METROLOGY for HYDROGEN VEHICLES 2

REPORT:

A4.3.1: Review on current measurement procedures and protocols for FC stack measurements for road applications

Authors:	Florian Ansorge, Ulrich Misz, Sylvie Escribano, Jaana Viitakangas

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Author(s) Florian Ansorge, ZBT, F.Ansorge@zbt.de Ulrich Misz, ZBT, ZBT, U.Misz@zbt.de Sylvie Escribano, CEA, Sylvie.Escribano@cea.fr Jaana Viitakangas, VTT, Jaana.Viitakangas@vtt.fi	**Pages** 27 pages

Summary

This report provides an overview of test protocols for measuring on fuel cell stack level. It was noticed that the development of stack test protocols was particularly advanced within European consortia and EU projects. Direct information from industry could not be added despite a request.

Based on the review, a further chapter was drawn up to provide a compact description of limits to be observed in the interaction between hardware and test protocols. In particular for system-related measurements with integrated recirculation loop, the design and measuring points must be clearly defined. Even if the comparability of the results decreases with increasing complexity, it is still advisable to carry out measurements that are as close to the system as possible. This applies in particular to measurements regarding the influence of contaminants on fuel cell stacks. The behaviour of stack is strongly dependent on accumulation and diffusion effects, which can only be analysed with an integrated anode loop.

For more details about this project please visit https://www.sintef.no/projectweb/metrohyve-2.

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Contents

1 – Introduction

Work package WP4 focuses on recommendations that could be used for the development of a standard test methodology for FC stack impurity measurements. The focus is on measurement setups, procedures, online analysis and measurement accuracy. The purpose of task 4.3 is to identify and select procedures for FC stack measurements for road applications. Furthermore, the aim is to apply these procedures for assessment and validation at laboratory scale, but also focus on effective representativeness for road application. Table 1 sums up important milestones to achieve the targets.

Table 1 - Task 4.3 activities

Activity	Description	Due date	Partners
4.3.1	**Review on current measurement procedures and protocols (report)**	**M07**	**ZBT**, VTT, CEA
4.3.2	Testing and validation of the selected procedures	M30	**CEA**, VTT, NPL
4.3.3	Recommendations on the test protocols for FC stack measurements (report)	M34	**CEA**, VTT, NPL, ZBT

To prepare prospective providing of activity 4.3.2 and 4.3.3, the current report "review of current measurement procedures and guidelines for fuel cell stack measurements for road applications" contains the results of activity 4.3.1.

The report is based on public guidelines that have been developed in joint work as well as in public funded European projects. In addition to publicly available data, specific information from industry was also requested. The evaluation of collected data will be divided into following categories:

- Operating conditions: temperature T, pressure P, relative humidity RH, stoichiometry λ
- Load profiles, comparability to real applications to assess representativeness
- Requirements of test benches for the feasibility of different test procedures
- Comparability and aim of different test procedures and guidelines

This report reviews the available fuel cell stack test guidelines, recommendations, protocols, measurement setups to define requirements for fuel cell stack tests, which will be performed in this project. Test protocols and test benches need to be considered together. Therefore, some recommendations for test bench operation and requirements as well as a comparison between the test procedures can be found in chapter 3. This chapter can be seen as important preparatory work for final recommendations and serves primarily as support for the definition of the measurements conducted in MetroHyVe 2, particularly addressing measurements with impurities in anode recirculation loop. For complex requirements of fuel cell stack tests, a modular design of test setups following defined parameters can be necessary. For example, it does not make sense to recommend very fast and demanding load changes, if the available test bench is not capable of handling this kind of profiles. Furthermore, load cycles should be clearly defined and properly applicable for measurements to be used as an evidence to develop a standard (here, ISO 14687). Since the description of stack test measurements and protocols according to automotive application with fuel recirculation is very limited, this report reviews also single cell tests, accelerated test procedures and specific load cycles.

2 – Review on Single Cell and Stack Measurements

A general overview of the publications mostly used for this review is shown in Table 2.

Table 2 - Overview of projects including PEMFC measurements procedures and protocols

Project / Period / Published	Brief Description
Stack-Test GA no: 303445 01/2012 – 08/2015	General information for industry wide uniform performance test procedures with focus on stack test operating conditions [1].
JRC EUR 27632 EN 27/01/2016	Presenting a test methodology to examine the relative influence of individual operating parameters exert on MEA performance in single cell configuration. The focus is on operating condition and load profiles related to their influence of cell lifetime and endurance based on automotive application [2].
HyCoRA GA no: 621223 03/05/2016	Comparison between state-of-the-art test equipment, consumables and test procedures of different research institutes and one industry partner are reported. Detailed description of test benches and their operating limits and programs. Possible test bench modifications to achieve real FC automotive application are addressed. Furthermore, description of cells, stacks as well as purity of hydrogen, air and water is also reported [3].
FCTT - Fuel Cell Technical Team Roadmap 09/2017	The FCTT Roadmap addresses technical targets and guidelines for stacks and also MEAs, membranes, bipolar plates as well as test procedures including operating condition, polarization protocols and fast aging methods for MEAs as well as membranes [5].
HYDRAITE GA no: 779475 29/10/2019	First recommendation for short stack test methods and studying contaminants in automotive PEMFC systems. Including short introduction into fuel cell operation and automotive system layouts. Structure and processes of automotive anode recirculation loop is discussed in detail and challenges of precise operation determination is described [6].
ID-FAST GA no: 779565 Start 01/01/2018	Description of drive cycles profile based on fleet data analysis. Application conducted in single cells and stacks on different benches. Overall protocol includes load cycles, temperature profile, and different stops / restarts events. Application for ageing study includes steps of cycles and characterizations [7].

These publications originate from projects that recommends uniform operating conditions for PEMFC single cell or stack characterization (power, endurance, degradation, etc.) and test setups to identify the impact of contaminants on PEMFC single cells or stacks. For example, HYDRAITE project provides a description of and a recommendation for an anode recirculation operation in combination with FC stack investigations and measurements of contaminant effects on performance and lifetime. In addition, all project reports include many publicly available publications of recent years.

2.1 – Operation Conditions

Operating conditions, such as temperature, humidity, pressure and stoichiometry affect fuel cell stack performance, lifetime and degradation. In order to generate valuable test results, it is important to clearly specify operating parameters to enable reproducibility of the results and comparison between fuel cell stacks and test bench hardware. In addition to selected operating conditions for specific measurements, specifications of stack manufacturer must always be considered. Table 3 presents examples of operating parameter values for automotive-type fuel cell stack and single cell testing taken from the reports in Table 2.

Table 3 - Overview of operating conditions for fuel cell single cell and stack testing

Parameter	[1]	[6]	[2]	[3]a	[3]b	[5][1]
Temperature	Stack		Single Cell			Both[2]
Cell / stack inlet °C	70	70 - 80	80	80	60	80
Fuel gas inlet °C	70	75 - 85	85	90	65	80 - 85
Oxidant gas inlet °C	70	75 - 85	85	90	65	80 - 85
Humidity						
Fuel gas inlet RH % @T cell / stack inlet	-	50 - 60	50	50	-[3]	-
Oxidant gas inlet RH % @T cell / stack inlet	-	50 - 60	30	50	40	-
Dewpoint fuel gas inlet °C	60	59 - 64	64	64	-[3]	53 - 83
Dewpoint oxidant gas inlet °C	60	59 - 64	53	64	40	53 - 83
Pressure						
Fuel gas bar_{abs} [1, 3, 5, 6] @outlet [2] @inlet	-	1.3	2.5	1.5	1 atm[4]	1 atm
Oxidant gas inlet bar_{abs} [1, 3, 5, 6] @outlet [2] @inlet	-	1.2	2.3	1.5	1 atm[4]	1 atm
Stoichiometry						
Fuel gas stoichiometry	1.5[5]	1.5[5] 1.01[7]	1.3[5]	1.2[5]	1.5[5] 1.05[7] 1.02[7]	1.6 - 96[6]
Oxidant gas stoichiometry	1.6	2	1.5	2	2	1.8 - 108
Min. current density for stoichiometry operation A/cm²	-	0.3	0.2	-	-	-

[1]E.g. operating conditions for drive cycling. The protocol is divided into a wet (top) and a dry part (bottom). In addition, the operating conditions to measure a polarization curve as well as MEA recovery and unmitigated start-up/shutdown durability are presented in this roadmap.

[2]Operating conditions for single cells and stacks.

