Project Final Report

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Stack-Test

Development of PEM Fuel Cell Stack Reference Test Procedures for Industry

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Report prepared by: Jürgen Hunger, Jens Mitzel, Frederik Berg-Nygaard, Thomas Jungmann, Corinna Harms, Sébastien Rosini, Ludwig Jörissen

Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg
Helmholtzstrasse 8, D-89081 Ulm
Tel: +49-731-9530-605
Fax: +49-731-9530-666
E-mail: ludwig.joerissen@zsw-bw.de
Project web page:http://stacktest.zsw-bw.de

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1 Summary

1.1 Project Objectives

The overall objectives of the project are the definition and validation of industrially relevant generic test modules and application oriented test programs addressing performance, durability and safety as well as environmentally related issues in testing PEM fuel cell stacks.

1.2 Executive Summary

Fuel cell systems are more and more reaching industrial product readiness. In applications such as uninterruptible power supply as well as combined heat and power generation products are already on the market, however still mostly subsidized by government programs. A good deal of these products is based on Polymer Electrolyte Membrane (PEM) Fuel Cell technology. The PEM fuel cell stack represents the key component in such systems.

The work carried out in this project aims at the development of harmonized, industrially relevant test procedures allowing an assessment of PEM fuel cell stacks with respect to:

- performance,
- endurance, and
- safety related issues.

The tests developed within this project have been written in a common format allowing sufficient flexibility to adopt specific requirements of fuel cell application oriented testing. Typical application areas identified for PEM fuel cells are vehicle propulsion where the fuel cell can act either as the prime mover or as a range extender, stationary applications such as combined heat and power generation (CHP), uninterruptible and backup power supply as well as portable power generators. It is evident that PEM fuel cell stacks are operated under significantly different operating conditions in each of these applications.

Figure 1: Interaction of test programs and test modules for complex testing tasks.
The particular challenge was to find a common methodology for testing which still is flexible enough to cover the application areas mentioned above while clearly defining requirements to the test equipment, the in- and output parameters and the points of control for the parameters defining the operating conditions.

The technical work of this project has been based on work previously carried out within the FP6 projects FCTETNET, FCTESQA, and FCTEDI which was mostly single cell and fuel cell system related. Although generally addressed, PEM fuel cell stack testing has been handled on a fairly general level in these previous projects.

While adopting the general methodology and the fundamental ideas of the harmonized test format set out in FCTESTNET and FCTESQA, the methodology has been further refined and the harmonized test format simplified and adopted to the requirements of PEM fuel cell stack testing.

The work has been organized in the following six technical work packages:

- WP1: Coordination
- WP2: Functional and performance testing
- WP3: Endurance testing
- WP4: Environmental / safety testing
- WP5: Liaison to international Standardization Organizations and Industry
- WP6: Specification and procurement of samples

Initially, the existing documents on PEM fuel cell testing and PEM fuel cell stack testing as well as proposals from the consortium have been collected, analysed and critically assessed with respect to potential relevance for industry and application. The results of this assessment have been documented in test matrices for performance, endurance, and safety testing.

The tests considered relevant during this exercise have been assessed further and - where appropriate - separated in test modules varying a single input parameter at a time while observing the reaction of key output parameters, and test programs forming a more complex series of individual test modules.

During the assessment, it became evident that the major part of test modules developed for performance testing are also suitable in test programs addressing endurance and safety related issues. Therefore, a common pool of Test Modules has been collected.

Draft versions of the test modules have been written in the revised harmonized test format. Topics common for all tests such as test bench set up, definitions, location of sensors and control parameters have been compiled in a master document for performance testing and safety testing respectively. After completing the definition of test modules, selected test programs have been drafted.

Test modules and subsequently test programs have been assigned to individual partners for experimental validation. In general, a two stage definition, validation and revision approach has been followed.

Key results of the project so far were:

- Assessment of the status in international standardization of PEM fuel cell testing.
- Provision of sample stacks to each partner to carry out experimental work.
- Definition and validation of 22 test modules in two iterations addressing performance, endurance, and safety related issues of PEM fuel cell stacks
• Definition and validation of nine test programs addressing performance, endurance, and safety related issues.

The methodology as well as the content of the Test Modules and test Programs defined has been discussed with an industrial advisory board consisting of members representing different application areas. Furthermore, Test Modules and test Programs have been provided to other FCH-JU R&D-projects. Feedback from the industrial advisory board as well as from other projects has been integrated in document revision.

The project results have been communicated in international workshops held within the project, through contributions to international and national conferences as well as through publications in peer reviewed scientific journals.

Final release versions of the documents have been written and are currently under language editing. The documents will be made publicly available once editing is completed and priority dates for publications have been secured.

2 Work Progress and Achievements

2.1 Project Objectives

The major objectives for the project are as follows:

• Review the status of international standardization with respect to PEM fuel cell testing.
• Agree upon a methodology how to describe performance, endurance, and safety test for PEM fuel cells.
• Define generic Test Modules to be used for performance, endurance, and safety testing addressing the reaction of a PEM fuel cell stack to the variation of a single input parameter.
• Provide samples of Test programs addressing more complex test tasks
• Provide a methodology to carry out PEM fuel cell stack tests under application specific boundary conditions.
• Form an industrial advisory board providing user feedback to the project results.
• Disseminate the project results in stakeholder workshops.
• Disseminate the project results in conferences and scientific papers.

2.2 Work Progress and Achievements

2.2.1 Summary of Achievements and Progress

In the course of the project the following progress with respect to prior activities has been achieved:

2.2.1.1 General

• The status of international standardization with respect to PEM fuel cell testing has been assessed at the beginning of the project. Annual updates have been provided.
• An industrial advisory board has been formed.
• A methodology to describe PEM fuel cell stack testing has been defined an agreed upon as a Master document TM P-00.
• Agreement has been found upon definitions such as sites of parameter control, stability criteria and test parameter nomenclature by all project partners to get reproducible results. Validation was performed within Round-Robin testing.
• Generic Test Modules addressing the reaction of a PEM fuel cell stack to the variation of a single input parameter to allow their use as building blocks for Test Programs have been defined.
• Test Modules have been defined and refined in a two stage process involving experimental validation, consultation with the industrial advisory board and discussion during dissemination workshops.
• Preparation of a one-page abstracts for each Test Module and Test Program to provide comprehensive information for use by experts.
• First approach of definitions to determine the degradation rate within a durability test
• Four stakeholder workshops have been held where project results have been disseminated. Feedback from the workshops has been integrated in the Test Modules and test Programs.
• Scientific papers derived from test results, partly already published
• Input for International Standardisation as a New Work Item Proposal submitted to IEC TC-105.

2.2.1.2 Functional and Performance Testing

Key achievements
• Definition and validation of test modules concerning sensitivity studies of different parameters in two iterations
• Reproducibility investigation of test results performed by different partners on different test benches using similar objects under test.
• Drafting and final validation of different test programs using the defined Test Modules.

Progress beyond the state of the art
• Definition of test modules and test programs on a stack level in a consistent manner
• Identification of critical parameter controls to assure comparable stack performance characterization

2.2.1.3 Endurance testing

Key achievements
• Drafting and validation of generic test modules and test programs:
  • Steady-State
  • Load cycling
  • Start-Stop
  • Performance Recovery
• Application specific adaption within the context of harmonisation efforts:
  • Transforming the NEDC dynamic load cycle to a “Fuel Cell Dynamic Load Cycle (FC-DLC)” which can be performed on a broad range of fuel cell test benches.
  • Definition of “test block”, containing a number of consecutive performed Fuel Cell Dynamic Load Cycles to perform degradation tests.
  • Results led to a proposal of how to measure degradation rates
  • Presentation of the results in a Brussels harmonization meeting
• Identifying of critical parameters during Start-Stop testing.
- Combination of the Test Modules "Start-Stop", "Load Cycling" and "Performance Recovery" within a validated automotive durability Test Program.
- Adoption WP2- definitions to WP3: same nomenclature and naming of parameters
- Transmission of the drafted test-modules to other running European Projects

Progress beyond the state of the art
- Effort of transformation of the generic test-module “load cycling” to an application specific test-module was successful.
- Broad acceptance within the project partners, good feedback from industry.
- Drafted test-modules and test-programs are (in combination of WP2-drafts) basic documents for planning of endurance tests in other running European projects.

2.2.1.4 Safety testing

Key achievements
- Selection, definition and validation of stack relevant safety tests.
- Drafting of safety related test-modules and test programs, based on the common standard IEC 62282-2 (Fuel Cell Modules), which gives only a framework of safety-tests.
  - Giving detailed test descriptions and examples beyond the general requirement of performing “according to manufacturer’s recommendation”.
  - Identification of existing experimental challenges (e.g. sample rate during short circuit test)

Progress beyond the state of the art
- Detailed description and validation of tests required for type approval by the IEC stack-standard by giving examples of validation experiments:
  - Description of test equipment,
  - Description of minimum requirements for test infrastructure,
  - Detailed declaration of test input and test output parameters.

- Adaptation of shaker test from battery testing and giving recommendations of how to gather additional information regarding mechanical stiffness by performing of resonance sweep tests.

2.2.2 Detailed Description of Achievements and Progress

The work carried out within the project Stack-Test has been based on previous work done within the FP6 project FCTESTNET, FCTESQA, and FCTEDI. In these projects a general methodology for fuel cell testing has been developed and validated at a single cell as well as a system level. Stack level testing of PEM fuel cells, however, has not been covered fully in these previous projects.

The overall objective of this work is to continue the line of work started in the FP6 projects and develop and experimentally validate test procedures specifically for PEM fuel cell stacks addressing performance, endurance, and safety related issues. Furthermore, a review of international standardization activities related to PEM fuel cell testing shall be given and kept updated during the course of the project. Liaison with standard developing organizations as well as industrial stakeholders shall be established.

Initially, the methodology describing fuel cell testing developed in the previous FP6 projects as well as the harmonized format describing the tests has been reviewed with
respect to applicability, ease of use and potential industrial relevance for testing PEM fuel cell stack performance, endurance, safety, and environmental issues.

2.2.2.1 Review of the Methodology

The general methodology describing PEM fuel cell testing based on generic test modules in which the reaction of stack output parameters (e.g. voltage) to the variation of a single stack input parameter (e.g. current) while keeping the other input parameters constant has been adopted also for stack testing.

Nevertheless, it has to be noted that unlike in single cell testing not all input parameters can be varied independently. In stack testing, the variation of the one input parameter (e.g. current) is likely to cause variations of other input parameters (e.g. gas flow, pressure drop, temperature spread etc.) as well. Therefore, it is necessary to carefully record and report all variations in in- and output parameters when carrying out stack testing. A precise definition where parameters such as stack temperature, pressure humidity are measured and controlled is essential.

Besides the review of the test procedures available from FCTESTNET and FCTESQA, the harmonized format for describing and reporting tests has also been reviewed. Based on experiences in the various laboratories, a simplified format has been developed. Furthermore, common issues to all test modules such as test bench quality and stability criteria, frequently used procedures etc. have been collected in a master document.

The test module description as used in FCTESTNET and FCTESQA has been updated to allow for flexibility in the definition of input parameters in order to cover application specific requirements. Recommended sets of input parameters characteristic for different applications are under development.

More complex tasks have been organized in test programs of individual test modules arranged in a series or loop structure. Such a sequence can be designed representative for different applications taking into account the different dynamic and lifetime requirements encountered in applications such as automotive propulsion, CHP or portable power generators.

Organization of PEM fuel cell tests in generic test modules and application oriented test programs thus provide great flexibility in designing application relevant tests as well as providing fundamental information on the stack operating characteristics.

All test modules and test programs developed in this project have been written using the updated description and reporting format.

2.2.2.2 Definition of generic PEM fuel cell stack test modules

Based on an initial compilation, 22 test modules have been selected as specific and relevant for PEM fuel cell stack testing. After writing up the details and further review, 17 of these test modules have been selected for experimental validation.

The test modules considered most important are being validated by all partners. Other test modules will be validated by a minimum of two partners by the end of the project.
<table>
<thead>
<tr>
<th>Module</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance</strong></td>
<td></td>
</tr>
<tr>
<td>TM P-00</td>
<td>Stack Test Master Document</td>
</tr>
<tr>
<td>TM P-01</td>
<td>Humidity Sensitivity</td>
</tr>
<tr>
<td>TM P-02</td>
<td>Temperature Sensitivity</td>
</tr>
<tr>
<td>TM P-03</td>
<td>Pressure Sensitivity</td>
</tr>
<tr>
<td>TM P-04</td>
<td>Stoichiometry Sensitivity</td>
</tr>
<tr>
<td>TM P-05</td>
<td>Fuel and Oxidant Composition</td>
</tr>
<tr>
<td>TM-P06</td>
<td>Low Temperature Test</td>
</tr>
<tr>
<td>TM P-07</td>
<td>Continuous Operation at Constant Load</td>
</tr>
<tr>
<td>TM P-08</td>
<td>Polarization Curve</td>
</tr>
<tr>
<td>TM P-09</td>
<td>Impact of Stack Tilt</td>
</tr>
<tr>
<td>TM P-10a</td>
<td>Electrochemical Method: Voltammetry</td>
</tr>
<tr>
<td>TM P-10b</td>
<td>Electrochemical Method: Potentiometry</td>
</tr>
<tr>
<td>TM P-10c</td>
<td>Electrochemical Method: Impedance Spectroscopy</td>
</tr>
<tr>
<td>TM P-10d</td>
<td>Electrochemical Method: Hydrogen Crossover</td>
</tr>
<tr>
<td>TM P-10e</td>
<td>Electrochemical Method: Methanol Crossover</td>
</tr>
<tr>
<td>TM P-11</td>
<td>Dead-End Operating Conditions</td>
</tr>
<tr>
<td><strong>Durability</strong></td>
<td></td>
</tr>
<tr>
<td>TM D-01</td>
<td>Constant Load Durability</td>
</tr>
<tr>
<td>TM D-02</td>
<td>Load Cycling</td>
</tr>
<tr>
<td>TM D-03</td>
<td>Start-Stop Durability</td>
</tr>
<tr>
<td>TM D-04</td>
<td>Stack Performance Recovery</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td></td>
</tr>
<tr>
<td>TM S-01</td>
<td>Gas Leakage Test</td>
</tr>
<tr>
<td>TM S-02</td>
<td>Vibration Test</td>
</tr>
<tr>
<td>TM S-03</td>
<td>Pressure Stability Test</td>
</tr>
<tr>
<td>TM S-04</td>
<td>Freeze-Thaw-Cycling Test</td>
</tr>
<tr>
<td>TM S-05</td>
<td>Excess Temperature Test</td>
</tr>
<tr>
<td>TM S-06</td>
<td>Short Time Rated Current</td>
</tr>
<tr>
<td>TM S-07</td>
<td>Dielectric Strength</td>
</tr>
<tr>
<td>TM S-08</td>
<td>Short Circuit Test</td>
</tr>
</tbody>
</table>

The project achieved its objective of selecting and validating industrially relevant test modules. Lessons learned and shortcomings identified during the first reporting period have been used for revision and subsequent successful validation of the test modules in the second reporting period.

