SURFACE VEHICLE RECOMMENDED PRACTICE

J2616

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Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System

Foreword

This recommended practice document was prepared by the Performance Working Group within the SAE Fuel Cell Standard Committee. This document is consistent with the J2615 Fuel Cell System and J2617 Fuel Cell Stack System Performance Test documents. It has also been submitted to ISO/TC22 for consideration as an international recommended practice document for vehicles. This document also strives to be consistent with ASME PTC-50 "Fuel Cell Power Systems Performance" for stationary power applications, and as such, references some of the same practices and techniques.

1. Scope

This recommended practice is intended to serve as a design verification procedure and not a product qualification procedure. It may be used to verify design specifications or vendor claims. Test procedures, methods and definitions for the performance of the fuel processor subsystem (FPS) of a fuel cell system (FCS) are provided. Fuel processor subsystems (FPS) include all components required in the conversion of input fuel and oxidizer into a hydrogen-rich product gas stream suitable for use in fuel cells. Performance of the fuel processor subsystem includes evaluating system energy inputs and useful outputs to determine fuel conversion efficiency and where applicable the overall thermal effectiveness. Each of these performance characterizations will be determined to an uncertainty of less than ± 2% of the value.

The method allows for the evaluation of fuel processor subsystems for two general cases.

- Compare fuel processors with different designs (e.g., catalytic partial oxidation reforming, autothermal reforming or steam reforming) on a common basis where no specific fuel cell system design has been identified.
- Assess the performance of a specific fuel processor in the context of a specific fuel cell system design.

This document applies to all fuel processor subsystems for transportation applications regardless of fuel processor type, fuel cell type, electrical power output, thermal output, or system application (propulsion or auxiliary power unit (APU)). For example, the fuel processor subsystems associated with proton exchange, molten carbonate and solid oxide fuel cells can differ due to the requirements of the fuel cells themselves.

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Performance of the fuel processor subsystem, and preprocessor if applicable, is evaluated. A stand alone fuel processor "system" or even the primary reactor (e.g., autothermal, partial oxidation or steam reforming reactor) of a fuel processor subsystem that would normally be integrated into a fuel cell system can be evaluated. The fuel processor together with the preprocessor (if required) converts the fuel (gasoline or other liquid hydrocarbon) to a reformate gas consisting largely of H_2, CO, CO_2, H_2O and N_2 (if air is used). After the fuel processor subsystem, reformate gas typically contains only trace levels of carbon bearing components higher than C_1. The FPS would be evaluated in a test facility that is designed to evaluate a stand-alone component rather than a portion of the reformer such as a specific catalyst or a particular vessel design.

Any fuel(s) mutually agreed to by the test parties can be used such as 1) straight run gasoline (EPA Fuel-CARB reformulated gasoline Tier II, 30 ppm sulfur), or 2) methanol or 3) hydrocarbon fuel such as iso-octane, naptha, diesel, liquefied natural gas (LNG) or LPG (propane), etc.

The procedures provide a point-in-time evaluation of the performance of the fuel processor subsystem. Steady state and transient (start-up and load-following) performance are included. Methods and procedures for conducting and reporting fuel processor testing, including instrumentation to be used, testing techniques, and methods for calculating and reporting results are provided. The boundary limits for fuel and oxidant input, secondary energy input and net energy output are defined. Procedures for measuring temperature, pressure, input fuel flow and composition, electrical power and thermal output at the boundaries are provided.

Procedures for determination of the FPS performance measures such as fuel processor efficiency and cold gas efficiency at a rated load or any other steady state condition are provided. Methods to correct results from the test conditions to reference conditions are provided.

SI units are used throughout the recommended practice document.

1.1 Limitations of Test Procedure

Performance measures included in this document are consistent with generally accepted conventions. Efficiency, for example, is based on hydrogen (or hydrogen and carbon monoxide in the case of solid oxide fuel cells) produced or consumed divided by fuel fed. This convention for fuel processor efficiency is not consistent with a strict thermodynamic definition of thermal efficiency based on a rigorous energy and material balance. Building on this convention, the recommended practice provides a method to evaluate fuel processor subsystems based on different designs or different scope (e.g., air compression or fuel pumping included or excluded). An approach based on ASME PTC 50 is provided that allows the test parties to adjust the efficiencies for systems operating at other than reference conditions during a performance test. In its simplest application, the approach enables the user to correct performance measures to a consistent basis without having to identify a specific fuel cell system or make assumptions about the performance of other subsystems. If the user has this information the approach allows for corrections for efficiencies of other subsystems or components (e.g., oxidant compression/expansion, water pump, or fuel pump). Terms are included that correct the compression energy for other inefficiencies in the system such as power conditioner inefficiency or electrical/mechanical conversion inefficiency. Values for these terms can be 1) provided based on the design of a specific system, 2) estimated based on typical values for these type of energy conversion processes, or 3) omitted from the expressions and results reported on an ideal compression basis. Option 3 introduces the least error in the reported efficiency value. Option 3 would also be the approach the user would use if the user wanted to use the measured FPS efficiency in the expression for overall fuel cell system efficiency given below.

$$\eta_{FCS} = \eta_{FPS} \bullet \eta_{FCSS} \bullet \eta_{PC} \bullet \eta_{el./mech} \qquad \text{(Eq. 1)}$$

In other words, the calculations to support the determination of FPS efficiency as provided in the recommended practice document collapse to a form that is suitable for incorporation in the generally accepted expression.

The following additional limitations are identified:

a. Excludes performance evaluation over the Federal Urban Driving Schedule (FUDS) driving cycle. Performance over FUDS driving cycle is left for evaluation at the vehicle level. A transient test is included to evaluate response of system to step change in input demand.
b. Assumes component is provided in its final form, i.e., insulated, inlet connections to receive fuel, steam or air (if required), and exhaust connections to vent reformate gas to flare stack or hood.
c. Excludes sulfur greater than 30 ppm as described above. It is assumed that impacts of sulfur or other contaminants such as chlorides will be addressed by a separate life cycle test to evaluate long-term performance.
d. Excludes consideration for manufacturers sampling for production.
e. Assumes specifications for catalyst conditioning are developed and agreed to by the testing parties.
f. Excludes survivability tests i.e., tilt, vibration, extremes in ambient conditions. These standard tests will be developed at a later date.
g. Does not address performance tests for specific components such as shift reactors or heat exchangers.
h. Excludes tests for environmental factors such as tilt.
i. Excludes tests for human factors such as acoustics/noise, vibration, harshness.
j. Intended to be a point-in-time test and therefore does not address aging studies or life.
k. Excludes performance tests for evaluating reliability.
l. Excludes discussion of general safety. Fuel cell system safety is covered by J2578 document. Safety concerns and precautions unique to the FPS are addressed.
m. Excludes vehicle level performance (efficiency, acceleration, emissions, etc.) evaluation.
n. Excludes contamination.
o. Excludes emissions characterization.
p. Does not assess performance on any cost basis.

An example of a fuel contaminant which is likely to have a cumulative effect on some systems' performance is sulfur (as determined by ASTM D 129, D 1266, D 1552, D 2427 or D 5453). Another is chlorine but, there are many others that can affect system performance through catalyst degradation. For these reasons, fuel composition and quality have implications far beyond simple heating values and far beyond the implications for other types of energy converters. Degradation in long-term performance due to the presence of contaminants in the fuel is not considered.

1.2 Rationale

Not applicable.

2. References

2.1 Applicable Publications

The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

1. SAE J312—Automotive Gasolines
2. SAE J1515—Impact of Alternative Fuels on Engine Test and Reporting Procedures
3. SAE J1715—Electric Vehicle Definitions Document
4. SAE J1829—Stoichiometric Air-Fuel Ratios of Automotive Fuels
5. SAE J2574—SAE Information Report—Fuel Cell Electric Vehicle Terminology
6. SAE J2578—Recommended Practice for General Fuel Cell Vehicle Safety
7. SAE J2615—Testing Performance of Fuel Cell Systems for Automotive Applications
8. SAE J2617—Testing Performance of PEM Fuel Cell Stack Subsystem for Automotive Applications

2.1.2 ASTM PUBLICATIONS

Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

9. ASTM D 129—Test Method for Sulfur in Petroleum Products (General Bomb Method)
10. ASTM D 240—Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter
11. ASTM D 482—Test Method for Ash from Petroleum Products
12. ASTM D 1018—Test Method for Hydrogen in Petroleum Fractions
13. ASTM D 1217—Test Method for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pycnometer
14. ASTM D 1266—Test Method for Sulfur in Petroleum Products (Lamp Method)
15. ASTM D 1298—Density, Relative (Specific Gravity) or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
16. ASTM D 1552—Test Method for Sulfur in Petroleum Products (High-Temperature Method)
17. ASTM D 2427—Instrumental Determination of C2 through C5 Hydrocarbons in Gasolines by Gas Chromatography, Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants.
18. ASTM D 2427—Mercaptan Sulfur in Gasoline, Kerosene, Aviation Turbine, and Distillate Fuels (Potentiometric Method)
19. ASTM D 3228—Test Method for Nitrogen in Lubricating Oils and Fuel Oils by Modified Kjeldahl Method
20. ASTM D 3231—Phosphorus in Gasoline
21. ASTM D 3588-98—Standard Practice for Calculating Heat Value, Compressibility Factor and Relative Density of Gaseous Fuels.
22. ASTM D 4057—Manual Sampling of Petroleum and Petroleum Products
23. ASTM D 4177-95 (C2000)—Practice for Automatic Sampling of Petroleum and Petroleum Products
24. ASTM D 4809—Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Intermediate Precision Method)

25. ASTM D 4809-95—Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
26. ASTM D 4814—Specification for Automotive Spark-Ignition Engine Fuel
27. ASTM D 5453—Determination of Total Sulfur in Light Hydrocarbons, Motor Fuels, and Oils by Ultraviolet Fluorescence
28. ASTM D 5622—Determination of Total Oxygen in Gasoline and Methanol Fuels by Reductive Pyrolysis

2.1.3 OTHERS

29. CRC Handbook of Chemistry and Physics, edited by R. C. Weast, and M. J. Astle, Chemical Rubber Company (CRC) Press, Inc., 1981
30. Chemical Engineer's Handbook, 5th edition, edited by R. H. Perry and C. H. Chilton, McGraw-Hill Book Company, 1973
31. 40 CFR Chapter 1 – 86.113-04 Fuel Specifications
32. ASME PTC 19.1 Appendix B Uncertainty Analysis
33. I&A, Leakage Measurement, ASME PTC 19.21
34. I&A, Pressure Measurement ASME PTC 19.2
35. ASME Temperature Measurement and Calibration ASME PTC 19.3
36. ASME Fluid Flow Measurement PTC 19.5
37. ASME PTC 50 on Fuel Cell Power Systems Performance, November 29, 2002
38. Steam – Its Generation and Use, 40th ed. Babcock & Wilcox, 1992
39. NIST Technical Note 1297, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST, 1994 edition
40. NIST Special Publication 811, Guide for the Use of the International System of Units (SI), NIST, 1995 edition
41. Fuel Cell Handbook, 4th ed. Parsons Corporation for U. S. Department of Energy-FETC, DOE/FETC-99/1076
42. API Technical Data Book
43. Fuel Cell Systems Explained. James Larminie and Andrew Dicks. John Wiley & Sons, Ltd. Chichester. 2000.
44. ASME Boiler and Pressure Vessel Code Section V Article 10, The American Society of Mechanical Engineers. New York, New York. July 1, 2001
45. U.S. Fuel Cell Council Fuel Cell Glossary, Second Edition, May 2000
46. Meyer, C. A., et al, ASME 1983 Steam Tables, 5th ed., The American Society of Mechanical Engineers, New York, 1983.
47. Bosch Automotive Handbook 5th Edition, June 12, 2001.

3. Definitions

The primary reference for fuel cell terminology is SAE Standard J2574. Another important reference for fuel cell terminology is the U.S. Fuel Cell Council's Glossary (May 2000). Some definitions that are required for fuel processor testing, but that are not included in J2574 are listed below. Where differences occur between the various references the definitions as provided here will apply.

3.1 Air

Standard air composition assumes 60% relative humidity (0.0128 kg water/kg dry air at 25 °C) and inerts included as nitrogen.

Mass Fraction N_2+Inerts	0.7586 (wet basis)
Mass Fraction O_2	0.2286 (wet basis)
Mass Fraction H_2O	0.0128 (wet basis)

3.2 Air Processing Sub-system (APS)

The assembly of components that deliver air (oxygen) for reaction in the fuel cell system. The air processing sub-system can provide air as required to the fuel processing sub-system, thermal management sub-system and the fuel cell stack sub-system. The air processing sub-system may include filtration, purification, compression, and flow control components.

3.3 Consistent Liquid or Gaseous Fuels

Fuels with a heating value that varies less than one percent over the course of a performance test.

3.4 Cold Gas Efficiency

The quotient of lower heating value of useful gases exiting the fuel processor divided by the lower heating value of fuel fed to the reformer.

