JRC Scientific and Technical Reports

Testing the humidification sensitivity of a single PEFC

Characterisation of the performances of a PEFC operating with fuel and oxidant at various relative humidity

Test Module PEFC SC 5-1

30 April, 2010

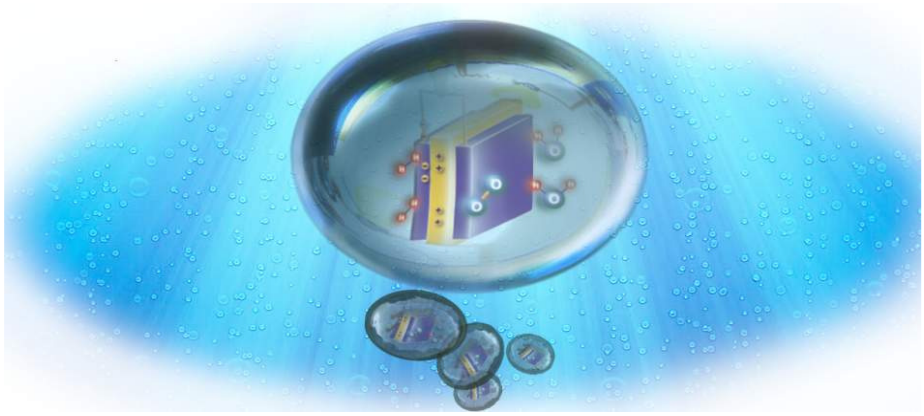
T Malkow, G De Marco, A Pilenga, M. Honselaar, G Tsotridis
European Commission, Joint Research Centre, Institute for Energy, Petten

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



EUR xxxxx EN 2010

JRC EUROPEAN COMMISSION

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

Contact information
Address: Postbus 2, NL-1755 ZG Petten
E-mail: jrc-ie-info@ec.europa.eu
Tel.: +31 224 56 5656
Fax: +31 224 56 5600

http://ie.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

JRC 56063

EUR XXXXX EN
ISBN XXX-XX-XX-XXXXX-X
ISSN XXXX-XXXX
DOI XX.XXXX/XXXXX
Luxembourg: Publications Office of the European Union

Printed in the Netherlands

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 5-1 entitled “Testing the humidification sensitivity of a PEFC single cell. Characterisation of the performance of a PEFC operating with fuel and oxidant at various relative humidity”. The scope of the module is the characterization of the performance of PEFC in terms of voltage and power as a function of the fuel and oxidant at various relative humidity values. 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

Preface iii

FCTESTNET vii

FCTES^{QA} viii

Test Module PEFC SC 5-1 1

1 Objective and scope 3

2 Terminology, definitions, and symbols Error! Bookmark not defined.
2.1 TERMINOLOGY AND DEFINITIONS ..... ERROR! BOOKMARK NOT DEFINED.
2.2 SYMBOLS ..... ERROR! BOOKMARK NOT DEFINED.

3 Test Inputs 7
3.1 VARIABLE TEST INPUTS 7
3.2 STATIC TEST INPUTS 8

4 Test Outputs 9

5 References, required Documentation and Provisions 10
5.1 REFERENCES 10
5.2 REQUIRED DOCUMENTATION 10
5.3 PROVISIONS 10

6 Test Equipment and Setup 11
6.1 TEST SET-UP 11
6.2 SENSORS OR CONTROL/ACQUISITION EQUIPMENT NEEDED 12

7 Test Procedure 13
7.1 STEP 1: PRE-CONDITIONING OF TEST OBJECT 13
7.2 STEP 2: SETTING THE TEST CONDITIONS (TEST INPUTS) 14
7.3 STEP 3: MEASURING THE TEST OUTPUTS 17
7.4 STEP 4: DATA POST PROCESSING 17
7.5 ACCEPTANCE CRITERION 18

Appendix A. Relative humidity versus dew point at cell 19

Appendix B. Protocol for data acquisition 20

Appendix C. Test information for test report 23

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.

