TM PEFC ST 5-3 - Testing the voltage and the power as function of the current density (Polarization curve for a PEFC stack)

Version 1.5

Test input........................Current density
Class of test input ....Functional
Test output.......................Voltage and power *(individual cell voltages if available)*
Class of test output.........Functional

Class of test object..........Stack
Class of application ....Generic
Specific application ....none

Author(s) ....FCTESTNET WP PEFC and FCTES^{QA} WP PEFC groups

Latest revision date.........December 2009

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1 Objective and scope

The purpose of this test module (testing procedure) is to characterize the performance of a PEFC stack under constant current conditions. The module is used for measuring the voltage and the power of the stack as a function of drawn current. If properly instrumented, individual cell voltages, different temperatures, reactant flows, humilities and stack fluid pressure drops may also be measured.

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

Note 1: The ranges of the base line operating conditions considered for this test module correspond to the current conditions used by the members of the fuel cell community (from the FCTESTNET network or not) and are based on the analysis of the answers to the questionnaire proposed by the network and on the experience of the FCTESTNET partners. The parameters, values and ranges used throughout this document are recommended only.

Note 2:This test module is primarily for stacks with water cooling and without dead end configuration on the fuel side.

2 Terminology, definitions, and symbols

2.1 Terminology and definitions

Terminology and definitions used in this document correspond to the FCTESTNET terminology document (see Section 5.1).

2.2 Symbols

Additional symbols are defined as follows:

Table 1. Definition of symbols used.

Symbol	Description
A	Common active geometric area of the individual cells in the stack
F	Faraday's constant
I	Stack current
I_{max}	Maximum stack current
M	Molar mass
N	Number of atoms per oxygen molecule
P	Stack power
$Q_{v,\,x}$	Volumetric flow rate of stack fluid x (i.e. coolant, cool and dry reactant gas, fuel or ox) under SATP[1] conditions
$Q_{v,\,x,\,\lambda}$	Volumetric flow rate (dry basis) of reactant gas x at stoichiometry λ_x
$Q_{v,x,\,min}$	Minimum volumetric flow rate of stack fluid x
$Q_{m,\,x}$	Mass flow rate of stack fluid x
$RH_{x,\,y}$	Relative humidity of reactant gas x at stack location y (i.e. inlet, in or outlet, out)
$T_{x,\,y}$	Temperature of stack fluid x at stack location y
T_A	Ambient temperature
$T_{dew\ x,\,y}$	Dew point of reactant gas x at stack location y
T_s	Surface temperature of the stack
T_{stack}	Stack temperature
V	Stack voltage
V_{min}	Minimum allowable stack voltage
V_i	Individual cell voltage of cell number i ($1 \leq i \leq n$)
$V_{i,\,min}$	Minimum allowable voltage of every cell i in the stack
V_{rev}	Reversible cell voltage under SATP conditions
W_{el}	Electrical work
X_k	Test variable X_k (place holder) related to interval k
$Y_k(X_1,\ldots,X_s)$	Test variable Y_k $(X_1,\ldots,X_s)$ being a function of s test variables X_1 to X_s related to interval k
c_p	Specific heat capacity of water under isobaric conditions and at stack temperature
i	Stack current density ($i = I / A$)
k	Interval k belonging to current density set point k during measurement of the test outputs
l	Number of data points recorded during t_{acq} (data acquisition index)
m	Number of data points per interval k
n	Number of cells in the stack
$\dot{n}$	Molar flow rate
p_A	Ambient pressure
$p_{x,\,y}$	Pressure of reactant gas x at stack location y

Symbol	Description
t	Duration, period, or time
t_{acq}	Duration of data acquisition at interval k
t_{dwell}	Minimum dwell time between two set points belonging 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 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 data point l 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 criterion at interval k prior to data acquisition
z	Number of electrons exchanged in the fuel cell reaction for one mole of reactant
$\#V_{i,\,k\,max/min}$	Cell number i exhibiting the maximum/minimum voltage in the stack at interval k
Greek symbols	
$\Delta H^0{}_f\,(H_2O_{(g)})$	Standard enthalpy of water vapour formation
$\Delta\,p_x$	Pressure drop of in the flow path of the fluid x (i.e. coolant, reactant gas) between stack outlet and inlet
ΔT_x	Temperature difference of fluid x between its stack outlet and inlet
ΔV_i	Maximum allowable cell voltage deviation (range between maximum and minimum cell voltages at a given instant or for a given duration)
$\Delta u_k(X_k)$	Measurement uncertainty of test variable X at interval k
ΛX_k	Stability of parameter X (place holder) measured/calculated during t_{acq} at interval k
$\sum P_i$	Sum of power of n cells in the stack ($1 \le i \le n$)
$\sum V_i$	Sum of voltage of n cells in the stack ($1 \le i \le n$)
λ_x	Stoichiometric ratio of the flow rate of reactant gas x supplied to the stack to that theoretically required to sustain the stack current or load applied
η	Efficiency
η_e	Instantaneous electrical stack efficiency
η_t	Instantaneous thermal stack efficiency
φ_{H2}	Volumetric hydrogen content of dry fuel gas
φ_{O2}	Volumetric oxygen content of dry oxidant gas
ρ	Density of dry reactant gas under SATP conditions

[1] *SATP = Standard Ambient Temperature and Pressure (298.15 K, 101.325 kPa)*

The flow rates of the reactant gases can be calculated from Equation 1:

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

Table 2. Properties of reactant gases for calculating $Q_{v,\lambda}$.

Reactant gas	***M*** [g/mol]	***z***	***ρ*** [g/dm^3]
H_2	2.02	2	0.0899
O_2	32.0	4	1.43
Air	28.8	4	1.29

Using these values at SATP, the reactant gas flow rates can be calculated using the expressions given in Table 3.

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

Reactant gas	$Q_{v,\lambda}$ [ml/min]
H_2	$6.97 \cdot n \cdot I\,(A) \cdot \lambda$
O_2	$3.49 \cdot n \cdot I\,(A) \cdot \lambda$
Air	$3.49 / 0.209 \cdot n \cdot I\,(A) \cdot \lambda = 16.7 \cdot n \cdot I\,(A) \cdot \lambda$

The $Q_{v,\lambda}$, values 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.

