



SURFACE VEHICLE RECOMMENDED PRACTICE

SAE J2617

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Recommended Practice for Testing Performance of PEM Fuel Cell Stack Sub-system for Automotive Applications

RATIONALE

The goal of this Recommended Practice is to provide a method for users to conduct fuel cell stack sub-system functional tests on a common basis that will allow the comparison of fuel cell stack sub-systems with different designs where no specific fuel cell system design has been identified. Alternatively, the functional performance of a specific fuel cell stack sub-system can be assessed in the context of a specific fuel cell system design based on the agreement of the testing parties.

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FOREWORD

This Recommended Practice document was prepared by the Performance Working Group within the SAE Fuel Cell Standards Committee. This document is consistent with SAE J2615 Fuel Cell System and SAE J2616 Fuel Cell Processor Sub-system Performance Test documents. 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.

INTRODUCTION

1. SCOPE

This recommended practice is intended to serve as a procedure to verify the functional performance, design specifications or vendor claims of any PEM (Proton Exchange Membrane) type fuel cell stack sub-system for automotive applications. In this document, definitions, specifications, and methods for the functional performance characterization of the fuel cell stack sub-system are provided. The functional performance characterization includes evaluating electrical outputs and controlling fluid inputs and outputs based on the test boundary defined in this document.

In this document, a fuel cell stack sub-system is defined to include the following:

- Fuel cell stack(s) – An assembly of membrane electrode assemblies (MEA), current collectors, separator plates, cooling plates, manifolds, and a supporting structure.
- Connections for conducting fuels, oxidants, cooling media, inert gases and exhausts.
- Electrical connections for the power delivered by the stack sub-system.
- Devices for monitoring electrical loads.
- Devices for monitoring cell voltage.
- Humidification devices.
- Instrumentation for detecting normal and/or abnormal operating conditions.
- Enclosures (that may qualify as pressure vessels), and ventilation systems for the enclosure.

Not included in the sub-system are the following:

- Fuel and air processors
- Thermal management system
- Power conditioner and distributor
- Controllers

1.1 Limitations of Recommended Practice

The test article of this document is the fuel cell stack sub-system that is the primary component within the fuel cell power system. Therefore, it may not represent the performance characterization of either the fuel cell system or the stack sub-system components. Among different types of fuel cell stack sub-systems, only the PEM type is covered in this document.

A generic test boundary that specifies the power inputs and outputs is defined in this document (Section 5.1.1). If other configurations are used, modifications to the test boundary should be made based on the agreement of the testing parties.

This document is designed to determine the functional performance characterization of a PEM fuel cell stack sub-system at the beginning of life. This document does not cover the following:

- **Start up characteristics** of a fuel cell as this property is highly dependant on the system to which it is connected. All start ups should be carried out according to a protocol provided by the stack manufacturer/supplier, unless a different protocol is agreed to by the testing parties.
- **Robustness performance** characteristics such as the effects on the fuel cell stack sub-system by tilt, vibration, and harshness are not included in this document. These should be considered in conjunction with fuel cell vehicle requirements
- **Cumulative effects due to fluid contamination.** The cleanliness of fluid inputs such as maximum parts per million of sulfur and chlorine should be determined by the testing parties prior to stack sub-system testing. For minimizing the effect of carbon monoxide residuals within the fuel cell stack, the fuel input line may be equipped with an air bleed.
- **Performance related to governmental regulations or certification.**
- **Shelf life, aging, and piece-to-piece variance of the fuel cell stack sub-system.**
- **Environmental effects** such as temperature, humidity, and altitude of the area around the stack.

The discussion of general safety is not included. However, general fuel cell system safety is covered in SAE J2578. Safety concerns and precautions specific to the fuel cell stack sub-system and its testing methods are addressed in this document.

In this document, the formula used to calculate stack sub-system efficiency is based on stack power produced relative to the lower heating value of the hydrogen gas consumed (see Equation 4 in Section 7.2.3). This approach was chosen instead of one based on calculating Gibbs' free energy for the following reasons:

- a. The Gibbs' free energy must assume a single temperature throughout the stack, and this is not always the case.
- b. The Gibbs' free energy makes use of an 'ideal voltage' that is not strictly valid in a system where temperatures are not fixed.
- c. The approach taken can be verified empirically, without making any assumptions.
- d. The approach taken can be easily integrated into a fuel cell system calculation and thus can be related mathematically to the work in SAE J2615 and SAE J2616.

2. REFERENCES

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

2.1 Applicable Publications

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

2.1.1 SAE Publications

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J2574	Fuel Cell Vehicle Terminology
SAE J2578	Recommended Practice for General Fuel Cell Vehicle Safety
SAE J2615	Testing Performance of Fuel Cell Systems for Automotive Applications
SAE J2616	Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
SAE J2719	Information Report on the Development of a Hydrogen Quality Guideline for Fuel Cell Vehicles

2.1.2 NIST Publication

Available from National Institute of Standards and Technology, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

NIST Technical Note 1297 (1994 Edition) Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results

2.1.3 NFPA Publication

Available from the National Fire Protection Agency, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

NFPA 70 National Electrical Code, Article 500—Hazardous (Classified) Locations, Classes I, II, and III, Divisions 1 and 2

2.1.4 ASME Publications

Available from the ASME, 22 Law Drive, PO Box 2900, Fairfield, NJ 07007-2900, Tel: 973-882-1170, www.asme.org.

ASME PTC 50 Performance Test Code 50 on Fuel Cell Power Systems Performance

ASME PTC 19.1 Measurement Uncertainty

2.1.5 DOE/FETC Publication

Available from the National Technical Information Service, US Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, USA, www.ntis.gov.

Fuel Cell Handbook, Fourth Edition, DOE/FETC-99/1076

2.1.6 CGA Publication

Available from Compressed Gas Association, 4221 Walney Road, 5th Floor, Chantilly VA 20151-2923, Tel: 703-788-2700, www.cganet.com.

CGA G-7.1 Grade J—Compressed Gas Association Specialty Grade Air

2.2 Related Publications

The following publications are provided for information purposes and are not a required part of this document.

2.2.1 SAE Publications

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1349 Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating

SAE J1715 Electrical Vehicle Terminology

2.2.2 NIST Publication

Available from National Institute of Standards and Technology, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

NIST Special Publication 811 (1995 Edition) Guide for the Use of the International System of Units (SI)

2.2.3 NFPA Publications

Available from the National Fire Protection Agency, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

NFPA 50A Standard for Gaseous Hydrogen Systems at Consumer Sites

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

2.2.4 CSA Publication

Available from CSA America, 8501 East Pleasant Valley Road, Cleveland, OH 44131-5575, Tel: 216-524-4990, www.csa-america.org.

CSA Component Acceptance Service No. 33

2.2.5 ASTM Publication

Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D1193-99 Standard Specifications for Reagent Water

2.2.6 ASME Publication

Available from the ASME, 22 Law Drive, PO Box 2900, Fairfield, NJ 07007-2900, Tel: 973-882-1170, www.asme.org.

