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Testing the voltage and power as function of the current density

Polarisation curve for a SOFC Stack

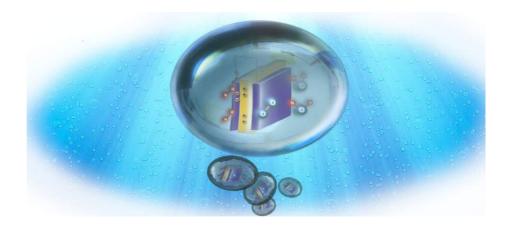**Test Module TM SOFC ST M21**

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Preface

This report is part of a series of reports on harmonised testing procedures for SOFC Solid Oxide fuel cell stacks. 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 SOFC ST M21 "Testing the voltage and power as function of current density. Polarisation curve for SOFC stacks". The scope of the module is the characterization of the performance of SOFC stacks 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 SOFC; for example, to perform baseline measurements for qualification of SOFC materials, components and designs in a given application. Also this module can be part of a Quality Assurance process in cell production. 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 SOFC 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).

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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.
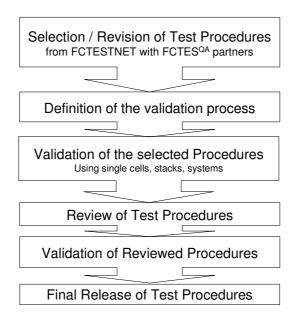
FCTES^QA

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.

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┌─────────────────────────────────────────┐
│  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       │
└─────────────────────────────────────────┘
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                    ▼
┌─────────────────────────────────────────┐
│      Validation of Reviewed Procedures   │
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┌─────────────────────────────────────────┐
│      Final Release of Test Procedures    │
└─────────────────────────────────────────┘
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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 Cell Testing, Safety and Quality Assurance

Programme: ENERGY 3 -Sustainable Energy Systems

Test Module SOFC ST M21

Testing the voltage and power as function of the current density

Polarisation curve for a SOFC stack

Version 30-04-2010

1   Objective and scope

The purpose of this test module (testing procedure) is to characterize the performance of a SOFC (solid oxide fuel cell stack) at different current density conditions. The module is used for measuring the voltage and the power of the Fuel Cell stack as a function of drawn current. If properly instrumented fuel and oxidant compositions, fuel and oxidant flows and their relative humidity (RH), FC fluid pressures and pressure drops and temperatures may also be measured.

The test procedure has no target application. However this procedure is a general characterization method that is used in research and development of the SOFC and for quality assurance in cell production. The test can be used as a baseline measurement for the qualification of a SOFC stack and its components in a given application.

This module is applied in combination with a test programme, which will describe the operating conditions of the FC stack.

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 one fuel cell into the stack
F	Faraday's constant (F = 96485.3 C/mol)
I	Electrical fuel cell stack current
I_{max}	Maximum electrical fuel cell stack current
M	Molar mass
N	Number of cells in the stack (ranging from 2 to 5)
P	Electrical fuel cell stack power
Q_v	Volumetric flow rate
$Q_{v, x}$	Volumetric flow rate of fuel cell fluid x (i.e. dry reactant gas, fuel gas=$fuel$ or oxidant gas=ox) under STP conditions
X_{fuel}	Fuel composition
X_{Ox}	Oxidant composition
$Q_{v, x, min}$	Minimum volumetric flow rate of fuel cell fluid x
T	Temperature
$T_{x, y}$	Temperature of FC Stack fluid x at FC Stack 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 FC Stack location y (i.e. inlet=in or outlet=out)
T_c	Fuel cell stack temperature
U_f	Fuel utilisation factor ($0 < U_f \leq 1$)
V	Fuel cell stack voltage
V_{min}	Minimum allowable voltage of one cell into the stack
i	Fuel cell stack 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}
m	Total number of data points per interval k

