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SOFC Stacks Performance and Endurance Test Modules
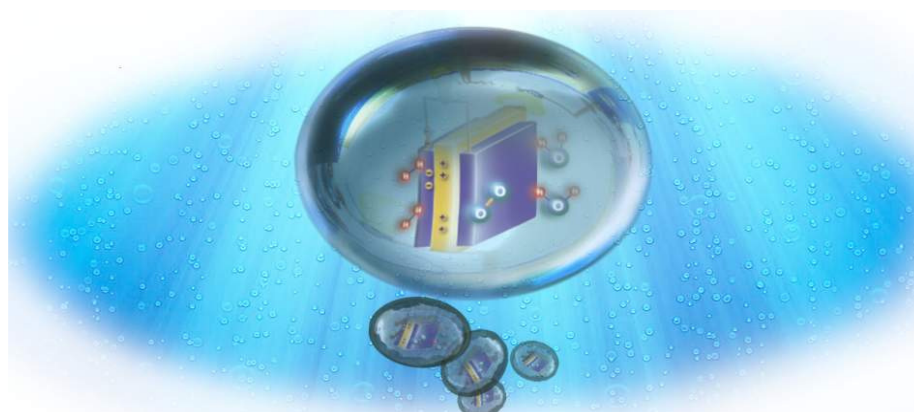
Test Modules TM SOFC 25-28HD

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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 following Performance and Endurance Test Modules for SOFC stacks operating with:

1. TM 25-HD hydrogen; Heavy Duty Test module

2. TM 26-HD internally steam reformed (ISR) methane pre-reformed at 10%; Heavy Duty Test module

3. TM 27-HD simulated fuel representative of externally stem reformed methane and steam reformed diesel (ESR); Heavy Duty Test module

4. TM 28-HD simulated fuel representative of partially oxidised (POX) and auto-thermally reformed diesel (ATR); Heavy Duty Test module

These Modules are 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 these modules 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 modules 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.
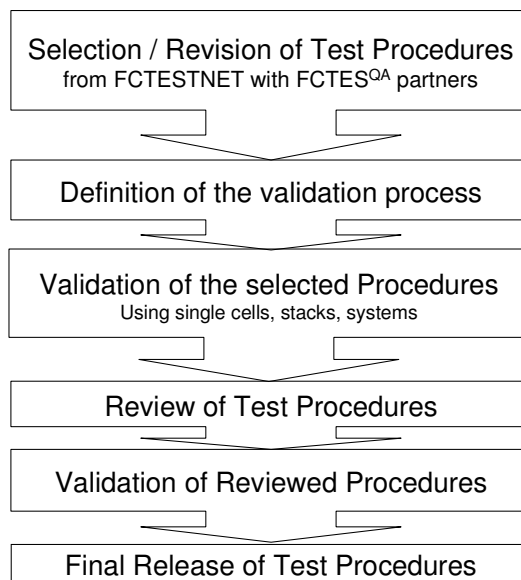
FCTES^{QA}

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.

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}

$\underline{F}$uel $\underline{C}$ell $\underline{Te}$sting, $\underline{S}$afety and $\underline{Q}$uality $\underline{A}$ssurance

Programme: ENERGY 3 -Sustainable Energy Systems

SOFC Stacks Performance and Endurance Test Modules

Heavy Duty Test module with hydrogen; TM 25-HD
Heavy Duty Test Module with ISR; TM 26-HD
Heavy Duty Test Module with ESR; TM 27-HD
Heavy Test Module with POX or ATR; TM 28-HD

Version 30-04-2010

1   Objective and scope

Procedure for evaluation of performance and endurance at heavy duty operating conditions, of SOFC stack operated with:

1. hydrogen; Heavy Duty Test module TM 25-HD

2. internally steam reformed (ISR) methane pre-reformed at 10%; Heavy Duty Test module TM 26-HD

3. simulated fuel representative of externally stem reformed methane and steam reformed diesel (ESR); Heavy Duty Test module TM 27-HD

4. simulated fuel representative of partially oxidised (POX) and auto-thermally reformed diesel (ATR); Heavy Duty Test module TM 28-HD

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 tests can be used as a baseline measurement for the qualification of a SOFC and its components in a given application.