[3]Dry gas due to bubbler by-pass

[4]No active pressurization at both open-end operation and operation recirculation loop

[5]Fuel stoichiometry single pass

[6]Anode inlet composition of 80% H2/20% N2 (excluding water vapor)

[7]Fuel stoichiometry recirculation mode

In Table 3, the publications [2] and [3] are presenting only operating parameters for single cell investigations, while [1] and [6] are focused on stack investigations and report [5] including operating parameters for both stacks and single cells. Operating conditions in [1] are not all defined because some features like temperature and stoichiometries were here recommended by the project protocol whereas other operating conditions were specified by stack manufacturers, or even regarding the test bench used depending on the aim of the study.

However, from all the conditions listed here as known and public examples, it can be noticed clear common trends with a sharp range of 70°C - 80°C for inlet stack temperature, with relative humidity of about 50 – 60%, fuel stoichiometry of 1,5 or below 1,05 with recirculation, slightly broader range covered by air stoichiometry, probably more influenced by the flow-field design.

Temperature

The temperatures are commonly in the range of 70-80 °C for investigations of individual cells and fuel cell stacks. The temperature of 80°C is close to real cell temperature for automotive application [2]. In general, the inlet temperatures of fuel and oxidiser are chosen at least 5 °C above stack/cell temperature to prevent water condensation. This especially in the case of single cells, as the “too cold flows” would cool the cell, and therefore, probably cause water condensation an exception is the dry part of lifetime determination [5]. In this procedure, the inlet temperatures are identical to stack/cell temperature, as the MEA should not dry out during operation due to low humidity conditions.

Another difference between stack and single cell testing is the temperature control or location of temperature measurement. In a single cell, in some cases it is possible to measure the temperature of the cell by a thermocouple directly on the bipolar plate [6]. This allows an accurate determination and thus the cell temperature can be measured without deviation rate. The parasitic heat losses of the single cell are significantly higher than the internal heat output. For this reason, it is often necessary to heat a single cell via a heating loop or electrical devices for start-up and constant temperature operation. A slight cooling is only necessary at higher current densities in order to keep the operating temperature as constant as possible.

The temperature control of a fuel cell stack is carried out via measuring and controlling of coolant temperatures (measuring point next to inlet and/or outlet of stack) [1, 4]. An internal temperature measurement is difficult to realize since no central temperature measurement can be realised easily in a PEMFC stack. Particularly at high current densities, it is necessary to cool the stack actively to prevent too high temperatures that could damage the components locally. Depending on the number of cells in the stack and the current density, a temperature difference of up to 10 °C or even higher may occur. The level of stack temperature difference first related to the stack and bipolar plates design, is strongly dependent on test set up and accordingly on cooling capacity provided by the test bench. It is thus of primary importance to be clear if the temperature is controlled at coolant inlet or outlet, and to record the difference if the control is not possible. During a test, active heating or cooling should be able to provide the specified temperature level for stack operation, as defined for the measurement aim (constant temperature is most often recommended to study the impact of another parameter such as fuel quality for example).

Humidity

Humidification is required for an efficient operation and performance of PEMFC. A PEMFC membrane needs humidity for good proton conductivity. Variation of relative humidity of inlet gases due to variation of water amount by using direct evaporator or within recirculation loop ensure different operating characteristics of single cells and fuel cell stacks. Humidity can be expressed in terms of

relative humidity, i.e. ratio of the water vapour content to the maximum at that temperature, or as dew point that is the temperature to cool the gas to reach 100% relative humidity. Table 3 shows that there is a variety of values for relative humidity. In the report E, one test protocol even covers two different values for relative humidity. A fuel cell stack or an individual cell is operated in a humid or a dry condition. The relative humidity in project HYDRAITE was chosen to 60 % at operation temperature of 70°C for cathode and anode. The control of anode inlet gas humidity is more demanding with anode recirculation loop, and a constant humidity is difficult to maintain during load-cycling operation with anode recirculation loop. The lower the gas humidification, the higher the risk of the membrane drying out, especially at low current densities and high operating temperatures as well as high stoichiometry.

Humidification of reactant gases can be realized with different types of humidifiers, e.g. direct evaporator, bubble humidifier or close-to-system membrane humidifier. Different humidifier designs have an effect on the dynamics of humidification during test procedures. Bubblers, for example, must be refilled after a certain time, and their cooling can be slow. This process results in non-stationary operating conditions. In addition, the water used for humidification needs to be clean, deionized and degassed, to keep it non-conductive and to avoid adding unwanted species to reactant flow.

Recirculation of the anode gas can provide sufficient humidification of hydrogen fuel. This setup is closer to systems in real applications, but also leads to varying humidity conditions, especially when load cycles are applied. As for the temperature, even if not controlled, relative humidity of reactants should be measured and reported.

Pressure

Recommendations for operating pressure of PEMFC on the anode and cathode side varies widely in terms of defined values and location of pressure control. There are two ways possible for (active) pressure control in a test setup: A pressure reducer that is integrated upstream of the stack (and recirculation loop) or a back-pressure regulator integrated downstream of the stack (and recirculation loop). A back-pressure regulator can only be used in flow-through system. A pressure regulator works for both, dead-end operation (anode, with or without purge) and bleed (flow through).

For example, the inlet pressure can be used as a control value, both at anode and cathode [2]. Considering mass transfer phenomena and water management as well as the choice of a typical value for an automotive application, a pressure of 2.5 bar_{abs} on anode and 2.3 bar_{abs} on cathode were chosen [2]. In this respect, implementing pressure control as a back-pressure regulator could be recommended [2]. However, it can be noticed that a pressure regulator downstream of PEMFC leads to a variable inlet pressure depending on operating conditions, such as volume flow and current density.

Publications [2] and [6] specify that anode side should often be subjected to a slightly higher pressure compared to cathode side. The pressure values for stack investigations are generally often limited by the test stand-infrastructure components. Furthermore, when operating with an anode recirculation loop, the pressure rating of the recirculation pump needs to be considered. Another specification that limits the pressure values is the mechanical operating limits of the stacks.

Stoichiometry

The stoichiometry is an important key figure for PEMFC operation. It is the reciprocal value of fuel utilization of hydrogen and air. The lower the stoichiometry, the higher the rate of conversion. Also, the test setup has a strong influence on the operating stoichiometry. In laboratory test benches state

of the art PEMFC single cells and stacks are mostly operated in open-end mode. Figure 1 provides the schematic structure for the open-end operation of a PEMFC stack.

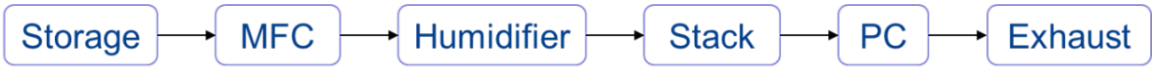

Figure 1 - Open-end test setup for PEMFC stack testing [4]. MFC is mass flow controller, PC pressure control.

In this configuration, hydrogen flows once through a stack and, afterwards, directly into the exhaust. By applying the open-end mode of operation, the stoichiometry at anode is typically set in a range of 1.3 to 1.5 and at cathode in a range of 1.5 to 2 as seen in Table 3.

This prevents a partial undersupply of reactants and should ensure a stable operation, which is for example important to hinder overlapping different PEMFC degradation mechanisms and to identify the influence of harmful contaminants on the lifetime of PEMFC stacks and single cells. Mass flow controllers regulate the reactant flows.

State of the art in automotive applications to increase the fuel utilization is a transient closed-end operation setup with hydrogen anode recirculation and a purge valve. Usually, stoichiometries in the range of 1.01 to 1.2 are achieved [4]. In addition, hydrogen is supplied in a pressure-dependent manner. The purge valve is normally closed. In pressure-controlled operation and with a closed valve, only as much hydrogen is supplied as is consumed by the reaction. The purge valve opens periodically for a defined time of a few milliseconds to a second to purge nitrogen diffused from cathode to anode as well as non-separated water out of anode department. During this process, a residual amount of unconsumed hydrogen is also transferred out of the anode system. This is the reason why a 100% turnover of hydrogen is not possible in real application. The purge strategy is strongly dependent on stack (e.g., diffusion coefficient of membrane and flow-field design) and operating strategy. To collect high amount of condensing water, a water trap is installed in the piping in the lowest part of the loop [4]. This also enables the partial removal of water-soluble harmful components that could negatively affect the performance of the cell. As a result, stack operation with recirculation set up and water separator might need an analysis of contaminant concentrations at different defined points in anode loop [4]. The use of an anode recirculation setup influences PEMFC contamination dynamics [3]. Figure 2 shows the schematic structure of an anode recirculation system, which is similar to an automotive application.