Symbol	Description
p_A	Ambient pressure (absolute)
$p_{x, y}$	Pressure (gauge) of reactant gas x at FC Stack location y (i.e. inlet=in or outlet=out)
t	Duration, period, or time
t_{acq}	Duration of data acquisition at interval k
t_{hold}	hold time between two current density set points belonging respectively to interval k and $k+1$
z	Number of electrons exchanged in the fuel cell reaction for one mole of reactant
Greek symbols	
Δp_x	Pressure drop in the flow path of fluid x (i.e. fuel, reactant gases) between fuel cell outlet and inlet
$\Delta p_{x, max}$	Maximum allowable pressure drop in the flow path of the fluid x (e.g. fuel) or between fuel and oxidant (fuel-to-ox) in the fuel cell (at a given instant or for a given duration)
ΔT_x	Temperature difference of fluid x between the fuel cell outlet and inlet
λ	Excess oxidant (air or oxygen) coefficient (≥ 1)
ρ	Density (i.e. dry reactant gas under STP[1] 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 as function of the FC stack active area can be calculated as per the following equations:

Equations for fuel flow calculation:

$$Q_{v,x} \quad (ml \cdot min^{-1} \cdot cm^{-2}) = \frac{6 \cdot 10^4 \cdot M(g/mol) \cdot N \cdot i(A \cdot cm^{-2})}{z \cdot F(C/mol) \cdot \rho(kg/m^3) \cdot U_f} \qquad \text{(Equation 1)}$$

Table 2a: Fuels properties for calculating the volumetric flow rate, $Q_{v,x}$ of the fuel.

Reactant gas	M	z	ρ
	[g/mol]		[kg/Nm^3]
H_2	2.02	2	0.0898
CH_4	16.04	4	0.7168

Should in the fuel composition be there others hydrocarbons use the following equation to convert (reform) them into hydrogen; the Eq. 2 can also be used to calculate the water content needs to complete the reaction:

$$C_x H_y + 2x \cdot H_2 O \rightarrow (2x + y/2) \cdot H_2 + x \cdot CO_2 \qquad \text{(Equation 2)}$$

Equation for oxidant flow calculation:

$$Q_{v,x} \quad (ml \cdot min^{-1} \cdot cm^{-2}) = \frac{6 \cdot 10^4 \cdot M(g/mol) \cdot N \cdot i(A \cdot cm^{-2}) \cdot \lambda}{z \cdot F(C/mol) \cdot \rho(kg/m^3)} \qquad \text{(Equation 3)}$$

Table 2b: Oxidants properties for calculating the volumetric flow rate, $Q_{v,x}$ of the oxidant gas.

Reactant gas	M	z	ρ
	[g/mol]		[kg/Nm^3]
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.

Note: F = 96485.3 C/mol

Table 3: Expressions for calculating the volumetric flow rate, $Q_{v,x}$ of the reactant gases based on Equation 1 and the data of Table 2a or Equation 3 and the data of Table 2b.

Reactant gases	$Q_{v,x}$ [Nml $\cdot$ min^{-1} $\cdot$ cm^{-2}]
H_2	$6.97 \cdot N \cdot i \ / \ U_f$
CH_4	$1.74 \cdot N \ i \ / \ U_f$
O_2	$3.35 \cdot N \cdot i \cdot \lambda$
Air	$(3.35/0.209) \cdot N \cdot i \cdot \lambda$

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 stack start-up and shut-down procedure as to the stack 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 (test conditions) variable and static (see the tables in Sections 3.1 to 3.2). 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. Deviations from the test module should be reported in the test report.

The test is conducted at constant fuel and oxidant flows for all current density steps.

3.1   Variable Test Inputs

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

Table 4: Variable test inputs during the test.

Input	Value / Range	Control accuracy	Sample rate
i	$0 - 1.25^*$ A/cm^2 See Appendix A	$\pm$ 2% FS for i <0.1A/cm² $\pm$ 1% FS for i $\geq$ 0.1A/cm²	$\geq$ 1 Hz
t_{hold}	$\geq$ 20 sec	-	$\geq$ 1 Hz
t_{acq}	$\geq$10 sec	-	$\geq$ 1 Hz
Note: Either this maximum current density or limiting the minimum cell voltage to 600mV			

3.2 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).

