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4. **Inhouse Engineering** GMBH
5. **AREVA** Stockage d’Energie SAS

MATISSE

MANufacturing Improved Stack with textured Surface Electrodes for Stationary and CHP applications

SP1-JTI-FCH. 2013.3.2

Improved cell and stack design and manufacturability for application-specific requirements for stationary fuel cell power and CHP systems

Collaborative project

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Deliverable abstract

This report summarizes the activities conducted in the frame of the Matisse project from initial objectives to final achievements highlighting main results concerning developments, manufacturing processes, performance and durability of electrodes and MEAs (Membrane Electrode Assemblies) specifically designed and tested for their implementation into PEMFC systems of three industry partners ArevaSE, Nedstack and inhouse operating respectively with H2/O2, H2/Air and Reformate/Air.

First part after the executive summary, is the reminder of the overall context and objectives as also reported in the periodic reports.

Unlikely of the project and of the periodic reports following the tasks of the description of work, the core part of this final report is built to show first the equipment and processes used to make the components, then the major selected developments and achievements by stack design and related application with results and conclusions of MATISSE MEAs tests in respectively Areva SE, Nedstack and inhouse hardwares.

A final section is reminding the main conclusions of the cost assessment conducted on the stacks with the MEAs developed.

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1. Executive Summary

MATISSE is addressing the main objectives needed for PEMFC systems' market deployment which are the increase of performance (power density and efficiency) and the improvement of robustness and lifetime, associated with the reduction of the systems cost for stationary applications. The project is focusing on fuel cell core improvements with the development of advanced Membrane Electrodes Assembly (MEA) with automated processes, for three specific stack designs and related conditions of ArevaSE, Nedstack and inhouse systems operating under H₂/O₂, H₂/Air and Reformate H₂/Air. Developments are based on application specifications as defined by the industry partners and are assessed on industrial stack and system hardware. End-users expectations are considered thanks to stack manufacturers' information.

Homogeneous electrodes have been first developed as references to show the capability of implementing prototype MEAs into the industry partners fuel cells stacks keeping performance level higher or similar to the commercial references. Parametric studies and ageing tests associated to current density distribution measurements conducted with segmented cells on few-cell-stacks have been used to assess performance, degradation issues and to determine heterogeneities in the performance and particularly local losses to identify zones to be modified. Based on these results, textured electrodes have been formulated with non-homogeneous catalyst layers in order to counterbalance the local issues related to drying or flooding sensitivity. In parallel, automated processes have been adapted and improved to make all electrodes and MEAs more robust and reproducible. In parallel to electrodes development, sealing and anti-wicking solutions were also considered to improve robustness of the MEAs for the different designs.

Both homogeneous reference and textured electrodes could thus be defined, made automatically on the screen-printing pilot-line and validated with respect to two main criteria which were respectively, reaching at least similar level as commercial reference for the reference and demonstrating improved performance and/or durability thanks to selected textured electrodes and automated manufacturing of MEAs.

Indeed, better performance or similar level with lower catalyst loading were achieved for all MATISSE reference MEAs while selected new MATISSE MEAs actually demonstrated clear impact onto the current density profiles allowing to improve local or overall performance for specific conditions as well as positive effect on stability with reduced degradation rates thanks to the implementation of textured electrodes, made by adapting in one zone near gases inlet or outlet the catalyst layer composition in noble metal and/or ionomer, and of automatically assembled MEAs.

It could be demonstrated that MEAs developed on the pilot-line scale could be implemented in full stacks and tested in real operating conditions respectively in a pilot plant or in a system with a reformer.

Long term endurance tests could be conducted for different stacks allowing particularly to reach about 2700 hours and 2100 hours with low degradation rates of respectively 8 and 6 μV/hrs with textured and automatically assembled MEAs developed for operation under H₂/air and reformate/air.

In addition, information acquired thanks to MATISSE achievements have been analysed to try and define recommendations for further system operation or developments. Means to adapt systems operating conditions to stack components have been proposed with respect to specific results achieved particularly during parametric studies performed on short stacks or from systems.

Cost assessment has been done for the three stack designs and fuel cell technologies using first the reference data with commercial components and then the new data with MATISSE MEAs and results for each case.

The final outcomes such as particularly improved MEA components and proposal of adapted operating conditions are envisioned for further stack or system developments by the 3 industry partners for their applications.

2. Summary description of project context and objectives

MATISSE (Manufacturing improved stack with textured surface electrodes for stationary and CHP applications) is a 39-month project targeting to the delivery of PEMFC advanced cells and stacks. MATISSE is addressing the main objectives needed for market deployment which are the increase of performance (power density and efficiency) and the improvement of robustness and lifetime, associated with the reduction of the systems cost. The project intends to reach these objectives focusing on fuel cell core improvements with the development of advanced cell components and automated processes for Membrane Electrodes Assembly (MEA) and stack manufacturing.

