JRC Scientific and Technical Reports

Testing the voltage and power as function of current density

# Polarisation curve for a PEFC single cell

Test Module PEFC SC 5-2

T Malkow, G De Marco, A Pilenga, M. Honselaar, G Tsotridis
European Commission, Joint Research Centre, Institute for Energy, Petten

S Escribano, L Antoni
Commissariat à l'énergie atomique et aux énergies alternatives, Grenoble

R Reißner, O Thalau
Deutsches Zentrum für Luft- und Raumfahrt e.V., Stuttgart

E Sitters
ECN-Fuel Cell Technology

G Heinz
SolviCore GmbH & Co. KG

JRC
EUROPEAN COMMISSION

ie
Institute for Energy
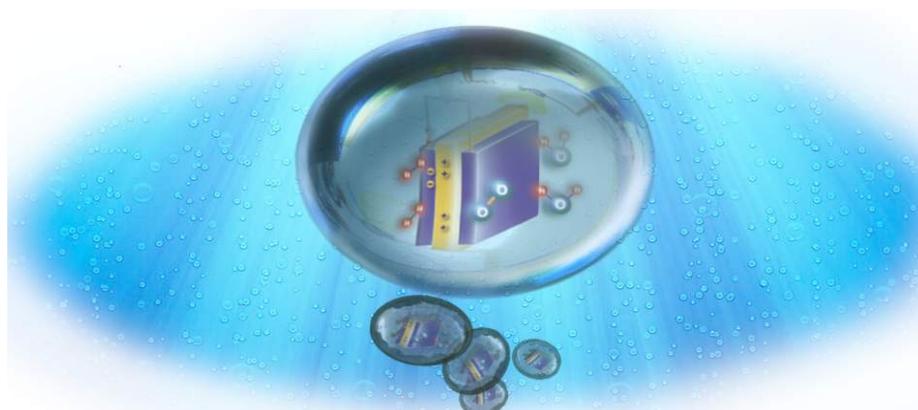
The mission of the JRC-IE is to provide support to Community policies related to both nuclear and non-nuclear energy in order to ensure sustainable, secure and efficient energy production, distribution and use.

European Commission
Joint Research Centre
Institute for Energy

Legal Notice
Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

Europe Direct is a service to help you find answers
to your questions about the European Union

Freephone number (*):

00 800 6 7 8 9 10 11

(*) Certain mobile telephone operators do not allow access to 00 800 numbers or these calls may be billed.

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server http://europa.eu/

Contributors

A Ravachol (Commissariat à l'Energie Atomique et aux Energies Alternatives, Grenoble)

Preface

This report is part of a series of reports on harmonised testing procedures for PEFC polymer electrolyte or proton exchange membrane fuel cell. The testing procedures called Test Modules are originally developed under the Research & Training Network (RTN) FCTESTNET (Fuel Cells Testing & Standardisation NETwork). This project was partly funded by the 5th European Community Framework Programme on Research, Technological Development and Demonstration (FP5).

The present report contains the Test Module TM PEFC SC 5-2 entitled "Testing the voltage and power as function of current density. Polarisation curve for single cell". The scope of the module is the characterization of the performance of PEFC in terms of voltage and power as a function of current density (polarisation curves) under constant operating conditions. The module has no target application. It is a general characterization method used in research & development (R&D) of PEFC; for example, to perform baseline measurements for qualification of PEFC materials, components and designs in a given application. The module character of this testing procedure makes it suitable to apply it as a part of an entire test programme.

The present version of the module is the result of an extensive review process carried out by the participating members to work package PEFC of the FCTES[QA] (Fuel Cell Systems Testing, Safety & Quality Assurance) Specific Targeted REsearch Project (STREP). FCTES[QA] is the successor project to FCTESTNET. It is in part funded by the Sixth Framework Programme of the European Community on Research, Technological development and Demonstration activities (FP6).

Table of Contents

FCTESTNET

The 55 partner strong FCTESTNET thematic network was established to define harmonised test procedures applicable to the component level (single cells, fuel cell stacks, Balance-of-Plant or BoP), sub-systems, and entire fuel cell systems. The project started in January 2003 and presented its final results in December 2005. It targeted apart from PEFC two other major types of fuel cells namely solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) in stationary, transport, and portable applications.

The main objectives of FCTESTNET were to compile already existing testing procedures and methodologies and to further develop harmonised testing procedures and methodologies applicable to transport applications, stationary power sources, and portable fuel cells, focusing on:

- fuel cells,
- fuel cell stacks and
- fuel cell systems.

The main deliverables of the network were:
- Contribution to the FC glossary EUR 2295 EN
- Mapping of testing competencies and inventory of equipment around Europe;
- Compilation and further development of methodologies for testing procedures;
- Common measuring criteria;
- Agreement on and harmonisation of approaches;
- Release of testing procedures
- Establishing links between European, US and Japanese standardisation bodies in the frame of harmonising test procedures.

FCTESTNET had not a mandate to establish formal standards for fuel cell test procedures. Instead FCTESTNET strived to provide harmonisation of application and technology oriented to ensure the support and integration of European industrial interests. The idea was to start from an analysis of fuel cell applications to define test parameters, test methods and conditions that are relevant for testing of single cells, stacks, sub-systems, and systems. The project output is considered useful input for standard setting bodies, but also for definition of *ad-hoc* test procedures applied by R&D organisations and industry.
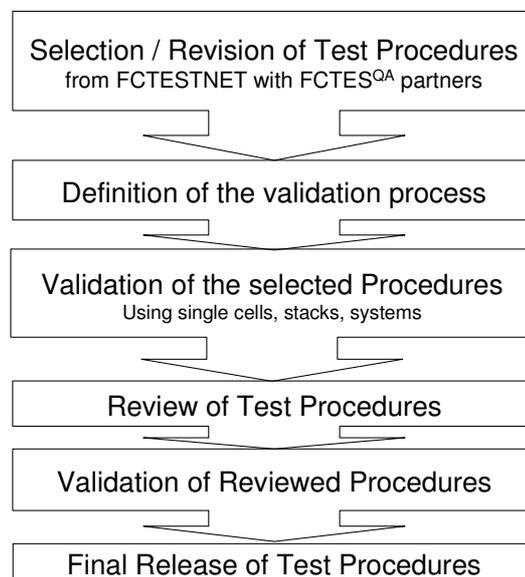
In fact various fuel cell test procedures were developed and compiled individually as Test Modules. These modules are accessible at the FCTES^{QA} website.

FCTES^{QA}

Started in May 2006, the FCTES^{QA} project addresses pre-normative research, benchmarking, and experimental validation through Round Robin Testing of harmonised, industry wide test protocols and testing methodologies for three types of fuel cells: PEFC, SOFC, and MCFC in stationary applications. The main objective of the project is the validation and benchmarking - by means of experimental campaigns – of the results of FCTESTNET testing procedures for three different levels (single cells, fuel cell stacks, and entire systems). The Round Robin Testing campaigns of FCTES^{QA} are carried out by world class laboratories from among the 27 European project participants and participants from China, Japan, Korea, and US.