Table 5: Static test inputs applied during the test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	$10.7 \div 17.4$ ml·min^{-1}·cm^{-2} H$_2$	$\pm 5\%$ (rel)	-
	$0.3 \div 11.6$ ml·min^{-1}·cm^{-2} H$_2$O	$\pm 10\%$ (rel)	-
X_{ox}	$6.7 \div 8.7$ ml·min^{-1}·cm^{-2} O$_2$	$\pm 5\%$ (rel)	-
	$25.2 \div 32.8$ ml·min^{-1}·cm^{-2} N$_2$	$\pm 10\%$ (rel)	-
T_c	$400 - 1050$ ℃	± 4℃	≥ 1 Hz
$Q_{V,fuel}$	$11.0 \div 29.0$ ml·min^{-1}·cm^{-2}	$\pm 10\%$ (rel)	≥ 1 Hz
$Q_{V,ox}$	$31.9 \div 41.5$ ml·min^{-1}·cm^{-2}	$\pm 10\%$ (rel)	≥ 1 Hz

4 Test Outputs

Table 6 below lists the test outputs that are determined in the application of this test module.

Table 6: Test outputs determined in this test module.

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

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.

5.3   Provisions

Standard local safety precautions for working with the fuels and oxidants used shall be followed. Standard local safety precautions for working with all the chemicals contained by the SOFC and the electrical installations norms must be respected.

6 Test Equipment and Setup

This test procedure does not prescribe the type, geometry and size of the Stack. Materials, design, geometry and sizes of the electrolyte, current collectors and cell will have to be described in the test report (Cf. Appendix C).

To perform the polarisation curve test module M21 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 stack test facility comprises sub-systems to provide fuel and oxidant to the stack 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/cooling) sub-system for controlling the cell temperature. The facility is controlled by a computer, which can also act as data acquisition unit.

Note: The precision of test inputs and outputs shall be significantly lower than the parameter sensitivity of the tested fuel cell stack.

Note: The test stand hardware shall ensure the proper reproducibility and repeatability of the test. This means that a supposed instability of one (static or variable) test input parameter (e. g. stack load I) shall not lead to any instability of the primary test output parameter which is the stack voltage.

A schematic of a typical fuel cell test environment is shown in Figure6.1. Some systems may not be required depending on the features of the stack.
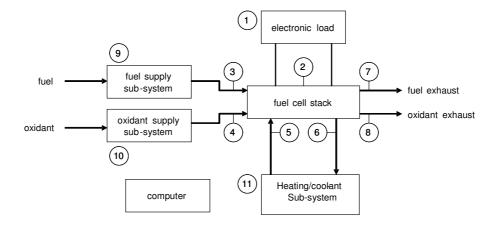

Figure 6.1: Test set-up with sub-systems, sensors and sensor locations (see also Table 7 and Table 8).

6.2 Sensors or control/acquisition equipment needed

Table 7: Sensors corresponding to the test inputs and outputs (see also Figure 6.1 and Table 8)

Description	Sensor ID*	Sensor location(s)
Stack current (I)	I-0	1
Stack voltage (V)	U-0	2
Cell voltage (V_i)*	U-1..n	2
Stack surface temperature (T_s)	T-1	2
Fuel gas inlet temperature ($T_{fuel, in}$)	T-2	3
Fuel gas outlet temperature ($T_{fuel, out}$)**	T-5	7
Oxidant gas inlet temperature ($T_{ox, in}$)	T-3	4
Oxidant gas outlet temperature ($T_{ox, out}$)**	T-6	8
Fuel inlet pressure ($p_{fuel, in}$)	P-3	3
Fuel gas outlet pressure ($p_{fuel, out}$)	P-3	7
Fuel pressure drop (Δp_{fuel})**	P-3 – P-1	7 – 3
Oxidant gas inlet pressure ($p_{ox,in}$)	P-4	4
Oxidant gas outlet pressure ($p_{ox, out}$)	P-4	8
Oxidant gas pressure drop (Δp_{ox})**	P-4 – P-2	8 – 4
Fuel flow rates according to Eqs. 1 and 2	F-1	9
Oxidant flow rates according to Eqs. 1 and 2	F-2	10

Note 1: T=temperature or temperature difference, P=pressure or pressure drop, F=flow, I=current and U=voltage.

** Note 2: The measurement of these test outputs is recommended depending on the configuration of the stack and the test bench.*

*** Note 3: A recommendation of the measurement uncertainty of the test inputs and outputs is showed in tables 4, 5 and table 6.*

Table 8: Recommended data acquisition sample rates and sensor quantities (see also Table 7).