3 Test Inputs

There are two types of test inputs (test conditions), variable and static. They are listed in the tables in Sections 3.1 and 3.2.
Concerning the measurement uncertainties and the sample rates, the values given in the following tables are the values commonly available with most of the instrumentations. The most important is to clearly state the actual values in the test report.

3.1 Variable Test Inputs

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

Table 4. Variable test inputs during test step 3.

Input	Value / Range	Measurement uncertainty	Sample rate
i	0 – 2 A/cm^2 See Appendix A	± 2% for i < 0.1A/cm² ± 1% for i > 0.1A/cm²	≥ 1 Hz
$Q_{v,\ fuel}$	Corresponding to the stoichiometry, see Equation 1	± 1% FS*	≥ 1 Hz
$Q_{v,\ ox}$			

** 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 (FS or maximum flow) and with a minimum measurable flow (generally 10% of the maximum flow). That means that the measurement uncertainty decreases with increasing flow rate and, hence, decreases with increasing current density when operating at fixed stoichiometry.*
** Note 2: The actual volumetric flow rates of the reactant gases used during measuring the test outputs might either be kept constant or be controlled by stoichiometry unless these values are smaller than the minimum flow rates, $Q_{v,\ fuel,\ min}$ and $Q_{v,\ ox,\ min}$ These minimum values usually correspond to stoichiometric flow rates for low current densities of between 50 and 200 mA/cm² or are as to the stack manufacturer recommendations. They shall be stated in the test report.*

3.2 Static Test Inputs

The static inputs applied during test step 3 are given in Table 5. Static inputs do not vary during the entire duration of test step 3 (see Section 7.3) or during the duration of each current density step *k* (see Table 11 in Appendix A) in the course of test step 3.

Table 5. Static test inputs applied during test step 3.

Input	Value / Range	Measurement uncertainty	Sample rate
p_A	100 kPa	-	1 Hz
φ_{fuel}	Up to 100% H_2	± 0.005%	
φ_{ox}	21% O_2 - 79% N_2	± 1% O_2	
T_{stack}	T_{amb} - 80°C	± 2°C	1 Hz
$T_{cool,in}$	T_{amb} - 75°C		
ΔT_{cool}	*Maximum according to stack manufacturer recommendation*	± 4°C	
$Q_{v,\ cool}$ *	*according to stack manufacturer recommendation*	± 1% FS**	
$p_{fuel/ox,\ out}$	100 – 300 kPa	± 2% FS**	≥ 1 Hz
λ_{H2}	1.1 – 1.5 (dimensionless)	-	

Input	Value / Range	Measurement uncertainty	Sample rate
λ_{Ox}	2 – 2.5 (dimensionless)		
$Q_{v,\ fuel/ox\ min}$	*according to stack manufacturer recommendations or as limited by test bench*	± 1% FS**	≥ 1 Hz
$T_{fuel/ox,in}$	T_{amb} - 80°C	± 2°C	1 Hz
$T_{dew\ fuel/ox,\ in}$ ***			
$RH_{fuel/ox}$ ***	0 - 100 %	depending on dew point measurement uncertainties	
T_A	T_{amb} – 50 ºC	± 2°C	
$p_{fluid,in}$	*according to stack manufacturer recommendation*		

** Note 1: It is recommended that T_{stack} to be defined as $T_{cool,out}$. For water cooled stacks, $Q_{v,\ cool\ in}$ shall be regulated to maintain, where appropriate to the stack design, either $T_{cool,\ in}$ or $T_{cool,\ out}$ as to prevent fuel and oxidant condensation at the stack inlet.*

*** Note 2: see Note 1 of Table 4.*

**** Note 3: The method of reactant gas humidification is not stipulated in this test module. The method shall however be described in the test report along with the reactant gas dew points (and relative humidity, RH).*

Depending on the nature of the stack, the nature of some of the inputs may change. This means that, under certain conditions, some of the static inputs may not necessarily be regulated or become variable. For example, $Q_{v,\ cool}$ may increases as I increases.

4 Test Outputs

Table 6 below lists the test outputs that are determined in this test module. Some test outputs may not be applicable for stacks with specific features (e.g. no pressure drop data for stacks in dead end configuration).

Table 6. Test outputs determined in this test module.

Output	**Value / Range**	**Measurement uncertainty**	**Sample rate**
P	Calculated		-
V		± 1 %	≥ 1 Hz
$V_{i(1 \leq i \leq n)}$*		± 1 mV	
$\sum P_i$	Calculated		-
$\sum V_i$			
T_s*, **		±2 °C	1 Hz
$T_{fuel/ox,out}$*			
$T_{dew\ fuel/ox,out}$*			
$T_{cool,out}$*			
ΔT_{cool}*			
$\Delta p_{fuel/ox}$*		± 2 %	≥ 1 Hz
Δp_{cool}*			
η_e	Calculated		-
η_t			

** Note 1: The measurement of these test outputs is recommended. It may not be possible to measure all test outputs depending on the configuration of the stack and the test bench*

*** Note 2: In case the surface temperature is measured, the measurement location shall be specified in the test report.*

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 self-assembled test bench.
2. Calibration certificates of the fuel cell test bench instrumentation. These documents will be necessary to determine the actual accuracy 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 stack.

5.3 Provisions

Standard local safety precautions for working with the fuels and oxidants used shall be followed.
Recommended alarm and emergency values are given in Table 12 of Appendix A.

6 Test Equipment and Setup

Recommendations on the test object: the tests are to be performed on a polymer electrolyte fuel cell stack, as defined in the FCTESTNET terminology document. However, due to the requirements of the stack, certain subsystems in the test bench may not be needed. These include reactant supply and waste heat removal. The actual configuration of these subsystems should be described in the test report.

Table 7. Stack features and concomitant system control requirements.

Control ⇒ / Stack feature ⇓	Coolant flow	Fuel flow	Oxidant flow	Reactant Humidification
Active cooled	√			
Passive cooled	-			
Fuel dead end		-		
Oxidant dead end			-	
Air breathing			-	
External humidification				√
Internal humidification				-

This test procedure does not prescribe the type, geometry and size of the stack components. Materials, design, geometry and sizes of the MEA, plates and stack will have to be described in the test report (cf. Appendix D).

