CALL 2013 – FINAL REPORT

December 1, 2015

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Final report

1. Project details

Project title	Udvikling af testprocedurer for PEM-stakke
Project identification (program abbrev. and file)	Energinet.dk project no. 2013-1-12031
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Technical University of Denmark Anker Engelunds Vej 1, 2800 Kgs. Lyngby
Project partners	Technical University of Denmark (DTU), Aalborg University (AAU)
CVR (central business register)	30 06 09 46
Date for submission	1st of December 2015

2. Short description of project objective and results

UK Version:

Proton exchange membrane (PEM) fuel cells will play a significant role in the energy systems of the future. This project has aimed at developing industry-wide harmonized test procedures for PEM stacks and is part of a larger European project.

The objective of the project was to develop test procedures for PEM FC Stacks within: Function and performance; durability and degradation; and safety and environment.

In the project 23 test modules and nine test programs have been defined and validated. The procedures have been written in a common uniform format. All test procedures can be adjusted to the application in focus, such as automotive and stationary and the test procedures also give recommended values for such applications.

DK version:

PEM-brændselsceller ventes at udgøre en væsentlig del af fremtidens energisystem. Dette projekt vil på tværs af industrier udvikle harmoniserede testprocedurer for PEM-stakke. Projektet er en del af et større europæisk projekt.

Formålet med projektet var at udvikle testprocedurer for PEM-brændselscellestakke indenfor: Funktion og ydelse; robusthed og degradering, og sikkerhed og miljø.

I projektet er der defineret og valideret 22 testprocedurer og ni testprogrammer. Procedurerne er blevet skrevet i et ensartet format. Alle testprocedurer kan tilpasses til den relevante anvendelse, såsom automotive eller stationær anvendelse, og testprocedurerne beskriver også anbefalede værdier for sådanne anvendelser.

3. Executive summary

New technologies such as Proton exchange membrane fuel cells (PEM FC's) are faced with strong barriers towards mainstream marked acceptance, as the technology is challenging conventional industries and traditional business models. New technologies are further challenged by the lack of trust in the performance and durability of products, both from the consumer and businesses. PEM FC's have a long history, but never before has the technology gained traction as now, with fuel cell cars reaching series production, and PEM fuel cells becoming the preferred solution for many telecom and backup power solutions.

The path from material development to final products is not trivial, with many stakeholders representing the entire value chain, component suppliers over stack integrators to system integrators and end users. In the route from manufacturing to integrating and operating fuel cell systems, many interfaces are being established which require consistent and comparable data. The consistency and quality of the data are crucial for taking proper technical and commercial decisions.

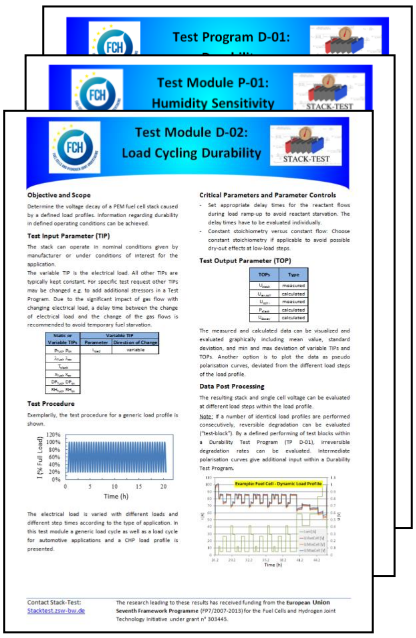
The purpose of the Stack-Test project was to develop industry-wide harmonized test procedures for PEM FC stacks. The project has closed the present gap between cell level testing and system level testing by establishing uniform test categories and generic test modules for testing performance, durability and safety of PEM FC stacks.

The test procedures have been developed for stationary, portable and transportation applications. They are highly relevant for the Danish PEM FC industry, which can develop better products within the areas of micro-combined heat and power generation (µ-CHP), uninterruptable power supply (UPS) and hydrogen electric vehicles.

NB. This project is part of a European research project (Stack-Test, EU-FCH-JU, project no. 303445). This ForskEL Stack-Test project was granted to provide the top-up funding of costs not covered by the European project due to funding restrictions and in this way ensuring Danish participation in the European development activities. By having DTU and AAU present in the project, a significant addition to the existing Danish knowledge base has taken place.

The work carried out in the project has been achieved by the eleven partners of the EU-project and has resulted in:

- 21 test modules
- 6 test programs
- Proposed work item to international standardisation



The test modules and programs developed on performance and durability testing cover a wide range of test objectives, ranging from sensitivity to parameters changes (temperature, humidity, pressure, stoichiometry) to evaluating stack performance in-depth (polarisation curve, electrochemical impedance spectroscopy, voltammetry), and methods for evaluating durability under multiple different operation modes (constant load, load cycling, start-stop cycles).

The test procedures follow a uniform methodology, with test modules constituting the main content of testing, to be arranged into test programs. The methodology allow for flexibility to create test programs tailored to user's needs. In Figure 1 the methodology is illustrated.

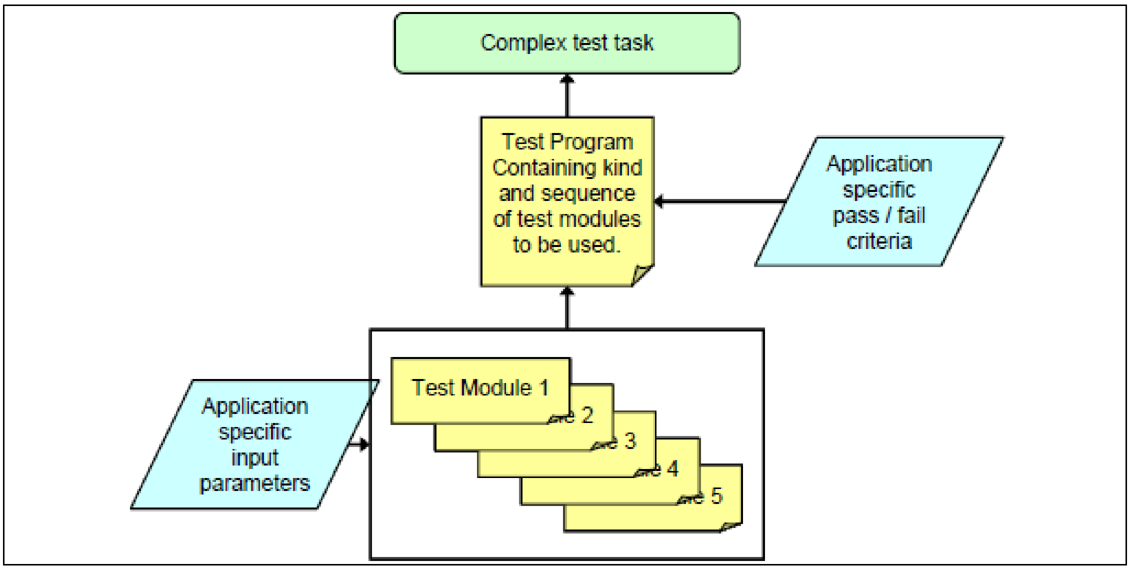


Figure 1 - Interaction of test programs and test modules for complex testing tasks

The test modules and programs have been defined during multiple iterations and through discussion with industry and academia. The industrial advisory board has contributed with valuable information on application specific test operating conditions, and test procedures relevant to industry. The test modules and programs have been validated at the EU-project and show good comparability.

Aalborg University (AAU) and the Technical University of Denmark (DTU) have ensured that Danish industry was part of the industrial advisory board, and also part of several workshops, and have disseminated the project results nationally during the project, to ensure national interest could be brought into the project.

The project results have been transferred to the international standardisation organisation IEC (International Electrotechnical Commission), where it will begin the process of standardizing them, with the decision of the IEC pending as of late 2015.

The test documents are under final language editing and formatting, and the documents will be published once priority dates for publications under preparation have been secured. They can already be requested from stacktest.zsw-bw.de.

4. Project objectives

This project was part of a European research project (Stack-Test, EU-FCH-JU, grant no. 303445). This ForskEL project was applied for to provide the top-up funding of costs not covered by the European project due to funding restrictions and in this way ensure Danish participation in the European development activities. By having DTU and AAU present in the project, a significant addition to the existing Danish knowledge base has taken place and wit a special focus to Danish interests and national dissemination.

The structure of the European project can be seen Figure 2, where the multiple validation phases can be seen, during the 36 month long project, where test modules and test programs are iteratively defined. The ForskEL-project begins in month five of the EU-project, and covers the full EU-project with the addition of two months after project end, to allow for financial and reporting of results. The project plan of this project can be found in Figure 3.

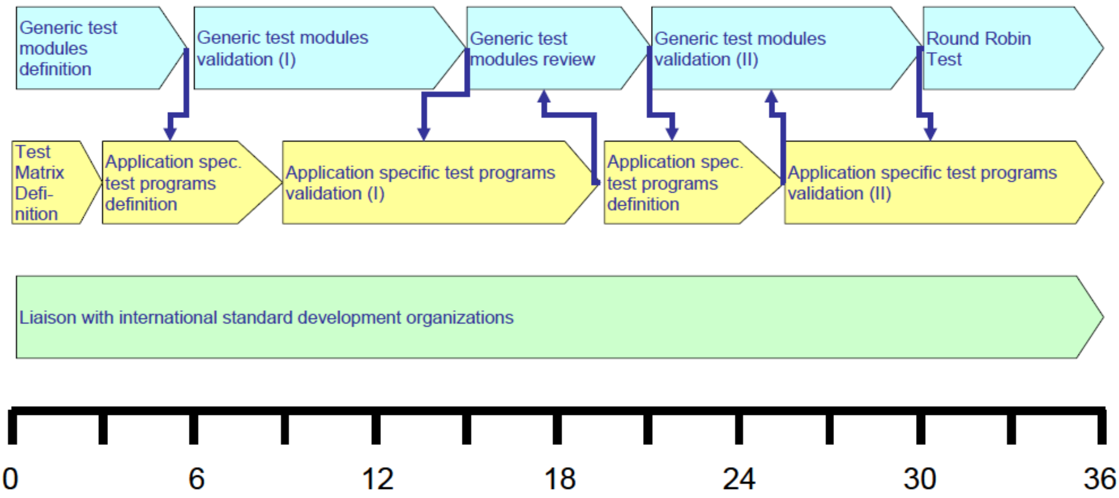


Figure 2 - Work flow / Project Phases - FCH-JU project months

Year	2012				2013												2014												2015									
Calender month	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O
Project month No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
EU project: 01.09.12 - 31.08.15																																						
ForskEL project: 01.01.13 - 31.10.15																																						
WP 1 - Project management																																						
Financial reporting																	x												x									x
Progress reporting																	x												x									x
WP 2 - Performance testing																																						
Milestone 2.1. Generic test performance module validation report															x																							
Milestone 2.2. Application oriented performance test program validation report																																				x		
WP 3 - Endurance testing																																						
Milestone 3.1. Generic test endurance module validation report															x																							
Milestone 3.2. Application oriented endurance test program validation report																																				x		
WP5 - Liason to SDO and industry																																						
Milestone 5.1. Meeting with industrial advisory group																					x																	
Milestone 5.2. Public dissemination workshop																																			x			

Figure 3 - Milestone chart - ForskEL

The project plan describes the main work packages of the EU-project, where Aalborg University and the Technical University of Denmark participate. Milestones selected are for the purpose of interim reporting and follow-up. Actual deliverable or milestone reports are confidential to the EU-project and cannot be publicised. Note that work package 4 and 6 from the EU-project are not included in the top-up project.

