing, by authorized signatures of all principal parties to the test. The test plan shall reflect any contract requirements that pertain to the test objectives and agreement shall be reached prior to the test on the following issues:

(a) extent of the system to be tested; i.e., test boundary;

(b) base reference conditions;

(c) data to be recorded and method of recording and archiving data;

(d) personnel to be conducting the test, and the responsibilities of each individual in certifying that the test is conducted in accordance with the Code;

(e) place where the test is to be conducted: at the manufacturer's facility, the customer site, or other location where the prevailing ambient conditions are acceptable to the parties;

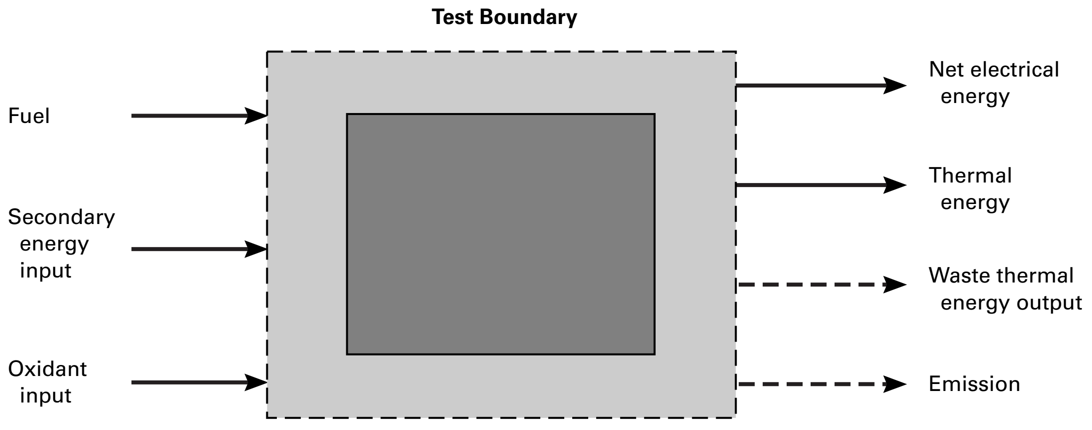
(f) date when the test is to be conducted. For an acceptance test, the test should be undertaken soon after the fuel cell system is operational, with appropriate time to condition the fuel cell in accordance with the supplier's requirements;

(g) procedures for recording the test data and observations, including sample frequency;

(h) type, number, and systematic uncertainty of all instruments to be used to establish test conditions and test results and how they shall be installed;

(i) instrument calibration schedule or procedures;

(j) designation of the laboratory and any other facilities required for determining pertinent fuel characteristics;



GENERAL NOTES:

→ Required to be measured for test calculation

- - → Not required to be measured for test calculation

FIG. 3.1 GENERIC FUEL CELL SYSTEM TEST BOUNDARY

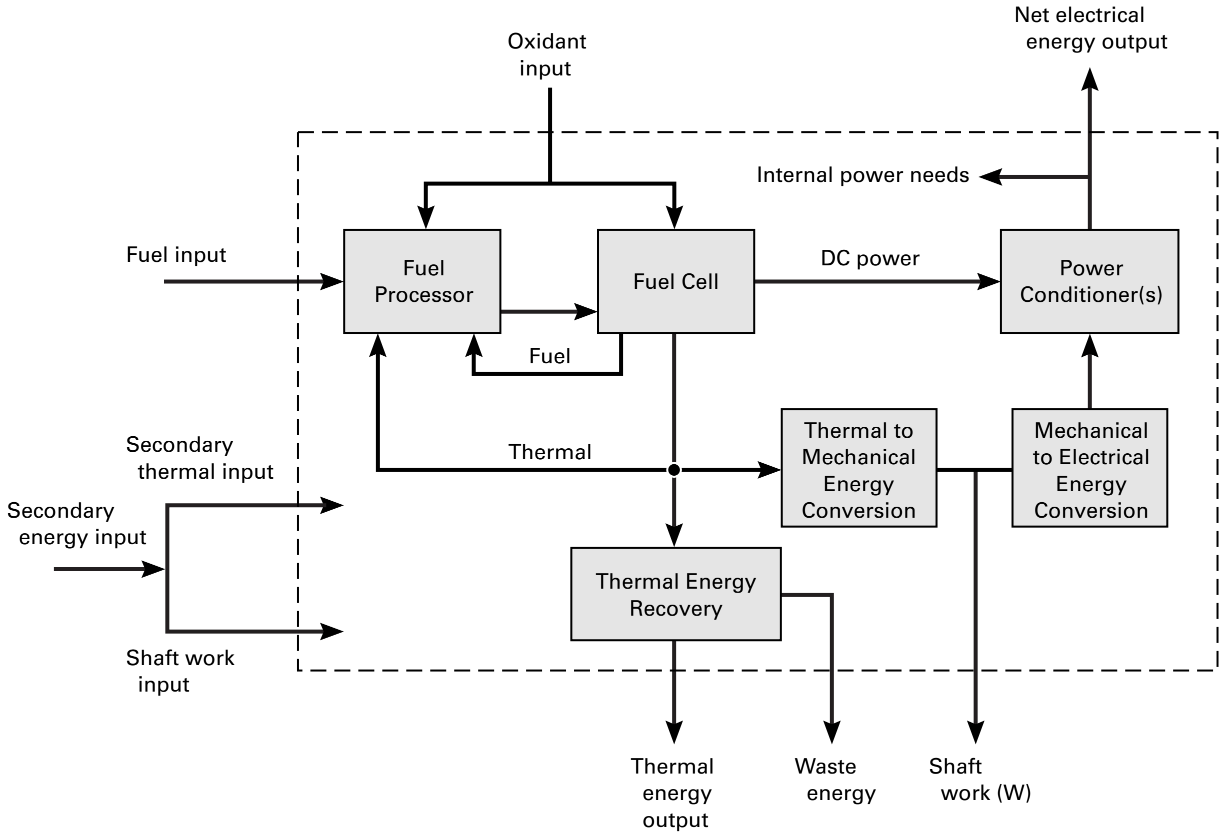


FIG. 3.2 FUEL CELL SYSTEM TEST BOUNDARY ILLUSTRATING INTERNAL SUBSYSTEMS

(k) requisite facilities for maintaining constancy of load during test;
(l) number of identical tests to be conducted to assure statistically significant accuracy;
(m) duration of the test runs;
(n) acceptance of test run when disruptions occur;
(o) test acceptance criteria for test completion;
(p) confidentiality of test results.

3.4.1 Test Goals. This Code recognizes that different types of conditions might require different types of test goals. The following illustrates three different test goals that are acceptable by this Code.

(a) The test can be run at a specified corrected net power that is near the design value of interest. Examples of this test would be an acceptance test of a fuel cell power system where electric efficiency is guaranteed at a specific load, or a partial load, on a specific fuel composition, but the available pipeline composition differs from the design value.

(b) The test can be run at a specified net power regardless of ambient or other external conditions. An example of this test goal is an acceptance test on a fuel cell power system with a rated power and electrical efficiency guarantee over a range of ambient temperatures.

(c) The test can be run at a specified maximum power overload state point. The test shall include run times to demonstrate the ability to operate for the stated limited time periods, and the test results must be reported with operational time limitations. An example would be a short term (e.g., less than a few hours) overload power excursion that would be useful for a peak power demand. This overload power operation might legitimately be accomplished with an incomplete thermal transient in a subsystem.

While only steady-state operation is treated in the Code, it should be recognized that there might be cases when operation and subsequent performance under non-steady-state conditions is important. Examples could include start up and shut down transients, load following operation, and idle standby. In general, system performance, especially average efficiency, will be different under transient conditions as compared to corresponding steady-state conditions. As an aid to achieving a more meaningful characterization of fuel cell performance, including non-steady-state operation, it is recommended that the total energy input into the system be compared to the net useful energy output produced during the time frame of interest using one or more representative load cycle(s).

Regardless of the test goal, the results of a performance test per this Code will be corrected net power, corrected electrical efficiency, corrected thermal effectiveness, and corrected thermal efficiency.

3.4.2 Schedule of Test Activities. A test schedule shall be prepared which should include the timing of the test events, notification of parties, test preparation and conduct, and the preparation of the test report.

3.5 PREPARATION FOR TEST

3.5.1 Pretest Records. Nominal performance data and operating limitations supplied by the manufacturer of the fuel cell system shall be available on the test site. This shall include the expected output parameter values, and the limitations on the operating range. General physical conditions of the fuel cell system prior to the test shall be documented with photos and data recording. Information on subsystems that may be temporarily nonfunctional shall be recorded, including the reason for the nonfunctionality and the expected effect on the test results. The fuel cell power system shall be fully characterized by identification of the design and construction features that can significantly affect the results. The system shall be identified by the manufacturer's serial number of the unit and of the major components. When tested in the field, the date of delivery and other pertinent historical information shall be recorded.

3.5.2 Preliminary Operation and Adjustment. Before starting the test, the fuel cell system should be operated for a sufficient length of time to demonstrate steady-state operation, and to make any necessary adjustments to the electrical and thermal loads for assuring conformity with the Code.

3.5.3 Site Applicability of Instrument Calibration. Current, applicable calibration certificates of the critical system instrumentation shall be available prior to the start of the test. Parties to the test shall agree that the ambient conditions at the test site do not have an adverse effect on the calibration of the test instruments or they shall agree to the mitigation measure if ambient conditions do have an adverse effect.

3.6 PARAMETERS TO BE MEASURED OR DETERMINED DURING THE TEST PERIOD

(a) Data Periods

t = time (hr) of the test period

tr = time (hr) of the data period

(b) Ambient Conditions

$ELEV_{site}$ = test site elevation

P_{amb} = barometric pressure at the test site, kPa

RH_{amb} = relative humidity at the test site, percent R.H.

T_{amb} = ambient Temperature at the test site ,°C

(c) Fuel

C_{fp} = specific heat of fuel at the test boundary (at constant pressure), kJ/kg·K

HHV_{avg} = fuel high-heating value at the test boundary in kJ/kg for calculations based on High Heating Value

LHV_{avg} = fuel low-heating value at the test boundary in kJ/kg for calculations based on Low Heating Value

M_f = total fuel flow to the fuel cell during the test or data period, kg

M_fR = fuel flow into the test boundary in kg/s during the data period (may be used to calculate the total fuel flow by integrating the flowrate over the data period)

MW_f = molecular weight of the gaseous fuel, kg/kmol

P_f = fuel pressure at the test boundary in kPa (absolute)

RH_f = relative humidity of the fuel, at the test boundary, percent R.H.

T_{ff} = fuel temperature at the test boundary, K

(d) Secondary Thermal Input

H_i = average enthalpy of the secondary thermal input heat transfer fluid entering the fuel cell system at the test boundary, kJ/kg

H_o = average enthalpy of the secondary thermal input heat transfer fluid exiting the fuel cell system at the test boundary, kJ/kg

M_{htf} = mass of heat transfer fluid into and out of the fuel cell system from the source of secondary thermal energy during the test period, kg

$M_{htf}R$ = mass flow rate of heat transfer fluid into and out of the fuel cell system from the source of secondary thermal energy during the data period (may be used to compute the total flow by integrating over the data period), kg/sec

P_{stii} = average pressure of the secondary thermal input heat transfer fluid entering the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate the enthalpy of the heat transfer fluid)

P_{stio} = average pressure of the secondary thermal input heat transfer fluid leaving the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate the enthalpy of the heat transfer fluid)

T_{stii} = average temperature of the secondary thermal input heat transfer fluid entering the fuel cell system at the test boundary, K, (may be used to calculate the enthalpy of the heat transfer fluid)

T_{stio} = average temperature of the secondary thermal input heat transfer fluid leaving the fuel cell system at the test boundary, K, (may be used to calculate the enthalpy of the heat transfer fluid)

(e) Oxidant

M_o = total oxidant flow to the fuel cell system during the test period, kg

M_oR = oxidant flow into the test boundary, kg/sec, during the data period (may be used to calculate the total oxidant flow by integrating the flow over the data period)

MW_o = molecular weight of the oxidant (28.9644 kg/kmol for standard dry air)

P_o = average oxidant pressure at the test boundary, kPa (absolute)

T_o = average oxidant temperature at the test boundary, K

(f) Auxiliary Electrical Input

E_a = kilowatt-hours into the system crossing the test boundary

I_a = auxiliary electrical input current, A, at the test boundary

KW_a = auxiliary electrical input power into the test boundary, kWe

V_a = auxiliary electrical input voltage, at the test boundary *(g) Electrical Output*

E_g = total kilowatt-hours out of the system test boundary during the test period

I_g = electrical output current, A, at the test boundary

KVA = total real and reactive power out of the test boundary, kVA

KW_g = real electrical output power out of the test boundary, kWe

PF_g = power factor of the output current and voltage from the system at the test boundary

V_g = electrical output voltage at the test boundary

(h) Cooling System Heat Sink Temperature

T_{cooling} = cooling system heat sink temperature, K

(i) Thermal Energy Capture (TEC)

H_{in} = enthalpy of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, kJ/kg

H_{out} = enthalpy of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, kJ/kg

M_w = total mass of TEC water or heat transfer fluid circulating through the test boundary during the test period, kg

M_wR = flow rate of TEC water or heat transfer fluid circulating through the system

P_{teci} = pressure of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate enthalpy)

P_{teco} = pressure of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate enthalpy)

T_{delivery} = useful thermal energy delivery temperature, K

T_{teci} = temperature of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, K (may be used to calculate enthalpy)

T_{teco} = temperature of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, K (may be used to calculate enthalpy)

(j) Shaft Work Into the System During the Test

W_{si} = mechanical shaft work done on the system by an outside prime mover resulting in energy added to the system from across the system boundary, kJ

(k) Shaft Work Out of the System During the Test

W_{so} = mechanical shaft work done by the system to an outside industrial or other energy user system resulting in energy produced by the system being exported across the system boundary, kJ. This is analogous to mechanical cogeneration.