3.5 Electric Load System

A device used to apply electric load to a fuel cell. A load system is also referred to as a load bank for historical reasons. A load system generally allows the user to set a load as a current (Amperes) or power level (kW). A load system may be resistive or inductive. More sophisticated systems allow for the setting of a voltage (VDC or VAC) and for programming of the set points as a function of time. While in general performance testing the load system serves as a sink for electrical power, it may also be used to supply current to the fuel cell for diagnostic and conditioning purposes.

3.6 Fuel Cell Control System (FCCS)

A system that controls and/or monitors fuel cell system conditions and automatically responds to vehicle power demands while preventing hazardous conditions and damage to the fuel cell system. The automatic control system generally includes a microprocessor based device with input and output functions and may provide a diagnostic or troubleshooting function.

3.7 Fuel Cell Stack Sub-system (FCSS)

The assembly containing one or more fuel cell stacks that provides for the reaction of fuel and oxidant to produce electric current by means of an electrochemical reaction. The fuel cell stack sub-system generally includes connections for conducting fuels, oxidants, and exhausts; electrical connections for the power delivered by the stack sub-system; and means for monitoring electrical loads, which are for interface to the fuel cell system (FCS). Additionally, the FCSS may incorporate means for conducting additional fluids (e.g., cooling media, inert gas), means for detecting normal and/or abnormal operating conditions, enclosures or pressure vessels, and ventilation systems. The fuel cell stack sub-system is also known as a fuel cell module, fuel cell power module or fuel cell stack assembly.

3.8 Fuel Cell System (FCS)

A combination of subsystems and components designed to provide electrical power as a result of the implementation of a fuel cell (defined elsewhere.) A fuel cell alone, is not capable of providing useful electrical power, and therefore requires other functions in order to be of use. A fuel cell system is described schematically in Figure 1 and may include, for example, a fuel processing sub-system, a thermal management sub-system, an air processing sub-system, a power distribution sub-system, and a fuel cell control sub-system.

3.9 Fuel Processing Sub-system (FPS)

The assembly of components that chemically or physically converts the supplied fuel to a form suitable for use in the fuel cell stack sub-system. A FPS may, for example, include reactor beds, heat exchangers, and controls used to reform a hydrocarbon fuel into a hydrogen rich stream known as reformate gas or simply reformate. In a hydrogen fueled fuel cell system, the FPS may include pressure regulation, humidification and mixing components. The fuel processing sub-system also may be referred to as the fuel processor subsystem or simply the fuel processor.

3.10 Fuel Processor Subsystem Efficiency

The fuel processor subsystem efficiency is defined as the lower heating value of hydrogen (or hydrogen plus CO in the case of the solid oxide fuel cells) consumed by the fuel cell plus any hydrogen (plus CO) vented from the fuel cell divided by the lower heating value of fuel fed to the fuel processor. The fuel processor subsystem efficiency also may be defined as the lower heating value of hydrogen (plus CO) produced by the fuel processor divided by the lower heating value of the fuel fed to the fuel processor. If any hydrogen-depleted anode gas is recycled to the fuel processor subsystem from the fuel cell, then the lower heating value of this recycled gas is subtracted from the lower heating value of the hydrogen (plus CO) produced by the fuel processor subsystem.

3.11 Fuel Supply System (FSS)

The assembly of components that stores and delivers reactant fuel to the fuel cell system. For example, the fuel supply system may be comprised of an elevated pressure tank for storage of hydrogen and appropriate pressure regulating equipment, safety devices and instrumentation. Another example of a fuel supply system is a tank, pump and plumbing used for the storage and delivery of a hydrocarbon fuel. The fuel supply system ends at the point where the fuel is either first (1) reacted, (2) cleaned of contaminants or (3) mixed with any other fuel cell system stream.

3.12 Heat Input

The flow of fuel(s) multiplied by the higher heating value (HHV) or lower heating value (LHV) of the fuel(s).

3.13 Heat Sink

The reservoir to which the heat rejected by the system is transferred. For an evaporative or dry air-cooled heat exchanger system, the reservoir is the ambient air.

3.14 High or Gross Heating Value or (HHV)

The enthalpy change or 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 typically serves as basis for heating value for the fuel buyer. Reference state of products of reaction is 288.15 K and 101 325 Pa. The higher heating value of liquid fuels can be determined with ASTM D 240, ASTM D 4809 or ASTM D 4809-95. The higher heating value of gaseous fuels can be determined with ASTM D 3588-98.

3.15 Idle Power

This is the gross power level at which the FCS operates when no external load is applied (i.e., zero net power). This power level is sufficient to supply all parasitic power required by the FCS. A fuel processor subsystem performance test would be conducted at the FPS load corresponding to this condition.

3.16 Lower or Net Heating Value (LHV)

The enthalpy change or heat of combustion per unit quantity of fuel assuming all water remains 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. Lower heating value can be calculated from the measured higher heating value (e.g., ASTM D 240) as follows:

$$QLHV(net, 15\ ^\circ C) = QHHV(gross, 15\ ^\circ C) - 0.2122 \times H$$

Where:

QLHV(net, 15 °C) = net heat of combustion at constant pressure, MJ/kg
QHHV(gross, 15 °C) = gross heat of combustion at constant volume, MJ/kg
H = mass % of hydrogen in the sample

3.17 Maximum Continuous Power

Operating condition corresponding to the maximum continuous power achievable in the fuel cell system without intervention. The FPS load corresponding to this operating point.

3.18 Maximum Design Efficiency Power

Operating condition corresponding to the maximum design efficiency power of the fuel cell system. The FPS load corresponding to this operating point. Note that the fuel processor maximum operating design efficiency point may not correspond to the maximum efficiency design point for the fuel cell system.

3.19 Peak Power

The maximum instantaneous net power output of the FCS. The FPS load corresponding to this operating point.

3.20 Power Conditioning System (PCS)

The collection of components that converts the power generated by the fuel cell system into power useful for vehicular purposes. The power conditioning system may include voltage regulators (DC/DC) and/or converters (DC/AC) that provide the interface between the fuel cell system and the vehicle loads.

3.21 Power Distribution Sub-system (PDS)

The collection of components that connects the fuel cell stack sub-system to the power conditioning system and that converts power for fuel cell system use. The power distribution sub-system may include cables, switches and/or contactors and/or relays, buses, other connectors and instrumentation. As illustrated in Figure 1, the PDS has only DC power as input.

3.22 Pressure and Temperature

Expressed as total values unless otherwise specified. 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.

3.23 Reference Conditions

The values of all the external parameters, i.e., parameters outside the test boundary to which the test results are corrected. In addition, the specified secondary heat inputs and outputs are calculated with respect to the reference conditions. Heats of formation of elements and compounds in their standard states, heat of combustion, and latent heats of phase changes and free energy changes are determined with respect to reference conditions. For this recommended practice the reference conditions are as follows:

Temperature:	15 °C (288.15 K, 59 °F)
Pressure:	101 325 Pa (1 atmosphere, 14.696 psia, 101.325 kPa)
Air:	60% relative humidity (0.006 kg H_2O/kg dry air) at 15 °C

3.24 Reformate Gas or Reformate

The product of a fuel processing sub-system, generally rich in hydrogen. This gaseous fluid results from the reformation of the fuel within the fuel processing sub-system. The quality and/or composition of this fluid depends on the location within the FPS; i.e. which reactor is sampled.

3.25 Secondary Thermal Energy Inputs

The additional heat inputs to the test boundary which must be accounted for, such as cycle make-up and process condensate return.

3.26 Secondary Energy Input

The additional energy inputs to the test boundary which must be accounted for, such as electrical resistance heating.

3.27 Standard Temperature and Pressure (STP)

101 325 Pa (14.696 psia), 273.15 K (0 °C, 32 °F).

3.28 Test Boundary

Identifies the energy streams required to calculate corrected results.

3.29 Test Facility

A physical area and requisite utilities designated for the purpose of testing the performance of a fuel cell system. For example, a typical test facility may include ventilation, reactant supply systems, auxiliary cooling systems, data acquisition systems, load simulation device, and supplemental hazard mitigation devices.

3.30 Test Operator(s) / Personnel

An individual or group responsible for the immediate administration and application of a test procedure to the test article.

3.31 Testing Parties

Those entities with an interest in the methods applied and results obtained from the performance testing of the fuel cell system. For example, the testing parties may include the article manufacturer, a testing organization, and /or the system integrator.

3.32 Test Reading

One recording of all required test instrumentation.

3.33 Test Run

A group of test readings taken while the fuel cell power system is operating at steady state at a specified operating condition.

3.34 Test Stand

The fixture and supporting equipment in which a fuel processor subsystem is placed to conduct a performance test.

3.35 Test Subject

The fuel processor subsystem or component of the fuel processor subsystem that is being evaluated in the test facility.

3.36 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.

3.37 Thermal Management Sub-system (TMS)

The assembly of components which provide both thermal and water management for the fuel cell system. The thermal management sub-system may include an accumulator, pump, radiator and/or condenser.

3.38 Turndown

Gross continuous power to gross idle power level.

3.39 Vehicle Control System (VCS)

A system that regulates the operation of the vehicle in response to driver demand and vehicle system conditions.

3.40 Water Balance Power Level

The net power level at which the FCS is able to maintain (coolant) balance. The fuel processor subsystem load corresponding to this operating point.

3.41 Water Treatment Sub-system (WTS)

The assembly of components which provide the treatment necessary for the process water in the fuel cell system. For example, the water treatment sub-system may include a demineralizing / deionizing resin bed and instrumentation and may provide water recovery and process humidification functions.

4. Nomenclature, Physical Constants and Units

C_{C}	Mole fraction carbon in fuel
C_{CO}	Mole fraction carbon monoxide in reformate, wet basis
C_{CO2}	Mole fraction carbon dioxide in reformate, wet basis
C_{H}	Mole fraction hydrogen in fuel
C_{HC}	Mole fraction hydrocarbon in reformate, wet basis
C_{H2}	Mole fraction hydrogen in reformate, wet basis
C_{H2O}	Mole fraction water in fuel/reformate
C_{N}	Mole fraction nitrogen in fuel
C_{N2}	Mole fraction nitrogen in air/reformate, wet basis
C_{P}	Specific heat (generalized) at constant pressure, kJ/kgK
C_{Pf}	Specific heat of fuel at the test boundary (at constant pressure), kJ/kgK
$C_{Pf,liq}$	Specific heat of fuel liquid phase at the test boundary (at constant pressure), kJ/kgK
$C_{Pf,vap}$	Specific heat of fuel vapor phase at the test boundary (at constant pressure), kJ/kgK
C_{Pr}	Specific heat of reformate at the test boundary (at constant pressure), kJ/kgK
C_{Phtf}	Specific heat of heat transfer fluid at the test boundary (at constant pressure), kJ/kgK
E_{a}	Kilowatt-hours into the system crossing the test boundary, kW-h
E_{aux}	Auxiliary energy
E_{C}	Compression energy
E_{Cf}	Fuel pressure energy input
E_{Co}	Oxidant pressure energy input
E_{Cr}	Reformate pressure energy output
E_{Crg}	Recycled gas from fuel cell exhaust pressure energy input
E_{Cw}	Water pressure energy input
EE_{a}	Auxiliary electrical input
$ELEV_{site}$	Test site elevation, meters
FUDS	Federal Urban Driving Schedule

ΔH_{fvap}	Heat of vaporization of fuel, kJ/kg
HHV_{avg}	Fuel higher heating value at the test boundary for calculations based on High Heating Value, kJ/kg
H_{htfin}	Average enthalpy of the secondary thermal input heat transfer fluid entering the fuel processor at the test boundary, kJ/kg
H_{htfout}	Average enthalpy of the secondary thermal input heat transfer fluid exiting the fuel processor at the test boundary, kJ/kg
H_o	Average enthalpy of the oxidant entering the fuel processor at the test boundary, kJ/kg
H_w	Average enthalpy of water entering fuel processor at the test boundary, kJ/kg
I_a	Auxiliary electrical input current at the test boundary, amps
KW_a	Auxiliary electrical input power into the test boundary, kWe
LHV_{H2}	Lower heating value of hydrogen, 120 000 kJ/kg
LHV_{CO}	Lower heating value of carbon monoxide, 10 100 kJ/kg
LHV_{avg}	Fuel lower heating value at the test boundary for calculations based on Lower Heating Value, kJ/kg
MB	Overall material balance closure, %
MB_c	Carbon component balance closure, %
MB_{N2}	Nitrogen component balance closure, %
M_f	Total fuel flow to the fuel processor during the test or data period, kg
m_f	Fuel flow rate into the test boundary during the data period (may be used to calculate the total fuel flow by integrating the flow rate over the data period), kg/s
MW_f	Molecular weight of the fuel, kg/kmol
M_{htf}	The mass of heat transfer fluid into and out of the fuel processor from the source of secondary thermal energy during the test period, kg
m_{htf}	The mass flow rate of heat transfer fluid into and out of the fuel processor 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/s
M_o	Total oxidant flow to the fuel processor during the test period, kg
m_o	Oxidant flow rate into the test boundary during the data period (may be used to calculate the total oxidant flow by integrating the flowrate over the data period), kg/s
MW_o	Molecular weight of the oxidant (28.9644 kg / kmol for standard dry air), kg/kmol
M_r	Total reformate flow exiting the fuel processor subsystem during the test or data period, kg
m_r	Reformate flow rate exiting the test boundary during the data period (may be used to calculate the total reformate flow by integrating the flow rate over the data period), kg/s
M_{rg}	Total recycled gas flow from fuel cell exhaust, kg
m_{rg}	Recycled gas flow rate from exhaust of fuel cell, kg/s
MW_r	Molecular weight of the reformate based on gas analysis, kg/kmol
M_w	The mass of water into the fuel processor during the test period, kg
m_w	The mass flow rate of water into the fuel processor during the data period (may be used to compute the total flow by integrating over the data period), kg/s
n_i	Number of moles of component i
O_2/C	Oxygen-to-carbon molar ratio
P_{amb}	Barometric pressure at the test site, kPa
P_f	Fuel pressure at the test boundary, kPa (absolute)