4.1 Deviation to project plan

The project involves multiple phases of stack testing during both test bench validation and validation of test procedures (modules and programs). As such stack testing is not trivial complicated, as test benches are not identical from one institution to another, and test phases have been the main reason for delays during the project.

Still, the partners have reduces the delay during the project, and all milestones and deliverables have been completed by end of project.

4.2 Risks

There are several elements in a large project that constitute risk. The project has 11 partners, six work packages with plenty of tasks. The major project risks included disagreements among the partners, inability to meet deadlines and milestones, and results failing to be relevant to industry and standard organisations. Risk were managed in monthly steering committee meetings as well as by work package leaders.

There are no risk related problems to mention.

In hindsight, the largest risks of the project were in fact meeting milestones timely, and surprisingly, getting high involvement from industry proved very difficult and time consuming. Even though the industrial advisory board was set up very early, it proved difficult to get enough participants, and further proved difficult to get feedback to the project results.

We have in the project tried to mediate this risk, by having several international workshops, where both members of the industrial advisory board, and other industry representatives have been present, having bilateral discussions with several board members, and by presenting the project results in a more accessible way.

4.3 Unforeseen developments

The project has produced new knowledge on stack testing for performance, durability and safety, that is new and very relevant to industry, but that was also the ambition of the project. On unforeseen developments, a new task arose during the project, looking into the behaviour of stacks during durability operation, where PEM stack exhibit reversible degradation during testing. This was already known, but this project has developed a method of factoring this into the test procedure, for both to be able to distinguish between reversible and irreversible degradation, and to reset the reversible degradation phenomena during operation.

5. Project results and dissemination of results

5.1 Overview of project results

The results of this project is the combined efforts of the 11 partners in the EU-project, namely:

Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW)
Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
Technical University of Denmark (DTU)
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
InstYtut Chemii Przemyslowej (ICRI)
Aalborg University (AAU)
EWE-Forschungszentrum für Energietechnologie e.V. (NEXT-E)
Fundacion Cidetec (CIDETEC)
Fraunhofer-Institut für Solare Energiesysteme ISE, Division Energy Technology (Fraunhofer)
JRC-Joint Research Centre-European Commission (JRC-IET)
SymbioFcell S.A. (Symbio FC)

The main result of the project is the test procedures developed. Furthermore, there are additional outcomes worth mentioning.

- General
- Test modules and programs

Master document

The project has contributed with a uniform methodology for testing PEM fuel cell stacks, described in the test module TM P-00 "Master Document". This document is not similar to the other test modules, and is not used to perform an actual stack test, but is a compendium that the other test modules and programs refer to.

This document is a comprehensive guide to testing, describing nomenclature, test bench setup, parameter and stability control etc.

Approach to testing

In the project an approach to testing was suggested, borrowing from computer programming methodology, where subroutines are part of larger programs, and subroutines can be reused by many different programs. This approach is illustrated in Figure 4, which shows an example of a test program.

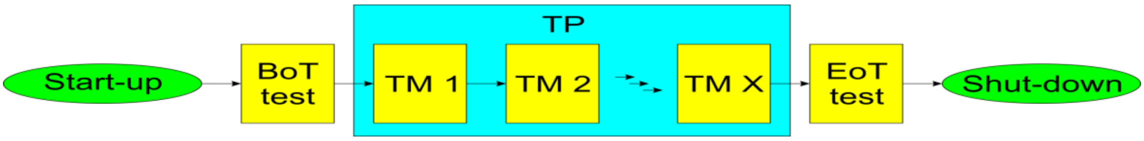


Figure 4 - Test approach

Liaison with industry

An industrial advisory board was constructed, constituting members of industry, covering all relevant part of the value chain around the PEM fuel cell stack, as well as members from industry from key application areas. All test modules and test programs have further been described in short-form to allow for easy dissemination to stakeholders. Industry has had a key role in advising and forming the test procedures, directly or through projects running in parallel with this project, where liaison also has taken place.

The process of furthering the research through international standardisation

All project partners agreed to allow for the international standardisation organisation IEC to rely on the project results in case a new proposed standard will be developed. Project partners also submitted an application for a new work item (NWIP) in the latest IEC plenary meeting, and this is now under voting of the IEC members.

If this results in a standard being developed, several members of the project have expressed interest in being part of the work group in the IEC drafting the standard, thereby ensuring a European influence in this work.

Test modules and test programs

Within work package 3 and work package 4, 21 test modules and 6 test programs have been defined.

- 21 number of test modules
- 6 number of test programs
- Reproducibility investigated
- Test procedures validated if possible
- Application specific testing validated
- Proposal of how to measure degradation rate

5.2 Methodology

The fundamental principle in the development of the test procedures in the project has been to describe relevant generic test modules that allow for variation of only a single input parameter, keeping other input parameters constant if possible, thereby allowing for measuring the fuel cell stack response to this single parameter.

In reality some input parameters are dependent on one another, but the principle is sound. All input and output parameters shall be monitored during the testing, and procedures for this is described in the test modules and programs.

The concept of describing generic tests, such as influence to temperature or pressure variation, as standalone test modules, gives the user the flexibility to design a test program suited for their specific needs. All test programs described in the project are only recommendations, and they can be altered as needed. With the comprehensive range of test modules and programs developed, a thorough testing of the fuel cell stack can be done, under realistic, transparent and not least comparable conditions.

For the actual testing it is clear that many decisions on how the stack should be operated are extremely specific to the exact fuel cell stack in question, and the operating parameters, ranges etc. should be decided. In case of benchmarking the project has suggested a set of operating parameters for the main relevant applications relevant for the fuel cell stack, see *Table 1*.

Table 1 : Operating conditions relevant to specific applications

Parameter		Automotive				Stationary		Portable Generators	
Name	**Symbol**	**Propulsion (I)**	**Propulsion (II)**	**Range Extender.**	**APU**	**CHP**	**Backup**	**Hydrogen**	**DMFC**
Stack Temperature (Coolant inlet)	T_{Stack}	80 °C	68 °C	75 °C	75 °C	70 °C	65 °C	50 °C	70 °C
Reactant inlet temperature	$T_{gas,in}$	85 °C	73 °C	80 °C	80 °C	75 °C	70 °C	Ambient	Ambient
Fuel (H_2) stoichiometry	λ_{fuel}	1.3	1.4	1.5	1.5	1.2	1.25	1.2	5.0
Oxidant (air) stoichiometry	λ_{Ox}	1.5	1.6	2	2.0	2.0	2	2	2.5
Fuel relative humidity	RH_{fuel}	50%	40%	80%	80%	80%	40%	50%	-
Dew point temperature fuel	DP_{fuel}	63.5 °C	48.2°C	69.5 °C	69.5 °C	65 °C	45.5 °C	36.5 °C	-
Oxidanr relative humidity	RH_{ox}	30%	50%	80%	80%	80%	40%	Ambient	Ambient
Dew point temperature oxidant	DP_{ox}	52.5 °C	52.5 °C	69.5 °C	69.5 °C	65 °C	45.5 °C	Ambient	Ambient
Fuel outlet pressure	P_{fuel}	220 kPa_{abs}	220 kPa_{abs}	150 kPa_{abs}	150 kPa_{abs}	Ambient	120 kPa_{abs}	150 kPa_{abs}	Ambient
Oxidant outlet pressure	P_{ox}	200 kPa_{abs}	200 kPa_{abs}	150 kPa_{abs}	150 kPa_{abs}	Ambient	Ambient	Ambient	ambient

5.3 Work package 1

Main tasks in work package 1 in the Forskel project includes:

- Project management of the ForskEL-project
- Reporting to Energinet.dk/ForskEL
- Financial reporting
- Dissemination of project results

DTU has been responsible for reporting to ForskEL and four interim reports have been uploaded timely to the ForskEL online portal, as well as copies sent to project officer at Energinet.dk. AAU has contributed to the interim reports, as well as the financial reports.

The specific Danish dissemination activities has been performed through several channels, mainly:

- Homepage (http://www.fch.dk/Projects/Stack-Test)
- Danish Standard Organisation Committee S-605 Hydrogen and Fuel Cells
- Partnership for Fuel Cells and Hydrogen
- Invitation and participation to EU-project industrial advisory board of Danish companies
- Bilateral discussions with Danish companies

Key points on dissemination of the EU-projects are:

- A project web-page has been implemented (http://stacktest.zsw-bw.de)
- Four international workshop were organised during the project:
  - The first workshop was held the 28th and 29th of January 2014 in Oldenburg, hosted by NEXT ENERGY, entitled "Progress in PEMFC Stack Testing Procedures".
  - The second workshop was held the 3rd- 4th of June 2014 at Stuttgart, hosted by DLR and was entitled "PEMFC Stack and Stack Component Testing".
  - The third workshop was organised by Fraunhofer Institute for Solar Energy Systems ISE in January 20th and 21st, 2015.
  - The fourth and last workshop was occurred the 16th and 17th of June 2015 at ZSW in ULM.
  - Multiple publication published or in the process of publication.
  - Multiple presentations at conferences, exhibitions etc.

5.4 Work package 2

Work package 2 was about the definition and validation of generic test modules and test programs for performance testing. The test modules and procedures developed in this work package can be seen in Table 2.

Table 2 - Test modules for performance testing

final number	document title	final name
	Test Module	
TM P-00	Stack-Test Master Document	TM_P-00_Stack-Test_Master_Document.docx
TM P-01	Humidity Sensitivity	TM_P-01_Humidity_Sensitivity.docx
TM P-02	Temperature Sensitivity	TM_P-02_Temperature_Sensitivity.docx
TM P-03	Pressure Sensitivity	TM_P-03_Pressure_Sensitivity.docx
TM P-04	Lambda Sensitivity	TM_P-04_Lambda_Sensitivity.docx
TM P-05	Fuel/Oxidant Composition	TM_P-05_Fuel_Oxidant_Composition.docx
TM P-06	Low Temperature Test	TM_P-06_Low_Temperature_Test.docx
TM P-07	Continuous Operation at Constant Load	TM_P-07_Continuous_Operation_at_Constant_Load.docx
TM P-08	Polarisation Curve	TM_P-08_Polarisation_Curve.docx
TM P-09	Impact of Stack Tilt	TM_P-09_Impact_of_Stack_Tilt.docx
TM P-10a	In-Stack Electrode Voltammetry	TM_P-10a_Electrochemical_Method_Voltammetry.docx
TM P-10b	In-Stack Electrode Potentiometry	TM_P-10b_Electrochemical_Method_Potentiometry.docx
TM P-10c	H_2-PEMFC and DMFC Stack Electrochemical Impedance Spectroscopy	TM_P-10c_Electrochemical_Method_Impedance_Spectroscopy.docx
TM P-10d	Hydrogen Crossover in H_2-PEMFC Stack	TM_P-10d_Electrochemical_Method_Hydrogen_crossover.docx
TM P-10e	Methanol Crossover in DMFC Stack	TM_P-10e_Electrochemical_Method_Methanol_crossover.docx
TM P-10f	DMFC Anodes Polarization Curves	TM_P-10f_Electrochemical_Method_DMFC_Anode_Polarisation.docx
TM P-11	Dead End Operating Conditions	TM_P-11_Dead_End_Operating_Conditions.docx

The list of test modules is comprehensive, and all test modules are selected as they are relevant for the testing of the fuel cell stack. All test modules are designated a "number" e.g. "TM P-08", which is short for "Test module Performance – 08". Similarly, several test programs were developed, as seen in Table 3.