3.6.1 Class I Primary Variables

(a) Data Periods

t_{dp} = time, in hours and seconds, of the data period

t_{tp} = time, in hours and seconds, of the test period

(b) Fuel

HHV_{avg} = fuel high heating value at the test boundary, kJ/kg, for calculations based on High Heating Value

LHV_{avg} = fuel low heating value at the test boundary, kJ/kg, for calculations based on Low Heating Value

M_f = total fuel flow to the fuel cell during the test or data period, kg

P_f = fuel inlet pressure at the test boundary, kPa (absolute)

T_{ff} = fuel temperature at the test boundary, K

(c) Secondary Heat Input

H_i = average enthalpy of the secondary thermal input heat transfer fluid entering the fuel cell at the test boundary, kJ/kg

H_o = average enthalpy of the secondary thermal input heat transfer fluid exiting the fuel cell at the test boundary, kJ/kg

M_{htf} = mass of heat transfer fluid into and out of the fuel cell from the source of secondary thermal energy during the test period, kg

T_{stii} = average temperature of the secondary thermal input heat transfer fluid entering the fuel cell at the test boundary, K (may be used to calculate the enthalpy of the heat transfer fluid)

T_{stio} = average temperature of the secondary thermal input heat transfer fluid leaving the fuel cell at the test boundary, K (may be used to calculate the enthalpy of the heat transfer fluid)

(d) Oxidant

M_o = total oxidant flow to the fuel cell during the test period, kg

P_o = average oxidant pressure at the test boundary, kPa (absolute)

T_o = average oxidant temperature at the test boundary, K

(e) Auxiliary Electrical Input

E_a = total kilowatt-hours into the system crossing the test boundary during the test period

(f) Electrical Output

E_g = total kilowatt-hours out of the system crossing the test boundary during the test period

(g) Thermal Energy Captured (TEC)

H_{out} = enthalpy of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, kJ/kg

H_{in} = enthalpy of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, kJ/kg

M_w = total mass of TEC water or heat transfer fluid circulating through the test boundary during the test period, kg

T_{teci} = temperature of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, K, (may be used to calculate enthalpy)

T_{teco} = temperature of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, K, (may be used to calculate enthalpy)

(h) Shaft Work Into the System During the Test

W_{si} = mechanical shaft work done on the system by an outside prime mover resulting in energy added to the system from across the system boundary, kJ.

(i) Shaft Work Out of the System During the Test

W_{so} = mechanical shaft work done by the system to an outside industrial or other energy user system resulting in energy produced by the system being exported across the system boundary, kJ

3.6.2 Class II Primary Variables

(a) Ambient Conditions

$ELEV_{\mathrm{site}}$ = test site evaluation, m

P_{amb} = barometric pressure at the test site, kPa

RH_{amb} = relative humidity at the test site, percent R.H.

T_{amb} = ambient temperature at the test site, °C

(b) Fuel

C_{fp} = specific heat of fuel at the test boundary (at constant pressure), kJ/kg·K

M_fR = fuel flow into the test boundary, kg/sec, during the data period (may be used to calculate the total fuel flow by integrating the flow over the data period

MW_f = molecular weight of the gaseous fuel, kg/kmol

RH_f = relative humidity of the fuel at the test boundary, percent R.H.

(c) Secondary Thermal Input

$M_{htf}R$ = mass flow rate of heat transfer fluid into and out of the fuel cell from the source of the secondary thermal energy during the data period (may be used to compute the total flow by integrating over the data period), kg/sec

P_{stii} = average pressure of the secondary thermal input heat transfer fluid entering the fuel cell at the test boundary, kPa (absolute) (may be used to calculate the enthalpy of the heat transfer fluid)

P_{stio} = average pressure of the secondary thermal input heat transfer fluid leaving the fuel cell at the test boundary, kPa (absolute) (may be used to calculate the enthalpy of the heat transfer fluid)

(d) Oxidant

M_oR = oxidant flowrate into the test boundary, kg/sec, during the data period (may be used to calculate the total oxidant flow by integrating the flow over the data period)

MW_o = molecular weight of the oxidant (28.9644 kg/kmol for standard dry air)

P_o = average oxidant pressure at the test boundary, kPa (absolute) *(e) Auxiliary Electrical Input*

I_a = auxiliary electrical input current, A, at the test boundary
KW_a = auxiliary electrical input power into the test boundary, KWe
V_a = auxiliary electrical input voltage, at the test boundary

(f) Electrical Output

E_g = electrical output power out of the test boundary, KWe
I_g = electrical output current, A, at the test boundary
PF_g = power factor of the output current and voltage output from the system at the test boundary
V_g = electrical output voltage, at the test boundary

(g) Thermal Energy Captured (TEC)

M_wR = flowrate of TEC water or heat transfer fluid circulating through the system measured at the test boundary, kg/sec, (may be used to compute the total mass of water by integrating over the data period)
P_{teci} = pressure of TEC water or heat transfer fluid entering the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate enthalpy)
P_{teco} = pressure of TEC water or heat transfer fluid leaving the fuel cell system at the test boundary, kPa (absolute) (may be used to calculate enthalpy)
T_{cooling} = cooling system heat sink temperature, K
T_{delivery} = useful thermal energy delivery temperature, K

3.7 OPERATION OF THE TEST

3.7.1 Specified Conditions. Every effort shall be made to run the test under the agreed-upon base reference conditions, such as output, pressures, and temperatures, or as close to specified conditions as possible, in order to limit the application of corrections.

3.7.2 Stabilization. Before starting the test, the fuel cell power system shall be run until steady-state conditions have been established and maintained for an agreed upon time period. Steady state will be achieved when continuous monitoring indicates that readings are within the maximum permissible variations.

TABLE 3.1 MAXIMUM PERMISSIBLE VARIATIONS IN TEST OPERATING CONDITIONS

Parameter	Allowable Variation During Test Run
System stabilization parameter as specified by the manufacturer and agreed to by all parties	As specified
Real power output, kWe	±2%
Total power, kVA	±2%
Barometric pressure at site	±0.5%
Inlet air temperature	±3°C (5°F)
Heating Value—fuel per unit value	±1%
Gaseous fuel pressure as delivered to system	±1%
Absolute exhaust pressure	±0.5%
Absolute inlet air pressure to system	±0.5%
Heat rejection rate to external cooling rate	±2%
Fuel flow	±2%
Fuel temperature	±3°F
Secondary thermal energy input temperature	±5°F
Secondary thermal energy input delivery rate	±2%
Inlet air/oxidant flow rate	Not specified
Thermal energy output delivery rate	±2%

3.7.3 Maximum Permissible Variations in Operating Test Conditions. Each observation of an operating condition during a test run shall not vary from the computed average for that operating condition during the complete run by more than the amount shown in Table 3.1, except by written agreement among the parties to the test. If operating conditions vary during any test run beyond the limits prescribed in Table 3.1, and if such variations are not covered by written agreement, the results of the test run shall be discarded.

3.7.4 Duration of Test Run and Frequency of Readings. A test run shall not be less than 1 hr. A sufficient number of readings shall be spaced in time to show the range of fluctuations and to provide a reliable average for the test run and to meet the uncertainty requirements of this Code. The interval between readings shall be not less than 1 min.

3.8 CALCULATION AND REPORTING OF RESULTS

3.8.1 Validity of Results. If, during the conduct of a test or during the subsequent analysis or interpretation of the observed data, an inconsistency is found which affects the validity of the results, the parties should make every reasonable effort to adjust or eliminate the inconsistency by mutual agreement. Failure to reach such agreement will constitute rejection of the run or test.

3.8.2 Reporting of Results. In all cases, the test results shall be reported:

(a) as calculated from the test observations, with instrument calibrations only having been applied; and

(b) as corrected for deviations of the operating conditions from the specified conditions.

3.8.3 Objectives of Uncertainty Analysis. The application of uncertainty analysis to a Code test procedure has two objectives:

(a) determine compliance of the test procedure with the uncertainty requirements of the Code; and

(b) reduce the risk of making an erroneous decision when evaluating the results.

3.8.4 Uncertainty. Test uncertainty and contract tolerance are not interchangeable terms. This Code does not address contract tolerance, which is a commercial term.

3.8.5 Uncertainty Calculations. Reference should be made to ASME PTC 19.1 for definitions and theory behind uncertainty analyses, as well as for the mathematical derivations of the formulas used.

3.8.5.1 This Code provides a test procedure that produces results with the lowest practicable uncertainties. Since no measurement is error-free, the uncertainty of each test result should be evaluated by the parties.

3.8.5.2 To assist the parties in developing an uncertainty analysis, Mandatory Appendix I contains an outline of the procedure, guidance on the application of the analysis, and a sample calculation.

3.8.5.3 All uncertainty values that have been determined and agreed upon by the parties to a test shall be included in the report (see Section 6).

3.8.6 Uncertainty Limits. As illustrated in Mandatory Appendix I, it is not possible to define a single value of uncertainty in order to be designated a Code test. The Code defines the uncertainty limits of the combined measurements. The limits for each of the measured parameters will be determined by the pretest uncertainty analysis and agreed to by the parties to the test. Trade-offs may be made between instrument uncertainties as long as the overall uncertainty value is within the requirements of this Code. No specific individual instrumentation uncertainties are given in this Code; but the overall requirements to have an absolute uncertainty on the result of less than 2% shall be met by appropriate instrumentation selected by the user.

3.9 RECORDS

3.9.1 Test Observations. Test observations shall be recorded on a data acquisition system or entered on log sheets and authenticated by the observers' signatures. For acceptance tests, a complete set of unaltered data sheets and recorded charts, or facsimiles thereof, shall be available to the buyer and manufacturer and distributed as specified by any contractual agreements. The observations shall include the date and time of day. They shall be the actual readings without application of any corrections. The log sheets and all recorded charts constitute a complete record.

3.9.2 Direct Observations. Where direct observations of instrument readings are to be recorded at frequent intervals during a test, it is not always necessary to observe simultaneously all readings, which are made at the same intervals. In cases where the average of a series of readings is used in calculating results, uniform time periods, adapted to conditions of the test and nature of data required, may be employed.

3.9.3 Data Reliability. During acceptance tests, it is recommended that data considered to be especially important be recorded electronically or manually taken by at least two observers. A comparison of these observations should be made as soon as possible and any discrepancies reconciled before the end of the test.

3.9.4 Test Log. All events connected with the progress of a test should be recorded on the test log sheets, together with the time of occurrence and name of the observer. Particular care should be taken to record any adjustments made to any equipment under test, whether made during a run or between runs. The reasons for each adjustment shall be stated in the test records.

3.9.5 Test Recording Errors. In case of an error in a recorded observation, a line shall be drawn through the incorrect entry; the correct reading is to be recorded above the incorrect entry and initialed, and an explanation entered in the proper place in the test records.