2.2.2.3 Definition of application oriented PEM fuel cell stack test programs

A series of application oriented test programs addressing performance, endurance, and safety aspects have been drafted and validated.
Table 2: Test Programs relevant for PEM fuel cell stack testing

<table>
<thead>
<tr>
<th>Module</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Performance</td>
</tr>
<tr>
<td>TP P-01</td>
<td>Stack Performance Assessment</td>
</tr>
<tr>
<td>TP P-02</td>
<td>Stack Performance Mapping</td>
</tr>
<tr>
<td>TP P-03</td>
<td>Deviant Stack Performance</td>
</tr>
<tr>
<td>TP P-04</td>
<td>Dead-End Performance</td>
</tr>
<tr>
<td>TP P-05</td>
<td>Stack Performance Optimization</td>
</tr>
<tr>
<td></td>
<td>Durability</td>
</tr>
<tr>
<td>TP D-01</td>
<td>Durability</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
</tr>
<tr>
<td>TP S-01</td>
<td>Mechanical Safety Analysis</td>
</tr>
<tr>
<td>TP S-02</td>
<td>Temperature Safety Analysis</td>
</tr>
<tr>
<td>TP S-03</td>
<td>Electrical Safety Analysis</td>
</tr>
</tbody>
</table>

Intense discussions at the beginning of the project led to the approach to cover application specific differences in test conditions for performance and endurance testing by representative Test Input Parameters (TIP). This approach allows sufficient flexibility to use the test modules while simultaneously providing guidelines to take application specific differences as they are known today into account. This approach has been discussed with the industrial advisory board. Table 3 gives a recommendation for application specific Test Input parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Automotive</th>
<th>Stationary</th>
<th>Portable Generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Symbol</td>
<td>Symbol</td>
<td>Symbol</td>
</tr>
<tr>
<td>Stack Temperature (Coolant inlet)</td>
<td>$T_{stack}$</td>
<td>$T_{stack}$</td>
<td>$T_{stack}$</td>
</tr>
<tr>
<td>Reactant inlet temperature</td>
<td>$T_{gas,in}$</td>
<td>$T_{gas,in}$</td>
<td>$T_{gas,in}$</td>
</tr>
<tr>
<td>Fuel (H$_2$) stoichiometry</td>
<td>$\lambda_{fuel}$</td>
<td>$\lambda_{fuel}$</td>
<td>$\lambda_{fuel}$</td>
</tr>
<tr>
<td>Oxidant (air) stoichiometry</td>
<td>$\lambda_{ox}$</td>
<td>$\lambda_{ox}$</td>
<td>$\lambda_{ox}$</td>
</tr>
<tr>
<td>Fuel relative humidity</td>
<td>$RH_{fuel}$</td>
<td>$RH_{fuel}$</td>
<td>$RH_{fuel}$</td>
</tr>
<tr>
<td>Dew point temperature fuel</td>
<td>$DP_{fuel}$</td>
<td>$DP_{fuel}$</td>
<td>$DP_{fuel}$</td>
</tr>
<tr>
<td>Oxidant relative humidity</td>
<td>$RH_{ox}$</td>
<td>$RH_{ox}$</td>
<td>$RH_{ox}$</td>
</tr>
<tr>
<td>Dew point temperature oxidant</td>
<td>$DP_{ox}$</td>
<td>$DP_{ox}$</td>
<td>$DP_{ox}$</td>
</tr>
<tr>
<td>Fuel outlet pressure</td>
<td>$P_{fuel}$</td>
<td>$P_{fuel}$</td>
<td>$P_{fuel}$</td>
</tr>
<tr>
<td>Oxidant outlet pressure</td>
<td>$P_{ox}$</td>
<td>$P_{ox}$</td>
<td>$P_{ox}$</td>
</tr>
</tbody>
</table>
Two different sets of TIPs have been adopted representing most likely future vehicle operating conditions (Propulsion (I)) at elevated temperature and reduced humidity. These conditions are harmonized with the current definition of harmonized test reference conditions for single cell testing. Obvious differences in pressure levels are originating from pressure control positions. While Stack-test recommends control of stack pressure at the exit, the harmonized European test conditions ask for pressure control at the cell inlet. TIPs defined in Propulsion (II) are more representative for state of the art vehicle operating conditions.

In total, the project has achieved its objectives in drafting and experimentally validating the test programs.

2.2.2.4 Review of international standards related to PEM fuel cell stack testing and liaison to standard developing organizations

Existing international standards are having substantial influence on different aspects of fuel cell testing. As a consequence, test modules and test programs are developed in the different work packages keeping in mind the existing standards and tests procedures elaborated all around the world. Following a review and a first update on the status of international standardization relevant for PEM fuel cell stack testing carried out in the first reporting period, a second update has been compiled.

Procedures and program tests can be found from the following documents:

- FCTESQA: procedures dedicated to fuel cell stack characterisations [7]–[11]
- IEC 62282-2:2012: International standard providing minimum requirements for safety and performance of fuel cell modules in all applications [12]
- SAE J 2574 : FUEL CELL VEHICLE TERMINOLOGY [3]
- IEC 62282-6-100 :2010 [16]

Additional information can be extracted from the fuel cells standards website [18]. Some national relevant procedures which are not available in English language (e.g. Chinese) have not been taken into account in this document.

A summary of the contents of these documents can be found in the corresponding deliverables.

Members of the consortium are active in relevant standardization committees on IEC and ISO level. The work carried out in the project has been used as the basis of a new work item proposal on PEM fuel cell stack testing to the IEC TC-105. It has been suggested to treat this as part of the fuel cell module standard (IEC 62282-2).
An industrial advisory group with representatives from relevant application areas has been formed. A joint meeting has been held during the first general assembly in October 2013.

The project reached its objectives.

2.2.2.5 Specification and manufacturing of sample stacks for experimental validation.

Partners active in experimental validation of test modules and test programs have been supplied with sample stacks using graphitic bipolar plates from ZSW and stacks using metallic bipolar plates from CEA. The stack technologies chosen are representing CHP / portable power generation (100 cm² graphitic bipolar plates) and automotive (220 cm² metallic bipolar plates) applications respectively.

The stacks and reference operating conditions have been jointly specified. All partners active in experimental validation have been supplied with one graphitic and one metallic stack by end of 2013. The stack performance at begin of life was consistent with the current state of the art of commercial MEA and BPP technology. Stack performance was homogeneous within less than 20 mV at a current density of 1 A/cm².

The project fully achieved this objective.

2.2.3 Work Package 1: Coordination

Day to day communication among the steering committee has been established via regular telephone conferences. Individual communication among the partners could be established. Day to day communication was supported by a joint file server hosted at DTU.

Initially, the project required the development of a common understanding of the harmonized definition and parameterization of PEM fuel cell testing. This has been addressed by the work package leaders by organizing specific technical workshops for each work package. During these meetings potential tests have been compiled and analyzed with respect to industrial relevance and applicability. Details are reported in the subsequent chapters on individual work packages.

The definition of reference conditions as well as the development of a common understanding of control parameters and stability criteria has been established after intense discussions. The positions agreed upon have been documented in a common master document for all work packages.

Dissemination of project results has been done via the project web page, public workshops held in the framework of the project, presentations on international conferences as well as peer reviewed publications in scientific journals.

The project results are exchanged with the members of the industrial advisory board and directly communicated to other FCH-JU projects such as AutoStack-CORE, IMPACT, IMPALA, NanoCat, SAPPHIRE, SOCTESQA, and HYCORA.

2.2.4 Work Package 2:

In the beginning of the Stack-Test project, a Test Matrix (Table 4) was prepared as described in "Milestone 10 - Test Matrix for application oriented testing defined". Therefore, all potential tests with relevance to functional and performance testing were summarised and evaluated regarding their relevance to the stack level. Some of the tests were excluded from the matrix since they were considered to be relevant at system level only. However, the initial numbering of the Test Matrix was not modified to assure the
possibility to include them if the evaluation was incorrect and, e.g., the feedback from industry makes a consideration necessary.

Table 4: Test matrix for application oriented testing in WP2

<table>
<thead>
<tr>
<th>Generic Test Module/Function Test</th>
<th>Automotive propulsion</th>
<th>Stationary Residential</th>
<th>Stationary APU</th>
<th>Portable Backup Power</th>
<th>Portable Power Generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.03 Humidity Sensitivity</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2.04 Temperature Sensitivity</td>
<td>x</td>
<td>x/-</td>
<td>x</td>
<td>x/-</td>
<td>x/-</td>
</tr>
<tr>
<td>2.05 Pressure Sensitivity</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>2.06 Lambda Sensitivity</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2.07 Fuel/Oxidant Composition (CO sensitivity)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>2.11 Freeze Start</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>2.14 Continuous operation at minimum load</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>2.15 Polarisation curve</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2.17 Ambient conditions</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.18 Electrochem. Methods (C, CV, EIS, LSV)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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</table>

Table 5: final designation for Stack-Test WP2 Test Modules

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<thead>
<tr>
<th>#</th>
<th>CURRENT number</th>
<th>current name</th>
<th>final number</th>
<th>document title</th>
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<td>TM P-00</td>
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<tr>
<td>1</td>
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<td>Humidity Sensitivity</td>
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<td>TM_P-02_Temperature_Sensitivity.docx</td>
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<tr>
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<td>5</td>
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<td>Fuel/Oxidant Composition</td>
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<td>TM_P-05_Fuel_Oxidant_Composition.docx</td>
</tr>
<tr>
<td>6</td>
<td>TM2.11</td>
<td>Low Temperature Test</td>
<td>TM P-06</td>
<td>Low Temperature Test</td>
<td>TM_P-06_Low_Temperature_Test.docx</td>
</tr>
<tr>
<td>7</td>
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<tr>
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<td>TM P-08</td>
<td>Polarisation Curve</td>
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</tr>
<tr>
<td>9</td>
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<td>TM P-09</td>
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<tr>
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<td>TM P-10a</td>
<td>In-Stack Electrode Voltammetry</td>
<td>TM_P-10a_In-Stack_Electrochemical_Method_Voltagmetry.docx</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>TM P-10b</td>
<td>In-Stack Electrode Potentiometry</td>
<td>TM_P-10b_In-Stack_Electrochemical_Method_Potentiometry.docx</td>
</tr>
<tr>
<td></td>
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<td>TM P-10c</td>
<td>PEMFC and DMFC Stack Electrochemical Impedance Spectroscopy</td>
<td>TM_P-10c_PEMFC_and_DMFC_Electrochemical_Impedance_Spectroscopy.docx</td>
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<td>TM P-10d</td>
<td>Hydrogen Crossover in H2-PEMFC Stack</td>
<td>TM_P-10d_Hydrogen_Crossover_in_H2-PEMFC_Stack.docx</td>
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<tr>
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<td>TM P-10f</td>
<td>DMFC Anodes Polarisation Curves</td>
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</tr>
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<td>TM P-11</td>
<td>Dead End Operating Conditions</td>
<td>TM_P-11_Dead_End_Operating_Conditions.docx</td>
</tr>
</tbody>
</table>

After considering feedback from the industrial advisory board and from the workshops, the overall number of relevant Test Modules was confirmed and consecutively the Test Modules were given a final, unique designation according TM P-xy. The designation P indicates the test module primarily addresses performance. A correlation between the initial and the final numbering scheme is summarised in Table 5.

Table 5: final designation for Stack-Test WP2 Test Modules

<table>
<thead>
<tr>
<th>#</th>
<th>CURRENT number</th>
<th>current name</th>
<th>final number</th>
<th>document title</th>
<th>final name</th>
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</thead>
<tbody>
<tr>
<td>Test Module</td>
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<td></td>
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<tr>
<td>0</td>
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<td>Black Test Master Document</td>
<td>TM P-00</td>
<td>Stack-Test Master Document</td>
<td>TM_P-00_Stack-Test_Master_Document.docx</td>
</tr>
<tr>
<td>1</td>
<td>TM2.03</td>
<td>Humidity Sensitivity</td>
<td>TM P-01</td>
<td>Humidity Sensitivity</td>
<td>TM_P-01_Humidity_Sensitivity.docx</td>
</tr>
<tr>
<td>2</td>
<td>TM2.04</td>
<td>Temperature Sensitivity</td>
<td>TM P-02</td>
<td>Temperature Sensitivity</td>
<td>TM_P-02_Temperature_Sensitivity.docx</td>
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<tr>
<td>3</td>
<td>TM2.05</td>
<td>Pressure Sensitivity</td>
<td>TM P-03</td>
<td>Pressure Sensitivity</td>
<td>TM_P-03_Pressure_Sensitivity.docx</td>
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<tr>
<td>4</td>
<td>TM2.06</td>
<td>Lambda Sensitivity</td>
<td>TM P-04</td>
<td>Lambda Sensitivity</td>
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<td>5</td>
<td>TM2.07</td>
<td>Fuel/Oxidant Composition</td>
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<td>TM_P-05_Fuel_Oxidant_Composition.docx</td>
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<tr>
<td>6</td>
<td>TM2.11</td>
<td>Low Temperature Test</td>
<td>TM P-06</td>
<td>Low Temperature Test</td>
<td>TM_P-06_Low_Temperature_Test.docx</td>
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<td>7</td>
<td>TM2.12</td>
<td>Continuous Operation at Constant Load</td>
<td>TM P-07</td>
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<td>TM_P-07_Constant Operation at Constant_Load.docx</td>
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<tr>
<td>8</td>
<td>TM2.15</td>
<td>Polarisation curve</td>
<td>TM P-08</td>
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<td>9</td>
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<td>Impact of Stack Tilt</td>
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<td>Electrochemical Methods</td>
<td>TM P-10a</td>
<td>In-Stack Electrode Voltammetry</td>
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<td>TM P-10b</td>
<td>In-Stack Electrode Potentiometry</td>
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<td>TM P-10c</td>
<td>PEMFC and DMFC Stack Electrochemical Impedance Spectroscopy</td>
<td>TM_P-10c_PEMFC_and_DMFC_Electrochemical_Impedance_Spectroscopy.docx</td>
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<td>TM P-10f</td>
<td>DMFC Anodes Polarisation Curves</td>
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<td>Dead End Operating Conditions</td>
<td>TM P-11</td>
<td>Dead End Operating Conditions</td>
<td>TM_P-11_Dead_End_Operating_Conditions.docx</td>
</tr>
</tbody>
</table>

In accordance with the Test Modules, the Test Programs were consecutively renumbered at the end of the Stack-Test project to assure a non-confusing use of the TPs and all documents were checked for consistency. The renumbering process is summarised in Table 6.
The TP and TM names and numbers used in this report are adapted to the final nomenclature to assure the non-confusing use of this nomenclature within the document.

2.2.4.1 Functional / Performance Test Modules

In this section the TMs in work package 2 “Functional / Performance output testing” are discussed. The revised TM documents available after the first project period were further modified according to the results and discussions during the second project period. In this period the TMs were validated by several partners either implemented in TPs and the Round Robin Test or as isolated TMs. The realised test plan for TM validation is shown in Table 7.

<table>
<thead>
<tr>
<th>Test Module</th>
<th>Partner</th>
<th>Number of tests</th>
</tr>
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<tbody>
<tr>
<td>TM F-00 Master Document (Start-up etc.)</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>TM F-01 Humidity Sensitivity</td>
<td>TP-P-02/RR</td>
<td>-</td>
</tr>
<tr>
<td>TM F-02 Temperature Sensitivity</td>
<td>TP-P-02</td>
<td>-</td>
</tr>
<tr>
<td>TM F-03 Pressure Sensitivity</td>
<td>TP-P-02</td>
<td>-</td>
</tr>
<tr>
<td>TM F-04 Lambda Sensitivity</td>
<td>TP-P-02</td>
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<td>TM F-05 Fuel/Oxidant Composition</td>
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<td>TM F-06 Low Temperature</td>
<td>TP-P-03</td>
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</tr>
<tr>
<td>TM F-07 Continuous operation at constant load</td>
<td>TP-P-05</td>
<td>6</td>
</tr>
<tr>
<td>TM F-08 Polarisation curve</td>
<td>TP-P-02/RR</td>
<td>10</td>
</tr>
<tr>
<td>TM F-09 Stack Tilt</td>
<td>TP-P-03</td>
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<tr>
<td>TM F-10 Electrochem. Methods</td>
<td>TP-P-04</td>
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</tr>
<tr>
<td>TM F-11 Dead end operating conditions</td>
<td>TP-P-04</td>
<td>2</td>
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</table>

It was obvious during the TM validation that the parameter control is of high importance for the test procedures and the reliability of the test results. The position of the control sensor as well as the direction of parameter changes has a significant impact. Therefore, the consortium has defined the recommended positions and directions based on an intensive discussion considering result reliability, stack safety, and test duration. The result of this discussion is summarised in Table 8 and implemented in TM P-00 Stack-Test Master Document. These aspects are also pointed out in the different TMs when one or more parameters are of relevance.
2.2.4.2 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 and shut-down procedures for the stacks used in the Stack-Test project and for stacks without recommendation by the stack manufacturer are defined.

Modifications in the second project period:

- Defined document style updated
- Procedure for leak testing of stack and test bench added
- Procedure for stack break-in added
- Visualisation of procedures for stack break-in, start-up and shut-down
- Explanation for the term “nominal conditions” added
- General aspects for the measurement of polarisation curves are added
- The determination of standard and min/max deviation is explained in detail
- The importance and a recommendation for the use of a Logbook is added
- Use of Magnus equation for water vapour calculation has been checked and confirmed
- Table for application specific Test Operating Conditions (TOC) added
- The section regarding mechanical check of stack health is updated

Final document: TM_P-00_Stack-Test_Master_Document.docx

2.2.4.3 Sensitivity Testing

Sensitivity testing is intended to assess the reaction of the stack voltage at selected load points to changes in operation parameters such as humidity, temperature, pressure, and stoichiometry. Furthermore, the sensitivity to changes in reactant composition is also considered.
2.2.4.3.1 Test Module TM P-01: Humidity Sensitivity

Objectives:
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.

![Test Module P-01: Humidity Sensitivity]

**Objective and Scope**
Determine the sensitivity of a PEM fuel cell stack to the variation in relative humidity of the used reactants 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 humidity (new point recommended) and the electrical load. Due to the significant impact of humidity on stack performance, the accuracy of the gas humidity at the stack inlet has to be assured over the entire gas flow range.

<table>
<thead>
<tr>
<th>Static TIPs</th>
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<tr>
<td>Parameter</td>
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<td>Linear Temp</td>
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</tr>
<tr>
<td>Temp</td>
<td>low to high</td>
</tr>
</tbody>
</table>

**Test Outputs Parameters (TOPs)**
- Stabilization time and analysis time depend on the test objective. Recommended minimum values:
  - Stabilization 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.

**Test Procedure**
As an example, a test procedure to study the impact of the cathode dew point at constant anode dew point is presented. It is recommended to vary the electrical load on each humidification step rather than change the humidification level at constant electrical load. This accelerates the attainment of stack equilibrium and shortens the test duration, especially when bubbler systems are used for humidification.