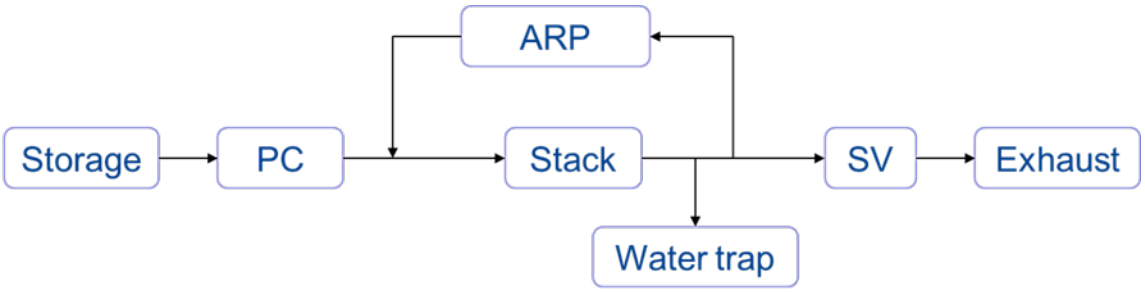

Figure 2 - Anode automotive fuel cell system recirculation configuration [4]. PC is pressure control, ARP is anode recirculation pump and SV is purge valve

In addition to the description of anode recirculation setup, the publications also contain a few remarks on operation with anode loop. For example, the anode recirculation rate and relative humidity of the recycled hydrogen regulate the relative humidity of the stack depending on the operating setpoint.

Moreover, measurements of hydrogen concentration and monitoring its variation in concentration due to cathode diffusion and oxidation is mentioned. However, analytics and measurement of specific gas compositions is not the subject of this report.

Besides projects HyCoRA and HYDRAITE, there is limited publicly available information, which is representative for automotive applications, regarding operation of anode gas recirculation. After reviewing and describing the operating parameters, the following sections (subsections) provide information on the current status of the essential parts of PEMFC single cell and stack test protocols. The essential functions of the leakage test (Chapter 2.2), the break-in and preconditioning procedure (Chapter 2.3), different load profiles (Chapter 2.4), and options for determining the performance and lifetime of PEMFC stacks and single cells are described.

2.2 – Leakage Test

Each test should start with a leakage test [1, 2]. This is primarily for safety purposes, as leaks can be detected at an early stage and also for overall efficiency. A leakage rate can be determined by measuring the pressure drop over a defined period of time. The leakage rate should be defined according to the test setup and be as low as possible, since otherwise the actual volume flows will be considerably reduced during the test due to the leakage rate. Depending on gas supply, this leads to erroneous results, since, for example, the stoichiometry and the humidity are changed. The measurement time and pressure level as well as a suitable pressure drop acceptance criterion must be specified in advance. A general specification of the leakage rate is difficult to realize, as it depends on the complexity of the test setup and the leakage rate of the stack. It is recommended to follow specifications defined by the stack provider if available.

2.3 – Break-in and Preconditioning

After the successful completion of a leakage test, a break-in and a preconditioning of a PEMFC stack or a single cell is carried out. It is important to distinguish whether a stack need a break-in procedure or whether it only needs to be preconditioned before testing. In the case of break-in procedure, specific processes are carried out that push the stack to its maximum performance level as quickly as possible. These processes are MEA and design dependent and often specified or carried out directly by the stack manufacturers.

Break-in

Break-in procedures are primarily designed to achieve stable operating stack conditions to provide a basis performance level for further assessment of degradation. The break-in is carried out for the initial startup of a stack or single cell. Break-in procedures and operating conditions are described in publications [1], [2] and [6]. As a general guideline, stack manufacturer also specifies or has already carried out the necessary sub-steps for initial operation of PEMFC single cells and stacks. Several variants of break-in procedures exist, but they all follow the same purpose. During a break-in procedure, the aim is a completely conditioned PEMFC single cell or stack electrolyte and to achieve a constant and maximum voltage profile and a defined nominal electrical power [1, 2]. Figure 3 shows an example of a typical break-in process of a PEMFC [6].

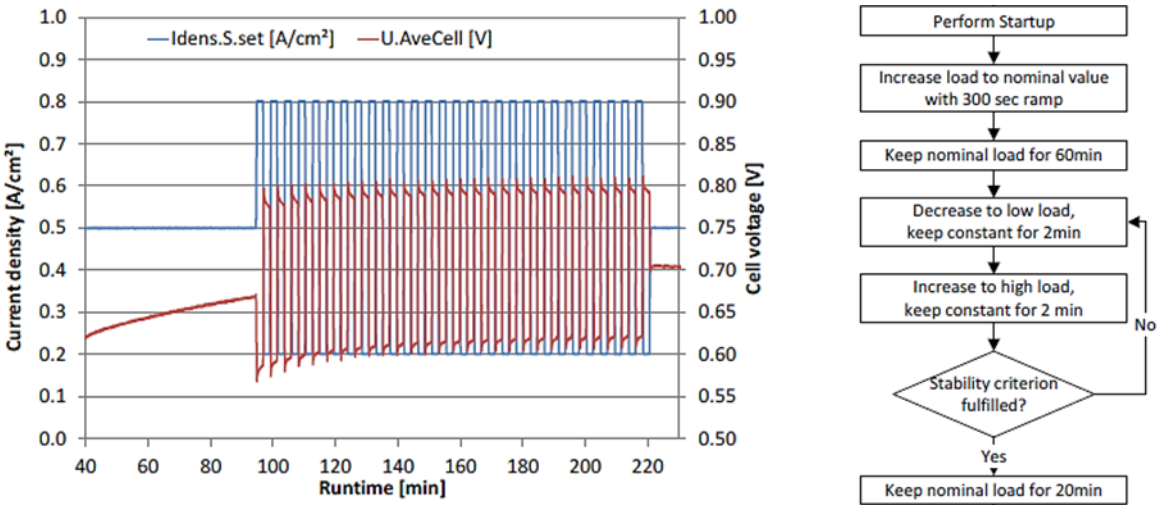

Figure 3 - Example of a break-in procedure for PEMFC conditioning. Current density in blue and cell voltage in red [1].

Initially, the stack is operated at a constant current for 60 min, for example, to increase the power of the stack. This process is often carried out at high current densities and therefore good self-humidification of the stack. Afterwards, current changes between 0.2 and 0.8 A/cm² follow. The increasing trend of cell voltage indicates that the power increases during the break-in procedure of a PEMFC stack until a stable operating state is reached. A stability criterion is used to determine if a stable operating state is reached [1]. The stability criterion is checked by measuring voltage variation at a constant load point for a specified time period [1, 2]. If the stability criterion is not reached, the break-in process is repeated or extended, and the stability criterion is subsequently checked again [1, 2]. Figure 4 shows the voltage curve for evaluating the operational stability.

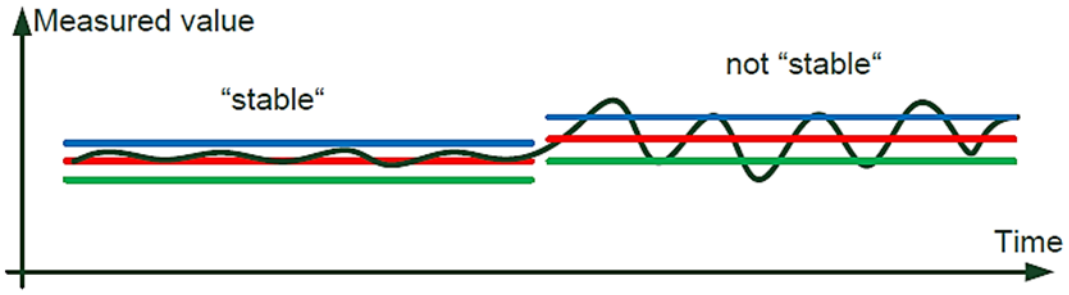

Figure 4 - Stability criterion to evaluate a constant performance of the PEMFC single cell or a stack [1]

Preconditioning

Before performing tests, the stack or single cell should be preconditioned [1, 2]. The preconditioning guarantees that starting conditions are as comparable as possible before each experiment, thus ensuring comparability of test results. The conditioning conditions are based on the operating conditions from Table 3. Preconditioning is a quick (though not comprehensive) tool allowing to check the status of the stack before each measurement. In this way, differences can already be identified as a function of test setup or as transport consequences but also regarding possible alteration during one measurement step of an experiment. An example of a preconditioning procedure for PEMFC is given

for stacks in publication [1] and for single cells in report [2]. After preconditioning, defined load profiles can be used to assess performance, lifetime and possible influence of harmful components or operating conditions on stack. For this purpose, it is necessary to specify suitable profiles in advance, especially to enable comparability.