The results of this four years project are discussed debated and agreed in cooperative progress meetings and dedicated international workshops under the auspices of the International Partnership for the Hydrogen Economy (IPHE) and the International Energy Agency (IEA). The outcome of FCTES^{QA} will support to lessen the gap between individual and independent management decision making within companies and research groups as far as fuel cells are concerned following accepted international quality practices.

The flow chart below describes the methodology used to improve/validate the original FCTESTNET procedures up to the final release of the procedures. The same validation methodology has been considered for all the 3 technologies and for testing of fuel cells, fuel cell stacks and fuel cell systems.

Selection / Revision of Test Procedures
from FCTESTNET with FCTES^{QA} partners

Definition of the validation process

Validation of the selected Procedures
Using single cells, stacks, systems

Review of Test Procedures

Validation of Reviewed Procedures

Final Release of Test Procedures

The test procedures can be downloaded from the website and will feed into the appropriate standardization platforms for further consensus building and international approval (like IEC TC 105).

FCTES^{QA}

Fuel **C**ell **Te**sting, **S**afety and **Q**uality **A**ssurance

Programme: ENERGY 3 -Sustainable Energy Systems

Test Module PEFC SC 5-2

Testing the voltage and power as function of the current density

Polarisation curve for a PEFC single cell

Version 30-04-2010

1 Objective and scope

The purpose of this test module (testing procedure) is to characterize the performance of a PEFC (polymer electrolyte or proton exchange membrane fuel cell) single cell at different current density conditions. The module is used for measuring the voltage and the power of the Fuel Cell as a function of drawn current. The cell performance is preferably measured from open circuit voltage to the highest current density fixed by the properties/specifications of the test object or by the measurement method.

The single cell and the test station have to be properly instrumented, to allow also the measurement of the following main parameters: cell temperature, reactant flows, relative humidity (RH) and pressures.

The test procedure has no target application. However this procedure is a general characterization method that is used in research and development of the PEFC. The test can be used as a baseline measurement for the qualification of a PEFC and its components, such as MEA (membrane electrode assemblies) and bipolar plates, for a given application.

Most important, the parameters, values and range of values including uncertainties used throughout this document are recommended only.

2 Terminology, definitions, and symbols

2.1 Terminology and definitions

Terminology and definitions used in this document correspond to the European 5th FCTESTNET terminology document EUR 22295 EN (see Section 5.1).

2.2 Symbols

Symbols used in this document are defined as follows:

Table 1: Definition of symbols used.

Symbol	Description
A	Common active geometric area of the fuel cell
F	Faraday's constant (F = 96485.3 C/mol)
I	Electrical fuel cell current
I_{max}	Maximum electrical fuel cell current
M	Molar mass
P	Electrical fuel cell power
P_k	Electrical fuel cell power related to interval k
Q_{cool}	Flow rate of the fuel cell coolant
Q_v	Volumetric flow rate
$Q_{v,\lambda}$	Volumetric flow rate (dry basis) of a reactant gas at stoichiometry λ under STP[1] conditions
$Q_{v,x}$	Volumetric flow rate of fuel cell fluid x (i.e. dry reactant gas, fuel gas=*fuel* or oxidant gas=*ox*) under STP conditions
$Q_{v,x,\lambda}$	Volumetric flow rate (dry basis) of reactant gas x at stoichiometry λ under STP conditions
$Q_{v,x,min}$	Minimum volumetric flow rate of fuel cell fluid x
$RH_{x,y}$	Relative humidity of reactant gas x at fuel cell location y (i.e. inlet=in or outlet=out)
T	Temperature
$T_{x,y}$	Temperature of fuel cell fluid x at fuel cell location y (i.e. inlet=in or outlet=out)
T_A	Ambient temperature
$T_{dew\ x,y}$	Dew point temperature of reactant gas x at fuel cell location y (i.e. inlet=in or outlet=out)
T_c	Fuel cell temperature
V	Fuel cell voltage
X_{O2}	Oxygen content in oxidant gas (molar fraction)
X_{H2}	Hydrogen content in fuel gas (molar fraction)
i	Fuel cell current density ($i = I / A$)
k	Interval k belonging to current density set point k during the measurement of the test outputs
l	Data acquisition index or number of data points recorded during t_{acq}

Symbol	Description
m	Total number of data points per interval k
$\dot{n}$	Molar flow rate
p_A	Ambient pressure (absolute)
$p_{x,y}$	Pressure (gauge) of reactant gas x at fuel cell location y (i.e. inlet=in or outlet=out)
t	Duration, period, or time
t_{acq}	Duration of data acquisition at interval k
t_{dwell}	Minimum dwell time between two current density set points belonging respectively to interval k and $k+1$
t_{eq}	Duration at the start of interval k to allow the test inputs and outputs to attain quasi-steady state upon the load change and where necessary, to account for load ramping and adjustments of the reactant flow rates by the test bench
t_k	Time elapsed for measuring the test outputs at the beginning of interval k
$t_{k,l}$	Time elapsed for measuring the test outputs to acquire l data points number at interval k
t_{offs}	Duration between end of data acquisition at interval k and start of data acquisition at interval $k+1$ to account, when necessary, for delays in data acquisition by the test bench
t_{smpl}	Duration for sampling at interval k
t_{stab}	Duration for the stability check of the test inputs and outputs according to their defined criteria at interval k prior to data acquisition
z	Number of electrons exchanged in the fuel cell reaction for one mole of reactant
Greek symbols	
λ_x	Stoichiometric ratio of the flow rate of reactant gas x supplied to the fuel cell to that theoretically required to sustain the fuel cell electrical current or electrical load applied
φ_{H2}	Volumetric hydrogen content of dry fuel gas
φ_{O2}	Volumetric oxygen content of dry oxidant gas
ρ	Density (i.e. dry reactant gas under STP conditions)

[1] *SATP = Standard Ambient Temperature and Pressure (298.15 K, 100 kPa or 1 bara)*

STP = Standard Temperature and Pressure (273.15 K, 101.325 kPa).

The volumetric flow rates of the reactant gases can be calculated as follows:

$$Q_{v,\lambda}\left(l/\sec\right) = \frac{M(g/mol)\cdot I(A)\cdot \lambda}{z\cdot F(C/mol)\cdot \rho(kg/m^3)\cdot \varphi} \qquad \text{(Equation 1)}$$

Note: F = 96485.3 C/mol.

Table 2: Properties of reactant gases for calculating the volumetric flow rate, $Q_{v,\lambda}$ of the reactant gases.

Reactant gas	M	z	ρ
	[g/mol]		[kg/Nm^3]
H$_2$	2.02	2	0.0898
O$_2$	32.0	4	1.429
Air	28.8	4	1.292

Using these values at STP (273.15K, 101.325kPa), the reactant gas flow rates can be calculated using the expressions given in Table 3.

Table 3: Expressions for calculating the volumetric flow rate, $Q_{v,\lambda}$ of the reactant gases based on Eq. 1 and the data of Table 2.