Table 3 - Test programs for performance testing

document title	final name
Test Program	
Stack Performance Assessment	TP_P-01_Stack_Performance_Assessment.docx
Stack Performance Mapping	TP_P-02_Stack_Performance_Mapping.docx
Deviant Stack Performance	TP_P-03_Deviant_Stack_Performance.docx
Dead End Performance	TP_P-04_Dead_End_Performance.docx
Stack Performance Optimisation	TP_P-05_Stack_Performance_Optimisation.docx

In the following, all test modules and test programs will be presented in brief. Final test documents are not yet publicised, as publication is pending following publication of articles in journals etc. by the project partners. Estimated time of publication, primo 2016 though the EU Joint Research Centre Central Library (http://www.eurolibnet.eu/).

Test Module TM P-00: Stack-Test Master Document

Objective:

This document is providing general considerations relevant for Fuel Cell Stack testing. The focus of this document is on stack test operating conditions (TOC). TOC are those parameters that directly and intrinsically influence the fuel cell stack performance. The TOC table covers several applications addressed by PEM fuel cells. They are automotive, mobile and stationary applications. Furthermore, the start-up und shut-down procedures for the stacks used in the Stack-Test project and for stacks without recommendation by the stack manufacturer are defined.

Final document: TM_P-00_Stack-Test_Master_Document.docx

Test Module TM P-01: Humidity Sensitivity

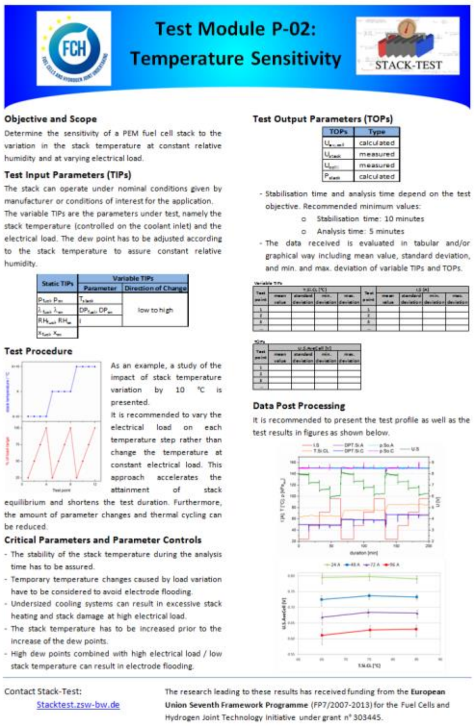
Objective:

The TM can be used to determine the sensitivity of a PEM fuel cell stack to the variation in relative humidity of the used reactants under varying load. Furthermore, the optimum of humidification for the anode and the cathode can be found for the examined load levels.

Final document:

TM_P-01_Humidity_Sensitivity.docx

Test Module TM P-02: Temperature Sensitivity



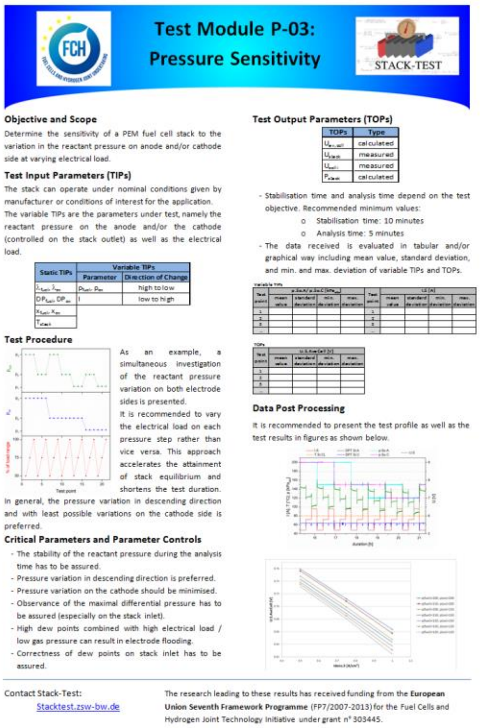
Objective:

The TM is addressed to investigate the influence of the stack temperature on stack performance and efficiency. It can be used to determine the sensitivity of a PEM fuel cell stack to the variation in the stack temperature under varying load. Furthermore, the optimum of a given temperature range can be found for the examined load levels.

Final document:

TM_P-02_Temperature_Sensitivity.docx

Test Module TM P-03: Pressure Sensitivity



Objective:

The TM is addressed to investigate the influence of the reactant pressure on the anode and the cathode side on the stack performance and the stack efficiency. By the use of this Test Module an optimum of a given pressure range can be found for a wide load range.

Final document:

TM_P-03_Pressure_Sensitivity.docx

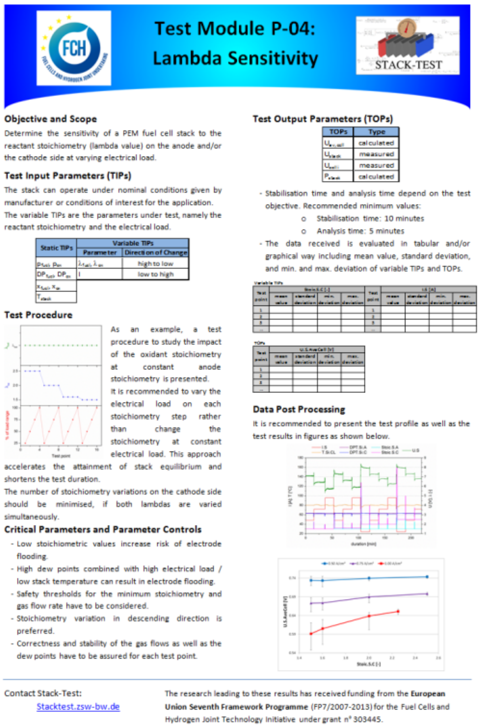
Test Module TM P-04: Lambda Sensitivity

Objective:

The TM is addressed to investigate the influence of the reactant stoichiometry (lambda value) on the anode and the cathode side on the stack performance and the stack efficiency. By the use of this Test Module an optimum of a given lambda range can be found for a wide load range.

Final document:

TM_P-04_Lambda_Sensitivity.docx



Test Module P-04: Lambda Sensitivity

Objective and Scope

Determine the sensitivity of a PEM fuel cell stack to the reactant stoichiometry (lambda value) on the anode and/or the cathode side at varying electrical load.

Test Input Parameters (TIPs)

The stack can operate under nominal conditions given by manufacturer or conditions of interest for the application. The variable TIPs are the parameters under test, namely the reactant stoichiometry and the electrical load.

Static TIPs	Variable TIPs	
	Parameter	Direction of Change
p_{fuel}, p_{ox}	λ_{fuel}, λ_{ox}	high to low
DP_{fuel}, DP_{ox}	I	low to high
x_{fuel}, x_{ox}		
T_{stack}		

Test Procedure

As an example, a test procedure to study the impact of the oxidant stoichiometry at constant anode stoichiometry is presented. It is recommended to vary the electrical load on each stoichiometry step rather than change the stoichiometry at constant electrical load. This approach accelerates the attainment of stack equilibrium and shortens the test duration. The number of stoichiometry variations on the cathode side should be minimised, if both lambdas are varied simultaneously.

Critical Parameters and Parameter Controls

- Low stoichiometric values increase risk of electrode flooding.
- High dew points combined with high electrical load / low stack temperature can result in electrode flooding.
- Safety thresholds for the minimum stoichiometry and gas flow rate have to be considered.
- Stoichiometry variation in descending direction is preferred.
- Correctness and stability of the gas flows as well as the dew points have to be assured for each test point.

Test Output Parameters (TOPs)

TOPs	Type
$U_{av.cell}$	calculated
U_{stack}	measured
$U_{cell\,i}$	measured
P_{stack}	calculated

- Stabilisation time and analysis time depend on the test objective. Recommended minimum values:
  - Stabilisation time: 10 minutes
  - Analysis time: 5 minutes
- The data received is evaluated in tabular and/or graphical way including mean value, standard deviation, and min. and max. deviation of variable TIPs and TOPs.

Variable TIPs

Test point	Stoic.S.C [-]				Test point	I.S [A]			
	mean value	standard deviation	min. deviation	max. deviation		mean value	standard deviation	min. deviation	max. deviation
1					1				
2					2				
3					3				
...					...				

TOPs

Test point	U.S.AveCell [V]			
	mean value	standard deviation	min. deviation	max. deviation
1				
2				
3				
...				

Data Post Processing

It is recommended to present the test profile as well as the test results in figures as shown below.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

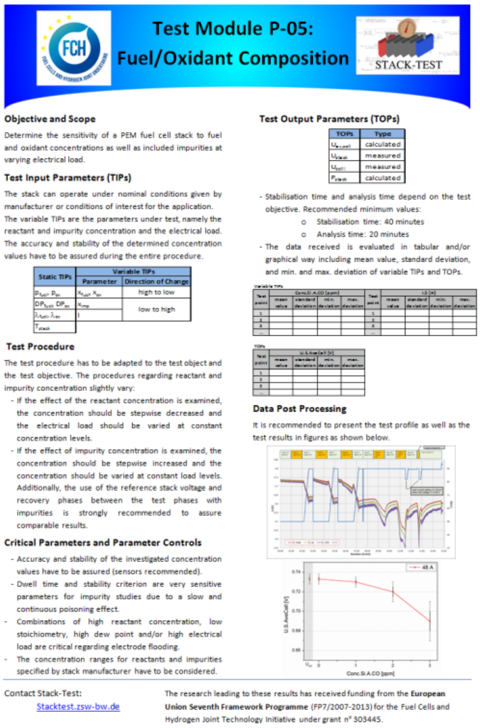
Test Module TM P-05: Fuel/Oxidant Composition

Objective:

The TM is a testing procedure to characterise the influence of fuel and oxidant concentrations as well as included impurities on the single cell voltages, the stack voltage and the electrical stack power output at different current densities. The target of this Test Module is to find the optimum fuel and oxidant composition and to clarify the influence of present impurities on the stack performance.

Final document:

TM_P-05_Fuel_Oxidant_Composition.docx



Test Module P-05: Fuel/Oxidant Composition

Objective and Scope

Determine the sensitivity of a PEM fuel cell stack to fuel and oxidant concentrations as well as included impurities at varying electrical load.

Test Input Parameters (TIPs)

The stack can operate under nominal conditions given by manufacturer or conditions of interest for the application. The variable TIPs are the parameters under test, namely the reactant and impurity concentration and the electrical load. The accuracy and stability of the determined concentration values have to be assured during the entire procedure.