SECTION 4
INSTRUMENTS AND METHODS OF MEASUREMENT

Calibration equipment shall be calibrated using standards that are traceable to National Institute of Standards and Technology or equivalent source. Purchased calibration services are acceptable. Records shall be maintained for each instrument and its calibration interval.

4.1 GENERAL REQUIREMENTS

4.1.1 Introduction. This Code represents the mandatory requirements for instrumentation employed and the use of such devices. The instrumentation recommended herein may be replaced by new technology, as it becomes available. The Instruments and Apparatus supplements (ASME PTC 19 Series) outline the governing requirements for all ASME performance testing.

SI units, followed by U.S. customary units in parentheses, are shown in all equations in this Section. However, any other consistent set of units may be used.

4.1.2 Instrumentation Classification. The instrumentation employed to measure a variable will have different required type, accuracy, redundancy, and handling depending upon the use of the measured variable and depending upon how the measured variable affects the final result. For purposes of this discussion, variables are temperature, pressure, differential pressure, flow, velocity, voltage, current, frequency, stream constituency, and humidity. Measurements are classified as either primary or secondary variables.

4.1.2.1 Primary Variables. Variables that are used in calculation of test results are considered primary variables. Primary variables are further classified as Class 1 or Class 2. Class 1 primary variables are those which have a relative sensitivity coefficient of 0.2 or greater. These variables will require higher accuracy instruments with more redundancy than Class 2 primary variables, which have a relative sensitivity coefficient of less than 0.2. Some examples of primary Class 1 variables include input fuel flow measurement, fuel heating value, gross power output, and auxiliary or parasitic power consumed by the fuel cell power system (auxiliary or parasitic power is a primary variable only if gross and auxiliary power are measured separately; otherwise, net power output is the measured variable). Some examples of primary Class 2 variables include fuel cell power system output voltage, output current, and output frequency if they are only used in minor correction factors. The precise calculation of relative sensitivity coefficients is required in order to classify primary variables. Refer to ASME PTC 19.1 for example calculations.

4.1.2.2 Secondary Variables. Variables that are measured but do not enter into the calculation of the results are secondary variables. These variables are measured throughout the test period to ensure that the required test condition was not violated. Some examples of these variables are fuel cell reformate inlet temperature, barometric pressure at site, ambient temperature, and absolute exhaust pressure if they are not used in calculations or in correction factors.

This Code does not require high accuracy instruments for secondary variables.

The instruments that measure secondary variables may be permanently installed plant instrumentation. The Code does, however, require verification of instrument output prior to the test period. This verification can be accomplished by calibration or by comparison against two or more independent measurements of the variable referenced to the same location.

4.1.3 Instrument Calibration

4.1.3.1 Calibration. Calibration of an instrument is the act of applying process conditions to the candidate instrument and the reference standard and adjusting the instrument to match the standard, if appropriate. During calibration, readings are taken from the candidate instrument and the referenced standard. The output of the candidate instrument may be adjusted to the standard reading. As an alternative, the difference between the instrument and the referenced standard may be recorded and applied to the instrument reading. This alternative method is recommended in the case of the thermocouples or Resistance Temperature Devices (RTDs) because their output cannot be easily altered.

4.1.3.2 Referenced Standards. In general, all test instruments used to measure primary variables (Class 1 and Class 2) shall be calibrated against referenced standards traceable to the National Institute of Standards and Technology (NIST) in the United States, other recognized international standards organization, or recognized physical constants. All referenced standards shall be calibrated at an interval specified by the instrument manufacturer.

The referenced standard shall have an uncertainty of less than $^1/_4$ of the required uncertainty of the test instrument to be calibrated.

Instrumentation used to measure secondary variables need not be calibrated against a referenced standard. These instruments may be calibrated against a calibrated instrument that is traceable to the NIST standards.

4.1.3.3 Ambient Conditions. Calibration of instruments used to measure primary variables (Class 1 or Class 2) shall be performed in a manner which replicates the condition that the instrument will be used to make the test measurements. Consideration shall be given to all process and ambient conditions that may affect the measurement, including temperature, pressure, humidity, static electricity, electromagnetic interference, etc.

4.1.3.4 Instrument Ranges and Calibration Points. The number of calibration points depends on the classification of the variable the instrument will measure. All Class 1 or 2 instruments shall be serialized and carry a label indicating each instrument's calibration status and date of calibration. Instruments used continuously shall be calibrated per a defined interval and procedure as required per the instrument manufacturer's instructions. Instruments shall be calibrated by qualified personnel, authorized suppliers, or third party calibration services, using written procedures. Records or instrument calibration data sheets shall be maintained for each instrument used during the test along with each instrument's calibration interval. The calibration should closely bracket the expected measurement range anticipated for the test.

(a) Class 1 Primary Variables. The instruments measuring Class 1 primary variables shall be calibrated with at least two points more than the degree of the calibration curve fit. Each instrument shall be calibrated such that as the anticipated test measuring value or range is approached, an increasing number of calibration points are measured below, above and through the anticipated test value or range to minimize the hysteresis effects.

Some instruments are built with a mechanism to alter the range once the instrument is installed. In this case, the instrument must be calibrated at each range to be used during the test period.

(b) Class 2 Primary Variables. Instruments measuring Class 2 primary variables shall be calibrated with at least one point more than the order of the calibration curve fit. If the instrument can be shown to typically have a sufficiently low hysteresis of less than the required accuracy, the expected measuring point or range need only be approached from one direction (either increasing or decreasing to the point).

(c) Secondary Variables. The Code does require verification of instrument output prior to the test period. Instruments used to measure secondary variables can be checked in place with at least two or more instruments measuring the variable with respect to the same location or can be calibrated against a previously calibrated instrument. Should the instrument be calibrated, it need only be calibrated at one point in the expected operating range.

4.1.3.5 Timing of Calibration. All test instrumentation used to measure primary variables (Class 1 or Class 2) will be calibrated prior to the test and have calibration checked following the tests. The initial instrument calibration prior to tests and calibration check after the tests should be kept to a minimum length of time to obtain an acceptable calibration drift. Instruments that are within their approved calibration intervals shall be acceptable for use. The following exceptions to the prior and post-calibration requirement are allowed. Flow measurement devices, current transformers, and potential transformers by nature are not conducive to post test calibration checks. In the case of flow measuring devices used to measure Class 1 primary variables, the instrument shall be inspected following the test for physical integrity rather than recalibrating the device. Flow elements for Class 2 primary variables need not be inspected if steam blow or chemical cleaning has not occurred.

Post-test calibration of current and potential transformers is not required.

4.1.3.6 Calibration Drift and Shift. *Calibration drift* is defined as the difference in the calibration correction as a percent of reading. When the post-test calibration check indicates that the drift is less than the instrument bias uncertainty, the drift is considered acceptable and the pretest calibration is used as the bias for determining the test results. Should the calibration drift, combined with the reference standard accuracy as the square root of the sum of the squares, exceed the accuracy of the instrument, it is not acceptable.

Calibration shift can result from instrument malfunction, transportation, installation, or removal of the test instrumentation. Should this occur, engineering judgment must be used to determine whether the initial test calibration or the final calibration check is correct. Below are some good practices:

(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 can isolate when the shift may have occurred. An example of this check is a vented pressure transmitter, no load on wattmeter, and an ice point temperature check on a thermocouple or RTD with or without transmitter.

(b) Redundant instrumentation is two or more devices measuring the same parameter with respect to the same location. In locations where redundant instrumentation is employed, calibration drift should be analyzed to determine which calibration data the initial test calibration or the post-test check produces the better agreement between the redundant instruments.

4.1.3.7 Loop Calibration. All instruments used to measure primary variables (Class 1 or Class 2) should be loop calibrated. Loop calibration involves the calibration of the instrument through all of the signal-conditioning equipment utilized up to and including final indication. This may be accomplished by calibrating instrumentation employing the test signal conditioning equipment either in a laboratory or on site during the test setup before the instrument is connected to the 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 must be performed to ensure the combined uncertainty of the measurement and final indication system meets the accuracy requirements described herein.

4.1.3.8 Quality Assurance Program. Each calibration laboratory must have a quality assurance program. This program is a method of documentation where the following information can be found:

(a) calibration procedures
(b) calibration technician training
(c) standard calibration records
(d) standard calibration schedule
(e) instrument calibration histories with most recent individual instrument calibration sheets

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

All parties to the test should be allowed the opportunity to witness the calibration of instruments in the calibration laboratory and at the site. In addition, all test parties should have the right to review the quality assurance plan prior to or during the instrument calibration.

4.1.4 Plant Instrumentation. It is acceptable to use plant instrumentation for primary variables only if the plant instrumentation (including signal-conditioning equipment) can be demonstrated to meet the overall uncertainty requirements. Many times this is not the case. In the case of flow measurements, all measurements (process pressure, temperature, differential pressure, or pulses from a metering device) must be made available for correcting the primary instrument data, as plant conversions to flow are often not rigorous enough for the required accuracy.

4.2 CHECKLIST OF INSTRUMENTS AND APPARATUS

The following devices and instruments are typically used to measure the performance of a fuel cell power system:

(a) For fuel input measurement
  (1) fuel composition instruments, e.g., gas chromatograph
  (2) fuel input rate measurement, e.g., flow meters, pressure sensors, temperature sensors
(b) For ambient condition measurement
  (1) barometer, hygrometer, thermometer, etc.
(c) For electrical output
  (1) load; e.g., grid or load bank
  (2) output measurements, voltage and current transducers, real and reactive power measurement
(d) For thermal output
  (1) flow and temperature measurement

(e) For data collection

  (1) data acquisition system

  (2) timekeeping instruments

For pressure and temperature measurements, the total or stagnation properties (pressure and temperature) of a fluid stream are those that would exist if the stream were diffused adiabatically and reversibly; i.e., isentropically, to zero velocity.

4.3 DETERMINATION OF OUTPUTS

4.3.1 Thermal Output Measurements

4.3.1.1 Water or Heat Transfer Fluid Flow Measurement. The measurement of water, or heat transfer fluid flow, into the Thermal Energy Capture (TEC) unit is required to be within an accuracy that is consistent with the desired thermal output uncertainty.

Numerous methods are employed in industry to determine the flow of liquid, or gaseous streams. ASME PTC 19.5 is the primary reference for flow measurements. ASME documents MFC-3M, PTC 6, and ISO 5167 provide further information on flow measurement techniques. These sources include design, construction, location, and installation of flowmeters, the connecting piping, and computations of flow.

All water or heat transfer fluid leakage shall be eliminated; otherwise, it must be measured and accounted.

4.3.1.2 Water or Heat Transfer Fluid Temperature Measurement. Water temperatures shall be measured as close to the TEC unit as practical.

All temperature measuring instruments and wells shall be constructed, installed, and the instruments calibrated and operated in accordance with ASME PTC 19.3, except where the fluid stream Reynolds number exceeds 3.5×10^5. Appropriate allowances are required in well design to account for the increase in Strouhal number. Temperature measuring devices shall be installed so that adverse effects of radiation and/or conduction will be minimal.

The temperature sensing element and/or well shall be located such that it is subjected to the velocity of the measured fluid and not in a stagnant fluid pocket.

4.3.1.3 Other Measurements

(a) Water Pressures. Pressure gauges shall be located where they will not be affected by any disturbing influences, such as extremes of heat, cold, and vibration, and shall be located in convenient positions for reading. While calibrated Bourdon tube test gauges or deadweight gauges may be used, the use of the latter is preferred.

(b) Gauge Connections. Connections shall be as short and direct as possible. Gauges shall be protected with siphons or equivalent where needed. Convolutions of siphons shall be as few in number as possible, consistent with the gauge remaining cool, because of their tendency to introduce errors due to unbalanced water columns in the convolutions. All gauge connections shall be tight. Pressure sending tubing should be routed to continuously slope downward from the process to the instrument. The additional pressure sensed by the instrument resulting from this water leg should be taken into account. That means accurately measuring the vertical drop between the centerline of the process and the instrument.

(c) Static Pressure Connections. Shall be located and installed in order to avoid errors due to velocity vectors and eddies. Pressure gauge pulsations shall not be damped by throttling the connections to the gauge or by the use of commercial gauge dampers, but a volume chamber may be employed. The arrangement may be considered satisfactory if the maximum and minimum values of the instantaneous pressure do not differ by more than 2% from the mean value. Bourdon tube test gauges shall be calibrated, installed and used in accordance with ASME PTC 19.2, *Pressure Measurement.* These gauges shall be calibrated before and after the test.