**Critical Parameters and Parameter Controls**
- All parameters with impact on the humidity level have to be monitored and controlled with care.
- The use of humidity sensors on the stack inlet is recommended.
- Temporary changes in the cell temperature caused by the electrical load variation have to be considered to avoid electrode flooding and correct humidity levels.
- High dew points in combination with high electrical load / low stack temperature can result in electrode flooding.

**Figure 2:** One-page-abstract of Test Module P-01: Humidity Sensitivity

Final document: TM_P-01_Humidity_Sensitivity.docx
2.2.4.3.2 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.

Test Module P-02: Temperature Sensitivity

Objective and Scope
Determine the sensitivity of a PEM fuel cell stack to the variation in the stack temperature at constant relative humidity and 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 stack temperature (controlled on the coolant inlet) and the electrical load. The dew point has to be adjusted according to the stack temperature to assure constant relative humidity.

<table>
<thead>
<tr>
<th>Static TIPs</th>
<th>Variable TIPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{amb}$</td>
<td>$T_{dp}$, $P_{dp}$</td>
</tr>
<tr>
<td>$I_{nom}$</td>
<td>low to high</td>
</tr>
<tr>
<td>$P_{nom}$</td>
<td></td>
</tr>
</tbody>
</table>

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

Test Procedure
As an example, a study of the impact of stack temperature variation by 10°C is presented. It is recommended to vary the electrical load on each temperature step rather than change the temperature at constant electrical load. This approach accelerates the attainment of stack equilibrium and shortens the test duration. Furthermore, the amount of parameter changes and thermal cycling can be reduced.

Critical Parameters and Parameter Controls
- The stability of the stack temperature during the analysis time has to be assured.
- Temporary temperature changes caused by load variation have to be considered to avoid electrode flooding.
- Underdamped cooling systems can result in excessive stack heating and stack damage at high electrical load.
- The stack temperature has to be increased prior to the increase of the dew points.
- High dew points combined with high electrical load / low stack temperature can result in electrode flooding.

Contact Stack-Test: Stacktest.fch-louv.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 number 303445.

Final document: TM_P-02_Temperature_Sensitivity.docx
2.2.4.3.3 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.

Test Module P-03: Pressure Sensitivity

Objective and Scope
Determine the sensitivity of a PEM fuel cell stack to the variation in the reactant pressure on anode and/or 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 pressure on the anode and/or the cathode (controlled on the stack outlet) as well as the electrical load.

<table>
<thead>
<tr>
<th>Static TIPs</th>
<th>Variable TIPs</th>
<th>Function of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1, U2</td>
<td>P, DP</td>
<td>High to Low</td>
</tr>
<tr>
<td>CS, FS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test Output Parameters (TOPs)
- 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.

Test Procedure
As an example, a simultaneous investigation of the reactant pressure variation on both electrode sides is presented. It is recommended to vary the electrical load on each pressure step rather than vice versa. This approach accelerates the attainment of stack equilibrium and shortens the test duration.

In general, the pressure variation in descending direction and with least possible variations on the cathode side is preferred.

Critical Parameters and Parameter Controls
- The stability of the reactant pressure during the analysis time has to be assured.
- Pressure variation in descending direction is preferred.
- Pressure variation on the cathode should be minimised.
- Observation of the maximal differential pressure has to be assured (especially on the stack inlet).
- High dew points combined with high electrical load / low gas pressure can result in electrode flooding.
- Correctness of dew points on stack inlet has to be assured.

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.zwe-low.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.

Final document: TM_P-03_Pressure_Sensitivity.docx
2.2.4.3.4 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.

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.

<table>
<thead>
<tr>
<th>Scale TIPs</th>
<th>Variable TIPs</th>
<th>Direction of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>High, Low</td>
<td>Lambda, P</td>
<td>High to low</td>
</tr>
<tr>
<td>Low, High</td>
<td>Lambda, P</td>
<td>Low to high</td>
</tr>
</tbody>
</table>

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 lambda 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 maximum 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.

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@uni-hb.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.

Final document: TM_P-04_Lambda_Sensitivity.docx
2.2.4.3.5 Summary of operating parameter sensitivity testing

The four parameter sensitivity TMs are prepared in a consistent manner and consider the mentioned sensor position and the recommended direction for the variation of the test parameters. Consequently, the test is realised starting with the most stable conditions, for lambda sensitivities this approach results in a measurement from high to low stoichiometric values. Furthermore, the procedure for simultaneous examination of the parameter impact at both electrodes is described. The demonstration of the final test procedure and an example for the experimental validation is shown in Figure 3.

![Figure 3: scheme for variation of variable test input parameters (left) and test profile visualisation (right) for lambda sensitivity](image)

The output of these TMs is the visualisation of the sensitivity of a test object to the examined parameter for different electrical load levels as presented in Figure 4.
Figure 4: test result presentation including error bars for min/max deviation
2.2.4.3.6 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.
This procedure might cause permanent damage to the stack under investigation for example caused by irreversible adsorption of contaminants to the catalyst or the electrolyte. It is mandatory to have a suitable stack recovery procedure available in order to condition the stack between the test points.

This procedure includes the use of pure reactants without impurities and the use of a high electric load to assure the oxidation of catalyst poisons like CO. The test profile of a sensitivity test of a stack to CO concentration in the fuel feed is demonstrated in Figure 5.

![Figure 5: example for the CO tolerance test in TM P-05](image-url)

### 2.2.4.4 Test addressing the stack operational behaviour

PEM fuel cell stacks are operated under a variety of external conditions which can influence performance and endurance. This set of test modules addresses common conditions such as external temperature, stack tilt as well as operation under constant load. Furthermore, a test module describing the recording of a polarization curve is given. The polarization curve is one of the key tests addressing stack performance under a set of fixed operating conditions. The evolution of the polarization curve with time is a widely used method to assess stack degradation.
2.2.4.4.1 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.

Test Module P-06: Low Temperature Test

Objective and Scope
The target of this Test Module 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.

Test Input Parameter (TIP)
Depending on the aim of test (approach A or B) the stack has to be out of operation or in operation. The ambient test temperature has to be constant before starting test procedure.

In approach A in particular the coolant flow rate and the environmental test temperature are varied to analyse the response time to reach 50% and 100% of nominal power.

In approach B, the influence of the coolant temperature difference across the stack and of the environmental temperature on the stack performance will be analysed.

Test Procedure
To prepare the fuel cell stack for low ambient temperature test an operation at nominal conditions and a shut-down procedure have to be done. A climate chamber is needed for the validation of this Test Module.

In approach A, the stack has to be flushed with nitrogen before cooling to avoid water condensation inside the stack. After thermal equilibration it is recommended to characterise the time till 50% and 100% of electrical stack output power at nominal conditions will be reached at the tested environment.

In approach B the stack behaviour will be analysed during operation and is influenced by the TIP.

Critical Parameters and Parameter Controls
- Thermal equilibration between climate chamber and fuel cell stack
- Measured stack temperature during test phase
- Control coolant flow rate
- Control pressure adjustment

Test Output Parameter (TOP)

<table>
<thead>
<tr>
<th>Approach A</th>
<th>Approach B</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOPs</td>
<td>Type</td>
</tr>
<tr>
<td>$T_{in}$</td>
<td>measured</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>measured</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>measured</td>
</tr>
<tr>
<td>$U_{out}$</td>
<td>measured</td>
</tr>
</tbody>
</table>

- Approach A: time to reach 50% and 100% of nominal rated power (and corresponding stack temperature)
- Approach B: stack performance, minimum cell voltage and required coolant flow depending on the TIPs

Data Post Processing
It is recommended to present the test profile and the test results as shown below.

Contact Stack-Test:
Stacktest.zaw-low.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.
The procedure for both approaches, the stack start-up and the stack operation at low ambient temperature, were revised and the workflow is visualised in the final document. In contrast to the other TMs, it was obvious during the TM P-06 validation that the cooling system has a significant impact on the test results. Consequently, the tests for comparative studies are defined to use the same cooling system and different fuel cell stacks.

![Workflow and test profile](image)

**Figure 6:** workflow (left) and scheme for the test profile (right) of approach A in TM P-06

The acquired procedure for approach A “stack start-up at low ambient temperature” is presented in Figure 6 as an example. The defined workflow clearly describes the different test phases including stack operation, shut-down, cool-down, restart, and determination of the main output, the response time to 50 % ($t_{50\%}$) and 100 % ($t_{100\%}$) of the nominal rated power. These parameters can be determined by the use of TM P-06 for different set points of the ambient temperature and the coolant flow rate by the use of a predefined Test Point Matrix. An example for the resulting test profile of such a test is shown on the right hand side of Figure 6.
2.2.4.4.2 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.

Test Module P-07: Continuous Operation at Constant Load

Objective and Scope

Determine the short-term or the long-term steady-state behaviour of a fuel cell stack at different test operating conditions (TDCs). The TDCs can differ in more than one parameter and the different parameters can be varied simultaneously.

Test Input Parameters (TIPs)

The stack operates under different TDCs and these are characterised by a set of all TIPs. Consequently, various parameters can be varied simultaneously depending on the test objective.

Test Output Parameters (TOPs)

- Stabilization time and analysis time depend on the test objective. Recommended minimum values:
  - Stabilization time: 20 minutes
  - Analysis time: 10 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.

Test Procedure

There are two phases during this test procedure: the nominal phase and the test phase. After each test phase, the stack can be operated under nominal conditions as an option. The stack voltage in this nominal phase can be used to check the stability of the stack operation. Additionally, the voltage stability during the different test phases has to be assured.

Critical Parameters and Parameter Controls

- Increase of gas flows prior to increase load.
- Decrease of load prior to decrease of gas flows.
- Avoid reactant starvation during ascending pressure variation.
- Risk of electrode flooding by the combination of high dew point, high load and/or low stack humidity.
- More details are given in the Master Document (TM P-00) and in the stack sensitivity documents (TM P-01 – P-04).

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 807445.

Contact Stack-Test:
Stacktest@rwz-bw.de

Final document: TM_P-07_Continuous_Operation_at_Constant_Load.docx
2.2.4.3 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.

Test Module P-08: Polarisation Curve

---

**Test Module P-08: Polarisation Curve**

**Objective and Scope**

Polarisation curves are the most common way to characterise fuel cell stack performance over a wide range of electrical power. The resultant stack voltages are determined stepwise as a function of the stack current.

**Test Input Parameters (TIPs)**

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

<table>
<thead>
<tr>
<th>Static TIPs</th>
<th>Variable TIPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Volt</td>
<td>TOCx</td>
</tr>
<tr>
<td>Fixed</td>
<td>Low → High</td>
</tr>
</tbody>
</table>

**Test Procedure**

After optional preconditioning the stack is operated under load before the test. The direction of load change has to be defined previously to get reproducible results. Thereby, "High → Low → High" is recommended. First the current is increased to the maximum specified by the stack manufacturer then decreased stepwise to OCV (or a minimum) followed by increasing it to the maximum. The step dwell time depends on the stability of the cell voltages and should be determined and set depending on the test object. The recommended step dwell time is 5 minutes and 2 minutes for low load set points to avoid excessive stack deterioration caused by over stoichiometric reactant flow. A stability criterion of ±5 mV based on the average cell voltage is used. The result is a polarisation curve with a descending and ascending part. A step dwell time-dependent hysteresis effect is usually observed due to different stack conditioning states at each load step of the descending and ascending parts of the polarisation curve.

**Critical Parameters and Parameter Controls**

- Test operating conditions (TOCs), step dwell time, load set points and the direction of load variation have to be defined for comparable studies.
- A minimum reactant flow should be defined for comparable stoichiometry and humidity levels in the part of the polarisation curve dominated by activation losses.
- All operating parameters have to be held constant, monitored and recorded.

---

Contact Stack-Test: Stacktest.rw-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° 838445.

Final document: TM_P-08_Polarisation_Curve.docx
The Test Point Matrix for polarisation curves was modified in the second project period and separated in two phases. The first phase is characterised by a stoichiometric reactant flow between 20 and 100 % of the maximum stack current. In this phase, the stabilisation time is defined to 3 minutes and the analysis time to 2 minutes (resulting dwell time is 5 minutes). The second phase is characterised by an over-stoichiometric reactant flow below 20 % of the maximum stack current due to the limitation of the minimum reactant flow. The test points in this second phase have to be handled with care to minimise stack performance deterioration and stack dry-out. The stabilisation and analysis times are shortened to 1 minute each (resulting dwell time is 2 minutes). As a result of the shortened test point duration the overall test duration could be minimised for faster stack characterisation in industry. The procedure can be completed within 74 minutes using the mandatory test points and within 118 minutes using all test points.

The new defined Test Point Matrix including mandatory and optional test points is shown in Table 9.

Table 9: recommended Test Point Matrix

<table>
<thead>
<tr>
<th>test point</th>
<th>% of maximum current density</th>
<th>dwell time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 *</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>2 *</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>3 *</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>5 *</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>7 *</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>10 *</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>12 *</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>13 *</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>14 *</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>15 *</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>16 *</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>17 *</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>18 *</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>20 *</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>21</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>22</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>23 *</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>25 *</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>26</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>27 *</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>28 *</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>29 *</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>

The test profile used during the second validation phase and the test results in form of the polarisation curve are shown in Figure 7.
Figure 7: Test profile (left) and test results (right) for polarisation curve measurements in the second validation phase.
2.2.4.4 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

After the modification of the objective of this TM from ambient conditions to stack tilt in the first project phase, the description of the stack performance test depending on the applied stack tilt was revised in the second phase. The final document includes definitions of the rotation axis and of the directions for positive and negative stack tilt. The
procedure is prepared in accordance with the other sensitivity TMs. An example for the test result presentation including the visualisation of the applied stack tilt is shown in Figure 8.

Figure 8: stack performance characterisation towards stack tilt in TM P-09

2.2.4.5 Diagnostic Tests
Diagnostic tests are used to assess the stack and cell state of health. They are giving a more in depth insight into the performance of electrodes and membranes. Voltammetry, coulometry, and impedance spectroscopy are used to investigate electrode behaviour while the electrochemical determination of hydrogen crossover is used as a method to study the membrane state of health.

Among the diagnostic test modules, tests using methanol as a fuel were addressed as well. Furthermore, a test module to assess the stack behaviour under conditions of dead-end-operation has been defined.
2.2.4.6 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.

Test Module P-10a: Voltammetry

Objective and Scope

Information from voltammetry about the catalysts includes:
- the electrochemically active surface area (ECSA),
- the surface chemistry, and
- the nature and the degree of contamination.
Voltammetry can also detect and quantify minor electrical shorting in the stack MEAs. Simple electrodes voltammetry and stripping voltammetry (CO and methanol) are described.

Test Setup

A precision potentiostat, preferably a four-wire, and low-resistance connectors to bipolar plates are required.

Test Input Parameters (TIPs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Value/Range</th>
<th>Measurement uncertainty</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opn. Pot.</td>
<td>0–200 mV</td>
<td>≤5%</td>
<td>–</td>
</tr>
<tr>
<td>Te.</td>
<td>20–30°C</td>
<td>≤5%</td>
<td>–</td>
</tr>
<tr>
<td>Re.</td>
<td>0.010–0.050 V/mΩ</td>
<td>≤5%</td>
<td>–</td>
</tr>
<tr>
<td>Step</td>
<td>100–800 mV/min</td>
<td>≤5%</td>
<td>–</td>
</tr>
<tr>
<td>Step</td>
<td>10 s/min</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Amplitude</td>
<td>10–180 mV/min</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Rate</td>
<td>10–120 mV/min</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Time</td>
<td>15–48 min</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Test Procedure

During data recording, the studied and the counter sides of the stack are provided with H2 and O2, respectively. In stripping voltammetry, this is preceded by a CO or methanol adsorption step under controlled studied side potential. The studied side potential is swept at a constant scan rate and the result is a dynamic current-potential characteristic.

Critical Parameters

Care to completely fill the studied side with inert gas is important for the current-potential curve recording step. Cu should be selected not excessively corrosive to the catalyst. Cu should not be too low to avoid intense H2 evolution. In stripping voltammetry, adsorption must be driven to completion, and then care is needed to avoid accidental introduction of oxygen over the studied side during adsorbent flushing with the inert medium.

Main Test Output Parameters (TOPs)

<table>
<thead>
<tr>
<th>Output</th>
<th>Parameter type</th>
<th>Measurement uncertainty</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECSA</td>
<td>secondary</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>QO2</td>
<td>secondary</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>QH2</td>
<td>secondary</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>QM</td>
<td>secondary</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Data Post Processing

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 303443.

Final document: TM_P-10a_Electrochemical_Method_Voltemmetry.docx
Test Module P-10b: Potentiometry

Objective and Scope

This method is useful for fast determining of the catalysts’ electrochemically active surface areas (ECSAs) in the electrodes of a PEMFC stack.

Test Setup

A precision galvanostat and a sufficiently fast cell voltage monitoring (CVM) system are required.