Static TIPs	Variable TIPs	
	Parameter	Direction of Change
p_{fuel}, p_{ox}	x_{fuel}, x_{ox}	high to low
DP_{fuel}, DP_{ox}	x_{imp}	low to high
λ_{fuel}, λ_{ox}	I	
T_{stack}		

Test Procedure

The test procedure has to be adapted to the test object and the test objective. The procedures regarding reactant and impurity concentration slightly vary:

- If the effect of the reactant concentration is examined, the concentration should be stepwise decreased and the electrical load should be varied at constant concentration levels.
- If the effect of impurity concentration is examined, the concentration should be stepwise increased and the concentration should be varied at constant load levels. Additionally, the use of the reference stack voltage and recovery phases between the test phases with impurities is strongly recommended to assure comparable results.

Critical Parameters and Parameter Controls

- Accuracy and stability of the investigated concentration values have to be assured (sensors recommended).
- Dwell time and stability criterion are very sensitive parameters for impurity studies due to a slow and continuous poisoning effect.
- Combinations of high reactant concentration, low stoichiometry, high dew point and/or high electrical load are critical regarding electrode flooding.
- The concentration ranges for reactants and impurities specified by stack manufacturer have to be considered.

Test Output Parameters (TOPs)

TOPs	Type
$U_{av.cell}$	calculated
U_{stack}	measured
$U_{cell\,i}$	measured
P_{stack}	calculated

- Stabilisation time and analysis time depend on the test objective. Recommended minimum values:
  - Stabilisation time: 40 minutes
  - Analysis time: 20 minutes
- The data received is evaluated in tabular and/or graphical way including mean value, standard deviation, and min. and max. deviation of variable TIPs and TOPs.

Variable TIPs

Test point	Conc.Sl.A.CO [ppm]				Test point	I.S [A]			
	mean value	standard deviation	min. deviation	max. deviation		mean value	standard deviation	min. deviation	max. deviation
1					1				
2					2				
3					3				
...					...				

TOPs

Test point	U.S.AveCell [V]			
	mean value	standard deviation	min. deviation	max. deviation
1				
2				
3				
...				

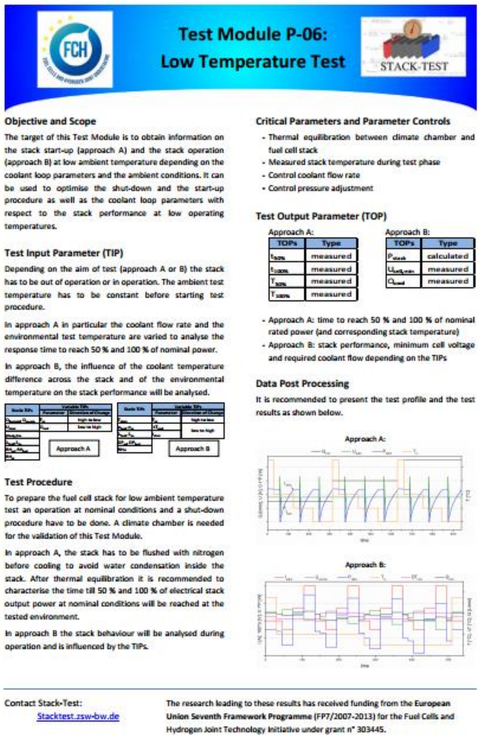
Data Post Processing

It is recommended to present the test profile as well as the test results in figures as shown below.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

Test Module TM P-06: Low Temperature Test



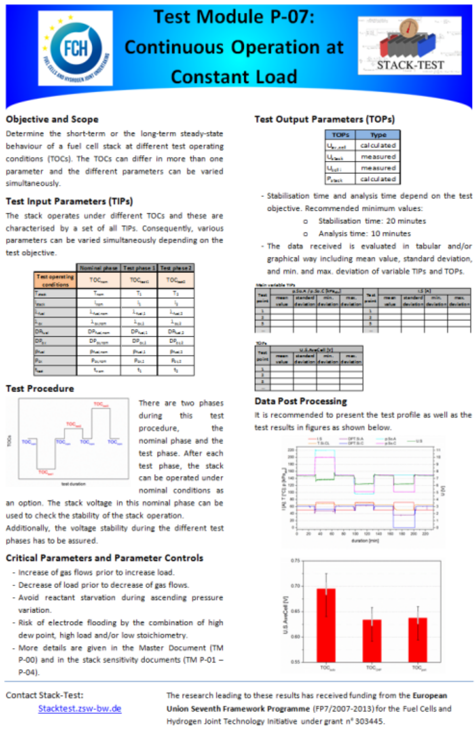
Objective:

The target of this TM is to obtain information on the stack start-up (approach A) and the stack operation (approach B) at low ambient temperature depending on the coolant loop parameters and the ambient conditions. It can be used to optimise the shut-down and the start-up procedure as well as the coolant loop parameters with respect to the stack performance at low operating temperatures.

Final document:

TM_P-06_Low_Temperature_Test.docx

Test Module TM P-07: Continuous Operation at Constant Load



Objective:

The target of this TM is to investigate the short-term or the long-term steady-state behaviour of a stack under different test operating conditions. Different stack operating parameters can influence this behaviour and can be varied simultaneously. It can be used to study the adaptability of a stack to different applications or to study the stack behaviour at different load points, which are characterised by additional changes in other parameters like temperature, relative humidity, etc.

Final document:

TM_P-07_Continuous_Operation_at_Constant_Load.docx

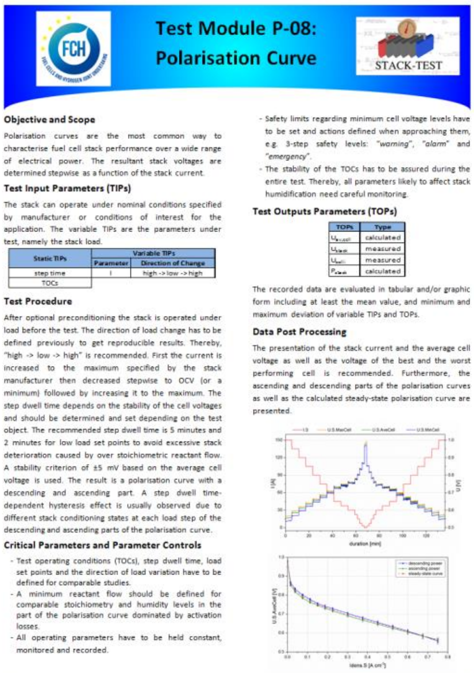
Test Module TM P-08: Polarisation Curve

Objective:

Polarisation curves are the most common method to characterise the performance of a fuel cell stack over a wide range of electrical power. The stack voltage is determined stepwise as a function of the stack current. This TM addresses the measurement of the polarisation curves in a reproducible and comparable manner allowing a comparison of different stacks as well as of different stack components when used in the same stack.

Final document:

TM_P-08_Polarisation_Curve.docx



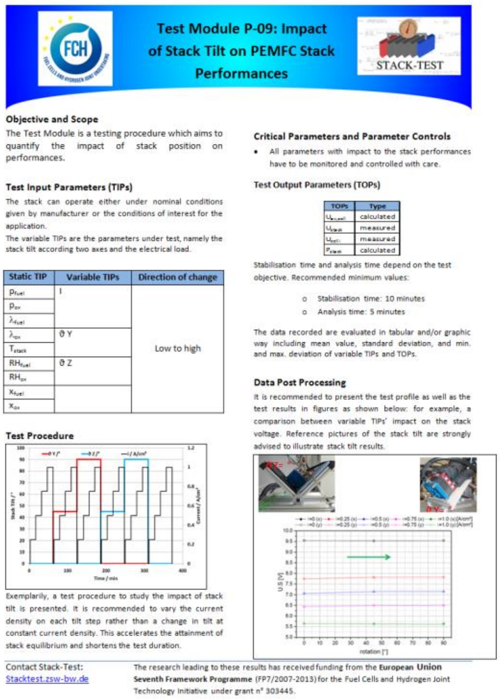
Test Module TM P-09: Impact of Stack-Tilt

Objective:

The Test Module is a testing procedure which aims to quantify the impact of stack position on performance.

Final document:

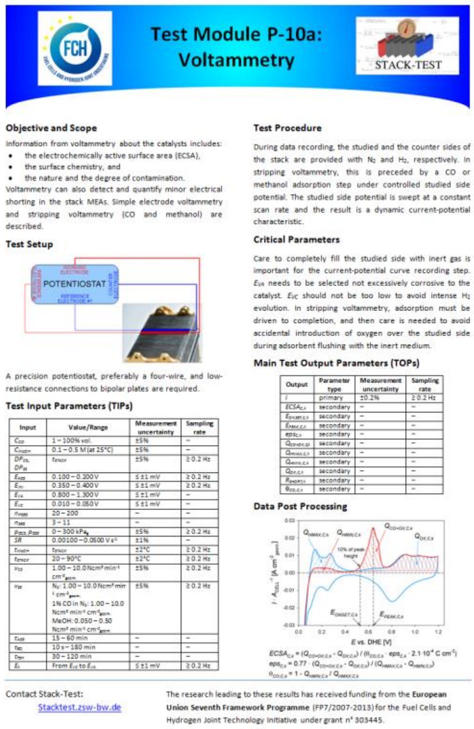
TM_P-09_Impact_of_Stack_Tilt.docx



Test Module TM P-10: Electrochemical Methods

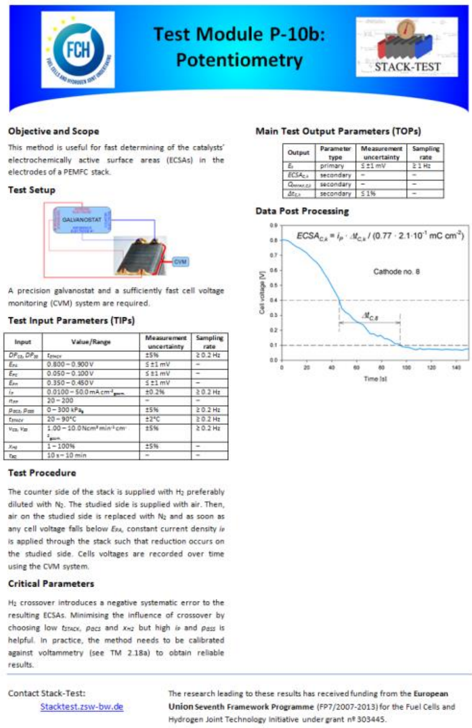
Objective:

The purpose of this TM is to provide tools for in-depth characterisation of PEM fuel cell stacks. By means of the presented electrochemical methods, many sources of the stack polarisation under load, their distribution among the individual cells in the stack, as well as phenomena affecting the performance durability can be scrutinised. These are considered additional outputs possible to be obtained concurrently with the outputs of most of the other functional/performance and durability TMs.



