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RECOMMENDED
PRACTICE**

SAE J2615 OCT2011

Issued 2005-01
Stabilized 2011-10

Superseding J2615 JAN2005

Testing Performance of Fuel Cell Systems for Automotive Applications

RATIONALE

Integrating FCS's into a vehicle requires the, (1) alignment of interface and environmental conditions between each, as well as (2) an understanding about the system's performance capabilities. Inherently linked by the FCS design, both (1) & (2) are commonly manipulated to produce data-based performance comparisons. This document is intended to aid in the comparison of competing FCS designs by providing a common recommended practice for performance testing. In doing so, this document will define performance measurements relative to manufacture claims and provides a format for recording test conditions.

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Introduction

1. Scope of Test Procedures

This recommended practice is intended to provide a framework for performance testing of fuel cell systems (FCS's) designed for automotive applications with direct current (DC) output. The procedures described allow for measurement of performance relative to claims by manufacturers of such systems with regard to the following performance criteria.

- Power
- Efficiency
- Transient Response
- Start and Stop Performance
- Physical Description
- Environmental Limits
- Operational Requirements
- Integration

Since this recommended practice is based on the principal of performance measurement relative to a claim, the testing parties should take care to include any qualifying or unique circumstances leading to the test results reported in order to achieve full disclosure. For example, efficiency as defined in section 3.1.9 allows for the inclusion of thermal output benefit. If a test result is reported which takes advantage of this allowance this stipulation should be noted with the efficiency figure and the useful purpose of the thermal output (e.g. cabin heating) should be made clear.

1.1 Limitations of Test Procedures

The procedures described do not provide methods for testing performance related to the following criteria.

- Human Factors (Acoustics/Noise, Vibration, Harshness)
- Life (State of technology limits this)
- Reliability
- Safety
- Vehicle Level Performance (efficiency, acceleration, emissions, etc).
- Contamination
- Tilt testing
- Governmental regulations or certification
- Alternating Current (AC) Output

2. References

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

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. 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 J2574—SAE Information Report—Fuel Cell Vehicle Terminology
2. SAE J2578—Recommended Practice for General Fuel Cell Vehicle Safety
3. SAE J2616—Recommended Practice for Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
4. SAE J2617—Recommended Practice for Testing Performance of PEM Fuel Cell Stack Sub-System for Automotive Applications (DRAFT)

2.1.2 ASTM PUBLICATIONS

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

5. ASTM D 240—Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter
6. ASTM D 3588-98—Standard Practice for Calculating Heat Value, Compressibility Factor and Relative Density of Gaseous Fuels
7. ASTM D 4809—Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Intermediate Precision Method)
8. ASTM D 4809-95—Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)

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2.1.3 OTHER PUBLICATIONS

9. ASME PTC 19.1—Appendix B, Uncertainty Analysis
10. I&A PTC 19.21—Leakage Measurement
11. I&A, ASME PTC 19.2—Pressure Measurement
12. ASME PTC 19.3—Temperature Measurement and Calibration
13. ASME PTC 19.5—Fluid Flow Measurement
14. ASME PTC 50—Fuel Cell Power Systems Performance Test Code
15. ASME PTC19.5—Fluid Meters
16. ASME PTC22—Gas Turbine (for LHV's)
17. ASME PTC6—Test Measurement Uncertainty (from Gas Turbines)
18. NIST Technical Note 1297—Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST, 1994 edition
19. NIST Special Publication 811—Guide for the Use of the International System of Units (SI), NIST, 1995 edition
20. Fuel Cell Handbook, 4th ed., Parsons Corporation for U. S. Department of Energy-FETC, DOE/FETC-99/1076
21. API Technical Data Book
22. ASME Boiler and Pressure Vessel Code Section V Article 10, The American Society of Mechanical Engineers. New York, New York, July 1, 2001
23. IEEE Std 120—Master Test Guide for Electrical Measurement in Power Circuits
24. IEEE Std 4—Standard Techniques for High Voltage Testing
25. IEEE Std 1159—Recommended Practice for Monitoring Electric Power Quality
26. NFPA 50—Standard for Hydrogen Systems at Consumer Sites
27. NFPA 50A—Standard for Gaseous Hydrogen Systems at Consumer Sites
28. NFPA 497—Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
29. NEC Article 500—Hazardous (Classified), Class 1 Locations
30. CGA G-5.4—Standard for Hydrogen Piping Systems at Consumer Locations

3. Definitions

Terminology used in this document is consistent with SAE J2574 "Fuel Cell Vehicle Terminology." In addition to terminology presented in J2574, the following definitions are provided for clarity.

3.1 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.

3.2 Test Operator(s) / Personnel

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

3.3 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.

3.4 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.

3.5 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.

3.6 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 fuel processing system may, for example, include reactor beds, heat exchangers, and controls used to reform a hydrocarbon fuel into a hydrogen rich stream known as reformat gas or simply reformat. In a hydrogen fueled fuel cell system, the fuel processing sub-system 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.

3.7 Air Processing Sub-system (APS)

The assembly of components that delivers 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.

3.8 Thermal Management Sub-system (TMS)

The assembly of components that provides both thermal and water management for the fuel cell system. The thermal management sub-system may include an accumulator, pump, radiator, and/or condenser. It may also provide water recovery and process humidification functions.

3.9 Water Treatment Sub-system (WTS)

The assembly of components that provides the treatment necessary for the process water used 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.

3.10 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.

3.11 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.

3.12 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.

3.13 Fuel Cell Control Sub-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.

3.14 Vehicle Control System (VCS)

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

3.15 Electrical Load System

A device used to apply electrical 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.

3.16 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:	101325 Pa (1 atmosphere, 14.696 psia, 101.3 kPa)
Air:	60% relative humidity (0.006 kg H ₂ O/kg dry air) at 15 °C

The above conditions are also known as nominal day conditions. To aid in the comparison of various FCS's in various environmental conditions, the following additional reference conditions are provided for the use of conducting tests and reporting results at other than nominal conditions.

	Freezing Day	Cold Day	Hot Day
Temperature	-20 °C	5 °C	40 °C
Pressure	101.3 kPa	101.3 kPa	90.0 kPa
Air	0% RH at 20 °C	0% RH at 5 °C	0% RH @ 40 °C

The test procedures provided in section 3.3 can be applied repeatedly at these different conditions to provide a more complete summary of FCS performance at various conditions and when reporting results the testing parties should use the appropriate day designation and reference to this recommended practice to qualify the reported result. The inclusion of these recommended reference conditions is not intended to limit the range of test conditions supported by this recommended practice. Testing parties should maintain necessary flexibility to test conditions deemed relevant to the specific FCS and test objectives.

3.17 Reformate or Reformate Gas

The product of a fuel processing sub-system, generally rich in hydrogen. This gaseous fluid results from the reformation of the fuel within a 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.