ASME Boiler and Pressure Vessel Code Section V Article 10

2.2.7 IEEE Publication

Available from the IEEE, 445 Hoes Lane, Piscataway, NJ 08854-1331, Tel: 732-981-0060, www.ieee.org.

IEEE 90 Institute of Electrical and Electronics Engineers, IEEE Standard Computer Dictionary

3. DEFINITIONS

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

3.1 Active Area

Active area refers to the catalyzed area of a MEA. Typically, the size of the active area is equal for both the anode and cathode sides of a MEA and among all MEAs within a fuel cell stack sub-system. The size of the active area should be supplied by the stack supplier so that the current density can be calculated.

3.2 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 ₂ O	0.0128 (wet basis)

3.3 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.

3.4 Anode

The electrode at which oxidation occurs.

3.5 Catalyst Coated Membrane (CCM)

Term used to describe a membrane (in a PEM fuel cell) whose surfaces are coated with a catalyst layer to form the reaction zone of the electrode.

3.6 Cathode

The electrode at which reduction occurs.

3.7 Consistent Liquid or Gaseous Fuels

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

3.8 Current Collector

Term used to describe the conductive material in a fuel cell that collects electrons (on the anode side) or disburse electrons (on the cathode side).

3.9 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.

3.10 Electrode

The conducting body through which current enters or leaves a cell.

3.11 Electrolyte

The medium that provides ion transport between the positive and negative electrodes of a cell.

3.12 Fuel Cell

Electrochemical energy conversion device in which fuel and oxidant react to generate electricity without any consumption, physically or chemically, of its electrodes or electrolyte.

3.13 Fuel Cell Control System (FCCS)

A system which monitors fuel cell system conditions and responds automatically to provide power for the vehicle 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 Fuel Cell Stack

An assembly of membrane electrode assemblies (MEA), current collectors, separator plates, cooling plates, manifolds, and a supporting structure that electrochemically converts hydrogen rich gas and air (oxygen) reactants to DC power, heat, water and other byproducts. The fuel cell stack is also known as the fuel cell stack assembly or cell stack assembly.

3.15 Fuel Cell Stack Sub-system (FCSS)

An assembly containing one or more fuel cell stacks which provide for the reaction of fuel and oxidant to produce electric current by means of the electrochemical reaction. The FCSS generally includes: connections for conducting fuels, oxidants, and exhausts; electrical connections for the power delivered by the stack sub-system; a device for monitoring single cell voltages; and a 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, means to humidify gases and ventilation systems. The FCSS is also referred as the fuel cell power module or the fuel cell module.

3.16 Fuel Cell System (FCS)

A combination of sub-systems and components designed to provide electrical power as a result of the implementation of a fuel cell (defined above). 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 0 and may include, for example, a fuel processing sub-system, a thermal management sub-system, an air processing sub-system and a power distribution sub-system.

3.17 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 reformat gas or simply reformat. 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.

3.18 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.

3.19 Gas Diffusion Layer (GDL)

The gas diffusion layer is a device that facilitates the removal of product water and the supply of reactant gases to the electrode.

3.20 Maximum Continuous Power

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

3.21 Membrane Electrode Assembly (MEA)

Structure consisting of a proton exchange membrane with surface in contact with catalyst/carbon/binder layers and sandwiched by two micro porous conductive layers (which function as the gas diffusion layers (GDL)) and current collectors. When combined with the current collectors, the MEA is referred as an integrated or unitized MEA.

3.22 Open Circuit Voltage (OCV)

The voltage measured at the terminals when a fuel cell stack sub-system is disconnected from an external circuit. Also called no-load voltage.

3.23 Peak Power

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

3.24 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.

3.25 Power Distribution Sub-system (PDS)

The collection of components that connects the fuel cell stack sub-system to the power conditioning system and which 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 0, the PDS has only DC power as input.

3.26 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.

3.27 Proton Exchange Membrane (PEM)

The separating layer in a PEM fuel cell that acts as an electrolyte that is proton conducting as well as a barrier film separating the hydrogen-rich feed in the anode compartment of the cell from the oxygen-rich cathode side.

3.28 Proton Exchange Membrane Fuel Cell (PEMFC or PEFC)

A type of acid based fuel cell in which the exchange of protons (H⁺) from the anode to the cathode is achieved by a solid membrane impregnated with an appropriate acid.

3.29 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 document the reference conditions are as follows:

Temperature: 288.15 °K (15 °C, 59 °F)
Pressure: 101.325 kPa (1 atmosphere, 14.696 psia)
Air: 60% relative humidity (0.006 kg H₂O/kg dry air) at 15 °C

3.30 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 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.

3.31 Reliability

The ability of a system or component to perform its required functions under stated conditions for a specified duration; measured using probability.

3.32 Separator Plate

A solid piece of electrically conductive material (usually a metal or graphite) that separates gases on the anode in one cell from gases on the cathode of adjacent cells. The separator plate is also known as the bipolar plate or the monopolar plate

3.33 Stack Sub-system Temperature

The temperature of the fuel cell stack sub-system should be defined by test parties prior to tests and calculated based on actually measured parameters such as coolant flow temperatures, fluid flow temperatures, and individual cell temperatures.

3.34 Test Facility

A physical area and requisite utilities designated for the purpose of testing the performance of a fuel cell stack sub-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.

3.35 Test Reading

One recording of all required test instrumentation.

3.36 Test Run

A group of test readings taken while the test article is operating at steady state at a specified operating condition.

3.37 Test Stand

The fixture and supporting equipment in which a test article is placed to conduct a performance test.

3.38 Test Article

The fuel cell stack sub-system or component of the fuel cell stack sub-system that is being evaluated in the test facility.

3.39 Testing Parties

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

3.40 Test Operator(s) / Personnel

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

3.41 Thermal Equilibrium Condition

The temperature of a system or process when it is in equilibrium to environmental temperature in a specified time and space prior to testing or operation.

3.42 Thermal Equivalence Condition

The temperature of a system or process, when performing its required functions, is kept constant or changes negligibly over the specified time and space.

3.43 Thermal Management Sub-system (TMS)

The assembly of components that 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, and may provide water recovery and process humidification functions.

3.44 Vehicle Control System (VCS)

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

3.45 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.

3.46 Test Operating Conditions (TOC)

A set of operating conditions that have been agreed to by all parties as the 'normal' set points under which the test article is to be operated during the test. Changes in these conditions are made as the basis for the operational sweep checks listed in this document.