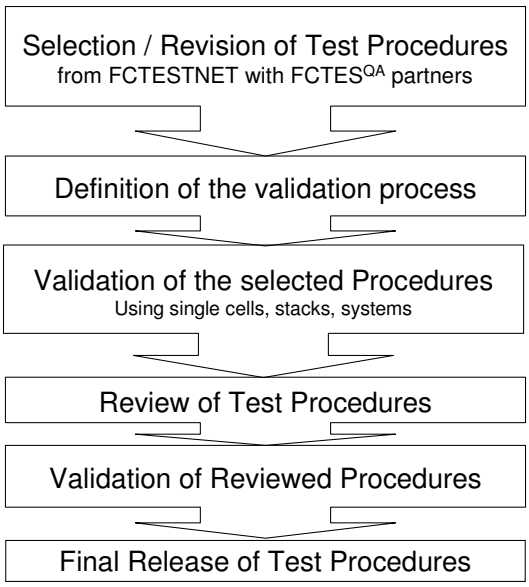
In fact various fuel cell test procedures were developed and compiled individually as Test Modules. These modules are accessible at the FCTES^{QA} website.

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.



The test procedures can be downloaded form 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 PEFC SC 5-1

Testing the humidification sensitivity of a PEFC single cell

Characterisation of the performance of a PEFC operating with fuel and oxidant at various relative humidity

Version 30-04-2010

1 Objective and scope

The purpose of this test is to qualify the sensitivity to gases relative humidity of a PEFC single cell in particular for an automotive application (low pressure and 80°C).

The objective is to determine the performance of a PEFC single cell submitted to a sequence of steady tests in specific environmental operating conditions: namely operating with pure hydrogen and air at different level of relative humidity at different current densities.

The test is a specific test to be used for the qualification of PEFC components such as MEAs or sub-components of MEAs such as the membranes, the active layers and/or the gas diffusion layers.

Note: The variable and static inputs described in the generic test modules used in this test program have been defined within ranges corresponding to the current operating conditions generally used in the field of PEFC testing.

This program being dedicated to automotive application, the test procedure will be applied at operating conditions commonly used for the qualification of PEFC components for this application (low pressure and 80°C). *But this test program can also be applied for different conditions*.

Note: this performance test procedure describes how the corresponding generic tests modules are sequenced to complete the objective.

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

2 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).

2.1 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}
m	Total number of data points per interval k

Symbol	Description
$\dot{n}$	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:

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

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

In tables below are listed 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 give the actual values in the test report when these values differ from what is required by the test module.

3.1 Variable Test Inputs

Among the following inputs, T_{cell} should be variable only during the start-up and the conditioning steps. The other inputs are variable during the humidification sensitivity measurement step.

Table 4: Variable test inputs during test step 3.

Input	Value / Range	Control accuracy	Sample rate
i	200; 400; 600 and 800 mA/cm^2	± 2% FS for i < 0.1A/cm² ± 1% FS for i ≥ 0.1A/cm²	≥ 1 Hz
T_c	T_A ÷ 80 ºC	± 2 ºC	≥ 1 Hz
$Q_{v,\,fuel}$**	Corresponding to the fuel stoichiometry, see Eq. 1	± 1% FS*	≥ 1 Hz
$Q_{v,\,ox}$**	Corresponding to the oxidant stoichiometry, see Eq. 1	± 1% FS*	≥ 1 Hz
RH_{ox}	25 – 75 %***	± 5% FS	≥ 1 Hz
RH_{fuel}	0 – 75 %***	± 5% FS	≥ 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.*

**** Note 3: 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).*

3.2 Static Test Inputs

The following inputs should be static and fixed at one single value in the given ranges during all the steady measurement steps.

Table 5: Static test inputs

Input	Range/Value	Control accuracy	Sample rate
X_{H2}	H_2*	+0/-0.001% H_2	-
X_{O2}	air or pure O_2**	±1% O_2	-
P_{ox}***	ambient to 120 kPa	± 2%	≥1 Hz
P_{fuel}***	ambient to 120 kPa	± 2%	≥1 Hz
λ_{ox}	2 (dimensionless)	-	-
λ_{fuel}	1.2 (dimensionless)	-	-
T_c	$T_{amb.}$ – 80 °C	± 2°C	≥1 Hz

** Note 1: to be defined (composition)*

*** 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.*

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

** Note 1: The cell power density can also be calculated (W/cm^2).*

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.
3. The specific test report template: FCTESQA_TR_TM_PEFC_SC_5-1_2010-05.doc - This test report template describes how to report all the needed information when this procedure has been applied.