The test step and sensors should be described in order to use the test inputs and outputs given in Sections 3 and 4.

6.1 Test set-up

The test bench shall consist of sub-systems to provide fuel and oxidant to the stack in a defined manner (flow rate, pressure, temperature, and humidity); an electronic load to draw current/load from the stack; and a coolant sub-system for controlling stack temperature. The test bench should be computerized including DAQ (data acquisition) hardware. A schematic of a typical fuel cell test environment is shown in Figure 6.1. Some systems may not be required depending on specific stack features (cf. Table 7).

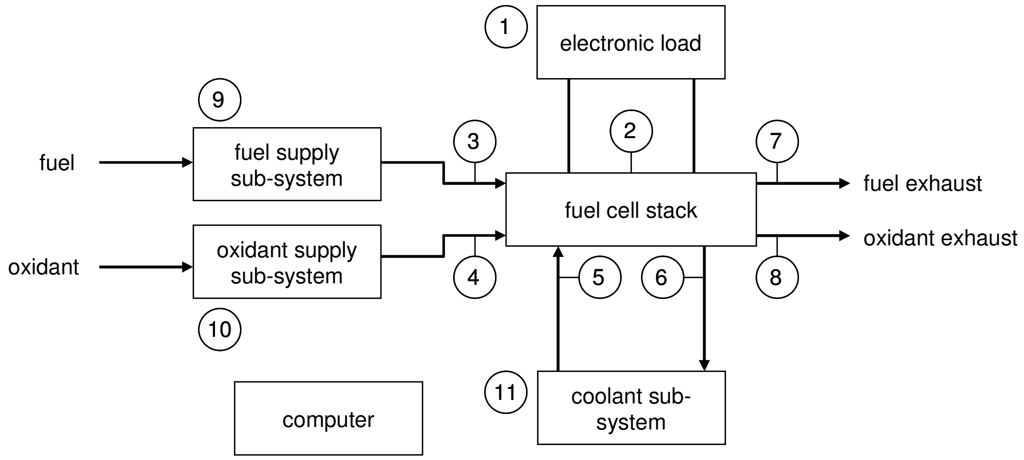


Figure 6.1: Test set-up with sub-systems and sensors and sensor locations (see also Table 8 and Table 9).

6.2 *Sensors or control/acquisition equipment needed*

Table 8. Sensors corresponding to the test inputs and outputs (see also Figure 6.1 and Table 9).

Description	**Sensor ID (T=temperature or temperature difference, P=pressure drop, F=flow, I=current, U=voltage)**	**Location(s) of sensor(s) (refer to Figure 6.1)**
Stack current	I-0	1
Stack voltage	U-0	2
Cell voltage *	U-1..*n*	2
Stack surface temperature	T-1	2
Gas temperature at fuel inlet	T-2	3
Gas temperature at oxidant inlet	T-3	4
Coolant outlet-inlet temperature difference *	T-5 – T-4	6 – 5
Pressure drop in coolant flow path *	P-4 – P-3	6 – 5
Stack temperature	T-5	6
Stack coolant out temperature *	T-5	6
Pressure drop in fuel flow path *	P-5 – P-1	7 – 3
Gas temperature at fuel outlet *	T-6	7
Gas pressure at stack outlet	Fuel: P-5 Oxidant: P-6	7 8
Gas temperature at oxidant outlet *	T-7	8
Pressure drop in oxidant flow path *	P-6 – P-2	8 – 4
Fuel flow rates according to Equations 1 & 2	F-1	9
Oxidant flow rates according to Equations 1 & 2	F-2	10
Coolant flow rate	F-3	11

** Note: 1: The measurement of these test outputs is recommended depending on the configuration of the stack and the test bench.*

Table 9. Recommended data acquisition sample rates and sensor quantities (see also Table 8).

Sensor ID	Description	Sample rate	Qty
U-0	Stack voltage	1 Hz	1
I-0	Stack current		
U-1..*n*	Cell voltage		*n* *
T-1..7	Temperature		7 * (1 minimum)
P-1..6	Pressure		6 * (2 minimum)
R-1,2	Relative humidity		2**
F-1,2	Flow rate controller		2

** Note 1: These are recommended measurements. 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 injection.*

Table 10. Recommended test bench components and equipments

Description	Specification	Qty
Programmable electronic load	Maximum current at $V = 0$ V possible, in constant current mode	1
Oxidant supply sub-system*	Temperature ambient..90℃, RH 0..100 %	
Fuel supply sub-system*	Temperature ambient..90℃, RH 0..100 %	
Coolant sub-system	Provide necessary coolant flow rate (according to test inputs Is-6), sufficient heat dissipation capacity	
Control & Measurement Computer	The capacity of the DAQ hardware and computer has to be sufficient to record all test inputs and outputs with the sample rates as defined in Table 8.	
DAQ hardware / software		

** Note: This shall be described in the test report.*

7 Test Procedure

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

The objective of this test procedure is to determine the performance of a PEFC stack and the stability of test inputs/outputs as a function of test duration, current density, and stack power. It is important to operate the stack under stable conditions prior to the start of test step 3.

Stability criteria for at least the current, the stack temperature and the stack voltage should be defined in the test report. The check on the stability of the test outputs shall follow the check on the stability of the test inputs. The check on attainment of a stability criterion may also be carried out offline during data post processing (cf. Appendix C).

In that case, non-attainment of the stability criterion may lead to the rejection of the test if the stability criterion is an acceptance criterion for the test. Detailed information shall be given in the test report.

For example, a stability criterion for a test input can be defined as follows:

Step 1: Pre-conditioning of test object: A test input is considered stable when the range of its values measured during the last 30 minutes (stabilization time) of the elapsed duration of this test step falls within the measurement uncertainty of this input as specified in Table 4 and Table 5.

Step 2: Setting the test conditions (test inputs): In case a test input differs in this step from that of test step 1, this input is considered stable when the range of its values measured during an appropriate stabilization time falls within the measurement uncertainty as specified in Table 4 and Table 5. This stabilization time shall be specified in the test report.