4.3.2 Electrical Output Measurements. Fuel cells generate direct current electricity. When alternating current is required, some type of DC to AC conversion must take place. In practice, this will normally be accomplished through the use of static power converters. All static power converters generate some degree of harmonic distortion, which must be taken into account during test measurements. This is a practical reason for using modern digital measurement apparatus since, in most cases, the sampling speed and computational power is such that a true reading of power, current, voltage and power factor can be obtained in the presence of harmonic distortion. A measurement apparatus that can accurately report power measurements, in the presence of harmonics, is referred to as a “true RMS” reading device. A standard RMS reading device might not account for harmonic distortion and thus may introduce measurement errors.

Electrical test measurement procedures are provided in IEEE Std. 120, *IEEE Master Test Guide for Electrical Measurements in Power Circuits*, which should be consulted before applying this Code.

4.3.2.1 Net Electrical Power Output. Net electrical power output of a fuel cell power system is equal to the electrical output directly produced by the fuel cell power system at the rated voltage minus auxiliary loads supplied by an external power source.

4.3.2.2 Instrumentation. Calibrated true RMS reading watt and VAR meters shall be used. The calibration and accuracy should include associated current and voltage transformers.

4.3.2.3 Current and Potential Transformers. Potential transformers are typically required when the measured three-phase voltage rating is greater than 600 V rms. Current and potential transformers must be operated within stated ratings to prevent saturation or similar sources of measurement error.

4.4 DETERMINATION OF FUEL INPUT

4.4.1 Fuel Types Considered. Either gaseous and liquid fuels types may be used when testing fuel cell power systems. Fuel heating values must be consistent throughout the test period.

4.4.2 Consistent Gaseous or Liquid Fuels. Consistent liquid or gaseous fuels are those with heating values, which vary less than 1% over the course of the performance test. Since liquid and gas flows and heating values can be determined with high accuracy, the heat input from these type fuels is usually determined by the direct measurement of fuel flow and laboratory or on-line chromatography-determined heating value. Consistent liquid or gaseous fuels heat input can also be determined by calculation using the fuel constituents percentage multiplied by the constituent heating value.

Homogenous gas and liquid fuel flows are usually measured directly for fuel cell power systems.

Some types of fuel (landfill gas or wastewater treatment digester gas) may vary enough to fall outside the 1% heating value range (specified above) over the test period. Variations in fuel cell power system power output can be expected to follow the fuel heating value at constant fuel flow with some associated lag time depending on the internal storage of fuel and fuel utilization within the fuel cell power system. Fuel cell system performance can be estimated (although not in compliance with this code) if fuel heating value and fuel flow are recorded on frequent intervals, and the lag time associated with processing stored high heating value or low heating value fuel can be ascertained from observation and agreement of the test parties.

4.4.3 Consistency of Fuel Flow. Fuel flows to the fuel cell power system must be stable throughout the test. For gaseous fuels, fluctuations in flow may be induced by reciprocating compressors or by other sources of pulsation. The difference between the indicated maximum and minimum flow shall be less than 2% of the average flow for gases for an acceptable test. Introduction of a cushion chamber, surge chamber, pulsation dampener, or other means of absorbing the pulsations between the source of pulsation and the metering device before measurement are considered acceptable for gaseous fuel usage. Leakage of liquid fuels after the point of measurement shall be measured and included in the calculation of liquid fuel mass flow.

4.4.4 Determination of Fuel Heating Value. The heating value of the fuel can be measured by an on-line chromatograph or by sampling periodically (at a minimum of three samples per test) and analyzing each sample individually for heating value. Sampling of fuels shall be done in accordance with para. 4.6.9. The analysis of gaseous fuels, either by on-line chromatography or from laboratory samples shall be done in accordance with ASTM D 1826-94 (1998), *Standard Test Method for Calorific (Heating) Value of Gases in Natural Gas Range by Continuous Recording Calorimeter*; ASTM D 1945-96, *Standard Test Method for Analysis of Natural Gas by Gas Chromatography*; or ASTM 588-98, *Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuels*. ASTM D 1945 gives the results in the type and amount of gaseous constituents from which the heating value is calculated.

ASTM 3588-98, *Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuels*. ASTM D 1945 gives the results in the type and amount of gaseous constituents from which the heating value is calculated.

Liquid fuel heating value shall be determined by calorimeter in accordance with ASTM D 4809-95,

TABLE 4.1 POTENTIAL BIAS LIMIT FOR HEATING VALUES

Fuel	Analysis Procedure	Bias Limits	Comments
Natural gas	ASTM D 1826	0.3–0.55%	High heating value
Fuel oil	ASTM D 4809	± 49 Btu/lbm, all fuels ± 51 Btu/lbm, non-volatiles ± 44 Btu/lbm, volatiles	

Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method). (ASTM D 240 shall not be used because it results in lower precision.)

For liquid fuels both the lower and high heating value and the specific gravity shall be determined from the fuel analyses. The specific gravity of the fuel should be determined at three temperatures covering the range of temperatures measured.

When analyzing the fuel heating value, the bias or systematic error associated with the measurement of such shall be considered. Table 4.1 contains the bias limits for various fuel heating values. If a fuel is used that is not included on the table, a bias limit for heating value that is consistent with the accuracy of this code must be agreed upon by the parties to the test.

4.4.5 Determination of Liquid Fuel Specific Gravity. The liquid fuel specific gravity shall be determined from each fuel sample taken. Each sample shall have the specific gravity evaluated at three temperatures covering the range of temperatures measured during testing. The specific gravity at flowing temperatures shall then be determined by interpolating between the measured values to the correct temperature. Specific gravity determinations shall be completed in accordance with ASTM D 1217.

Numerous methods are employed in industry to determine the flow of solid, liquid, or gaseous streams. ASME PTC 19.5 is the primary reference for flow measurements. ASME MFC-3M, PTC 6, and ISO 5167 provide further information on flow measurement techniques. These sources include design, construction, location, and installation of flowmeters, the connecting piping, and computations of flow.

4.4.6 Measurement of Liquid Fuel Flow. Liquid fuel flows shall be measured using flowmeters that are calibrated per para. 4.1.3 throughout their Reynolds number range expected during the test using the actual flow. For volume flowmeters the temperature of the fuel also must be accurately measured to correctly calculate the flow. Other flowmeter types are acceptable, provided a measurement error consistent with the required accuracy for the test is achievable. Where an oil return system from the fuel cell power system is used, both supply and return flows shall be measured by calibrated meters.

Positive displacement type oil flowmeters may be used without temperature compensation. The effects of temperature on fluid density can be determined by calculating the mass flow based on specific gravity at the flowing temperature based on the formula below:

Customary Units

$$Q_{mh} = (8.337)(60)Q_v S_g$$

where

Q_{mh} = mass flow, lbm/hr
Q_v = volumetric flow, gal/min
S_g = specific gravity of flowing temperature, dimensionless
8.337 = density of water at 60°F, lbm/gal
60 = minutes per hour

SI Units

$$Q_{mh}\,(\text{kg/hr}) = \frac{Q_{mh}\,(\text{from above})}{2.20462}$$

where

2.20462 = lbm per kg

4.4.7 Measurement of Gaseous Fuel Flow. Gaseous fuel flows may be measured using orifices or turbine-type flowmeters. Measurements used to determine the mass flow, such as fuel analysis to determine density, the static and differential pressures, temperature, and frequency (if a turbine meter), must be within an uncertainty range to meet the uncertainty requirement of this Code. Other flowmeters are permitted if it can be demonstrated that the total uncertainty of the mass flow is consistent with the required accuracy for the test.

The use of turbine meters is one alternative to orifice gas flow measurement. The turbine meter measures actual volume flow. Uncertainty of turbine meters is by statement of the manufacturer and calibrated in atmospheric air or water, with formulations for calculating the increased uncertainty when used in gas flow at higher temperatures and pressures. Sometimes a turbine meter is calibrated in pressurized air. The turbine meter calibration report must be examined to confirm the uncertainty as calibrated in the calibration medium.

Mass flow as shown by computer printout or flow computer is not acceptable without showing intermediate results and the raw data used for calculations.

EXCEPTION: If the computer printout or flow computer has been loop calibrated in series with the flow device, intermediate results are not required.

When required, intermediate results for an orifice would include discharge coefficient, corrected diameter for thermal expansion, expansion factor, etc. Raw data includes static and differential pressures, and temperatures. For a turbine meter, intermediate results include the turbine meter constant(s) used in the calculation, and how it is determined from the calibration curve of the meter. Raw data also includes frequency, temperature, and pressure. For turbine meters and orifices, fuel analysis and the intermediate results used in the calculation of density is required.

Ensure that the actual gas composition is properly considered relative to the expected gas composition utilized in the flowmeter calibration.

4.4.8 Calculation of Fuel Input. The calculation of fuel input is the product of the fuel mass flow at test conditions multiplied by the fuel heating value at test conditions.

4.4.9 Sampling of Fuels. Automatic sampling of gaseous fuels shall be done in accordance with ASTM D 5287. Manual sampling of liquid fuels shall be done in accordance with ASTM D 4057. Automatic sampling of liquid fuels shall be done in accordance with ASTM D 4177-95 (2000), *Standard Practice for Automatic Sampling of Petroleum and Petroleum Products*.

4.5 DATA COLLECTION AND HANDLING

4.5.1 Data Collection Systems. A data collection system should be designed to accept multiple instrument inputs and be able to sample data from all of the instruments within 2 sec to 3 sec to obtain all necessary data with the plant at the same condition. The system should be able to collect and store data and results within 1 min. The system should also have the ability to plot the test data and each instrument reading over time to look for trends and outlying data.

The data collection system shall be calibrated for primary variables per para. 4.1.3.7.

4.5.2 Data Management

4.5.2.1 Storage of Data. Signal inputs from the instruments should be stored to permit post-test data correction for application of new calibration corrections. The engineering units of each instrument along with the calculated results should be stored in removable medium to secure against equipment damage during transport.

4.5.2.2 Manually Collected Data. Most test programs will require some data to be taken manually. The data sheets should each identify the data point, test site location, date, time, data collector, and data collected.

4.5.3 Construction of Data Collection Systems

4.5.3.1 Design of Data Collection System Hardware. With advances in computer technology, data collection system configurations have a great deal of flexibility. They can consist of a centralized processing unit or distributed processing to multiple locations in the plant.

Each measurement loop must be designed with the ability to be loop calibrated separately, if required (see para. 4.1.3.7). Each measurement loop should be designed so that they can be individually checked for continuity and power supply if applicable to locate problems during equipment setup.

Each instrument signal cable should be designed to reject any stray induced currents.

4.5.3.2 Usage of Existing Plant Data Collection and Control System. The code does not prohibit the use of the plant measurement and control system for code testing. However, this system must meet the requirements of this Section.

Some plant systems do not allow the instrument signal prior to conditioning to be displayed or stored. The signal must be available to check the signal conditioning calculation for error.

Distributed control systems typically only report changes in a variable which exceed a set threshold value. The threshold value must be low enough so that all data signals sent to the distributed control system during the test are reported and stored.

SECTION 5
COMPUTATION OF RESULTS

5.1 INTRODUCTION

This Section gives guidance on the computation of results, including the following:

(a) Determining power output, electrical conversion efficiency, and thermal effectiveness at specified operating conditions are the primary objectives of this test. Electrical conversion efficiency can also be expressed as specific fuel consumption (heat rate) or fuel chargeable to power.

(b) In computing results, a test result is computed from the averaged values of observations made during a single test run, after applying instrument and other corrections as necessary and as prescribed in this Code.

(c) For a test involving several runs, it is suggested that plots of heat input versus power output be made to indicate test runs that may have significant errors. Any test runs leading to suspect results that are to be used for guarantee determination should be discarded and rerun.

5.2 COMPUTATION OF INPUTS

5.2.1 Introduction. Inputs for the purpose of this Standard refer to inputs crossing the test boundary. In no particular order they are:

(a) fuel
(b) oxidant (air)
(c) secondary energy input
(d) secondary thermal energy input
(e) auxiliary shaft work
(f) auxiliary electrical energy into fuel cell systems, if any

Any other type of substance or energy, which represents energy input to the fuel cell system, must also be quantified. These inputs will include chemical energy (e.g., heating values of fuel) as well as energy associated with pressurization, heating or otherwise conditioning the input streams prior to entering the fuel cell system. The baseline state of fuel, oxidant (air), and water inputs shall be ambient conditions.