P_o	Average oxidant pressure at the test boundary, kPa (absolute)
P_r	Reformate pressure at the test boundary, kPa (absolute)
P_{rg}	Pressure of recycled gas from fuel cell, kPa (absolute)
P_{stii}	The average pressure of the secondary thermal input heat transfer fluid entering the fuel processor at the test boundary (may be used to calculate the enthalpy of the heat transfer fluid), kPa (absolute)
P_{stio}	The average pressure of the secondary thermal input heat transfer fluid leaving the fuel processor at the test boundary (may be used to calculate the enthalpy of the heat transfer fluid), kPa (absolute)
P_w	The average pressure of the water entering the fuel processor at the test boundary (may be used to calculate the enthalpy of the water), in kPa (absolute)
Q_{elec}	Electrical resistance heating of system
Q_f	Fuel chemical energy Input
Q_{ft}	Fuel thermal energy (enthalpy) input
QI	Total input energy
Q_{loss}	Heat loss from fuel processor subsystem
Q_{ot}	Oxidant thermal energy (enthalpy) input
Q_{rg}	Recycled gas from fuel cell chemical energy input
Q_{rgt}	Recycled gas from fuel cell thermal energy input
Q_r	Reformate chemical energy output
Q_{rt}	Reformate thermal energy output
Q_{stin}	Secondary thermal energy (enthalpy) input
Q_{stout}	Secondary thermal energy (enthalpy) output
Q_{wt}	Water thermal energy (enthalpy) input
Q_{rt}	Reformate gas thermal energy output
RH_{amb}	Relative humidity at the test site, percent R.H.
RH_f	Relative humidity of the fuel, at the test boundary, percent R.H.
Ru	Universal gas constant 8.314 kJ/kmol K
t	Time of the test period, h
T_{amb}	Ambient temperature at the test site, K
T_{bp}	Boiling point temperature of liquid fuel, K
$T_{cooling}$	Cooling system heat sink temperature, K
T_f	Fuel temperature at the test boundary, K
T_r	Reformate temperature at the test boundary, K
T_{htfin}	The average temperature of the secondary thermal input heat transfer fluid entering the fuel processor at the test boundary (may be used to calculate the enthalpy of the heat transfer fluid), K
T_{htfout}	The average temperature of the secondary thermal input heat transfer fluid leaving the fuel processor at the test boundary (may be used to calculate the enthalpy of the heat transfer fluid), K
T_o	Temperature of oxidant, K
T_{Ref}	Reference temperature (15 °C) = 288.15 K
T_{rg}	Temperature of recycled gas from fuel cell, K
t_r	Time of the data period, h
T_w	The average temperature of the water entering the fuel processor at the test boundary (may be used to calculate the enthalpy of the water), K
V_a	Auxiliary electrical input voltage, at the test boundary in volts

x_C	Mass fraction carbon in fuel
x_{CO}	Mass fraction carbon monoxide in reformate, wet basis
x_{CO2}	Mass fraction carbon dioxide in reformate, wet basis
x_H	Mass fraction hydrogen in fuel
x_{HC}	Mass fraction hydrocarbon in reformate, wet basis
x_{H2}	Mass fraction hydrogen in reformate, wet basis
x_{H2O}	Mass fraction water in fuel/reformate
x_N	Mass fraction nitrogen in fuel
x_{N2}	Mass fraction nitrogen in air/reformate, wet basis
x_s	Mass fraction sulfur in fuel

Greek Symbols

δ	Steam-to-carbon ratio
η	Efficiency
λ	Stoichiometric air/fuel ratio
ν	Specific volume, m^3/kg
θ	Fuel equivalence ratio

Subscripts

a	Anode gas
amb	Ambient conditions
aux	Auxiliary
cc	Carbon conversion
cge	Cold gas efficiency
CH	Hydrocarbon
CH4	Methane
C3H8	Propane
CO	Carbon monoxide
CO2	Carbon dioxide
Cooling	Cooling system heat sink
el/mech	Electrical to mechanical conversion
FCS	Fuel cell system
FCSS	Fuel cell stack subsystem
FPS	Fuel processor subsystem
H,H2	Hydrogen – elemental or molecular
H2O	Water or steam
in	System boundary inlet
liq	Liquid phase
N,N2	Nitrogen – elemental or molecular
f	Fuel
htf	Secondary heat transfer fluid
o	Oxidant or air
out	System boundary outlet
PC	Power conditioner
r	Reformate
rg	Recycled gas from fuel cell
Ref	Reference conditions
t	Thermal
vap	Vapor phase
w	Water or steam

TABLE 1—CONSTANTS AND PHYSICAL PROPERTIES

Constant or Physical Property	Units	Value	Ref.
Universal gas constant, Ru	kJ/kmol K	8.314	29.
Molecular Weight of Air (dry)	kg/kmol	28.964	29.
Molecular Weight of Methane	kg/kmol	16.043	29.
Molecular Weight of Propane	kg/kmol	44.09	29.
Molecular Weight of Carbon Monoxide	kg/kmol	28.010	29.
Molecular Weight of Carbon Dioxide	kg/kmol	44.010	29.
Molecular Weight of Carbon	kg/kmol	12.011	29.
Molecular Weight of Hydrogen	kg/kmol	2.016	29.
Molecular Weight of Nitrogen	kg/kmol	28.013	29.
Molecular Weight of Water	kg/kmol	18.015	29.
Molecular Weight of Oxygen	kg/kmol	31.999	29.
Standard Temperature	K	273.15	29.
Standard Pressure	kPa	101.325	29.
Reference Temperature	K	288.15	N/A
Reference Pressure	kPa	101.325	N/A
LHV of hydrogen	kJ/kg	120,000	30.
LHV of carbon monoxide	kJ/kg	10,100	30.
HHV of hydrogen	kJ/kg	142,000	30.
HHV of carbon monoxide	kJ/kg	10,100	30.
Boiling point of gasoline	K	488.15	47.

5. Pre-test Conditions

This section outlines the recommended steps required to plan, conduct, and evaluate a performance test of a fuel processor subsystem (FPS). The subsections discuss the following:

1. Definition of Test Subject with Schematic
2. Specifications of Test Facility and Equipment
3. Inspection of Test Subject and Connections to Facilities and Equipment
4. Pretreatment Procedures
5. Test Plan
6. Training of Test Personnel
7. Agreements

5.1 Definition of Test Subject with Schematic

A generic fuel cell power system block diagram is shown in Figure 1. The 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, CH_4, or methanol is reacted in the cell to produce hydrogen, CO_2 is also a product. These reactions are 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 quality dc or 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:

Fuel Supply can be as simple as a hookup to a filtered, regulated gaseous fuel source (hydrogen, natural gas, propane, etc.) or can include a liquid fuel such as methanol, gasoline or diesel fuel or gaseous fuel.

Oxidant Supply usually consists of a means of providing fresh air to the system, typically with a compressor or blower.

Fuel Processing involves a variety of steps, depending on the fuel cell type. If the fuel cell is running on bottled hydrogen, fuel processing is minimal. Fuel cell power system for transportation applications may be run on common liquid fuels, such as methanol, gasoline or diesel. Fuel processing usually involves cleaning to remove possible fuel cell poisons (e.g. sulfur compounds). It can include reforming of the fuel to produce hydrogen (in “externally reformed” systems) or this function can occur inside the stacks in some types of fuel cells, e.g., direct-methanol fuel cells. The fuel processor may also include other equipment, such as shift reactors, CO oxidation reactors, higher hydrocarbon removal, etc.

Heat Recovery systems in fuel cell systems usually consist of fairly conventional heat exchange equipment that is used to extract waste heat (typically from the system exhaust stream) to provide reactant preheat and steam generation.

Cogeneration Heat Recovery consists of equipment to export thermal energy for use outside the fuel cell or fuel processor subsystem, e.g., heating for passenger compartment.

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 as in the case of automotive applications.

Fuel Cell Stack consists of the fuel cell stack or stacks that produce the DC power.

This document applies to the fuel processor subsystem as shown in Figure 1. A test boundary can be defined for the FPS as shown in Figure 2. Input and output streams for the FPS can be defined.