Sensor ID	Description	Sample rate	Quantity
U-0	Stack voltage	1 Hz	1
I-0	Stack current		
U-1…n	Cell voltage		*n
T-1…5	Temperature		5 (1 minimum)*
P-1…4	Pressure		4 (2 minimum)*
F-1-2	Flow rate controller		2

Note 1: These are recommended measurements. However, they may not be possible, considering the configuration of the stack and test bench.

** Note 2: The measurement can be direct with temperature sensors to measure the dew points or indirect, for example, with water flow meters in the case of water or steam injection.*

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 4bar for the considered range of Oxidant flow rates	1
Fuel Gas back pressure sensor	Pressure ambient to 4bar 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 *	Dew-point temperature from ambient temperature to 90°C	1*
Fuel Gas humidification device *	Dew-point temperature from ambient temperature to 90°C	1*
Cell Temperature sensor	Temperature ambient to 1050°C	1 minimum
Cell heating/cooling devices	Temperature ambient to 1050°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.

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 stack voltage be stable before the actual measurement step starts. A stability criterion can be defined based on the deviation of the fuel cell stack voltage measured over a fixed period of time. It is recommended that the variations in each 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 stack 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 stack. The conditioning consists in keeping the previous conditions stable until each cell voltage reaches a stable value.

The stabilisation of the conditions for the conditioning of the stack can be part of the start-up procedure. If this is not the case it is recommended to operate the stack 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 0.05 A/cm² while keeping each cell voltage higher than 0.6 V until reaching the current density identified for the conditioning. The current density for the conditioning of the stack will correspond either to the maximum current reachable at 0.6 V/cell in the selected conditions or to a current density specified by the specific objective of the test (e.g. 0.3 A/cm²).
The conditioning step has to last at least 20h with each 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 voltages might be observed. However it should be verified that the average cell voltages (averaged over 5 min) varies less than +/-5 mV in the last hour before starting the polarisation curve 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 dew point.

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 (e.g. 0.3 A/cm²). The initial value of the stack 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 stack 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.

7.3 Step 3: Measuring the test outputs

During the test, the static test inputs are to be kept at the values selected within the ranges and with the accuracy specified (see Tables 4 and 5).

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

All the functional inputs and outputs are measured versus time.

The main purpose of step 3 is to determine fuel cell stack voltage (and consequently the fuel cell stack power and/or power density) at each defined set point of the current density. Fixed either by the measurement methods recommended in Appendix A or by the specific objective of the test when it is part of a test program.

The duration of this step depends on the measurement method (number of steps, current increasing/decrease rate) and if the "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 equipment.

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.

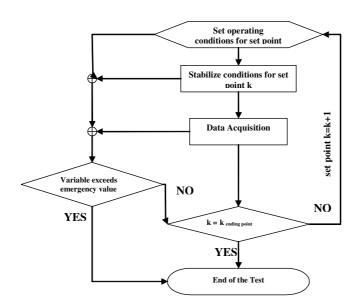An overview of the test procedure is shown in Figure 7.1

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 one of the cell voltages goes below a pre-defined minimum voltage. It is recommended to use a minimum voltage of 0.6 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 cell voltage not lower than 0.5 V is recommended to avoid irreversible damage of the stack components.

7.4   Step 4: Data Post Processing

The average voltage during t_{acq} (e.g. the last 5 seconds of each current density step) is determined. The power and/or the power density *[P (W/cm²) = V (V) · i (A/cm²)]* will be a calculated as output of this test. The Area Specific cell Resistance (ASR) which is defined by *dV/di* at 0.8 V is determined from the slope of the best fitting line over the measurement data within and including the interval 0.75 - 0.85 V of each cell.

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

The current density is changed step by step instantaneously. The duration of each step (hold time; see Figure 7.3 in Appendix B) is a given value and should be the same for each step.

A.2.　Current density profile

The typical current density profile starts from the same current density value (e.g. 0.3 A/cm²) used during the conditioning step.