5.2.2 Significance of Fuel Composition. The evaluation of electrical efficiency of a fuel cell power producing system is dependent upon evaluating energy streams into and out of the system. In the usual energy conversion heat engine, such as an internal combustion engine, a gas turbine, etc., the input fuel energy is directly determined by the primary input variables of input fuel heating value kJ/kg (Btu/lbm) and input fuel flow kg/h (lbm/hr). This fuel cell performance test code adheres to that heat engine convention, thereby enabling a comparison to be easily made between the measured electrical efficiency of a fuel cell power generation system and a heat engine power generation system.

However, it should be recognized that the conversion of the input fuel energy stream to electrical power is more directly dependent upon the available electrons in the input fuel molecules than it is on the heating value of the input fuel. That is, a fuel cell is an electrochemical device converting molecules.

A particular fuel system is normally designed to operate on a volume flow of fuel, such as hydrogen or natural gas. If designed for a "nominal" natural gas consisting of approximately 94% methane, 4% ethane, and 2% hydrogen, that natural gas would have a "nominal" low heating value of 195 kCal/mole (925 Btu/SCF). However, if the natural gas contained significant percentages of higher hydrocarbons, such as pentane, then the natural gas would likely be diluted with nitrogen, by the natural gas supply company. This would result in a low heating value of diluted natural gas to be in the "nominal" 1,040 Btu/ft^3 range. However, that natural gas would provide fewer fuel molecules per unit volume, necessitating a higher input fuel feed rate than the nominal natural gas. A lower electrical efficiency would result; although, it is possible that the fuel cell system may be able to recapture and make useful additional heat energy.

Due to the large number of potential variables in common fuels (such as natural gas), and the large number of system variations with which the fuel variables could interact, it is not practical to account for direct fuel effects on performance other than to consider only the heating value of the fuel when computing heat rate or thermal efficiency. However, it is important for all interested parties to realize that, as stated above, fuel variables other than heating value can affect computed values of heat rate and thermal efficiency.

For some fuel cell systems, the composition of the fuel may affect performance sufficiently to require accounting for this fact, and some correction to fuel input, bringing it back to design composition specifications may be necessary. For these systems the manufacturer is responsible for furnishing correction factors and curves to be applied using manufacturer supplied correction methods. These correction factors may be additive, multiplicative, or both.

5.2.3 State of Input Fuel. For a pressurized stack (utilizing gaseous fuel) the power to compress the gas is not negligible and thus must be taken into account. In addition, pressurized fuel may be used to drive a pressure-reducing turbine to recover some mechanical energy for use in the system or to power other auxiliaries. Specifically, if part of the gas pressurization is provided by the external supply system, the power required for pressurization shall be charged to the fuel cell system. Thus, for computational purposes, it should be assumed that all fuel is provided to the system boundary at local ambient barometric pressure. Fuel delivery to the test boundary at above atmospheric pressure shall result in an additive correction factor of the form:

$$E_{cf} = (M_f\, RT_{\text{std}})\ \ln \frac{\begin{array}{c}\text{absolute fuel inlet}\\ \text{pressure at test boundary, kPa}\end{array}}{\text{ambient barometric pressure, kPa}}$$

where

E_{cf} = ideal Pressure Energy Content of the Fuel, kJ

M_f = mass of fuel into the system during the test period, kg

MW_f = molecular weight of the gaseous fuel (16.043 kg/kmol for methane)

R = R_u/MW_f

R_u = 8.314 kJ/kmol K (universal gas constant)

T_{std} = standard temperature (15°C) = 288.15 K

This formula is based on an ideal isothermal compression of the fuel at standard temperature and does not take into account the compression efficiency. If a fuel compressor is used, it must be treated as within the test boundary with its energy consumption taken as a net loss against output (see test boundary diagram). If a fuel compressor is used with the fuel cell system, it shall be included within the test boundary, and any energy used to run it shall be either supplied from within the test boundary or shall be deducted from the net electrical energy out.

If a pressure-reducing regulator is used to reduce pressure without energy recovery, the test boundary can be defined such that the pressure-reducing regulator is outside of the test boundary.

5.2.4 State of Input Oxidant. Oxidant must be supplied to the fuel cell systems at rates which are likely to greatly exceed the stoichiometric air/fuel ratio which is about 15:1 for most hydrocarbon fuels. Thus, the power to compress the air will be much greater than that to compress the fuel and thus can be a significant fraction of the stack output power in the case of pressurized systems. Consequently, for computational purposes, it must be assumed that the oxidant (air) is supplied at ambient temperature and pressure, and some method of accounting for the power associated with compressed air from an air supply system is needed.

The composition of the supply air will also have an effect on fuel cell system performance. In particular, water vapor in the air will add to the power required to compress the air and subtract from the oxygen available for the oxidation of fuel. Therefore, as it is already customary with heat engines, corrections may be made to adjust performance to standard dry air.

Oxidant (air or other) delivery to the test boundary at above local ambient barometric pressure shall require the use of an additive correction factor of the form:

$$E_{co} = (M_o\, RT_{\text{std}})\ \ln \frac{\begin{array}{c}\text{absolute oxidant (air) inlet}\\ \text{pressure at test boundary, kPa}\end{array}}{\text{ambient barometric pressure, kPa}}$$

where

E_{co} = ideal pressure energy content of the oxidant, kJ

M_o = mass of oxidant into the system during the test period, kg

MW_o = molecular weight of the oxidant (28.9644 kg/kmol for standard dry air)

R = R_u/MW_o

R_u = 8.314 kJ/kmol K (universal gas constant)

T_{std} = standard temperature (15°C) = 288.15 K

If an oxidant (air or other) compressor or blower is used with the fuel cell system, it shall be included within the test boundary and the power to run the compressor shall be supplied from either inside the test boundary or shall be deducted from the net electrical energy output.

5.2.5 Computation of Input Energy. Input energy crossing the test boundary might include:

(a) fuel chemical energy input, Q_f
(b) fuel pressure energy input, E_{cf}
(c) fuel thermal energy input, TQ_f
(d) secondary thermal energy input, Q_{st}
(e) oxidant pessure energy input, E_{co}
(f) oxidant thermal energy input, TQ_o
(g) auxiliary electrical input, E_a
(h) shaft work input, W_{si}

5.2.5.1 Fuel Chemical Energy Input, Q_f. Q_f is determined by measuring the total fuel flow to the fuel cell for the test period and multiplying by the average heating value of the fuel during the test period. The unit of this parameter is kJ.

For calculations based on High Heating Value:

$$Q_f = M_f\,(\text{kg}) \times HHV_{\text{avg}}$$

For calculations based on Low Heating Value:

$$Q_f = M_f\,(\text{kg}) \times LHV_{\text{avg}}$$

where

M_f = total fuel flow to the fuel cell during the test period, kg

5.2.5.2 Fuel Pressure Energy Input, E_{cf}

$$E_{cf} = (M_f\,RT_{std})\ln\frac{\text{absolute fuel inlet pressure at test boundary, kPa}}{\text{ambient barometric pressure, kPa}}$$

where

E_{cf} = ideal pressure energy content of the fuel, kJ
M_f = mass of fuel into the system during the test period, kg
MW_f = molecular weight of the gaseous fuel (16.043 kg/kmol for methane)
R = R_u/MW_f
R_u = 8.314 kJ/kmol K (universal gas constant)
T_{std} = standard temperature (15°C) = 288.15 K

5.2.5.3 Fuel Thermal Energy Input, TQ_f

$$TQ_f = M_f\,(\text{kg}) \times C_{fp}\,(\text{kJ/kgK}) \times (T_{ff} - 288.15\ \text{K})$$

where

C_{fp} = average specific heat at constant pressure of fuel delivered during the test period, kJ/kg·K
M_f = total fuel flow to the fuel cell, kg
T_{ff} = average fuel temperature at the test boundary, K
TQ_f = total heat energy content required to heat the fuel from 15°C (288.15 K) to the average fuel temperature at the test boundary during the test duration, kJ

Standard temperature (15°C) = 288.15 K

5.2.5.4 Secondary Thermal Energy Input, Q_{st}

(a) For closed loop secondary thermal inputs the total heat input is determined by:

Q_{st} = total thermal energy input to the fuel cell during the test period

Q_{st} shall be calculated by measuring the change in heat content of the steam or heat transfer fluid as it passes through the system within the test boundary, and multiplying by the total flow of the steam or heat transfer fluid through the system within the test boundary:

$$Q_{st} = M_{htf} \times (H_i - H_o)$$

where

H_i = average enthalpy of the heat transfer fluid entering the fuel cell during the test period, kJ/kg
H_o = average enthalpy of the heat transfer fluid exiting the fuel cell during the test period, kJ/kg
M_{htf} = mass of steam or heat transfer fluid into and out of the fuel cell from the source of secondary thermal energy during the test period, kg

The unit of Q_{st} is kJ.

(b) Or, for steam or liquid thermal inputs that do not exit the system boundary, the total heat input is determined by:

Q_{st} = total thermal energy input to the fuel cell during the test period

Q_{st} shall be calculated by measuring the heat content of the heat transfer fluid, and multiplying by the total flow of the heat transfer fluid into the test boundary and correcting to a base value enthalpy of saturated water at 15°C=62.99 kJ/kg.

$$Q_{st} = M_{htf} \times (H_i - 62.99 \text{ kJ/kg})$$

where

H_i = average enthalpy of the steam or heat transfer fluid entering the fuel cell during the test period, kJ/kg

M_{htf} = mass of steam or heat transfer fluid into the fuel cell from the source of secondary thermal energy during the test period, kg

(c) Or, for gaseous thermal inputs that do not exit the system boundary, the total heat input is determined by:

Q_{st} = the total thermal energy input to the fuel cell during the test period

Q_{st} shall be calculated by measuring the heat content of the input gas stream, and multiplying by the total flow of the heat input gas stream into the test boundary and correcting to a base value enthalpy of dry air at atmospheric pressure and 15°C=33.0291 kJ/kg.

$$Q_{st} = M_{htf} \times (H_i - 33.0291 \text{ kJ/kg})$$

where

H_i = average enthalpy of the air or gaseous heat transfer fluid entering the fuel cell during the test period, kJ/kg

M_{htf} = mass of air, or gaseous heat transfer fluid into the fuel cell from the source of secondary thermal energy during the test period, kg

5.2.5.5 Oxidant Pressure Energy Input, E_{co}

$$E_{co} = (M_o\, RT_{std}) \ln \frac{\text{absolute oxidant inlet pressure at test boundary, kPa}}{\text{ambient barometric pressure, kPa}}$$

where

E_{co} = ideal pressure energy content of the oxidant, kJ

M_o = mass of oxidant into the system during the test period, kg

MW_o = molecular weight of the oxidant (28.9644 kg/kmol for standard dry air)

R = R_u / MW_o

R_u = 8.314 kJ/kmol K (universal gas constant)

T_{std} = standard temperature (15°C) = 288.15°K

If an oxidant (air or other) compressor or blower is used with the fuel cell system, it shall be included within the test boundary and the power to run the compressor shall be supplied from either inside the test boundary or shall be deducted from the net electrical energy out.

5.2.5.6 Oxidant Thermal Energy Input, TQ_o

$$TQ_o = M_o \text{ (kg)} \times C_{op}\ [(\text{kJ/(kg·K)}] \times T_{of} - 288.15(°\text{K})$$

where

C_{op} = average specific heat at constant pressure of oxidant delivered during the test period, kJ/kg·K

M_o = the total oxidant flow to the fuel cell during the test period, kg

T_{of} = average oxidant temperature at the test boundary, K

TQ_o = the total heat energy content required to heat the oxidant from 15°C (288.15 K) to the average oxidant temperature at the test boundary during the test duration

Standard Temperature=15°C (288.15 K)

5.2.5.7 Auxiliary Electrical Input, E_a

$$E_a = \Sigma\, kWh_i \text{ (kW·h)}$$

where

E_a = sum of all electrical inputs into the test boundary for the duration of the test period. This will be subtracted from the electrical energy out of the system to calculate net electrical generation.

kWh_i = kilowatt-hours into the system during the test period (measured)

5.2.5.8 Shaft Work Input, W_{si}

W_{si} = mechanical shaft work done on the system by an outside prime mover resulting in energy added to the system from across the system boundary, kJ

W_{si} shall be computed using torque and RPM measurements consistent with results in kJ. Where torque and RPM cannot be obtained due to system constraints, the input fuel, steam, or heat transfer fluid or fluid drive state points shall be determined to within 1% accuracy and the energy input by shaft work shall be computed. No penalty or correction for turbine or prime mover efficiency is permitted. Wherever possible the prime mover shall be moved inside the test boundary and energy inputs to the prime mover shall be considered as fuel, auxiliary thermal input, or auxiliary electrical loads.