4. Nomenclature, Physical Constants and Units

TABLE 1—NOMENCLATURE

Symbol	Description	Units
P	Power	W
i	Subscript indicating in, inlet, or input	-
o	Subscript indicating out, outlet, output	-
e	Subscript indicating electrical or exit	-
f	Subscript indicating fuel	-
h	Enthalpy	J/g
s	Subscript indicating system	-
I	Current	Amps, Amperes
DC, dc	Subscript: Direct Current	-
t	Subscript: Thermal	-
V	Voltage	Volts
x	Width	m
y	Height	m
z	Length	m
LHV	Lower Heating Value	J/g
η	Efficiency	-
m	Mass	G
\dot{m}	Mass flow rate	g/s
T	Temperature	$^{\circ}\text{C}$
c_p	Specific heat at constant pressure	J/g-K
n	Subscript indicating Net	-
g	Subscript indicating Gross	-
E	Energy, electrical	J
Q	Energy, thermal	J
t	Time	s

4.1 Pre-test Conditions

4.1.1 DEFINITION OF TEST SUBJECT WITH SCHEMATIC

This test will be administered to a fuel cell system that operates on either hydrogen or a hydrocarbon fuel. The system being tested produces electrical power as a result of the electrochemical reaction of hydrogen and oxygen. The oxygen for this reaction is typically derived from supplied air. The hydrogen for this reaction is derived from the fuel by various methods.

A typical fuel cell system contains several subsystems, that are interconnected as shown in Figure 1.

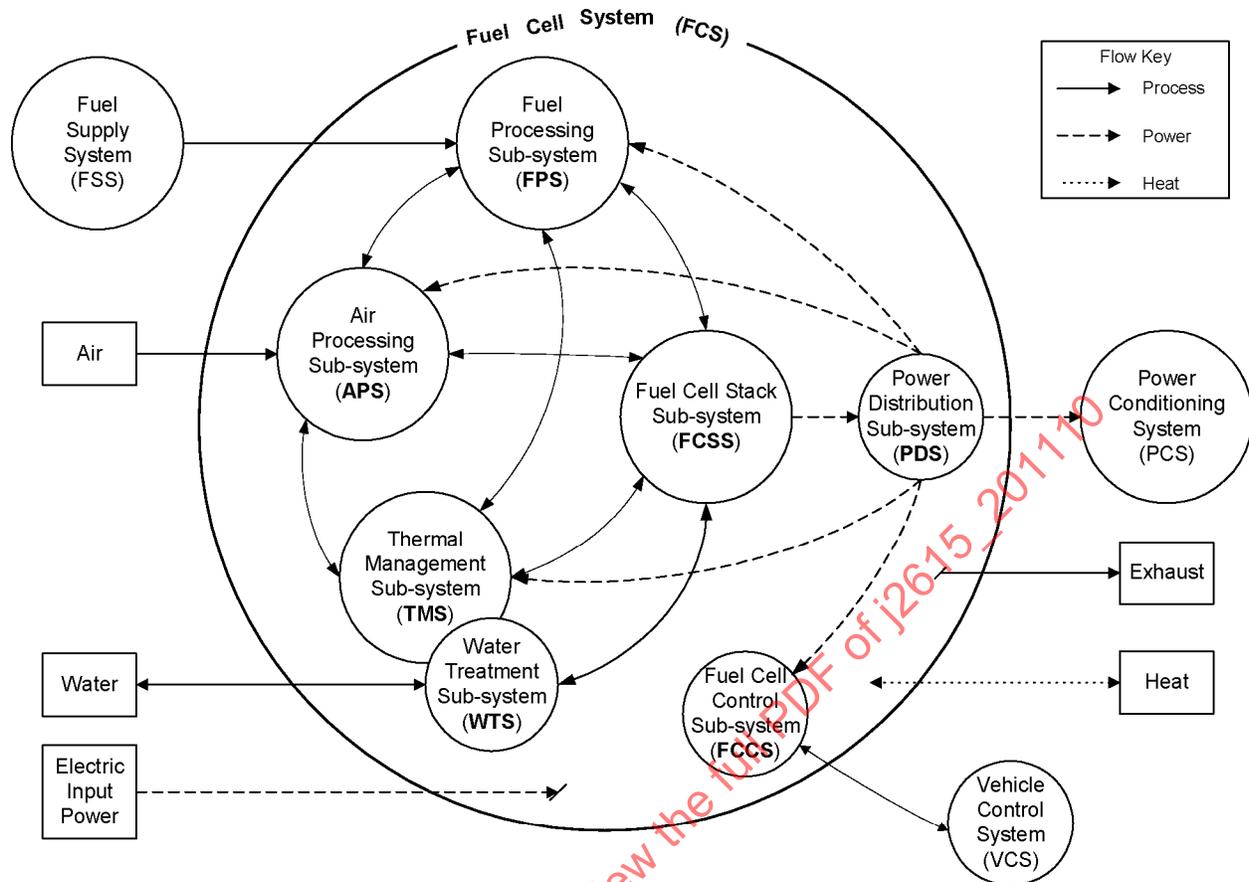


FIGURE 1—SCHEMATIC ILLUSTRATING A GENERIC FUEL CELL SYSTEM TO BE USED FOR PURPOSES OF THIS TEST. THE LARGE CIRCULAR BOUNDARY INDICATES THE BOUNDARY WHERE PERFORMANCE PARAMETERS ARE TO BE MEASURED.

4.1.2 TEST BOUNDARY

The test boundary serves to define the interfaces used for measurement of performance parameters. The test boundary and pertinent material and energy streams that cross it are to be determined by agreement of the test parties prior to the start of test.

Different systems will result in different test boundaries based on conceptual design and integration philosophies. A generic and representative set of interfaces may come from Figure 1. The specifics of the interfaces (e.g. location of thermal interface relative to radiator, or location of the air filter relative to the FCS and the vehicle) are left to the testing parties and should be documented in the test report.

4.2 Specifications of Test Facility and Equipment

4.2.1 FUEL STORAGE

The test facility should have a fuel storage area designed in accordance with applicable codes and standards. The region should be adequately ventilated, appropriately distanced from any sources of ignition, well labeled with "No Smoking or Open Flames" placards, and secured from tampering. All electrical equipment should be rated in accordance with reference 29.

4.2.2 FACILITY VENTILATION

The test facility should provide adequate ventilation in accordance with applicable codes and standards such that the normal leakage or leakage in a failure mode does not endanger personnel or equipment. All process exhausts and emissions should be safely vented out of the local test area to prevent further hazard.

4.2.3 ALARMS

The test facility should provide for continuous monitoring of hazardous conditions including combustible and toxic substances, and flame detection. Audible and visible alarms should be provided and set in accordance with the design limits recommended in reference 2 and should allow for prompt communication of the nature and general location of the hazard. All sensors and related equipment must be rated in accordance with reference 29.

4.2.4 SHUTDOWN 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.

4.2.5 LOAD SYSTEM

The testing described in this recommended practice requires that a variable load be placed on the fuel cell system in order to draw current from it. As such, the test facility should provide the means with which to apply this variable load. The load range should accommodate the complete power range to be verified in the test, nominally from idle power to peak power as described in Section 5.1.2. The load bank should provide for constant resistance and constant current testing.