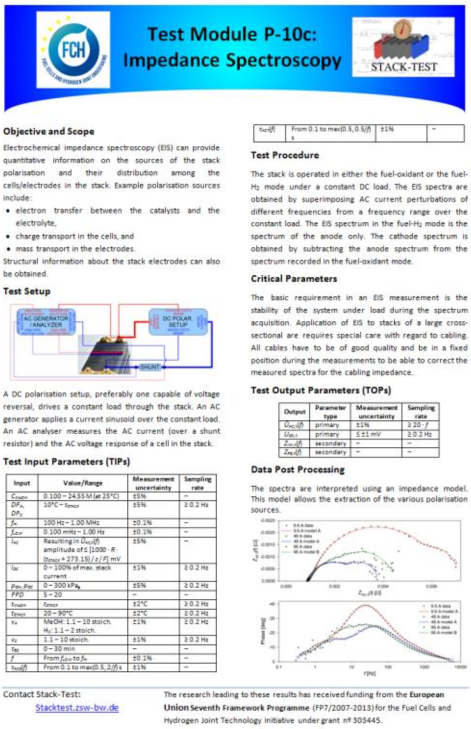
Final document:

TM_P-10a_Electrochemical_Method_Voltammetry.docx



Final document:

TM_P-10b_Electrochemical_Method_Potentiometry.docx


Test Module P-10c: Impedance Spectroscopy

STACK-TEST

Objective and Scope

Electrochemical impedance spectroscopy (EIS) can provide quantitative information on the sources of the stack polarisation and their distribution among the cells/electrodes in the stack. Example polarisation sources include:

- electron transfer between the catalysts and the electrolyte,
- charge transport in the cells, and
- mass transport in the electrodes.

Structural information about the stack electrodes can also be obtained.

Test Setup

A DC polarisation setup, preferably one capable of voltage reversal, drives a constant load through the stack. An AC generator applies a current sinusoid over the constant load. An AC analyser measures the AC current (over a shunt resistor) and the AC voltage response of a cell in the stack.

Test Input Parameters (TIPs)

Input	Value/Range	Measurement uncertainty	Sampling rate
C_{MeOH}	0.100 – 24.55 M (at 25°C)	±5%	–
DP_A, DP_C	10°C – t_{stack}	±5%	≥ 0.2 Hz
f_H	100 Hz – 1.00 MHz	±0.1%	–
f_{LOW}	0.100 mHz – 1.00 Hz	±0.1%	–
I_{AC}	Resulting in $\hat{U}_{AC,i}(f)$ amplitude of ≤ [1000 · R · (t_{stack} + 273.15) / z / F] mV	±5%	–
I_{DC}	0 – 100% of max. stack current	±1%	≥ 0.2 Hz
p_{aA}, p_{aC}	0 – 300 kPa$_g$	±5%	≥ 0.2 Hz
PPD	5 – 20	–	–
t_{MeOH}	t_{stack}	±2°C	≥ 0.2 Hz
t_{stack}	20 – 90°C	±2°C	≥ 0.2 Hz
v_A	MeOH: 1.1 – 10 stoich. H$_2$: 1.1 – 2 stoich.	±1%	≥ 0.2 Hz
v_C	1.1 – 10 stoich.	±1%	≥ 0.2 Hz
t_{BC}	0 – 30 min	–	–
f	From f_{LOW} to f_H	±0.1%	–
$t_{ACD}(f)$	From 0.1 to max(0.5, 2/f) s	±1%	–

$t_{ACI}(f)$	From 0.1 to max(0.5, 0.5/f) s	±1%	–

Test Procedure

The stack is operated in either the fuel-oxidant or the fuel-H_2 mode under a constant DC load. The EIS spectra are obtained by superimposing AC current perturbations of different frequencies from a frequency range over the constant load. The EIS spectrum in the fuel-H_2 mode is the spectrum of the anode only. The cathode spectrum is obtained by subtracting the anode spectrum from the spectrum recorded in the fuel-oxidant mode.

Critical Parameters

The basic requirement in an EIS measurement is the stability of the system under load during the spectrum acquisition. Application of EIS to stacks of a large cross-sectional are requires special care with regard to cabling. All cables have to be of good quality and be in a fixed position during the measurements to be able to correct the measured spectra for the cabling impedance.

Test Output Parameters (TOPs)

Output	Parameter type	Measurement uncertainty	Sampling rate
$\hat{U}_{AC,i}(f)$	primary	±1%	≥ 20 · f
$U_{DC,i}$	primary	≤ ±1 mV	≥ 0.2 Hz
$Z_{Re,i}(f)$	secondary	–	–
$Z_{Im,i}(f)$	secondary	–	–

Data Post Processing

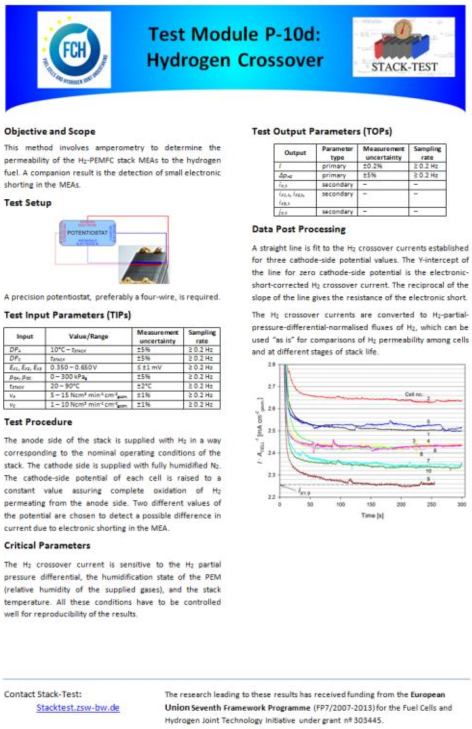
The spectra are interpreted using an impedance model. This model allows the extraction of the various polarisation sources.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant nº 303445.

Final document:

TM_P-10c_Electrochemical_Method_Impedance_Spectroscopy.docx


Test Module P-10d: Hydrogen Crossover

STACK-TEST

Objective and Scope

This method involves amperometry to determine the permeability of the H_2-PEMFC stack MEAs to the hydrogen fuel. A companion result is the detection of small electronic shorting in the MEAs.

Test Setup

A precision potentiostat, preferably a four-wire, is required.

Test Input Parameters (TIPs)

Input	Value/Range	Measurement uncertainty	Sampling rate
DP_A	10°C – t_{stack}	±5%	≥ 0.2 Hz
DP_C	t_{stack}	±5%	≥ 0.2 Hz
E_{X1}, E_{X2}, E_{X3}	0.350 – 0.650 V	≤ ±1 mV	≥ 0.2 Hz
p_{aA}, p_{aC}	0 – 300 kPa$_g$	±5%	≥ 0.2 Hz
t_{stack}	20 – 90°C	±2°C	≥ 0.2 Hz
v_A	5 – 15 Ncm³ min⁻¹ cm⁻²$_{geom}$	±1%	≥ 0.2 Hz
v_C	1 – 10 Ncm³ min⁻¹ cm⁻²$_{geom}$	±1%	≥ 0.2 Hz

Test Procedure

The anode side of the stack is supplied with H_2 in a way corresponding to the nominal operating conditions of the stack. The cathode side is supplied with fully humidified N_2. The cathode-side potential of each cell is raised to a constant value assuring complete oxidation of H_2 permeating from the anode side. Two different values of the potential are chosen to detect a possible difference in current due to electronic shorting in the MEA.

Critical Parameters

The H_2 crossover current is sensitive to the H_2 partial pressure differential, the humidification state of the PEM (relative humidity of the supplied gases), and the stack temperature. All these conditions have to be controlled well for reproducibility of the results.

Test Output Parameters (TOPs)

Output	Parameter type	Measurement uncertainty	Sampling rate
I	primary	±0.2%	≥ 0.2 Hz
Δp_{H2}	primary	±5%	≥ 0.2 Hz
$I_{X,i}$	secondary	–	–
$I_{X1,i}$, $I_{X2,i}$, $I_{X3,i}$	secondary	–	–
$j_{X,i}$	secondary	–	–

Data Post Processing

A straight line is fit to the H_2 crossover currents established for three cathode-side potential values. The Y-intercept of the line for zero cathode-side potential is the electronic-short-corrected H_2 crossover current. The reciprocal of the slope of the line gives the resistance of the electronic short.

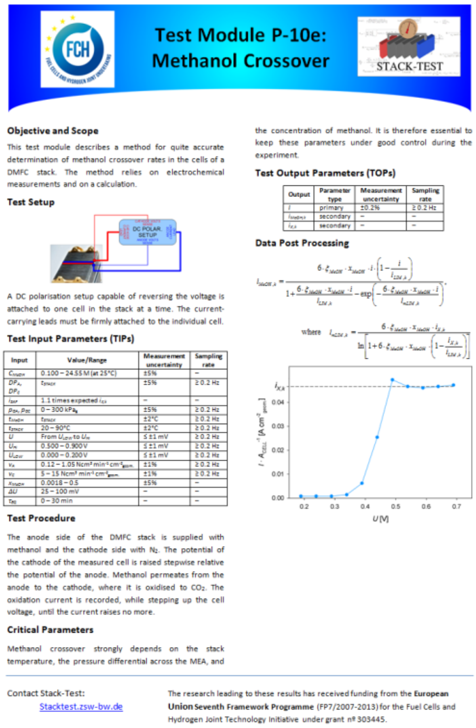
The H_2 crossover currents are converted to H_2-partial-pressure-differential-normalised fluxes of H_2, which can be used "as is" for comparisons of H_2 permeability among cells and at different stages of stack life.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant nº 303445.

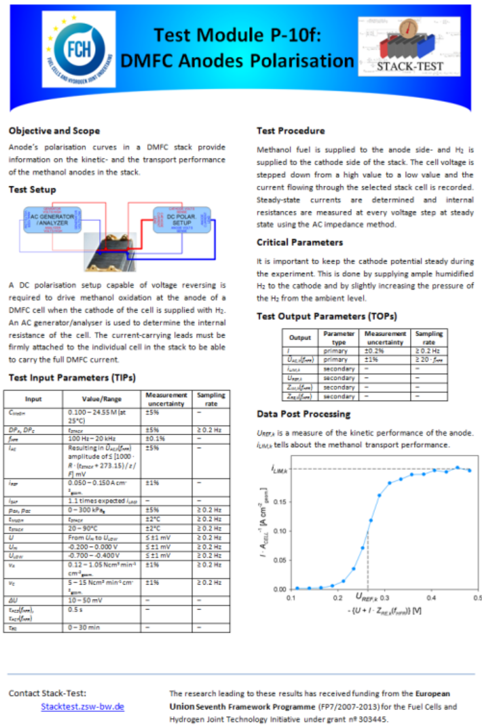
Final document:

TM_P-10d_Electrochemical_Method_Hydrogen_crossover.docx



Final document:

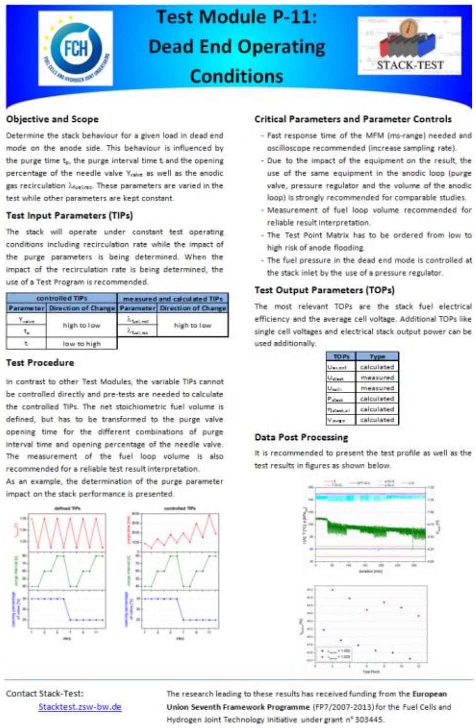
TM_P-10e_Electrochemical_Method_Methanol_crossover.docx



Final document:

TM_P-10f_Electrochemical_Method_DMFC_Anode_Polarisation.docx

Test Module TM P-11: Dead End Operating Conditions



Objective:

This TM is a test procedure concerning the fuel cell stack behaviour in dead end mode on the anode side. This behaviour is influenced by the purge time, the purge interval time and the opening percentage of the needle valve as well as the anodic gas recirculation. These parameters are varied in the test while other parameters are kept constant. The target of this TM is the optimisation of the parameters for a dead end operating fuel cell stack. Thus, occurring problems with water management as well as inert gas and impurity enrichment have to be considered.