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.

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.

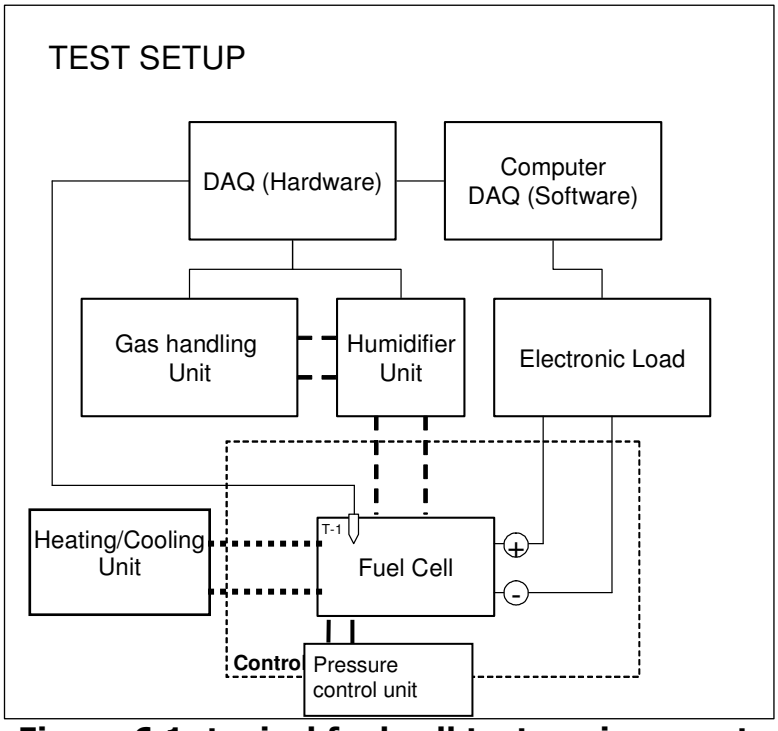


Figure 6.1: typical fuel cell test environment.

6.2 Sensors or control/acquisition equipment needed

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

Table 7: 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.*

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)

Four levels of relative humidity are considered for the hydrogen and three for air. The sequence of measurements included several humidification steps (as described in **Table 8** and in **Figure 7.17.1**) in order to cover the whole relative humidity ranges given in the inputs Table in section 3.
The fuel relative humidity will be set at a fixed value (starting by the highest one of the range defined in the inputs Table) while the oxidant relative humidity will be increased step by step from the lowest to the highest value of the range defined in **Table 8.**

Table 8: gases relative humidity sequence to be applied with the operating conditions defined in the inputs Table.

Humidification step n°	Fuel Relative Humidity	Oxidant Relative Humidity
1.	75%	25%
2.	75%	50%
3.	75%	75%
4.	50%	25%
5.	50%	50%
6.	50%	75%
7.	25%	25%
8.	25%	50%
9.	25%	75%
10.	0%	25%
11.	0%	50%
12.	0%	75%