2.4 – Load Profiles

Some load profiles and procedures are described in publications which are suitable for determining performance and degradation of PEMFC single cells and stacks. For example, polarization curve, static load conditions, dynamic load conditions or CO reference measurements as procedure are suitable for this purpose. In each case, the goal must be defined in advance. For example, identical loads are recommended in different load profiles of a test procedure in order to be able to evaluate defined degradation rates under different load conditions of the stack. The CO reference, on the other hand, is a good method for evaluating indirectly the active catalyst area of the anode with respect to CO tolerance. However, it must be ensured afterwards that CO is completely removed from the catalyst thanks to a cleaning oxidative procedure to enable relevant comparison afterwards. All evaluations and load profiles must be carried out in a reproducible manner.

Polarization Curve

Operating parameters for performing polarization curve are given in all publications. The polarization is an easy to practice method and basically used to determine irreversible performance loss of PEMFC single cells and stacks over time [1]. During the performance, the current density is increased or decreased stepwise and resulting voltage is measured. It is important to reach a constant voltage as result at each operating point. In addition, the operating time at low load level should be relatively short in order to prevent drying out as well as long time at high voltage promoting increased platinum oxide formation. For example, the operating time of load points with low current density is limited to a maximum of 60 seconds and load points with high current density are operated for at least 120 seconds [2]. This ensures that the PEMFC voltage stabilizes under the applied operating conditions at the respective operating point. It is usually recommended to calculate a voltage average over the last minutes of the respective current stage and to use this value as an evaluation. Several testing methods, including the harmonized EU test protocols for PEMFC MEA testing in single cell configuration for automotive applications [JRC], to perform the polarization curve or evaluate performance data have been proposed and first standardization action was conducted within the IEC TC105 to propose the document IEC62282-7-1 Test methods – Single cell performance tests for polymer electrolyte fuel cells (PEFC).

Depending on operating conditions, the maximum current density is defined in advance and subsequently operating points as well as the step widths are defined. By repeating the curve at fixed time periods during stack tests, change in performance over time or a relative voltage decay can be measured. By comparing voltage values, degradation rate at defined load points of PEMFC cell and stack can be determined. Figure 5 presents an example of the comparison of polarization curves.

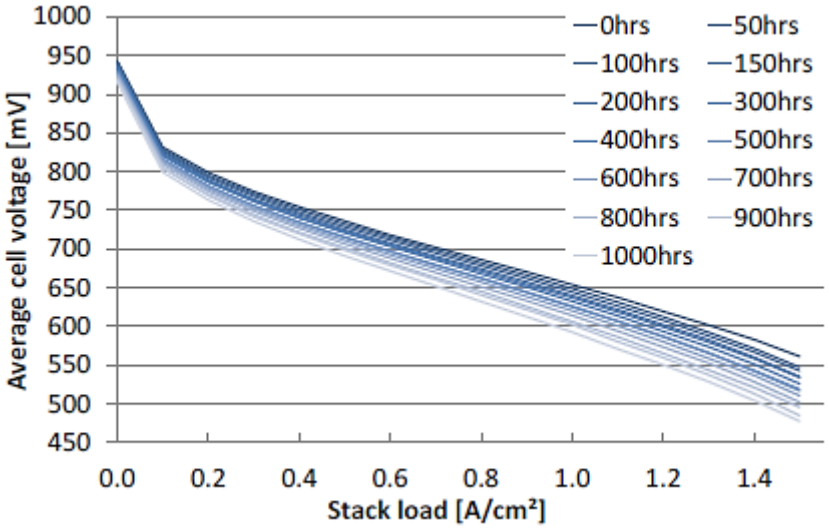

Figure 5 - Polarization curves comparison at different test times [1]

Constant Load

One method for determining a time-dependent voltage loss of a PEMFC single cell or a stack consists in the analysis of the voltage curve during constant load operation. The simplest method is to compare voltage end and start and taking test time into account [2]. As a result, a time-dependent degradation rate can be determined. Typically, the degradation rate is given in the unit µV/h. In addition to considering the entire test interval, linear regression can be used to determine the degradation rate in different time intervals. Depending on the duration of the test, the degradation rate could be used to make initial predictions regarding lifetime of stacks. This method is suitable for lifetime studies.

Dynamic Load Profile FC-DLC

For good comparability between real application and investigations in laboratory test benches, it makes sense to determine a load profile that represents driving profiles of a vehicle. Since load profiles in vehicles could run very quickly and variably, depending on hybridization scheme, compromises have to be made when implementing such profiles in test benches. The Fuel Cells Dynamic Load Cycle Profile (FC-DLC) has been established as one of several for this purpose in recent years [1, 2, 6]. This is a dynamic load profile that is carried out according to a defined scheme. It is based on the "New European Driving Cycle" (NEDC) and simplified for fuel cell testing [2]. Moreover, to prevent operating conditions at critical cell voltages the stack is operated at minimum load of 5 percent derived from the maximum load point. In addition, the triangular signal of the NEDC has been converted into a square-wave signal. The running time is approximately 20 minutes per cycle. For this reason, several cycles are often run in a row. Due to the quite fast load changes and partly strong load steps, it is necessary to use a test bench that is able to reproduce this dynamic. Figure 6 shows the load profile of the FC-DLC.

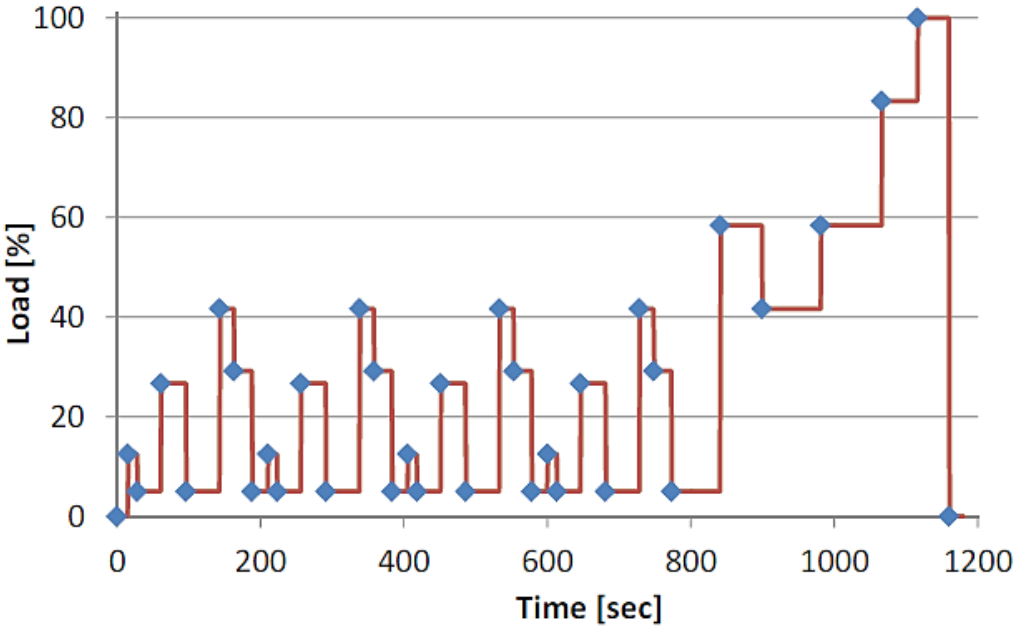

Figure 6 - Load profile Fuel Cell Dynamic Load Cycle (FC-DLC) [2]

Similar to the determination of degradation rates with a static load operation or polarization curves, the FC-DLC can also be used to compare these values. To differentiate between reversible and irreversible voltage loss, the presented load profiles are possible in combination with regenerative processes. For this purpose, in addition to the load profiles, start-stop processes can be carried out under defined conditions.

Possible approaches to these processes are described in publications [1, 6]. In most cases, reversible voltage losses are higher than irreversible ones [2]. The assessment of whether a voltage loss is reversible or irreversible is also particularly important for investigating the effects of harmful components. For measurements concerning particularly the impact of anode side, such as tests about hydrogen quality, a CO poisoning reference can be carried out to determine the reduction of active catalyst area on anode due to harmful species or load profiles. Nevertheless, there are more accurate ways to measure active catalyst area than CO poisoning, e.g. cyclic voltammetry. However, they might be difficult to perform for a stack within any test bench. The faster the voltage drops under constant CO contamination at a constant load point, the further the degradation has progressed. This method is used in the test procedures of publication A from HYDRAITE project, including stacks studies with anode recirculation. In Table 4 the load points and operating times of the FC-DLC are given.