Step 3: Measuring the test outputs: The test input is considered stable when the range of its values measured during the stabilization period, t_{stab} falls within the measurement uncertainty of this input as specified in the Table 4 and Table 5. For each interval k, the duration of t_{stab} shall at least be twice that of data acquisition, t_{acq}. (cf. Appendix B).

The stability criterion for a test output can, for example, be defined as follows:

Step 1: Pre-conditioning of test object: The test output is considered stable when during the last 30 minutes of the elapsed duration of this test step the RSD (relative standard deviation, see Equation 13 in Appendix C) is less than 1%.

Step 2: Setting the test conditions: A check on the stability of a test output needs not to be performed in this step.

Step 3: Measuring the test outputs: The test output is considered stable when during t_{stab} the RSD is less than 1%.

7.1 Step 1: Pre-conditioning of test object

The start-up of the stack and conditioning step can be conducted either following the procedure:

- proposed by the manufacturer of the test object
- or proposed by the manufacturer of a component tested in the test object
- or the one that is common practice at the testing organisation
- or recommended below:

The most important aspect of this step is to reach the stability of all the static inputs, the stack voltage, and the voltage of the cells prior to start test step 3.

The test starts by bringing the test conditions (test inputs) to the values specified for the conditioning of the stack. The conditioning consists of keeping these conditions stable and to have the resulting stack voltage equilibrated according to the stability criteria. This would normally correspond to an optimized state of humidification of the electrolyte.

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 until its temperature, and the test inputs of the reactant gases as given in Section 3.2 become stabilised. Following that, the stack should be operated in galvanostatic load (constant current) mode for at least 30 minutes at the current density as specified by the stack manufacturer. Alternatively, the stack should be operated in this mode for the same duration at a current density allowing the voltage of each cell being in excess of 500 mV (or the minimum cell voltage specified by the stack manufacturer*)*. The increase in current density is recommended to be in instantaneous steps or by ramping with a rate as recommended by the stack manufacturer. In the absence of such recommendation, it is recommended to apply current density steps of 100 mA/cm² or ramping the current density at a rate not exceeding 10 mA/cm² per second.

The procedures for start-up and pre-conditioning of the stack including the test inputs and outputs of this step shall be detailed in the test report.

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

This step of the test starts by bringing the test inputs to the values specified in Table 5. It is conducted in galvanostatic load mode. The first set point for the current density will correspond either to the value used for test step 1 or to a value specified by the test objective. In the latter case, stability criteria may be defined for the test inputs.

7.3 Step 3: Measuring the test outputs

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

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

The main objective is to determine the evolution of the stack voltage (and of the stack power) during one complete cycle of increasing the current density from an arbitrary start value of (e.g. as may occur in cycling and long term testing with intermittent polarization curve measurements) to a specified maximum, by decreasing it to zero (open circuit voltage, OCV) and finally, by increasing it to the start value (see Figure 7.2 in Appendix A).

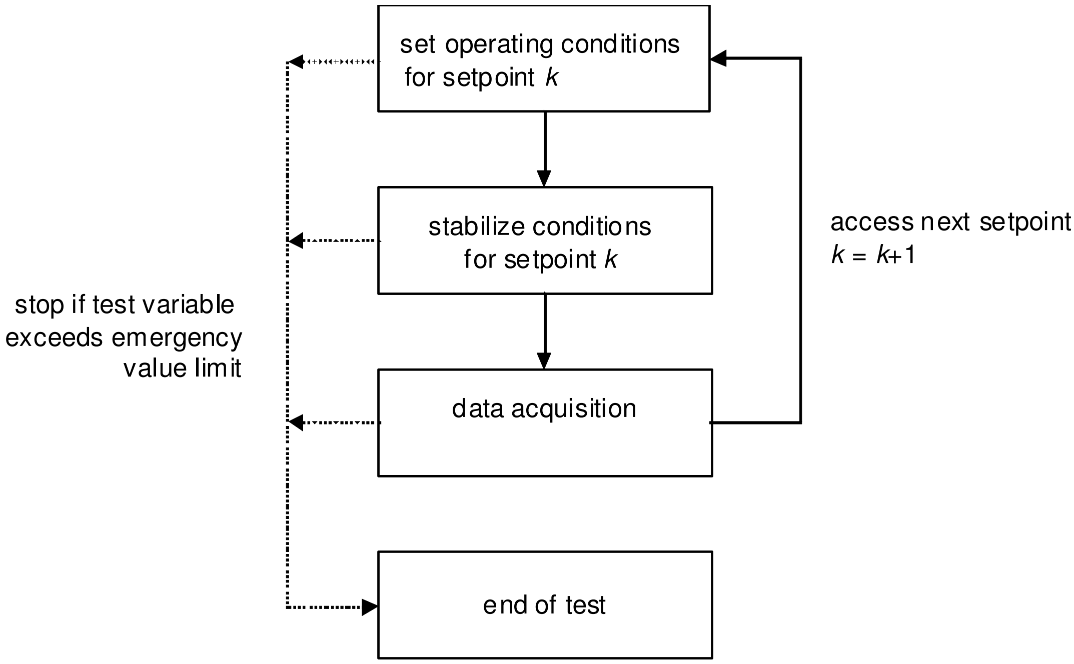


Figure 7.1: Schematic for measuring the test inputs and outputs.

Note 1: The measurement method for this step of the test 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 Appendix B.

It is proposed to derive the polarization curves (graphs of stack voltage, V and power, P vs. current density, i) from these two averaged test outputs during the decrease of the current density from the maximum to OCV conditions (cf. Figure 7.2 in Appendix A). The duration of this test step depends on the measurement method in particular on the actual dwell time, t_{dwell} at each current step (cf. Figure 7.2 in Appendix A and Figure 7.3 in Appendix AB), the applied rate of current increase/decrease for these steps, and the test ending cause: either maximum current or minimum stack/cell voltage attained.

Test ending criterion: The test shall be stopped after one complete current density cycle. The test may prematurely be stopped upon an emergency value (e.g. given in Appendix A) is obtained.

7.4 Step 4: Data Post Processing

The stack power,

$$P(W) \quad = \quad V(V) \cdot I(A) \qquad \text{(Equation 2)}$$

is a calculated test output.