Test Input Parameters (TIPs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Value/Range</th>
<th>Uncertainty</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECc</td>
<td>3.0–5.5 V</td>
<td>±0.1 mV</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>ECv</td>
<td>1.0–1.5 V</td>
<td>±0.1 mV</td>
<td>–</td>
</tr>
<tr>
<td>Ecn</td>
<td>1.0–5.5 V</td>
<td>±0.1 mV</td>
<td>–</td>
</tr>
<tr>
<td>i</td>
<td>0.1–100 mA</td>
<td>5%</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Pu</td>
<td>10–200 mV</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Freq</td>
<td>10–200 mHz</td>
<td>±5%</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Temp</td>
<td>20–50°C</td>
<td>±2°C</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Me VA</td>
<td>1.0–100 mV</td>
<td>±5%</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Me VA</td>
<td>1.0–100 mV</td>
<td>±5%</td>
<td>1000 Hz</td>
</tr>
</tbody>
</table>

Test Procedure

The counter side of the stack is supplied with H2 preferably diluted with N2. The studied side is supplied with air. Then, air on the studied side is replaced with H2, and as soon as any cell voltage falls below Ec, constant current density i is imposed through the stack such that reduction occurs on the studied side. Cells voltages are recorded over time using the CVM system.

Critical Parameters

H2 crossover introduces a negative systematic error to the resulting ECSAs. Minimizing the influence of crossover by choosing low ECv, low, and high Pu but high i and Pe, and Pe is helpful. In practice, the method needs to be calibrated against voltammetry (see TM 2.188) to obtain reliable results.

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

The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant no. 306445.

Final document: TM_P-10b_Electrochemical_Method_Potentiometry.docx
Test Module P-10c: Impedance Spectroscopy

Objective and Scope
Electrochemical impedance spectroscopy (EIS) can provide quantitative information on the sources of the stack polarization and their distribution among the cells/electrodes in the stack. Example polarization 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 polarization setup, preferably one capable of voltage reversal, drives a constant load through the stack. An AC generator supplies a current sourced over the constant load. An AC analyzer measures the AC current (over a short resistor) and the AC-voltage response of a cell in the stack.

Test Input Parameters (TIPs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Value/Range</th>
<th>Measurement Uncertainty</th>
<th>Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Em</td>
<td>0.05</td>
<td>1000 mV to 1000 mV</td>
<td>± 1%</td>
</tr>
<tr>
<td>DoF</td>
<td>0.10</td>
<td>150 mV to 150 mV</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>f</td>
<td>0.10</td>
<td>1 Hz to 10 Hz</td>
<td>± 1%</td>
</tr>
<tr>
<td>Re</td>
<td>0.10</td>
<td>1 mS to 1 mS</td>
<td>± 1%</td>
</tr>
<tr>
<td>C0</td>
<td>0.10</td>
<td>1 F to 100 F</td>
<td>± 1%</td>
</tr>
</tbody>
</table>

Test Procedure
The stack is operated in either the fuel-oxidant or the fuel-H2 mode under a constant DC load. The EIS spectra are obtained by superimposing AC current perturbations of different frequencies over the constant load. The EIS spectrum in the fuel-H2 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 EG measurement is the stability of the system under load during the spectrum acquisition. Application of EG to stacks of a large cross-sectional area requires special care with regard to cabling. All cables have to be of good quality and lie in a fixed position during the measurements to be able to correct the measured spectra for the cabling impedance.

Data Post Processing
The spectra are interpreted using an impedance model. This model allows the extraction of the various polarization sources.

Contact Stack-Test: Stacktest.rivw.bv.de

Final document: TM_P-10c_Electrochemical_Method_Impedance_Spectroscopy.docx
Test Module P-10d: Hydrogen Crossover

Objective and Scope
This method involves permeometry to determine the permeability of the H2-PMEC 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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Range</th>
<th>Measurement uncertainty</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP</td>
<td>120°C</td>
<td>5%</td>
<td>2.0 Hz</td>
</tr>
<tr>
<td>EMF, EM</td>
<td>0.350 V</td>
<td>1%</td>
<td>50 Hz</td>
</tr>
<tr>
<td>EM, EM</td>
<td>0.350 V</td>
<td>1%</td>
<td>50 Hz</td>
</tr>
<tr>
<td>EM</td>
<td>25°C</td>
<td>1%</td>
<td>2.0 Hz</td>
</tr>
<tr>
<td>EM</td>
<td>1 - 10 mmHg</td>
<td>1%</td>
<td>2.0 Hz</td>
</tr>
</tbody>
</table>

Test Procedure
The anode side of the stack is supplied with H2 in a way corresponding to the nominal operating conditions of the stack. The cathode side is supplied with fully humidified H2. The cathode-side potential of each cell is raised to a constant value assuring complete oxidation of H2 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 H2 crossover current is sensitive to the H2 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.

Data Post Processing
A straight line is fit to the H2 crossover currents established for three cathode-side potential values. The Y-intercept of the line for zero cathode-side potential is the electrode-short-corrected H2 crossover current. The reciprocal of the slope of the line gives the resistance of the electronic short.

The H2 crossover currents are converted to H2-partial pressure-differential-normalised fluxes of H2, which can be used “as is” for comparisons of H2 permeability among cells and at different stages of stack life.

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

The research leading to these results has received funding from the European Union’s Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative, under grant agreement no. 803445.

Final document: TM_P-10d_Electrochemical_Method_Hydrogen_crossover.docx
Test Module P-10e: Methanol Crossover

Objective and Scope
This test module describes a method for quite accurate determination of methanol crossover rates in the cells of a DMFC stack. The method relies on electrochemical measurements and on a calculation.

Test Setup
A DC polarization setup capable of reversing the voltage is attached to one cell in the stack at a time. The current-carrying leads must be firmly attached to the individual cell.

Test Input Parameters (TIPs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Value/Range</th>
<th>Measurement uncertainty</th>
<th>Sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_meth</td>
<td>0.100 – 24.55 M (25°C)</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>D_meth</td>
<td>0.0003 – 0.0013</td>
<td>±5%</td>
<td>0.02 s^-1</td>
</tr>
<tr>
<td>P_meth</td>
<td>0 – 3001 Pa</td>
<td>±5%</td>
<td>1.02 Hz</td>
</tr>
<tr>
<td>T</td>
<td>20 – 30°C</td>
<td>±5°C</td>
<td>1.02 Hz</td>
</tr>
<tr>
<td>T</td>
<td>From DME to CO2</td>
<td>±5°C</td>
<td>1.02 Hz</td>
</tr>
<tr>
<td>M</td>
<td>0.000 – 0.005</td>
<td>±5%</td>
<td>±0.2 Hz</td>
</tr>
<tr>
<td>L_CO2</td>
<td>0.1 – 1.0 kPa</td>
<td>±5%</td>
<td>±0.2 Hz</td>
</tr>
<tr>
<td>F</td>
<td>1 – 15 kPa</td>
<td>±5%</td>
<td>±0.2 Hz</td>
</tr>
<tr>
<td>a</td>
<td>0.002 – 0.01</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>t</td>
<td>30 – 180 s</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Test Procedure
The anode side of the DMFC stack is supplied with methanol and the cathode side with CO2. The potential of the cathode of the measured cell is raised stepwise relative to the potential of the anode. Methanol permeates from the anode to the cathode, where it is oxidized to CO2. The oxidation current is recorded, while stepping up the cell voltage, until the current rises no more.

Critical Parameters
Methanol crossover strongly depends on the stack temperature, the pressure differential across the MEA, and the concentration of methanol. It is therefore essential to keep these parameters under good control during the experiment.

Test Output Parameters (TOPs)

Data Post Processing

\[
I_{\text{max}} = \frac{1}{1 + 0.5 \cdot \tau \cdot \tau \cdot \frac{1}{t}}
\]

where

\[
I_{\text{max}} = \frac{1}{1 + 0.5 \cdot \tau \cdot \tau \cdot \frac{1}{t}}
\]

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

Final document: TM_P-10e_Electrochemical_Method_Methanol_crossover.docx
Test Module P-10f: DMFC Anodes Polarisation

Objective and Scope
Anode's polarization curves in a DMFC stack provide information on the kinetics and the transport performance of the methanol anodes in the stack.

Test Setup
A DC polarization setup capable of voltage reversal is required to drive methanol oxidation at the anode of a DMFC cell when the cathode of the cell is supplied with H2. An AC generator/analyzer is used to determine the internal resistance of the cell. The current-carrying leads must be firmly attached to the individual cell in the stack to be able to carry the full DMFC current.

Test Input Parameters (TIPs)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Range</th>
<th>Measurement Uncertainty</th>
<th>Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>200 - 2043 mA (21°C)</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>f_H2</td>
<td>100 Hz – 20 kHz</td>
<td>±5%</td>
<td>0.02 Hz</td>
</tr>
<tr>
<td>f_Farad</td>
<td>100 Hz – 20 kHz</td>
<td>±5%</td>
<td>0.02 Hz</td>
</tr>
<tr>
<td>i_Farad</td>
<td>i_Farad [iA]</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>i_O2</td>
<td>i_O2 [mA]</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>i_H2</td>
<td>i_H2 [mA]</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>i_Anomal</td>
<td>i_Anomal [mA]</td>
<td>±5%</td>
<td>–</td>
</tr>
<tr>
<td>i_Farad</td>
<td>i_Farad [mA]</td>
<td>±5%</td>
<td>–</td>
</tr>
</tbody>
</table>

Test Procedure
Methanol fuel is supplied to the anode side, and H2 is supplied to the cathode side of the stack. The cell voltage is stepped down from a high value to a low value, and the current flowing through the selected stack cell is recorded. Steady-state currents are determined and internal resistances are measured at every voltage step at steady state using the AC impedance method.

Critical Parameters
It is important to keep the cathode potential steady during the experiment. This is done by supplying ample humidified H2 to the cathode and by slightly increasing the pressure of the H2 from the ambient level.

Test Output Parameters (TOPs)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
<th>Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uref</td>
<td>primary</td>
<td>20.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Uref</td>
<td>secondary</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Uref</td>
<td>tertiary</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Uref</td>
<td>supplementary</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Data Post Processing
Uref is a measure of the kinetic performance of the anode. It offers information about the methanol transport performance.

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

Final document: TM_P-10f_Electrochemical_Method_DMFC_Anode_Polarisation.docx
2.2.4.6.1 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.

Test Module P-11: Dead End Operating Conditions

Objective and Scope
Determine the stack behaviour for a given load in dead end mode on the anode side. This behaviour is influenced by the purge time \( t_p \), the purge interval time \( t_i \) and the opening percentage of the needle valve \( Y_{valve} \) as well as the anodic gas recirculation \( M_{recirc} \). These parameters are varied in the test while other parameters are kept constant.

Test Input Parameters (TIPs)
The stack will operate under constant test operating conditions including recirculation rate while the impact of the purge parameters is being determined. When the impact of the recirculation rate is being determined, the use of a Test Program is recommended.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Controlled TIPs</th>
<th>Measured and Calculated TIPs</th>
<th>Direction of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_p )</td>
<td>high to low</td>
<td>high to low</td>
<td>high to low</td>
</tr>
<tr>
<td>( t_i )</td>
<td>low to high</td>
<td>low to high</td>
<td>high to low</td>
</tr>
</tbody>
</table>

Test Procedure
In contrast to other Test Modules, the variable TIPs cannot be controlled directly and pre-tests are needed to calculate the controlled TIPs. The net stoichiometric fuel volume is defined, but has to be transformed to the purge valve opening time for the different combinations of purge interval time and opening percentage of the needle valve. The measurement of the fuel loop volume is also recommended for a reliable test result interpretation.

As an example, the determination of the purge parameter impact on the stack performance is presented.

Critical Parameters and Parameter Controls
- Fast response time of the MFM (ms-range) needed and oscilloscope recommended (increase sampling rate).
- Due to the impact of the equipment on the result, the use of the same equipment in the anodic loop (purge valve, pressure regulator and the volume of the anodic loop) is strongly recommended for comparable studies.
- Measurement of fuel loop volume recommended for reliable result interpretation.
- The Test Point Matrix has to be ordered from low to high risk of anode flooding.
- The fuel pressure in the dead end mode is controlled at the stack inlet by the use of a pressure regulator.

Test Output Parameters (TOPs)
The most relevant TOPs are the stack fuel electrical efficiency and the average cell voltage. Additional TOPs like single cell voltages and electrical stack output power can be used additionally.

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@fch-lux.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.
The description for the additional setup for dead end and recirculation measurements was set up with respect to functionality and safety. A safety device upstream of the pressure regulator is recommended to limit the maximum possible continuous hydrogen flow and minimise the risk of hydrogen release in case of a problem of anode loop integrity. Additionally, a water trap is added to the recirculation setup for removal of liquid water from the anodic loop. For these measurements is also pointed out that the positioning of the mass flow meter (MFM) upstream to the pressure regulator is advantageous for lifetime (avoidance of humidity) and signal stability of the MFM. The updated recommendation for the test setup is shown in Figure 9.

Figure 9: required additional equipment for fuel supply and anodic purging in (a) dead end mode and (b) recirculation mode

The stack fuel electrical efficiency was added to the TOPs in the final document and an equation is presented for calculation of this efficiency based on the determined parameter in the test. By the use of this parameter, the impact of the net fuel stoichiometric coefficient on the performance can be determined as demonstrated in Figure 10.

Figure 10: test results represented by stack voltage (left) and by stack fuel electrical efficiency (right)
2.2.4.7 Functional/Performance Test Programs

In the following section the Test Programs (TP) defined in work package 2 “Functional / Performance output testing” are discussed. Test programs are built from test modules and arranged in a sequence to address more complex test tasks. The test programs defined in this project are intended to be examples how to use individual test modules to assess and optimize stack performance. Users are free to define further test programs to address their specific needs. The test plan for TP validation is shown in Table 10.

Table 10: test plan for TP validation

<table>
<thead>
<tr>
<th>#</th>
<th>Test Program</th>
<th>ZSW</th>
<th>CEA</th>
<th>DTU</th>
<th>DLR</th>
<th>ICRI</th>
<th>AAU</th>
<th>NEXT-E</th>
<th>CIDETEC</th>
<th>Fraunhofer</th>
<th>IET</th>
<th>SFC</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP P-01</td>
<td>Stack performance assessment</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>TP P-02</td>
<td>Stack performance mapping</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>TP P-03</td>
<td>Deviant performance</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>TP P-04</td>
<td>Dead end performance</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>TP P-05</td>
<td>Stack performance optimization</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
</tbody>
</table>

In the following, the modifications of each Test Program document during the second project period are described in detail. Also for the TPs, some examples for the acquired test procedures are given.
2.2.4.7.1 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.

Test Program P-01: Stack Performance Assessment

Objective

This test program 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.

Implemented TMs

- P-09 – Stack-Test Master Document
- P-07 – Continuous Operation at Constant Load
- P-10a – In-stack Electrode Voltammetry
- P-10c – H2-PEMFC and DMFC Stack Electrochemical Impedance Spectroscopy
- P-10d – Hydrogen Crossover
- P-10e – Methanol Crossover
- P-10f – DMFC Anodes Polarisation Curves

Workflow

- ELECTRODE VOLTMETRY (TM P-09)
- START-UP (Provider's recommendations or TM P-09)
- CONTINUOUS OPERATION AT CONSTANT LOAD (TM P-07)
- EIS IN FUEL/OXIDANT MODE (TM P-10c)
- BEST POLARIZATION CURVE (TM P-10d)
- EIS IN FUEL/OXIDANT MODE (TM P-10c)
- ANODE POLARIZATION (TM P-10d)
- FUEL CROSSOVER (TM P-10d or P-10e)
- SHUT-DOWN (almodified TM P-09)

DMFC only

Assumed test duration

Depending on the type of the available equipment (single-channel or multi-channel), this program may take from one up to three testing days.

Test Program Output

- Constant-load cells' performance and stability records
- Best polarisation curve
- Electrochemical methods outputs

Contact Stack-Test: Stacktest.zsw-bvg.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° 804445.

Final document: TP_P-01_Stack_Performance_Assessment.docx
2.2.4.7.2 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.

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-06 Stack-Test Master Document
- P-01 Humidity Sensitivity
- P-03 Temperature Sensitivity
- P-03 Pressure Sensitivity
- P-04 Lambda Sensitivity
- P-08 Polarisation Curve
- P-16a-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.fch-liv.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.
An example for the procedure defined in TP P-02 is given in Figure 11. This TP summarises measurements regarding stack sensitivity to different parameters and includes a characterisation of the performance before (BoT) and after (EoT) the realised test procedure. The final versions of the TM documents were used for the validation of this TP.

Figure 11: overall test profile during TP P-02

The results for the stack sensitivity to temperature and oxidant humidity are shown in Figure 12 to demonstrate the outputs of this Test Program.

Figure 12: stack sensitivity test results for stack temperature (left) and oxidant humidity (right)
2.2.4.7.3 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.

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.

Implemented TMs

- 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.

Contact Stack-Test: Stacktest.aww-lbw.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.

Final document: TP_P-03_Deviant_Stack_Performance.docx
2.2.4.7.4 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.

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.