Final document:

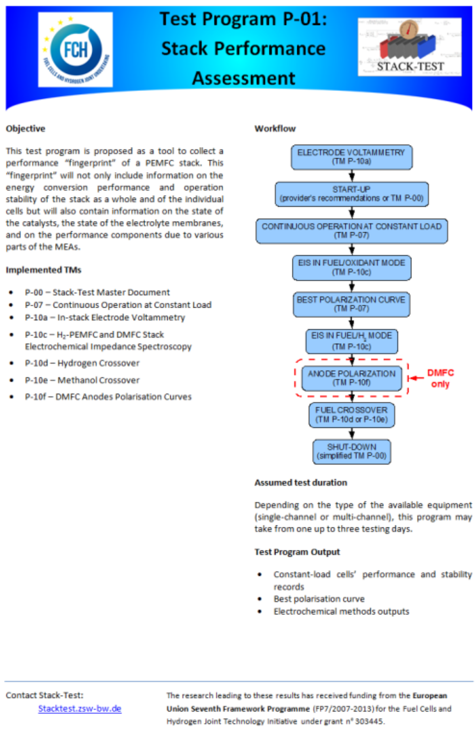
TM_P-11_Dead_End_Operating_Conditions.docx

Functional/Performance Test Programs

Test programs in work package 2 constitute test modules arranged in a specific sequence to address complex test tasks. The test programs developed are examples of how relevant test objectives can be achieved, but users can define further test programs as needed following the Stack-Test structure.

In the following the test programs are presented.

Test Program TP P-01: Stack Performance Assessment



Objective:

This TP is proposed as a tool to collect a performance “fingerprint” of a PEMFC stack. This “fingerprint” will not only include information on the energy conversion performance and operation stability of the stack as a whole and of the individual cells but will also contain information on the state of the catalysts, the state of the electrolyte membranes, and on the polarisation components due to various parts of the MEAs.

Final document:

TP_P-01_Stack_Performance_Assessment.docx

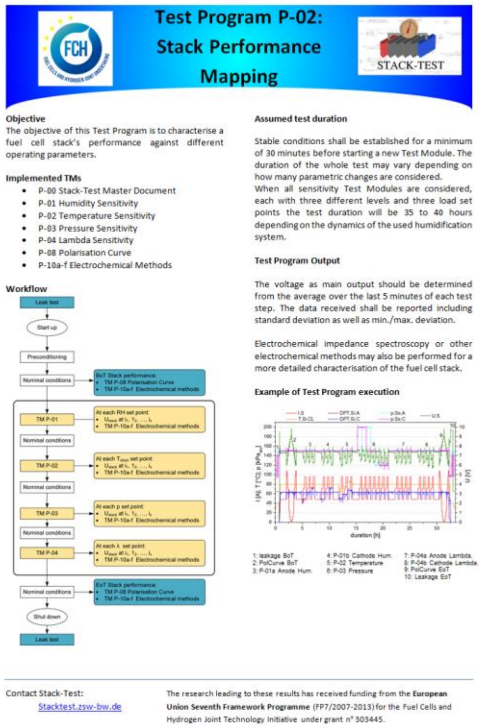
Test Program TP P-02: Stack Performance Mapping

Objective:

The performance of a fuel cell stack is affected by variations in operating conditions. These conditions include the variation of parameters, such as, humidity, temperature, pressure and stoichiometry. Characterising a fuel cell stack's performance against these parameters is crucial for optimising the operating conditions and for proper stack design. Therefore, this Test Program shall be used to map the performance of a fuel cell stack against these operating parameters.

Final document:

TP_P-02_Stack_Performance_Mapping.docx


Test Program P-02: Stack Performance Mapping

Objective
The objective of this Test Program is to characterise a fuel cell stack's performance against different operating parameters.

Implemented TMs
- P-00 Stack-Test Master Document
- P-01 Humidity Sensitivity
- P-02 Temperature Sensitivity
- P-03 Pressure Sensitivity
- P-04 Lambda Sensitivity
- P-08 Polarisation Curve
- P-10a-f Electrochemical Methods

Workflow

Assumed test duration

Stable conditions shall be established for a minimum of 30 minutes before starting a new Test Module. The duration of the whole test may vary depending on how many parametric changes are considered.
When all sensitivity Test Modules are considered, each with three different levels and three load set points the test duration will be 35 to 40 hours depending on the dynamics of the used humidification system.

Test Program Output

The voltage as main output should be determined from the average over the last 5 minutes of each test step. The data received shall be reported including standard deviation as well as min./max. deviation.

Electrochemical impedance spectroscopy or other electrochemical methods may also be performed for a more detailed characterisation of the fuel cell stack.

Example of Test Program execution

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

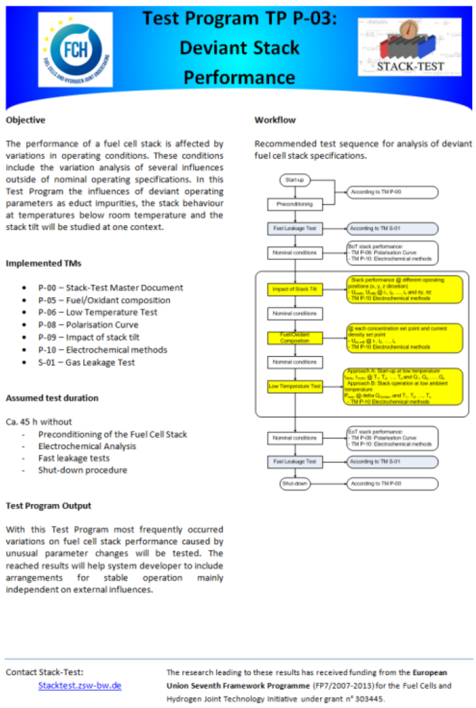
Test Program TP P-03: Deviant Stack Performance

Objective:

The performance of a fuel cell stack is affected by variations in operating conditions. These conditions include the variation analysis of several influences outside of nominal operating specifications. In this Test Program the influences of deviant operating parameters like feed impurities, the stack behaviour at temperatures below room temperature and the stack tilt will be studied in one context.

Final document:

TP_P-03_Deviant_Stack_Performance.docx


Test Program TP P-03: Deviant Stack Performance

Objective

The performance of a fuel cell stack is affected by variations in operating conditions. These conditions include the variation analysis of several influences outside of nominal operating specifications. In this Test Program the influences of deviant operating parameters as educt impurities, the stack behaviour at temperatures below room temperature and the stack tilt will be studied at one context.

Implemented TMs

- P-00 – Stack-Test Master Document
- P-05 – Fuel/Oxidant composition
- P-06 – Low Temperature Test
- P-08 – Polarisation Curve
- P-09 – Impact of stack tilt
- P-10 – Electrochemical methods
- S-01 – Gas Leakage Test

Assumed test duration

Ca. 45 h without
- Preconditioning of the Fuel Cell Stack
- Electrochemical Analysis
- Fast leakage tests
- Shut-down procedure

Test Program Output

With this Test Program most frequently occurred variations on fuel cell stack performance caused by unusual parameter changes will be tested. The reached results will help system developer to include arrangements for stable operation mainly independent on external influences.

Workflow

Recommended test sequence for analysis of deviant fuel cell stack specifications.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

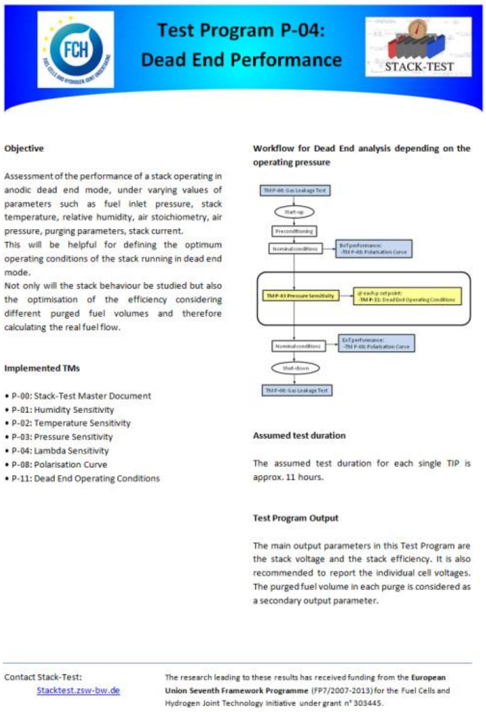
Test Program TP P-04: Dead End Performance

Objective:

The objective of this TP is to know the performance of a stack operated in anodic dead end mode under varying values of parameters such as fuel inlet pressure, stack temperature, relative humidity, air stoichiometry, air pressure, purging parameters, current density, etc. This will be helpful for defining the optimum operating conditions of the stack running in dead end mode. Not only will the stack behaviour be studied but also optimisation of the efficiency by considering different purged fuel volumes and therefore calculating the real fuel flow will be done.

Final document:

TP_P-04_Dead_End_Performance.docx


Test Program P-04:
Dead End Performance

STACK-TEST

Objective

Assessment of the performance of a stack operating in anodic dead end mode, under varying values of parameters such as fuel inlet pressure, stack temperature, relative humidity, air stoichiometry, air pressure, purging parameters, stack current.
This will be helpful for defining the optimum operating conditions of the stack running in dead end mode.
Not only will the stack behaviour be studied but also the optimisation of the efficiency considering different purged fuel volumes and therefore calculating the real fuel flow.

Implemented TMs

- P-00: Stack-Test Master Document
- P-01: Humidity Sensitivity
- P-02: Temperature Sensitivity
- P-03: Pressure Sensitivity
- P-04: Lambda Sensitivity
- P-08: Polarisation Curve
- P-11: Dead End Operating Conditions

Workflow for Dead End analysis depending on the operating pressure

Assumed test duration

The assumed test duration for each single TIP is approx. 11 hours.