Reactant gas	$Q_{v,\lambda}$ [Nml/min]
H$_2$	$6.97 \cdot I \,(A) \cdot \lambda$
O$_2$	$3.35 \cdot I \,(A) \cdot \lambda$
Air	$3.35 / 0.209 \cdot I \,(A) \cdot \lambda = $ $16.59 \cdot \cdot I \,(A) \cdot \lambda$

Note: The reactant flow rates calculated using the expressions provided for in Table 3. represent the actual flow rates applicable to measuring the test outputs. Other values may be used for the Fuel Cell start-up and shut-down procedure as to the Fuel Cell manufacturer recommendation or the common practice at the testing organisation.
The unit Nml/min reflects the volume flow under STP. In case of using Mass Flow Controllers (MFC) to feed reactant gases to the Fuel Cell it is recommended to check whether the MFC is calibrated to the same reference temperature and pressure like used in this calculation.

3   Test Inputs

There are two types of test inputs: variable and static (see the tables in Sections 3.1 to 3.1.2). Tables below list all the test inputs (operating conditions) that must be controlled in this testing procedure.

Concerning the control accuracy, the measurement uncertainties and the sample rates, the values given in the following tables are the values commonly available with most of the equipments in the middle of the ranges but they can be too difficult to get in the extremities of the ranges or with particular operating conditions. The most important is to clearly precise the actual values in the test report when these values differ from what is required by the test module.

Alternative ways of controlling the fuel and oxidant rates are possible: the test can either be conducted at constant air and fuel stoichiometries changing the flows with current density, or at constant air and fuel flow rate for all current densities.

3.1 Test at constant stoichiometry

3.1.1   Variable Test Inputs

The variable test inputs applied during test step 3 are given in Table 4.

Table 4: Variable test inputs during test step 3.

Input	Value / Range	Control accuracy	Sample rate
i	$0 - 2$ A/cm^2 See Appendix A	$\pm$ 2% for i < 0.1A/cm² $\pm$ 1% for i $\geq$ 0.1A/cm²	$\geq$ 1 Hz
T_c	$T_A - 80$ ºC	$\pm$ 2 ºC	$\geq$ 1 Hz
$Q_{v,\,fuel}$**	Corresponding to the fuel stoichiometry, see Eq. 1	$\pm$ 1% FS*	$\geq$ 1 Hz
$Q_{v,\,ox}$**	Corresponding to the oxidant stoichiometry, see Eq. 1	$\pm$ 1% FS*	$\geq$ 1 Hz

Note 1: usually the digital mass flow meters used on the test benches are provided with an accuracy level of 1% of the Full Scale (maximum flow) and with a minimum measurable flow (generally 10% of the maximum flow).That means that the measurement uncertainty decreases with the flow rate and so decreases while increasing the current density when operating at fixed stoichiometry. In order to guarantee sufficient precision the digital mass flow meter should be selected in such a way that its maximum flow does not exceed by more than 100% $Q_{V,\,\lambda}$ at the maximum desirable current density.

** Note 2: $Q_{V,\,\lambda fuel}$ and $Q_{V,\,\lambda ox}$ are respectively the stoichiometry controlled volumetric flow rates of fuel and oxidant unless these values are smaller than the minimum flow rates: $Q_{V,\,fuel,min}$ and $Q_{V,\,ox,min}$, These minimum values may correspond to the stoichiometric flow rates for a low current density comprised between 0.05 and 0.2 A/cm². The actual minimal current density will have to be clearly given in the test report with the related fuel and oxidant flow rates and stoichiometries.*

3.1.2 Static Test Inputs

The static inputs applied during test step 3 of the test procedure (see Section 7) are given in Table 5. Static inputs do not vary during the entire duration of test step 3 (see Section 7) or during the duration of each current density step k (see Table) in the course of test step 3.

Table 5: Static test inputs applied during test step 3 of the test procedure (see Section 7).

Input	Value / Range	Control accuracy	Sample rate
p_A	100 kPa (abs)	± 1%	
X_{H2}	Up to 100% H_2	± 0.005%	
X_{O2}	21% O_2 - 79% N_2 or pure O_2	± 1% O_2	
T_c	T_A - 80 °C	± 2°C	≥1 Hz
$p_{fuel/ox,***}$	p_A – 300 kPa (gauge)	± 2%	
λ_{H2}	1.1 – 2 (dimensionless)	-	≥ 1 Hz
λ_{O2}	2 – 3 (dimensionless)		
$Q_{v, fuel/ox\ min}$	*according to the fuel cell manufacturer recommendations or as limited by test bench*	± 1% FS*	≥ 1 Hz
$T_{dew\ fuel/ox,\ in}^{**}$	0 - 80 °C	± 2°C	
$RH_{fuel/ox}^{**}$	0 - 100 %	± 5%	≥1 Hz
T_A	Room temperature – 50ºC	± 2°C	

Note 1: see Note 2 of Table 4.

*** Note 2: The method of reactant gas humidification is not defined in this test module. The method should however be described in the test report along with the reactant gas dew point temperatures (and RH). For example the temperatures of the water and of the lines in the case of bubblers or the water flow rates in the case of injectors – The dew points corresponding to the relative humidity of the gases should also be given in the test report (calculated or measured if humidity sensors are available at the gases inlets).*

**** Note 3: State in the test report which option was selected, whether the cell inlet pressure or the cell outlet pressure is controlled to be constant.*

3.2 Test at constant flow rate

3.2.1   Variable Test Inputs

The variable test inputs applied during test step 3 are given in Table 6.

Table 6: Variable test inputs during test step 3.

Input	Value / Range	Control accuracy	Sample rate
i	$0 - 2$ A/cm^2 See Appendix A	± 2% for i <0.1A/cm² ± 1% for i ≥ 0.1A/cm²	≥ 1 Hz
T_c	$T_A - 80$ ºC	± 2 ºC	≥ 1 Hz
λ_{H2}	> 1.1 (dimensionless)	-	-
λ_{O2}	> 2 (dimensionless)	-	-

3.2.2   Static Test Inputs

The static inputs applied during test step 3 of the test procedure (see Section 7) are given in Table 7. Static inputs do not vary during the entire duration of test step 3 (see Section 7) or during the duration of each current density step k (see Table) in the course of test step 3.

Depending on the fuel cell, the nature of some of the inputs may change. This means that, under certain conditions, some of the static inputs may not necessarily be regulated or become variable.

Table 7: Static test inputs applied during test step 3 of the test procedure (see Section 7).

Input	Range/Value	Control accuracy	Sample rate
p_A	100 kPa (abs)	± 1%	
X_{H2}	Up to 100% H_2	± 0.005%	-
X_{O2}	21% O_2 - 79% N_2 or pure O_2**	±1% O_2	-
$p_{fuel/ox}$***	ambient pressure – 300 kPa (gauge)	± 2%	≥1 Hz
$T_{dew\ fuel/ox,\ in}$*	0 - 80 ℃	± 2°C	≥1 Hz
$RH_{fuel/ox}$*	0 - 100 %	± 5%	≥1 Hz
T_c	$T_{amb.}$ – 80 ℃	± 2°C	≥1 Hz
$Q_{V,fuel}$	$Q_{V,\lambda fuel}(I_{max})$*****	± 5%****	≥1 Hz
$Q_{V,ox}$	$Q_{V,\lambda ox}(I_{max})$*****	± 5%****	≥1 Hz
T_A	Room temperature – 50ºC	± 2°C	

*Note 1: The method to humidify the reactants is not imposed by the test module. However, it has to be described in the test report as the corresponding inputs (for example the temperatures of the water and of the lines in the case of bubblers or the water flow rates in the case of injectors) – The dew points corresponding to the relative humidity of the gases should also be given in the test report (calculated or measured if humidity sensors are available at the gases inlets).