5.2.5.9 Total Energy Into the System for Calculation of Input Energy. This is expressed by:

$$QI_{total} = Q_f + E_{cf} + TQ_f + Q_{st} + E_{co} + TQ_o + W_{si}$$

where

QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency

5.3 COMPUTATION OF ELECTRIC POWER OUTPUT

5.3.1 Averaging of Test Data. The current, voltage and power measurements shall be averaged over the test run period. 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.

5.3.2 Real Power. Digital power measurement instrumentation may provide direct readings of real power in addition to voltage and current. When direct readings of power are not available, the following equation may be used to determine real power when the phase angle θ between voltage and current is known.

For a three phase system:

$$P_{\text{real}} = \sqrt{3 \times V_{\text{rms}} \times I_{\text{rms}} \times PF}$$

and

For a single phase system:

$$P_{\text{real}} = V_{\text{rms}} \times I_{\text{rms}} \times PF$$

where power factor PF is given by:

$$PF = \cos(\theta)$$

The efficiency of solid-state inverters will vary with power factor setting. In most inverters now on the market, the efficiency of the inverter will be at its maximum at unity power factor.

5.3.3 Electrical Total Energy. The total electrical energy (kilowatt-hours) measured over the test duration may be obtained by integrating the power measurements over the test run period:

$$E_g = \Sigma\, Kw{\cdot}h_e \text{ (kWhr)}$$

where

E_g = total sum of all electrical output from the fuel cell across the test boundary for the duration of the test period

$Kw{\cdot}h_e$ = kilowatt-hours out of the system during the test period (measured)

5.3.4 Net Electrical Energy. The total electrical energy out of the system, integrated over the test duration, must be reduced to account for any auxiliary electrical loads supplied from external electrical power sources. For computation of electrical conversion efficiency, the net electrical energy produced is given by:

$$E_n = E_g - E_a$$

where

E_a = total auxiliary electrical energy input over the test duration from para. 5.2.5.7

E_g = total (gross) electrical energy measured over the test duration from para. 5.3.3

E_n = net electrical energy for the test duration, kW·h

5.4 COMPUTATION OF THERMAL AND MECHANICAL OUTPUTS

5.4.1 Computation of Thermal Energy Captured (TEC)

5.4.1.1 General. Supplementing the water heating requirements of a facility by capturing the thermal energy of a fuel cell and putting it to use is a simplified form of cogeneration.

5.4.1.2 The scope of para. 5.4 only encompasses small units with supplemental heating of water. For large steam generation systems, refer to ASME PTC 4.4, *Gas Turbine Heat Recovery Steam Generators*.

5.4.1.3 Computation of Thermal Energy Captured (*TEC*) for useful service (space/water heating, etc.) is calculated by:

$$TEC = M_w (H_{out} - H_{in})$$

where

H_{in} = average enthalpy of water or heat transfer fluid entering the test boundary during the test period, kJ/kg

H_{out} = average enthalpy of water or heat transfer fluid leaving the test boundary during the test period, kJ/kg

M_w = total mass of water or heat transfer fluid circulating through the test boundary during the test period, kg

TEC = thermal energy captured for the duration of the test period, kJ

5.4.2 Computation of Shaft Work Out Of System

W_{so} = mechanical shaft work done by the system on an outside industrial process or prime mover resulting in energy recovered from the system and delivered across the system boundary, kJ

W_{so} shall be computed using torque and RPM measurements consistent with results in kilojoules. Where torque and RPM cannot be obtained due to system constraints, the output process parameters shall be determined to within 1% accuracy and the energy output by shaft work shall be computed. No penalty or correction for process efficiency is permitted.

5.5 COMPUTATION OF AVERAGE NET POWER

Net Power, KW_e, can be computed from watt-hour meters on the output terminals divided by the duration of the test. Average net power over the test period will document the unit capacity.

$$KW_e = E_n / t_{tp}$$

where

E_n = net electrical energy delivered across the test boundary for the test duration from para. 5.3.4., kW·h

t_{tp} = duration of the test, hr

5.6 COMPUTATION OF EFFICIENCIES

5.6.1 Computation of Electrical Efficiency. The efficiency of thermal energy conversion to electrical energy is computed in the same manner as for Carnot Cycle Units. Electrical Conversion Efficiency is calculated by dividing the net electrical energy produced by the total energy input, per unit of time, as follows:

$$\eta_{el} = \left\{ (E_n \times 3600\,] / QI_{total} \right\} \times 100$$

where

100 = to convert to percent

3600 = kJ/kW·h conversion factor

E_n = net electrical energy for the test duration from para. 5.3.4

η_{el} = Electrical Conversion Efficiency, %

QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency from para. 5.2.5.9

The heat rate (H.R.) in U.S. Customary units can be computed as:

$$\text{H.R. (in Btu/kW·h)} = (\eta_{el} / 100)\ 3412.14$$

The result should be clearly identified as to the type of fuel used and either low or high heating value (LHV or HHV). See para. 3.6.

Constants for other frequently used units are given below.

Power Outage	Energy Input	Constant
hp	Btu/hr	2544.43
kW	kJ/sec	1

5.6.2 Computation of Thermal Effectiveness. Thermal effectiveness is a measure of energy utility; that is, the percentage of total energy input, which is captured and put to useful service by conversion to electrical energy or as thermal energy:

$$\eta_{eff} = \left\{ [(E_n \times 3600) + TEC\,] / QI_{total} \right\} \times 100$$

where

100 = convert to percent

3600 = kJ/kW·h conversion factor

E_n = net electrical energy for the test duration from para. 5.3.4

η_{eff} = thermal effectiveness, %

QI_{total} = total energy Into the system for calculation of input energy and electrical conversion efficiency from para. 5.2.5.9

TEC = thermal energy captured for useful service (space/water heating, etc.), kJ from para. 5.4.1

For systems that export shaft work to a process outside the test boundary, the thermal effectiveness may be modified to include credit for the shaft work done on the external system. The modified equation will take the form of:

$$\eta_{eff} = \left\{ [(E_n \times 3600) + (TEC + W_{so})] \ / \ QI_{\text{total}} \right\} \times 100$$

where

E_n = net electrical energy for the test duration from para. 5.3.4, kW·h
η_{eff} = thermal effectiveness, %
QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency from para. 5.2.5.9
TEC = thermal energy captured for useful service (space/water heating, etc.), kJ, from para. 5.4.1
W_{so} = mechanical shaft work done by the system to an outside industrial or other energy user system resulting in energy produced by the system being exported across the system boundary, kJ (see para. 5.4.2)
3600 = kJ/kW·h conversion factor
100 = to convert to percent

5.6.3 Computation of Heat Rate. Heat Rate is electrical conversion efficiency, expressed as Btu/(kW·h). This can be calculated as follows:

The heat rate ($H.R.$) in U.S. customary units can be computed as:

$$H.R.\ [\text{Btu/(kW·h)}] = \frac{3421.14}{\eta_{el}/100}$$

where

100 = convert from percent
3412.14 = BTU/(kW·h) conversion factor
η_{el} = Electrical Conversion Efficiency, % from para. 5.6.1

5.6.4 Computation of Fuel Chargeable to Power Heat Rate. Fuel chargeable to power can be used to compute the cost of electrical generation, giving credit for cogeneration heat as a credit towards the fuel used. Credit is given equivalent to the fuel that would be used to produce the thermal cogeneration heat (assuming 100% heat exchanger effectiveness). FCP is expressed in BTU/(kW·h).

$$FCP = [(QI_{\text{total}} - TEC) \times 1.05435] \ / \ E_n$$

where

1.05435 = conversion factor for Btu/kJ
E_n = net electrical energy for the test duration from para. 5.3.4, kW·h
QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency from para. 5.2.5.9, kJ
TEC = thermal energy captured, kJ, for the duration of the test period from para. 5.4.1

5.7 CORRECTION OF TEST RESULTS TO REFERENCE CONDITIONS

The baseline state of fuel, air, and water inputs will be standard temperature and pressure and 60% relative humidity for the air and zero humidity for the fuel. This may be agreed to or otherwise modified by the parties, but absent an agreement to the contrary, performance shall be based on units operating at sea level, at 15°C, with a relative humidity of 60% and dry fuel. All inputs that vary from these baseline parameters shall be corrected using manufacturer supplied correction curves prior to computing the results of the test. All corrections to test data shall be made and documented before the calculations in para. 5.5 are made. All values in para. 5.5 refer to corrected values only.

The procedure for correction of test results to specified conditions depends on the type of fuel cell system and its inverter and heat load. It is necessary to have the test conditions within limits agreed to by the parties to the test, to avoid operation at extreme conditions far from its design or specified condition, which could make the determination of accurate results impossible.

The off-design characteristics of each fuel cell system type are unique. Hence, the manufacturer's published performance curves for the particular fuel cell system must be used to correct that actual test data to rated or standard conditions. Unless otherwise agreed by the parties to the test, these correction curves (or data) are applied without any uncertainty.

A step-by-step method of correcting test data will be prepared by the manufacturer. The user will review this procedure and any discrepancies must be resolved prior to the start of the test.

5.7.1 Humidity. High ambient humidity may affect performance by limiting oxygen content and increasing blower or compressor power requirements. If ambient humidity is expected to be different from design parameters, the manufacturer shall provide correction factors and methods prior to the test.

5.7.2 Fuel Composition. Fuel composition may affect output or efficiency. If fuel composition is expected to be different from design parameters, the manufacturer shall provide correction factors and methods prior to the test.

5.7.3 Ambient Temperature. Ambient temperature may affect output or performance by limiting heat exchanger duty, overloading components, or increasing power conversion losses. If ambient temperature is expected to be different from design parameters, the manufacturer shall provide correction factors and methods prior to the test.

5.7.4 Ambient Pressure. If the fuel cell system is to be tested above sea level, the decreased ambient pressure may affect output or efficiency due to increased blower or compressor power requirements, or decreased oxygen content. If the test is to be conducted above design elevations, the manufacturer shall provide correction factors and methods prior to the test.

5.7.5 Useful Heat Load. If the heat supplied to the useful heat load is provided at a temperature different from the design of the heat exchange loop, insufficient heat exchanger duty may limit heat recovery. If heat is to be supplied at temperatures outside design parameters, the manufacturer shall provide correction factors and methods prior to the test.

5.7.6 Power Factor. If the power conversion and power conditioning equipment is sensitive to power factor, power factor shall be adjusted to be within design parameters during the test. No correction factor for power factor is allowed.

SECTION 6
TEST REPORT REQUIREMENTS

6.1 GENERAL REQUIREMENTS

The test report shall clearly and concisely document all data generated by the test as well as all ensuing computations. Definitive statements of the purpose of the test and attainment of the objectives should be provided.

The test report for a performance test should incorporate the following:

(a) title page
(b) executive summary
(c) introduction
(d) instrumentation
(e) results
(f) conclusions
(g) appendices

This outline is a recommended report format. Other formats are acceptable; however, the test report should contain all the information described in the following sections as a minimum.

6.1.1 Title Page. The title page shall include the following:

(a) report number
(b) date and time of test
(c) location of test
(d) title of test
(e) equipment owner
(f) equipment identification
(g) parties conducting test
(h) parties responsible for test report
(i) date of report
(j) report acceptance

6.2 EXECUTIVE SUMMARY

The executive summary shall concisely address the following:

(a) general information about the fuel cell power system and the performance test, such as the plant type and operating configuration, and the test objective;

(b) any agreements among the parties to the test to allow any major deviations from the test requirements;

(c) date and time of the test;

(d) summary of the test results including uncertainty;

(e) conclusions.

6.3 INTRODUCTION

The introduction shall include the following:

(a) test objective and all agreements among the parties to the test;

(b) a listing of the representatives of the parties to the test;

(c) a process flow diagram showing the test boundary;

(d) a brief historical background.

6.4 INSTRUMENTATION

The following should be included in the instrumentation section:

(a) tabulation of instrumentation used for primary and secondary measurements, including make, model number, etc.;

(b) description of the instrument location;

(c) means of data collection for each data point, such as temporary data acquisition system print-out, plant control computer print-out, or manual data sheet, and any identifying tag number and/or address of each;

(d) identification of any instrument which was used as a back-up;

(e) description of data acquisition system used;

(f) summary of pretest and post-test calibration of each instrument used in the test.