4. NOMENCLATURE, PHYSICAL CONSTANTS AND UNITS

4.1 Physical Characteristics

A_{active}	Active area of a single cell (cm^2)
N_{cell}	Number of cells in a fuel cell stack sub-system (-)
$\text{Vol.}_{\text{stack sub-system}}$	Envelope volume of fuel cell stack sub-system (L)
$M_{\text{dry-stack sub-system}}$	Dry mass of fuel cell stack sub-system (kg)
$M_{\text{operating-stack sub-system}}$	Operating mass of fuel cell stack sub-system (kg)

4.2 Controlled and/or Measured Parameters

$I_{\text{stack sub-system}}$	Stack sub-system current (A)
$E_{\text{stack sub-system}}$	Stack sub-system voltage (DC V)
E_{cell}	Cell voltage (DC V)
T_{cell}	Cell temperature ($^{\circ}\text{K}$)
$m'_{\text{hydrogen-consumed}}$	Mass flow-rate of consumed dry hydrogen (kg/s)
$m'_{\text{fuel-input}}$	Mass flow-rate of fuel dry-gas input (kg/s)
$p_{\text{fuel-input}}$	Fuel input absolute pressure (kPa)
$T_{\text{fuel-input}}$	Fuel input temperature ($^{\circ}\text{K}$)
$\text{RH}_{\text{fuel-input}}$	Fuel input humidity (%)
λ_{fuel}	Fuel mass stoichiometric ratio (-)
---	Gas compositions of fuel input (ppm)
$p_{\text{fuel-output}}$	Fuel output absolute pressure (kPa)
$T_{\text{fuel-output}}$	Fuel output temperature ($^{\circ}\text{K}$)

$m'_{\text{oxidant-input}}$	Mass flow-rate of oxidant dry-gas input (kg/s)
$p_{\text{oxidant-input}}$	Oxidant input absolute pressure (kPa)
$T_{\text{oxidant-input}}$	Oxidant input temperature ($^{\circ}\text{K}$)
$\text{RH}_{\text{oxidant-input}}$	Oxidant input humidity (%)
λ_{oxidant}	Oxidant mass stoichiometric ratio (-)
---	Gas compositions of oxidant input (ppm)
$p_{\text{oxidant-output}}$	Oxidant output absolute pressure (kPa)
$T_{\text{oxidant-output}}$	Oxidant output temperature ($^{\circ}\text{K}$)
m'_{coolant}	Mass flow-rate of coolant (kg/s)
$p_{\text{coolant-input}}$	Coolant input absolute pressure (kPa)
$T_{\text{coolant-input}}$	Coolant input temperature ($^{\circ}\text{K}$)
$C_{\text{coolant-input}}$	Coolant electrical conductivity ($\mu\text{S}/\text{cm}$)
$p_{\text{coolant-output}}$	Coolant output absolute pressure (kPa)
$T_{\text{coolant-output}}$	Coolant output temperature ($^{\circ}\text{K}$)

4.3 Calculated or Estimated Parameters

$J_{\text{stack sub-system}}$	Stack sub-system current density (mA/cm^2)
$E_{\text{average-cell}}$	Average cell voltage (DC V)
$P_{\text{stack sub-system electrical}}$	Stack sub-system power (kW)
$T_{\text{stack sub-system}}$	Stack sub-system temperature ($^{\circ}\text{K}$)
η_{FCSS}	Efficiency of fuel cell stack sub-system (%)

TABLE 1 - CONSTANT PROPERTIES

Constant or Physical Property	Unit	Value
Reference temperature (T_{ref})	$^{\circ}\text{K}$	288.15
Reference pressure, absolute (p_{ref})	kPa	101.325
Lower heating value of hydrogen gas ($\text{LHV}_{\text{hydrogen}}$)	kJ/kg	120 000

5. PRE-TEST CONDITIONS

This section outlines the recommended steps required to plan, conduct, and evaluate a functional performance test of a PEM fuel cell stack sub-system. The subsections discuss the following:

- Definition of Test article with Schematic
- Specifications of Test Facility and Equipment
- Inspection of Test article and Connections to Facilities and Equipment
- Pretreatment Procedures
- Shutdown
- Test Plan
- Training of Test Personnel
- Agreements

5.1 Definition of Test Article 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 oxidant (usually oxygen from air) to produce DC power, water, and heat. A system should be built around the fuel cell stack sub-system 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 sub-system.

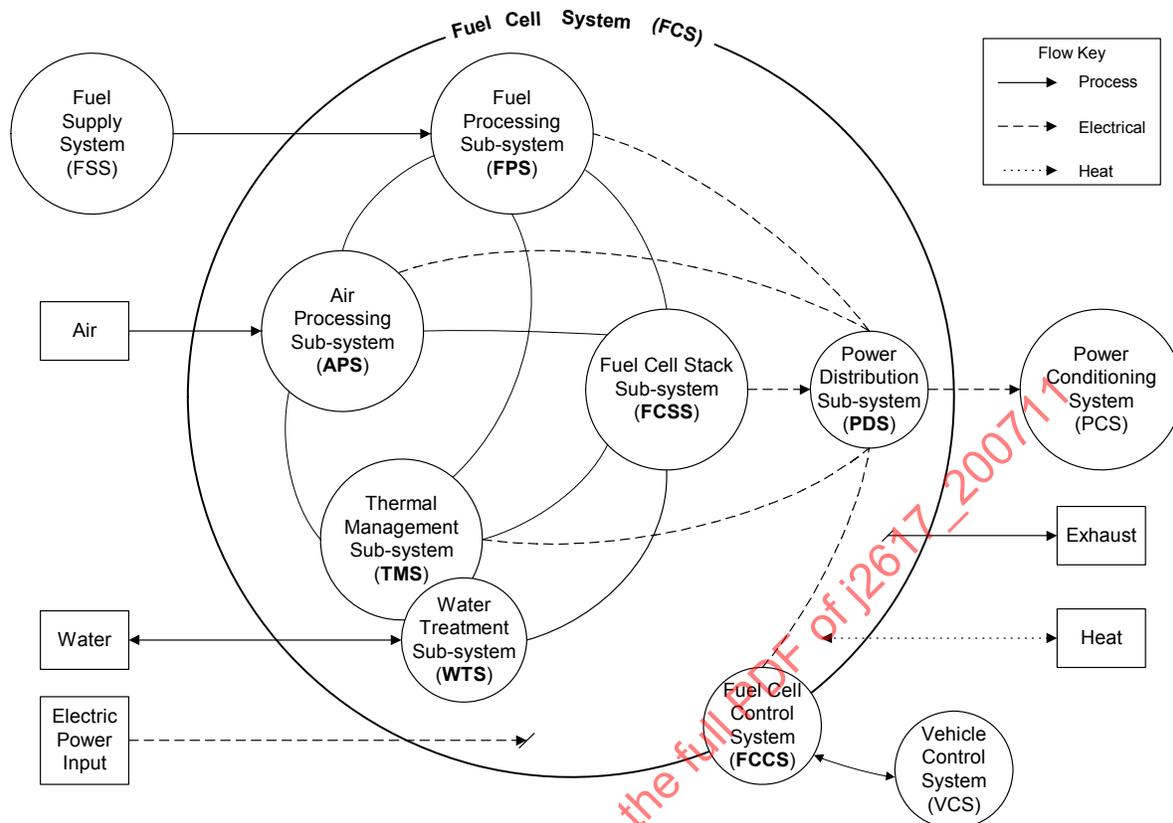


FIGURE 1 - SCHEMATIC ILLUSTRATING A GENERIC FUEL CELL SYSTEM

The test article of this document is the fuel cell stack sub-system that is the primary component within the fuel cell power system. Among different types of fuel cell stack sub-systems, only the PEM (Proton Exchange Membrane) type is covered in this document. A typical PEM fuel cell stack sub-system includes one or more fuel cell stacks which provide for the reaction of fuel and oxidant to produce electric current by means of the electrochemical reaction. It might also include connections for conducting fuels, oxidants, and exhausts; electrical connections for the power delivered by the stack sub-system; a device for monitoring single cell voltages; and means for monitoring electrical loads. Additionally, a typical PEM fuel cell stack sub-system might 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, a method to humidify reactant gases. Other components such as fuel and air processors, thermal management, power conditioner and distributor, and controllers, which are required to effectively convert input fuel and oxidant into output electrical and thermal energy at the system level, are not included in the sub-system.