** Note 2: to be defined in the test report (laboratory or synthetic air with its composition (RH, particle size and composition for instance))

*** Note 3: please state in the test report which option was selected, whether the cell inlet pressure or the cell outlet pressure is controlled to be constant.

****Note 4: usually the digital mass flow meters used on the test benches are provided with an accuracy level of 1% of the Full Scale (maximum flow) and with a minimum measurable flow (generally 10% of the maximum flow). That means that the measurement uncertainty decreases with the flow rate. In order to guarantee sufficient precision the digital mass flow meter should be selected in such a way that its maximum flow does not exceed 5 Q_V.

*****Note 5: select the constant flows $Q_{V,fuel}$ and $Q_{V,ox}$ in such a way that at the maximum current I_{max} the fuel stoichiometry will be in the range $1.1 \leq \lambda_{H2} \leq 2$ and the oxidant stoichiometry in the range $2 \leq \lambda_{O2} \leq 3$.

4   Test Outputs

Table 8 below lists the test outputs that are determined in the application of this test module. Some test outputs may not be applicable for fuel cells with certain features.

Table 8: Test outputs determined in this test module.

Output	Measurement uncertainty	Sample rate
V	± 0.5 % FS	≥ 1 Hz
P	Calculated	-

5 References, required Documentation and Provisions

5.1 References

1. FCTESTNET Fuel Cells Glossary, EUR Report 22295 EN, Scientific and Technical Research Series, Office for Official Publications of the European Communities, Luxembourg, ISBN 92-79-02747-6, 2006.
2. IEC 62282-2 Ed.1: Fuel cell technologies – Part 2: Fuel cell modules.

5.2 Required documentation

The following are required:
1. Documentation (including installation and safety instructions) provided by the fuel cell test bench manufacturer or component manufacturers for a self-assembled test bench.
2. Calibration certificates of the fuel cell test bench instrumentation. These documents will be necessary to determine the actual uncertainty of the measurements of the test inputs and outputs and to check whether the requirements of this test module are met.
3. Test object or components documentation provided by the manufacturers including start-up, conditioning and shut-down procedures.
4. Safety instructions for the fuel cell.
5. Information about the software and conversion and calculation procedures applied during the testing and data processing.

5.3 Provisions

Standard local safety precautions for working with the fuels and oxidants used shall be followed.

6 Test Equipment and Setup

This test procedure does not prescribe the type, geometry and size of the single cell. Materials, design, geometry and sizes of the MEA, monopolar plates and cell will have to be described in the test report (Cf. Appendix C).

The performance measurement will need at least the test set-up and the sensors described or listed below in order to apply and measure the test inputs and outputs listed in sections 3 and 4.

6.1 Test set-up

The fuel cell test facility comprises sub-systems to provide fuel and oxidant to the cell in defined manner (flow rate, pressure, temperature, humidity), an electronic load for dissipating the delivered electrical energy of the cell, and a heating (possible heating/coolant) sub-system for controlling cell temperature. The facility is controlled by a computer, which also acts as data acquisition unit. A schematic of a typical fuel cell test environment is shown in Figure 6.1.
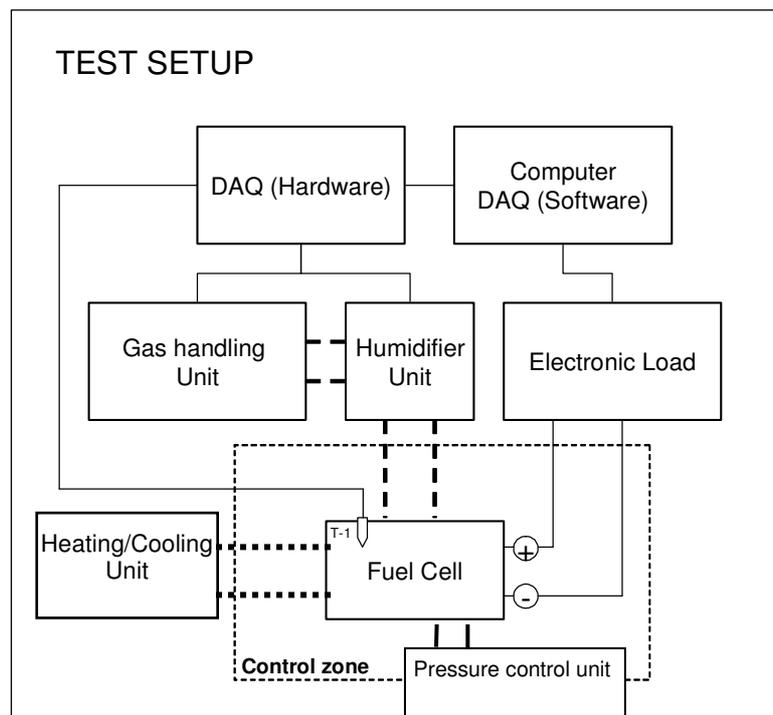

Figure 6.1: typical fuel cell test environment.

6.2 Sensors or control/acquisition equipment needed

The needed test facility equipments are described in the following Table with main specifications.

Table 9: Test equipments and instruments.

Description	Specifications	Qty
Oxidant Gas back pressure sensor	Pressure ambient to 500 kPa for the considered range of Oxidant flow rates	1
Fuel Gas back pressure sensor	Pressure ambient to 500 kPa for the considered range of Fuel flow rates	1
Oxidant Gas flow meter	Flow rates for the considered range of current	1
Fuel Gas flow meter	Flow rates for the considered range of current	1
Oxidant Gas humidification device *	Temperature 25 to 90 °C, RH 0 to 100 %	1*
Fuel Gas humidification device *	Temperature 25 to 90 °C, RH 0 to 100 %	1*
Cell Temperature sensor **	Temperature ambient to 100 °C	1 minimum
Cell heating/cooling devices	Temperature ambient to 100 °C	1 minimum
Electronic Load	Max current reachable at $1.2 > U > 0$ V - Possible galvanostatic mode	1
Control and measurement device (DAQ hardware and software and computer)	The capacity of the data acquisition system has to be sufficient to record all test variables with the sample rates defined	1

Note 1: one device includes sensors and equipment adapted to the temperature and relative humidity ranges specified. For example: bubblers + heated lines equipped with temperature sensors or water flow meters in case of water injection.

** Note 2: The sensor for measuring the cell temperature (Type K thermocouples are recommended) should be located as close as possible to the MEA, at least in contact with the current collectors in contact with the electrodes. For liquid cooled fuel cells, it is recommended T_c to be defined as outlet temperature $T_{cool,out}$. The coolant flow rate $Q_{cool, in}$ shall be regulated to maintain the T_c stable. In function of the fuel cell design, either $T_{cool, in}$ or $T_{cool, out}$ can be controlled.

7   Test Procedure

Note: Deviations from the following recommended procedure shall be described in the test report.