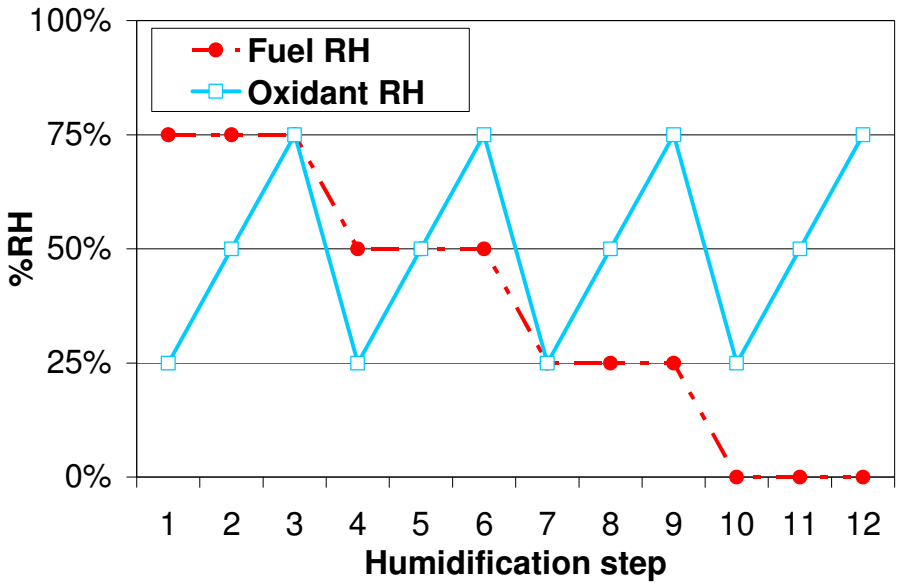


Figure 7.1: relative humidity of the gases for each measurement step.

Every humidification step of the relative humidity sequence will be applied at four current densities following the order given in **Table 9**.

Table 9: current density sequence to be applied for each humidification step defined in Table 8.

Current density stage	Current density
(1)	800 mA/cm²
(2)	600 mA/cm²
(3)	400 mA/cm²
(4)	200 mA/cm²

The conditioning step should be applied only one time before setting the specific conditions of the test program: operating conditions given in the inputs Table 4; current density (1); humidification step n°1.

For each humidification step, the steady test will last at least 2 hours and until the cell voltage reaches the following stability criterion: the variations in the cell voltage have to be lower than +/- 5 mV during the last 20 minutes before ending this step and starting the next one.

Note: with the relative humidity sequence proposed in this program, it should be possible to perform the test in four days after the conditioning step. It should indeed be possible to perform the measurements corresponding to 3 humidification steps at the first fixed fuel relative humidity during the first day and to stabilize the conditions corresponding to the next fuel relative humidity (decreasing again the oxidant relative humidity to its minimum) during the first night etc…

An overview of the test procedure is shown in Figure 7.2:

Note: It can be interesting to perform the same test program after having modified one or more operating conditions in order to qualify for example the effect of temperature or pressure or stoichiometry on the humidification sensitivity.