5.1.1 Test Boundary and Specifications of Test Article

The test boundary serves to define the interfaces between a fuel cell stack sub-system and its inputs and outputs. Different systems will result in different test boundaries based on conceptual design and integration philosophies. The testing parties should define the test boundaries before the start of the test. For this document, a generic and representative form of a fuel cell stack sub-system is defined and illustrated in Figure 2 which contains multiple inputs and outputs as follows:

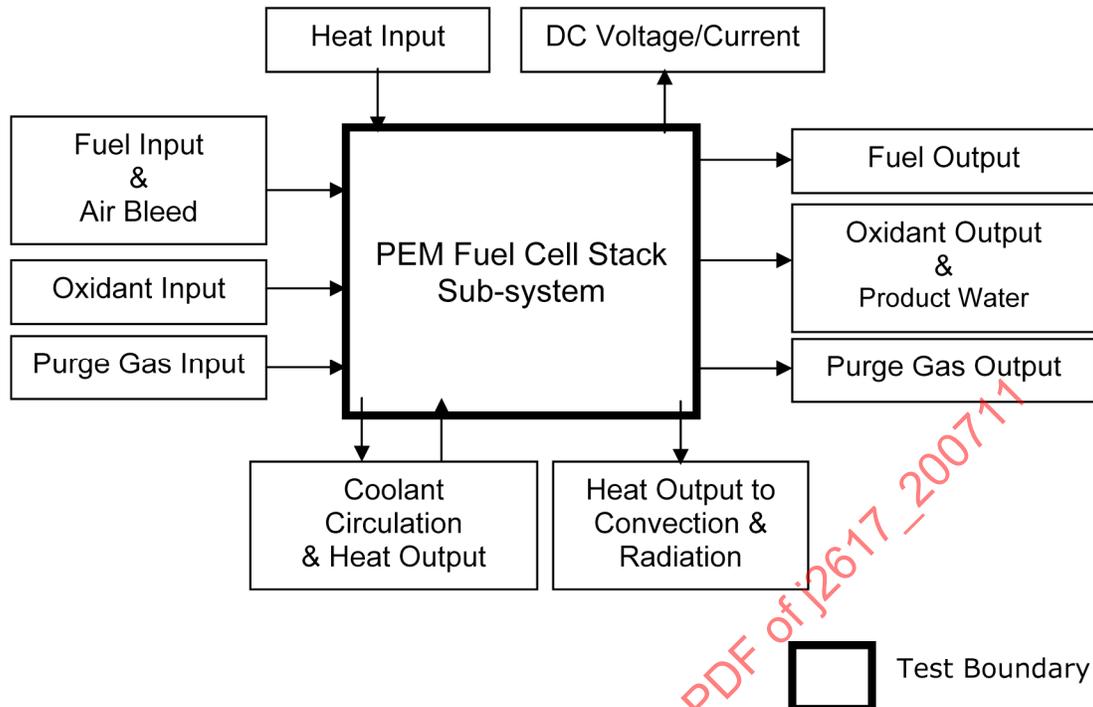


FIGURE 2 - TEST BOUNDARY OF A GENERIC FUEL CELL STACK SUB-SYSTEM

5.1.1.1 Fuel Input

The fuel (anode) input should be hydrogen based and in a gaseous form delivered to the fuel cell stack sub-system with the required composition. At the entrance of the test boundary, the fuel input should be conditioned in terms of pressure, temperature, and humidity and provided at a rate that is specified either by the stack supplier or by the testing parties. Some fuel cell stack sub-systems also may be equipped with air bleeds at the line of the fuel input to convert carbon monoxide residuals within the stacks. Appendix A includes examples of fuel input compositions. Refer to Appendix B for the measurement locations of the input.

5.1.1.2 Oxidant Input

The oxidant (cathode) input should be in a gaseous form and delivered to the fuel cell stack sub-system with the required composition. At the entrance of the test boundary, the oxidant input also should be conditioned in terms of pressure, temperature, and humidity and provided at a rate that is specified either by the stack supplier or by the testing parties. Appendix A includes an example of oxidant input composition. Refer to Appendix B for the measurement locations of the input.

5.1.1.3 Purge Gas Input

The test stand for the fuel cell stack sub-system should be equipped with a purging system. If necessary, the system should use an inert gas to remove any combustible gases from the stack sub-system when the power of the stack sub-system is off.

5.1.1.4 Heat Input

In order to achieve effective electrochemical reactions, some fuel cell stack sub-systems may need to be heated by an external heating source, especially during startup modes. Means should exist in the test station to deliver heat input independent of other test inputs.

5.1.1.5 Fuel, Oxidant, Purge Gas and Product Water Outputs

Exhaust gases (including purge gases, if used) and product water should be taken care of in an appropriate manner.

5.1.1.6 Coolant Circulation and Heat Output

If a fuel cell stack sub-system is equipped with a cooling system, the coolant should consist of de-ionized water or other suitable anti-freeze that meets the stack manufacturer's requirements for conductivity (measured in $\mu\text{S}/\text{cm}$) and conditioned in terms of pressure and temperature. The stack supplier should provide a recommended coolant control procedure and this should be agreed to by the testing parties before testing.

5.1.1.7 DC Voltage and Current

The DC voltage of the fuel cell stack sub-system can be measured at the individual cell level, the individual stack level, and the gross stack sub-system level. In this document, voltages at all three levels are used for the performance characterization of the fuel cell stack sub-system.

5.1.1.8 Heat Output to Convection and Radiation

In addition to heat output through a cooling system, excess heat is rejected from a fuel cell stack sub-system in the form of convection and radiation. The total amount of the exhausted heat may be estimated from energy boundary calculations based on other inputs and outputs of the test boundary.

5.2 Specifications for Test Facility and Equipment

This section provides recommendations about the general specifications for a fuel cell test facility and equipment.