6.5 RESULTS

The following should be included in this Section:

(a) the performance equations used and applicable correction factors;

(b) tabulation of reduced data necessary to calculate the performance results;

(c) summary of operating conditions corresponding to the reduced data;

(d) step-by-step calculation of the performance results from the reduced data including uncertainty analysis;

(e) detailed calculation of flow;

(f) detailed calculation of heat input;

(g) detailed calculations of fuel properties — heating value, density, etc.;

(h) any calculations showing the elimination of data for outlier reason, or for any other reason.

6.6 CONCLUSIONS

The conclusion section should address:

(a) the results of the test versus the test objectives/performance guarantees;

(b) the recommended changes to future test procedures due to lessons learned;

6.7 APPENDICES

Appendices to the test report should include:

(a) the signed test requirements contract;

(b) copies of original data sheets and/or data acquisitions system printouts;

(c) copies of operator logs or other recording of operating activity during each test;

(d) results of laboratory fuel analysis;

(e) instrumentation calibration results from laboratories;

(f) certification from manufacturers.

MANDATORY APPENDIX I
UNCERTAINTY ANALYSIS AND SAMPLE CALCULATION

I-1 GENERAL

A pretest uncertainty analysis is recommended. The pretest uncertainty analysis allows corrective action to be taken prior to the test, which will either decrease the uncertainty to an appropriate level consistent with the overall objective of the test or will reduce the cost of the test while still attaining the test uncertainty.

A post-test uncertainty analysis is mandatory. It will make use of empirical data to determine random measurement errors and test observations to establish whether the required degree of uncertainty has been achieved.

This Appendix serves as a guide for pretest and post-test uncertainty calculations when the Code is used.

I-2 BACKGROUND

The measurement of fuel cell power plant performance is dependent upon the measurement of the various parameters that are used to calculate efficiency, kilowatt output, heat rate, and fuel chargeable to power. These parameters are not known with absolute certainty, but can be obtained with high accuracy instrumentation in order to minimize the uncertainty associated with the final results.

It is the intent of this procedure that all results be expressed with a minimum of uncertainty. This test is expected to give results with less than 2% total uncertainty (at 95% confidence). This is a high accuracy test and careful selection of instrumentation and careful test planning is necessary. For each test run, at least thirty independent data points are necessary to obtain the expected level of accuracy. In order to maintain independence of the data points, a minimum of 1 min between data points is also required. A 1 hr test run duration is recommended, with sixty data points. This will allow for some data points to be discarded if data can be shown to be erroneous without requiring that the entire test run be discarded. It is not necessary that each data point be taken at exactly the same time, since steady-state operation is a basic assumption of the test, but taking data at nearly the same time, consistent with test performance, is recommended. Additional test duration will, in most cases, result in lower uncertainty. For this reason the 1 hr test run duration should be considered a minimum and a longer test run duration is recommended.

If fewer than thirty data points are taken for a particular parameter, the calculation must be modified for those parameters in accordance with Appendix B of ASME PTC 19.1.

I-3 BASIS

The guidance in this Appendix is based on ASME PTC 19.1-1998, *Test Uncertainty*. Although ASME PTC 19.1 provides guidance for special circumstances, unique applications, and detailed calculation methods that might be necessary in some cases, the guidance herein is simplified for use with fuel cell systems, using assumptions consistent with their design as well as good testing practice dictated by this Code.

Basic assumptions include:

(a) All systematic uncertainty sources are assumed normally distributed and are estimated as $\pm 2\sigma$ for 95% coverage. If this assumption is not adequate for analysis, more complex methods are handled in ASME PTC 19.1, Appendix B.

(b) At least thirty independent data points are taken for all parameters. If fewer than thirty independent data points are taken for one or more parameters, consult Appendix B of ASME PTC 19.1 for calculation procedures.

(c) All random uncertainty sources are estimated as $+2S_{\overline{X}}$ which is a 95% confidence estimate of the effect on the average of a particular random uncertainty source.

(d) These uncertainty estimates are grouped as systematic or random and root-sum-squared to obtain the systematic and random uncertainties of a measurement, B, and $+2S_{\overline{X}}$ for large samples.

(e) These are then root-sum-squared to obtain a 95% confidence uncertainty as follows:

$$+ U_{95} = \pm 2 \left[(B/2)^2 + (S_{\overline{X}})^2 \right]^{1/2}$$

which is equivalent to

$$+ U_{95} = \left[B^2 + (2S_{\overline{X}})^2 \right]^{1/2}$$

I-4 NOMENCLATURE AND DEFINITION OF TERMS

This Appendix provides general guidance and sample calculations. For detailed nomenclature and definitional information, please refer to ASME PTC 19.1-1998.

confidence level: the probability that the true value falls within the specified limits.

erroneous data: data that has been shown by physical evidence or the test log to have been taken in error can be discarded.

outliers: spurious data that are believed to be not valid and should not be included as part of the calculations and uncertainty analyses. Causes of outliers are human errors in reading and writing values and instrument errors resulting from electrical interference, etc. Several documents provide guidance and statistical methods for determining outliers; among them are ASME PTC 19.1 and ASTM E 178. This Code does not recommend a particular statistical method for determining outliers. It is important to note that the use of statistical methods to determine outliers can produce unrealistic results depending on the method and criteria used. Most outliers are obvious when all data recorded for a given parameter are compared. The rejection of outliers based on engineering judgment and/or pretest agreements by the parties involved in the test is recommended. It is also recommended that the test engineer and all parties involved determine the likely cause of any outliers.

random error: sometimes called *precision;* the true random error that characterizes a member of a set of measurements. This varies in a random, Gaussian (normal) manner, from measurement to measurement. Random error is typically related to the normal variations of the system being tested, the test procedure, and the performance of the test.

sensitivity: sometimes called *influence coefficient;* the ratio of the change in a result to a unit change in a parameter.

systematic error: sometimes called *bias;* the true systematic or fixed error that characterizes every member of any set of measurements from the population. The constant component of total measurement error.

systematic uncertainty: the 95% confidence level estimate of the limits of a true systematic error, often determined by judgment. Systematic uncertainty is likely to be caused by calibration effects and for our purposes we will treat calibration uncertainty as systematic uncertainty.

I-5 GENERAL APPROACH

ASME PTC 19.1 gives a step-by-step calculation procedure as follows:

(a) Define the Measurement Process

(1) Review test objectives and test duration.

(2) List all independent measurement parameters and their nominal levels.

(3) List all calibrations and instrument setups that will affect each parameter. Be sure to check for uncertainties in measurement system components that affect two or more measurements simultaneously (correlated uncertainties).

(4) Define the functional relationship between the independent measurement parameters and the test result.

(b) List Elemental Error Sources. Make a complete and exhaustive list of all possible test uncertainty sources for all parameters.

(c) Calculate or Assign the Systematic and Random Standard Deviation for Each Parameter

(d) Propagate the Systematic and Random Standard Deviation for Each Parameter

(1) The systematic and random (sample) standard deviations of the independent parameters are propagated separately all the way to the final result.

(2) Propagation of the standard deviations is done, according to the functional relationship defined in step (a)(4) above, by using the Taylor series method (see Appendix C of ASME PTC 19.1-1998). This requires a calculation of the sensitivity factors, either by differentiation or by computer perturbation.

TABLE I-1 SUMMARY OF VARIABLES AND THEIR NOMINAL VALUES

Parameter	Description	Units	Nominal Value
LHV_{avg}	Fuel lower heating value	kJ/kg	50 000
M_f	Mass of fuel delivered	kg	14.4
MW_f	Molecular weight of fuel delivered	kg/kmol	16.043
Pf	Fuel pressure at the test boundary	kPa	140
T_{ff}	Fuel temperature at the test boundary	K	290
C_{fp}	Fuel specific heat	kJ/kg	2.2379
E_n	Net kW·h delivered	. . .	100
3 600	Conversion factor	. . .	3 600
100	Conversion factor	. . .	100
R_u	Universal gas constant	kJ/kmol K	8.314
288.15	Standard temperature	K	288.15
BP	Ambient barometric pressure	KPa	101.325

(e) Calculate the Uncertainty. Calculation of uncertainty is done in accordance with para. 7.5 of ASME PTC 19.1, combining the systematic and random uncertainties to get the total uncertainty.

(f) Prepare the Report in Accordance With ASME PTC 19.1-1998.

ASME PTC 19.1 provides a thorough treatment of the subject and includes specific requirements for report format, general guidance, details of special calculations that may be required in some circumstances, and background information.

I-6 EXAMPLE CALCULATIONS

I-6.1 Pretest Uncertainty Calculation

I-6.1.1 Define the Measurement Process. This example will focus on the calculation of system efficiency. The system will be assumed to be a simple 100 kW SOFC fuel cell system, without heat recovery or mechanical inputs or mechanical outputs. The system is assumed to use natural gas fuel and provide 480 V single-phase output at unity power factor. Oxidant is provided at ambient temperature and pressure.

The basic system consists of a fuel cell with fuel input and electrical output. All auxiliary loads are fed from an internal bus. The fuel flow is measured with a precision mass flow meter and online sampling is used to compute the lower heat value of the fuel. Electrical output is measured using a high accuracy revenue quality RMS reading true power kWh meter. Test duration is 1 hr, with data taken at 1 min intervals.

The efficiency calculation is:

$$\eta_{el} = 100\ [(3600\ E_n)\ /\ QI_{\text{total}}\ ]$$

where

100 = to convert to percent
3600 = kJ/kW·h conversion factor
E_n = net electrical energy for the test duration from para. 5.3.4, kW·h
η_{el} = electrical conversion efficiency, %
QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency from para. 5.2.5.9

Independent testing parameters are:

C_{fp} = specific heat of fuel at the test boundary (at constant pressure), kJ/(kg·K)
E_n = net electrical energy for the test duration from para. 5.3.4, kWh
LHV_{avg} = fuel low heating value at the test boundary in for calculations based on Low Heating Value, kJ
M_f = total fuel flow to the fuel cell during the test or data period, kg
MW_f = molecular weight of the gaseous fuel, kg/kmol
P_f = fuel pressure at the test boundary, kPa (absolute)
RH_f = relative humidity of the fuel, at the test boundary, percent R.H.
T_{ff} = fuel temperature at the test boundary, K

Table I-1 lists these independent testing parameters and their nominal values.

$$QI_{\text{total}} = Q_f + E_{cf} + TQ_f + Q_{st} + E_{co} + TQ_o + W_{si}$$

where

TABLE I-2 VARIOUS MEASURED PARAMETERS AND THE NOMINAL CALCULATED RESULTS

Calculated Results			
Results	Description	Units	Nominal Value
Q_f	Energy content of fuel, kJ	kJ	7.2000E+05
E_{cf}	Compression energy content of fuel	kJ	6.9522E+02
TQ_f	Temperature energy content of fuel	kJ	5.9618E+01

QI_{total} = total energy into the system for calculation of input energy and electrical conversion efficiency, kJ

For this example, Q_{st} , E_{co} , TQ_o , and W_{si} are all taken to be zero so the total input energy equation reduces to:

$$QI_{\text{total}} = Q_f + E_{cf} + TQ_f$$

$$\eta_{el} = \frac{3600E_n}{Q_f + E_{cf} + TQ_f} \times 100$$

And the efficiency equation can be expanded as:

$$Q_f = (M_f)\,(\text{LHV}_{\text{avg}})\ \text{(from para. 5.2.5.1)}$$

and

$$E_{cf} = (M_f\,RT_{\text{std}})\ \ln \frac{\text{absolute fuel inlet pressure at test boundary, kPa}}{\text{ambient barometric pressure, kPa}}$$

and

$$TQ_f = M_f\,C_{fp}\,(T_{ff} - 288.15\ \text{K})$$

where

C_{fp} = specific heat at constant pressure of fuel delivered during the test period, kJ/(kg·K)

E_{cf} = ideal pressure energy content of the fuel, kJ

E_n = net electrical energy for the test duration from para. 5.3.4, kW·h

LHV_{avg} = fuel low heating value at the test boundary for calculations based on Low Heating Value, kJ/kg

M_f = total fuel flow to the fuel cell during the test period, kg

MW_f = molecular weight of the gaseous fuel (16.043 kg/kmol for methane)

P_f = fuel pressure at the test boundary, kPa (absolute)

R = R_u / MW_f

R_u = 8.314 kJ/kmol K (universal gas constant)

RH_f = relative humidity of the fuel, at the test boundary, percent R.H.