The instantaneous electrical stack efficiency, η_e is calculated as follows:

$$\eta_e \quad = \quad \frac{V(V) \cdot I(A)}{\dot{n}_{H_2\,supplied}(mol/s) \cdot \Delta H_f^0(H_2O_{(g)})} \qquad \text{(Equation 3)}$$

where
$\dot{n}_{H2\ supplied}$ is the molar rate of hydrogen supplied at the stack inlet,
V = stack voltage,

I = stack current, and
$\Delta H^0{}_f\,(H_2O_{(g)})$ = 241.826 kJ/mol is the enthalpy of formation of water vapour at SATP. It is equivalent to the lower heating value (LHV) of hydrogen.

The instantaneous thermal stack efficiency (or heat recovery efficiency), η_t is calculated as follows:

$$\eta_t = \frac{Q_{cool}(g/s)\cdot c_p(J/gK)\cdot \Delta T(K)}{\dot{n}_{H_2\,\mathrm{sup}\,plied}(mol/s)\cdot \Delta H_f^0(H_2O_{(g)})} \qquad \text{(Equation 4)}$$

where
Q_{cool} is the flow of cooling water,
c_p is the specific heat capacity of water at stack temperature, and
ΔT is the difference between coolant outlet and inlet temperature.

Note: A detailed statistical analysis of the raw data is proposed in Appendix C.

7.5 Acceptance Criterion

The acceptance criterion (or criteria) for the test shall be specified in the test report.

For example, an acceptance criterion for the test can be attainment of stability of one or more test inputs/outputs during data acquisition.

Appendix A. Measurement method for test step 3

A.1. Introduction

The current density values (set points) to be set for stack performance evaluation are listed below in Table 11.
The current density is changed step by step instantaneously, or by ramping. The duration of each step (dwell time; see Figure 7.3 in Appendix A) is either a given value or depends on the stability criterion (cf. Section 7).

Note: It is highly recommended to increase the reactant flow rates prior to an increase in current and vice versa!

A.2. Current density profile

Table 11. Set points are expressed in percentage of the maximum rated current density (defined either experimentally by reaching the minimum cell/stack voltage or by the stack manufacturer).

Set point *k*	**Percentage of the maximum rated current density**
0	0 (OCV)
1	2%
2	5%
3	10%
4	15%
5	20%
6	25%
7	30%
8	40%
9	50%
10	60%
11	70%
12	80%
13	90%
14	100%

Note: The number of steps of the cycle may be reduced to shorten the test duration but needs to be detailed in the test report.

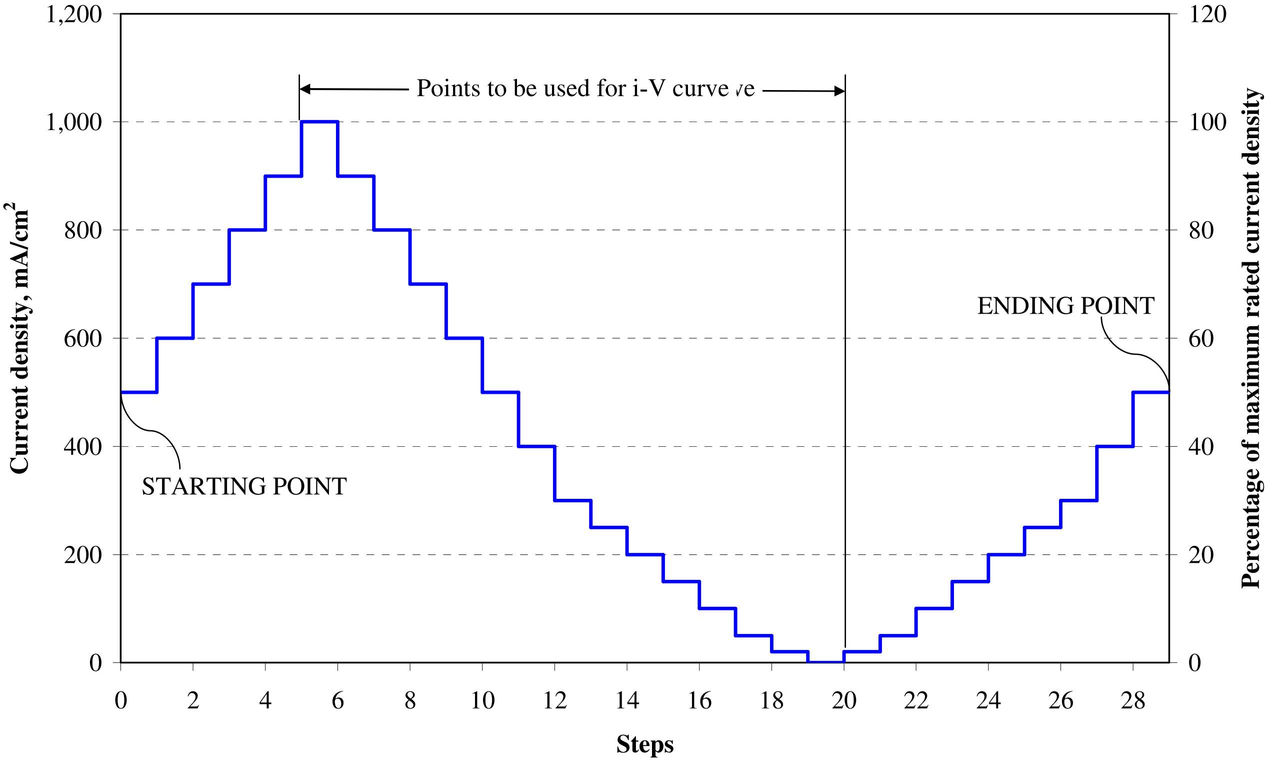


Figure 7.2 Example of one complete current density cycle with 28 steps of instantaneous changes in current according to the 15 set points *k* in Table 11. This cycle has a start value (starting point) and end value (ending point) at 500 mA/cm² and the maximum current density is 1,000 mA/cm² . The number of steps during the current increase from the starting point to the maximum current density and also from the minimum current density (OCV) to the ending point may be reduced to shorten the overall test duration which shall be documented in the test report.