Test Program Output

The main output parameters in this Test Program are the stack voltage and the stack efficiency. It is also recommended to report the individual cell voltages. The purged fuel volume in each purge is considered as a secondary output parameter.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

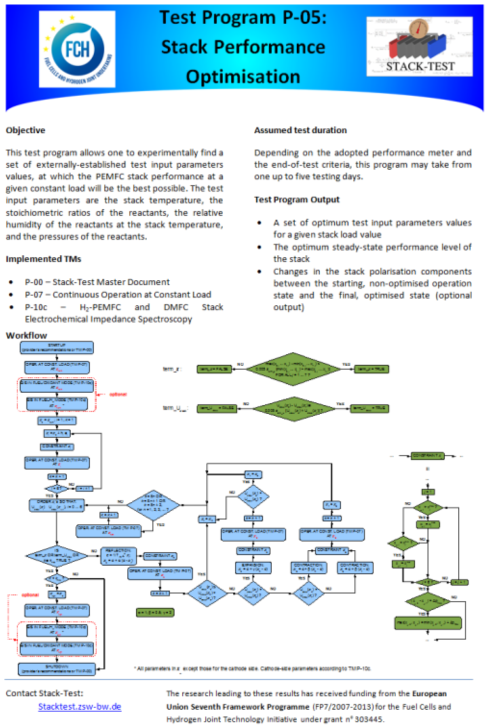
Test Program TP P-05: Stack Performance Optimisation

Objective:

This Test Program allows one to experimentally find a set of externally-established Test Input Parameters (TIPs) values, at which the PEMFC stack performance at a given constant load will be the best possible. The test input parameters are the stack temperature, the stoichiometric ratios of the reactants, the relative humidity of the reactants at the stack temperature, and the pressures of the reactants.

Final document:

TP_P-05_Stack_Performance_Optimisation.docx


Test Program P-05:
Stack Performance
Optimisation

STACK-TEST

Objective

This test program allows one to experimentally find a set of externally-established test input parameters values, at which the PEMFC stack performance at a given constant load will be the best possible. The test input parameters are the stack temperature, the stoichiometric ratios of the reactants, the relative humidity of the reactants at the stack temperature, and the pressures of the reactants.

Implemented TMs

- P-00 – Stack-Test Master Document
- P-07 – Continuous Operation at Constant Load
- P-10c – H_2-PEMFC and DMFC Stack Electrochemical Impedance Spectroscopy

Assumed test duration

Depending on the adopted performance meter and the end-of-test criteria, this program may take from one up to five testing days.

Test Program Output

- A set of optimum test input parameters values for a given stack load value
- The optimum steady-state performance level of the stack
- Changes in the stack polarisation components between the starting, non-optimised operation state and the final, optimised state (optional output)

Workflow

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

Conclusion for Work Package "Functional / Performance Testing"

The developed test modules and test programs were discussed with the industrial advisory board, as well as bilaterally with relevant companies on several levels of the value chain; system integrators, stack manufacturers and component manufacturers. The valuable input has been considered and integrated into the final documents.

In summary, the following documents were prepared in work package 2:

- 17 Test Modules
- 4 Test Programs

5.5 Work package 3

Work package 3 was about the definition and validation of generic test modules and test programs for durability testing. The test modules and procedures developed in this work package can be seen in Table 4.

Table 4 - Test modules for durability testing

Final number	Document title	Final name
Test Module		
TM D-01	TM D-01 Constant Load Durability	TM_D-01_Constant_Load_Durability.docx
TM D-02	TM D-02 Load Cycling Durability	TM_D-02_Load_Cycling_Durability.docx
TM D-03	TM D-03 Start Stop Durability	TM_D-03_Start_Stop_Durability.docx
TM D-04	TM D-04 Stack Performance Recovery	TM_D-04_Stack_Performance_Recovery.docx

In Table 5 is shown the single test program developed in work package 3. The test program is able to encompass all test objectives explored in the four test modules, and can further be designed for a various number of test objectives.

Table 5 - Test programs for durability testing

Final number	Document title	Final name
Test Program		
TP D-01	TM D-01 Durability	TP_D-01_Durability.docx

Durability Test Modules

In the following, all test modules and test programs will be presented in brief. Final test documents are not yet publicised, as publication is pending following publication of articles in journals etc. by the project partners. Estimated time of publication, primo 2016 though the EU Joint Research Centre Central Library (http://www.eurolibnet.eu/).

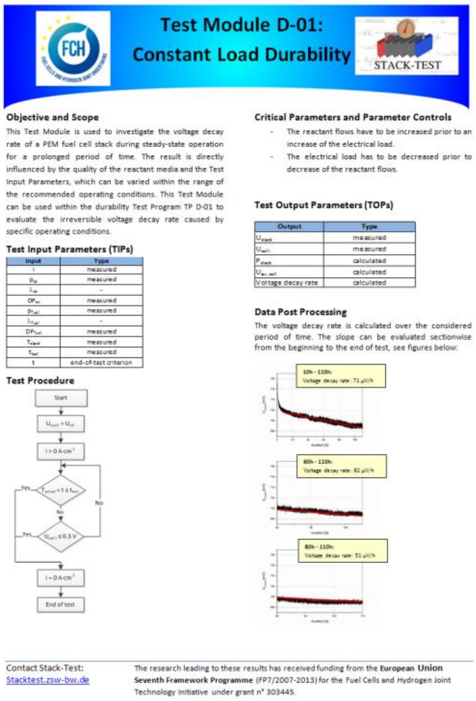
Test Module TM D-01: Constant Load Durability

Objective:

This Test Module is used to investigate the voltage decay rate of a PEM fuel cell stack during steady-state operation for a prolonged period of time. The result is directly influenced by the quality of the reactant media and the Test Input Parameters, which can be varied within the range of the recommended operating conditions. This Test Module can be used within the durability Test Program TP D-01 to evaluate the irreversible voltage decay rate caused by specific operating conditions.

Final document:

TM_D-01_Constant_Load_Durability.docx



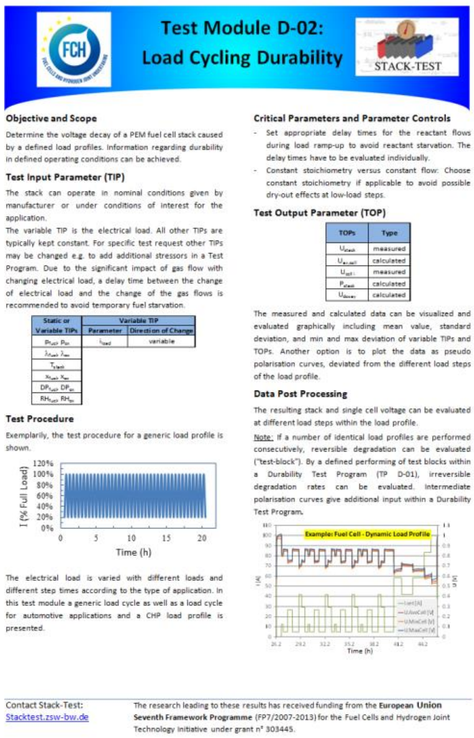
Test Module TM D-02: Load Cycling Durability

Objective:

Load cycling can be a stress factor on the catalyst, membrane and carbon support materials compared to holding load constant. It is usually carried out by a defined cycling of the stack current and recording the voltage responses.

Final document:

TM_D-02_Load_Cycling_Durability.docx



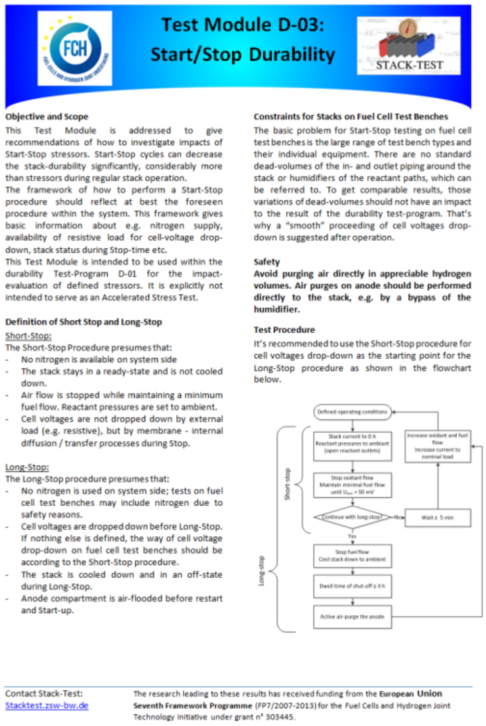
Test Module TM D-03: Start/Stop Durability

Objective:

This Test Module is addressed to give recommendations of how to investigate impacts of Start-Stop stressors. Start-Stop cycles can decrease the stack-durability significantly, considerably more than stressors during regular stack operation.

Final document:

TM_D-03_Start-Stop_Durability.docx



Test Module D-03: Start/Stop Durability

STACK-TEST

Objective and Scope

This Test Module is addressed to give recommendations of how to investigate impacts of Start-Stop stressors. Start-Stop cycles can decrease the stack-durability significantly, considerably more than stressors during regular stack operation.

The framework of how to perform a Start-Stop procedure should reflect at best the foreseen procedure within the system. This framework gives basic information about e.g. nitrogen supply, availability of resistive load for cell-voltage drop-down, stack status during Stop-time etc.

This Test Module is intended to be used within the durability Test-Program D-01 for the impact-evaluation of defined stressors. It is explicitly not intended to serve as an Accelerated Stress Test.

Definition of Short Stop and Long-Stop

Short-Stop:

The Short-Stop Procedure presumes that:

- No nitrogen is available on system side
- The stack stays in a ready-state and is not cooled down.
- Air flow is stopped while maintaining a minimum fuel flow. Reactant pressures are set to ambient.
- Cell voltages are not dropped down by external load (e.g. resistive), but by membrane - internal diffusion / transfer processes during Stop.

Long-Stop:

The Long-Stop procedure presumes that:

- No nitrogen is used on system side; tests on fuel cell test benches may include nitrogen due to safety reasons.
- Cell voltages are dropped down before Long-Stop. If nothing else is defined, the way of cell voltage drop-down on fuel cell test benches should be according to the Short-Stop procedure.
- The stack is cooled down and in an off-state during Long-Stop.
- Anode compartment is air-flooded before restart and Start-up.

Constraints for Stacks on Fuel Cell Test Benches

The basic problem for Start-Stop testing on fuel cell test benches is the large range of test bench types and their individual equipment. There are no standard dead-volumes of the in- and outlet piping around the stack or humidifiers of the reactant paths, which can be referred to. To get comparable results, those variations of dead-volumes should not have an impact to the result of the durability test-program. That's why a "smooth" proceeding of cell voltages drop-down is suggested after operation.

Safety

Avoid purging air directly in appreciable hydrogen volumes. Air purges on anode should be performed directly to the stack, e.g. by a bypass of the humidifier.

Test Procedure

It's recommended to use the Short-Stop procedure for cell voltages drop-down as the starting point for the Long-Stop procedure as shown in the flowchart below.

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

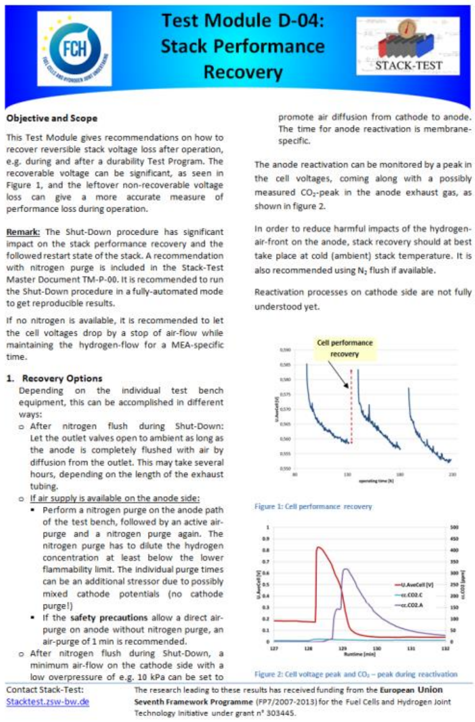
Test Module TM D-04: Stack Performance Recovery

Objective:

This Test Module gives recommendations on how to recover reversible stack voltage loss after operation, for example during and after a durability Test Program. The recoverable voltage can be significant and the non-recoverable voltage loss can give a more accurate measure of performance loss during operation.