4.2.6 CODES AND STANDARDS

The test facility should be constructed and certified in accordance with all applicable codes and standards. These may include, but are not limited to, the National Fire Protection Association, the National Electric Code, the American Society of Mechanical Engineers, American National Standards Institute, Compressed Gas Association, the American Petroleum Institute, and the Society of Automotive Engineers.

4.2.7 FLUID SPECIFICATIONS

The test stand should provide fluids to the FCS as necessary for the production of power over the range of operation and conditions to be tested. These fluids are outlined in the following sections.

4.2.8 COOLANT

De-ionized water and/or other cooling and anti-freezing additives such as ethylene glycol, meeting the manufacturers minimum requirements for resistance.

4.2.9 FUEL

The fuel specifications are to be determined and agreed upon by the testing parties. These specifications should be documented as part of the test report in the form of a batch and/or composition certification. The lower heating value (LHV) of the fuel should be determined in accordance with Section 5.1.5.2, and should be recorded as part of the test report.

Any conditioning of the fuel supply should be indicated in the test report. Conditioning may include filtration, humidification, and heating that takes place outside of the test boundary.

4.2.10 AIR/OXIDANT

The process oxidant is to be provided from ambient conditions.

Any conditioning of the process air should be indicated in the the test report. Conditioning may include filtration, humidification, and heating that takes place outside of the test boundary.

Corrections may be applied to convert all test results to standard ambient conditions for comparison purposes.

4.2.11 WATER FOR HUMIDIFICATION

Some FCS's may use water for humidification of reactants that is separate from the coolant. This water may require conditioning in order to maintain dielectric properties specifically required for fuel cell applications.

4.2.12 DATA ACQUISITION AND TIMING EQUIPMENT

Data acquisition and logging should be provided to record test results. Automatic data acquisition is preferred, however a manual log of test activities and key results should be included in the test report. Data acquisition should provide for resolution sufficient to support any claim by the manufacturer. This minimum resolution is required after filtration or other signal conditioning has been applied. Therefore the sampling rate of the data acquisition system may have to be much faster than that required to meet the minimum log rate.

Timing equipment should be provided for the time stamping of logged data, averaging of test data, and for assessing transient performance response. This timing may be accomplished by automatic data acquisition and logging systems or by manual means.

4.2.13 TEST INSTRUMENTATION REQUIREMENTS

Test instrumentation should meet the accuracy requirements of reference 14. All test instrumentation used in the measurement of performance variables should be traceable in accordance with NIST standards.

4.2.14 TEST EQUIPMENT CALIBRATION

All test equipment and related instrumentation should maintain a high level of calibration to ensure that all testing is performed accurately. This calibration should be conducted in accordance with reference 14. Documentation of calibration should be traceable in accordance with NIST standards. The design and calibration of the test equipment should allow for control of the test parameters in accordance with reference 14. To ensure adequate accuracy in the instrumentation an uncertainty error analysis should be performed on critical measurements and their impact on reported performance results (see section 6.1.5).

4.2.15 PRE-TEST RECORDS

Pretest records should follow reference 14. 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

4.3 Inspection of Test Items and Connections to Facilities and Equipment

4.3.1 COMPONENT CERTIFICATION

Components, connections, and systems should be designed, built, and tested to relevant national or international standards (SAE, ASME, ISO, etc.) and meet applicable local, state, and federal regulations.

4.3.2 LEAK DETECTION AND GAS PURGING

All test equipment and the FCS should be leak tested prior to test with an inert gas such as Nitrogen. This test should follow the recommended practice of reference 2.

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.

4.3.3 ELECTRICAL CONNECTIONS

Electrical equipment and connections are to be designed in accordance with reference 2.

4.3.4 ELECTRICAL ISOLATION

All test equipment is to be electrically grounded and bonded in accordance with reference 2.

4.3.5 FUNCTIONAL CHECK

The complete test system should be determined to be functionally sound prior to test. This determination requires a test of both system hardware and control functions, data acquisition systems 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 FCS may be addressed separately by separate parties if documentation of each test component is provided in the test report.

4.3.6 CONNECTIONS BETWEEN TEST FACILITY AND TEST ARTICLE

Prior to the start of testing, all mechanical connections between the test article and the test facility should be verified as leak tight and electrical connections should be verified as sound. The connections may include fluid supply connections, drains, electrical connections, instrumentation signal connections, power supply and load system connections.

4.4 Pretreatment Procedures

4.4.1 AMBIENT TEMPERATURE AND PRESSURE

Ambient temperature and pressure should be per reference 14. Test results from tests run at conditions other than those indicated as standard should be converted to account for this difference.

4.4.2 EQUIPMENT TEMPERATURE

The FCS should be at thermal equilibrium prior to the start of testing. This equilibrium should be determined according with test intent. Examples include testing at ambient conditions, and starting from extreme cold temperatures.

One exception to this requirement is for tests of hot restart time, when FCS temperatures are transient and system dependant.

A second exception regards portions of the FCS which include means for sustained avoidance of thermal equilibrium (e.g. keeping water at elevated temperatures with electric heaters). These portions of the FCS are not required to reach ambient temperature as long as the supplemental energy for the additional functionality is accounted for.

Other exceptions may be agreed to by the testing parties depending on the intent of the performance test.

4.4.3 FCS CONDITIONING

The FCS 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 fuel cell stack sub-system, or of reactors in the fuel processing sub-system.

4.4.4 PRELIMINARY OPERATION AND ADJUSTMENT

The test article delivered to this 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 modifications should be made to the test article. If modifications are required in order to obtain complete test results, the testing should be restarted following the modifications.

4.5 Test Plan

4.5.1 GENERAL

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

- a. Extent of the system to be tested, i.e., test boundary
- b. Base reference conditions
- c. Data to be recorded, and method of recording and archiving data
- d. Personnel to 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 test article is operational, with appropriate time to condition it in accordance with the supplier's requirements.
- g. Procedures for recording the test data and observations, including sample frequency.
- h. Type, number, and systematic uncertainty of all instruments to be used to establish test conditions and test results and how they should be installed.
- i. Instrument calibration schedule or procedures.
- j. Designation of the laboratory and any other facilities required for determining pertinent fuel characteristics.
- k. Requisite facilities for maintaining constancy of load during test, if applicable.
- l. Number of identical tests to be conducted to assure statistically significant accuracy and repeatability.
- m. Duration of each test segment.
- n. Acceptance of test when disruptions occur.
- o. Acceptance criteria for test completion.
- p. List of agreements between test parties as identified throughout this recommended practice.

It is also recommended that the test plan 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. Where appropriate the test plan should reflect any contract requirements that pertain to the test objectives.

4.5.2 SCHEDULE OF TEST ACTIVITIES

A test schedule should be prepared that should include the timing of the test events, notification of parties, test preparation and conduct, and the preparation of the test report.

4.6 Training of Test Personnel

All test personnel should be well trained on the use of the test station, test facility equipment, fuel cell system operations, the safe handling of hazardous fluids, and all other applicable safety procedures. The test personnel should also be trained regarding the test plan and detailed test procedures.

4.7 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 system supplier, and possibly an independent contractor, for example, a testing agency.