A.3. Test ending criterion

Permanent monitoring of critical test inputs and outputs is mandated to prevent damage to the stack and its constituents as well as to safely conduct the test. These critical test variables are given in the table below. Deviations from it shall be detailed in the test report.
In case an emergency value is attained, the test shall immediately be aborted in a safe manner. It is recommended to employ an automated shutdown procedure.

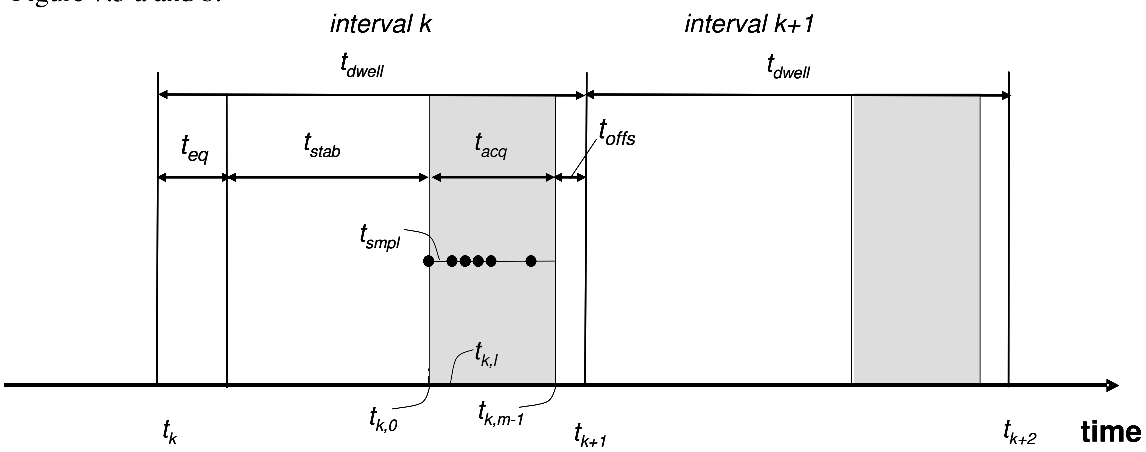
Table 12. Recommended alarm values and emergency test abortion criteria.

Criterion	Symbol	Alarm	Emergency
1	V_{min}	$0.3 \cdot n$ V	$0.2 \cdot n$ V
2	$V_{i,\ min}\ (1 \leq i \leq n)$	0.3 V	0.2 V
3	ΔV_i	*according to stack manufacturer recommendation*	
4	I_{max}	*according to stack manufacturer recommendation*	
5	T_{stack}	+ 3.5°C versus T_{stack} set point	+ 5°C versus T_{stack} set point
6	$T_{cool,out}$ *	+ 3.5°C versus T_{cool} set point	+ 5°C versus T_{cool} set point
7	$T_{fuel/ox,\ out}$	+ 3.5°C versus $T_{fuel/ox}$ set point	+ 10°C versus $T_{fuel/ox}$ set point
9	ΔT_{cool} *	3.5 K	5 K
8	$p_{fluid,in}$	*according to stack manufacturer's recommendation*	
10	$\Delta p_{fluid,\ max}$		
11	$\Delta p_{fuel\text{-}to\ ox,\ max}$		

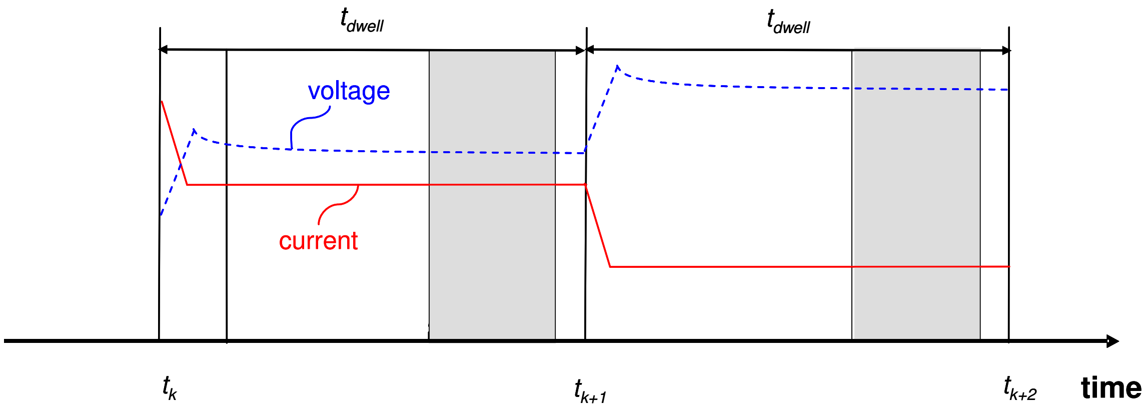
** Note: 1:The measurement of these test outputs are recommended depending on the configuration of the stack and the test bench.*

Appendix B. Protocol for data acquisition

The dwell time for each set point k (see Table 11) comprises periods of equilibration, t_{eq}, of stabilization, t_{stab}, and of data acquisition, t_{acq}, and it ends with an offset time, t_{offs}. The equilibration period shall account 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) shall be performed during the stabilization period whether online which implies a variable t_{stab} 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 stack voltage profiles are schematically shown in respectively Figure 7.3 a and b.



(a)



(b)

Figure 7.3: Schematic of the timeline for two consecutive set points k and $k+1$ of test step 3 each having a dwell time of same duration (a). The test input and output (test variables) are sampled l times at $t_{k,l}$ ($0 \leq l \leq m-1$) to collect m measurements with a sampling interval of t_{smpl} during t_{acq} (see also Table 13). The principle profile of the current as a main test input and of the resulting stack 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 (inclusive) the maximum current density and the minimum current density in step 3 of the test (see also Figure 7.2).

Table 13. Recommended parameters related to test step 3 (see also Figure 7.3).

Symbol	Value	Unit
t_k	$(k-1) \cdot t_{dwell}$	[min]
t_{dwell}	$t_{eq} + t_{stab} + t_{acq} + t_{offs}$	[min]
t_{eq}	*According to load ramping & adjustment of reactant flow rates*	[min]

Symbol	Value	Unit
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). In case t_{stab} is a given value, the stability check is to be performed offline. If a stability criterion is not met, the test may need to be performed again by adapting t_{eq} and/or t_{stab} and thereby also t_{dwell}. This applies especially when as a consequence of failing to meet the stability criterion, the test acceptance criterion (or criteria) is (are) not met either.
Note 2: This table shall be reproduced in the test report.