Table 4 - FC-DLC test points, time and loads [2]

Loop	Step	Dwell [sec]	Load [%]
	1	15	0
4x	2 / 9 / 16 / 23	13	12.5
	3 / 10 / 17 / 24	33	5
	4 / 11 / 18 / 25	35	26.7
	5 / 12 / 19 / 26	47	5
	6 / 13 / 20 / 27	20	41.7
	7 / 14 / 21 / 28	25	29.2
	8 / 15 / 22 / 29.1	22	5
	29.2	46	5
	30	58	58.3
	31	82	41.7
	32	85	58.3
	33	50	83.3
	34	44	100
	35	21	0

Based on FC-DLC, which is representative of an automotive application, a load profile for heavy duty application can also be created by adapting some parts. By increasing dwell times of load points, reduced dynamics are achieved and the proportion of static load increased. In any case, however, it must be ensured that during load points at low current density humidification is still sufficient to prevent dry out effects of membranes. Specific load profiles for heavy duty applications are not yet available but could be proposed during the time frame of this project. If possible and relevant, they could be considered for some measurements to be applied or within the report on final recommendations.

Start-up and Shut-down of Single Cell and Stack

Most difficult to define and therefore also to compare are start-up and shut-down processes of a stack. Start-up and shut-down of Single cell or stack that are carried out incorrectly can lead to increased degradation. Hence stack-specific modules (procedures) are also defined. The modules contain process steps, e.g. heating, reactant flows, pressurization, adaption of humidification, keeping or changing stack load. Existing definitions of start-stop procedures intend to reflect more or less systems specifications for real applications. When real start-stop procedures are carried out without nitrogen, attention is drawn to safety aspects in the implementation in the test bench. Detailed descriptions of possible start-stop processes were created especially within HYDRAITE project [6] based also on the procedures previously developed and described in the STACK-TEST project. In general, both testbenches and PEMFC stacks are built individually and are subject to certain operating specifications. A simple transfer of the presented load and operating conditions profiles from the various publications to a representative PEMFC stack study is therefore often not practical. In particular, experience from the test set up operation should also be considered to adapt appropriately the procedures.

2.5 – ID-FAST Load Cycle and Durability Test Program

As an example of the description of load cycles and test programs, the following ID-FAST drive cycle is presented in an extended form. Choosing a relevant load cycle, e.g. realistic for the automotive application, and defining an appropriate durability test program poses a major challenge when trying to perform meaningful ageing experiments on a fuel cell test bench with the objective to mimic the conditions the stack would experience during vehicle operation.

Thus, the ID-FAST consortium decided to spend some effort to define a representative drive cycle, based on comprehensive customer fleet data available at the partner BMW. In the following, the drive cycle and the methodology used by BMW to derive it will be briefly explained. Of course, introducing a new test protocol requires comparison to the existing ones, specifically the FC-DLC. This will be dealt with in a separate publication planned by the IDFAST project.

The "ID-FAST drive cycle" can be operated on a test bench and is based on known relevant customer data such as vehicle speed over time, state of the art electrical powertrain hybridization- and FCS operation-strategy, cross-checked with "avoidable" events from FCEV Demo fleet operation.

The fuel cell system load cycle ("ID-FAST drive cycle") was derived from several thousand hours of real vehicle data from customers (vehicle speed versus time). The fuel cell system power cycle (P(FCS) vs.t) was obtained by applying a vehicle or powertrain hybridization model and also contains information on fuel cell system or fuel cell stack temperature vs. time.

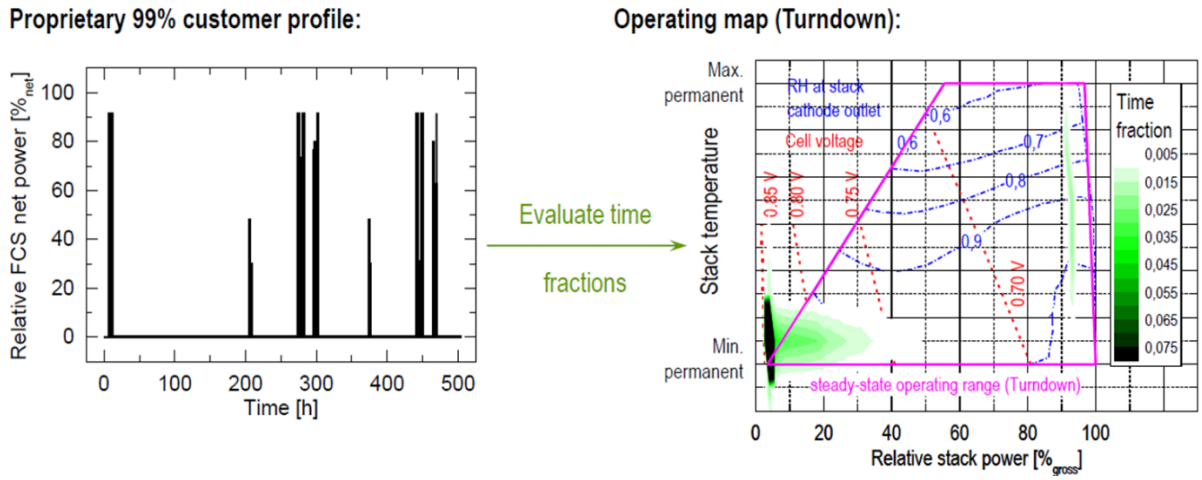

Figure 7 - Visualization of the customer use profile derived from data covering several thousands of operating hours driven by BMW customers in their ICE cars (left). This is use profile was transformed into a 'heat map' of operating conditions (right).

A FCS power distribution, which represents 99% of the customers for the class of vehicle chosen, was obtained using statistical methods from the data shown in Figure 7 (left). Next step in deriving a testable stack load cycle was to use a state-of-the-art FCS operation strategy model to translate this power distribution into a heat map based on stack power (P(Stack)) and stack temperature (T(stack)) for the 99% customer load cycle. The main stressors considered were half-cell potential (approximated with cell voltage), stack temperature and MEA relative humidity (RH). Figure 7 (right) shows the heat map, the permissible operating range is shown in purple. Figure 7 (right) also features the equal-voltage lines and the equal-RH lines calculated from the proprietary FCS model and experiments.

Further simplifications concerning voltage, temperature and RH domains were done in order to finally design the "ID FAST load cycle" shown in Figure 8. As a remarkable feature, it contains a simultaneous rise of temperature and RH starting after 45 minutes corresponding to the highest load requests, followed by a decline back to the nominal level. Whereas this is clearly closer to the conditions in a real vehicle system than testing at constant temperature and RH over the complete time, of course it is also more challenging to perform this cycle on a standard fuel cell test bench.

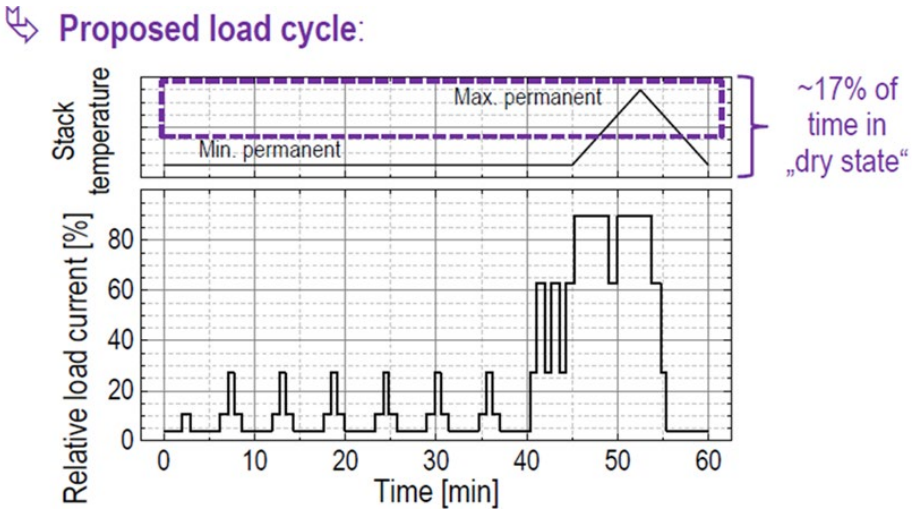

Figure 8 - ID-FAST drive cycle proposed as the key building block of a realistic durability test program.