The most important factor, regardless of conditioning procedure, is that the cell voltage be stable before the actual measurement step starts. A stability criterion can be defined based on the deviation of the fuel cell voltage measured over a fixed period of time. It is recommended that the variations in the cell voltage be lower than +/- 5 mV during the last hour before ending the conditioning step.

7.1 Step 1: Pre-conditioning of test object

The start-up of the fuel cell and conditioning step can be performed following one of these procedures:
• proposed by the manufacturer of the test object,
• proposed by the manufacturer of a fuel cell component,
• the one that is common practice at the testing organisation, or
• as recommended herein (see below).

The test starts by bringing the operating conditions (inputs) to the values specified for the conditioning of the cell. The conditioning consists in keeping the previous conditions stable until the cell voltage reaches a stable value (normally corresponding to an optimized humidified state of the MEA electrolyte).

The stabilisation of the conditions for the conditioning of the cell can be part of the start-up procedure. If this is not the case it is recommended to operate the cell in galvanostatic mode at the selected operating temperature and at the gas conditions of the paragraph *7.2*, by increasing the current density by steps of 0.1 A/cm² while keeping the cell voltage higher than 0.5 V until reaching the current density identified for the conditioning. The current density for the conditioning of the cell will correspond either to the maximum current reachable at 0.5 V in the selected conditions or to a current density specified by the specific objective of the test.
The conditioning step has to last at least 24h with a cell voltage variation of less than +/-5 mV in the last hour before starting the test.

Note: this stability criterion can be reduced for specific conditions, depending on the test objective, especially at high current densities where fluctuations of the cell voltage might be observed. However it should be verified that the average cell voltage (averaged over 5 min) varies less than +/-5 mV in the last hour before starting the test.

Applied conditions and procedure for start-up, stabilisation and conditioning should be described in the test report (Cf. Appendix C).

7.2 Step 2: Setting the test conditions (test inputs)

The polarisation curve is performed under galvanostatic control at a fixed operating temperature, gas pressure and relative humidity.

The step starts by bringing the operating conditions to the values specified for the measurement, if not corresponding to the conditioning step or to the previous step in a test program. This step is conducted in galvanostatic mode and the current density will be specified by the specific objective of the test. The initial value of the cell voltage is measured at this current density when the operating conditions have reached a stable value.

Note: the comparison of this first value with the cell voltage measured at the same current density during the measurement step (polarisation curve) should be used as an indicator of the accuracy of the test.

Prior to starting the polarisation curve, the cell voltage is brought to OCV (and, in parallel, the gas flow rates to their minimum values, as described in the "variable test inputs" table) for a fixed period allowing the stabilisation of the operating conditions. It is recommended to measure the OCV during at least 30 s but less than one minute.

Note: long time at OCV can irreversibly damage the MEA.

7.3 Step 3: Measuring the test outputs

During this test step, the static test inputs are to be maintained at their values within the specified ranges (see Table 4 or Table 5).

All the test inputs and outputs should be measured versus the test duration.

The main objective of the polarisation curve is to determine the change in the single cell voltage (and consequently in the power density) generated by variation of the current density. For a single cell test, the current density is preferably increased from 0 (OCV) to the maximum current, the latter being fixed either by the recommended measurement methods or by the specific objective of the test when it is part of a test program.
Hence, the main technical purpose of step 3 is to determine fuel cell voltage (and the fuel cell power) at each defined set point of the current density (see table 10 in appendix A).

The duration of this step depends on the measurement method (number of steps, current increasing/decrease rate) and an end-of-test criterion has been reached: maximum current or minimum voltage.

At the end of the polarisation curve, the current density has to be fixed at the value required for the following step in the test program. When the end of the polarisation curve corresponds to the end of the test program, the current density will be fixed to zero before stopping all the testing equipments.

Note: For some experiments it might be necessary to verify that the polarisation curve is measured in quasi stationary state. In this case, after having increased the current up to the maximum current, the current will be reduced again down to OCV with the same steps and step length as in the first part of the curve.

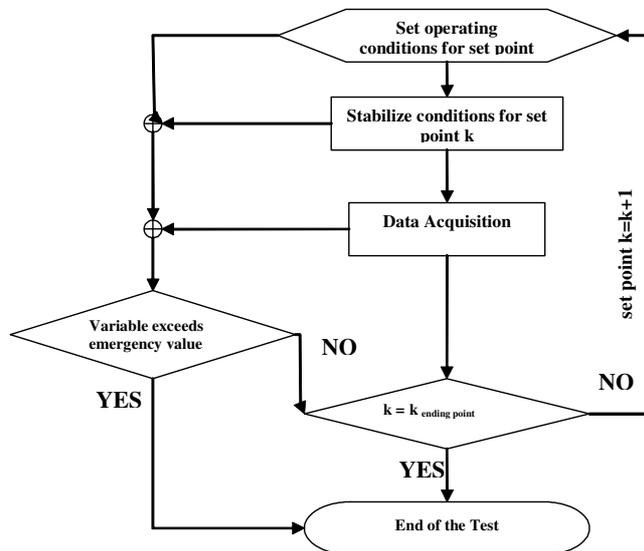An overview of the test procedure is shown in Figure 7.1

Figure 7.1: Schematic for measuring the test inputs and outputs.

Note 1: The measurement method for this step is proposed in Appendix A.
Note 2: The protocol for data acquisition that is measuring the test inputs and outputs for each current density set point k is proposed in Appendix B.

Ending criteria: for all the measurement methods, the test must be ended when the maximum current density is reached or if the cell voltage goes below a pre-defined minimum voltage. It is recommended to use a minimum voltage of 0.5 V if the measurements should be repeated e.g. during a long term measurement; for research purposes e.g. testing diffusion and water transport processes a minimum voltage of 0.3 V is recommended to avoid irreversible damage of the cell components.

7.4 Step 4: Data Post Processing

The average voltage during the last 5 minutes of each current step is determined as well as the voltage standard deviation value during this time. The power density *[P (W/cm²) = V (V) · i (A/cm²)]* will be a calculated output of this test.

7.5 Acceptance Criterion

To be specified by the user of this test module.

It is recommended that the initial value of the cell voltage prior to the polarisation curve should not deviate more than 5 mV from the corresponding value during the polarisation curve.

Appendix A.   Measurement methods for test step 3

A.1.   Introduction

Measuring single cell polarisation curves uses galvanostatic control, starting at the open circuit voltage using either current density steps or current density ramps.

A.2.   Current density profile with steps method

The current density values (set points) to be set for fuel cell performance evaluation with steps are listed below in Table.

The current density is changed step by step instantaneously, or by ramping. The duration of each step (dwell time; see Figure 7.3 in Appendix A) is either a given value or depends on the stability criterion (cf. Section 7). In the case of fixed given value, it is recommended a dwell time of 15 minutes for each current density (except for OCV). In the case of variable steps, it is recommended to have a minimum dwell time of 5 minutes and then to increase the current only when the variations in the cell voltage are lower than +/- 5 mV during the last 5 minutes of measurements.

Note: if problems of voltage loss are encountered when going from one step to the next one, it can be recommended to increase the reactant flow rates prior to the increase in current density.

Table10a, 10b: Set points of current density expressed in percentage of the maximum current density (a) or in current density steps (b).