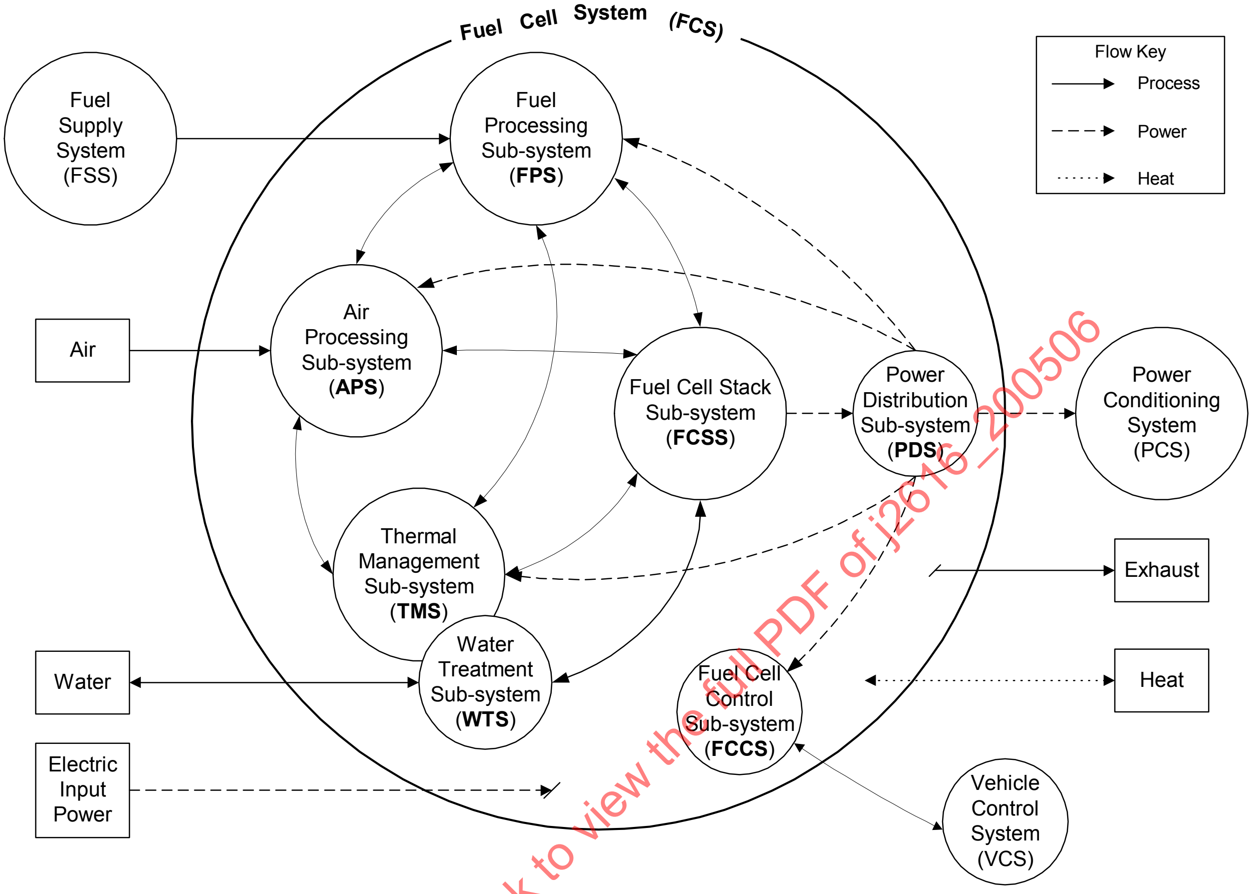

FIGURE 1—SCHEMATIC ILLUSTRATING A GENERIC FUEL CELL SYSTEM

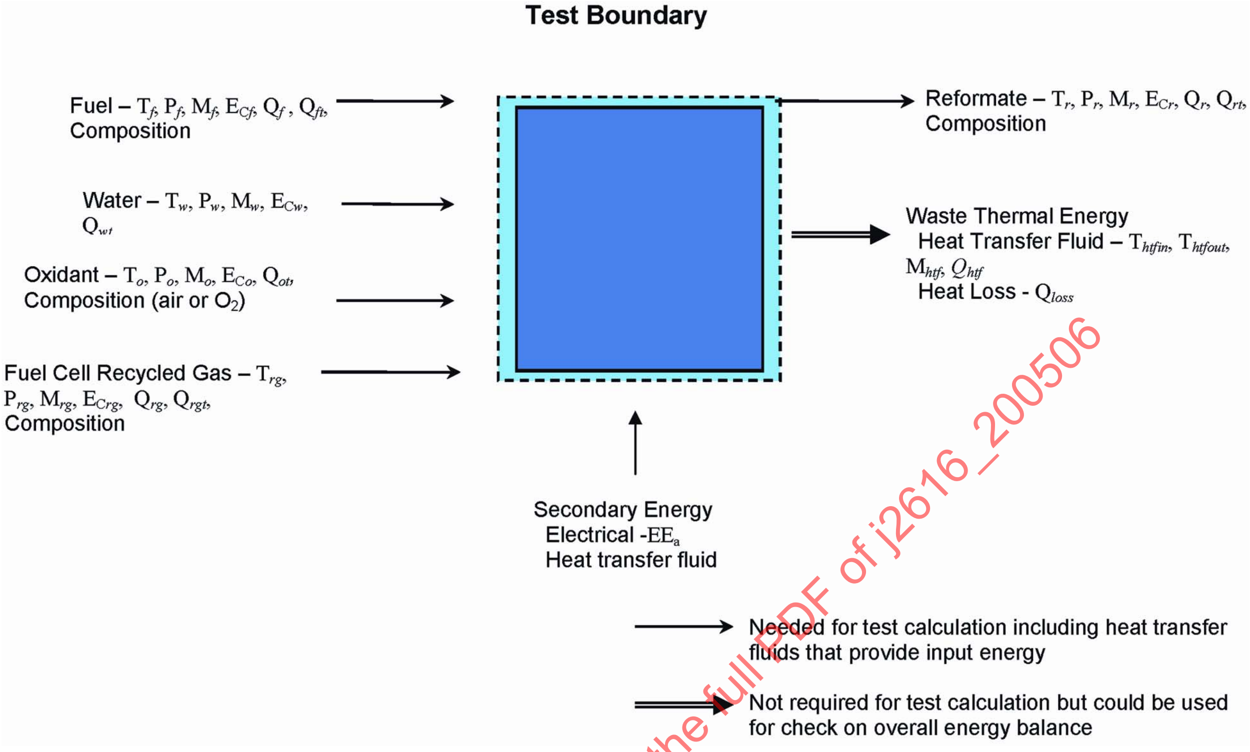

FIGURE 2—GENERIC FUEL PROCESSOR SUBSYSTEM TEST BOUNDARY

5.1.1 TEST BOUNDARY OF TEST SUBJECT

The test boundary as defined in Figure 2 serves to define the interfaces used for measurement of performance parameters. The test boundary and the pertinent material and energy streams that cross the test boundary are to be determined and agreed upon by the test parties during the preparations for the performance test.

Different fuel processor technologies will yield unique configurations. In every system, however, fuel and an oxidant will cross the boundary into the unit and reformate gas, and at least one heat and waste stream will cross the boundary out of the unit. Each unique fuel processor subsystem can have numerous additional streams into and out of the system. These streams of material and energy into and out of the subsystem need to be identified, quantified as to significant energy content, and measured if significant to evaluate the system performance. The specifics of the interfaces are left to the testing parties to define and should be documented in the test report.

The test subject includes the fuel processor subsystem. The test facility includes means to provide preheated fuel, water and air (if required) over a range of temperatures expected to satisfy the needs of the most commonly available fuel processor technologies. Therefore, pumps/compressor, pressure regulators, and preheater heat exchangers should be sized to cover a wide range of operating conditions. The test facility also has the means to meter the flow of fuel, steam and air to the required accuracy. Gas composition is measured with gas analysis equipment (e.g., gas chromatography, IR or UV) to the required accuracy. If the facility includes heat tracing to maintain the shell temperature of the reactor at its design temperature, this will be important for determining heat loss and evaluating overall efficiency. The testing parties must agree on the approach for incorporating the contribution of heat tracing to the fuel processor performance.

5.2 Specifications for Test Facility and Equipment

Specifications for the following items must be established for a test facility to allow evaluation of a FPS. Definition and agreement on the specifications are left to the testing parties. The list is intended to serve as a guide to define the requirements of the test facility and test equipment.

5.2.1 FUEL STORAGE AND SUPPLY SYSTEM

The fuel storage and supply system may consist of the following items.

- Fuel Tank - Capacity - sufficient to allow evaluation of the FPS over the expected load range
- Fuel Pump
- Fuel Supply Pressure Regulator
- Fuel Preheater Heat Exchangers

5.2.2 FACILITY VENTILATION

The test cell where the fuel processor subsystem is tested should be adequately ventilated to prevent the accumulation of combustible gases in the event of an undetected leak.

5.2.3 SAFETY AND ALARMS

The following safety and alarm systems should be installed.

- H_2S, H_2, CO detection safety system
- Automatic shutoff for fuel
- Thermal overload detection

5.2.4 SHUTDOWN AND MAINTENANCE PRECAUTIONS

The test stand should provide for appropriate and timely shutdown in the case of a hazardous situation through the use of gas/flame detection system for dangerous accumulations of combustible or toxic gases, such as hydrogen and carbon monoxide. Additionally, it is recommended that the test facility provide for a clearly marked manual emergency shutdown mechanism to be used at the discretion of the test operator.

5.2.5 OTHER APPLICABLE CODES

A hydrogen and nitrogen supply system for catalyst activation may consist of bottled gases with pressure regulators and flow meters. The bottled gas may be connected to the inlet of a preheater heat exchanger to provide preheat during catalyst conditioning.

5.2.6 FLUID SPECIFICATIONS

5.2.6.1 Fuel

5.2.6.1.1 Fuel Types

Liquid fuels types, such as gasoline, diesel or methanol as well as gaseous fuels such as compressed natural gas and liquefied propane gas may be used when testing fuel processor subsystems. Fuel heating values must be consistent throughout the test period.

5.2.6.1.2 Fuel Sampling

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

5.2.6.1.3 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. Liquid fuel heating value should be determined by calorimeter in accordance with ASTM D 4809-95, Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method). ASTM D 240 is not recommended because it results in lower precision.

For liquid fuels the lower and higher heating value and the specific gravity (ASTM D 1217 or D 1298) should be determined from the fuel analyses. The specific gravity of the fuel should be determined at three temperatures covering the range of temperatures measured.

Consistent liquid fuels are those with heating values, which vary less than 1% over the course of the performance test. Since liquid flows and heating values can be determined with high accuracy, the heat input from these fuels is usually determined by the direct measurement of fuel flow and laboratory analysis, or on-line chromatography-determined heating value. Consistent liquid fuel heat input may also be determined by calculation using the fuel constituents percentage multiplied by the constituent heating value. Homogenous liquid fuel flows are usually measured directly for fuel processor subsystems.

Fuel containing diluents may limit output or influence efficiency, for example oxygenates. If diluents such as oxygenates are present in the fuel the efficiency and performance calculations should be modified to accommodate the impact of these additives on system performance. Operation outside design parameters should be corrected in accordance procedures described below.

5.2.6.1.4 Fuel Specific Gravity

The liquid fuel specific gravity should be determined from each fuel sample taken. Each sample should have the specific gravity evaluated at three temperatures covering the range of temperatures measured during testing. The specific gravity at flowing temperatures should then be determined by interpolating between the measured values to the correct temperature. Specific gravity determinations should be completed in accordance with ASTM D1217 or D 1298.

5.2.6.2 Air/Oxidant

The definition of standard composition and reference conditions for air is provided in Section 3 Definitions. The standard composition should be adjusted for the actual humidity of the air at the time the test is conducted.

5.2.6.3 Coolant/Water

The coolant or water supply system may consist of the following items.

- Water Supply System – Reforming and Cooling
- Deionized Water Tank-Capacity - sufficient to allow evaluation of primary reformer over load range
- Water Pump
- Water Supply Pressure Regulator
- Steam Generator and Superheater Heat Exchangers

5.2.6.4 Anode/Cathode Off Gas

Some reformer designs require that some or all of the hydrogen-depleted anode gas (or hydrogen- and carbon monoxide-depleted anode gas in the case of solid oxide fuel cells) be recycled to the fuel processor for heat generation. Similarly, some or all of the oxygen-depleted cathode gas can be recycled to the fuel cell exhaust burner for combustion. Consequently, if a stand alone performance test is being performed on the fuel processor subsystem it becomes necessary to simulate the recycled gases. This can be accomplished several ways. First, tank farms of compressed gases and a mixing station can be set up at the test facility. The anode and cathode recycle gases can be simulated by feeding the appropriate mixture of gases to the fuel processor. The composition of the surrogate gases can be agreed to by the test parties. Second, the fuel processor reformate gas can be split—a portion could be recycled to the fuel processor and a portion vented. Inert gases such as nitrogen or carbon dioxide can be added to the used portion to create the right heating value and flame temperature. A good splitting technique would have to be devised to allow accurate flow and energy measurement. Third, a gas generator could be used to produced synthetic anode exhaust gas.

5.2.7 DATA ACQUISITION AND TIMING EQUIPMENT

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 to 3 seconds 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 minute. 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 should be calibrated for all measurements used in the calculation of results.

5.2.7.1 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 system.

Each measurement loop should be designed with the ability to be loop calibrated separately, if required. Each measurement loop should be designed to 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.

5.2.7.2 Use of Existing Test Facility Data Collection and Control System

The test procedure does not prohibit the use of the test facility's measurement and control system for testing. However, this system should meet the requirements of this section. Some test facility systems do not allow the instrument signal prior to conditioning to be displayed or stored. The signal should 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 should be low enough so that all data signals sent to the distributed control system during the test are reported and stored.

5.2.8 TEST INSTRUMENTATION REQUIREMENTS

The following devices and instruments are typically used to measure the performance of a fuel processor subsystem:

a. Fuel composition analyzers (gas chromatographs)
b. Fuel, air/oxidant, water, reformate gas and off gas flow

Numerous methods are employed in industry to determine the flow rate of solid, liquid, or gaseous streams. ASME PTC 19.5 is one such reference for flow measurement. References such as PTC 19.5 include information on the design, construction, location, and installation of flow meters, the connecting piping, and computations of flow rates. The measurement of fluid flow into or out of the fuel processor is required to be within accuracy consistent with the desired performance calculation uncertainty. The user is referred to these documents for guidance in defining the appropriate measurement device. Only special considerations associated with fuel processor subsystem testing are discussed here.

Where a fuel return system from the FPS is used, both supply and return flows should be measured by calibrated meters. Fuel flows to the fuel processor subsystem must be stable throughout the test.

Leakage of fluids, which may affect test results, should be eliminated or measured. Leakage or bypassing of fluids after the point of measurement should be measured and accounted for in the calculation of liquid fuel mass flow.

Fluid temperatures should be measured as close to the fuel processor as practical. All temperature measuring instruments and wells should be constructed, installed, and the instruments calibrated and operated in accordance with accepted standards such as ASME PTC 19.3.

Where temperature measurements are required as part of the flow measurement the temperature measuring devices should be installed so that adverse effects of radiation and/or conduction will be minimal. The temperature sensing element and/or well should be located such that it is subjected to the velocity of the measured fluid and not in a dead fluid pocket.

c. Gas and fluid pressure sensors (Ref. Pressure Measurement ASME PTC 19.2)
d. Temperature sensors
e. Electrical output
f. Voltage and current transducers
g. Reformate gas composition, recycled anode gas composition, or simulated recycled anode gas composition - gas analysis equipment (e.g., gas chromatograph)—H_2, CO, CO_2, CH_4, H_2S, N_2, HC, NH_3. Grab samples for GC analysis and continuous gas analysis monitors can be used.
h. Data Periods
t = Time, in hours, of the test period.
i. General
T_{amb} = Ambient Temperature at the test site, K
$ELEV_{site}$ = Test site elevation, meters
P_{amb} = Barometric Pressure at the test site, kPa (barometer)
RH_{amb} = Relative Humidity at the test site, percent R.H. (hygrometer)

5.2.9 Test Equipment Calibration

All test equipment and related instrumentation should maintain a high level calibration to ensure that all testing is performed accurately. This calibration should be conducted in accordance with ASME PTC 19.1 and NIST Technical Note 1297. The design and calibration of the test equipment should allow for control of the test parameters in accordance with ASME PTC 19.1 and NIST Technical Note 1297. To ensure adequate accuracy in the instrumentation an uncertainty analysis should be performed on critical measurements and their impact on reported performance results.