These modules are applied in combination with a test programme, which will describe the operating conditions of the cell.

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 each 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
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 stack 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 current stack 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 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_{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 stack 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 stack (at a given instant or for a given duration)
ΔT_x	Temperature difference of fluid x between the fuel cell stack 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 cell active area can be calculated as follows:

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

Note: F = 96485.3 C/mol

Table 2: Properties of reactant gases for calculating the volumetric flow rate, $Q_{v,x}$ 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
CH$_4$	16.04	4	0.7168
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.

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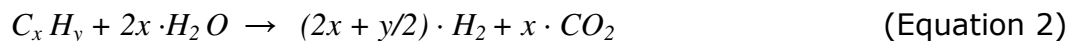
$$C_x H_y + 2x \cdot H_2 O \rightarrow (2x + y/2) \cdot H_2 + x \cdot CO_2 \qquad \text{(Equation 2)}$$

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

Reactant gas	$Q_{v,x}$ [Nml $\cdot$ min^{-1} $\cdot$ cm^{-2}]
H$_2$	$6.97 \cdot n \cdot i / U_f$
O$_2$	$3.35 \cdot n \cdot i / U_f$
CH$_4$	$1.74 \cdot n \cdot i / U_f$
Air	$(3.35/0.209) \cdot n \cdot i / U_f$

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 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 stack 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
t	20 ÷ 3000 h (operating time)	± 1 hour	≥ 1 Hz
T_c	400 – 1050 °C	± 4°C	≥ 1 Hz

3.2 Static Test Inputs

The static inputs applied during performance and endurance phase, and during the polarisation curve phase of test procedure (see Section 7) are given the following sections from Table 5aa up to Table 5bd.

3.2.1   TM 25-HD - Heavy Duty Test Module with Hydrogen

The Tables in this section show the variable test inputs for the evaluation of performance and endurance at heavy-duty operating conditions, of SOFC stack operated with hydrogen.

The test conditions applied by this performance and endurance test are considered more representatives for practical systems, with respect to fuel composition and current density, compared to the light-duty test procedure for performance and endurance. The inlet fuel composition in this test corresponds to a 40% utilised fuel, while the fuel flow results in an actual cell utilisation of 20% at the applied current density of $0.5 \; A \cdot cm^{-2}$.

Table 5aa: Static test inputs applied during the performance and endurance phase of test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	$17.5 \; ml \cdot min^{-1} \cdot cm^{-2} \; H_2$	± 5% (rel)	-
	$11.6 \; ml \cdot min^{-1} \cdot cm^{-2} \; H_2O$	± 10% (rel)	-
X_{ox}	$8.7 \; ml \cdot min^{-1} \cdot cm^{-2} \; O_2$	± 5% (rel)	-
	$32.8 \; ml \cdot min^{-1} \cdot cm^{-2} \; N_2$	± 10% (rel)	-
$Q_{V,fuel}$	$29.0 \; ml \cdot min^{-1} \cdot cm^{-2}$	± 10% (rel)	≥ 1 Hz
$Q_{V,ox}$	$41.5 \; ml \cdot min^{-1} \cdot cm^{-2}$	± 10% (rel)	≥ 1 Hz
i	$0.5 \; A \cdot cm^{-2}$	$\pm 10 \; mA \cdot cm^{-2}$	≥ 1 Hz
T_c	400 – 1050 ℃	$\pm 4^o C$	≥ 1 Hz

Table 5ba: Static test inputs applied during the polarisation curve measurement at start and end of the test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	$10.7 \; ml \cdot min^{-1} \cdot cm^{-2} \; H_2$	± 5% (rel)	-
	$0.3 \; ml \cdot min^{-1} \cdot cm^{-2} \; H_2O$	± 10% (rel)	-
X_{ox}	$6.7 \; ml \cdot min^{-1} \cdot cm^{-2} \; O_2$	± 5% (rel)	-
	$25.2 \; ml \cdot min^{-1} \cdot cm^{-2} \; N_2$	± 10% (rel)	-
$Q_{V,fuel}$	$11.0 \; ml \cdot min^{-1} \cdot cm^{-2}$	± 10% (rel)	≥ 1 Hz
$Q_{V,ox}$	$31.9 \; ml \cdot min^{-1} \cdot cm^{-2}$	± 10% (rel)	≥ 1 Hz
T_c	400 – 1050 ℃	$\pm 4^o C$	≥ 1 Hz

3.2.2   TM 26-HD - Heavy Duty Test Module with ISR Methane

The Tables in this section show the variable test inputs for the evaluation of performance and endurance at heavy-duty operating conditions, of SOFC stack operated with Internally Steam Reformed (ISR) methane.