T_{ff} = fuel temperature at the test boundary, K

T_{std} = standard temperature (15°C) = 288.15 K

Table I-2 lists the measured parameters and their nominal calculated values.

I-6.1.2 List Elemental Error Sources. Elemental error sources can be estimated based on judgment, calculated using prior test data, or developed using calibration laboratory calculations. Elemental error sources for the various parameters in the example procedure are given in Table I-3.

I-6.1.3 Calculate or Assign the Systematic Uncertainty and Random Standard Deviation for Each Parameter

(a) Systematic Uncertainty. Calibration errors will account for the majority of the systematic uncertainty and so they are used with judgment as the absolute systematic uncertainty for those instruments where the calibration uncertainty is known. For instruments or instrument loops where calibration is ±1% of full scale, the absolute uncertainty is calculated by multiplying 0.01 by the full-scale reading of the instrument. For instruments where the calibration uncertainty is ±1% of reading, the absolute uncertainty is calculated by multiplying 0.01 by the nominal reading. Different calibration uncertainties will require different numerical inputs.

All uncertainties are assumed to be at 95% confidence.

For the fuel mass flowmeter, a revenue quality meter with an uncertainty of ±0.75% (of reading) is available.

For the fuel heating value, laboratory procedures are adequate to achieve and uncertainty of ±0.5% of reading.

The molecular weight of the fuel can be calculated by the laboratory with an uncertainty of ±0.5% of the value.

TABLE I-3 ELEMENTAL ERROR SOURCES

Parameter	Description	Units	Nominal Value	Elemental Error Sources
LHV_{avg}	Fuel lower heating value	kJ/kg	50 000	Sampling errors, laboratory analysis errors, errors in tabular data, mass chromatograph calibration errors, random errors
M_f	Mass of fuel delivered	kg	14.4	Meter calibration errors, random errors
MW_f	Molecular weight of fuel Delivered	kg/kmol	16.043	Sampling errors, laboratory analysis errors, errors in tabular data, mass chromatograph calibration errors, random errors
Pf	Fuel pressure at the test Boundary	kPa	140	Pressure gauge calibration errors, pressure transducer calibration errors, loop calibration errors, random errors
T_{ff}	Fuel temperature at the test boundary	K	290	Temperature gauge calibration errors, pressure transducer calibration errors, loop calibration errors, random errors
C_{fp}	Fuel specific heat	kJ/kg	2.2379	Sampling errors, laboratory analysis errors, errors in tabular data, mass chromatograph calibration errors, random errors
E_n	Net kW·h delivered	. . .	100	Revenue meter calibration errors, loop calibration errors, random errors
3 600	Conversion factor	. . .	3 600	Constant
100	Conversion factor	. . .	100	Constant
R_u	Universal gas constant	kJ/kmol K	8.314	Constant
288.15	Standard temperature	K	288.15	Constant
BP	Ambient barometric pressure	kPa	101.325	Pressure gauge calibration errors, loop calibration errors, random error

TABLE I-4 ABSOLUTE STANDARD DEVIATION OF THE MEAN OF ONE-HOUR TESTS

Parameter	Description	Units	Nominal Value	Absolute Systematic Uncertainty, B_i	Absolute Standard Deviation of the Mean, $S_{\overline{X},i}$
LHV_{avg}	Fuel lower heating value	kJ/kg	50 000	250	85
M_f	Mass of fuel delivered	kg	14.4	0.108	0.036
MW_f	Molecular weight of fuel delivered	kg/kmol	16.043	0.0802	0.0273
P_f	Fuel pressure at the test boundary	kPa	140	7	7
T_{ff}	Fuel temperature at the test boundary	K	290	2	1
C_{fp}	Fuel specific heat	kJ/kg	2.2379	1.1190E-02	4.4759E-03
E_n	Net kW·h delivered	. . .	100	0.5	0.2
3 600	Conversion factor	. . .	3 600	0	0
100	Conversion factor	. . .	100	0	0
R_u	Universal gas constant	kJ/kmol K	8.314	0	0
288.15	Standard temperature	K	288.15	0	0
BP	Ambient barometric pressure	kPa	101.325	5	0.5

TABLE I-5 EXAMPLE OF A COMPUTER SPREADSHEET PERTURBATION

Parameter	Description	Units	Nominal Value	0.00001% Delta	Effective Nominal	Eff + Delta	Absolute Sensitivity
LHV_{avg}	Fuel lower heating value	kJ/kg	50 000	0.005	4.9948E+01	4.9948E+01	−9.9791E-04
M_f	Mass of fuel delivered	kg	14.4	0.00000144	4.9948E+01	4.9948E+01	−3.4686E+00
MW_f	Molecular weight of fuel delivered	kg/kmol	16.043	16.043E-06	4.9948E+01	4.9948E+01	3.0031E-03
P_f	Fuel pressure at the test boundary	kPa	140	0.000014	4.9948E+01	4.9948E+01	−1.0644E-03
T_{ff}	Fuel temperature at the test boundary	K	290	0.000029	4.9948E+01	4.9948E+01	−2.2332E-03
C_{fp}	Fuel specific heat	kJ/kg	2.2379	2.23793E-07	4.9948E+01	4.9948E+01	−1.8461E-03
E_n	Net kW·h delivered	. . .	100	0.00001	4.9948E+01	4.9948E+01	4.9948E-01
3 600	Conversion factor	. . .	3 600	. . .	. . .	. . .	. . .
100	Conversion factor	. . .	100	. . .	. . .	. . .	. . .
R_u	Universal gas constant	kJ/kmol K	8.314	. . .	. . .	. . .	. . .
288.15	Standard temperature	K	288.15	. . .	. . .	. . .	. . .
BP	Ambient barometric pressure	kPa	101.325	0.101325	4.9948E+01	4.9948E+01	1.4699E-03

The fuel pressure gauge is able to achieve an uncertainty of ±5% of full scale.

The fuel temperature gauge is able to achieve an uncertainty of ±2 K.

Fuel specific heat is assumed to be measured by the laboratory within an uncertainty of ±0.5% of measured value.

Net kW·h delivered can be measured within an uncertainty of ±0.5% of reading.

Ambient barometric pressure can be measured within an uncertainty of ±5 kPa of reading.

(b) Random Uncertainty. Since this is a pretest uncertainty estimate, the random uncertainty contribution must be estimated from previous data. Prior test data indicate that the absolute standard deviation of the mean of one-hour tests with one-minute data sets is as shown in Table I-4. For a post-test analysis, the actual standard deviation must be used. If the random uncertainty is too high, additional test duration and additional data points should lower the standard deviation.

I-6.1.4 Propagate the Systematic and Random Standard Deviation for Each Parameter. The systematic and random (sample) standard deviations of the independent parameters are propagated separately all the way to the final result.

Propagation of the standard deviations is done, according to the functional relationship defined in section I-5, step (a)(4), by using the Taylor series method (see Appendix C of ASME PTC 19.1-1998). This requires a calculation of the sensitivity factors, either by differentiation or by computer perturbation.

The systematic uncertainty and random standard deviations for each parameter must be multiplied by the proper sensitivity in accordance with the following equation.

θ_i = sensitivity coefficient for the parameter i

In order to propagate the various uncertainties properly through the equation, the various sensitivities of each parameter must be calculated. The sensitivity of a particular parameter is calculated by either taking the partial differential of the parameter with respect to the result (the efficiency in this case) or doing a computer perturbation of the data fields using small changes in each parameter independently to ascertain the change in the result for a small change in the parameter. See Section 7 of ASME PTC 19.1-1998 for the details of this process. For this example, a computer spreadsheet perturbation was done and the results are shown as Table I-5. Table 1-5 gives the various parameters, the perturbation amount used in the computer program, and the resulting sensitivities.

I-6.1.5 Calculate the Uncertainty. Calculation of uncertainty is done in accordance with para. 7.5 and Section 9 of ASME PTC 19.1, combining the

TABLE I-6 ABSOLUTE RANDOM UNCERTAINTY CONTRIBUTION FOR EACH PARAMETER

Parameter	**Description**	**Units**	**Nominal Value**	**Absolute Systematic Uncertainty, B_i**	***Absolute Standard Deviation of the Mean, $S_{\overline{x},i}$***	Absolute Sensitivity	Absolute Systematic Uncertainty Contribution	Absolute Random Uncertainty Contribution
LHV_{avg}	Fuel lower heating value	kJ/kg	50 000	2.5000E+02	8.5000E+01	−9.9791E-04	1.5560E-02	7.1948E-03
M_f	Mass of fuel delivered	kg	14.4	1.0800E-01	3.6000E+02	−3.4686E+00	3.5083E+00	1.5592E-02
MW_f	Molecular weight of fuel delivered	kg/kmol	16.043	8.0215E-02	2.7273E-02	3.0031E-03	1.4507E-08	6.7081E-09
P_f	Fuel pressure at the test boundary	kPa	140	7.0000E+00	7.0000E+00	1.0644E-03	1.3879E-05	5.5514E-05
T_{ff}	Fuel temperature at the test boundary	K	290	2.0000E+00	1.0000E+00	−2.2332E-03	4.9874E-06	4.9874E-06
C_{fp}	Fuel specific heat	kJ/kg	2.2379	1.1190E-02	4.4759E-03	1.8461E-03	1.0668E-10	6.8278E-11
E_n	Net kW·h delivered	. . .	100	5.0000E-01	2.0000E-01	4.9948E-01	1.5592E-02	9.979E-03
3 600	Conversion factor	. . .	3600	0	0	. . .	. . .	. . .
100	Conversion factor	. . .	100	0	0	. . .	. . .	. . .
R_u	Universal gas constant	kJ/kmolK	8.314	0	0	. . .	. . .	. . .
288.15	Standard temperature	K	288.15	0	0	. . .	. . .	. . .
BP	Ambient barometric pressure	kPa	101.325	5.0000E+00	5.0000E-01	1.4699E-03	1.3505E-05	5.4018E-07

systematic and random uncertainties to get the total uncertainty.

The absolute systematic uncertainty contribution is calculated for each parameter separately by multiplying one half the absolute systematic incertainty by the Sensitivity for that parameter and squaring the result:

$$\left(\frac{B_i}{2}\,\theta_i\right)^2$$

where

θ_i = sensitivity coefficient for the parameter i
B_i = absolute systematic uncertainty for the parameter i

The absolute random uncertainty contribution for parameter i is calculated similarly:

$$\left(S_{\overline{x},i}\,\theta_i\right)^2$$

where

θ = sensitivity coefficient for the parameter i
$S_{\overline{x},i}$ = absolute standard deviation of the mean for the i parameter.

Table I-6 gives the parameters, the nominal values expected, the calculated sensitivities, the absolute systematic uncertainty contribution, and the absolute random uncertainty contribution for each parameter, calculated as described above. All of these calculations are based on ASME PTC 19.1-1998, Section 9.

The Total Absolute Uncertainty of the Result is computed by combining the absolute systematic uncertainty with the absolute random uncertainty in the following manner.

$$UR=\sqrt{B^2{}_R + 2S_R{}^2}$$

where

B_R = the absolute systematic uncertainty

$$= 2\sqrt{\Sigma\left(\frac{B_i}{2}\,\theta_i\right)^2}$$

$2S_R$ = absolute random uncertainty

$$= 2\sqrt{\Sigma\left(S_{\overline{x},i}\,\theta_i\right)^2}$$

TABLE I-7 FINAL RESULTS OF THE ABSOLUTE, RANDOM, AND TOTAL UNCERTAINTIES OF THE RESULTS

Result	Description	Units	Nominal Value	Absolute Systematic Uncertainty of Result	Absolute Random Uncertainty of Result	Student's *T*	Total Absolute Uncertainty	Percent Uncertainty
Q_f	Energy content of fuel	kJ	7.2000E+05	. . .	. . .	. . .	. . .	. . .
E_{cf}	Compression energy content of fuel	kJ	6.9522E+02	. . .	. . .	. . .	. . .	. . .
TQ_f	Temperature energy content of fuel	kJ	5.9618E+01	. . .	. . .	. . .	. . .	. . .
η_{el}	Electrical efficiency	%	4.9948E+01	5.1485E-01	3.6237E-01	2	0.62958444	1.2605%

Table I-7 shows the final results with the absolute systematic uncertainty of the result, the absolute random uncertainty of the result, and the total absolute uncertainty of the result. This table also shows the percent uncertainty, expressing the absolute uncertainty as a percent of the result.

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