Appendix C. Statistical analysis of data

A.4. Introduction

For a meaningful representation of the test results, the raw data may be processed as described below. Further tables and graphs may be added to the ones required for the test report.

A.5. Statistics on Test Variables

For each test variable, input and output and for each set point *k*, number *m* of the raw data are analysed statistically to assess their average, variability and stability.

The following statistical values are calculated from the *m* sampled values for any given test variable X_k (i.e. test input or test output) or test variable $Y_k(X_{k,1},\ldots,X_{k,s}$:) being a function (i.e. stack power, sum of cell voltages and efficiencies) of test variables $X_{k,1},\ldots,X_{k,s}$:

Sample average or arithmetic mean (measure of central tendency) of test variable X_k:

$$X_{k,avg} = \frac{1}{m}\sum_{l=0}^{m-1} X_{k,l} \ . \qquad \text{(Equation 5)}$$

Sample average of a calculated test variable Y_k being the result of the summation of *n* test variables X^i_k ($1 \le i \le n$):

$$Y_{k,avg} = \frac{1}{m}\sum_{l=0}^{m-1}\sum_{i=1}^{n} X^i_{k,l} \ . \qquad \text{(Equation 6)}$$

Sample variance of test variable X_k:

$$Var(X_k) = \frac{1}{m-1}\sum_{l=0}^{m-1}(X_{k,l} - X_{k,avg})^2 \ . \qquad \text{(Equation 7)}$$

Sample standard deviation (measure for variability) of test variable X_k:

$$X_{k,stdev} = \sqrt{Var(X_k)} \ . \qquad \text{(Equation 8)}$$

Sample covariance of two test variables, X^i_k and X^j_k:

$$Cov\left(X^i_k, X^j_k\right) = \frac{1}{m-1}\sum_{l=0}^{m-1}(X^i_{k,l} - X^i_{k,avg})\cdot(X^j_{k,l} - X^j_{k,avg}) \ . \qquad \text{(Equation 9)}$$

Combined standard deviation of a test variable $Y_k(X^1_k,\ldots,X^s_k)$ being a function of *s* test variables X^i_k ($1 \le i \le s$):

$$Y_{k,stdev} = \sqrt{\sum_{i=1}^{s}\left(\left.\frac{\partial Y_k}{\partial X^i_k}\right|_{X^i_{k,avg}}\right)^2 Var(X^i_k) + 2\sum_{i=1}^{s}\sum_{j=i+1}^{s}\left.\frac{\partial Y_k}{\partial X^i_k}\frac{\partial Y_k}{\partial X^j_k}\right|_{X^i_{k,avg},X^j_{k,avg}} Cov\left(X^i_k, X^j_k\right)} \qquad \text{(Equation 10)}$$

When Y_k only involves a sum (or difference), $Y_k = X^1_k \pm \ldots \pm X^s_k$, Equation 10 simplifies to

$$Y_{k,stdev} = \sqrt{\sum_{i=1}^{s} Var(X^i_k) \mp 2\sum_{i=1}^{s}\sum_{j=i+1}^{s} Var(X^i_k)\cdot Var(X^j_k)} \ . \qquad \text{(Equation 11)}$$

When Y_k involves only a product (or quotient), $Y_k = X^1_k \cdot \ldots \cdot X^s_k$ ($Y_k = X^1_k / X^2_k \ldots X^s_k$), it simplifies to

$$Y_{k,stdev} = Y_{k,avg} \sqrt{\sum_{i=1}^{s} \left(\frac{X^i_{k,stdev}}{X^i_{k,avg}} \right)^2 - 2 \sum_{i=1}^{s} \sum_{j=i+1}^{s} \frac{Var(X^i_k)}{\left| X^i_k \right|} \cdot \frac{Var(X^j_k)}{\left| X^j_k \right|}} . \qquad \text{(Equation 12)}$$

For uncorrelated X_k, the second summation term in respectively Equation 10 and 11 vanishes.

Sample relative standard deviation (measure of relative variability) of test variable X_k:

$$X_{k,rsd} = \frac{X_{k,stdev}}{\left| X_{k,avg} \right|} \cdot 100\% . \qquad \text{(Equation 13)}$$

Sample standard error (measure for normalized variability) of m measurements of test variable X_k:

$$X_{k,sterr} = \frac{X_{k,stdev}}{\sqrt{m}} . \qquad \text{(Equation 14)}$$

Highest recorded sample value of test variable X_k:

$$X_{k,\max} = \max(X_{k,0 \le l \le m-1}) . \qquad \text{(Equation 15)}$$

Lowest recorded sample value of test variable X_k:

$$X_{k,\min} = \min(X_{k,0 \le l \le m-1}) . \qquad \text{(Equation 16)}$$

Stability of test variable X_k:

$$\Lambda X_k = \frac{dX_k}{dt} \cdot t_{acq} \qquad \text{(Equation 17)}$$

with slope,

$$\frac{dX_k}{dt} = \frac{m \sum_{l=0}^{m-1} \left(t_{k,l} \cdot X_{k,l} \right) - \sum_{l=0}^{m-1} t_{k,l} \cdot \sum_{l=0}^{m-1} X_{k,l}}{m \sum_{l=0}^{m-1} t_{k,l}{}^2 - \left(\sum_{l=0}^{m-1} t_{k,l} \right)^2} . \qquad \text{(Equation 18)}$$

The statistical values generated for each set point k of the polarization curve are finally collated in an overview table.

Table 14. Statistics on the test variable X_k.