The test conditions applied by this performance and endurance test are considered more representatives for practical systems, with respect to fuel composition and current density, compared to the light-duty test procedure for performance and endurance.

This test procedure deviates from the equivalent test procedures for evaluation at heavy duty operating conditions with other fuels. An inlet fuel composition corresponding to a 40% utilised fuel of ISR-CH_4 would actually correspond to an external steam-reformed fuel (that is not containing any methane), and this should be considered a relatively mild condition.
Therefore, in this case the inlet fuel composition corresponds to a 0% utilised fuel mixture of methane and water, pre-reformed at 10%, and the actual cell fuel utilisation is 60%, instead of 20% in the comparable test procedures. At a current density of 0.5 A.cm^{-2}, this would imply a relatively low fuel flow, which might possibly introduce unwanted sensitivity for flow distribution and local leakage. For reducing this sensitivity, the fuel is mixed with 50% N_2, which is supposed to be only a diluent and not affecting the cell performance.

Table 5ab: Static test inputs applied during the performance and endurance phase of test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	3.8 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} CH_4	± 4% (rel)	-
	7.6 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2O	± 5% (rel)	-
	1.6 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2	± 10% (rel)	
	0.5 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} CO_2	± 20% (rel)	
	13.6 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N_2	± 5% (rel)	
X_{ox}	8.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O_2	± 5% (rel)	-
	32.8 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N_2	± 10% (rel)	-
$Q_{V,fuel}$	27.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	± 10% (rel)	≥ 1 Hz
$Q_{V,ox}$	41.5 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	± 10% (rel)	≥ 1 Hz
i	0.5 A $\cdot$ cm^{-2}	± 10 mA $\cdot$ cm^{-2}	≥ 1 Hz
T_c	400 – 1050 ℃	± 4℃	≥ 1 Hz

Table 5bb: Static test inputs applied during the polarisation curve measurement at start and end of the test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	10.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2	± 5% (rel)	-
	0.3 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2O	± 10% (rel)	-
X_{ox}	6.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O_2	± 5% (rel)	-
	25.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N_2	± 10% (rel)	-
$Q_{V,fuel}$	11.0 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	± 10% (rel)	≥ 1 Hz
$Q_{V,ox}$	31.9 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	± 10% (rel)	≥ 1 Hz
T_c	400 – 1050 ℃	± 4℃	≥ 1 Hz

3.2.3   TM 27-HD - Heavy Duty Test Module with ESR Methane or Diesel

The Tables in this section show the variable test inputs for the evaluation of performance and endurance at heavy-duty operating conditions, of SOFC stack operated with a simulated fuel representative of Externally Steam Reformed (ESR) methane or diesel.

The test conditions applied by this performance and endurance test are considered more representatives for practical systems, with respect to fuel composition and current density, compared to the light-duty test procedure for performance and endurance. The inlet fuel composition in this test corresponds to a 40% utilised fuel, while the fuel flow results in an actual cell utilisation of 20% at the applied current density of 0.5 A.cm^{-2}.

Table 5ac: Static test inputs applied during the performance and endurance phase of test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	17.4 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2	$\pm$ 4% (rel)	-
	14.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2O	$\pm$ 10% (rel)	-
	8.9 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} CO_2	$\pm$ 10% (rel)	
X_{ox}	8.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O_2	$\pm$ 5% (rel)	-
	32.8 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N_2	$\pm$ 10% (rel)	-
$Q_{V,fuel}$	40.5 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
$Q_{V,ox}$	41.5 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
i	0.5 A $\cdot$ cm^{-2}	$\pm$ 10 mA $\cdot$ cm^{-2}	$\geq$ 1 Hz
T_c	400 $-$ 1050 °C	$\pm$ 4°C	$\geq$ 1 Hz