Final document: TP_P-04_Dead_End_Performance.docx
The final document for TP P-04 was adapted to the modification in TM P-11 and the procedure was refined regarding additional conditioning phases. For measurements at different load levels the adaption of the purge interval time is demonstrated to assure comparable water management during the different test points. An example for use of the defined procedure is given in Figure 13. The procedure was realised for different set points of the pressure in the anodic loop and the purge parameters were varied. For the assessment of the test outputs, the impact of the parameters on the stack voltage and on the stack fuel electrical efficiency is presented.

Figure 13: stack voltage and stack fuel electrical efficiency for TP P-04 tests at different fuel loop pressure
2.2.4.7.5 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.
The Test Output Parameter (TOP) for performance optimisation is defined more flexible in the final document of TP P-05. Beside the stack voltage, the new stack efficiency defined in the Stack-Test project as well as combination functions of several parameters can be used.

Figure 14: optimisation of the stack efficiency at 0.25 A / cm² (24 A) using a ZSW stack

As a result the examined stack can be optimised regarding stack voltage, stack efficiency, and single cell homogeneity in a simultaneous optimisation process. The optimisation of the stack efficiency at 0.25 A / cm² is shown in Figure 14. The algorithm defined in the Test Program “Performance Optimization” has been successfully implemented in an automated script.

The optimisation process was validated for different electrical load levels with respect to the optimisation of the stack voltage and the results are summarised in Table 11.
Table 11: optimised parameters for high stack voltage and efficiency

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>best parameter</th>
<th>average parameter</th>
<th>best parameter</th>
<th>average parameter</th>
<th>best parameter</th>
<th>average parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{stack}}$</td>
<td>[°C]</td>
<td>77.6</td>
<td>74.5</td>
<td>78.8</td>
<td>81.6</td>
<td>90</td>
<td>84.5</td>
</tr>
<tr>
<td>$\lambda_{\text{fuel}}$</td>
<td>[-]</td>
<td>1.37</td>
<td>1.42</td>
<td>1.58</td>
<td>1.84</td>
<td>2.41</td>
<td>2.23</td>
</tr>
<tr>
<td>$\lambda_{\text{ox}}$</td>
<td>[-]</td>
<td>4</td>
<td>3.9</td>
<td>3.93</td>
<td>3.64</td>
<td>3.63</td>
<td>3.57</td>
</tr>
<tr>
<td>RH$_{\text{fuel}}$</td>
<td>[%]</td>
<td>79.9</td>
<td>77.1</td>
<td>80.8</td>
<td>80.5</td>
<td>17</td>
<td>39.2</td>
</tr>
<tr>
<td>RH$_{\text{ox}}$</td>
<td>[%]</td>
<td>70.2</td>
<td>68.4</td>
<td>68.9</td>
<td>80.5</td>
<td>65.7</td>
<td>78.7</td>
</tr>
<tr>
<td>$p_{\text{fuel}}$</td>
<td>[kPa abs]</td>
<td>293</td>
<td>293.2</td>
<td>300</td>
<td>295</td>
<td>300</td>
<td>290.3</td>
</tr>
<tr>
<td>$p_{\text{ox}}$</td>
<td>[kPa abs]</td>
<td>260</td>
<td>290</td>
<td>300</td>
<td>299</td>
<td>300</td>
<td>291.9</td>
</tr>
<tr>
<td>$U_{\text{stack}}$</td>
<td>[V]</td>
<td>8.266</td>
<td>8.226</td>
<td>7.889</td>
<td>7.854</td>
<td>7.42</td>
<td>7.383</td>
</tr>
</tbody>
</table>

The optimisation for the stack voltage always results in very high reactant pressures and oxidant stoichiometry that are close to the specified maxima. It is well known that these parameters, especially the oxidant pressure and stoichiometry, highly affect the stack voltage, but the improvement can be counterproductive in a system due to the massive increase of the power demand for the compressor. In contrast, the new defined stack efficiency results in parameters well applicable for a system.

The results also demonstrate that the algorithm can significantly improve the stack voltage as well as the efficiency. Table 12 summarises improvements regarding these parameters during the optimisation process. It is obvious that the optimisation potential for the examined stack increases with increasing electrical stack load.

Table 12: optimised test output parameters for the realised tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>nominal conditions</th>
<th>optimized (average)</th>
<th>nominal conditions</th>
<th>optimized (average)</th>
<th>nominal conditions</th>
<th>optimized (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement</td>
<td>[V]</td>
<td>0.556</td>
<td>0.618</td>
<td>0.556</td>
<td>0.618</td>
<td>0.556</td>
<td>0.618</td>
</tr>
<tr>
<td>Improvement</td>
<td>[%]</td>
<td>7.2</td>
<td>8.5</td>
<td>7.2</td>
<td>8.5</td>
<td>7.2</td>
<td>8.5</td>
</tr>
<tr>
<td>$\eta^*_{\text{stack}}$</td>
<td>[%]</td>
<td>49.53</td>
<td>50.47</td>
<td>45.77</td>
<td>47.31</td>
<td>40.97</td>
<td>43.28</td>
</tr>
<tr>
<td>Improvement</td>
<td>[$\eta^*_{\text{stack}}$]</td>
<td>0.94</td>
<td>1.54</td>
<td>0.94</td>
<td>1.54</td>
<td>0.94</td>
<td>1.54</td>
</tr>
<tr>
<td>Improvement</td>
<td>[%]</td>
<td>1.9</td>
<td>3.4</td>
<td>1.9</td>
<td>3.4</td>
<td>1.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

2.2.4.8 Conclusion for Work Package “Functional / Performance Testing"
The documents for the description of the Test Module and Test Program procedures after the first project phase were validated and revised in a two stage process.
All documents are prepared consistently and renumbered consecutively including the letter “P” for procedures with relevance to functional and performance testing (“D” for durability and endurance testing; “S” for safety and environmental testing). The results and the document structures were discussed with OEMs (including the industrial advisory board of Stack-Test) and SDOs. The feedback from the different organisations was taken into account during the revision phase and the procedures were modified to assure their correctness and applicability in industry.

In summary, the following documents were prepared in WP 2:

- Stack-Test Master Document (general aspects and definitions)
- 11 Test Modules
- 5 Test Programs

It should be mentioned that the defined Test Programs are examples for possible programs. Additional Test Programs can be defined by the end user based on the combination of several Test Modules depending on the application and the test objective.

### 2.2.5 Work Package 3

In work package 3, focusing on durability testing of stacks, a number of different test procedures/objectives was suggested already in the project applications phase, and has during the first period of the project been subject to relevance testing by the consortium as well as industry. The original number of test procedures has been described in “Milestone 16 – Test Matrix for endurance oriented testing defined”. Original proposed test procedures included the like of shock and vibration testing for durability, accelerated stress testing and other, which were excluded during the first part of the project, for a number of reasons, also described in the milestone report. The main reasons were that test objectives were either covered by work package two or four, or because it was evaluated as only relevant on a system level.

The original three test modules have remained since the start of the project and the test procedures have been refined in with input from industry, to a set of relevant test modules and a single test program, able to cover most types of test objectives, be that benchmarking, development of durable stacks and components etc.

NB. Originally, the descriptions endurance and durability were used interchangeably, but to endurance testing is in the industry used to describe testing under harsh conditions to find the breaking point or limit, Stack-Test instead opted for Durability, as the test modules in work package three aim at observing and understanding how the stack performs over time, as well as the aging effects.

In Table 13 and Table 14 the final test modules and programs are summarized, with previous numbering from the first periodic report (for continuity) as well as the final numbering and naming.

### Table 13: final designation for Stack-Test WP3 Test Modules

<table>
<thead>
<tr>
<th>Test Program</th>
<th>Steady State Endurance</th>
<th>TP D-01</th>
<th>TM D-01 Durability</th>
<th>TP_D-01_Durability.docx</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>TP3.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>TP3.02</td>
<td>Load Cycling Endurance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

STACK-TEST : FCH-GA 303445 Final ReportPage 48
Table 14: final designation for Stack-Test WP3 Test Programs

<table>
<thead>
<tr>
<th>#</th>
<th>Previous number</th>
<th>Previous name</th>
<th>Final number</th>
<th>Document title</th>
<th>Final name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>TP3.01</td>
<td>Steady State Endurance</td>
<td>TP D-01</td>
<td>TM D-01 Durability</td>
<td>TP_D-01_Durability.docx</td>
</tr>
</tbody>
</table>

The TP and TM names and numbers used in this report are adapted to the final nomenclature to assure the non-confusing use of this nomenclature within the document.

2.2.5.1 Durability Test Modules

The test modules have been prepared by designated partners and reviewed and commented on by all partners, and subsequently the TMs have been experimentally validated, both individually in the first project period and as part of a test program in the second. All test modules have been validated at least in two rounds, and some as part of the Round Robin Test. The validation plan for the second project phase can be seen on Table 15.

Table 15: test plan for TM validation

<table>
<thead>
<tr>
<th>Test Module</th>
<th>Partner</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM D-01</td>
<td>RR</td>
<td>11</td>
</tr>
<tr>
<td>TM D-02</td>
<td>RR</td>
<td>10</td>
</tr>
<tr>
<td>TM D-03</td>
<td>RR</td>
<td>3</td>
</tr>
<tr>
<td>TM D-04</td>
<td>RR</td>
<td>7</td>
</tr>
</tbody>
</table>

In the following the final release versions of the TMs are summarised including their objective and modifications realised in the second project period. Additionally, examples for the acquired test procedures are given for some of the TMs.
2.2.5.1.1 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.

---

**Test Module D-01: Constant Load Durability**

**Objective and Scope**

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.

**Critical Parameters and Parameter Controls**

- The reactant flows have to be increased prior to an increase of the electrical load.
- The electrical load has to be decreased prior to a decrease of the reactant flows.

**Test Output Parameters (TOPs)**

<table>
<thead>
<tr>
<th>Output</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_start</td>
<td>measured</td>
</tr>
<tr>
<td>t_end</td>
<td>measured</td>
</tr>
<tr>
<td>i</td>
<td>measured</td>
</tr>
<tr>
<td>V_ref</td>
<td>measured</td>
</tr>
<tr>
<td>P</td>
<td>calculated</td>
</tr>
<tr>
<td>V_mon</td>
<td>calculated</td>
</tr>
<tr>
<td>Voltage decay rate</td>
<td>calculated</td>
</tr>
</tbody>
</table>

**Data Post Evaluation**

The voltage decay rate is calculated over the considered period of time. The slope can be evaluated sectionwise from the beginning to the end of the test, see figures below.

---

Contact Stack-Test: Stacktestsuzan-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 303445.

Final document: TM_D-01_Constant_Load_Durability.docx
This relative non-complex test module has similarities to Test Module P-07 Continuous Operation at Constant Load, but other than difference in duration, this test module addresses the specific conditions concerning durability, namely degradation rate, where a reversible/recoverable degradation phenomenon takes place in addition to irreversible degradation.

Figure 15: Example of the evolution of the average cell voltage.

In Figure 15 a typical example of the results of a test block can be observed, the very characteristic performance of the stack makes it difficult to calculate accurate comparable rates of performance loss. But like the other Test Modules in work package 3, degradation rate can be measured and calculated in a Test Program.

If comparing directly between single test blocks, care should be taken to observe relative steady time periods, and making sure the test blocks are of identical length and under same conditions.
2.2.5.1.2 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.

Test Module D-02: Load Cycling Durability

Objective and Scope
Determine the voltage decay of a PEM fuel cell stack caused by a defined load profile. Information regarding durability in defined operating conditions can be achieved.

Test Input Parameter (TIP)
The stack can operate in nominal conditions given by manufacturer or under conditions of interest for the application. The variable TIP is the electrical load. All other TIPs are typically kept constant. For specific test request other TIPs may be changed e.g. to add additional stressors in a Test Program. Due to the significant impact of gas flow with changing electrical load, a delay time between the change of electrical load and the change of the gas flows is recommended to avoid temporary fuel starvation.

<table>
<thead>
<tr>
<th>Static or Variable TIP</th>
<th>Variable TIP</th>
<th>Description of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>t</td>
<td>test</td>
</tr>
<tr>
<td>x_final</td>
<td>t</td>
<td>variable</td>
</tr>
</tbody>
</table>

Test Procedure
Dynamically, the test procedure for a generic load profile is shown.

The electrical load is varied with different loads and different step times according to the type of application. In this test module a generic load cycle as well as a load cycle for automotive applications and a CHP load profile is presented.

Critical Parameters and Parameter Controls
- Set appropriate delay times for the reactant flows during load ramp-up to avoid reactant starvation. The delay times have to be evaluated individually.
- Constant stoichiometry versus constant flow: Choose constant stoichiometry if applicable to avoid possible dry-out effects at low load steps.

Test Output Parameter (TOP)

<table>
<thead>
<tr>
<th>TOP</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uca</td>
<td>measured</td>
<td>measured</td>
</tr>
<tr>
<td>Ucalc</td>
<td>calculated</td>
<td>calculated</td>
</tr>
</tbody>
</table>

The measured and calculated data can be visualized and evaluated graphically including mean value, standard deviation, and min and max deviation of variable TIPs and TOPs. Another option is to plot the data as pseudo polarization curves, deviated from the different load steps of the load profile.

Data Post Processing
The resulting stack and single cell voltage can be evaluated at different load steps within the load profile.

Note: If a number of identical load profiles are performed consecutively, reversible degradation can be evaluated (‘test-block’). By a defined performing of test blocks within a Durability Test Program (TP D-01), irreversible degradation rates can be evaluated. Intermediate polarization curves give additional input within a Durability Test Program.

Contact Stack-Test: StackTest@in-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 363445.

Final document: TM_D-02_Load_Cycling_Durability.docx

The load cycling Test Module can be used to define a load profile and do all the preparative work for a (possibly) subsequent performed Test Program. In a Test Program
the reversible and/or irreversible voltage decay of a fuel cell stack can be evaluated during defined application specific operating conditions. This Test Module includes each one example for a dynamic and stationary load profile.

TM D-02 has been validated using the within the Stack-Test project defined Fuel Cell Dynamic Load Cycle (FC-DLC) for automotive, which is a demanding load cycle with rapid load high step load changes. When using a load cycle with various load steps spanning the full load range, the possibility presented using the voltage response of specific load steps to evaluate the stack performance by “pseudo”-polarisation curves, plotting the corresponding values. In Figure 16 and Figure 17 it can be seen how multiple load points from a load cycle can be used as input for a pseudo polarisation curve.

![Figure 16: dynamic load cycle (FC-DLC)](image)

![Figure 17: pseudo-polarisation curve - evaluation of load steps from one dynamic load cycle](image)
2.2.5.1.3 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.

Test Module D-03: Start/Stop Durability

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 Short-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, these 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@fch-iwv.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.

Final document: TM_D-03_Start-Stop_Durability.docx

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. An identified main stressor during a Start-Stop test is the presence of reactant gases after Stop with the effect of keeping cell voltages high for a long time. Consuming them by external or resistive load may lead to both serious starvation and reverse current effects if the parameters are not properly individually adjusted. Results may also be not comparable due to very different test bench equipment and piping volumes from one lab to the other. Moreover, the presence of a hydrogen-air front at anode is proved to be a stressor during the re-start phase of the stack, predominantly in higher operating temperatures.

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.

The Test Module is developed in such a way that it can be adapted to different types of stack stops and restarts, e.g. for automotive short stops and longer stops reflecting actual use scenarios, as seen on Figure 18.

The Test Module further describes in detail several strategies to, on the test bench, get rid of excess reactant gases during stop, to represent actual conditions where anodic and cathodic compartments fill with air, as described in the excerpt of the corresponding Test Module below:

*To be sure that the anode is fully flushed with air, an active Air-Purge should be performed for minimum 1 minute before restart. The Air-Purge mass flow should be equivalent to a high current density, e.g. 1 A/cm² at reference operating stoichiometry to minimize the possible impact-time of the hydrogen-air front. The anode humidifier and tubing should be bypassed to avoid purging air in appreciable hydrogen volumes -> Safety-Issue!*
If no bypass to anode humidifier and tubing is realizable:

- **Option 1: Nitrogen purge on the anode before air purge**
  Perform a nitrogen purge on the anode path of the test bench before the air-purge to dilute the hydrogen concentration significantly and after the air-purge to dilute the remaining oxygen.

- **Option 2: (Long passive) Air refilling at the anode via the vents**
  Set the stop time during the long stop as long as the air from ambient has completely flushed the anode compartment by diffusion from the outlet and/or cathode side. This may take 8 hours or more and has to be individually investigated.

- **Option 3: Air permeation from the cathode to the anode**
  After the long stop 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 flushed.
2.2.5.1.4 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.

Test Module D-04: Stack Performance Recovery

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 instant state of the stack. A recommendation with nitrogen purge is included in the Stack-Test Master Document TM-P-08. 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 aMEA-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 dislodge 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 L/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 CO₂-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 N₂ flush if available.

Reactivation processes on cathode side are not fully understood yet.

Contact Stack-Test: StackTest@uni-bay.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° 362445.

Final document: TM_D-04_Stack_Performance_Recovery.docx
The stack performance recovery can be regularly evaluated within the durability Test Program (TP D-01). Recoverable and non-recoverable voltage decay rates can be visualised as exemplary shown in Figure 19.