All electrical (including sensors and instrumentation) test equipment should be classified in accordance with the requirements of NFPA 70 National Electrical Code, Article 500 in conjunction with its operating environment. This should include adequate ventilation, electrical grounding and bonding, emergency shutdown capability, inert gas purging, and visible/audible alarms.

5.2.1 Gas/Flame Detection System

Indoor test facilities should provide for continuous monitoring of hazardous conditions including combustible and toxic gases, and flame detection. The sensors should be connected to an alarm system and the test station gas supply emergency shut off valves. Audible and visible alarms should be provided for the prompt communication of the nature and general location of the hazard.

5.2.2 Facility Ventilation

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

5.2.3 Shutdown Precautions

The test facility should provide for appropriate and timely shutdown in the case of a hazardous situation through the use of a gas/flame detection system for dangerous accumulations of combustible or toxic gases. The test facility should also include a manually activated alarm. Additionally, it is recommended that the test stations provide a clearly marked manual emergency shutdown command to be used at the discretion of the test operator.

5.2.4 Purge Gas Storage and Supply System

The test facility should have a gas storage and supply system that can provide inert gas such as nitrogen to the test stand and fuel cell stack sub-system, if necessary. The purge gas should be available before and after testing, and during emergency shutdowns. The gas storage should be designed in accordance with applicable local fire regulations.

5.2.5 Fuel Storage and Supply System

The test facility should have a fuel storage area and supply system that is designed in accordance with applicable local fire regulations. The storage area should be adequately ventilated, appropriately distanced from any sources of ignition, labeled appropriately and secured from tampering. All associated electrical equipment should be rated in accordance with the appropriate Electrical Code.

5.2.6 Oxidant Storage and Supply System

The test facility should have an oxidant storage and supply system to provide clean/dry oxidant to the test stand at specified conditions. Should the oxidant consist of stored oxygen, its storage should be designed in accordance with applicable local fire regulations. The storage area should be adequately ventilated, appropriately distanced from any sources of ignition, labeled appropriately and secured from tampering. All associated electrical equipment should be rated in accordance with the appropriate Electrical Code.

5.2.7 Coolant Storage and Supply System

The test facility should have a coolant storage and supply system for the test stand. The conditions and conductivity of the coolant should be specified and monitored by the testing parties.

5.2.8 Data Acquisition and Timing Equipment

A data collection system should be available to collect data automatically at a rate sufficient to obtain meaningful results. The data should be stored in a secure area that can be accessed by all authorized parties for further analysis.

5.2.9 Test Stand Requirements

The fuel cell test stand typically provides appropriately conditioned fuel, oxidant, and coolant inputs to the fuel cell stack sub-system. Users should be able to control and collect data on stack sub-systems while varying parameters such as gas composition, flow-rate, pressure, temperature, and stack sub-system load. Both the fuel and oxidant gases might be required to be humidified before entering the stack sub-system. The voltages of the cells within a fuel cell stack sub-system may be individually monitored as requested. The equipment may provide means of sampling or collecting product water. The test equipment should have a means of measuring the conductivity of the coolant. In the event of dangerous or unusual operating conditions, the test stand should be capable of providing a safe shutdown.

5.2.10 Test Equipment Calibration

All test equipment and related instrumentation should be calibrated 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 the above codes as well.

5.2.11 Pretest Records

At a minimum the following should be documented regarding the test article prior to the start of testing:

- 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 article and Connections to Facilities and Equipment

5.3.1 Inspection of Test Article

Upon receipt of the test article at the test facility, it should be inspected to ensure no damage incurred during transport. Any fabrication documentation and certifications should accompany shipment of the test article.

5.3.2 Measurement of Mass and Volume

The mass and volume of the test article should be measured in the as-delivered configurations, including all components that comprise the fuel cell stack sub-system.

5.3.2.1 Operating Mass

The operating mass is the mass of the fuel cell stack sub-system as it is prior to a normal start. This mass includes any fluids which are normally present during the course of operation, or through the normal maintenance schedule (i.e. coolants, etc.).

5.3.2.2 Envelope Volume

The envelope volume represents the three dimensional outline of the fuel cell stack sub-system. 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 components.

5.3.3 Leak Detection and Gas Purging

All test equipment should be leak 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). The testing parties should agree to a procedure and parameters for the leak check before the start of testing.

Prior to testing, the fuel cell stack sub-system should be leak tested for crossover from anode to cathode, from gases to coolant as well as external leaks for each fluid manifold. Leak testing pressure values and limitations should be provided by the stack sub-system supplier, especially for crossover tests.

All lines containing combustible gases should be purged with an inert gas before and after all testing, and prior to any maintenance work performed on these lines. The inlets and outlets of the stack sub-system should be sealed when it is not in use to prevent contamination.

5.3.4 Electrical Connections

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

5.3.5 Functional Check

The complete test system should be determined to be functionally sound prior to the test. This determination requires a check 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 cell stack sub-system may be addressed separately if documentation of each test component is provided in the test report.

5.4 Pretreatment Procedures

5.4.1 Conditioning and Cell Shorting

A new fuel cell stack sub-system should be conditioned as per manufacturer specifications before testing is performed.

Prior to the start of testing, each cell should be individually inspected for electrical shorting by observing cell voltage at the open circuit condition with the minimum rates of fuel and oxidant inputs. If the open circuit voltage does not meet the manufacturer's specifications, the cell should be replaced prior to testing, unless otherwise agreed to by the testing parties.

The fuel cell stack sub-system supplier should specify how it is to be stored once the stack has been run – this may include caps or sealing devices for the fluid ports.

5.5 Startup and Shutdown Procedures

The fuel cell stack sub-system supplier should specify a startup procedure and a shut down procedure (including emergency shut downs) for the sub-system before performance testing is conducted. The testing parties should agree on performance measurements to be made during startup and shutdown and also establish purging requirements.

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:

- Test purpose and goals
- Date when the test is to be conducted and test schedule
- List of agreements among testing parties as identified throughout this document
- Location of the test: at the manufacturer's facility, the customer site, or other location that is acceptable to the testing parties
- Equipment calibration schedule or procedures.
- Designation of the laboratory and any other facilities required for determining pertinent fuel characteristics
- Requisite facilities for maintaining constancy of load during test, if applicable
- Type, number, and systematic uncertainty of all equipment to be used to establish test conditions and test results and how they should be installed
- Extent of the system to be tested, i.e., test boundary
- Base reference conditions
- Data to be recorded, and method of recording and archiving data
- Personnel to conduct the test, and the responsibilities of each individual in certifying that the test is conducted in accordance with the recommended practice
- Procedures for recording the test data and observations, including sample frequency
- Duration of each test segment
- Acceptance of test when disruptions occur
- Acceptance criteria for test completion
- Number of identical tests to be conducted to assure statistically significant accuracy and repeatability
- 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.
- The expected sequence of testing

5.7 Training of Test Personnel

All test personnel should be well trained on the use of the test station, test facility equipment, fuel cell stack sub-system 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, exceptions and plan for the test. The parties normally include the purchaser/customer, vendor or fuel cell stack sub-system supplier, and possibly an independent contractor, for example, a testing agency.