Table 5bc: Static test inputs applied during the polarisation curve measurement at start and end of the test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	10.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2	$\pm$ 5% (rel)	-
	0.3 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H_2O	$\pm$ 10% (rel)	-
X_{ox}	6.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O_2	$\pm$ 5% (rel)	-
	25.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N_2	$\pm$ 10% (rel)	-
$Q_{V,fuel}$	11.0 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
$Q_{V,ox}$	31.9 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
T_c	400 $-$ 1050 °C	$\pm$ 4°C	$\geq$ 1 Hz

3.2.4   TM 28-HD - Heavy Duty Test Module with POX or ATR Diesel

The Tables in this section show the variable test inputs for the evaluation of performance and endurance at light-duty operating conditions, of SOFC stack operated with a simulated fuel representative of Partially Oxidised (POX) and Auto-thermally Reformed (ATR) diesel.

The test conditions applied by this performance and endurance test are considered more representatives for practical systems, with respect to fuel composition and current density, compared to the light-duty test procedure for performance and endurance. The inlet fuel composition in this test corresponds to a 40% utilised fuel, while the fuel flow results in an actual cell utilisation of 20% at the applied current density of 0.5 A.cm^{-2}.

Table 5ad: Static test inputs applied during the performance and endurance phase of test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	17.4 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H$_2$	$\pm$ 1.5% (rel)	-
	19.8 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H$_2$O	$\pm$ 5% (rel)	-
	12.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} CO$_2$	$\pm$ 10% (rel)	
	29.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N$_2$	$\pm$ 5% (rel)	
X_{ox}	8.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O$_2$	$\pm$ 5% (rel)	-
	32.8 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N$_2$	$\pm$ 10% (rel)	-
$Q_{V,fuel}$	79.1 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 7.5% (rel)	$\geq$ 1 Hz
$Q_{V,ox}$	41.5 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
i	0.5 A $\cdot$ cm^{-2}	$\pm$ 10 mA $\cdot$ cm^{-2}	$\geq$ 1 Hz
T_c	400 $-$ 1050 $\degree$C	$\pm$ 4$\degree$C	$\geq$ 1 Hz

Table 5bd: Static test inputs applied during the polarisation curve measurement at start and end of the test.

Input	Range/Value	Control accuracy/tolerance	Sample rate
X_{fuel}	10.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H$_2$	$\pm$ 5% (rel)	-
	0.3 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} H$_2$O	$\pm$ 10% (rel)	-
X_{ox}	6.7 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} O$_2$	$\pm$ 5% (rel)	-
	25.2 ml $\cdot$ min$^{-1}\cdot$ cm^{-2} N$_2$	$\pm$ 10% (rel)	-
$Q_{V,fuel}$	11.0 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
$Q_{V,ox}$	31.9 ml $\cdot$ min$^{-1}\cdot$ cm^{-2}	$\pm$ 10% (rel)	$\geq$ 1 Hz
T_c	400 $-$ 1050 $\degree$C	$\pm$ 4$\degree$C	$\geq$ 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.
3. Test module M21 Polarisation curve for a SOFC stacks.

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 A).

To perform the performance & endurance tests 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.
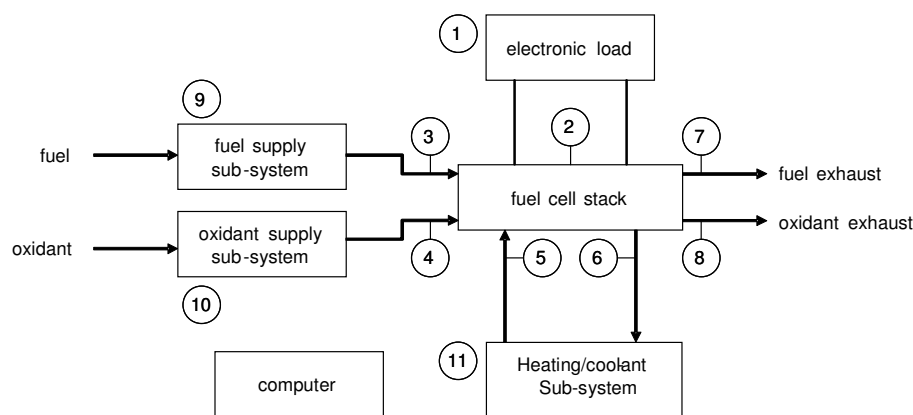

Figure 6.1: Test set-up with sub-systems, sensors and sensor locations (see also Table 7 and Table 8).