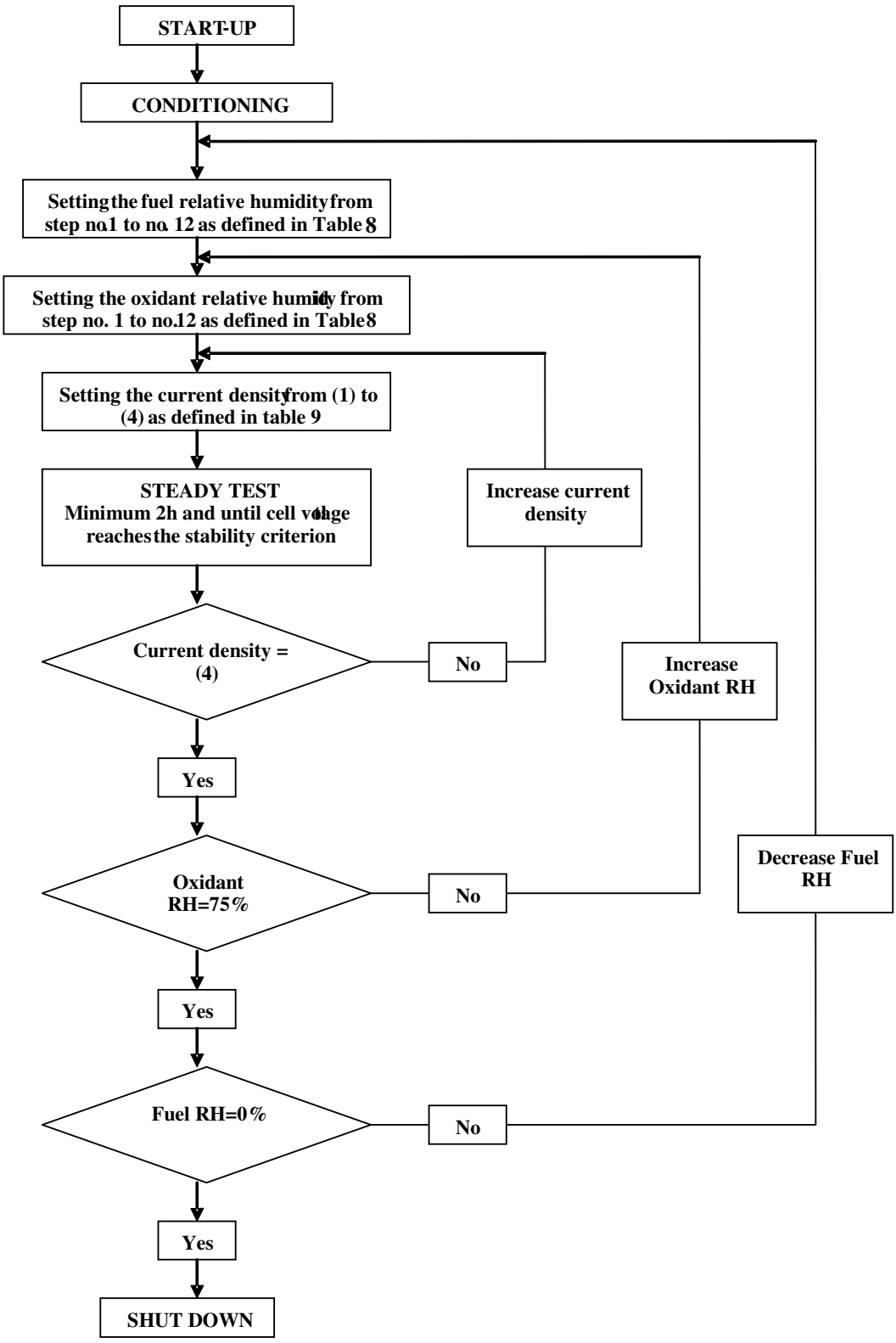


Figure 7.2: Test procedure overview

7.3 Step 3: Measuring the test outputs

During the test the static test inputs (temperatures, gases stoichiometry, composition and pressures) are to be kept at the values selected within the ranges and with the accuracy specified.
All the functional inputs and outputs are measured versus time.

The main objective is to determine the cell voltage under different relative humidity levels for hydrogen and air at four different current densities.

End of test criterion: for one set of operating conditions, the test has to be stopped at any stage if the single cell voltage becomes lower than 0.3V during a steady step.
If the ending criterion is reached for a humidification step n° < 12, the test program can be continued by shifting to the next humidification step.
If the ending criterion is reached during the humidification step n°12, the test program will be completely stopped (load off, temperatures, pressures and gases off).

7.4 Step 4: Data Post Processing

The evolution of the voltage over time is the main output of this test.

The power density [$P\ (W/cm^2) = V\ (V) \cdot i\ (A/cm^2)$] should be calculated as a further output for this test and can be calculated for all the measurement steps.

No other specific data processing is needed.

It can be interesting to calculate for each current density the performance loss between the best one (usually corresponding to humidification step n°12) and the other humidification levels in order to compare the humidification sensitivity of different cells or components presenting different performance levels.
The performance loss should be calculated in % as follow:

$$[V_{(\text{humidification n°12})} - V_{(\text{humidification n°1to11})}] / V_{(\text{humidification n°12})} \quad \text{(Equation 2)}$$

Other performance loss can be interesting to calculate using same kind of method, particularly to check the sensitivity to the relative humidity of one gas for a fixed relative humidity of the other gas.
As an example, here is the way to calculate the performance loss in % when reducing the oxidant relative humidity from 50% to 25% for a fixed fuel relative humidity fixed at 50%:

$$[V_{(\text{humidification n°5})} - V_{(\text{humidification n°4})}] / V_{(\text{humidification n°5})} \quad \text{(Equation 3)}$$

7.5 Acceptance Criterion

Since the test module is to be used as a sensitivity test, the acceptance criteria could be defined either as a maximum acceptable performance (power or voltage) loss over the ranges of gases relative humidity considered.

Appendix A. Relative humidity versus dew point at cell

The relative humidity is defined as the ratio between the current actual vapour pressure and the vapour pressure at saturate state:

$RH = P_{vap} / P_{vap\ sat}$ (Equation 4)

$P_{vap\ sat}$ can be calculated from the following equation [C.L. Yaws, Chemical properties handbook (1999) Mc Graw Hill]:

$Log\ (Pvap\ sat) = A + B/T + C \cdot Log(T) + D \cdot T + E \cdot T^2$ (Equation 5)
(pressure in Pa, temperature in K)

	A	B	C	D	E
H_2O	31,9797	-3152,2	-7,3037	$2,42^{E-09}$	$1,81^{E-06}$

Where T is the gas temperature expressed in K and P_{sat} is expressed in Pa.