Figure 19: stack performance recovery

Similarly to TM D-03 Start/Stop Durability, the shut-down and restart of stack can be damaging to the stack if not performed correctly, therefore the test module give specific instructions on how to perform the test. Following these instructions, a safe reactivation can take place. The reactivation can take a considerable amount of time, is dependant of the membrane design, and the needed dwell time should be investigated in advance to automate the test.

2.2.5.2 Durability Test Programs

As the original three Test Programs were combined into one Test Program in the latter part of the second project period, the test program TM D-01 has been validated with all the different Test Modules. The original Test Programs have been described in milestone report M18 and M20.

Table 16: test plan for TP validation

<table>
<thead>
<tr>
<th>Test Program</th>
<th>Partner</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP D-01 Durability (Constant Load Durability)</td>
<td>x</td>
<td>7</td>
</tr>
<tr>
<td>TP D-01 Durability (Load Cycling Durability)</td>
<td>x  x  x</td>
<td>8</td>
</tr>
<tr>
<td>TP D-01 Durability (Start-Stop Durability)</td>
<td>x  x</td>
<td>3</td>
</tr>
</tbody>
</table>
2.2.5.2.1 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.
The Test Program does not necessarily reflect actual use within a system, and can therefore not necessarily be used to forecast actual lifetime of the stack. Nevertheless, a defined Test Program can be used to benchmark stacks or stack components. The Test Program is a set of Test Modules. Any combination of Test Modules and variance of test parameters may be performed. The Test Program gives the overall test framework including e.g. duration/repetition, sequence of Test Modules, electrochemical measurements, stack recovery etc.

![Diagram](image)

Figure 20: proposed test sequence for a stack durability Test Program.

As seen on Figure 20 the Test Program can contain any durability Test Module, as they are designed to be interchangeable. The test program can even be expanded to various application specific designs. In Figure 21 an specific automotive test procedure is shown, including short and long stops as well as load cycling and stack performance recovery, thereby effectively using TM D-02, TM D-03, TM D-04 as well as various performance and safety Test Modules.
Figure 21: workflow of application specific Start/Stop procedure

2.2.5.2.2 Conclusion for Work Package Durability

The documents for the description of the Test Module and Test Program procedures were validated and revised in two loops.

All documents are prepared consistently and numbered consecutively including the letter “D” for procedures with relevance to durability testing (“P” for functional and performance testing; “S” for safety and environmental testing).

The results and the document structures were discussed with OEMs (including the industrial advisory board of Stack-Test) and SDOs. The feedback from the different organisations was considered during the revision phase and the procedures were modified to assure their correctness and applicability in industry.

In summary, the following documents were prepared in WP 3:

- 4 Test Modules
- 1 Test Programs

It should be mentioned that the defined Test Programs are examples for possible programs. A Test Program can be defined by the end user based on the combination of several Test Modules depending on the application and the test objective.
2.2.6 Work Package 4

Based on an initially developed Test Matrix (see MS22 “Test matrix for application oriented testing defined”) different aspects regarding safety test procedures were considered and grouped in thematically related Test Programs (TP). All Test Modules and Test Programs were validated by the WP partners.

During the second revision it has been decided to take all test procedures dealing with environmental aspects out of the further consideration due to the following reasoning: Fuel cell stacks are typically part of a fuel cell power system which has a major influence on the interaction of its components with the environment. Environmental influences to the stack and influences of the stack to the environment need to be addressed on a system level. Direct interactions of the stack with the environment caused by leakage are also safety related. Environmental temperature influences have been dealt with in the corresponding performance Test Module “Low Temperature Test” TP P-06.

The final Test Modules and Test Programs were consistently numbered within the project. The final documents in this work package got the letter “S” for safety in comparison to “P” for performance testing in work package 2 and “D” for durability in work package 3. Table 1 below gives the summary of all Test Modules in work package 4.

<table>
<thead>
<tr>
<th>#</th>
<th>current number</th>
<th>current name</th>
<th>final number</th>
<th>document title</th>
<th>final name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TM 4.00</td>
<td>Gas Leakage Test</td>
<td>TM S-01</td>
<td>Gas Leakage Test</td>
<td>TM_S-01_Gas_Leakage_Test.docx</td>
</tr>
<tr>
<td>2</td>
<td>TM 4.01</td>
<td>Vibration</td>
<td>TM S-02</td>
<td>Vibration Test</td>
<td>TM_S-02_Vibration_Test.docx</td>
</tr>
<tr>
<td>3</td>
<td>TM 4.02</td>
<td>Freeze-Thaw-Cycling</td>
<td>TM S-04</td>
<td>Freeze-Thaw-Cycling Test</td>
<td>TM_S-04_Freeze-Thaw_Cycling_Test.docx</td>
</tr>
<tr>
<td>4</td>
<td>TM 4.04</td>
<td>Pressure Stability Test</td>
<td>TM S-03</td>
<td>Pressure Stability Test</td>
<td>TM_S-03_Pressure_Stability_Test.docx</td>
</tr>
<tr>
<td>5</td>
<td>TM 4.05</td>
<td>Short-Time Rated Current Test</td>
<td>TM S-06</td>
<td>Short-Time Rated Current Test</td>
<td>TM_S-06_Short-Time_Rated_Current_Test.docx</td>
</tr>
<tr>
<td>6</td>
<td>TM 4.06</td>
<td>Dielectric Strength Test</td>
<td>TM S-07</td>
<td>Dielectric Strength Test</td>
<td>TM_S-07_Dielectric_Strength_Test.docx</td>
</tr>
<tr>
<td>7</td>
<td>TM 4.07</td>
<td>Short-Circuit Test</td>
<td>TM S-08</td>
<td>Short-Circuit Test</td>
<td>TM_S-08_Short-Circuit_Test.docx</td>
</tr>
<tr>
<td>8</td>
<td>TM 4.12</td>
<td>Excess temperature Test</td>
<td>TM S-05</td>
<td>Excess Temperature Test</td>
<td>TM_S-05_Excess_Temperature_Test.docx</td>
</tr>
</tbody>
</table>

In addition, the Test Programs were renumbered as well to give a clear overview of all safety relevant topics which are recommended to be analysed during a detailed PEM fuel cell stack characterisation. Table 18 shows all Test Programs dealing with safety testing.

<table>
<thead>
<tr>
<th>#</th>
<th>current number</th>
<th>current name</th>
<th>final number</th>
<th>document title</th>
<th>final name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TP 4.01</td>
<td>Safety Temperature Behaviour Analysis</td>
<td>TP S-02</td>
<td>Safety Temperature Behaviour Analysis</td>
<td>TP_S-02_Safety_Temperature_Behaviour_Analysis.docx</td>
</tr>
<tr>
<td>2</td>
<td>TP 4.02</td>
<td>Safety Mechanical Behaviour Analysis</td>
<td>TP S-01</td>
<td>Safety Mechanical Behaviour Analysis</td>
<td>TP_S-01_Safety_Mechanical_Behaviour_Analysis.docx</td>
</tr>
<tr>
<td>3</td>
<td>TP 4.03</td>
<td>Electrical Safety Analysis</td>
<td>TP S-03</td>
<td>Electrical Safety Analysis</td>
<td>TP_S-03_Electrical_Safety_Analysis.docx</td>
</tr>
</tbody>
</table>

2.2.6.1 Safety Test Modules

In the following section, the contents of the final versions of Test Modules in work package 4 are summarised. The Test Modules and Test Programs went through a 2-
stage definition, validation and revision process. Table 19 presents an overview of performed Test Module validation.

Table 19: test plan for final Test Module validation

<table>
<thead>
<tr>
<th>Partner</th>
<th>S-01</th>
<th>S-02</th>
<th>S-03</th>
<th>S-04</th>
<th>S-05</th>
<th>S-06</th>
<th>S-07</th>
<th>S-08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraunhofer ISE</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>JRC-IET</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Next Energy</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ZSW</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>

The main focus during the validation phase was the further improvement of initial proposed gas leakage test procedures. The proper determination of the gas leakage rate is the most relevant safety parameter of fuel cell stacks. Within the specific Test Programs validation the revised Test Modules imposing mechanical, thermal and electrical impacts was performed.

In the following section, the final revised versions of the Test Modules are presented including their scope. Furthermore, some examples for the test procedures developed are given for several TMs.

One common modification related to all safety related Test Modules is the scheme of Test Input and Test Output Parameters (TIPs and TOPs) as exemplary presented in Figure 22 for Test Module “Freeze Thaw” (TM S-04). Additionally the kind of stressor like mechanic, thermal or electric is pointed out and recommended Test Input Parameters are integrated.
Figure 22: TIP-TOP scheme of TM S-04
2.2.6.1.1 Test Module TM S-01: Gas Leakage Test

Objective: This Test Module S-01 “Gas Leakage Test” is based on the fuel cell standard for safety issues, IEC 62282-2 (edition Jan. 2013), and describes the recommended procedure of a defined preconditioning followed by the direct Gas Leakage Measurement of a fuel cell stack. “Direct” in this context means a measurement in [ml/min]. The most relevant safety criterion is the external and internal gas leakage rate of the anode (fuel) compartment, but also the cathode and cooling compartment are equivalent considered.

Contact Stack-Test: Stacktest.jasurbiev.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.

Final document: TM_S-01_Gas-Leakage-Test.docx
In addition, a short summary of various methods of indirect gas leakage analysis like e.g. pressure drop or differential pressure measurement is given (Fast Leakage Analysis), being aware of the need for automatization and the detection of error sources. Figure 23 schematically presents the direct Gas Leakage Test, Figure 24 the test sequence.

**External gas leakage:**

![Diagram of external gas leakage test setup](image1)

**Internal gas leakage (low pressure)**

Example anode compartment:

![Diagram of internal gas leakage test setup (low pressure)](image2)

**Internal gas leakage (high pressure)**

Example anode compartment:

![Diagram of internal gas leakage test setup (high pressure)](image3)

Figure 23: recommended test setups for Gas Leakage Tests

Figure 24: developed process flow-chart for detailed Gas Leakage Tests.

In addition to the detailed Gas Leakage Test an indirect leakage measurement procedure was developed. This Fast Leakage Test uses the pressure drop method. The principle graph is shown in Figure 25 and the equation to calculate the Leakage Rate LR is declared in Equation 1 below.
Equation 1: LR calculation with the pressure drop method

$$LR = \frac{(p_1 - p_2) \text{ [mbar]} \times V[\text{l}]}{(t_1 - t_2) \text{ [s]}}$$

Figure 25: Principal graph of a leakage test, performed with the method of pressure drop (p-t graph)
2.2.6.1.2 Test Module TM S-02: Vibration Test

Objective: This Test Module describes the evaluation of the resistance against vibration impacts for a non-operated fuel cell stack when moved from one location to another in a vehicle travelling on a simulated road profile. As an effect, the stress by vibration applied during the test should not cause a significant increase of the gas leakage rate.

Test Module S-02: Vibration Test

Objective and Scope

This non-application-specific oriented Test Module describes the evaluation of the resistance against impact from simulated road vibrations for a non-operated fuel cell stack when transported by a vehicle (or air craft). The basic safety requirement for the fuel cell stack is the gas tightness of the fuel compartment. Vibration should not cause an increase in the leakage rate neither should change the clamping torque of the mounting bolts of the stack.

Test Input Parameter (TIP)

The vibration profile, controlled at the fixing plate of the stack, is defined by acceleration and amplitudes, shall be sinusoidal with logarithmic frequency sweep between 1-200 Hz forth and back traversed in 15 minutes as follows:

Test Procedure

- Determine the gas leakage rate at defined stack conditions and (if applicable) the stack compression.
- Fix the stack to the mounting plate.
- Apply the vibration profile as shown in the TIPs before.
- Optional: Perform a resonance sweep in an extended frequency range [e.g. 5-2,000 Hz] test to get an enlarged database regarding the mechanical characteristics/stiffnesses.
- Determine the gas leakage rate and (if applicable) the stack compression and compare with the initial values.

Critical Parameters and Parameter Controls

- Stack fixation on the vibration mounting plate
  - Have to be agreed with the manufacturer
  - Stack shall be torion-free clamped
  - Fixed stack has to be free from float
- Resonance peaks
  - Set maximum limits to avoid overstress
  - Blocksize
  - Can be very crucial. Torsion-effects have to be considered

Test Output Parameter (TOP)

- Changes of gas leakage rates and (if applicable) parameters regarding mechanical stack compression.
- Resonance peak-points.

Data Post Processing

Besides possible changes of gas leakage rates, response values like resonance peaks of the fuel cell stack can give important information for the later system integrator for structural integrity and stack design.

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_S-02_Vibration-Test.docx
When carrying out the Test Module, one should be aware that vibration testing on stack level cannot fully assess the impact of the later application when used in a power system.

The recommended in this Test Module vibration profile is based on a standardised profile for battery testing (United Nations’ Recommendations on the “Transport of dangerous Goods: Manual of Tests and Criteria, section 38.3.4.”)

The result of vibration testing on stack level is strongly influenced by the mounting interface between stack and vibration mounting plate and has to be closely defined by the stack manufacturer.
2.2.6.1.3 Test Module TM S-03: Pressure Stability Test

Objective: The aim of the Test Module is to evaluate the resistance of fuel cell stacks against increased gas pressures which can lead to gas crossover between anode and cathode gas compartment and to external leakage. Additionally, pressurisation of the cooling system is included in this Test Module. This Test Module is separated into three parts: simultaneous increased pressure at the anode and at the cathode (TM S-03a), differential pressure at the anode and at the cathode (TM S-03b) and increased operating pressure of the cooling system (TM S-03c). The impact of this mechanical stress on the fuel cell stack can be evaluated by specific Gas Leakage Tests before and after each test.

Test Module S-03: Pressure Stability Test

Objective and Scope

Determine the sensitivity of a PEM fuel cell stack to increased pressures in the gas and cooling compartment, whereas the gas leakage rate measurement is the main test indicator. The most safety-relevant stack compartment is the anode. Nevertheless changes of leakage rates at the other stack compartments are also of interest.

Test Input Parameter (TIP)

The tests with overpressure are divided into “allowable working pressure”, where simultaneously a defined high pressure at the anode and at the cathode side is applied (TM S-03a), “differential pressure” consecutively at the anode and at the cathode compartment (TM S-03b) and “overpressure of the cooling system” (TM S-03c).

The static TIPs are the Test Module specific pressures, the clamping torques and the specific initial leakage rates.

<table>
<thead>
<tr>
<th>Static TIPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM S-03a, P</td>
</tr>
<tr>
<td>TM S-03b, P</td>
</tr>
<tr>
<td>TM S-03c, P</td>
</tr>
</tbody>
</table>

Test Procedure

Exemplarily, a test procedure to study the impact of an increased pressure at the cathode and at the anode side is presented. The maximum (Pmax) or the minimum (Pmin) allowable working temperature shall be used during the test and should be held constant. The outlets of the fuel cell stack should be closed and the gas pressure recorded and held constant. All other possible input parameters should be held constant. The pressure should be increased by a defined rate (ΔPtest) depending on the temperature up to 1.3 - 1.5 times of the gauge pressure as specified by manufacturer, whereas the PEM fuel cell stack can withstand without any damage or permanent loss of functional properties.

Critical Parameters and Parameter Controls

- Leakage tests should not be performed with flammable gases like hydrogen. Gases like nitrogen or helium may be used.

Contact Stack-Test:
Stacktest@vsvv.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_S-03_Pressure_Stability_Test.docx
2.2.6.1.4 Test Module TM S-04: Freeze-Thaw-Cycling Test

Objective: The scope of this Test Module is to evaluate impacts of Freeze-Thaw Cycles to a PEM fuel cell stack, performed in off-operation mode. This test intends to simulate mechanical "stress" caused by freeze-thaw cycles during transportation.

Test Module S-04: Freeze-Thaw-Cycling Test

Objective and Scope
The scope of this Test Module is to evaluate impacts of Freeze-Thaw Cycles to a PEM fuel cell stack, performed in off-operation mode. The main test criterion is the safety demand of gas tightness. This test intends to simulate mechanical "stress" caused by freeze-thaw influences during potential transport situations.

Test Input Parameters (TIPs)
The test has to be performed with a complete assembled fuel cell stack in a passive status. Before starting the Freeze-Thaw-Cycling Test a Gas Leakage Test and a nominal rated power analysis according to TM S-01 and P-00 have to be performed.

During the test procedure the stack is disconnected from fuel, oxidant and coolant supply and all reactant in- and outlets are locked during the test.

Critical Parameters and Parameter Controls
- Temperature sensors should be applied on different stack surface positions to observe the heat transfer during the test.
- A Gas Leakage Test with inert gas after Test Module completion is mandatory.

Test Output Parameters (TOPs)
The test is passed if the Gas Leakage Rate and the nominal rated power do not significantly differ from the initial values.

Data Post Processing
The result of the Gas Leakage Test as the most important Test Output Parameter has to be recorded. Nominal rated power and test parameters like stack and ambient temperature of the climate chamber, but also the humidity data should be evaluated and visualised.