5.2.10 Pretest Records

ASME PTC-50 suggests a list of pretest records. At a minimum the following should be documented regarding the test article.

- General physical conditions (e.g., serial number, photos and drawings)
- Nominal (pre-test) performance data
- Operating limitations supplied by the manufacturer
- Temporarily non-functional components or sub-systems, reason for lack of function, and anticipated impact on test results.

5.3 Inspection of Test Subject and Connections to Facilities and Equipment

5.3.1 Inspection of Test Subject

Upon receipt of the test subject at the test facility a receipt inspection of test subject should be performed to ensure no damage incurred during transport. The test subject should be inspected to ensure that it is fabricated according to required codes. Finally, fabrication documentation such as Pressure Vessel Certification provided with test subject such as ASME or SAE pressure code stamp and certifications should accompany shipment of the test subject.

5.3.2 LEAK DETECTION AND GAS PURGING

All test equipment and the fuel processor subsystem should be pressure tested prior to the test with an inert gas such as nitrogen or preferably helium for areas of increased risk (high pressure, near ignition sources). This pressure test should follow generally accepted procedures such as described in ASME Section V Article 10 Pressure Vessel Code Leak Check Procedures. The procedure and parameters for the leak check should be agreed to by the test parties.

Subsequently all lines containing combustible gases are to be purged with an inert gas before and after all testing, and prior to any maintenance work performed on these lines.

5.3.3 ELECTRICAL CONNECTIONS

It is recommended that electrical equipment and connections are to be designed in accordance with SAE J2578. It is also recommended that all test equipment is to be electrically grounded and bonded.

5.3.4 FUNCTIONAL CHECK

The complete test system should be determined to be functionally sound prior to the test. This determination requires a test of the control system, data acquisition system and test safety equipment. Results of this test should be included in the test report. The responsibility for this testing should be determined by the testing parties. The test components that comprise the fuel processor subsystem may be addressed separately by separate parties if documentation of each test component is provided in the test report.

5.3.5 CONNECTIONS BETWEEN FACILITY AND TEST SUBJECT

Physical connections between the test facility and test subject should be checked prior to the start of the test. A pressure test of piping connections should be performed to ensure no leaks are present (See Leak Detection and Gas Purging above). Mechanical connections such as support brackets should be reviewed to ensure thermal expansion will not introduce undue mechanical stresses in the test subject or test facility. Electrical connections should be reviewed for proper grounds and proper shielding to avoid electrical interference of signals (e.g., 60 Hz noise).

5.4 Pretreatment Procedures

5.4.1 AMBIENT TEMPERATURE AND PRESSURE

Reference conditions for ambient temperature and pressure should be 15 °C (288.15 K) and 101 325 Pa (1 atmosphere). Test results from tests run at conditions other than those indicated as standard should be converted to account for this difference.

5.4.2 EQUIPMENT TEMPERATURE

The fuel processor subsystem should be at thermal equilibrium prior to the start of testing. This equilibrium should be determined according to the test intent. Examples include testing at ambient conditions or starting from extremely cold temperatures. An exception to this requirement is for tests of hot restart time, during which the fuel processor subsystem temperatures are transient and system dependent. The fuel processor subsystem should be conditioned in accordance with manufacturer requirements. This conditioning should be described in the test report. Such conditioning may include special treatment of the catalysts in the reactors in the fuel processor subsystem.

5.4.3 FPS CONDITIONING

The FPS should be conditioned in accordance with the manufacturer's requirements. For example, some catalysts must be activated prior to subjecting them to the process gas. If necessary, provision should be made in the test facility to enable these catalysts to be properly conditioned. The conditioning should be described in the test report.

5.4.4 PRELIMINARY OPERATION AND ADJUSTMENT

The test subject delivered for the test is assumed to be configured and tuned for nominal operation. This may require testing and operation prior to application of this recommended practice.

Once testing has commenced, no modification should be made to the test subject. If modifications are required in order to obtain complete test results, the testing should be restarted following the modifications.

5.5 Shutdown

The fuel processor supplier should specify a shutdown procedure for the fuel processor subsystem after a performance test is completed. For example, pyrophoric catalysts should be inerted with nitrogen to avoid overheating when exposed to air. The test parties should agree on the performance measurements to be made during the shutdown process. Some considerations include:

- Time for shutdown
- Parasitic power to shutdown
- Durability
- Pyrophoric catalysts must be inerted with nitrogen
- Emissions impacts-quantify post shutdown emissions
- Other requirements for specific system

5.6 Test Plan

5.6.1 GENERAL

The development of an overall test plan, including detailed test procedures, is recommended prior to the start of the test. The plan should focus especially on the following issues:

a. Extent of the system to be tested, i.e., test boundary
b. Reference conditions
c. Data to be recorded, and method of recording and archiving data
d. Personnel to conduct the test, and the responsibilities of each individual in certifying that the test is conducted in accordance with the recommended practice
e. Location of test: 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 FPS is operational, with appropriate time to condition the fuel processor in accordance with the supplier's requirements.
g. Test goals
h. Procedures for recording the test data and observations, including sample frequency

i. Type, number, and systematic uncertainty of all instruments to be used to establish test conditions and test results and how they should be installed
j. Instrument calibration schedule or procedures.
k. Designation of the laboratory and any other facilities required for determining pertinent fuel characteristics
l. Requisite facilities for maintaining constancy of load during test, if applicable
m. Number of identical tests to be conducted to assure statistically significant accuracy and repeatability
n. Duration of the test segment
o. Allowable and unallowable modifications to the FPS or operating conditions during a test period.
p. Acceptance of test when disruptions occur
q. Acceptance criteria for test completion
r. Failure mode analysis to ensure safe operation during the test
s. List of agreements between test parties as identified throughout this recommended practice

The test plan should also 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, should be defined and identified along with the expected sequence for testing them.

5.6.2 TEST GOALS

The recommended practice recognizes that different types of conditions might require different types of test goals. The following suggests three different test goals that could be useful for a performance test.

a. The test can be run at a specified corrected net reformate production (e.g., equivalently hydrogen production for PEM fuel cells or hydrogen and carbon monoxide for solid oxide fuel cells) that is near the design value of interest. Examples of this test would be an acceptance test of a fuel processor subsystem where cold gas efficiency is guaranteed at a specific load, or a partial load, on a specific fuel composition, but the available fuel composition differs from the design value. Other tests may include steady-state test conditions—full load or idle, start-up transient test condition—cold to full load, or load change response test condition—e.g., 10-90% load change.
b. The test can be run at a specified reformate production regardless of ambient or other external conditions. An example of this test goal would be a test on a fuel processor subsystem to compare the reformate gas production rate and fuel processor cold gas efficiency to guaranteed values over a range of ambient temperatures.
c. The test can be run at a specified maximum reformate production. The test should 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 reformate production excursion that would be useful for a peak power demand. This overload reformate production operation might legitimately be accomplished with an incomplete thermal transient in a system.

5.6.3 SCHEDULE OF TEST ACTIVITIES

A test schedule should 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.

5.7 Training of Test Personnel

All test personnel should be well trained on the use of the test station, test facility equipment, fuel processor subsystem operations, the safe handling of hazardous fluids and all other applicable safety procedures.

5.8 Agreements

The parties to the test should agree in writing on the object, scope, and plan for the test. The parties normally include the purchaser/customer, the vendor or fuel processor sub-system supplier, and possibly an independent contractor, for example, a testing agency.

6. Test Description

6.1 Specifications of Test Variables and Measured Performance

The test procedure addresses three separate tests to characterize the performance of the fuel processor—a steady state test at a fixed load, a start-up transient test, and a load response test. Separate test procedures are described for each of the three tests. First general requirements are described.

Specified Conditions. Every effort should be made to run the test under the agreed specified conditions (e.g., output, pressures, and temperatures) as possible, in order to limit the application of corrections.

Stabilization. Before starting a steady state test, the fuel processor should 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 variation. Before starting a cold-start test the parties should agree on a suitable soak time to ensure the fuel processor is at the desired ambient temperature.

Maximum Permissible Variations in Operating Test Conditions. Each observation of an operating condition during a test run should not vary from the agreed upon value by more than the agreed upon limits. If operating conditions vary during any test run beyond the agreed upon limits, and if such variations are not covered by an agreement, the results of the test run should be discarded.

Duration of Test Run and Frequency of Readings. The duration of a test run and the frequency of readings within that test run will be determined by the type of fuel processor being tested, the load, and the fluctuations in the readings. A sufficient number of readings should be spaced in time to show the range of fluctuations, to provide a reliable average for the test run and to meet the uncertainty requirements as agreed to by the testing parties. Some suggested maximum permissible variations in test conditions are available from the ASME PTC-50.

Recommended performance parameters and measurements for the fuel processor subsystem are summarized in Table 2.

TABLE 2—PERFORMANCE PARAMETERS AND MEASUREMENTS

Category	Examples	Measurements
Hydrogen Production	Peak Rating (hydrogen production) Maximum Continuous rating Maximum Design Efficiency rating Water Balance Rating Level Idle Rating Maximum Turndown	Reformate flow rate Hydrogen concentration in reformate
Input Power	Operational Auxiliary Power Startup Energy Shutdown Energy Thermal Input	DC Current DC Voltage
Efficiency	Thermal Efficiency Fuel Processor Subsystem Efficiency Cold Gas Efficiency Carbon Conversion Efficiency	Fuel Flow Into Fuel Processor Fuel LHV Reformate gas flow Reformate gas composition – CO, CO_2, N_2, H_2, H_2O, CH_4, and HCs, NH_3
Response	Cold Start Hot Start Normal Stop Emergency Stop Step/Ramp Transient Cycle Transient	Elapsed Time Power Deficit/Surplus over cycle Voltage Stability on Transient
Physical	Mass Volume	System Mass System Envelope System Displaced Volume
Environmental	Temperature Range Attitude (Tilt) Altitude (Pressure)	Min Operating Temperature Max Operating Temperature Maximum Operating Tilt Maximum Operating Altitude
Operational	Water Sufficiency Auxiliary Power Requirements (Voltage, Current) Steam-to-carbon ratio Fuel equivalence ratio O_2-to-carbon ratio Pressure drop	Water Surplus / Deficit Purity Measurements Auxiliary Power Use
Integration	Specific Power Power Density	Watts equivalent of hydrogen Mass, Volume

6.2 Test Precautions and Abnormalities

Since hydrogen and carbon monoxide are generated in a fuel processor subsystem precautions must be taken to handle and dispose of the product gas safely. During the reforming process hydrogen sulfide is also generated if the fuel contains sulfur. In sufficiently-high concentrations, hydrogen sulfide is a toxic gas that requires monitoring. Test areas should be vented to maintain the concentration below safe limits. During transient operation or atypical operation of the fuel processor it is also possible that hydrocarbon fractions can be generated that may be hazardous. Again, care must be taken to properly vent the test subject and test area occupied by test personnel. SAE J2578 addresses some of these safety issues.

Some catalysts are pyrophoric (i.e., react exothermically when exposed to air). Care must be taken when flushing the fuel processor after testing to ensure that the catalysts do not overheat which may damage the catalyst or equipment.

6.3 Test Procedure

6.3.1 STEADY STATE TESTS

The objective of the Steady State Tests is to determine fuel processor performance at critical design points, such as peak reformate gas production, maximum continuous rating or maximum design efficiency or idle. However, the test procedure may be used to evaluate the performance of the fuel processor at other design conditions. Measurement of the fuel input and fuel processor reformate production are measured simultaneously during the test period. The procedures for collecting and calculating this information are provided below.

During a performance test, fuel may be fed to the reformer inlet, an anode exhaust gas burner and, if applicable, a start-up burner or an auxiliary fuel burner (e.g., as in the case of steam reforming). The total fuel input is the sum of all end users.