P_{vap} is calculated following the same formula, where T is the dew point:

$Log\ (P_{vap}) = A + B/T_{dew} + C \cdot Log\ (T_{dew}) + D \cdot T_{dew} + E \cdot T_{dew}^2$ (Equation 6)

When the dew point of fuel / oxidant gas at inlet is equal to the cell temperature, the gas *RH* is 100 %.

Using these equations, the relative humidity can be calculated as a function of the dew point for a particular cell temperature (Cf. Figure A.1).

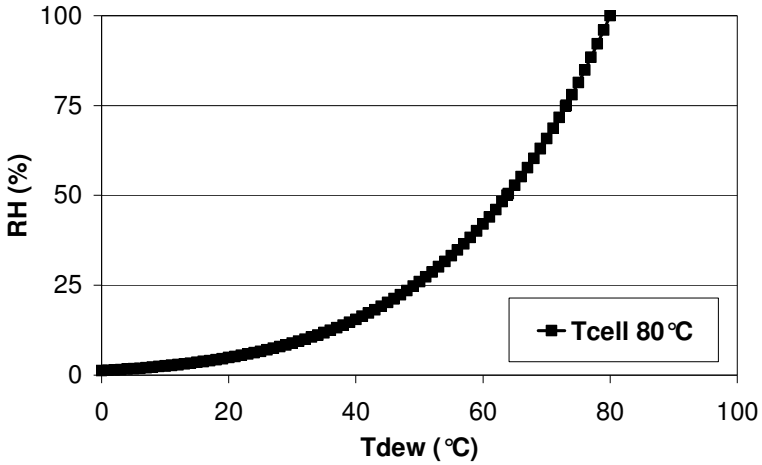


Figure A.1: relative humidity versus dew point for a cell operating at 80°C

Note: for an actual system like a test bench, the control of the relative humidity is not always performed by a direct measurement of the dew point of gases at the test object inlets. In general it is necessary to perform measurements to get the dew point versus the variable actually controlled during the test (for example versus the temperature of the bubblers).

Appendix B. Protocol for data acquisition

The dwell time for each current density set point *k* (see Table 9) 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 B.1 a and b.