A.2.1　Stable state at each current density step data acquisition method

The current density rises to the maximum current density value in current density steps of e.g. 0.05 A/cm². Each current density step has an hold time long enough to reach the stable state of the measured voltage or current before the measurement is taken. Stability criteria must be stated in the test report. The stabilisation time is generally two times longer that the measurements time. Therefore the t_{hold} is typically 10 minutes for each current density step at least. Then the current density descends, always in steps of e.g. t_{hold} = 10 minutes and 0.05 A/cm² to OCV. The data for the polarisation curve are acquired during the descending part of the test. The test could be completed at the OCV. The test could also be completed at same current density used during the conditioning step (e.g. 0.3 A/cm²). In this latest case the current density re-rises from OCV to the end current density value in steps of e.g. 0.05 A/cm² and t_{hold} = 10 minutes.

A.2.2　Fast hold time data acquisition method

The aim of the test method is to avoid sensible temperature variation of the SOFC during the test execution. Therefore each current density step has an hold time of 30 seconds for each current density step. The current density rises to the maximum current density value in current density steps of e.g. 0.05 A/cm². Then the current density descends, always in steps of e.g. t_{hold} = 30 seconds and 0.05 A/cm² to OCV. The data for the polarisation curve are acquired during the descending part of the test. The test could be completed at the OCV. The test could also be completed at same current density used during the conditioning step (e.g. 0.3 A/cm²). In this latest case the current density re-rises from OCV to the end current density value in steps of e.g. 0.05 A/cm² and t_{hold} = 30 seconds.

Note 1: The number of set points may be reduced to shorten the test duration, in particular during the 1st current increase and the final return to nominal conditions. This should be detailed in the test report.

Note 2: The set points at OCV and at very low current densities may be omitted or be substituted by a minimum current density depending on fuel cell manufacturer recommendations.
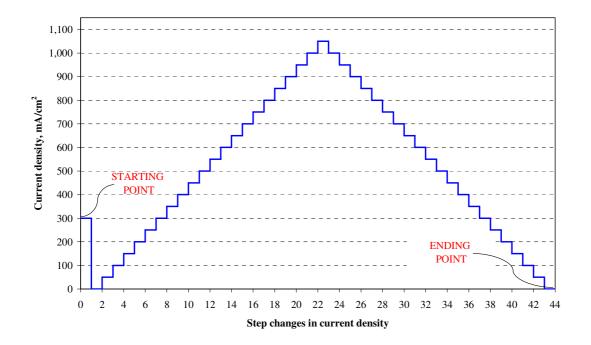

Figure 7.2: Example of a current density cycle with 44 steps of instantaneous change in current density. The start value (starting point) and end value (ending point) of the cycle chosen is at OCV. The maximum current density of this cycle is at 1.05 A/cm².

Appendix B. Protocol for data acquisition

The *hold* time (t_{hold}) for each set point *k* (see Figure 7.2) comprises the period of data acquisition, t_{acq}. The data acquisition time is the last part of the t_{hold} *(e.g. t_{hold}=30sec. t_{acq}=10sec.).* The data acquired during t_{acq} are averaged and used to build the polarisation curve.

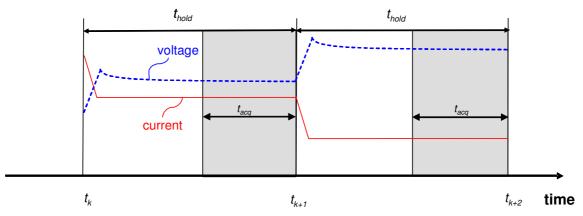The data acquisition timeline and the principle current and fuel cell voltage profiles are schematically shown in Figure 7.3.

Figure 7.3: Schematic of the timeline for two consecutive set points *k* and *k+1* of test step 3 each having a hold time of same duration (t_{hold}). 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} .
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 decreases at the beginning of each interval. This is representative for the ramping down 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 Figure7.2).

Table 10: Recommended parameters related to test step 3 (cf. Figure 7.3).

Symbol	Values Fast t_{hold} test method	Values Stable state test method	Unit
t_{hold}	$20 \div 60$	≥ 600	[s]
t_{acq}	≥ 10	≥ 60	[s]
t_{smpl}	≤ 1	≤ 1	[s]
m	$\dfrac{t_{acq}}{t_{smpl}}+1$	$\dfrac{t_{acq}}{t_{smpl}}+1$	-

Appendix C.   SOFC stack 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 FCTESQA FC stack using the FCTESQA procedure TM SOFC M21- v10…

3   Objective and scope of the test

The objective is to determine the polarization curve of a SOFC stack 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 solid oxide fuel cell single cell
...SOFC components such as YSZ electrolyte or current collectors or other sub-component 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...