The following test procedure is recommended for evaluating performance at steady state conditions. It is modeled after the steady state test procedure in ASME PTC-50. The test duration and sample times are suggested in this document, but test parties should agree on appropriate test parameters. Other steady state test procedures can be developed as agreed upon by the test parties.

a. Each test should be performed for duration of 60 minutes following heat-up and stabilization.
b. Confirm that the fuel flow rate to the main fuel supply as measured by the flow controller is zero under a no flow condition. If it is not at zero, contact appropriate individual to have instrument zeroed. Confirm the instrument is calibrated.
c. Start-up the fuel processor according to manufacturer's recommendation.
d. Allow processor to operate for two hours at test condition to allow the system to come to thermal equilibrium.
e. If the start-up burner is operating, confirm that the flow meter is operational and calibrated.
f. If the anode exhaust gas burner is operating, confirm that the flow meter is operational and calibrated.
g. At the beginning of the test period and after each 6-minute interval, record the main fuel flow to fuel preheater heat exchangers as indicated by a flow controller.
h. If the start-up burner is operating, record the fuel flow at the beginning of the test period and after each 6-minute interval as indicated by a flow controller.
i. If the anode exhaust burner is operating, record the fuel flow at the beginning of the test period and after each 6-minute interval as indicated by Flow Controller.
j. Measure motor amps and volts on fuel pump at the beginning of the test period and after each 6-minute interval. Record the values.
k. Measure the motor amps and volts on the water pump at the beginning of the test period and after each 6-minute interval. Record the values.
l. If additional secondary thermal sources are used, record the flow and temperature of the heat source (gas or liquid) or the watts associated with electrical heating at the beginning of the test period and after each 6-minute interval.
m. Measure the oxidant flow.
n. Calculate the oxidant flow at the beginning of the test and after each 6-minute interval.
o. Measure the oxidant temperature at the inlet to the fuel processor. Calculate the sensible heat of the oxidant.
p. Measure the reformate gas total flow.
q. If a flow orifice is used, confirm that the operating conditions at the orifice are above the gas dew point temperature.

r. Record the flow measurements on the data sheet at the beginning of the test period and after each 6-minute interval.
s. Record the temperature of the reformate gas flow at the test boundary.
t. The hydrogen and carbon monoxide concentrations (dry gas) are measured in a gas chromatograph. The frequency of hydrogen and carbon monoxide measurements are limited to the response time of the gas chromatograph. Typically, 20-minute measurements are possible. Record the gas composition at the beginning, middle and end of the test period.
u. The total wet gas reformate flow and composition should be measured during the test period.
v. If reformate gas (hydrogen-depleted or hydrogen-rich) is recycled to the fuel processor during the test period, measure the return flow, temperature and composition of reformate gas.
w. Confirm that the operating conditions at the orifice are above the gas dew point temperature and pressure.
x. Record the pressure and temperature measurements on the data sheet at the beginning of the test period and after each 6-minute interval. Record the temperature of the reformate gas returning across the test boundary.
y. For each 6-minute interval, add together the flows and record this value on the data sheet.
z. At the end of the test period, calculate the average flow rates for each end user. Record the average flow for each end user. Record the average value for the total flow during the test.
aa. At the end of the test period, calculate the performance parameters.

6.3.2 START-UP TRANSIENT TEST

The objective of the Start-up Transient Test is to determine the time required for the fuel processor to start up from a cold condition and generate hydrogen at the equivalent reformate flow rate for the agreed upon Fuel Cell System load. The hydrogen analyzer should have a suitable response time (<10 seconds). The procedures for collecting and calculating this information are provided below.

a. The involved parties reach agreement on reformate (H_2 or H_2 and CO) flow.
b. Confirm all fuel inputs and thermal inputs at zero.
c. Confirm all equipment (pumps, motors, etc.) is off.
d. Confirm reformate gas flow measurement device is operational.
e. Determine the lag in the hydrogen analyzer sampling system.
f. Establish flow of calibration gas through the analyzer sampling and conditioning system.
g. At time zero, switch from calibration gas to cylinder of nitrogen adjusted to same regulator supply pressure.
h. Time response of analyzer and sampling system to point at which hydrogen reading falls to 90% of initial value.
i. Record response time.
j. Follow manufacturer’s recommended procedure for starting up the system.
k. At time zero, start timer.
l. Log reformate flow and reformate (H_2 or H_2 and CO) concentration as a function of time in a data acquisition system.
m. Determine time corresponding to hydrogen flow reaching agreed upon load value.

6.3.3 TRANSIENT RESPONSE TEST

The objective of the test procedure is to determine the response time of the fuel processor to a change between any combinations of steady state conditions. The anticipated response time of the fuel processor to a step change input is less than 10 seconds (e.g., 10% to 90% load change or other load change as agreed to by the testing parties). This test determines the response of the fuel processor to an increase or decrease in demand.

The fuel processor responds to a demand signal from the fuel cell as electrical load on the fuel cell increases. The fuel processor responds to this demand signal by changing a primary control parameter. For the test, absent the presence of the fuel cell, the fuel processor response is determined by introducing a step change in primary control element.

a. The fuel processor is operated at the initial load condition according to manufacturer's recommended operating procedure.
b. At time zero, a step change demand signal representing an increase in load corresponding to final load condition is sent to the primary control device of the fuel processor control system.
c. Stop watch or timer used to time response triggered electrically from step change signal.
d. The reformate gas flow is monitored with a suitable flow measurement device and hydrogen analyzer.
e. The reformate gas flow is measured with a suitable flow measurement device. The flow orifice includes a calibrated static pressure transmitter, calibrated differential pressure transmitter and a temperature sensor.
f. The hydrogen analyzer is calibrated before and after the test.
g. The reformate gas flow, along with the hydrogen and CO concentrations are logged to an electronic data acquisition system that acquires data at no longer than 1 second intervals per scan.
h. The hydrogen flow is calculated from the reformate gas flow and hydrogen concentration. The test is continued until the hydrogen flow reaches the target load equivalent value.
i. The actual hydrogen flow is continuously compared to the target.
j. When the actual flow equals the target the time is recorded as the preliminary response time.
k. Post calibration of hydrogen analyzer provides a correction factor to the hydrogen flow calculation. (NOTE—It is assumed that the flow measurement device remains within calibration over the test period.)
l. The correction factor is applied to the hydrogen flow data and the final response time is determined.

7. Data Acquisition, Analysis and Reporting

7.1 Data Management

ASME PTC-50 (Reference 37) prescribes guidelines for the management of data collected before, during and after a performance test. An abbreviated discussion of those guidelines is provided here. The user is referred to ASME PTC-50 for a more comprehensive discussion of data management issues.

7.1.1 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.

7.1.2 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.

7.1.3 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.

7.1.4 TEST RECORDS AND RESULTS

Test records include electronically captured, manually recorded data, test observations, and test logs. All data and observations collected during the performance test should be retained and either reproduced or be made readily available to all the parties involved in the test.

In all cases, the test results should be reported as calculated from the test observations with corrections for instrument calibrations applied, and as corrected for deviations of the operating conditions from the specified conditions.

7.1.5 UNCERTAINTY ANALYSIS

Since no measurement is error-free, the uncertainty of each test result should be evaluated by the parties. All uncertainty values that have been determined and agreed upon by the parties to a test should be included in the report. During test preparation the uncertainty limits for each of the measured parameters should be defined based upon the configuration. The limits should be determined by the pre-test uncertainty analysis and agreed to by the parties. The pre-test 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 recommended. It will make use of empirical data to determine random measurement errors and test observations to establish whether or not the required degree of uncertainty has been achieved.

ASME PTC 19.1 (Reference 32) and NIST Technical Note 1297 (Reference 39) provide procedures for determining the uncertainty associated with calculated results. For a detailed discussion of uncertainty analysis the user is referred to those two reference documents.

The application of uncertainty analysis to a test procedure can reduce risk of making an erroneous decision when evaluating the results. Test uncertainty and contract tolerance are not interchangeable terms. This recommended practice does not address contract tolerance, which is a commercial term.

7.2 Formulas and Calculations

This section gives guidance on the computation of results including the following:

- Determination of fuel processor efficiency, cold gas efficiency and thermal efficiency at specified operating conditions is the primary objective of this test.
- 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 standard.
- For a test involving several runs, it is suggested that plots of cold gas efficiency 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 rerun.

7.2.1 CALCULATION OF INPUT ENERGY

Inputs for the purpose of this document refer to inputs crossing the test boundary. The following inputs are identified:

a. Fuel
  - Reforming
  - Auxiliary burner
    - Startup
    - Steam reforming
    - Recycled fuel cell off gas (anode gas or cathode gas)

b. Oxidant (air)
c. Water
d. Secondary energy input/output such as coolant/heater fluid
e. Auxiliary electrical energy into fuel processor subsystems
f. Anode gas exhaust

Any other type of substance or energy which represents energy input to the fuel processor subsystem should 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 processor subsystem. The reference conditions for fuel, oxidant (air), and water inputs that are assumed for this document are 15°C (288.15K) and 1 atmosphere.

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 = Q_{ft}
d. Secondary Thermal Energy Input = Q_{st}
e. Oxidant Pressure Energy Input = E_{Co}
f. Oxidant Thermal Energy Input = Q_{ot}
g. Water Pressure Energy Input = E_{Cw}
h. Water Thermal Energy Input = Q_{wt}
i. Auxiliary Electrical Input = EE_a
j. Recycled Gas From Fuel Cell Chemical Energy = Q_{rg}
k. Recycled Gas From Fuel Cell Thermal Energy = Q_{rgt}

Total Energy Into the system for calculation of input energy is expressed by:

QI = Total Energy Into the system for calculation of input energy and electrical conversion efficiency.

$$QI = Q_f + Q_{ft} + Q_{wt} + Q_{ot} + Q_{st} + E_{Co} + E_{Cf} + E_{Cw} + EE_a + Q_{rg} + Q_{rgt} \qquad \text{(Eq. 2)}$$

The ideal auxiliary input energy is defined as

$$E_{aux} = Q_{ft} + Q_{wt} + Q_{ot} + Q_{st} + E_{Co} + E_{Cf} + E_{Cw} + EE_a \qquad \text{(Eq. 3)}$$

The basis for the following equations is a one hour test period where energy into the system is totaled over the test period. An alternative basis could be used in which inputs are averaged over the test period. Totaling inputs is usually easier and more accurate compared to averaging flows and compositions over a test period.

7.2.1.1 Fuel

Due to the large number of potential variables in common fuels, 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 the heating value of the fuel and the sensible heat 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 processor subsystems, 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.

For a pressurized system, the power to compress a gaseous fuel (e.g., propane or natural gas) is not negligible and thus must be taken into account. Alternatively, 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 fuel pressurization is provided by the external supply system, the power required for pressurization should be charged to the fuel processor subsystem. Thus, for computational purposes, it should be assumed that all fuel is provided to the system boundary at local ambient barometric pressure and should be accounted for by a reduction in fuel processor efficiency.

If a fuel pump is used with the fuel processor subsystem, it should be included within the test boundary and the power to run the fuel pump should be supplied from either inside the test boundary or should be accounted for by a reduction in net electrical energy out. If the liquid fuel is pressurized outside the system then the pressure energy of the fuel should be calculated. The calculation should account for inefficiency in the pump/motor combination.

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.

Sensible heat of the fuel should account for the fuel being supplied at a temperature above the reference temperature of 15 °C. If the fuel at 288.15 K is liquid but is supplied to the system as a vapor at a higher temperature, the sensible heat should be taken to include energy required to heat the liquid fuel to saturation temperature, to vaporize the fuel and to heat the vapor to the fuel processor inlet temperature.

Fuel Chemical Energy Input = Q_f

Q_f is determined by measuring the total fuel flow to the fuel processor for the test period and multiplying by the average heating value of the fuel during the test period.

$$Q_f = M_f \bullet HHV_{avg} \quad \text{for calculations based on High Heating Value,} \qquad \text{(Eq. 4)}$$

or

$$Q_f = M_f \bullet LHV_{avg} \text{ for calculations based on Low Heating Value,} \qquad \text{(Eq. 5)}$$

Where:

M_f = the total fuel flow to the fuel processor during the test period in kg.
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,

Fuel Pressure Energy Input = E_{Cf}

For gaseous fuels:

$$E_{Cf} = M_f R T_{Ref} \ln \frac{\text{Absolute Fuel Inlet Pressure at Test Boundary in kPa}}{\text{Ambient Barometric Pressure in kPa}} \qquad \text{(Eq. 6)}$$

Where:

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

This is based on an ideal isothermal compression of the fuel at standard temperature and does not take into account the compression efficiency.

For liquid fuels:

$$E_{Cf} = M_f \bullet v_f \bullet (P_f - P_{amb}) \qquad \text{(Eq. 7)}$$

Where:

E_{Cf} =Total theoretical mechanical work imparted to the gasoline from an outside source, kJ
v_f = specific volume of gasoline, 1.40×10^{-3} m^3/kg
P_f = Fuel processor inlet pressure, kPa
P_{amb} = Absolute barometric pressure at elevation of test facility, kPa

Fuel Thermal Energy Input = Q_{ft}

Q_{ft} = The total fuel thermal 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.

The general expression for Q_{ft} assuming the fuel is fully vaporized at the test boundary is provided below.

$$Q_{ft} = M_f \bullet \left[C_{Pf,liq} \bullet \left(T_f - T_{Ref}\right)\right] + M_f \bullet \Delta H_{fvap} + M_f \bullet \left[C_{Pf,vap} \bullet \left(T_f - T_{bp}\right)\right] \qquad \text{(Eq. 8)}$$

Where:

M_f = the total fuel flow to the fuel processor during the test period in kg.
$C_{Pfp,liq}$ = Average specific heat at constant pressure of fuel delivered during the test period in (kJ/kg K), (typical value 0.490 cal/gm/°C)
$C_{Pfp,vap}$ = Average specific heat at constant pressure of fuel delivered during the test period in (kJ/kg K), (typical value 0.400 cal/gm/°C)
T_{bp} = Boiling point of liquid fuel, K
T_f = Average Fuel Temperature in degrees Kelvin at the test boundary.
T_{Ref} = Reference temperature 288.15 K
ΔH_{fvap} = Heat of vaporization of fuel kJ/kg (typical value for gasoline 340 kJ/kg)

In cases where the fuel is not vaporized the last two terms are zero. If the fuel is partially vaporized then the quality of the mixture must be considered in calculating the heat of vaporization contribution to the thermal energy.