6. TEST SEQUENCE DESCRIPTION

Prior to the start of testing, a set of Test Operating Conditions (TOC) needs to be agreed upon by all testing parties. These could be based on the stack supplier's recommendations or a customer system requirement. The TOC should be presented in a table as shown below. All values are related to a current density as the active area of different stack designs will vary. More rows can be added, as necessary

TABLE 2 - SAMPLE FORMAT FOR PRESENTING NORMAL OPERATING CONDITIONS
FOR STACK SUB-SYSTEM TESTING

J (A/cm ²)	Anode Stoichiometric Ratio	Anode P _{in} (barg)	Anode Dew pt (°C)	Cathode Stoichiometric Ratio	Cathode P _{in} (barg)	Cathode Dew pt (°C)	Coolant Inlet Temperature (°C)	Coolant Inlet Pressure	Coolant Flow Rate	Coolant dT (°C)
0.05	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
0.1	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
0.2	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
0.4	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
0.6	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
0.8	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
1.0	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z
1.2	X.X	Y.YY	ZZ.Z	X.X	Y.YY	ZZ.Z	ZZ.Z			Z.Z

The coolant pressure set point should be either as defined by the stack supplier or as agreed to by the testing parties. Rather than the dT, a coolant flow rate may be specified, if agreed to by the testing parties. The test sequence to be carried out to characterize the functional performance of the stack sub-system is shown below as a diagram and as a table.

For all tests, all cell voltages should be monitored and recorded so that the minimum, maximum, average and standard deviation of these values can be obtained. The testing parties may agree not to monitor individual cell voltages and this should be stated in the report.

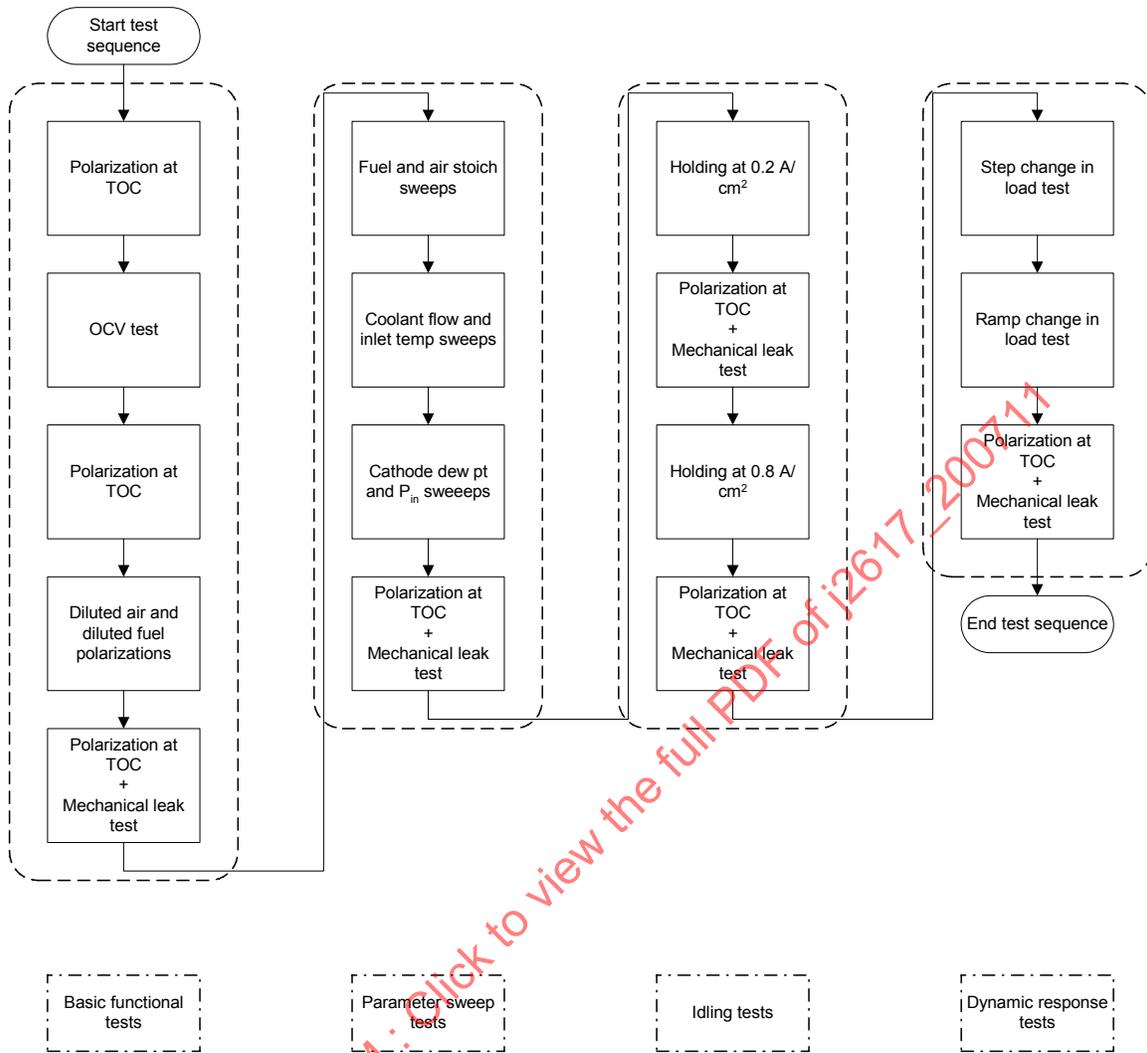


FIGURE 3 - TEST SEQUENCE FOR DETERMINING FUNCTIONAL PERFORMANCE OF A STACK SUB-SYSTEM

TABLE 3 - TEST SEQUENCE FOR DETERMINING FUNCTIONAL PERFORMANCE OF A STACK SUB-SYSTEM

Section	Test Description
3.2.1	H ₂ /Air polarization @ TOC
3.1	OCV Test
3.2.1	H ₂ /Air polarization @ TOC
3.2.2	H ₂ /Diluted O ₂ polarization @ TOC
3.2.3	Dilute H ₂ /Air polarization @ TOC
3.2.1	H ₂ /Air polarization @ TOC
	Perform mechanical leak test
3.3.1	Fuel Stoichiometry Sweep on H ₂ /Air
3.3.2	Air Stoichiometry Sweep on H ₂ /Air
3.3.3	Coolant Flow rate Sweep on H ₂ /Air
3.3.4	Coolant Inlet Temperature Sweep on H ₂ /Air
3.3.5	Cathode Inlet Dew Point Sweep on H ₂ /Air
3.3.6	Cathode Inlet Pressure Sweep on H ₂ /Air
3.2.1	H ₂ /Air polarization @ TOC
	Perform mechanical leak test
3.4.1	Holding at H ₂ /Air at 0.20 A/cm ²
3.2.1	H ₂ /Air polarization @ TOC
	Perform mechanical leak test
3.4.2	Holding at H ₂ /Air at 0.80 A/cm ²
3.2.1	H ₂ /Air polarization @ TOC
	Perform mechanical leak test
3.5.1	Step change to load on H ₂ /Air from 0.20 A/cm ² to 0.80 A/cm ²
3.5.2	Ramp change to load on H ₂ /Air from 0.20 A/cm ² to 0.80 A/cm ² at a rate of 0.06 A/cm ² /sec
3.2.1	H ₂ /Air polarization @ TOC
	Perform mechanical leak test

6.1 OCV Test

Purpose: To determine the open circuit potential, determine whether there is shorting in cell(s), to determine the rate at which hydrogen diffuses through the membrane, and to provide a baseline for future diagnostic shorting/crossover tests.