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5. Test Description

5.1 Specifications of Test Variables and Measured Performance

TABLE 2—SUMMARY OF PERFORMANCE TEST PARAMETERS FOR A FUEL CELL SYSTEM

Category	Performance Parameters	Measured Parameters
	Examples	
Power Output	Peak Power Maximum Continuous Power Maximum Design Efficiency Power Water Balance Power Level Idle Power Turndown Thermal Output	DC Voltage DC Current
Power Quality	Open Circuit Voltage Range Current Range Instantaneous Voltage Stability Long Term Voltage Stability	DC Voltage
Input Power	Auxiliary Power Startup / Shutdown Energy	DC Current DC Voltage Thermal Input Fuel Input
Efficiency	System Efficiency	Fuel Flow Into FCS Fuel LHV Power Output Input Power
Transient Response	Cold Start Hot Start Normal Shutdown Emergency Shutdown Step/Ramp Transient Cycle Transient	Elapsed Time Power Deficit/Surplus over cycle Voltage Stability on Transient Energy Input
Physical	Mass Volume	Dry Mass Operating Mass Envelope Volume
Environmental	Temperature Range Altitude / Pressure Humidity	Min Operating Temperature Max Operating Temperature Maximum Operating Altitude Maximum Operating Humidity Minimum Operating Humidity
Operational	Water Sufficiency Auxiliary Power Requirements (Voltage, Current)	Water Surplus / Deficit Purity Measurements Auxiliary Power Use
Integration	Specific Power Power Density	Voltage, Current Mass, Volume

5.1.1 DETERMINATION OF STEADY STATE

The steady state of any given parameter is achieved when the parameter varies no more than twice the required accuracy of the measurement indicated in reference 14. Some measured parameters may not reach a steady state based on this requirement. For such parameters an average reading should be used and the level of stability should be measured and recorded according to section 5.1.3.

5.1.2 POWER OUTPUT

5.1.2.1 *Net Electrical Output Power*

Electric power output should be measured at five specific power levels as described below. In each case, the FCS manufacturer should indicate the power level and the test should verify the performance claim. All power levels are to be in net terms with kilowatts (kW) as the unit of measure unless otherwise agreed to by the testing parties. Net power is determined by subtracting parasitic power from the gross output in each case (See Section 5.1.8 for net power determination).

5.1.2.2 *Peak Power*

This is the maximum instantaneous net power output of the FCS. The FCS manufacturer should indicate the time interval over which this power is sustainable. The duration of peak power and time interval over which this performance is sustainable should be noted in the test report, along with the ambient conditions of the test (see section 1.3.16). If any system pre-conditioning period is required, this should also be noted in the test report.

5.1.2.2.1 Maximum Continuous Power

This is the maximum net power sustainable, limited only by the supply of reactants and coolant makeup. The duration for this test should be determined by the testing parties. The duration of maximum continuous power and time interval over which this performance is sustainable should be noted in the test report, along with the ambient conditions of the test (see section 1.3.16). If any system pre-conditioning period is required, this should also be noted in the test report.

5.1.2.2.2 Maximum Design Efficiency Power

This is the net power level at which the FCS is most efficient (see Section 5.1.9 for efficiency calculations). The ambient conditions of the test (see section 1.3.16) should be noted in the test report, along with the resulting efficiency at this power level. If any system pre-conditioning period is required, this should also be noted in the test report.

5.1.2.2.3 Water Balance Power

This is the net power level at which the FCS is able to maintain water balance. This test may require external cooling capacity to simulate the FCS integration in a vehicle. The ambient conditions of the test (see section 1.3.16) should be noted in the test report. If any system pre-conditioning period is required, this should also be noted in the test report.

5.1.2.2.4 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.

5.1.2.3 Gross Electrical Output Power Measurement

Gross output power is to be measured at the interface between the fuel cell stack sub-system and the power distribution system (reference Fig. 1). At this boundary, the power is of the direct current type (DC). Voltage and current are to be measured in accordance with reference 17. The power is determined by the product of these two measures according to Equation 1. This is the gross electrical output power.

$$P_{e_o} = V_{dc} \cdot I_{dc} \quad (\text{Eq. 1})$$

5.1.2.4 Turndown (Gross)

Turndown is a measure of the gross power range of the FCS. It is the ratio of the maximum gross continuous power level to the gross idle power level as indicated in Equation 2.

$$TD = \frac{P_{g,max.cont}}{P_{g,idle}} \quad (\text{Eq. 2})$$

5.1.3 ELECTRICAL OUTPUT POWER QUALITY

In addition to the nominal power output at each power level tested, the power quality should be measured. Power quality is measured in terms of voltage stability at a constant current.

5.1.3.1 Open Circuit Voltage

This condition exists when no external or parasitic load is applied to the FCS. This is typically when no current is drawn through the fuel cell stack sub-system. This condition results in the highest generated interface voltage. This performance parameter is dependant on temperature, pressure and composition of the fuel and oxidant and should be measured at the limit of conditions that result in the highest voltage. For these reasons, measurement of this parameter may also require that the system be allowed to equilibrate for a certain period determined by the testing parties.

5.1.3.2 Maximum Operating Voltage

This condition exists when the minimum net load is applied to the FCS. This is typically when the least operational current is drawn through the fuel cell stack sub-system. This condition results in the highest operating interface voltage for the FCS.

5.1.3.3 Operating Voltage Range

The boundaries of the operating voltage range are determined by the minimum operating voltage and the maximum operating voltage of the FCS. The minimum will typically occur at the peak net power level and the maximum will typically occur at idle. The determination of operating voltage range should be taken from the voltage measurements performed at idle and peak power conditions.

It should also be noted that the minimum operating voltage may occur during transient performance when a higher load is requested. This should be considered when determining minimum operating voltage.

5.1.3.4 Output Voltage Measurement

Output voltage should be measured as DC voltage at the interface between the power distribution system (PDS) and the power conditioning system (PCS) (reference Figure 1). This measurement should be performed in accordance with Ref. 0. The testing parties should consider using a device that limits current when measuring FCS voltage.

5.1.3.5 Current Range

The range of current draw will depend on the minimum and maximum net power levels or the minimum and maximum voltage points. The determination of current range should be taken from the current measurements performed at idle and peak net power conditions. If the maximum current in a particular FCS design does not occur at peak power, then the maximum current must be measured separately from the peak power test.

5.1.3.6 Current Measurement

Current during on load operation should be measured at the boundary between the power distribution system (PDS) and the power conditioning system (PCS) (reference Figure 1). This measurement should be performed in accordance with reference 17.

5.1.3.7 Voltage Stability

Voltage stability is determined by observing and measuring any variation in output voltage while maintaining a constant current load on the fuel cell system. Steady state is described in section 5.1.1. In accordance with Figure 1, the voltage measurement should be taken between the power distribution subsystem and the power conditioning system, and is thus the DC voltage output of the fuel cell system.

The testing parties should take care to account for influences on voltage stability resulting from current ripple and other phenomena associated with load bank systems. If there is a known influence on voltage stability resulting from such facility interaction it should be corrected either by addressing the fundamental cause or by correction of the data based on the measured influence.