7.2.1.2 Secondary Thermal Input

The secondary thermal energy input (Q_{st}) is determined as follows.

a. For closed loop secondary thermal inputs the total heat input is accounted for as:

Q_{st} = Total thermal energy input to the fuel processor during the test period.

Q_{st} should 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.

$$Q_{st} = M_{htf} \bullet \left[H_{htfin} - H_{htfout}\right] \qquad \text{(Eq. 9)}$$

Where:

M_{htf} = the mass of steam or heat transfer fluid into and out of the fuel processor from the source of secondary thermal energy during the test period, in kg.
H_{htfin} = The average enthalpy of the heat transfer fluid entering the fuel processor during the test period, in kJ/kg.
H_{htfout} = The average enthalpy of the heat transfer fluid exiting the fuel processor during the test period, in kJ/kg.

b. Or, for steam or liquid thermal inputs that do not exit the system boundary, the total heat input is accounted for as:

Q_{st} = Total thermal energy input to the fuel processor during the test period.

Q_{st} should 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 the reference temperature.

$$Q_{st} = M_{htf} \bullet \left[H_{htfin} - H_{htf,Ref} \right] \quad \text{(Eq. 10)}$$

Where:

M_{htf} = the mass of steam or heat transfer fluid into the fuel processor from the source of secondary thermal energy during the test period, in kg.
H_{htfin} = The average enthalpy of the steam or heat transfer fluid entering the fuel processor during the test period in kJ/kg.

c. Or for gaseous thermal inputs that do not exit the system boundary, the total heat input is accounted for as:

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

Q_{st} should 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 the reference conditions (e.g., enthalpy of dry air at 101.325 kPa and 288.15 K.

$$Q_{st} = M_{htf} \bullet \left[H_{htfin} - H_{htfin,Ref} \right] \quad \text{(Eq. 11)}$$

Where:

M_{htf} = the mass of air, or gaseous heat transfer fluid into the fuel cell from the source of secondary thermal energy during the test period, in kg.
H_{htfin} = The average enthalpy of the air or gaseous heat transfer fluid entering the fuel cell during the test period in kJ/kg.

d. Heat tracing used to maintain vessel temperature.

Addressed under Auxiliary Electrical Inputs.

7.2.1.3 Oxidant

Oxidant may or may not be supplied to the fuel processor subsystem to participate in the reforming of hydrocarbon fuels. The power to compress the air will be much greater than that to compress the fuel in the case of pressurized systems. Consequently, for computational purposes, it must be assumed that the oxidant (air) is supplied at reference temperature and pressure, and some method of accounting for the power associated with compressed air from an air supply system is needed. The local ambient barometric pressure is used as the reference pressure for determining power consumption and energy contribution to the air.

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 should be made to adjust performance to standard dry air.

If an oxidant (air or other) compressor or blower is used with the fuel processor subsystem, it should be included within the test boundary and the power to run the compressor should be supplied from either inside the test boundary or should be accounted for by a reduction in net electrical energy out.

If the oxidant is preheated the sensible heat of the oxidant should be calculated with respect to a reference temperature of 15 °C.

Oxidant Pressure Energy Input = E_{Co}

$$E_{Co} = M_o R T_{Ref} \ln \frac{\text{Absolute Oxidant (Air) Inlet Pressure at Test Boundary in kPa}}{\text{Ambient Barometric Pressure in kPa}} \qquad \text{(Eq. 12)}$$

Where:

E_{Co} = ideal pressure energy content of the oxidant, in kJ
M_o = mass of oxidant into the system during the test period, kg
$R = R_u / MW_o$
R_u = 8.314 kJ / kmol K (Universal Gas Constant)
MW_o = molecular weight of the oxidant (28.9644 kg / kmol for standard dry air, neglects moisture in the air)
T_{Ref} = Reference temperature 288.15 K

If an oxidant (air or other) compressor or blower is used with the fuel processor subsystem, it should be included within the test boundary and the power to run the compressor should be supplied from either inside the test boundary or should be accounted for by a reduction in net electrical energy out. If correcting for the efficiency of the compressor and motor, it should be recognized that compressor efficiency that would be used to calculate the auxiliary power requirement associated with the portion of air that is supplied to the fuel processor will vary as a function of load. A compressor/expander performance map would be required.

Oxidant Thermal Energy Input = Q_{ot}

Or for gaseous thermal inputs that do not exit the system boundary, the total heat input is accounted for as:

Q_{ot} = Total thermal energy input to the fuel cell during the test period.

Q_{ot} should 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.

$$Q_{ot} = M_o \cdot \left[H_o - H_{o,Ref}\right] \qquad \text{(Eq. 13)}$$

Where:

M_o = the mass of air, or gaseous heat transfer fluid into the fuel cell from the source of secondary thermal energy during the test period, in kg.
H_o = the average enthalpy of the air or gaseous heat transfer fluid entering the fuel cell during the test period in kJ/kg.

The total thermal energy in equation 13 can be determined by evaluating the following integral over the appropriate temperature range.

$$Q_{ot} = M_o \bullet \int \left(28.94 + 0.4147T + 0.3191T^2 - 1.965T^3\right) dT \qquad \text{(Eq. 14)}$$

Where: the integral is evaluated over the temperature range T_{Ref} to T_o

T_o = Oxidant temperature, °C
$C_{P,Air}$ = Specific heat of air, J/(g mol)(°C)
T_{Ref} = 15 °C

7.2.1.4 Water

Water thermal energy (or enthalpy) is provided by steam tables at pressure and temperature of water or steam at system inlet conditions.

$$Q_{wt} = M_w \bullet \left[H_{win} - H_{w,Ref}\right] \quad \text{(Eq. 15)}$$

Where:

M_w = The mass of water into fuel processor during the test period, in kg.
H_{win} = The average enthalpy of the water/steam entering the fuel processor at the test boundary, in kJ/kg (Obtained from steam tables with T_w and P_w defined below.)
T_w = The average temperature of the water/steam entering the fuel processor at the test boundary in Kelvin (may be used to determine the enthalpy of the water from steam tables).
P_w = The average pressure of the water/steam entering the fuel processor at the test boundary, in kPa (absolute) (may be used to determine the enthalpy of the water from steam tables).

The ideal water pressure energy E_{Cw} is determined by the pressure rise of the water across the water pump for that portion of the water that is fed to the fuel processor.

$$E_{Cw} = M_w \bullet v_w \bullet (P_w - P_{amb}) \quad \text{(Eq. 16)}$$

Where:

E_{Cw} = Total theoretical mechanical work imparted to the water from an outside source, kJ
v_w = specific volume of water, in m^3/kg
P_w = average pressure of water entering fuel processor in kPa

7.2.1.5 Auxiliary Electrical Input (Heat Tracing)

EE_a = Auxiliary Electrical Input

EE_a = Total sum of all electrical input 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. This should include electrical duty associated with heat tracing, if required, to maintain vessel temperature.

$$EE_a = \Sigma Kwh_i (kWh) \quad \text{(Eq. 17)}$$

Where:

Kwh_i = Kilowatt-Hours into the system during the test period (measured)

7.2.1.6 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, in kJ. This is analogous to mechanical cogeneration.

For the Fuel Processor test it is assumed that there is no shaft work performed by the system. Turboexpanders are assumed to be outside the fuel processor test boundary.

7.2.2 COMPUTATION OF OUTPUTS

Output energy crossing the test boundary might include:

- Reformate Chemical Energy Output = Q_r
- Reformate Pressure Energy Output = E_{Cr}
- Reformate Thermal Energy (Enthalpy) Output = Q_{rt}
- Secondary Thermal Energy (Enthalpy) Output = Q_{stout}

Reformate Gas

$$Q_r = M_r \bullet \left(x_{H2} \bullet LHV_{H2} + x_{CO} \bullet LHV_{CO} + x_{CH4} \bullet LHV_{CH4}\right) \qquad \text{(Eq. 18)}$$

Where:

HHV_{ri} = Reformate gas component i high heating value at the test boundary in kJ/kg for calculations based on higher heating value,
LHV_{ri} = Reformate gas component i lower heating value at the test boundary in kJ/kg for calculations based on lower heating value,
M_r = Total reformate flow exiting the fuel processor subsystem during the test or data period in kg.
m_r = Reformate gas flow rate exiting the test boundary in kg/s during the data period (may be used to calculate the total reformate gas flow by integrating the flow rate over the data period).
MW_r = Molecular weight of the reformate gas based on gas analysis in kg/kmol
x_{H2O} = Moisture content of the reformate gas, at the test boundary, mass fraction.

$$E_{Cr} = M_r R\, T_{Ref} \ln \frac{\text{Absolute Reformate Gas Pressure at Test Boundary Outlet in kPa}}{\text{Ambient Barometric Pressure in kPa}} \qquad \text{(Eq. 19)}$$

Where:

$R = R_u / MW_o$
R_u = 8.314 kJ / kmol K (Universal Gas Constant)
T_{Ref} = Reference temperature 288.15 K
P_r = Reformate gas pressure at the test boundary in kPa (absolute).
T_r = Reformate gas temperature at the test boundary in K.

$$Q_{rt} = M_{ri} * \int \left(28.94 + 0.4147T + 0.3191T^2 - 1.965T^3\right) dT \qquad \text{(Eq. 20)}$$

Where: the integral is evaluated for each component i in the reformate gas over the temperature range from T_{Ref} to T_r

The following terms do not contribute to the useful energy generated by the fuel processor and therefore, are not included in the efficiency calculation but need to be included in the energy balance calculation:

- Oxidant Pressure Energy Output = EC_{oout}
- Oxidant Thermal Energy (Enthalpy) Output = $Q_{othermal\ out}$
- Water Pressure Energy Output = EC_{wout}
- Water Thermal Energy (Enthalpy) Output = $Q_{wthermalout}$
- Auxiliary Electrical Output = EE_{aout}

7.2.3 COMPUTATION OF EFFICIENCIES AND PERFORMANCE PARAMETERS

7.2.3.1 Computation of Efficiencies

Thermal efficiency 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. A number of definitions are used to define fuel processor subsystem thermal efficiency.

For PEMFC the thermal efficiency can be based on the total hydrogen produced divided by total energy input. The carbon monoxide and methane terms are set to zero in the equation for Q_r.

$$\eta_{Thermal} = \frac{Q_{r,produced} \bullet 100}{Q_f + Q_{ft} + E_{Cf} + Q_{wt} + E_{Cw} + Q_{ot} + E_{Co} + Q_{st} + Q_{rg} + Q_{rgt} + E_{Crg} + EE_a} \qquad \text{(Eq. 21)}$$

In the case of SOFC the lower heating value of hydrogen plus carbon monoxide is used.

The efficiency can also be based on the hydrogen (chemical energy) used in the fuel cell. This definition is also consistent with the overall fuel cell system efficiency as defined in J2615. For reference the overall fuel cell system efficiency is defined as

$$\eta_{FCS} = \eta_{FPS} \bullet \eta_{FCSS} \bullet \eta_{PC} \bullet \eta_{el./mech} \qquad \text{(Eq. 22)}$$

Specifically, the fuel processor subsystem efficiency is defined as

$$\eta_{FPS} = \frac{\left(Q_{r,consumedbyfuelcell} + Q_{r,ventedfromfuelcell}\right) \bullet 100}{Q_f} \qquad \text{(Eq. 23)}$$

When the test is run the fuel processor will operate at a certain fuel conversion and gas quality. Based on the fuel inlet feed flow this yields a calculated hydrogen production rate. The above fuel processor subsystem efficiency calculation is based on a hydrogen consumption rate, which in turn allows the calculation of the equivalent hydrogen utilization or stoichiometry in the fuel cell. If the utilization is within the acceptable level for the fuel cell, then the calculated fuel processor subsystem efficiency is reasonable and consistent. If the utilization is too high then a higher fuel conversion point must be tested (e.g., higher fuel feed and/or air flow to the reformer or more anode vent gas flow to the reformer burner, etc.) to satisfy the fuel cell utilization requirements. If the fuel conversion is already at a maximum or limited, then the fuel processor subsystem feed flow must be increased or the anode vent gas rate must be increased (lower efficiency) to satisfy the fuel cell utilization requirement. If the calculated hydrogen utilization is too low then the fuel conversion may be lowered (higher efficiency) as long as undesirable fuel conversion species are not produced.