Set point k	Percentage of the maximum rated current density*
0	0 (OCV)**
1	2 %
2	5 %
3	10 %
4	20 %
5	30 %
6	50 %
7	70 %
8	90 %
9	100 %

(a)

Set point k	Current density (A/cm²)
0	0 (OCV)
1	0.020
2	0.050
3	0.100
4	0.200
5	0.400
6	0.600
7	0.800
8	1.000
9	1.200
10	1.400
11	1.600
12	1.800
13	2.000

(b)

*Note 1: the maximum current density will be indicated by the manufacturer or fixed by the specific objective of the test. Preliminary measurements by increasing current density step by step like in the proposed conditioning step can be applied to evaluate the value corresponding to the minimum voltage recommended (0.3 V or 0.5 V depending on the test objective).
If the maximum current density is unknown the current steps indicated in table (b) can be chosen.

**Note 2: as written in paragraph 7.2, step 2, it is recommended to measure the OCV during at least 30 s but less than one minute.
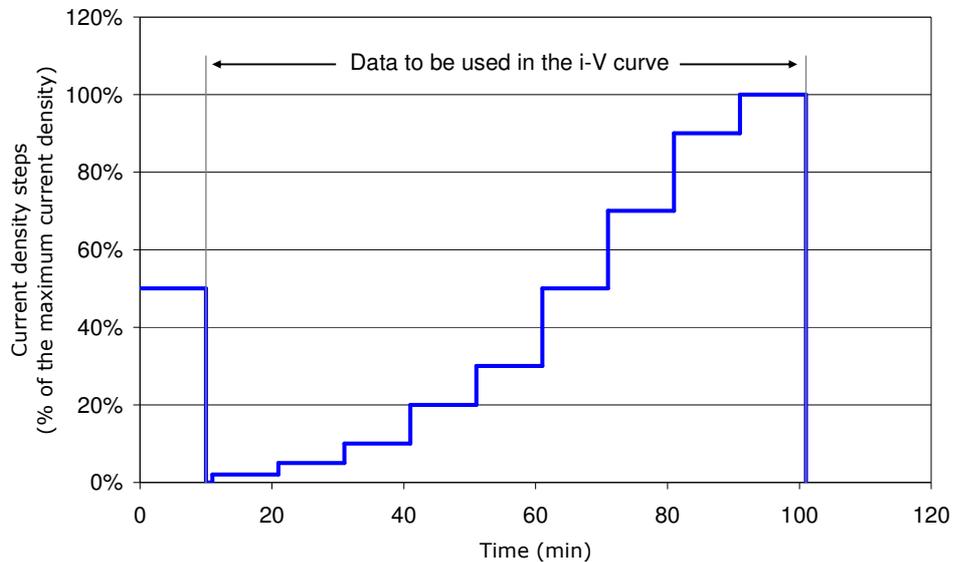
Figure 7.2: Example of a current density cycle with 10 steps of instantaneous change in current density according to the set points *k* in Table. The start value and end value chosen are Open Circuit Voltage. The polarization curve is started after stabilization at 50% of maximum current (e.g. 500 mA/cm² if maximum current density planned is 1 A/cm²). In this example, it is assumed that the stability criterion of less than +/-5 mV variations during the last 5 minutes is reached after 10 minutes for all the points (except OCV limited to 1 minute).

A.3.   *Variable current density method with different rates*

In this case the current density is increased at a fixed rate, depending of the current density range.

The rate can be lower in the first part of the curves (namely 8 mA/cm²/min for i < 0.100 A/cm²) in order to take into account the logarithmic behaviour of the activation overpotential. Then, the current density can increase more rapidly (namely 40 mA/cm²/min for i > 0.100 A/cm²). If a unique rate is chosen, it is recommended to take it equal to or lower than 40mA/cm²/min, knowing that this rate is more adapted to the high current densities.

Appendix B.   Protocol for data acquisition

The dwell time for each set point k (see Table) comprises periods of equilibration, t_{eq}, of stabilization, t_{stab}, and of data acquisition, t_{acq}, and if needed it ends with an offset time, t_{offs}. The equilibration period accounts for the test inputs and outputs to attain quasi-steady state upon the load change and where appropriate, for the ramping of the load from interval k to interval $k+1$ and for delays due to adjustments of the test bench particularly of the reactant flow rates as a result of the load change. The check on the stability of the test inputs and outputs according to their criteria (cf. Section 7) should be performed during the stabilization period whether online which implies t_{stab} being variable or offline, when t_{stab} assumes a given value. The period of data acquisition is the actual measurement of the test inputs and outputs. The offset time may account for delays in the acquisition of the test inputs and outputs by the test bench.

The data acquisition timeline and the principle current and fuel cell voltage profiles are schematically shown in respectively Figure 7.3 a and b.
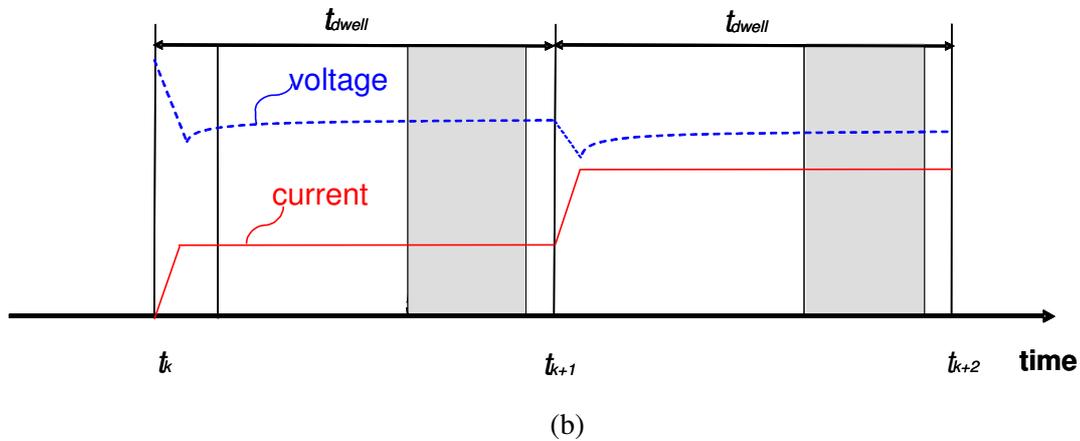

(a)