5.1.3.7.1 Transient Voltage Stability

The Transient voltage stability is a measure of how consistent the voltage output of the fuel cell system is relative to time scales on the order of seconds. This performance measure provides for an understanding of how responsive the power conditioning system must be to provide constant voltage to the vehicle power train system.

Transient voltage stability is to be measured as the standard deviation about the mean voltage over a time period. The minimum sample period should be 1 minute, with a maximum sample interval of 50 milliseconds.

5.1.3.7.2 Long Term Voltage Stability

The long term voltage stability is a measure of how the supply voltage from the fuel cell system varies over periods of time on the order of an hour. This measurement provides a determination of how the fuel cell stack subsystem efficiency changes over a longer period of relatively constant power output.

Long term voltage stability is to be measured as the standard deviation about the mean voltage over a time period of 15 minutes. The maximum sample interval should be 100 milliseconds.

5.1.4 THERMAL OUTPUT

The thermal output of the fuel cell system may be useful for vehicular purposes (reference “heat” in Figure 1). The verification of this claim should be tested at the maximum continuous operating power level. Other power levels may be tested according to the agreement of the testing parties. If credit is taken for thermal output, when determining FCS efficiency, it should be noted in the test report when indicating the claimed efficiency.

5.1.4.1 Thermal Output Power Measurement

Thermal output may be available from the fuel cell system for a variety of reasons. Thermal output power is accounted for by measuring and summing the output duties as shown in Equation 3, when the FCS is operated at the required operating temperatures.

$$\dot{Q}_{t_o} = \sum_k \dot{Q}_{k_o} \quad (\text{Eq. 3})$$

The duty of the thermal output can be measured on either the hot or cold side of a heat exchanger as noted in Equation 4.

$$\dot{Q}_{k_o} = \dot{m}_k \cdot (h_{k_i} - h_{k_o}) \quad (\text{Eq. 4})$$

5.1.5 FUEL

5.1.5.1 Fuel Flow

Fuel flow will be measured at the inlet boundary to the FCS in accordance with reference 14 (also see Figure 1). The nominal units of measure should be kilograms per second (kg/s), but others may be used by agreement of the testing parties.

5.1.5.2 Fuel Energy Content

The energy content of the fuel should be measured in accordance with references 5-8, as delivered to the FCS interface by the FSS per Figure 1. The nominal units of measure should be kilojoules per kilogram (kJ/kg), but others may be used by agreement of the testing parties.

5.1.6 INPUT POWER

5.1.6.1 Auxiliary Power

Auxiliary power is required to sustain operation of the FCS, and may be required to provide for start up and shutdown as well. Operational power is accounted for as an efficiency debit. Start and stop power is accounted for as energy inputs, since the fuel cell system power output is zero at the time these inputs are required.

5.1.6.1.1 Parasitic Electrical Input Power

During power level performance testing the electrical power inputs to the FCS should be measured in accordance with reference 23 (reference “electrical input power” in Figure 1).

If multiple power supplies are used with various voltages, several measurements will be required. For each power supply at each power level tested, the voltage and current should be measured and recorded for computation of total power input to the FCS according to Equation 5.

$$P_{e_i} = \sum_j V_j \cdot I_j \quad (\text{Eq. 5})$$

5.1.6.1.2 Thermal Input

Thermal input may be required for startup, operation or shutdown of the fuel cell system for a variety of reasons. This input is accounted for by measuring and summing the input duties as noted in Equation 6 (reference “heat” in Figure 1).

$$\dot{Q}_i = \sum_k \dot{Q}_{k_i} \quad (\text{Eq. 6})$$

The duty of the thermal input may be measured on either the hot or cold side of a heat exchanger used as noted in Equation 7. If the input is by means of electrical heat, it should be included in the measurement described in section 5.1.6.1.1.

$$\dot{Q}_{k_i} = \dot{m}_k \cdot (h_{k_i} - h_{k_o}) \quad (\text{Eq. 7})$$

5.1.7 STARTUP AND SHUTDOWN ENERGY

5.1.7.1 Electrical Startup Energy

The amount of electrical energy required for startup of the FCS should be determined by integration of the auxiliary power with respect to time over the duration of the start (reference “electrical input power” in Figure 1). This is provided by Equation 8 in two forms. The latter form is provided for direct calculation from logged data. The sample rate should be sufficient to minimize error in this calculation, by providing at least 10 samples over the characteristic transient period of interest.

$$E_{start_e} = \int_0^{t_{start}} P_{e_i}(t) \cdot dt \approx \sum_0^{t_{start}} P_{e_i}(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 8})$$

As noted in section 2.4.2, some FCS's may be designed to prevent certain portions from reaching thermal equilibrium with the environment. If so, the energy required to prevent such equilibrium should be accounted for in the startup energy, and the appropriate period of integration is the entire period between completion of shutdown and completion of startup.

5.1.7.2 Thermal Startup Energy

The amount of thermal energy input required for startup of the FCS should be determined by integration of the thermal input power with respect to time over the duration of the start, as shown in Equation 9 (reference "heat" in Figure 1). Similar to Equation 8, this is provided in two forms, the latter for numerical integration of logged data.

$$Q_{start} = \int_0^{t_{start}} \dot{Q}_i(t) \cdot dt \approx \sum_0^{t_{start}} \dot{Q}_i(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 9})$$

Testing of the FCS in a test facility may require heating of a larger volume of certain systems, for example a coolant system. The testing parties should be careful to consider the impact of such differences between the test configuration and an actual integration. Test result may require modification or annotation to ensure appropriate interpretation. Also, if the test facility is used to heat certain systems as a result of this type of difference, this heat must be accounted for in the start up energy test.

5.1.7.3 Fuel Input Startup Energy

The amount of fuel used during the start up mode of the FCS should be determined by measuring the cumulative amount of fuel input to the system and multiplying by the average LHV of the fuel. This is shown in Equation 10 in two forms, the latter is intended for numerical integration of logged data similar to Equation 8.

$$E_{start_f} = LHV_i \int_0^{t_{start}} \dot{m}_i(t) \cdot dt \approx LHV_i \sum_0^{t_{start}} \dot{m}_i(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 10})$$

Alternatively, if a direct cumulative or instantaneous mass or volume measurement can be made and is considered more accurate than an integration of an instantaneous measure of flow rate, this is acceptable. An application of this method is shown in Equation 11. This may be particularly useful when using liquid fuels.

$$\begin{aligned} E_{start_f} &= LHV_i \cdot (m_{t_0} - m_{t_{start}}) \\ &= LHV_i \cdot \Delta m_{start_f} \end{aligned} \quad (\text{Eq. 11})$$

5.1.7.4 Electrical Shutdown Energy

The amount of energy required for shutdown of the FCS should be determined by integration of the auxiliary power with respect to time over the duration of the shutdown (reference "electrical input power" in Figure 1). This is noted in Equation 12 in two forms, the latter is intended for numerical integration of logged data similar to Equation 8.

$$E_{shutdown_e} = \int_0^{t_{shutdown}} P_{e_i}(t) \cdot dt \approx \sum_0^{t_{shutdown}} P_{e_i}(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 12})$$