Further elements of the ID-FAST durability test program (Short Stop, Cold Soak, Long Stop) are explained in the following, with a detailed description of two test modules, Short Stop, Cold Soak and Long Stop as defined by the ID-FAST project mostly following the recommendations of the STACK-TEST project, are given [1].

Short stop

The short stop procedure is intended to reflect during a durability test program that a real vehicle is very rarely operated for several hours without stopping. Thus, the ID-FAST test program contains this element with relatively high frequency (each half hour / each hour), which is a substantial difference to the way testing was performed in former FCH-JU projects as IMPACT, AUTOSTACKCORE etc. It differs from the way the shut-down procedure is performed according to the STACK-TEST recommendations especially insofar that nitrogen purging is omitted as it is not realistic during vehicle operation. The short stop is performed as follows:

a) Reduce electric load to minimum load value needed for voltage clipping to 850 mV or 0.05 A/cm², as applicable, and simultaneously gas flows to the minimum flow value defined for stoichiometric operation (corresponding to 0.2 A/cm²). Reduce gas pressures to ambient.

b) Turn off the oxidant flow while keeping the minimum fuel flow and the minimum load value until the mean cell voltage drops below 0.2 V. Negative cell voltages must be avoided during this procedure.

c) Turn off the electric load

d) Remain in this state for 5 minutes, then start-up again. Specifically, do not cool down the stack, maintain the cooling liquid temperature and the minimum fuel flow during the complete time. Only air flow and electric load are turned off.

Cold Soak

The cold-soak procedure defines a prolonged stop and serves to mimic regular stops during vehicle operation which are long enough to allow for complete cool down of the system. During the ID-FAST test program, this element is used less frequently than the short stop, though by far more frequently than the shutdowns which were performed during durability test programs in the past, e.g. in the IMPACT or AUTOSTACKCORE test programs. It is performed as follows:

a) Perform steps a)-c) of the short stop procedure described above
b) Stop fuel supply
c) Bring down the stack temperature below 25°C as fast as possible by actively cooling via the cooling water flow, preferably within 10 minutes (if feasible on test bench used).
d) Close both anode and cathode stack in- and outlet valves.

Remain in this state for 2 hours, then start-up again. During this time, the minimum cooling liquid flow may be maintained for reproducible temperature control.

Long Stop

This procedure is specific for the ID-FAST durability cycle. It serves on one hand for anode reactivation and on the other hand introduces an additional stressor (off-spec event) which is a hydrogen/air front going through the anode at start-up. This procedure mimics the situation that a car is left in shutdown state without being started for a long time (several days/weeks), so diffusion between anode and cathode will lead to gas mixtures and specifically to a significant concentration of oxygen on the anode side. For the ID-FAST durability test program, it was decided that this should be a rare event, thus it is only performed after every 200th regular load cycle. It is performed as follows:

a) Perform steps a)-c) of the short stop procedure described above.
b) Stop fuel supply
c) Bring down the stack temperature below 25°C as fast as possible by actively cooling via the cooling water flow, preferably within 10 minutes (if feasible on test bench used).
d) Purge the anode compartment of the stack with dry nitrogen. The absolute flow rate depends on the stack employed. It is recommended to employ at least nitrogen flow equivalent to the minimum hydrogen flow for stoichiometric operation for at least 3 minutes to ensure vanishing hydrogen concentrations.
e) Close both anode and cathode stack in- and outlet valves.
f) Remain in this state for at least 12 hours. During this time, the minimum cooling liquid flow may be maintained for reproducible temperature control.
g) Purge cathode with air to induce diffusion to the anode side, it is recommended to employ at least the minimum air flow for stoichiometric operation at full humidification (dew point 25°C). Continue purging until voltage vanishes or at least for 3 minutes.
h) Stop air flow, wait for 5 minutes.
i) Perform normal start-up procedure, but with two important deviations:
    a. Do not use any nitrogen purge during start-up (maybe used for normal start-up, depending on the requirements of the stack design)
    b. Instead of the minimum gas flows for stoichiometric operation, employ flow rates equivalent to 1.0 A/cm² on both anode and cathode for at least one minute or until stable operation is reached.

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. The over-stoichiometric gas flow defined in step i)b will ensure defined conditions for the hydrogen/air front and will keep the time during which the front passes through the cell/stack short enough to avoid excessive damage.

3 – Review on Test Protocols

The aim of the report is to provide an overview of available single cell and stack test protocols with associated recommended or specified operating parameters. The research on protocols for stack tests revealed that, with the exception of some collaborative work and EU projects, only limited information is available. In order to obtain further information, contact has been made with the industry (several OEMs or stack manufacturers). However, this request for information on current test methods and test protocols did not result in any further usable input because many procedures are configured for individual stacks and system setups and are treated as confidential.

Accordingly, the information content is not very comprehensive, especially with regard to operation of fuel cell stacks in a close-to-system environment. For this reason, the report has been expanded to include the chapter "Recommendation and application of test protocols". The aim of the chapter is to focus on the comparability of test protocols and, in particular, on their practical application in and requirements for test benches. In addition, some experiences of ZBT with regard to stack tests are presented as supporting examples.

It is obvious that an increase in the complexity of test setups leads to a decrease in comparability of test protocols and results. This conclusion is particularly noteworthy with regard to an evaluation of impurities impact including accumulation effects and the possibility of integrating monitoring techniques in a test setup.

3.1 – Development of Test Protocols

The development of test protocols for stack measurements depends on both the objective of the measurement as well as possibility of implementation and reproducible realization of the tests. Examples of test protocol objectives are:

a) Assessing the performance level and stability of a stack regarding transport application by applying realistic test protocols or derived from real drive cycles.
    a. with or without contaminant
    b. For Light-duty vehicle or heavy-duty application
    c. Reproducing representative load profiles and start-up /shut-down steps.
b) Assessing durability but in a period of time shorter than in real life by applying accelerated aging protocols
    a. Designed to increase performance degradation rates
    b. Defined so as to promote real-life degradation mechanisms or phenomena by imposing selected stressors, e.g., longer periods at high potential for exacerbating oxidation issues for catalyst materials or coatings of metallic bipolar plates or harsher conditions (variations on temperature or relative humidity, on reactants feeding) or simulating the impact of specific events such as start-up / shut-down.

Accordingly, it must first be defined what should be required for the expected test protocols to be tested and validated. In order to avoid the need to define a large number of different test protocols, it is recommended to work in a way to define modules (procedures) that are more comfortable to define, apply and reproduce. In the following the procedures can be combined according to the required test protocol, e.g.:

a) Conditioning and break in procedures
b) Start-up / Shut-down procedures
c) Polarization curve (e.g. for degradation evaluation)
d) Load cycles

The more defined the procedures, the better the reproducibility and comparability. The disadvantage of a high defined module is the limited possibility of implementation in different test benches, e.g. with regard to defined times for heating processes and load changes. This is particularly the case with increasing system orientation of test setups. Therefore, only best possible recommendations can be given, the implementation has to be questioned at all times. In the following, some examples are given for limitations of test benches depending on planned setup and test protocol. Furthermore, first recommendations regarding comparability of protocols and test benches are given.

3.2 – Test Setup Configuration in Combination with Test Protocols

Depending on a test bench set up, limitations may exist that could affect the comparability of test results. Experience in performing stack tests shows that deviations increase compared to single cell measurements. This must be considered when creating test protocols for stack tests. In addition to the actual specifications for operating parameters, the requirements for the test setup must also be highly defined. This can be achieved not only with a nomenclature of the measuring points, but also with clear specifications for the test setup. The more system-oriented the setup should be, the more clearly dimensions and design must be defined, for example, pipe/tube diameters, heating concepts, exact location of measuring points and finally a compact design of a recirculation loop. An additional factor is the stack itself. Some parameters such as power output, max. current density, cooling concept, pressure drop, etc. are important factors that must be known in advance. In the following, limitations are described and discussed with the aid of some examples. The focus in chapter 3.1.1 is on operating conditions such as temperature, humidity, pressure and stoichiometry.

3.1.1 – Operating Conditions

Stack Temperature

In the case of stack measurements, the stack temperature is usually set by controlling the coolant temperature. The measuring points should be located just before the coolant enters the stack and next to stack outlet. In most cases, control is based on input temperature. Nevertheless, the measuring point at outlet is also very important in order to be able to determine delta T of the stack, especially during operating at high current densities. The coolant should be able to adequately dissipate the waste heat of the stack at maximum current densities. In case of insufficient heat removal, a significant temperature increase will lead to increased degradation and reduced comparability of the tests. As a consequence, it is advisable to reduce the maximum load point accordingly. Heating of the stack is also intended in various protocols. The heating capacity of test benches should be dimensioned sufficiently to ensure that specified temperatures can be reached within a defined period of time. Heating processes are often specified in start-up / shut-down procedures. In some cases, stack heating

must be realized active by test bench. In system-oriented tests, heating of the stack without external support is also conceivable.