(b)
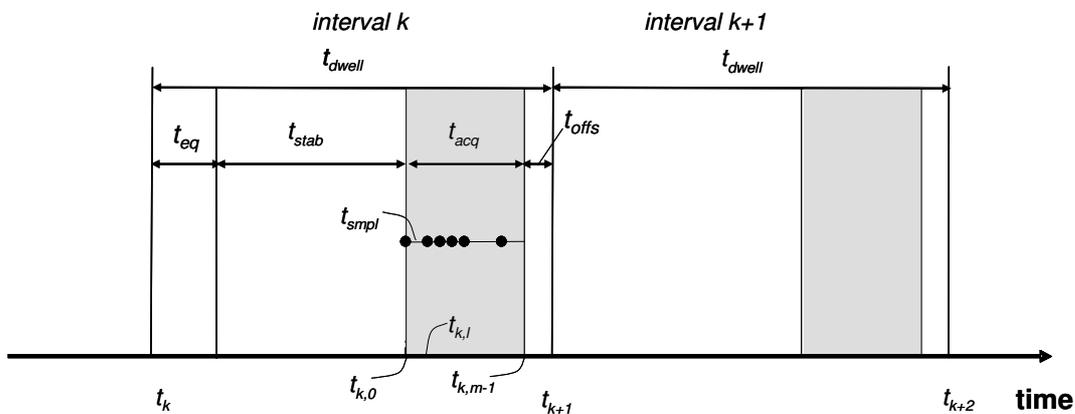
Figure 7.3: Schematic of the timeline for two consecutive set points *k* and *k+1* of test step 3 each having a dwell time of same duration (a). The test input and output (test variables) are sampled *l* times at $t_{k,l}$ (*0≤l≤m-1*) to collect *m* measurements with a sampling interval of t_{smpl} during t_{acq} (see also Table11). The principle profile of the current as a main test input and of the resulting fuel cell voltage as a major test output are shown for the two intervals *k* and *k+1* where the current increases at the beginning of each interval (b). This is representative for the ramping up of the current at anyone set point *k* and *k+1* between (inclusive) the maximum current density and the minimum current density in step 3 of the test (see also Figure 7.2).

Table 11 Recommended parameters related to test step 3 (cf. Figure 7.3).

Symbol	Value	Unit
t_k	$(k-1) \cdot t_{dwell}$	[min]
t_{dwell}	$t_{eq} + t_{stab} + t_{acq} + t_{offs}$	[min]
t_{eq}	*according to load ramping & adjustment of reactant flow rates*	[min]
t_{stab}	$\geq t_{acq}$	[min]
t_{offs}	*according to envisaged delay in data acquisition by the test bench*	[s]
t_{acq}	≥ 5	[min]
t_{smpl}	1	[s]
m	$\dfrac{t_{acq}}{t_{smpl}} + 1$	-
$t_{k,l}$ ($0 \leq l \leq m$-1)	$t_k + t_{k,eq} + t_{k,stab} + l \cdot t_{smpl}$	[min]

Note 1: The duration of t_{stab} should be chosen with regard to the stability criterion (or criteria).

Appendix C.   Test information for test report

Test information for single cell test report

In order to be useable and self-sufficient, the test report should at least include:
- An introduction explaining the objective of the test
- Test object and set-up descriptions
    - a description of the type, size, geometry, materials of the single cell (including available specifications of the MEA)
    - description of the test bench equipment
- The inputs, operating conditions and outputs of the test
- The actual performed procedures and the results
    - the start-up procedure
    - the stabilisation procedure
    - the measurement methods
    - the statement that the test procedure described here has been applied and any intentional or accidental deviations from this procedure

    Or

    - the actual test procedure
- The main results presented by :
    - Tables or graphs presenting the functional performance (main outputs of the test module versus the relevant input or versus time) obtained during the measurement step (here the cell voltage and the cell power density versus the current density for the polarisation curve) but also during the start-up, the conditioning and the stabilisation steps.
    - And, when relevant and applicable, particular graphs enhancing the analysis of the raw results (data post processing).
- Conclusions referring to the objective of the test and to the acceptance criteria when applicable.

SINGLE CELL TEST REPORT (template)

1   General information

1.1 General information on the test report

Test report reference/identification	
Test report title	
Authors	

1.2 General information concerning the test

Test module number			Test date	
Test version			Company performing test	
Company requesting test			Test location	
Test Request Nr			Test cell/equipment	

2   Introduction and test planning

Here the authors should refer to
- the procedure applied and if relevant explain the choice of this procedure.
- the test plan between tester and customer which may also include acceptance criteria
- any other documentation used in the report or in the test (terminology document , symbols harmonization, etc.)

For example:
The aim of this document is to provide a polarisation curve of the FCTESQA1 single cell using the FCTESQA procedure TM PEFC SC 5-2 v10…

3   Objective and scope of the test

The objective is to determine the polarisation curve of a PEFC single cell operating under specified operating conditions.

Here the authors should present further objectives and the scope of this test.

For example:
The test aims to qualify
...the generic performance of a polymer electrolyte fuel cell single cell
...PEFC components such as MEAs or sub-components of MEAs and bipolar plate materials or design.

The operating conditions considered for this test correspond to
...the current conditions used by the members of the fuel cell community
...the application considered...

25

The cell performance is measured from open circuit voltage to the highest current density that has been fixed by

...the properties of the test object
...by the specifications of the application considered
...by the measurement method

4   Test object description

Cell manufacturer	
Fuel cell technology	
Cell model	
Product or object tested	
Product number	
Test object identity number	

Fuel cell : material of the monopolar plates / technology	
Fuel cell : flow field design [1]	
Fuel cell : active area (cm^2)	
Gasket type [1]	
Gasket thickness	
Cell technology (collectors)	
Cell tightening	
Heating/cooling system	
Orientation of the cell [1]	
Gas flow direction (co-flow, counter-flow,…)	

MEA assembling (Yes/No, 3Layers, 5L, 7L)	
Electrodes	
Gas diffusion layers (thickness, type)	
Catalyst layer cathode (loading, composition)	
Catalyst layer anode (loading, composition)	
Membrane (thickness, type)	

[1] *For better understanding give a drawing*

Lowest cell voltage allowed (V)	
Pressure difference allowed between anode and cathode (kPa)	
Manufacturer recommendation for the air stoichiometry	

Additional remarks or information from the manufacturer about the cell or the MEA:

Status of the test object

The author presents here the testing history of the tested cell with a short description of all diagnostic experiments, specific or baseline experiments and their respective identifiers in sequential order.

For example:

1. *assembling of the cell and leakage test*
2. *break-in, with a cell voltage of 0.600 ±0.005 V over the last hour at 0.5 A/cm² (test report 2008-050)*
3. *3 i-V curves @ 80°C, 150 kPa, 100%RH using the procedure FCTESQA TM PEFC SC 5-2 (test report 2008-50)*
4. *Ageing test for 500 h @ 0.65 A/cm², 80°C, 150 kPa, 100%RH using the procedure FCTESQA TM PEFC SC 5-6 (test report 2008-62)*
5. *Disassemble from the test bench August 10, 2008 and storage under lab air…*
6. *Mounting of the test bench September 15, 2008*

5   Description of the test setup

A detailed description of the used test equipment and set up, including sensors type and location and specific devices (for example heating/cooling and humidification sub-systems), has to be given here in the test report to help the understanding of the results.

6   Description of the operating conditions, inputs and outputs

In the following tables, "?" has to be changed by the values corresponding to the experimentation.

6.1 Test inputs and operating conditions

In tables below are listed all the test inputs and the operating conditions that have been controlled during this test, with the measurement uncertainties and the sample rates.