5.1.7.5 Thermal Shutdown Energy

The amount of thermal energy required for shutdown of the FCS should be determined by integration of the thermal input power with respect to time over the duration of the shutdown (reference "heat" in Figure 1). This is noted in Equation 13 in two forms, the latter is intended for numerical integration of logged data similar to Equation 8.

$$Q_{shutdown} = \int_0^{t_{shutdown}} \dot{Q}_{t_i}(t) \cdot dt \approx \sum_0^{t_{shutdown}} \dot{Q}_{t_i}(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 13})$$

5.1.7.6 Fuel Input Shutdown Energy

The amount of fuel used during the shutdown mode of the FCS should be determined by measuring the cumulative amount of fuel input to the system and multiplying by the average LHV of the fuel. This is shown in Equation 14 in two forms, the latter is intended for numerical integration of logged data similar to Equation 8.

$$E_{shutdown_f} = LHV_i \int_0^{t_{shutdown}} \dot{m}_i(t) \cdot dt \approx LHV_i \sum_0^{t_{shutdown}} \dot{m}_i(t_i) \cdot (t_{i+1} - t_i) \quad (\text{Eq. 14})$$

Alternatively, if a direct cumulative or instantaneous mass or volume measurement can be made and is considered more accurate than an integration of an instantaneous measure of flow rate, this is acceptable. An application of this method is shown in Equation 15. This may be particularly useful when using liquid fuels.

$$\begin{aligned} E_{shutdown_f} &= LHV_i \cdot (m_{t_0} - m_{t_{shutdown}}) \\ &= LHV_i \cdot \Delta m_{shutdown_f} \end{aligned} \quad (\text{Eq. 15})$$

5.1.8 NET ELECTRICAL POWER

The net power output of the FCS is determined by subtracting the parasitic electrical input power during steady state operation from the gross power, as noted in Equation 16. If the FCS receives all parasitic power from the PDS (i.e. no additional inputs from the PCS or other supplies, than net power output can be measured between the PDS and the PCS for verification (reference Figure 1).

$$P_{e_{o,n}} = P_{e_o} - P_{e_i} \quad (\text{Eq. 16})$$

5.1.9 EFFICIENCY

5.1.9.1 System Efficiency

The overall FCS efficiency accounts for fuel, electric and thermal inputs and electric and thermal outputs at steady state. It is the ratio of the useful net power output to the fuel and thermal energy input, as shown in Equation 17. When the thermal output is used in the vehicle system \dot{Q}_{t_o} should be accounted for, otherwise it provides no benefit and should not be included in this calculation.

$$\eta_s = \frac{P_{e_{o,n}} + \dot{Q}_{t_o}}{\dot{m}_i \cdot LHV_i + \dot{Q}_{t_i}} \quad (\text{Eq. 17})$$

If the test parties agree to credit the FCS efficiency for the use of thermal output, it should be noted in the test report when indicating FCS efficiency.

5.1.10 DYNAMIC PERFORMANCE

5.1.10.1 Start-Up Performance

5.1.10.1.1 Cold Start

A cold start is a start of the power plant from any ambient conditions specified. The cold start represents the first start of the FCS after a period of shutdown long enough to reach a steady non-operational state. The specific conditions from that this start proceeds should remain the discretion of the manufacturer or designated tester and this test procedure should serve to verify the operational claim. However, the specific conditions should be included in the test report and cited when indicating the start time. A cold soak is recommended, and the conditions of the soak should be noted in the test report. Recommended reference conditions for “cold day” and “freezing day” are provided in section 1.3.16.

5.1.10.1.2 Hot Start

A hot start is one that closely follows a shutdown from a power production mode. It is expected that a hot start will be quicker than a cold start, particularly for those FCS's employing fuel processing of hydrocarbon fuels.

5.1.10.2 Shutdown Performance

5.1.10.2.1 Normal Shutdown

A normal shutdown is one that results from a request on the part of the user for the end of FCS operation. The measures of performance for a shutdown include the duration of the shutdown process, the amount of energy and power level required to perform the shutdown and any FCS conditioning required in the process. Completion of shutdown process is defined as the point when the system reaches the state enabling the next start-up. These conditions may differ for hot and cold start-ups.

5.1.10.2.2 Emergency Shutdown

An emergency shutdown is one that results from an immediate or urgent need for the end of FCS operation.

5.1.10.3 Transient Response

A key transient performance parameter is the capability of the FCS to respond to a change in requested power output within a specified period of time. This test endeavors to provide a standard framework for quantification and verification of claims relative to FCS response. The transients described in this section are intended to include both up and down transients. When reporting FCS transient response, the specifications of the transient (levels, rate) as well as the duration should be included.

5.1.10.3.1 Step Input

This form of request is a sharp increase or decrease of power with respect to time. The step input has a magnitude defined by the difference between the end point and the start point of the step and reported in units of kW. The duration of the step is generally very short and may be expressed in units of milliseconds.

5.1.10.3.2 Ramp Input

The ramped request is a linear increase or decrease in power of a specified magnitude from the start point to the end point with a specified slope. The slope of the ramp has units of kW/sec, and the magnitude of the ramp has units of kW.

5.1.10.4 Output Performance

The key performance parameter measured during the response tests is the assessment of whether or not the FCS performed the transient in the specified period of time. This condition is considered to have been satisfied if the target power level is achieved and sustained without a failure or shutdown of the FCS within the claimed period of time.

5.1.10.4.1 Voltage Stability

Another performance parameter that is important in terms of integration of the FCS in the vehicle is voltage stability over the transient. Section 5.1.3.7 provides guidelines for determining voltage stability.

5.1.10.4.2 Start Point Voltage Stability

At the start of the transient the reactant supply may lag the current draw due to the power request. If this is the case, a voltage dip is likely. It is important to quantify this dip to ensure that the power electronics in the PCS will be able to power the vehicle through the transient.

5.1.10.4.3 End Point Voltage Stability

The reactant supplies are most likely controlled using automatic control algorithms. Such algorithms and other characteristics inherent to the FCS may result in low level instabilities at the end point of the transient. The purpose of this test is to determine the stability of FCS output voltage following a specified transient. Section 5.1.3.7 provides guidelines for determining voltage stability.

5.1.11 MASS

The mass of the FCS should be measured in the as-delivered configuration including all subsystems, components, plumbing, wiring and insulation that comprises the FCS. Fluid inventories should be filled to the nominal level.

5.1.11.1 Dry

The dry mass of the FCS is the mass of all mechanical and electrical structure, void of fluids consumed during the normal course of operation. This mass does include solid materials that may deteriorate over time, but that are not to be replaced through routine maintenance (i.e. catalysts, resins, membranes, seals and o-rings, etc).

5.1.11.2 Operating

The operating mass is the mass of the FCS as it is prior to a normal start. This mass includes any fluids that are normally consumed during the course of operation, or through the normal maintenance schedule (i.e. coolants, etc).

5.1.12 VOLUME

The volume of the FCS should be measured in the as-delivered configuration including all subsystems, components, plumbing, wiring, and insulation that comprises the FCS being tested.