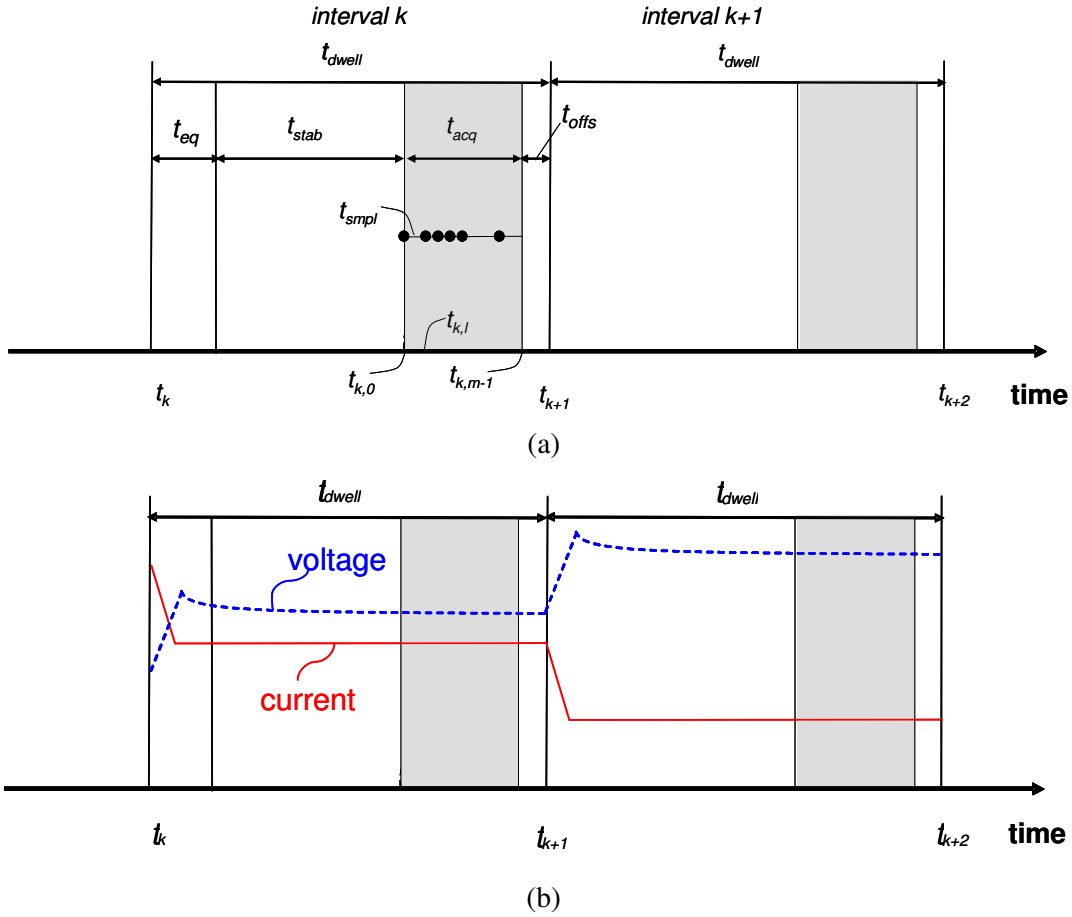


Figure B.1: Schematic of the timeline for two consecutive set points *k* and *k+1* of test step 3 each having a dwell time of same duration (a). The test input and output (test variables) are sampled *l* times at $t_{k,l}$ ($0 \le l \le m-1$) to collect *m* measurements with a sampling interval of t_{smpl} during t_{acq} (see also 10). 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 (b). This is representative for the ramping down of the current at anyone set point *k* and *k+1* between the maximum current density and the minimum current density in the test step 3 (see Table 9).

Table 10: Recommended parameters related to test step 3 (cf. Figure B.1).

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}	≥ 2 t_{acq}	[min]
t_{offs}	*according to envisaged delay in data acquisition by the test bench*	[s]
t_{acq}	*> 1*	[min]
t_{smpl}	1	[s]
m	$\frac{t_{acq}}{t_{smpl}}+1$	-
$t_{k,l}$ ($0 \le l \le m$-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).
Note 2: This table should be reproduced in the test report.

Appendix C. Test information for test report

It is strongly recommended to use for test reporting, a specific test report template related to this procedure. An example of test report can be found in the TM PEFC SC 5-2 test procedure.

Acknowledgements

This report is part of the efforts made by and the result of the support of many individuals and organisations from the participating members of FCTESTNET and FCTES^{QA}.

The editors of this report together with the Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) acting as the administrative and financial coordinator of the FCTES^{QA} project, and the Joint Research Centre (JRC) of the European Commission acting as the scientific coordinator of both projects would like to express their gratitude to the partners of both projects that have greatly contributed to the development of the testing procedure under the FCTESTNET thematic network and to the review of the procedure.

The funding by FP5 under contract # ENK5-CT-2002-20657 for FCTESTNET and by FP6 under contract # 020161 for FCTES^{QA} is appreciated by the project partners.

European Commission

EUR xxxxx EN – Joint Research Centre – Institute for Energy
Title: Humidification sensitivity of a single PEFC. Characterization of the performances of a PEFC operating with fuel and oxidant at various relative humidity. Test Module PEFC SC 5-1. Version 30 04 2010.
Author(s): G De Marco, A Pilenga, M Honselaar, T Malkow, G Tsotridis, S Escribano, L Antoni, R Reissner, O Thalau, E Sitters, G Heinz
Luxembourg: Office for Official Publications of the European Union
2010 – 36 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN xxxx-xxxx
ISBN xxx-xx-xx-xxxxx-x
DOI xx.xxxx/xxxxx

Abstract
This report contains the Test Module TM PEFC SC 5-1 entitled "Humidification sensitivity of a single PEFC. Characterization of the performances of a PEFC operating with fuel and oxidant at various relative humidity". 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 is 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.

LD- NA - 24126- EN- C

ISBN 978-92-79-14613-8