Contact Stack-Test: Stack-Test.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.

Final document: TM_S-04_Freeze-Thaw_Cycling_Test.docx
2.2.6.1.5 Test Module TM S-05: Excess Temperature Test

Objective: The aim of the Test Modules is to evaluate the response of a liquid or air cooled fuel cell stack under abnormal operating conditions. It targets situations such as loss of coolant when the stack is operated under nominal operating conditions and a totally breakdown of the cooling pump or air ventilator followed by a gradual or rapidly increasing stack temperature.

Test Module S-05: Excess Temperature Test

Objective and Scope
The aim of Test Module S-05 entitled “Excess Temperature Test” is to evaluate the response of a liquid or air cooled fuel cell stack under excess temperature conditions. It targets situations such as loss of coolant when the stack is operated under nominal operating conditions and a totally breakdown of the cooling pump or air ventilator followed by a gradual or rapidly increasing stack temperature.

Method A is to measure the response time of a stack under nominal operating conditions after stack coolant off until the minimum cell voltage drops below the specified safety limit.

Method B is to measure the response of a stack operating at excess stack temperature conditions caused e.g. by leaking cooling water while other operating parameters remain unaltered.

Test Input Parameter (TIP)

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Unit</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack temperature</td>
<td>°C</td>
<td>Data operating conditions according to manufacturer’s specifications</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td>°C</td>
<td>Data operating conditions according to manufacturer’s specifications</td>
</tr>
<tr>
<td>Coolant flow</td>
<td>L/min</td>
<td>0.5-1.5 L/min</td>
</tr>
<tr>
<td>Method</td>
<td></td>
<td>1 (manual settings)</td>
</tr>
<tr>
<td>Test duration</td>
<td>min</td>
<td>30 minutes</td>
</tr>
</tbody>
</table>

Test Procedure
Method A:
- Operate the stack under nominal conditions for a recommended duration of about 30 minutes.
- Set stack coolant off (zero flow).
- Monitor stack temperature and cell voltages and measure the elapsed time until minimum cell voltage drops below specified safety limit (Umin).
- Restore coolant flow immediately.

Method B:
- Operate stack under nominal conditions for a recommended duration of about 30 minutes.
- Set stack operating temperature to the specified excess temperature conditions.
- Operate stack within the specified range of current densities, e.g. polarization curve.

Critical Parameters and Parameter Controls
- **Manual test control**
  - Excess Temperature Test has to be manually observed by the presence of qualified test personal for intervention on demand to prevent stack damage.
- **Minimum cell voltage**
  - Keep specified lower limits!
- **Gas leakage rate**
  - Perform a Gas Leakage test and measure external and internal gas leakages upon every Excess Temperature Test to assess its impact.

Test Output Parameter (TOP)

<table>
<thead>
<tr>
<th>Output parameter</th>
<th>Unit</th>
<th>Normal conditions</th>
<th>Excess conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack voltage</td>
<td>V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data Post Processing
Examples are presented below:

Contact Stack-Test: StackTest.zwe-low.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_S-05_Excess_Temperature_Test.docx
This test is conducted using two methods:

- **Method A** is to establish the response of the stack operated under nominal conditions after a coolant-flow switch-off. The elapsed time until the minimum cell voltage drops below the specified safety limit can be a useful parameter for system integrators.

- **Method B** is to measure the response of a stack operating at a specified excess stack temperature with other operating parameters not altered. The relative humidity of the reactant inlet media is correspondingly decreased. The stack response is measured as stack voltage at a specified range of current densities, e.g. polarisation curve.

Additional to the standardised TIP-TOP scheme as shown in Figure 22, the parameters are also listed in tables; see Table 20 and Table 21 below.

### Table 20: TIPs of TM-S05

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Unit</th>
<th>Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{fu} ), ( \lambda_{ox} )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta P_{fuel}, \Delta P_{ox} )</td>
<td>°C</td>
<td>-</td>
</tr>
<tr>
<td>( T_{stack} ) (nominal conditions)</td>
<td>°C</td>
<td>-</td>
</tr>
<tr>
<td>( P_{fuel}, P_{ox} )</td>
<td>kPa</td>
<td>-</td>
</tr>
<tr>
<td>( x_{fuel}, x_{ox} )</td>
<td>vol.-%</td>
<td>-</td>
</tr>
<tr>
<td>( T_{excess} (T_{stack} \leq 70°C), \text{method B} )</td>
<td>°C</td>
<td>( T_{excess} = T_{stack} + 20°C )</td>
</tr>
<tr>
<td>( T_{excess} (T_{stack} &gt; 70°C), \text{method B} )</td>
<td>°C</td>
<td>( T_{excess} = 90°C )</td>
</tr>
<tr>
<td>( r_{max} ) (method B)</td>
<td>min</td>
<td>3 (if nothing else is defined)</td>
</tr>
<tr>
<td>Limit ( U_{min,cell} )</td>
<td>V</td>
<td>0,2 - 0,3</td>
</tr>
<tr>
<td>( T_{excess} )</td>
<td>A/cm²</td>
<td>1 (fix value) or 0 - 1 (e.g. polcurve)</td>
</tr>
</tbody>
</table>

### Table 21: TOPs of TM S-05

<table>
<thead>
<tr>
<th>Output parameter</th>
<th>Unit</th>
<th>Nominal Conditions</th>
<th>Excess-Conditions (T, Si, Cl: ...°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{off} ) (method A)</td>
<td>s</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( U_{stack}(\ldots A) ), method B</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( U_{cellMin}(\ldots A) ), method B</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( U_{cellMax}(\ldots A) ), method B</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( U_{cellAv}(\ldots A) ), method B</td>
<td>V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.6.1.6 Test Module TM S-06: Short-Time Rated Current Test

Objective: The aim of this Test Module is to measure the thermal energy of the fuel cell stack at a defined current above specification, while the time period of this "overcurrent" is limited to a defined. The test output provides valuable information for the system integrator to configure the capacity of the coolant subsystem.

Test Module S-06:
Short-Time-Rated Current Test

Objective and Scope
The scope of this Test Module is to check the capability of a fuel cell stack module with autonomous cooling and stack control system. A specified time-limited electrical "overload" should not lead to an overheating and damaging of the stack module.

Test Input Parameter (TIP)
The stack should be operated in nominal conditions given by the manufacturer or according to Stack-Test Master Document (TM P-40). The main Test Input Parameter is the Short-Time Rated Current (I_{ave}).

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Unit</th>
<th>Value/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_{ave} (I_{ave})</td>
<td>A</td>
<td>static operating conditions according to manufacturer's specifications</td>
</tr>
<tr>
<td>DH_{corr}, DH_{corr}</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>current ramp rate</td>
<td>A/sec</td>
<td></td>
</tr>
<tr>
<td>T_{in} (minimal conditions)</td>
<td>ºC</td>
<td></td>
</tr>
<tr>
<td>P_{in}, P_{in}</td>
<td>kW</td>
<td></td>
</tr>
<tr>
<td>X_{in}, X_{in}</td>
<td>vol.%</td>
<td></td>
</tr>
<tr>
<td>Rate</td>
<td>A</td>
<td>data from manufacturer</td>
</tr>
<tr>
<td>Rate</td>
<td>A</td>
<td>data from manufacturer</td>
</tr>
<tr>
<td>dwell time at I_{ave}</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td>dwell time at I_{ave}</td>
<td>min</td>
<td>data from manufacturer</td>
</tr>
</tbody>
</table>

Test Procedure
- Operate the stack at nominal stack current until it is stabilised, but at least for 10 min.
- Raise stack current up to the specified short-time rated current. The ramp time is defined by the manufacturer. If this is not defined, a current ramp rate of 10 A/sec is recommended. The dwell time shall be according to manufacturer's specification, but at least 5 minutes.
- Reduce current afterwards down to the nominal current or lower.

Critical Parameters and Parameter Controls
- Stack Temperature:
  - Keep specified upper limits of the stack module.
- Ramp rate stack current:
  - Avoid fuel and oxidant starvation.
- Minimum cell voltage:
  - Keep specified safety limits if the short-time rated current leads to a limit underin of cell voltages, consult the proceeding with the manufacturer.

Test Output Parameter (TOP)

<table>
<thead>
<tr>
<th>Output parameter</th>
<th>Unit</th>
<th>Nominal Conditions</th>
<th>Short-Time Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack current</td>
<td>A</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>T_{in}</td>
<td>°C</td>
<td>87</td>
<td>80</td>
</tr>
<tr>
<td>Minimum Cell Voltage</td>
<td>V</td>
<td>0.1</td>
<td>0.055</td>
</tr>
<tr>
<td>Time to reach steady-state conditions at I_{ave}</td>
<td>min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to reach steady-state conditions at I_{ave}</td>
<td>min</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Change of leakage rate</td>
<td>ml/min</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Data Post Processing
An example for a Data Post Processing table is shown below. The table should include all relevant test parameters. Additionally a graph with visualised original measurement data’s would be useful. The data’s have to be provided to the later system integrator.

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.

Final document: TM_S-06_Short-Time_Rated_Current_Test.docx
2.2.6.1.7 Test Module TM S-07: Dielectric Strength Test

Objective: This test has to be carried out in accordance with IEC 62282-2, edition January 2013, chapter 5.9, referring to test parameters based on EN 50178. The scope of this Test Module is to analyse the dielectric strength of the electrical insulation between active parts of the stack and not current leading metallic parts of the fuel cell stack. If the stack within the stack module or system is grounded, the test can there not be performed.

Test Module S-07: Dielectric Strength Test

Objective and Scope
The scope of this test is to analyses the dielectric strength of the electrical insulation between active parts of the stack and not current leading metallic parts of the fuel cell stack.

If the fuel cell stack is designed with a grounded stack, the test cannot be performed.

Test Procedure
The test voltage is either DC or an AC with a sinusoidal wave shape and within a frequency range of 48 to 62 Hz. There is no recommendation which wave shape has to be used. One output of the high voltage generator is connected to the active parts of the fuel cell stack, the other one is connected to not current leading (passive) metallic parts of the stack. The used test voltage is driven by the OCV.

Critical Parameters and Parameter Controls
Due to the high test voltage it has to be ensured that the analysed fuel cell stack is not grounded and placed at an adequate insulated plate.

Test Output Parameters (TOPs)
The test is passed if no interruption of the electrical insulating material or a flash over an air gap occurs and the leakage current is

\[ I_{leak} = \frac{U_{voltage}}{R_{load}} \]

Data Post Processing
It is recommended to present the test results in the table as shown below.

Contact Stack-Test:
Stack-Test@fch-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 308445.

Final document: TM_S-07_Dielectric_Strength_Test.docx
2.2.6.1.8 Test Module TM S-08: Short-Circuit Test

Objective: The Test Module is addressed to measure the short-circuit (SC) current and the correspondent short circuit voltage of a fuel cell stack, considered as relevant for all intended later system applications. The constitutive procedure of the short-circuit test is given in the IEC-standard 62282-2 under “test under abnormal conditions” (based on edition January 2013, chapter 5.14.4).

Test Module S-08: Short-Circuit Test

Objective and Scope
Measure the Short Circuit (SC) Current – and voltage of a full conditioned PEM fuel cell stack and provide those values to the later system integrator.

Test Input Parameter (TIP)
The stack should be in a fully conditioned state during the Short-Circuit Test. An electrical load has not to be applied; the stack should be in OCV-state during applying a SC. The conditioning parameters are set to nominal conditions, but the relative humidity should be 100 % due to the OCV-state.

Test Procedure
For the short-circuit test a representative smaller stack with same stack hardware and size of active area can be used. The proper preconditioning of the stack is an essential demand, because this will directly influence the result. The stack has to be in a fully conditioned steady-state mode and in thermal equilibrium. To avoid local reactant starvation during the Short-Circuit Test, the reactant flows are set to a constant value which is equivalent to maximum stack current.

Without any direct contacts by humans the short-circuit between the anode and cathode current collector has to be provided e.g. by a pneumatic mechanical device or by an automatically controlled electrical high-current switch.

The maximum parameter current and voltage values are of interest. This requires high-speed data acquisition equipment. The recommended sampling rate is ≥ 5,000 Hz.

Critical Parameters and Parameter Controls
- Conditioning parameters:
  - Have to be kept constant during SC.
- Conditioning Time:
  - Steady-State mode before SC ≥ 30 min.

Contact Stack-Test:
Stacktest@ewi.lmu.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 305445.

Final document: TM_S-08_Short-Circuit_Test.docx
Figure 26 presents an example for recommended data analysis. Essential information like short-circuit current, short-circuit voltage and sampling rate are highlighted.

![Recommended Graphical Representation of TM S-08 Test Results](image)

2.2.6.2 Safety Test Programs

Lessons learned from the validation phase during the first project period were considered in the revised Test Module versions and the following drafting of Test Programs.

The released documents are described in the respective milestone reports MS26 “Review on application safety / environmental specific Test Programs available” and MS27 “Release versions of generic safety / environmental Test Modules and application oriented Test Programs”.

A summary of Test Program validation is given in Table 22.
Table 22: Test Program validation in second project period

<table>
<thead>
<tr>
<th>Partner</th>
<th>TP S-01 Mechanical Safety Analysis</th>
<th>TP S-02 Temperature Safety Analysis</th>
<th>TP S-03 Electrical Safety Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fraunhofer ISE</td>
<td>X³</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2 JRC-IET</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Next Energy</td>
<td>X³</td>
<td>-</td>
<td>X⁴</td>
</tr>
<tr>
<td>4 ZSW</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**Legend:**
1 only Excess Temperature  
2 only Vibration / Shock  
3 only Pressure Stability Test  
4 only Short-time Rated Current with ZSW stack
2.2.6.2.1 Test Program TP S-01: Mechanical Safety Analysis

Objective: The aim of this Test Program is to evaluate the mechanical stack-robustness, considering specific degrees of overstress compared to regular operation. Impacts caused by media pressure and vibration is analysed by initial and follow-up tests of gas leakage and electrical power. The Test Program workflow comprises the Test Modules “Vibration Test” (TM S-02), “Pressure Stability Test” (TM S-03) and “Gas Leakage Test” (TM S-01).

Test Program S-01: Safety Mechanical Behaviour Analysis

Objective

The objective of this Test Program is to determine the influence of pressure and vibration on the stack. This influence is evaluated by initial test and follow-up examination of the stack by safety test procedures like nominal rated power and leakage tests.

This Test Program can be used for all applications.

Implemented TMs

- TM P-00 – Stack-Test Master Document
- TM S-01 – Gas Leakage Test
- TM S-02 – Vibration
- TM S-03 – Pressure Stability Test

Assumed test duration

Ca. 12 h without
- Preconditioning of the fuel cell stack
- Detailed leakage tests
- Shut-down procedure

Test Programme Output

With this Test Program unusual mechanical stress during fuel cell stack transportation or caused by peripheral component defects will be tested. The reached results will help fuel cell stack manufacturer’s to prepare the stack for safe transport and system developer to include arrangements for safety test procedures when system components are out of normal operation.

Contact Stack-Test:
Stacktest.zsw-bu.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: TP_S-01_Mechanical_Safety_Analysis.docx
Impacts to the electrical stack performance are traced by a nominal power test or a polarisation curve. The mechanical stress caused by the “Pressure Stability Test” is caused by a defined pressure above specifications of reactant and coolant media. The simulation of mechanical impacts to the stack during transport is covered by the Test Module “Vibration Test”, where a standardised vibration profile for battery safety tests was adapted to fuel cell stack testing. The test results help to construe the stack in a consolidated compromise of cost, power / lifetime, weight / dimensions and mechanical safety.

The Test Program workflow is presented in Figure 27.
2.2.6.2.2 Test Program TP S-02: Temperature Safety Behaviour Analysis

Objective: The aim of this Test Program is to evaluate the thermal stack-robustness, analysing the impact of defined temperature-stress on the fuel cell stack safety. It contains freeze-thaw cycling where the stack is in a passive stack state and possible excess temperature during operation.

Test Program S-02: Safety Temperature Behaviour Analysis

Objective:
The objective of this Test Program is to determine the influence of temperature on the fuel cell stack under safety issues. It contains an ambient temperature cycling analysis as well as an analysis of fuel cell stack behaviour under excess temperature effects during operation. This Test Program can be used for all stack applications.

Implemented TMs
- TM P-00 – Master document
- TM S-01 – Gas Leakage Test
- TM S-04 – Freeze-Thaw-Cycling Test
- TM S-05 – Excess Temperature Test

Assumed test duration
Ca. 120 h without
- Preconditioning of the fuel cell stack
- Detailed leakage tests
- Shut-down procedure

Test Programme Output
With this Test Program unusual temperature influences during fuel cell stack transportation or caused by peripheral component defects will be tested. The reached results will help fuel cell stack manufacturers to prepare the stack for safe transport and system developer to include arrangements for safety test procedures when system components are out of normal operation.

Workflow
Recommended test sequence for Safety Temperature Behaviour Analysis.