5.1.12.1 Envelope

The envelope volume represents the three dimensional outline of the FCS assembly. It is calculated by multiplying the three maximum dimensions in each of the three typical Cartesian coordinates (x = width, y = height, and z = length). This measure includes void interstices between the assembled subsystems and components.

5.1.12.2 Environmental

Although four categories of environmental conditions are provided in section 1.3.16, the test parties should consider exploring the actual range of FCS operability beyond those conditions provided for reference.

5.1.12.3 Temperature Range

The temperature range over which the FCS is capable of delivering acceptable levels of performance, including freezing conditions.

5.1.12.4 Temperature Cycling

The capability of the FCS to continue to deliver acceptable performance over a repeated range of changing temperatures, including freezing.

5.1.12.5 Altitude / Pressure

The altitude above sea level for which the FCS is capable of delivering an acceptable level of performance. This is also a measure of the pressure range over which the FCS may operate.

5.1.12.6 Humidity

The range of ambient humidity over which the FCS is capable of delivering acceptable levels of performance, including water balance.

5.2 Test Precautions and Abnormalities

Reference 2 contains recommended practices for mitigation of potential hazards associated with fuel cell systems designed for vehicle integration. This reference should be consulted during design and testing of a fuel cell system, and before application of the current recommended practice.

The test article and test stand should be designed to sense, alarm and shutdown if necessary based on the presence of a hazard (reference section 2.2). The test article should be designed to maintain structural integrity at least over the expected period of test.

5.3 Test Procedures

This section outlines a suggested test sequence for performing the measurements described in the above sections. In order to confirm repeatable results, each test should be conducted more than once. The exact number of test runs should be per agreement of the test parties.

5.3.1 MEASUREMENT OF AMBIENT CONDITIONS

The ambient conditions of the test environment should be measured and recorded. These conditions include:

1. Temperature
2. Pressure
3. Composition and level of humidity

Each for:

1. Air supplied at the air processing sub-system boundary
2. Fuel supplied at the interface between the fuel supply system and the fuel processing system
3. Coolant supplied at the thermal management sub-system boundary

5.3.2 PHYSICAL PERFORMANCE PARAMETERS

5.3.2.1 *Dry Mass*

Prior to filling the FCS with fluids required for operation, the mass should be measured. Since conditioning of certain systems may require that the system be filled with fluids, all fluids should be drained, as if for shipping, prior to this measurement.

The FCS should be free standing on the scales used for this measurement, and should be disconnected from any testing facility. Personnel should not be in contact with the FCS during this test.

All components within the test boundary described in Figure 1, should be included in this measurement (including the FCCS). If it is unrealistic, or unduly cumbersome to measure the entire FCS at once, subsystems may be measured individually and the sum may be reported as the total mass. Instrumentation imposed on the FCS for the purposes of testing should be subtracted from any measure of mass. Instrumentation that is required for normal operation should be included in the measurement of mass.

The dry mass should be measured and recorded in kilograms (kg).

5.3.2.2 *Envelope Volume*

The FCS dimensions should be taken along three orthogonal coordinates as the maximum dimension along each coordinate. The envelope volume should be calculated by determining the product of these three dimensions.

The dimensions used for determining envelope volume should be taken in meters (m) and envelope volume should be recorded in meters cubed (m^3).

5.3.2.3 *Operating Mass*

Following the measurement of dry mass, the FCS should be filled with fluids as required for operation.

The measurement of FCS mass should be repeated as in Section 5.3.2.1 to determine the operating mass. Only those assemblies or components that have been changed as a result of the filling must have the mass measured a second time.

5.3.3 STEADY STATE PERFORMANCE

This section of the test description provides detail on the tests used to determine parameters related to power production and efficiency. The section is categorized in a similar fashion as section 5.1.2.1

5.3.3.1 *Maximum Voltage*

Prior to application of internal or external loads, the fuel cell system interface voltage should be measured and recorded. The purpose of this test is to determine the maximum voltage that is possible at the interface with the PCS.

Test Procedure:

1. Initiate a normal startup of the FCS
2. Do not apply any external load to the FCS
3. Record output voltage

5.3.3.2 *Idle Power*

Following a normal startup to power production mode, and prior to application of external load the fuel cell system interface voltage should be measured and recorded manually, in addition to automatic data acquisition. If external power is supplied to the fuel cell system in this mode of operation, it should be measured and recorded as well.

The fuel flow rate into the FCS should also be measured and recorded in order to determine fuel consumption at idle.

Test Procedure:

1. Record fuel LHV prior to test
2. Allow FCS to reach steady state at idle power, and operate at this power level for a designated period of time
3. Record output voltage and current
4. Record input power and any other energy supplied
5. Record fuel flow rate

5.3.3.3 *Maximum Design Efficiency Power*

The fuel cell system should have an external load applied that is equivalent to the point at which the maximum design efficiency of the system is achieved. The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

Upon reaching steady power production at the desired maximum design efficiency point the current and voltage should be measured and recorded manually in addition to automatic data acquisition.

Test Procedure:

1. Record fuel LHV prior to test
2. Allow FCS to reach steady state at maximum design efficiency power, and operate at this power level for a designated period of time
3. Record output voltage and current
4. Record input power and any other energy supplied
5. Record fuel flow rate
6. Reduce load

5.3.3.4 *Water Balance Power*

The fuel cell system should have an external load applied that is equivalent to the point at which the system is in water balance (i.e. neither generating a surplus of water or reducing the accumulate water resources within the system). The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

Upon reaching steady power production at the water balance point, the output current and voltage should be measured and recorded manually in addition to automatic data acquisition.

The system is considered to be in water balance if the level of the free surface in the system water accumulator remains unchanged for a duration of more than 60 minutes. An alternative method is to calculate the net water addition or loss as a result of inlet and exit flow rate and composition measurements (see Figure 1).

Test Procedure:

1. Record fuel LHV prior to test
2. Allow FCS to reach steady state at water balance power, and operate at this power level for a designated period of time
3. Record output voltage and current
4. Record input power and any other energy supplied
5. Record fuel flow rate
6. Reduce load

5.3.3.5 *Maximum Continuous Power*

The fuel cell system should have an external load applied that is equivalent to the point at which the maximum continuous power of the system is achieved. The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

Upon reaching steady power production at the desired maximum continuous power point the current and voltage should be measured and recorded manually in addition to automatic data acquisition.

The system operation at maximum continuous power is confirmed if the system continues to operate without intervention (other than reactant supply, coolant makeup and auxiliary power supply) for a period agreed upon by the test parties. A minimum of 60 minutes is recommended.

Test Procedure:

1. Record fuel LHV prior to test
2. Allow FCS to reach steady state at maximum continuous power, and operate at this power level for a designated period of time
3. Record output voltage and current
4. Record input power and any other energy supplied
5. Record fuel flow rate
6. Reduce load

5.3.3.6 Peak Power

The fuel cell system should have an external load applied that is equivalent to the point at which the peak power of the system is achieved. The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

Upon reaching steady power production at the desired peak power point, the current and voltage should be measured and recorded manually in addition to automatic data acquisition.