Final document:

TM_D-04_Stack_Performance_Recovery.docx



Test Module D-04: Stack Performance Recovery

STACK-TEST

Objective and Scope

This Test Module gives recommendations on how to recover reversible stack voltage loss after operation, e.g. during and after a durability Test Program. The recoverable voltage can be significant, as seen in Figure 1, and the leftover non-recoverable voltage loss can give a more accurate measure of performance loss during operation.

Remark: The Shut-Down procedure has significant impact on the stack performance recovery and the followed restart state of the stack. A recommendation with nitrogen purge is included in the Stack-Test Master Document TM-P-00. It is recommended to run the Shut-Down procedure in a fully-automated mode to get reproducible results.

If no nitrogen is available, it is recommended to let the cell voltages drop by a stop of air-flow while maintaining the hydrogen-flow for a MEA-specific time.

1. **Recovery Options**

   Depending on the individual test bench equipment, this can be accomplished in different ways:

   - After nitrogen flush during Shut-Down: Let the outlet valves open to ambient as long as the anode is completely flushed with air by diffusion from the outlet. This may take several hours, depending on the length of the exhaust tubing.
   - If air supply is available on the anode side:
     - Perform a nitrogen purge on the anode path of the test bench, followed by an active air-purge and a nitrogen purge again. The nitrogen purge has to dilute the hydrogen concentration at least below the lower flammability limit. The individual purge times can be an additional stressor due to possibly mixed cathode potentials (no cathode purge!)
     - If the **safety precautions** allow a direct air-purge on anode without nitrogen purge, an air-purge of 1 min is recommended.
   - After nitrogen flush during Shut-Down, a minimum air-flow on the cathode side with a low overpressure of e.g. 10 kPa can be set to promote air diffusion from cathode to anode. The time for anode reactivation is membrane-specific.

The anode reactivation can be monitored by a peak in the cell voltages, coming along with a possibly measured CO_2-peak in the anode exhaust gas, as shown in figure 2.

In order to reduce harmful impacts of the hydrogen-air-front on the anode, stack recovery should at best take place at cold (ambient) stack temperature. It is also recommended using N_2 flush if available.

Reactivation processes on cathode side are not fully understood yet.

Figure 1: Cell performance recovery

Figure 2: Cell voltage peak and CO_2 – peak during reactivation

Contact Stack-Test:
Stacktest.zsw-bw.de

The research leading to these results has received funding from the **European Union Seventh Framework Programme** (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant n° 303445.

Durability Test Programs

Only one test program has finally been developed, and has been validated for all objectives described in the test modules.

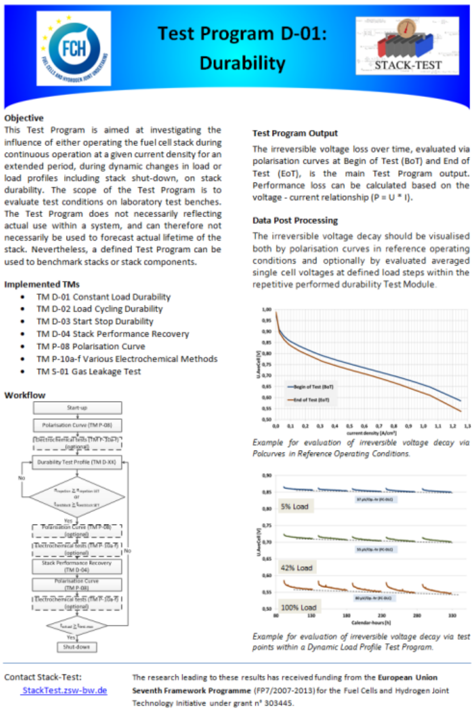
Test Program TP D-01: Durability

Objective:

This Test Program is aimed to evaluate impacts of stressors during steady-state operation, dynamic load profiles or start-stop cycling of fuel cell stacks. Periodically performed Shut-Downs within the Test Program are aimed to recover the reversible voltage decay of the stack. The main output of the Test Program is the evaluation of the irreversible voltage decay rate at a given set of operating parameters.

Final document:

TP_D-01_Durability.docx



Conclusion for Work Package Durability

The developed test modules and test programs were discussed with the industrial advisory board, as well as bilaterally with relevant companies on several levels of the value chain; system integrators, stack manufacturers and component manufacturers. The valuable input has been considered and integrated into the final documents.

In summary, the following documents were prepared in work package 3:

- 4 test modules
- 1 test programs

5.6 Work package 5

Work package 5 has addressed:

- Industrial advisory board
- Survey of international standardisation in the field of PEM stack testing
- Propose integration of project results into standardisation work

Industrial Advisory Board

A great effort was undertaken from early in the project to make sure there was an industrial advisory board representing as many application areas for PEM FC stacks as possible, as well as a broad representation of different parts of the value chain, such as stack manufacturers, system integrators etc. The industrial advisory board constitute 12 companies, as seen in Table 6.

Table 6 : Experts of the Industrial Advisory Board

Name	Company	Comments
I. Roche	PSA Peugeot Citroën	Automotive
P. Ekdunge	Powercell Sweden AB	APU
R. Mosdale	Paxitech SAS	Portable
S. Yde Andersen	IRD Fuel Cells A/S	Micro-chp stack developer
P. Balslev	Dantherm Power A/S	Backup and micro-chp
F. Beille	AREVA AS	Backup
T. Wannemacher	Proton Motor Fuel cell GmbH	Transport
D. Pfeffer	Schunk Bahn- und Industrietechnik GmbH	Transport
C. Hildebrandt	inhouse engineering GmbH	Micro-chp stack developer
G. Frank	Daimler	Automotive
M. Venturi	NuCellSys GmbH	Automotive
P. Klose	BAXI INNOTECH GmbH	Micro-chp system developer

Several Danish stakeholders were asked to join the board, in the end both IRD Fuel Cells A/S and Dantherm Power A/S joined.

The advisory board has provided valuable input during workshops and bilateral discussions on specific test procedures, and whether developed test modules reflected actual demands and realistic operating scenarios.

Work in standardisation

In the EU-project an overview of relevant international and national standards were prepared initially in the project, and subsequently updated during the project. It is clear that the standardisation work concerning fuel cells and hydrogen is very active, and the work also clearly showed and underlined the need for the work in the project.

As a natural consequence of this realisation, work was put into creating the frame for transferring the project results into standardisation through a New Work Item Proposal (NWIP), which if approved will lead to the formation of a working group creating a standard.

The NWIP Proposed in currently under vote in the IEC TC 105, and a decision is expected ultimo 2015. If positive, the drafting of the document should be able to begin early 2016, preferably with a large European contribution.

5.7 Impact to environment, financial growth etc.

The current project is not thought to have a direct impact on the environment, nor financial growth in participating partners, but the work in the project can have a significant stake in ensuring the time to market maturity for the PEM FC technology by creating an industry-wide accepted frame for stack testing. The industry as a whole is continuously working towards improving the performance and life time of PEM fuel cell stacks and by agreeing on common methodology and procedures. The current project is a step towards making this process more transparent and tests more comparable, which should benefit all parts of the value chain.

From a research perspective, the results created in this project also create a uniform approach to PEM FC Stack research and development, which could in turn increase the amount research results created and understanding of the performance and degradation behaviour of the technology.

6. Utilization of project results

The Stack-Test project has ensured that both DTU and AAU have build-up knowledge on PEM fc stack testing and specifically knowledge on applications specific testing. The knowledge gained in the project allows for further development of the national competencies and dissemination to the Danish hydrogen and fuel cell industry.

DTU is as a direct consequence of being part of Stack-Test also part of the large European project SOCTESQA (FCH JU GRANT AGREEMENT N° 621245) in which the project partners are developing test procedures for solid oxide fuel cell single cell and stacks, with similar objectives as in the Stack-Test project.

DTU has further as a consequence of being a part of the project increased the efforts within participating in standardisation work, through the National Standardisation Committee (Dansk Standard) in work group S-605 Hydrogen and Fuel Cells. In addition DTU has also started evaluation of the lab facilities, working towards processes for quality control of the test facilities.

AAU is also part of a newly funded European project HEALTH-CODE ((FCH JU grant agreement N° 671486), aimed at implementing an advanced monitoring and diagnostic tool for µ-CHP and backup PEM fuel cell systems equipped with different stacks. During this project, several performance and degradation tests will be carried out to investigate common fuel cell faults to ultimately support their detection. The consortium has showed interest in using the test procedures that resulted from the Stack-Test project and AAU being the only one among the partners who also participated in Stack-Test project, will act as a bridge due to its competencies and experiences in developing the mentioned test procedures. The effort of using test procedures developed in the Stack-Test project will be extended to all of AAU's fuel cell stack testing activities, wherever applicable.

Furthermore, AAU has published one paper during the project period and DTU is preparing another paper summarizing the work done on durability testing.

Neither AAU or DTU are planning to apply for patents as a direct consequence of the project.

7. Project conclusion and perspective

The project and its results can if accepted by the industry and research community be a significant way of shortening the time to market for PEM FC products by eliminating transaction/trade difficulties through standardized testing. At the same time, the results are very powerful tools for the industry and research for understanding and development of the next generations of PEM FC stack technologies (materials, components and systems).

First, if the test procedures developed are transferred into an international standard, it will likely become common practise following the procedures, and thereby creating credibility of test results, benchmarks etc. Second, even if an international standard is not created initially, the fuel cell community, in particular in Europe, can adopt the test procedures as common practice, as no reliable alternatives exist, and thereby still create an environment that makes exchange of information and trade more transparent.

The project has also yielded novel methods for measuring performance and durability of fuel cell stacks, as well as comprehensive analytical tools for optimizing the performance of fuel cell stacks. These tools will be readily available when published in 2016, and already now upon request.

In a national context the Danish companies within hydrogen and fuel cells have for many years been wanting an increased focus on comparability, as the lack of trustworthy ways of measuring performance is an obstacle for doing business. The Danish manufacturers of PEM fuel cell products further lack the tool to cost effectively evaluate PEM FC stack suppliers.

8. Annex

Publications:

Parametric Sensitivity Tests—European Polymer Electrolyte Membrane Fuel Cell Stack Test Procedures; *Araya, S. S., Andreasen, S. J. & Kær, S. K. Dec 2014; Journal of Fuel Cell Science and Technology. 11, 6, p. 061007-1 - 061007 -7 7 p., FC-14-1067*

Links:

EU-project homepage:
http://stacktest.zsw-bw.de/general-information.html

DTU Stack-Test homepage:
http://www.fch.dk/Projects/Stack-Test

AAU Stack-Test homepage:
http://vbn.aau.dk/en/projects/stack-test(5cfa2f1c-377b-4e55-a37c-9ecb48087ba1).html

IEC standardisation organisation homepage:
http://www.iec.ch/dyn/www/f?p=103:7:0

EU Joint Research Centre Central Library:
http://www.eurolibnet.eu/

EU-project SOCTESQA homepage:
http://www.soctesqa.eu/project