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		1
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 Programme**

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

The test programme described here consists of three phases.

The first phase comprises the assembly and pre-conditioning of the cell. The degree of specification for this part is limited. Preferably the recommendations of the cell supplier are applied. This phase is concluded with one polarisation curve measurement, as described in the test module M21, at the selected nominal operating temperature of this test and at the gas conditions of Table 5ba to 5 bd.

The second phase, the performance test, consists of a 20 hours period of galvanostatic controlled, steady-state operation. This phase is started and concluded with a series of polarisation curve measurements at three or five temperatures centred on the selected nominal operating temperature of this test. The polarisation curve measurement itself is described in the test module M21.

The third phase is the endurance test. The operating conditions are identical to those of the performance test. Recommended duration of the endurance test is 3000 hours. At each 500 hours interval during the endurance test a single polarisation curve measurement is executed, that is only at the selected operating temperature.
The endurance test is concluded with a series of polarisation curve recordings at three or five temperatures, as described in the test module M21.

The test programme is concluded with one polarisation curve measurement, as described in the test module M21, at the selected nominal operating temperature of this test and at the gas conditions of the Table5ba to 5bd.

7.1 Assembly and pre-conditioning of the FC Stack

The applied mechanical clamping pressure of the stack is according to the recommendations of the stack manufacturer or according to common practice at the testing organisation.

The start-up of the stack occurs according to the procedure recommended by the stack supplier or by the procedure that is common practice at the testing organisation.

The stabilisation of the stack can be part of the start-up procedure. If this is not the case it is recommended to follow either:

a) The recommendation of the cell supplier

b) The common practice at the testing organisation

c) Galvanostatic operation of the stack at the selected operating temperature, at the gas conditions of Table 5ba to 5bd, for minimum 2 hours, at a current density of 0.3 A.cm^{-2}.

After the start-up and stabilisation of the stack one polarisation curve measurement, as described in the test module M21, at the selected nominal operating temperature of this test and at the gas conditions of Table 5ba to 5bd is performed.

A second stabilisation period of minimum 2 hours galvanostatic operation at the selected operating temperature, the gas conditions of *3.2* and a current density of 0.3 A.cm^{-2} is applied before the next phase starts.

Applied conditions and procedure for start-up and stabilisation should be described in the report of the test result.

7.2 Recording of the initial polarisation curves

After the start-up and stabilisation phase of *7.1*, cell polarisation curves have to be recorded according to the Test Module M21 stack polarisation curve.

The gas conditions as prescribed in Table 5aa to 5ad are constant during all phases of the polarisation curve measurements.

It is recommended to perform polarisation curve measurements at minimum three operating temperatures, preferably five, each differing 50°C. In that case the first polarisation measurement is at the selected operating temperature.

After completion of the first polarisation curve measurement the stack is brought to the nearest lower temperature. The new temperature is reached if the actual registered cell temperature is within the interval ± 10°C of this new target temperature for 10 minutes. From that moment on, the performance stabilisation period starts.

At the new operating temperature, a performance stabilisation period of 2 hours at 0.3 A.cm^{-2} and at the gas conditions of table 5aa to 5ad is applied, after which the next procedure for recording the polarisation curve as described in the test module M21 is executed.

The consecutive phases of stabilisation and polarisation curve measurement are repeated at the next 50°C lower temperature.

After the polarisation measurement has been performed at the lowest temperature in the range, the temperature is ramped up to a temperature 50°C higher compared to the one of the first polarisation curve measurement. After the prescribed stabilisation procedure the polarisation curve is recorded.

The next polarisation curve measurement will be at a 50°C higher temperature.