The duration of operation at this point should be measured in order to present along with the peak power point.

Operation at peak power may also result in the minimum voltage of the FCS.

Test Procedure:

1. Record fuel LHV prior to test
2. Allow FCS to reach steady state at maximum continuous power
3. Apply a load consistent with peak power, noting time when load is initially applied
4. Record output voltage and current
5. Record input power and any other energy supplied
6. Record fuel flow rate
7. Reduce load to maximum continuous power
8. Record time spent at peak power

5.3.4 TRANSIENT RESPONSE PERFORMANCE

The response of this system to a change in load is determined by reaching a set power point, changing the setting, and confirming FCS response within a specified time frame according to Section 5.1.10.3.

This test may be performed for an individual change in power or a series of changes in power to simulate a driving cycle. In either case, the change in power is defined in terms of a starting point and an end point. Additionally a time over which to make the change is defined according to either Section 5.1.10.3.1 (step) or 5.1.10.3.2 (ramp).

The fuel cell system should have an external load applied that is equivalent to the start point of the transient. The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

Upon reaching steady power production at the desired starting power point, the current and voltage should be measured and recorded manually in addition to automatic data acquisition.

The transient is performed by changing the load on the system as intended by the test definition agreed to by the test parties. It is assumed that the automatic control system will adjust the fuel cell system accordingly to respond to the load. A successful transient is achieved when the system performs the transient without a shutdown or permanent damage to the system within the specified period of time.

At this time, the fuel cell system should have an external load applied that is equivalent to the end point of the transient (or a ramped setpoint according to 5.1.10.3.2). The determination of this point is generally iterative and may be done prior to this test or as part of it. This decision is left to the test parties.

The time for this transient is determined by measuring the elapsed time between the start power just prior to the transient and the first attainment of the end point (either automatically via data acquisition or manually by test personnel). The power level at the end point should be held for at least 60 seconds and the voltage stability is to be measured and recorded according to section 5.1.3.

This transient test may be performed for either an up transient (in which the end point is a higher power than the start point) or a down transient (in which the end point is lower than the start point).

In the case of an up transient, the FCS may exhibit the minimum output voltage.

Test Procedure:

1. Allow the FCS to reach steady state operation at the starting point of the transient
2. Perform transient noting time of start
3. Allow the FCS to reach steady state operation at the end point of the transient
4. Record time at completion of transient
5. Record any energy input required during transient
6. Record voltage during the transient and note minimum value

5.3.5 COLD START PERFORMANCE

Cold start test method is intended to measure the performance of the fuel cell system in terms of starting from a relatively cold temperature. This test method includes the following steps:

A cold soak temperature should be agreed to by the test parties per section 5.1.10.1.1. The fuel cell system should be left at the cold soak temperature long enough for the cold, non-operational state of the system to be reached. Non-operational indicates that no external power is supplied to the fuel cell system.

The fuel cell system should be started with a single initiating action such as a key or switch. The instant when this state change occurs represents time zero. This state change should be logged along with other performance parameters as noted in section 4.2.12 to allow for determination of start time after the test.

The automatic control system should be allowed to bring the fuel cell system to power production mode. The end of the start is the instant at which the power level agreed to by the test parties is first achieved. This power level should be held for at least 60 seconds and the stability is to be measured and recorded according to section

Test Procedure:

1. "Cold soak" at a designated temperature
2. Initiate a normal startup of the FCS to a designated power level
3. Record start time
4. Record energy input
5. Confirm normal operation has been achieved

5.3.6 HOT START PERFORMANCE

The hot start test method is intended to measure the performance of the fuel cell system in terms of starting relatively close to the end of a preceding shutdown. This test method includes the following steps:

Following a normal start, the fuel cell system should have an external load applied that is equivalent to the point at which the maximum continuous power of the system is achieved per Section 5.3.3.5. The fuel cell system should be operated at this power point long enough for the system performance to stabilize.

The fuel cell system should be commanded to shutdown via normal (i.e. non emergency shutdown) means. The system should be allowed to reach a non-operation state. Non-operational indicates that no external power is supplied to the fuel cell system.

The system should be left in this state for a duration determined among the test parties. The test may be run with various off times to determine the sensitivity of performance to the off time.

The fuel cell system should be started with a single initiating action such as a key or switch. The instant when this state change occurs represents time zero. This state change should be logged along with other performance parameters as noted in section 4.2.12 to allow for determination of start time after the test.

The automatic control system should be allowed to bring the fuel cell system to power production mode. The end of the start is the instant at which the power level agreed to by the test parties is first achieved. This power level should be held for at least 60 seconds and the stability is to be measured and recorded according to section.

Test Procedure:

1. Start the FCS and allow to reach steady state
2. Initiate an automatic, normal shutdown of FCS
3. Standby for a designated period of time
4. Record standby time
5. Record any energy input required during standby period
6. Initiate an normal startup of FCS to a designated power level
7. Record startup time
8. Record any energy required for startup from standby mode
9. Confirm normal operation has been achieved

5.3.7 SHUTDOWN PERFORMANCE

5.3.7.1 Normal Shutdown

The main performance parameters associated with the shutdown of the FCS are the duration of the shutdown and the energy required to achieve the shutdown.

This test should start with the FCS running for a period sufficiently long enough to achieve steady state and to soak at operating temperatures. The fuel cell system should be shutdown with a single initiating action such as a key or switch. The instant when this state change occurs represents time zero. This state change should be logged along with other performance parameters as noted in section 4.2.12 to allow for determination of start time after the test.

The FCS shutdown will likely be controlled by the ACS and may require several automated actions to conclude the shutdown. The shutdown is considered complete with the entire FCS has reached a state consistent with the manufacturer's definition of shutdown. This is usually a de-powered state.

Test Procedure:

1. Operate the FCS at steady state
2. Initiate a shutdown
3. Record the amount of time required to shutdown
4. Record the amount of energy required to perform the shutdown
5. Confirm that the FCS has reached a state consistent with the manufacturer's definition of shutdown.

5.3.7.2 Emergency Shutdown

The main performance parameter associated with an emergency shutdown is that the system reaches a de-powered, safe state in an expedient manner.

This test should start with the FCS running for a period sufficiently long enough to achieve steady state and to soak at operating temperatures. An emergency shutdown should be initiated by the operator allowing the FCS to shutdown. This activity is normally instantaneous since a typical implementation of an emergency shutdown directly removes power from the FCS.

Test Procedure:

1. Operate the FCS at steady state
2. Initiate an emergency shutdown
3. Record the amount of time required to shutdown
4. Confirm that the FCS has reached a safe state consistent with the manufacturer's definition of shutdown.

The functionality of the emergency shutdown should be confirmed not only at steady state but also during transient, start-up and shut-down modes.

6. Data Management, Analysis and Reporting

6.1 Data Management

Reference 14 prescribes guidelines for the management of data collected before, during and after a performance test. An abbreviated discussion of those guidelines are provided here. The user is referred to Reference 14 for a more comprehensive discussion of data management issues.

6.1.1 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.