Input	Description	Range/Value (unit)	Measurement uncertainty	Control accuracy	Sample rate (Hz)
i	Current density (i= applied current / active geometric area)	(A/cm^2)	± ?% for i < ? A/cm² ± ?% for i > ? A/cm²	± ?% for i < ? A/cm² ± ?% for i > ? A/cm²	
T_c	Cell temperature	(°C)	± ?°C	± ?°C	
X_{H2}	Fuel composition	%H$_2$; % other gases	+?% / -?%	+?% / -?%	-
X_{O2}	Oxidant composition	Air or O$_2$; % other gases	+?% / -?%	+?% / -?%	-
p_{ox}	Oxidant pressure at cell inlet or outlet [(3)] port	(kPa)	± ?%	± ?%	
p_{fuel}	Fuel back pressure at cell inlet or outlet [(3)] port	(kPa)	± ?%	± ?%	
$Q_{x,\ fuel}$ [(1)]	Fuel flow rate (NTP) [(1)]	max ($Q_{V,fuel,min}$, $Q_{V,\lambda fuel}$) or constant value (Nl/min)	± ? %	± ? %	

$Q_{V,ox}$ [1]	Oxidant flow rate (NTP) [1]	max ($Q_{V,ox,min}$, $Q_{V,\lambda ox}$) or constant value (Nl/min)	± ? %	± ? %	
$Q_{V,fuel,min}$	Fuel minimum flow rate (NTP)	(Nl/min)	± ? %	± ? %	
$Q_{V,ox,min}$	Oxidant minimum flow rate (NTP)	(Nl/min)	± ? %	± ? %	
λ_{fuel}	Fuel stoichiometry	(dimensionless)	-	-	-
λ_{ox}	Air stoichiometry	(dimensionless)	-	-	-
RH_{ox}	Inlet oxidant relative humidity [2]	%	± ?%	± ?%	
RH_{fuel}	Inlet fuel relative humidity [2]	%	± ?%	± ?%	
T_{ox}	Oxidant dew point	(°C)	± ?°C	± ?°C	
T_{fuel}	Fuel dew point	(°C)	± ?°C	± ?°C	
Tb_{ox}	Oxidant bubbler temperature	(°C)	± ?°C	± ?°C	
Tb_{fuel}	Fuel bubbler temperature	(°C)	± ?°C	± ?°C	
Tl_{ox}	Oxidant line temperature	(°C)	± ?°C	± ?°C	
Tl_{fuel}	Fuel line temperature	(°C)	± ?°C	± ?°C	
Qw_{ox}	Water flow rate (Oxidant side)	max ($Qw_{fuel,min}$, $Qw_{\lambda fuel}$) (cc/min)	± ? %	± ? %	
Qw_{fuel}	Water flow rate (Fuel side)	max ($Qw_{ox,min}$, $Qw_{\lambda ox}$) (cc/min)	± ? %	± ? %	

[1] *Note 1: $Q_{V,\lambda fuel}$ and $Q_{V,\lambda ox}$ are respectively the stoichiometry controlled volumetric flow rates of fuel and oxidant. The actual volumetric flow rates used during the test is the stoichiometry controlled flow rate, unless the values are smaller than the minimum flow rates: $Q_{V,fuel,min}$ and $Q_{V,ox,min}$. NPT = normal temperature and pressure: 0°C and 101,325 kPa (absolute)*

[2] *Note 2: The method to humidify the reactants is not imposed by the test module. However, they have to be described in the test report as the corresponding inputs (for example the temperatures of the water and of the lines in the case of bubblers or the water flow rates in the case of injectors) – The dew points corresponding to the relative humidity of the gases should also be given in the test report (calculated or measured if humidity sensors are available at the gases inlets).*

[3] *Note 3: please state in the test report which option was selected, whether the cell inlet pressure or the cell outlet pressure is controlled to be constant.*

6.2 Test Outputs

Output	Description	Range/Value (unit)	Measurement uncertainty	Sample rate (Hz)
V	Cell voltage	? V	± ? mV	? Hz
P	Cell power density	? W/cm^2	Calculated	

7   Test procedure and results

7.1 Description of the start-up and pre-conditioning steps

- o Detailed description of the setting of the conditions
- o Measurements (description, tables or graphs giving the inputs and the outputs during these steps)

Table: Cell performance before the measurement step

Dwell time (min)	Average current density (A/cm²)	Average Cell Voltage over the last XX min (V)	Average power density (W/cm²)
	...... ± σ	...... ± σ	...... ± σ

Graphs: main test inputs and outputs versus time during start-up and conditioning should be included here, in order to help the understanding of the main results.
For the polarisation curve: i, V, T_c, p_{ox}, p_{fuel}, RH_{ox} and RH_{fuel} (or relevant inputs related to RH) = f (time)

7.2 Description of the measurement step and results:

- o Setting the test conditions (initial test inputs) if an additional step is performed after the conditioning step and before setting the conditions for OCV.
- o Cause of the ending of the measurement step
- o Measurements (description, tables or graphs giving the inputs and the outputs during the measurement) (ex: table with dwell time, current density, voltage and power for the polarization curve)

Table: Functional performance during the polarisation step

Dwell time (min)	Average current density (A/cm²)	Average Cell Voltage over the last XX min (V)	Average Cell Power (W/cm²)
	...... ± σ	...... ± σ	...... ± σ

Graphs:
- o Main test inputs and outputs versus time during the measurement step should be included here, in order to help the understanding of the main results. *i, V, T_c, p_{ox}, $p_{fuel,}$ RH_{ox} and RH_{fuel} (or relevant inputs related to RH) = f (time). If possible use raw data, not averaged data.*
- o Main results = main outputs versus main inputs. *For the polarisation curve: V (V) and P (W/cm²) = f(i (A/cm²)), use average values and indicate standard deviations*

7.3 Description of the shut-down (if relevant)

The author describes the procedure how the cell has been shut down (if relevant).

7.4 Deviations from the procedure

The author describes the deviations from the procedure (if relevant).

8   Data Post Processing

Optional if any further processing of the data was performed.

9   Conclusion and acceptance criteria

Here the results of the test have to be commented considering the objective of the test and the acceptance criteria when they have been defined.

Acknowledgements

European Commission

Abstract
This report contains the Test Module TM PEFC SC 5-2 entitled "Testing the voltage and power as function of current density. Polarisation curve for a PEFC single cell". It is a testing procedure to characterize the performance of PEFC polymer electrolyte or proton exchange membrane fuel cell in terms of polarisation curves (FC voltage and power vs. current density) under constant current conditions. The module is a general characterization method used in research and development of PEFC with no target application. It may be used as a baseline measure to qualify fuel cells and its components in any given application.
The Test Module was originally developed and compiled under the Research & Training Network (RTN) FCTESTNET (Fuel Cell Testing and Standardisation). This project was partly funded during 2003-2005 under contract # ENK5-CT-2002-20657 by the 5th European Community Framework Programme on Research, Technological Development and Demonstration (FP5).
However, the present version of the Test Module is the result of a review undertaken in the frame of the FCTES^{QA} (Fuel Cell Systems Testing, Safety & Quality Assurance) Specific Targeted Research Project (STREP). This project started in April 2006 with funding provide in part under contract # 020161 by FP6. The Test Module was subject to an experimental validation by means of a Round Robin Testing campaign conducted on PEFC by the partners participating in Work Package 2 of FCTES^{QA}.

How to obtain EU publications

Our priced publications are available from EU Bookshop (http://bookshop.europa.eu), where you can place an order with the sales agent of your choice.

The Publications Office has a worldwide network of sales agents. You can obtain their contact details by sending a fax to (352) 29 29-42758.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

Publications Office
Publications.europa.eu