Gas Temperature

The gas temperature at stack inlet should always be higher than stack temperature, respectively stack temperature should always be higher than dew point of supplied gases in order to avoid condensation. Continuous heating of feeding tubes or hoses is mandatory. In particular, the location between heating hoses and stack connections can be problematic, depending on the set-up, as in some cases this area is not heated or insulated sufficiently.

When using a direct evaporator, the distance between evaporator and stack should be designed to be sufficiently long. Otherwise, at high volume flows, the gas temperature at stack inlet may be significantly too high and damage the MEA. Larger pipe cross-sections to slow down gas velocities are one possibility to solve this problem. The risk of too high inlet gases can be reduced when using bubble or membrane humidifiers.

Humidity

Humidification of the reactants is one of the most important parameters and strongly depends on the membrane used as well as the load profiles. In combination with fixed minimum volumetric flows during stack tests, see also next subsection, the membrane can rapidly dry out, especially during operation at low current densities and without sufficient gas humidification. This situation is exacerbated by simultaneous stack operation under high temperatures. The FC-DLC is an example of a load cycle with a relatively large percentage of low-current phases. If the maximum current density is known to be limited, it could be recommended to reduce the stack temperature or to increase the humidification.

Large deviations of humidification on the anode side can result from integration of a recirculation loop. The loop is considered as a passive humidification, which in turn varies depending on stack design, on current density and recirculation rate. With an integrated humidity sensor at stack anode inlet, the humidity can be measured and if possible configured as a function of recirculation rate at different current densities for better adaption to the properties of membrane. A system-based setup using only passive humidification entails the disadvantage that reproducible measurements are more difficult to achieve. Accordingly, an additional active humidification on the anode could be recommended as an alternative if needed to better mimic the system case. With this combination, however, the active and passive humidification must be precisely harmonised.

Stoichiometry

Stoichiometric operation of a stack in open end mode offers the best possibility for reproducibility of test protocols. Stoichiometric operation is the easiest for both application and reproducibility, but it is not real system-like.

In any case, a minimum fixed flow should be defined to prevent extremely small flows resulting in an uneven gas distribution and consequently undersupply of a stack. The minimum constant gas flow to be defined depends on several factors such as mainly flow-field design, gas feeding conditions (gas pressure and humidity).

However, operating the stack under stoichiometric control in through flow mode, if easier and more convenient for reproducing same conditions from one test set up to another, shows the drawback to be non-representative of systems operation (dead-end mode or recirculation with purges).

3.1.2 – Load Profiles

The faster load changes in profiles, the more these profiles are representative of real automotive application protocols. Particularly when performing rapid load changes, especially with large spreads, it must always be ensured that the stack is supplied with a sufficient amount of gas to prevent undersupply. In principle, electronic loads work faster than mass flow controllers. This means that a simultaneous increase in current density and gas supply can lead to a short-term undersupply of the stack. It is therefore recommended to first increase the gas flow and afterwards the current. The needed time span is specific to test setup. For information, a period of 3 seconds seems to be sufficient in most cases. With a pressure-regulated supply, there is always an adequate gas supply, as the pressure regulation usually reacts very quickly.

In most load profiles, the individual defined load steps are given as a percentage of the maximum current density. This definition makes perfect sense, as each stack has different maximum current densities depending on the design, the core components, the requirements or operating conditions. By specifying the maximum current density, load cycle and polarization characteristics can be clearly defined. After finalizing this specification, it is advisable to set minimum gas flows. Depending on the definition of a respective maximum load, the load profile may need to be sharpened in individual cases. For example, if a low maximum current density is specified, phases at very low current densities with correspondingly high cell voltages could become too dominant, possibly resulting in a higher degradation rate of the stack.

The FC-DLC is meanwhile used in many national and international projects and, by using appropriate operating conditions, it offers a good comparison with some breakpoints that can definitely be used as a degradation assessment in addition to polarization curves. Nevertheless, as already mentioned, the objective of the test protocol should be considered first. The FC-DLC seems to be suitable as a good, stable and reproducible load profile that can be used during investigations for a limited period of time, for example analysing the influence of harmful gases or also for lifetime assessment. Load cycles are only one of many procedures within a protocol. To get representative results it seems to be necessary to integrate start-up and shut-down procedures. In addition, depending on the duration of the test protocol, a repeated evaluation of the stack degradation rate should be integrated as a module.

3.1.3 – Degradation Analysis Methods

The aim of many test protocols is to determine degradation rates under defined operating conditions. Electrochemical measurement methods such as impedance measurement and cyclic voltammetry offer the possibility of targeted analysis of degradation mechanisms. The application of these methods is easier with single-cell set up compared to stack. However, CV and impedance measurements are also used at stack level. In order to achieve reproducible and accurate results, attention must be paid to the test setup and the measurement methods have to be adapted to stack requirements. This particularly requires electrical knowledge and advanced measuring devices due to higher number of cells, which also do not react uniformly and cannot be electrically disconnected during the measurements. An incorrect measurement setup or misunderstanding of electrochemical measurements will result in non-usable test values. A comparison of electrochemical measurements of stacks is accordingly complex. Currently no recommendations or fixed definitions are available.

For this reason, polarization curve as well as defined load points in load profiles are the most common degradation modules for evaluating stacks. In addition, CO reference measurements were introduced in HYDRAITE project, which provide a reproducible method to follow the evolution of the anode active catalyst surface of a stack.

Voltage - Current characteristics can display the trend of stack degradation at different load points when carried out repeatedly. Since each unit cell voltage is also measured in most stack tests, different degradation rates of individual cells can be determined accordingly. This is an important information in addition to the trend of an average stack voltage. A so-called bathtub curve is indicated as a result of many degradation evaluations. This means that the highest degradation rates can usually be seen in areas of low and very high current densities, while the lowest voltage losses are measured over time at a moderate average load.

The CO reference measurement has proven to be a sensible method for assessing the changes in the active surface of the anode catalyst, especially in tests with regard to Hydrogen impurities. Based on experience made within HYDRAITE project it can be noted that a precise definition of the operating conditions cannot be made easily without an information of the stack behaviour in operation. For example, it was defined that the anode side is contaminated with 5 ppm CO until a voltage drop of 50 mV of the average voltage or time range of 1 hour has been achieved [6]. Depending on the active catalyst area, this process can take several hours. For reproducibility of the measurement, it is important to define a specified current density for contamination and to guarantee a constant, non-deviating supply of harmful gas. In addition, it must be ensured that after each contamination CO is oxidised from the catalyst so that the following measurement can be started with a clean catalyst surface. This process can be done, for example, with an anode air purge during the shutdown procedure. Safety precautions and implementation on test benches must be checked before application of test methods. For impurity measurements with fuel cell stacks.

Nevertheless, the CO reference method is a good additional support for analysing degradation effects. For example, after stack contamination with hydrogen sulphide, a performed polarization curve has come close to the values of a U-I characteristic before sulphur contamination. This surprising result was achievable since the maximum current density was not set very high in the test protocol. In contrast, the CO reference measurement showed a significantly faster voltage drop compared to the results before contamination. This clearly indicates that the active area was still significantly reduced and the stack was partially irreversibly damaged. The described results do not mean that a polarization curve cannot provide useful information about degradation trends. However, it becomes clear that additional degradation tools can be helpful in some specific cases. Again, it is shown that the definition and implementation of a test protocol is strongly dependent on the integrated and used stack. CO reference and polarization curves can be defined and set up as modules and integrated in test protocols to the appropriate processes.

3.1.4 – Additional Test Procedures

In addition to load profiles and the determination of degradation, further modules are proposed for creating a test protocol. When operating a stack for the first time in a test bench, it is important to have a preconditioning procedure to determine stack performance under the existing conditions. With this procedure, major deviations from the expected performance can be quickly identified. If the stack is new and not yet conditioned, it must first be ensured that the maximum performance of the stack is achieved. Break-in as well as conditioning procedures are usually specified by stack manufacturer. It is recommended to operate a stack at several relevant current densities to achieve a better comparability. A preconditioning procedure should include stability criteria as well as different load points. Critical modules with regard to an implementation in various test benches are start-up and shut-down procedures Start-up and shut down procedures should be representative for those that are applied in automotive systems. However, some of these procedures are difficult to apply in test benches in a safe way.