Set point *k*	**Current Density** [mA/cm^2]	$X_{k\ avg}$ [unit of X_k]	$X_{k\ max}$ [unit of X_k]	$X_{k\ min}$ [unit of X_k]	$X_{k\ stdev}$ [unit of X_k]	$X_{k\ rsd}$ [%]	$X_{k\ sterr}$ [unit of X_k]	ΛX_k [unit of $X_k \cdot s^{-1}$]
0								
…								
14								

The significant figures of a test variable to be reported shall be consistent with the measurement uncertainty. For a calculated test variable, the lesser number of significant figures of all of the involved test variables shall determine

the significant figure of the calculated test variable. The same shall apply to the reported maximum, minimum, and range of such test variables.
The standard deviation and standard error shall be expressed with at least one more figure. The relative standard deviation shall be reported with 2 significant digits.

A.6. Stack Performance

Overall stack performance, being the primary output of this test, is represented as stack voltage and power and plotted as a function of stack current density. One standard deviation shall be plotted as error bars. In addition, the sum of the respectively voltage and power of all cells in the stack may be plotted for comparison.

Other test outputs (e.g. temperature, pressure drop, etc.) and test inputs may be represented in the same way or plotted as a function of test duration respectively dwell time for each interval. These test variables may also be plotted versus stack current density and power.

A.7. Individual Cell Voltages

For set point k, m voltage measurements of n individual cell, V_i are recorded, denoted as $V_{i,k,l}$ with $1 \le i \le n$ (cell voltage index) and $0 \le l \le m$-1 where l is the data acquisition index.

A.8. Cell Voltage and Power Statistics

It is recommended to carry out data post processing according to the Eq. (5) to (18) for the measured n individual cell voltages.

In addition, the cell numbers, $\#V_{i\,max}$ and $\#V_{i\,min}$ where respectively the maximum and minimum cell voltage occurred shall be reported.

The results of the cell voltage analysis may be given as the follows:

Table 15. Voltage statistics for cells # i ($1 \le i \le n$).

Set point *k*	**Current Density** [mA/cm^2]	$V_{i,\,k\,avg}$ [V]	$V_{i,\,k\,max}$ [V]	$V_{i,\,k\,min}$ [V]	$V_{i,\,k\,stdev}$ [V]	$V_{i,\,k\,rsd}$ [%]	$V_{i,\,k\,sterr}$ [V]	$\Lambda V_{i,\,k}$ [V.s^{-1}]	$\#V_{i\,max}$ [-]	$\#V_{i\,min}$ [-]
0										
…										
14										

Table 16. Power statistics for cells # i ($1 \le i \le n$).

Set point *k*	**Current Density** [mA/cm^2]	$P_{i,\,k\,avg}$ [W]	$P_{i,\,k\,max}$ [W]	$P_{i,\,k\,min}$ [W]	$P_{i,\,k\,stdev}$ [W]	$P_{i,\,k\,rsd}$ [%]	$P_{i,\,k\,sterr}$ [W]	$\Lambda P_{i,\,k}$ [W.s^{-1}]
0								
…								
14								

A.9. Calculation of Measurement Uncertainties

The measurement uncertainty $\Delta u_k(Y_k)$ at interval k of a calculated test variable $Y_k(X^1{}_k,\ldots,X^s{}_k)$ being a function of s test variables $X^i{}_k$ where $(1 \le i \le s)$ shall be calculated as:

$$\Delta u_k(Y_k) = \sqrt{\sum_{i=1}^{s}\left(\left.\frac{\partial Y_k}{\partial X_k^i}\right|_{X_{k,avg}^i}\Delta u_k(X_k^i)\right)^2 - 2\sum_{i=1}^{s}\sum_{j=i+1}^{s}\left.\frac{\partial Y_k}{\partial X_k^i}\frac{\partial Y_k}{\partial X_k^j}\right|_{X_{k,avg}^i, X_{k,avg}^j}\Delta u_k(X_k^i)\Delta u_k(X_k^j)} \qquad \text{(Equation 19)}$$

When Y_k involves only a sum (or difference) of uncorrelated test variables $X^1{}_k,\ldots,X^s{}_k$ with $\Delta u_k(X^1{}_k)=\ldots=\Delta u_k(X^s{}_k)$, Equation 19 simplifies to

$$\Delta u_k(Y_k) = \sqrt{s}\cdot\Delta u_k(X_k)\,. \qquad \text{(Equation 20)}$$

When Y_k involves only a product (or quotient) of uncorrelated test variables $X^1{}_k,\ldots,X^s{}_k$, Equation 19 simplifies to

$$\Delta u_k(Y_k) = \left|Y_{k,avg}\right|\cdot\sqrt{\sum_{i=1}^{s}\left(\frac{\Delta u_k\left(X_k^i\right)}{X_{k,avg}^i}\right)^2}\,. \qquad \text{(Equation 21)}$$

Appendix D. Test information for test report

Note: The document “PEFC STACK Test Report v1.2” describes in more detail how to report the obtained test results.

The main test results should be presented as follows:

- Tables or graphs presenting the functional performance (main test outputs versus the relevant test input or versus test duration) obtained during test start-up, step 1 and 3.
- Other graphs as appropriate to enhancing analysis of the test results including data post processing.
- Conclusions referring to the objective of the test and to the acceptance criteria when applicable.

Document Information

Version	Change	Date	Status	Text / revision by
1	Initial draft	2005-07	Draft	WP5 member PSI
2	Modification of the format (general)	2005-09	Draft	WP5 leader
3	Mainly addition of data processing	2006-01	Draft	WP5 leader with input from INTA
4	Modification of the format (description of inputs and outputs)	2006-02	Draft	WP5 leader
5	Modification for harmonization	2006-02	Final before qualification and validation	WP5 leader
6	Modification of the procedure title for harmonization	2006-05	Final before qualification and validation	WP5 leader
7	FCTesQA Revision 1	2006-09	Revision	WP2 members
8	Review procedure according to remarks from WP members during WP meeting in Florence (10/2008)	2009-01	Draft for stack	DLR
9	Modification of the current step sequence	2009-02	Revision	CEA/JRC
10	Review of procedure at FCTES^{QA} meeting in JRC Petten (5-6 March 2009)	2009-03	Revision	JRC/CEA
11	Round Robin Testing JRC-VITO test preparation meeting (24 November 2009)	2009-11	Revision	JRC/VITO
12	Modification of Figure 7.3 and of Table 13	2009-12	Revision	JRC/CEA
13	Modification of Figure 6.1 and Table 8	2009-12	Revision	DLR

Document Master

DLR