Procedure: Flow H₂/Air to the unit under test, measure open circuit voltage, turn off Air, and allow cell voltages to fall below 0.100 V per cell.

Set the following conditions (all other parameters as per TOC):

TABLE 4 - OPERATING CONDITIONS FOR OCV TEST

Parameter	Setting
Fuel	Hydrogen
Fuel Stoichiometry	0.10 A/cm ² equivalent
Oxidant	Air
Oxygen Stoichiometry	0.10 A/cm ² equivalent
Coolant Flow Rate	Based on coolant flow at 0.1 A/cm ²

- Hold OCV for 1 minute.
- Set Cathode Air flow to 0 g/s.
- Allow all cell voltages to fall to < 0.1 V.
- Resume initial stoichiometric ratio, equivalent to 0.10 A/cm² flow rate, on the cathode.
- Continue with testing.

6.2 Polarizations

The polarization curve is the key indicator of the operational capabilities of a fuel cell stack sub-system. The DC voltage of the fuel cell stack sub-system can be measured at the individual cell level, the individual stack level, and the gross stack sub-system level. In this document, voltages at all three levels are used for the performance characterization of the fuel cell stack sub-system. An example of the polarization curve is shown below:

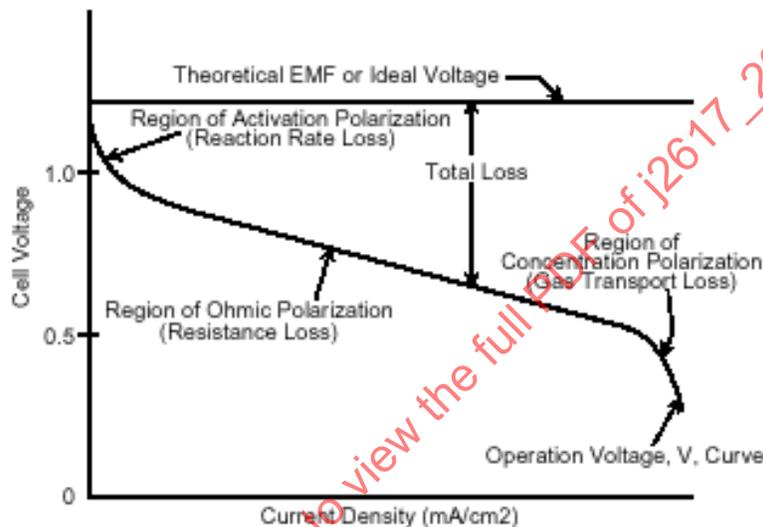


FIGURE 4 - EXAMPLE OF FUEL CELL POLARIZATION CURVE OF INDIVIDUAL CELL
(Source: pp25, Fuel Cell Handbook, Fourth Edition, DOE/FETC-99/1076)

For the generation of typical polarization curves, the Y-axis is typically (measured or averaged) cell voltage, stack voltage, or stack sub-system voltage, while the X-axis is current density or current. Cell-to-cell voltage variations with respect to a mean value and the minimum cell voltage can be visually determined by plotting individual cell voltages on the same graph.

When executing a polarization test, the load should first be increased from OCV to maximum load and then reduced to OCV so as to get an 'upward' and 'downward' polarization. In the test report, the direction of the polarization should be reported.

6.2.1 H₂/Air Polarization at Test Operating Conditions

Purpose: To determine the stack performance on H₂/Air at various current densities. The peak power point can be interpolated from this curve.

Procedure: Increase the current density and reactant settings per TOC table from OCV to maximum current density and then decrease in the same increments downwards from maximum current density to OCV.

- Hold all points for 5 minute
- Hold the OCV point for <1 minute.
- Step in increments of 200 mA/cm², after 200 mA/cm² until 0.4 V/cell or test stand limit is reached. (see note below)
⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.2.2 H₂/Diluted O₂ Polarization at Test Operating Conditions

Purpose: To determine the stack performance on H₂/Diluted O₂ at various current densities.

Procedure: Increase the current density and reactant utilizations per TOC table (except that on the cathode side, the oxidant must be a blend of 10% oxygen, 90% nitrogen) from OCV to maximum current density and then decrease in the same increments downwards from maximum current density to OCV.

- Hold each point for 5 minutes
- Hold the OCV point for <1 minute.
- Step in increments of 200 mA/cm² past the 200 mA/cm² until 0.4 V/cell or test stand limit is reached

6.2.3 Dilute H₂/Air Polarization at Test Operating Conditions

Purpose: To determine the stack performance on Dilute H₂/Air at various current densities.

Procedure: Increase the current density and reactant utilizations per TOC table, except that the hydrogen concentration fed to the anode should be varied as follows:

TABLE 5 - FUEL COMPOSITIONS TO BE EVALUATED

Fuel Composition (%H ₂ /%N ₂)
80/20
50/50

A polarization at each fuel concentration will be done as follows:

- Hold each point for 5 minutes
- Hold the OCV point for <1 minute.
- Step in increments of 200 mA/cm² past the 200 mA/cm² until 0.4 V/cell or test stand limit is reached. (see note below)
⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

Fuel concentrations will be checked with the flow meters. Cathode exhaust should be sampled during this portion of the testing to monitor CO₂ levels. Increases in CO₂ levels may indicate problems in the stack that may result in permanent performance loss.

6.3 Sensitivity Sweeps

6.3.1 Fuel Stoichiometry Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to fuel stoichiometric ratio with hydrogen fuel.

Procedure: Lower fuel stoichiometric ratio while at a constant current density and maintain all other parameters as per TOC. The fuel stoichiometric ratio sweep consists of setting the following points for 5 min each with the corresponding stoichiometric ratio levels – starting at the highest level and decreasing the stoichiometric ratio. Testing should be stopped if cell voltages drop below supplier specified min V/cell.

TABLE 6 - OPERATING CONDITIONS FOR FUEL STOICHIOMETRY SWEEPS

Sequence	Current Density (A/cm ²)	Fuel Stoichiometric Ratio Points to be Tested
1	0.05	1.67, 1.33, 1.25, 1.11
2	0.40	1.67, 1.33, 1.25, 1.11
3	0.80	1.67, 1.33, 1.25, 1.11
3	1.00	1.67, 1.33, 1.25, 1.11
4	1.20	1.67, 1.33, 1.25, 1.11

Cathode exhaust should be sampled during this portion of the testing to monitor CO₂ levels. Increases in CO₂ levels may indicate problems in the stack that may result in permanent performance loss.