The cell performance is measured from open circuit voltage to the highest current density. The highest current density 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

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

FC Stack : material of the current collectors / technology	
FC Stack : design [(1)]	
FC Stack : active area (cm^2)	
Object weight (kg)	
Object dimensions L x W x H (cm^3)	
Object nominal power (W)	
Object peak power (W)	
Object voltage range (V)	

[(1)] *For better understanding give a drawing*

Lowest cell voltage allowed (V)	
Manufacturer recommendation for the stoichiometry	

Additional remarks or information from the manufacturer about the cell:

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.

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, humidification sub-systems, grid types, geometry and sizes of the test housing), 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	Stack temperature	(℃)	± ?°C	± ?°C	
X$_{fuel}$	Fuel composition	%H$_2$; % other gases	+?% / -?%	+?% / -?%	-
X$_{ox}$	Oxidant composition	Air or O$_2$; % other gases	+?% / -?%	+?% / -?%	-
P_{ox}	Oxidant pressure at cell inlet or outlet port	(kPa)	± ?%	± ?%	
P_{fuel}	Fuel back pressure at stack inlet or outlet port	(kPa)	± ?%	± ?%	
Q_{fuel}	Fuel flow rate (NTP)	max (Q$_{fuel,min}$) or constant value (Nl/min)	± ? %	± ? %	
Q_{ox}	Oxidant flow rate (NTP)	max (Q$_{ox,min}$) or constant value (Nl/min)	± ? %	± ? %	
T_{ox}	Oxidant dew point	(℃)	± ?°C	± ?°C	
T_{fuel}	Fuel dew point	(℃)	± ?°C	± ?°C	
Tb$_{ox}$	Oxidant bubbler temperature	(℃)	± ?°C	± ?°C	
Tb$_{fuel}$	Fuel bubbler temperature	(℃)	± ?°C	± ?°C	
Tl$_{ox}$	Oxidant line temperature	(℃)	± ?°C	± ?°C	
Tl$_{fuel}$	Fuel line temperature	(℃)	± ?°C	± ?°C	

Note: _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 should also be given in the test report ._

6.2   Test Outputs

Output	Description	Range/Value (unit)	Measurement uncertainty	Sample rate (Hz)
V	Stack voltage	? V	± ? mV	? Hz
P	Stack power	? W	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)
- o   Applied clamping force

Table: Cell performance before the measurement step

hold time (sec.)	Average current density (A/cm²)	Average cell stack over the last XX sec. (V)	Average stack power over the last XX sec. (W)
	...... ± 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}, = 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 starting the test.
- 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 hold time, current density, voltage and power for the polarization curve)

Table: Functional performance during the polarisation steps

hold time (sec)	Average current density (A/cm²)	Average cell voltage over the last XX sec (V)	Average cell power over the last XX sec. (W)
	...... ± σ	...... ± σ	...... ± σ

The polarisation data should be presented by both:
- A two-dimensional graph with the current density on the abscissa (x-axis) and the cell voltage and the cell inlet temperature on the ordinate (y-axis). In case a reverse scan is done, the forward and backward scan should be plotted in the same graph.
- The following numeric data (see example table below):
  - The open circuit voltage (OCV), i.e. the cell voltage at a current density of zero.
  - The current density at 0.7 and 0.8 Volt.
  - The Area Specific cell Resistance (ASR) which is defined by dV/di at 0.8 V and is determined from the slope of the best fitting line over the measurement data within and including the interval 0.75 - 0.85 V.

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

Abstract
This report contains the Test Module TM SOFC M21 entitled "Testing the voltage and power as function of current density. Polarisation curve for a SOFC stack". It is a testing procedure to characterize the performance of SOFC solid oxide fuel cell stack 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 SOFC 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 is subject to an experimental validation by means of a Round Robin Testing campaign conducted on SOFC by the partners participating in Work Package 4 of FCTES^{QA}.

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