When information is not available to determine the amount of hydrogen consumed by the fuel cell and vented from the fuel cell, the quantity can be determined by taking the difference between the hydrogen produced by the fuel processor and any hydrogen recycled to the fuel processor in the hydrogen-depleted anode gas.

$$\eta_{FPS} = \frac{\left(Q_{r,producedbyfuelprocessor} - Q_{rg}\right) \bullet 100}{Q_f} \qquad \text{(Eq. 24)}$$

In the case where simulated recycled anode gas is used, a small potential error can occur due to the difference in heat capacity of the actual anode vent gas products including carbon dioxide and water vapor and its combustion air versus the heat capacity of the simulated anode vent gas and its combustion air. Carefully planning the choice of diluents and stoichiometric air can minimize this error. Burner fuel and air preheat temperatures would also be selected to simulate fuel cell system conditions.

The Cold Gas Efficiency is the quotient of lower heating value of useful gases exiting the fuel processor divided by the lower heating value of fuel fed to the reformer. The cold gas efficiency is calculated as follows.

$$\eta_{cge} = \frac{Q_{r,\ produced} \bullet 100}{Q_f} \qquad \text{(Eq. 25)}$$

$$\eta_{cge} = \frac{\left[M_r \bullet \left(x_{H2} \bullet LHV_{H2} + x_{CO} \bullet LHV_{CO}\right)\right]}{M_f \bullet LHV_{avg}} \bullet 100 \qquad \text{(Eq. 26)}$$

Where:

x_{CO} = Mass fraction carbon monoxide in reformate gas, wet basis
x_{H2} = Mass fraction hydrogen in reformate gas, wet basis
LHV_{H2} = 120 MJ/kg
LHV_{CO} = 10.1 MJ/kg
LHV_{avg} = lower heating value of liquid fuel, kJ/kg
M_f = Total mass flow of fuel during the test period, kg
M_r = Total mass flow of reformate gas during the test period, kg

For PEMFC the cold gas efficiency can be based on the total hydrogen produced divided by the lower heating value of fuel fed to the reformer. The carbon monoxide term is set to zero in the equation 26.

The associated auxiliary energy is

$$E_{aux} = Q_{ft} + Q_{wt} + Q_{ot} + Q_{st} + E_{Co} + E_{Cf} + E_{Cw} + EE_a \qquad \text{(Eq. 27)}$$

The auxiliary energy can be adjusted to account for the conversion efficiencies of the stack and power conditioner, or efficiencies associated with the electrical-to-mechanical conversion of energy for components such as pumps. The choice of conversion efficiencies is left to the test parties.

The carbon conversion efficiency is calculated as follows.

$$\eta_{CC}=\frac{\left[M_r\bullet\left(\frac{x_{CO}}{28.010}+\frac{x_{CO2}}{44.010}\right)\right]}{M_f\bullet\frac{x_C}{12.011}}\bullet 100 \qquad \text{(Eq. 28)}$$

Where:

x_C = Mass fraction carbon in fuel
x_{CO} = Mass fraction carbon monoxide in reformate, wet basis
x_{CO2} = Mass fraction carbon dioxide in reformate, wet basis
M_f = Total mass flow of fuel during the test period, kg
M_r = Total mass flow of reformate gas during the test period, kg

7.2.3.2 Steam-to-Carbon Ratio (Molar Basis)

Typically, the steam-to-carbon ratio is based only on water and fuel that is fed directly to the primary reformer reactor. For example, humidity in the air and water injected for spray cooling downstream of the primary reformer are not included in the reformer steam-to-carbon ratio calculation. Other steam-to-carbon ratios may be determined as agreed to by the test parties. The steam-to-carbon ratio is calculated as follows:

$$\delta=\frac{\left(\frac{M_w}{18.015}\right)}{\left(\frac{M_f\bullet x_C}{12.011}\right)} \qquad \text{(Eq. 29)}$$

Where:

M_w = Total mass flow of steam during the test period, kg
M_f = Total mass flow of fuel during the test period, kg
x_C = Mass fraction carbon in fuel

7.2.3.3 Fuel Equivalence Ratio

Fuel equivalence is the ratio of stoichiometric air requirement to actual air supplied for the give fuel flow.

$$\theta=\frac{\left(11.51\text{kgAir}/\text{kgC}\cdot x_C+34.29\text{kgAir}/\text{kgH}\cdot x_H+4.32\text{kgAir}/\text{kgS}\cdot x_S\right)\cdot M_f}{M_o} \qquad \text{(Eq. 30)}$$

Where:

x_C = Mass fraction carbon in fuel
x_H = Mass fraction hydrogen in fuel
x_S = Mass fraction sulfur in fuel
M_f = Total mass flow of fuel during the test period, kg
M_o = Total mass of oxidant (air) during the test period, kg

7.2.3.4 O_2-to-Carbon Ratio (Molar Basis)

The oxygen-to-carbon ratio is based on oxygen in the oxidant and therefore does not include the oxygen in the water that may be fed to the reactor. The oxygen-to-carbon ratio is calculated as follows:

$$O_2/C = \frac{M_o \bullet 0.2286/(31.9988)}{M_f \bullet x_C/12.011} \qquad \text{(Eq. 31)}$$

Where:

x_C = Mass fraction carbon in fuel
M_f = Total mass flow of fuel during the test period, kg
M_o = Total mass of oxidant (air) during the test period, kg

7.2.4 PRESSURE DROP

Pressure drop (pressure loss) through the fuel processor system is determined by measuring the maximum pressure of the feeds at the inlet to the test boundary and the pressure of the reformate gas at the outlet of the test boundary. The test parties should agree on the basis for the measurement. For example, the inlet pressure may be based on air pressure or fuel pressure at the inlet of the test boundary. The two pressures are not necessarily the same. Using the pressure of the oxidant will likely result in the minimum system pressure drop. The reformate gas outlet pressure measurement point needs to be agreed to by the test parties as well. The pressure difference is expressed as kPa.

$$\Delta P = P_o - P_r \qquad \text{(Eq. 32)}$$

Where:

ΔP = Fuel processor subsystem pressure drop, kPa
P_o = Average oxidant pressure at the test boundary, kPa
P_r = Average reformate gas pressure at the test boundary, kPa

7.2.5 CONSISTENCY CHECKS

An overall material balance should be performed to verify consistency. A suggested criterion for closure on the material balance is 95-105%, but this value can be agreed to by the test parties.

$$MB = \frac{(M_r)}{(M_f + M_o + M_w)} \bullet 100\% \qquad \text{(Eq. 33)}$$

Where:

MB = Overall material balance closure, %
M_r = Total mass of reformate exhausted during test period, kg
M_f = Total mass of fuel during the test period, kg
M_o = Total mass of oxidant during the test period, kg
M_w = Total mass of water during the test period, kg

Component balances such as carbon and nitrogen should also be checked for consistency.

$$MB_c = \frac{M_r \bullet \left(\frac{x_{CO}}{18.015} + \frac{x_{CO2}}{44.009} + \frac{x_{HC}}{MW_{HC}} \right)}{M_f \bullet \frac{x_c}{12.011}} \bullet 100\% \qquad \text{(Eq. 34)}$$

$$MB_{N2} = \frac{M_r \bullet \frac{x_{N2}}{28.014}}{M_f \bullet \frac{x_N}{28.014} + M_o \bullet \frac{0.7586}{28.014}} \bullet 100\% \qquad \text{(Eq. 35)}$$

Where:

MB_c = Carbon component balance closure, %
MB_{N2} = Nitrogen component balance closure, %
x_C = Mass fraction carbon in fuel
x_{CO} = Mass fraction carbon monoxide in reformate gas, wet basis
x_{CO2} = Mass fraction carbon dioxide in reformate gas, wet basis
x_{HC} = Mass fraction of hydrocarbon (methane) in reformate gas, wet basis
x_{N2} = Mass fraction of nitrogen in reformate gas, wet basis
x_N = Mass fraction of nitrogen in fuel

7.2.6 CORRECTION OF TEST RESULTS TO BASE REFERENCE CONDITIONS

The reference state of fuel, air, and water inputs is 15 °C and 1 atmosphere pressure for all feed streams, and 60% relative humidity for the air and zero humidity for the fuel. This may be agreed to or otherwise modified by the parties. All inputs that vary from these baseline parameters should be corrected using manufacturer supplied correction curves before computing the results of the test. All corrections to test data should be made and documented before the calculations in Section 7.2 Calculations and Formulae are made. All values in Section 7.2 refer to corrected values only.

The procedure for correction of test results to specified conditions depends on the type of FPS. 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 FPS type are unique. Hence, the manufacturer's published performance curves for the particular FPS should be used to correct that actual test data to rated or reference 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 should be prepared by the manufacturer. The user should review this procedure and any discrepancies should be resolved before the start of the test.

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 should provide correction factors and methods before the test.

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

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 should provide correction factors and methods before the test.

Ambient Pressure. If the FPS 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 should provide correction factors and methods before the test.

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 should provide correction factors and methods prior to the test.

7.3 Report Format

7.3.1 GENERAL REQUIREMENTS

ASME PTC-50 suggests a format for assembling the results of a performance test in a report. An abbreviated description of the elements of a test report are provided here as a guide. The user should refer to the ASME PTC-50 for a complete list of the elements of a report for a formal performance test. The test report should 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. Approach
e. Results
f. Conclusions
g. Appendices

This outline is a recommended report format. Other formats are acceptable; however, it is recommended that the test report contain all the information described in the following sections. The following serves as a handy checklist to aid the process of assembling the essential information for the performance test in a concise report.

7.3.2 TITLE PAGE

Some items to include on the test report Title Page include the title for the test, date of the report, location of the test, and parties involved in the test including the equipment owner, third party testing firm and customer requesting the test.

7.3.3 EXECUTIVE SUMMARY

The Executive Summary should provide a concise summary of the performance test. Some elements to include in the executive summary include general information about the fuel processor subsystem, performance test objectives, conditions under which the test was conducted, summary of the test results and conclusions.

7.3.4 INTRODUCTION

The Introduction should identify the parties involved in the test including the reference contract, the test objectives, a description of the test component and test boundary as well as general background such as location for the test.

7.3.5 APPROACH

The Approach should describe the procedures used to conduct the test including operating conditions, number of replicates, instrumentation used and calibration status, data acquisition system and known limitations.

7.3.6 RESULTS

The Results section should include the performance equations used, a tabulation of reduced data necessary to calculate the performance results, a summary of operating conditions corresponding to the reduced data and a step-by-step calculation of the performance results from the reduced data.

7.3.7 CONCLUSIONS

The Conclusions should address the results of the test versus the test objectives.

7.3.8 APPENDICES

Some examples of items to include in the Appendices to the test report include but are not limited to the following:

a. the signed test requirements contract
b. copies of original data sheets and/or data acquisitions system print-outs
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, certification from manufacturers
f. uncertainty analysis

7.4 Example Applications of the Recommended Practice

See Appendix A for a sample calculation of the application of this recommended practice to an autothermal reformer system suitable for use with a PEMFC.

PREPARED BY THE SAE PERFORMANCE WORKING GROUP
OF THE SAE FUEL CELL VEHICLE FORUM

APPENDIX A
SAMPLE CALCULATIONS

Autothermal Fuel Processor Subsystem

Assumptions and Sample Test Data

Fuel Processor: Autothermal with recycle of hydrogen-depleted anode gas to tail gas burner.

Basis:	1 hour test period
Nominal System Size:	50 kWe
Gasoline Fuel:	Regular Gasoline (Bosch Automotive Handbook 5th ed)
Density	0.740 kg/l (ASTM D 1298)
Specific Volume	1.351x10^{-3} m^3/kg
Latent Heat of Vaporization	440 kJ/kg
Net Calorific Value (LHV)	42 700 kJ/kg (ASTM D 240 or D 4809)
Mass Fraction Carbon (x_C)	85.6% (ASTM D 2427)
Mass Fraction Hydrogen (x_{H2})	14.4% (ASTM D 1018)
Boiling Point Temperature (T_{bp})	215°C (488.15 K) (Bosch Automotive Handbook 5th ed)

Boundary Operating Conditions

Fuel	
FP Fuel Flow, m_f	14.0 kg/hr
Pump Type	Piston
Pump Fuel Flow	20.0 kg/hr
Fuel Pressure	405 kPa
Fuel Temperature (T_{ff})	15 °C
Pump/Motor Efficiency	55% (Perry's Chemical Engineering Handbook 5th ed. pg 6-19)
Oxidant (Air)	
Air Flow (ATR+PROX)	58.0 kg/hr (ATR) + 2.0 kg/hr (PROX) = 60.0 kg/hr
Burner air flow	35.0 kg/hr
Air Pressure	320 kPa
Air Temperature	150 °C
Air Humidity	60% relative humidity
Mass Fraction N_2+Inerts	0.7586 (wet basis)
Mass Fraction O_2	0.2286 (wet basis)
Mass Fraction H_2O	0.0128 (wet basis)
Compressor/Motor Efficiency	60% (Assumed Compressor/Expander/Motor Combination)
Water (Steam for ATR)	
Water Flow, m_w	55.0 kg/hr
Water Temperature	55 °C
Water Pressure	305 kPa
Pump/Motor Efficiency	55%