6.3.2 Air Stoichiometric Ratio Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to air utilization.

Procedure: Lower air stoichiometric ratio while at a constant current density and maintain all other parameters as per TOC. The air stoichiometric ratio sweep consists of setting the following points for 5 min each with the corresponding stoichiometric ratio levels – starting at the highest level and decreasing the stoichiometric ratio.

The air utilization sweep consists of setting the following points for 5 min each. Testing should be stopped if cell voltages drop below supplier specified min V/cell.

TABLE 7 - OPERATING CONDITIONS FOR AIR STOICHIOMETRY SWEEPS

Sequence	Current Density (A/cm ²)	Air Stoichiometric Ratio Points to be Tested
1	0.05	2.00, 1.50, 1.25, 1.11, 1.05
2	0.40	2.00, 1.50, 1.25, 1.11, 1.05
3	0.80	2.00, 1.50, 1.25, 1.11, 1.05
4	1.00	2.00, 1.50, 1.25, 1.11, 1.05
5	1.20	2.00, 1.50, 1.25, 1.11, 1.05

6.3.3 Coolant Flow Rate Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to coolant flow rate.

Procedure: Increase the coolant flow rate while at constant current density and maintain all other parameters as per TOC. The actual flow rates to be tested may be specified either as flows (as shown) or as changes in the stack outlet temperatures – this should be determined by the testing parties prior to the start of testing.

The coolant flow rate sweep consists of setting the following points for 5 min each.

TABLE 8 - OPERATING CONDITIONS FOR COOLANT FLOW RATE SWEEPS

Sequence	Current Density (A/cm ²)	Coolant Inlet Flowrate to be Tested
1	0.40	TOC-10%, TOC, TOC+10%
2	0.80	TOC-10%, TOC, TOC+10%
3	1.00	TOC-10%, TOC, TOC+10%
4	1.20	TOC-10%, TOC, TOC+10%

Coolant flow rates per cell will be calculated at the end of the test for reporting purposes.

⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.3.4 Coolant Inlet Temperature Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to coolant inlet temperature

Procedure: Increase the coolant inlet temperature while at constant current density. The inlet gas conditioning should be adjusted when the coolant temperature is adjusted to maintain the same RH but all other parameters should be set as per TOC.

The coolant temperature sweep consists of setting the following points for 5 min each.

TABLE 9 - OPERATING CONDITIONS FOR COOLANT INLET TEMPERATURE SWEEPS

Sequence	Current Density (A/cm ²)	Coolant Inlet Temperature (°C)
1	0.40	TOC-10 °C, TOC-5 °C, TOC, TOC+5 °C
2	0.80	TOC-10 °C, TOC-5 °C, TOC, TOC+5 °C
3	1.00	TOC-10 °C, TOC-5 °C, TOC, TOC+5 °C
4	1.20	TOC-10 °C, TOC-5 °C, TOC, TOC+5 °C

The points to test may have to be specified differently to take into account different stack designs – this should be determined by the testing parties prior to the start of testing.

⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.3.5 Cathode Inlet Dew Point Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to cathode inlet dew point.

Procedure: Adjust the dew point while at constant current density by adjusting the settings on the humidification system as required (exact changes will depend on the humidification device in the test station) while keeping all other parameters set as per TOC. Each point should be held for 10 minutes. Care should be taken to consider both the stack hydration dynamics and the test station dynamics in reaching hydration equilibrium. The increased time for each point is an attempt to take this into account, however, this should be discussed and agreed upon by the testing parties before the test begins.

TABLE 10 - OPERATING CONDITIONS FOR CATHODE INLET DEW POINT SWEEPS

Sequence	Current Density (A/cm ²)	Cathode Inlet Dew Points to be Tested
1	0.10	TOC-5 °C, TOC, TOC+5 °C
2	0.40	TOC-5 °C, TOC, TOC+5 °C
3	0.80	TOC-5 °C, TOC, TOC+5 °C
4	1.00	TOC-5 °C, TOC, TOC+5 °C
5	1.20	TOC-5 °C, TOC, TOC+5 °C

The range of dew points to be tested can be adjusted, depending on the stack being tested - this should be determined by the testing parties prior to the start of testing. Care should be taken in executing this test as damage can result to the stack.

⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.3.6 Cathode Inlet Pressure Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to cathode inlet pressure.

Procedure: Increase the cathode inlet pressure while at constant current density and maintain all other parameters as per TOC. The cathode pressure sweep consists of setting the following points for 5 min each.

TABLE 11 - OPERATING CONDITIONS FOR CATHODE INLET PRESSURE SWEEP

Sequence	Current Density (A/cm ²)	Cathode Inlet Pressure (kPag)
1	0.10	TOC-30%, TOC, TOC+30%
2	0.40	TOC-30%, TOC, TOC+30%
3	0.80	TOC-30%, TOC, TOC+30%
4	1.00	TOC-30%, TOC, TOC+30%
5	1.20	TOC-30%, TOC, TOC+30%

Technologies are different and pressure cannot be the same for each. The range of pressure to be tested can be adjusted, depending on the stack being tested - this should be determined by the testing parties prior to the start of testing.

⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.3.7 Anode Inlet Dew Point Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to anode inlet dew point.

Procedure: Adjust the dew point while at constant current density by adjusting the settings on the humidification system as required (exact changes will depend on the humidification device in the test station) while keeping all other parameters set as per TOC. Each point should be held for 10 minutes. Care should be taken to consider both the stack hydration dynamics and the test station dynamics in reaching hydration equilibrium. The increased time for each point is an attempt to take this into account, however, this should be discussed and agreed upon by the testing parties before the test begins.

TABLE 12 - OPERATING CONDITIONS FOR ANODE INLET DEW POINT SWEEP

Sequence	Current Density (A/cm ²)	Anode Inlet Dew Points to be Tested
1	0.10	TOC-5 °C, TOC, TOC+5 °C
2	0.40	TOC-5 °C, TOC, TOC+5 °C
3	0.80	TOC-5 °C, TOC, TOC+5 °C
4	1.00	TOC-5 °C, TOC, TOC+5 °C
5	1.20	TOC-5 °C, TOC, TOC+5 °C

The range of dew points to be tested can be adjusted, depending on the stack being tested - this should be determined by the testing parties prior to the start of testing. Care should be taken in executing this test as damage can result to the stack.

⇒ **Testing should be stopped if cell voltages drop below supplier specified min V/cell.**

6.3.8 Anode Inlet Pressure Sweep on H₂/Air

Purpose: To determine the stack's sensitivity to anode inlet pressure.

Procedure: Increase the anode inlet pressure while at constant current density and maintain all other parameters as per TOC. The anode pressure sweep consists of setting the following points for 5 min each.