Contact Stack-Test:
Stacktest.zew-bu.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: TP_S-02_Temperature_Safety_Analysis.docx

These impacts of external stressors are covered in the Test Modules “Freeze-Thaw-Cycling Test” (TM S-04) and “Excess Temperature Test” (TM S-05). Changes of gas leakage rates
during a Test Program are traced by measurements based on the Test Module “Gas Leakage Test (TM S-01)”. Impacts to the electrical stack performance are traced by a nominal power test or a polarisation curve. The Freeze-Thaw Cycling Test is based on a defined temperature/humidity test profile to simulate potential impacts during transport, where the stack is in a passive state. The Excess Temperature Test considers possible system-failures like over temperature caused by a disruption or a complete breakdown of the cooling subsystem. Test outputs can be helpful information for system integrators to configure their system.

Table 23: recommended data summary in TP S-02. Upper table: gas leakage analysis. Lower table: data summary of included TMs

<table>
<thead>
<tr>
<th>State of the measurement</th>
<th>Date of measurement</th>
<th>test pressure / kPaabs</th>
<th>Gas Leakage Rate / Nml min⁻¹</th>
<th>calc. real value anode (external)</th>
<th>clamp. force (control parameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Test Program</td>
<td></td>
<td></td>
<td>limit anode (external) anode²</td>
<td>cathode² cooling² blank value test setup</td>
<td></td>
</tr>
<tr>
<td>After Test Program</td>
<td></td>
<td></td>
<td>blank value test setup</td>
<td>calc. real value anode (external)</td>
<td></td>
</tr>
</tbody>
</table>

1) Simultaneous pressurisation of anode, cathode and coolant compartment
2) keep the safety limit regarding differential pressure
3) if those additional values are of interest, not mandatory in the context of safety
2.2.6.2.3 Test Program TP S-03: Electrical Safety Analysis

Objective: This Test Program is aimed on evaluating the electrical safety of a PEM fuel cell stack exposed to induced system failure like short-circuit and electrical specified overload. Also electric shock protection demands are covered there.

Test Program S-03: Electrical Safety Analysis

Objective

The main objective of this Test Program is to analyse the electrical safety characteristic of a fuel cell stack. This Test Program is aimed to establish a standardised safety investigation of a PEM fuel cell stack. The involved Test Modules are strongly referring to the international standard IEC62882-2, Fuel cell technologies - Fuel cell modules.

Implemented TM

- TM P-00 - Stack-Test Master Document
- TM S-01 - Gas Leakage Test
- TM S-06 - Short-Time Rated Current Test
- TM S-07 - Dielectric Strength Test
- TM S-08 - Short-Circuit Test

Assumed test duration

Ca. 5 h without
- Preconditioning of the fuel cell stack
- Gas leakage tests
- Shut-down procedure

Test Programme Output

With this Test Program unusual influences caused by electrical effects, like short-circuit or raised operating currents will be tested as well as an analysis of isolating behaviour of the non-grounded fuel cell stack. The reached results will help fuel cell stack manufacturers to develop safe fuel cell stacks and system integrators to realise a fuel cell system with minimised hazards caused by electrical failure.

Recommended test sequence for Electrical Safety Analysis of PEM fuel cell stacks.

Final document: TP_S-03_Electrical_Safety_Analysis.docx

The Test Program workflow comprises the Test Modules “Short-time Rated Current Test (TM S-06)”, “Dielectric Strength Test (TM S-07)” and “Short-Circuit Test (TM S-08)".
Changes of gas leakage rates are traced by the Test Module “Gas Leakage Test (TM S-01)”. Impacts to the electrical stack performance are traced by a nominal power test or a polarisation curve. The Short-time Rated Current Test intends to analyse the capability of conveying a specific degree of excess thermal power caused by electrical overload for a defined time. Dielectric Strength measurements are aimed on testing isolation materials to avoid dangerous fault currents during possible human contact. Short-Circuit measurements are aimed on measuring the maximum current coming out from the stack as basic information for system safety configuration.

For all Test Programs several safety relevant End-of-Test criteria are developed. For leakage analysis are the following criteria worked out:

- The leakage rate has exceeded the specified limit given by the manufacturer.
- The nominal rated power decreases out of manufacturer’s life time specifications.
- The stack should show after each test no visible changes like fracture, rupture, deformation or other physical damage.

Additional End of Test criteria related to low single cell voltage or low overall stack voltage have been defined and agreed upon in the consortium.

2.2.6.3 Conclusion for Work Package “Safety / Environmental Testing”

All Test Modules and Test Programs could be validated in the second project phase and revised after final discussion approved within the consortium; all Milestones and Deliverables planned for the second project phase could be achieved:

- MS25 Review of generic safety / environmental test modules available
- MS26 Review on application safety / environmental specific test programs available
- MS27 Release versions of generic safety / environmental test modules and application oriented test programs available
- D4.2 Application oriented safety / environmental test program validation report including test program release version

The final documents are prepared consistently and renumbered including the letter “S” for procedures with safety relevance testing (“D” for durability; “P” for functional and performance).

The results and the documents developed in the course of the project were discussed with OEMs and SDOs considering feedback during the revision phase with the emphasis of relevance and applicability in industry.

In summary, the following documents were prepared in WP 4:

- 8 Test Modules
- 3 Test Programs

It should be pointed out that the defined Test Programs are examples of a useful ordering of Test Modules. Additional Test Program can be defined by the end user based on the combination of several Test Modules depending on the application and the test objective.
2.2.7  **Work Package 5**

The activities in this work package include:

i) the organisation of workshops for dissemination purposes and

ii) the formation of an industrial advisory group.

The latter gathers both industrial and academic partners involved in PEMFC stack development/testing so as to get their feedback on the test procedures.

2.2.7.1  Task 5.1: Assessment of existing international or relevant national standards

The task 5.1 in Stack-test project is related to the relationship between the project partners and the different standardisation organisations.

Existing international standards are having substantial influence on different aspects of fuel cell testing. As a consequence, test modules and test programs are developed in the different work packages keeping in mind the existing standards and tests procedures elaborated all around the world.

In this work package, a first deliverable on standards has been written, D5.1 “International Standards Status Report”. This document presents and analyses the relevant national and international standards dealing with PEM fuel cell stack testing. Information coming from FCTESTNET and FCTESQA projects, from JARI, the USFCC documents and from IEC standards (with a focus on IEC 62282-2 related to fuel cells modules) have acted as a guideline for the work done in the technical work packages 2-4.

Due to the modification of WP 5 leader at the beginning of the project, this first deliverable was postponed and delivered in March 2013. Nevertheless, information related to standards was available before delivery date in the EU database.

A first update of this document was delivered to the partners in the mid of March 2014, D5.2 “International Standards Status Report - 1st update”. In this update, some additional standards have been analysed in regards to safety and performances level of different fuel cell system when information contained were relevant regarding stack testing.

In addition to the analysis of these international standards and procedures, Stacktest members are taking part in standardisation and harmonisation activities. For example, these actions are initiated by JRC in the frame of automotive applications on the European level.

2.2.7.2  Task 5.2: Establishment of an Industrial Advisory Board

The task 5.2 is dedicated to the establishment of an Industrial Advisory Board (IAB) which is composed of key industrial stakeholders involving OEM from the automotive as well as from the power generation field, fuel cell system integrators, stack manufacturers and component manufacturers. During the period, each WP leader prepared some slides in order to present the main objectives of the project to these industrials.

In the same time, each partner provided industrial contacts to the consortium. According to these propositions, partners made a first selection for potential industrial members taking into account that each PEMFC domain should be represented. The potential members of the industrial advisory board initially selected by the consortium are resumed in Table 24.
Each member of the IAB was contacted by e-mail containing a brief description of project, its main objectives and a presentation depicting the work for each work package in the project. The members of the Industrial Advisory board were invited to the workshops organized in the course of the project as well as to the technical meetings of the consortium. In addition, bilateral discussions among members of the Industrial Advisory Board and members of the consortium have been held.

2.2.7.3 Task 5.3: Dissemination Workshop Organization

A project web-page has been implemented (http://stacktest.zsw-bw.de) giving general information about the project as well as information about upcoming events. The current draft versions of test modules and test programs are made available upon request.

As the aim of the project is to build test procedures and programs useful for PEMFC community, an important part of works within the project was dedicated to dissemination of project's results. In addition to classical dissemination activities, four international workshop were organised during Stack-test.

- 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” (http://www.next-energy.de/stacktest.html). During this meeting both results from the Stack-Test project were presented and discussed, but also excellent talks on test procedures and results on stack performance and durability testing, were presented. The participants consist of Stack-Test partners and colleagues, academic researchers, industry representatives within MEA and stack manufacturing, test benches providers and OEM for a wide range of applications.
  - 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” (https://stacktest-dlr.meetingmasters.de).
The third workshop was organised by Fraunhofer Institute for Solar Energy Systems ISE in January 20th and 21st, 2015. Approximately 50 persons were present during this meeting.

The fourth and last workshop was occurred the 16th and 17th of June 2015 at ZSW in ULM. During this meeting in addition to classical discussion about procedures and programs, an important focus was made on standards and guideline in general and on IEC activities in particular.

In addition to workshop organise during the project, several partners were involved in others dissemination activities. Moreover partners were presenting Stack-Test activities in international conferences and other international workshops and were involved in harmonisation activities lead by JRC and dedicated to single cell test for automotive applications.

2.2.7.4 Task 5.4. Prepare and propose new work item proposal to IEC TC 105

The target of the Stack-Test project is to create, write and validate harmonised and industrially relevant test procedures for PEMFC stacks thus contributing to pre-normative research. It is suggested to transfer the project results into a New Work Item Proposal (NWIP) to create a performance standard for fuel cell modules that currently is not available in this configuration. The documents from the project are structured in generic Test Modules with application specific Test Programs. The project includes a modular approach where Test Modules with the variation of one input parameter each are combined to Test Programs. There will be definitions of application specific Test Programs for different applications like automotive or stationary to generate or provide reliable data for a system design with the tested fuel cell stacks or modules.

The starting position was the lack of literature to compare results from even equal fuel cell stacks that are available from commercial manufactures. In the worst case a conflict between customer and reseller will be negotiated under the law of the countries involved. This issue could be solved using the project results from the Stack-Test project in the near future, by generating input for an international standard in the IEC 62282 series. The existing Module standard (IEC 62282-2:2012) was reviewed and tested and gives good approaches for the safety testing inside this part product of the module. In this standard performance testing is only integrated in form of a minimum specified output under conditions provided by the manufacturer, but this value is a minimum requirement.

There is a great opportunity to share and provide results of this project to the international standardisations organisations. To allow for that, a transfer agreement from all authors of the project results was obtained in writing to make the wording of project useable inside IEC documents. This implementation of the pre-normative work to the standardisation could be ensured by support of related parties to forward EU work into international normative projects like suggested by this submitted NWIP to IEC TC 105 from the German national committee of DKE.

The multinational input and proven results, definitions of terms and deep technology understanding make an enhancement in measurements of PEMFC Stacks possible thereby creating easy comparable results, independent of even different test benches. This makes it possible to detect in the future the influence of e.g. gas quality or impurities in different locations and without influence from the test operator.

The final document will provide overview of performance related Test Modules that cover performance and endurance related issues. All safety aspects will still be covered also in future by the fuel cell module - safety standard. Interaction to ISO TC 197 for hydrogen technologies is highly welcome.
The proposal was presented in the plenary meeting of IEC TC 105 on September 27th 2015 at the IEC plenary in Beijing to discuss the future structuring of the overall standard family including this suggested content. The decision on the NWIP will be expected end of 2015 to start the work on the document early 2016 under German leadership (convenor) and with European contribution. People and companies from all over the world are invited to join the new sub working group 2 in TC 105 by their active participation to ensure the knowledge transfer. The convenor will be responsible for the moderation with a neutral opinion and a selected secretary from the group will write the document in behalf of the convenor. That is one way how the outcome from PEMFC stack testing from the project Stack-Test could be used and influences the future as a strong European impact.

The advantage of standardisation is for engineering aspects the improvement of safety and product quality to optimise also the product costs. Also the relation to economy is important to generate free trade without barriers in a global market.

A publication of the international standard (IS) for fuel cell module performance is suggested for 2018. The standard should be used by industry and science in the future and the process to get there ensure by political and financial support from government. Anyway standardisation is a political issue, where the main players in the field of fuel cell come from US, CA, JP, CN, KR, DE and some other EU states, where it seems obvious that every country act in the way to protect their local market and market access or market position from the related industry.
Figure 28: NWIP purpose and proposed structure
2.2.8 Work Package 6

The Work Package 6 consists of with the supply of the different stacks used during the experimental phase to the partners. Two types of stack are tested during the project and are provided by ZSW and CEA, respectively. Depending on the capabilities of the test benches available at the partners, ZSW stacks are composed by ten or sixteen cells with an active surface of 100 cm² using composite bipolar plates (Figure 29). CEA stacks are composed of six or ten cells and based on stamped metallic bipolar plate with a 220 cm² active surface (Figure 30).

Figure 29: generic image of the stack provided by ZSW including descriptions of media connectors.

Figure 30: image of G stack from CEA. (a) Description of gases and coolant connections. (b) Description of the electrical connections.
2.2.8.1.1 Task 6.1 Specification of test stacks

Specification of test stacks has been defined in the first reporting period. No further update was necessary.

2.2.8.1.2 Task 6.2: Procurement of test stacks and post-test analysis

Each partner has provided a description of their test bench to be used during the Stack-Test project. According to the data collected in these documents, stacks with a number of cells comprised between 6 and 16 were convenient for all the partners as showed in Table 25.

Table 25: stack delivery calendar

<table>
<thead>
<tr>
<th>Institution</th>
<th>CEA-Stack</th>
<th>ZSW-Stack</th>
<th>CEA</th>
<th>ZSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZSW</td>
<td>10</td>
<td>16</td>
<td>25.09.2013</td>
<td>20/09/2013</td>
</tr>
<tr>
<td>CEA</td>
<td>10</td>
<td>10</td>
<td>20.10.2013</td>
<td>13/11/2013</td>
</tr>
<tr>
<td>DLR</td>
<td>10</td>
<td>10</td>
<td>30.07.2014</td>
<td>24/07/2013</td>
</tr>
<tr>
<td>ICRI</td>
<td>6</td>
<td>10</td>
<td>17.10.2014</td>
<td>26/07/2013</td>
</tr>
<tr>
<td>NEXT-E</td>
<td>10</td>
<td>16</td>
<td>22.11.2013</td>
<td>18/07/2013</td>
</tr>
<tr>
<td>CIDETEC</td>
<td>10</td>
<td>16</td>
<td>15.07.2014</td>
<td>09/08/2013</td>
</tr>
<tr>
<td>Fraunhofer ISE</td>
<td>10</td>
<td>10</td>
<td>22.11.2013/</td>
<td>06/08/2013</td>
</tr>
<tr>
<td>JRC-IET</td>
<td>10</td>
<td>10</td>
<td>not delivered</td>
<td>15/11/2013</td>
</tr>
</tbody>
</table>

Most project partners have initially tested during the first period on the ZSW stacks whereas measurements using the CEA stack were predominantly performed during the second phase of the project. Except CEA stack initially dedicated to JRC all Stacks were delivered in agreement with test scheduling. During the project, a certain number of stacks were refurbished in order to complete the test program in partners facilities.

Both manufacturers (CEA and ZSW) provided their stacks with an initial polarization curve, obtained after the initial conditioning phase, in order to check and validate the performances before delivery to partners. Results are resumed in Figure 31 and in Figure 32 for ZSW and CEA stacks, respectively. As shown on this figure, for a same technology, the performances obtained at beginning of life are quite comparable and as a consequence could be used in order to compare results obtained in the different work packages during the experimental phases. A complete description of the beginning of life characterisation of the stacks was sent to the partners, compiled in deliverable D6.2 “Stack Sample Report”.
Figure 31: “beginning of life”- polarization curve of the ZSW stack provided to Stack-Test partners.

Figure 32: “begin of life”- polarization curve of the G stacks provided to Stack-Test partners.
3 Potential Impact of the Project

The developed procedures for performance, durability and safety testing are prepared and validated in a consistent manner and can be used in industry for quality management for stack manufacturing and for stack benchmarking by system integrators with respect to the specifications of the system and the application. By the use of the test procedures with defined Test Operating Conditions, the tests of different stack manufacturers may become comparable and allow the assessment of stack performance, endurance and safety without additional test series by each system integrator.

Furthermore, the test procedures provide a common basis to be used in research projects on PEM fuel cell stacks in order to validate the respective development in each project and compare the results among different projects. Consequently, the key achievements within a project can be reliably assessed.

Test Modules and test Programs have been communicated to other FCH-JU projects where they have been used as a basis for stack related test tasks.

The project provided a New Work Item Proposal to the IEC TC-105 for performance testing of PEM fuel cell stacks. If accepted, the project results can be carried over to an international platform. Furthermore, regular maintenance is part of international standardization to take future development and findings in PEM fuel cell testing into account.

In general, the successful development of harmonised test procedures for PEMFC stacks within Stack-Test can support and accelerate the development of stack components and the improvement of the stack design. Thereby, the introduction of this technology to the market can be supported for the different applications.