In addition, automotive manufacturers are not particularly keen on publishing details of their start-up and shut-down procedures. If start-up and shut-down procedures are applied without inerting with nitrogen, safety precautions in the respective test benches must be followed. In hydrogen soak shut down, a reductive hydrogen atmosphere is kept all the time on the anode and also on the cathode after a short transition period in the beginning. In order to avoid large volumes at anode and cathode set up during shutdown diffusion processes, it is recommended to integrate solenoid valves on both sides downstream and upstream of stack. If anode gas volume is much smaller than cathode gas volume there is a risk that after closing the valves at the same time both on anode and cathode, oxygen atmosphere is formed on the anode side due to oxygen diffusion from the cathode, thus creating at restart a possible Hydrogen/air front which should be avoided as it is a primary cause for strong degradation of electrodes.

Even if safety aspects have to be clearly examined, a stop without nitrogen is still recommended, because only this procedure comes close to real systems and applications. Experiences previously conducted at several partners here involved (e.g. ZBT, CEA, VTT, etc.) showed that start-stop processes without nitrogen can be performed safely and reproducibly in a test bench environment. As for all the protocols or procedures steps, most important is to clearly define the appropriate conditions and profiles to be applied on the reactants and load features.

In addition to the safety notes, start stop processes must also be checked with regard to their feasibility in various test benches. Particularly important are sufficient heating and cooling capacities in order to be able to heat up and cool the stack quickly. For the reasons mentioned, it is difficult to define start-stop procedures. Hence, consulting when possible the stack manufacturer is recommended.

3.1.5 – Tests with Recirculation Loop

Tests with an integrated anode loop require a precise definition of the location of measuring points. So far, individual operating parameters have only been developed and defined in HYDRAITE project. A clear description and knowledge of used recirculation loops is particularly important for a comparison of test results and measurements due to the different test platforms. Experience from HYDRAITE partners shows that there are some important issues to consider when setting up recirculation in a test bench. Water management is one of the most important points. The installation location of a water separator must be defined. It is advisable to integrate a water separator after stack outlet and before recirculation pump. Consequently, the pump can be protected from liquid water as far as possible. On the one hand, some pumps are not permanently suitable for operation with liquid components, and on the other hand, a high amount of liquid component changes the pumping behaviour of the pump, which in turn leads to changed operating conditions. In order to maintain a high level of gas humidification in the loop and thus to humidify the stack well, the whole loop including water separator should be heated continuously. In this case, the test bench can also be operated on anode side without an external humidifier. It is therefore very helpful to realize a compact construction of the anode loop. As an example, in order to achieve continuous heating, the loop at ZBT is heated with flexible, adjustable resistance wires, Figure 9.

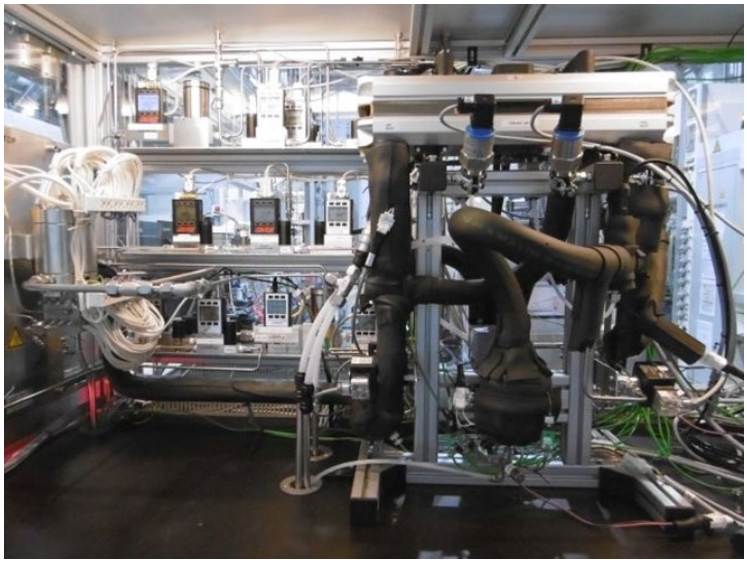

Figure 9 - Compact heated and isolated recirculation loop at ZBT

Depending on the application or planned tests, especially with sticky contaminants, pipe diameters should be defined to reduce the variability of gas contact surfaces. In addition, there is the question of coating pipes and connectors with regard to measurements of influence of the harmful gases on stacks. The accumulation of pollutant gases can be analysed with an anode loop application. The results are easier to compare if consistently coated loops were used. In turn, however, the effort and benefits must be carefully balanced, because both the stack itself and recirculation loops in real applications are uncoated. The analysis and location of measuring points in the anode recirculation loop will be discussed later in this project.

4. – Summary

This report provides an overview of test protocols for measurements on fuel cell stack level. It was found that the development of stack test protocols was particularly advanced within European consortia and EU projects. Direct information from industry could not be added despite a request. Special individual protocols that are subject to confidentiality are often used in industry. Various consortia provide information for stack test protocols and modules with regard to nomenclature, break in, start stop, load cycles and degradation assessments. These specifications should enable an improved comparability of stack measurements. The modular design allows better alignment of defined measurement targets without the need to develop completely new protocols.

The definitions and specifications of the protocols are always strongly dependent on the used stack and test bench infrastructure. Accordingly, adjustments and, depending on the test, additional parts are often necessary in order to increase comparability and to be able to carry out tests in available test set ups. In addition to the operating conditions, a decisive factor is therefore the implementation of protocols in respective test benches. Restrictions can occur as a result of limited speed of processes as well as limitations in the infrastructure, e.g. heating or cooling as well as humidifier capacities. Based on the review, a further chapter was drawn up to provide a compact description of limits to be observed in the interaction between hardware and test protocols.

In particular for system-related measurements with integrated recirculation loop, the measuring points should be clearly defined. The implementation of comparable test protocols is strongly dependent on the test bench hardware. The implementation should always be an important part of the development of test protocols.

Even if the comparability of the results decreases with increasing complexity, it is still advisable to carry out measurements that are as close to the system as possible. This applies in particular to measurements regarding the influence of contaminants on fuel cell stacks. The behaviour of stack is strongly dependent on accumulation and diffusion effects, which can only be analysed with an integrated anode loop.

References

[1] A. Kabza (author), L. Topal, P. Piela, B. Guicherd, J. Mitzel, J. Hunger and T. Jungmann (support), *Stack-Test Master Document – TM 2.00*, FUEL CELLS AND HYDROGEN JOINT UNDERTAKING, FCH JU 303445, 19.10.2015, available at: http://stacktest.zsw-bw.de/media-centre/test-modules.html

[2] G. De Marco, T. Malkow, G. Tsotridis, A. Pilenga, *EU harmonised test protocols for PEMFC MEA testing in single cell configuration for automotive applications*, Publications Office of the EU, DOI 10.2790/54653, 2015, available at: https://op.europa.eu/de/publication-detail/-/publication/82c28cc6-cef7-11e5-a4b5-01aa75ed71a1

[3] J. Ihonen, P. Koski, L. Perez, P.-A. Jacques, F. Sauzedde, F. Laurent, H. Laforet, S. Escribano, B. Hladys, F. Defoort, S. Thierry, T. Malkow, T. Tingelöf, *D 1.2 - Report on reference measurements and test protocols,* HyCoRa Hydrogen Contaminant, 2016, available at: http://hycora.eu/deliverables.htm

[4] A. Klymovskyi, A. Kabza, Jari Ihonen, Jaana Viitakangas, *D 2.3 - First recommendation for short stack test methods for studying hydrogen contaminants in automotive PEMFC systems,* HYDRAITE – Hydrogen Delivery Risk Assessment and Impurity Tolerance Evaluation, 2019, available at: https://hydraite.eu/public-reports/

[5] USDRIVE, *Fuel Cell Technical Team Roadmap,* 2017; available at: https://www.energy.gov/eere/vehicles/downloads/us-drive-fuel-cell-technical-team-roadmap

[6] J.Ihonen, J. Viitakangas, G. Smith, K. McCay, N. Mariage, S. Escribano, M. Männikkö, G. Göransson, H. Becker, G. Hinds, T. Bacquart, A. Klymovskyi, A. Kabza, U. Misz, T. Optenhostert, C. Spitta, Hydraite, *D2.2 - A summary report of FC measurements for the first half of the project,* available at: https://hydraite.eu/public-reports/

[7] http://id-fast.eu/uploads/media/ID-FAST_D4-3_Analysis_of_coupling_between_mechanisms_and_definition_of_combined_ASTs_OK.pdf