Example

Suppose the selected temperature for steady-state operation in this test is 750°C, then the temperature sequence at which the polarisation measurements are executed is:
−   750-700-650-800-850°C (in case of selecting five temperatures for polarisation measurements)
or
−   750-700-800°C (in case of selecting three temperatures for polarisation measurements).

7.3 Steady-state operation for performance evaluation

This test phase starts immediately after completion of the polarisation recordings described in *7.2*.

The performance test is under galvanostatic control at the selected operating temperature, and the gas conditions and current density of Table 5aa to 5ad.

The duration of the steady-state operation is typically 20 hours.

7.4 Recording of the second series of polarisation curves

This series of polarisation curves make-up the conclusion of the short-term performance test, and the start of the long-term endurance test.

The measurement procedure for recording the second series of polarisation curves is exactly identical to the initial series described in *7.2*.

7.5 Steady-state operation for endurance evaluation

This test phase starts immediately after completion of the polarisation recordings described in *7.4*.

The performance test is under galvanostatic control at the selected operating temperature, and the gas conditions and current density of Table 5aa to 5ad.

If duration of the steady-state operation is e.g. 3000 hours every 500 hours a single polarisation curve is performed, at the selected operating temperature only, and is recorded according to the procedure described in the test module M21 and at the gas conditions prescribed by Table 5aa to 5ad in this test procedure.

7.6   Recording of the last series of polarisation curves

This series of polarisation curves make-up the conclusion of the long-term endurance test.

The measurement procedure for recording the last series of polarisation curves is exactly identical to the initial series described in *7.2*.

A final stabilisation period of minimum 2 hours galvanostatic operation at the selected operating temperature, the gas conditions of Tables 5ba to 5bd and a current density of 0.3 A.cm^{-2} is applied before the programme is ended.

One final polarisation curve measurement, as described in the test module M21, at the selected nominal operating temperature of this test and at the gas conditions of Table 5aa to 5ad is performed.

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 each cell voltage be lower than +/- 5 mV during the last hour before ending the conditioning step.

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 cell 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.

Appendix A.   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 FC Stack/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 SOFC Stack using the FCTESQA procedure TM SOFC 25-HD version…

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 stack
...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 FC stack 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

FC Stack manufacturer	
FC Stack technology	
FC Stack model	
Product or object tested	
Product number	
Test object identity number	

Fuel cell : material of the current collectors / technology	
Fuel cell : design [1]	
Fuel cell : 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 stack:

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	FC 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 stack 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	

<u>Note</u>: *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	FC Stack voltage	? V	± ? mV	? Hz
P	FC 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 stack voltage 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 stack voltage over the last XX sec (V)	Average stack 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 stack voltage at a current density of zero.
- The current density at each cell voltage between 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 each cell voltage interval between 0.75 - 0.85 V.

Performance test:

- Graph representing the cell voltage versus the operating time
- Table representing the OCV, the current density at cell voltage of 0.7 V and the ASR recorded by or calculated from the polarisation curve measurements at all T and t.

Endurance test:

- Graph representing the cell voltage versus the operating time
- Table representing the OCV, the current density at the cell voltage of 0.7 V and the ASR recorded by or calculated from the polarisation curve measurements at all T and t.

7.3 Description of the shut-down (if relevant)

The author describes the procedure how the FC Stack 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.

Abstract

This report contains the following SOFC Performance and Endurance Test Modules for stacks operating with:

- **TM 25-HD hydrogen; Heavy Duty Test module**
- **TM 26-HD internally steam reformed (ISR) methane pre-reformed at 10%; Heavy Duty Test module**
- **TM 27-HD simulated fuel representative of externally stem reformed methane and steam reformed diesel (ESR); Heavy Duty Test module**
- **TM 28-HD simulated fuel representative of partially oxidised (POX) and auto-thermally reformed diesel (ATR); Heavy Duty Test module**

These modules are a general characterization method used in research and development of SOFC with no target application. They may be used as a baseline measure to qualify fuel cells and its components in any given application.

The Test Modules were 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 Modules 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 Modules are 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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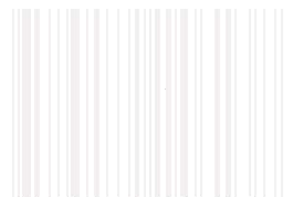
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