The project methodology is based on the assessment of stacks with improved MEAs, including new compositions in their electrodes or modified processes developed during the project. Three existing stack designs and fuel cell technologies are considered related to systems operating under three different conditions mainly differentiated by the gases used: H₂/O₂ (for Areva SE smart grid application), H₂/Air (for Nedstack back-up or CHP application in large power plant); and Reformate H₂/Air (for inhouse micro-CHP application).

Developments are based on application specifications as defined by the industry partners and will be validated on industrial stack and system hardware. End-users expectations are considered thanks to stack manufacturers' information.

The project considers process issues for manufacturability for all the components developed. Three keys components fabrication will be considered in automated process: electrode using screen printing line, automated MEA and stack assembly. Final optimized components should allow the industry partners involved to go beyond their state of art for their application.

Improvements over the state of the art of the industry partners involved are expected thanks to the following developments:

- Modified solutions of gasket and sub-gasket (anti-wicking) in order to improve cell robustness
- Optimized catalyst formulation and protection towards contamination
- Automated processes and optimized catalyst loading: limitation of defects, of poor operating zones
- Textured (or X-Y gradient) electrode design: better catalytic activity and better water management as well as limitation of local activity or local degradations due to heterogeneous operation. Electrodes, with a catalyst layer non-homogeneous along the surface, will be specifically designed based on the reference results obtained at the beginning on reference homogeneous components.

Assessment of these developments are done by different characterizations of cells and stacks:

- Components' qualification is conducted in short stacks with representative conditions and load profiles, ageing conditions or specific AST.
- Segmented cells are used to enable Current Density Distribution Mapping (CDDM) for the proposal of non-homogeneous electrodes composition allowing better performance, better stability and lower performance local degradation.
- Post-ageing analyses are performed to identify local degradation mechanisms and propose improvements. Costs reduction will be addressed through the optimization of MEA architecture, electrodes design and material loadings, and automation of processes.

In addition, the impact on overall systems cost of the improvements conducted on cells and stacks design and manufacturing is considered thanks to a cost assessment analysis that will be conducted and compared between reference cases (at beginning of the project) and after optimization (at the end of the project). These information will be used to propose recommendations for the systems improvement.

3. Description of main S & T results and foreground

3.1. Manufacturing equipment and processes

3.1.1. Electrodes manufacturing

Components development activities consist mainly in developing ink for reference homogeneous and textured MEA for 3 different applications, and using the anti-wicking technology. The evaluation of the results from the segmented cells, associated to the investigations of the overall performance and ageing are used as inputs to define inks for the electrodes.

First actions were to define the reference MEA with the appropriate inks for the specific application. Based on the anterior knowledge, CEA could propose ink formulation to the industrials in function of their application. CEA made directly large scale MEA for each stack design. Ink formulation and tool definition for electrode processing included adaptation to the use of screen printing process which is the equipment of the pilot line used for the electrode fabrication at CEA. This kind of process implies to adapt the rheology of the ink and to have an optimized dispersion of the particles not to plug the screen.

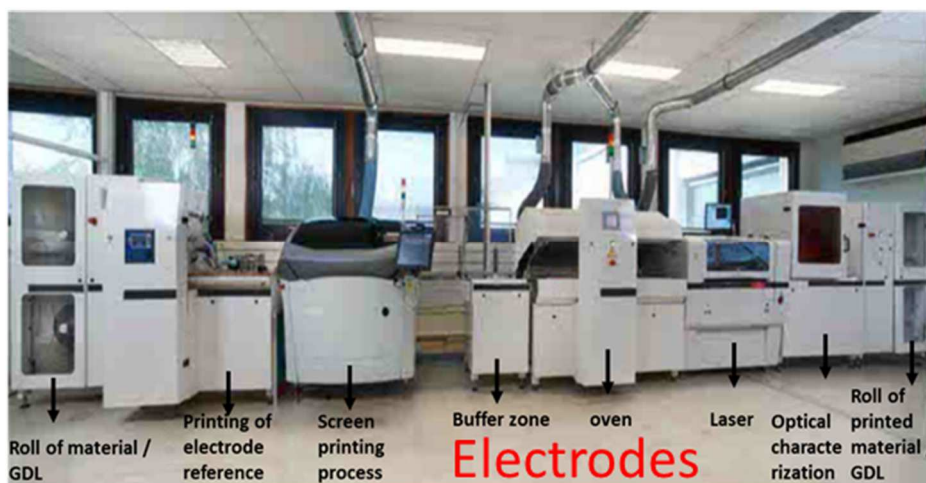


Figure 1: available screen-printing pilot line at CEA

For the 3 industrial partners, reference MEAs have been manufactured and delivered. The reference MEAs have shown better performances compared to industrials commercial references, for inhouse and Nedstack, and same performance for Areva SE but with lower noble metal loading.

Major issue encountered was to define the reference electrodes for operation under pure hydrogen/oxygen reaching the required performance level (similar to commercial reference): this was finally solved by finding the right catalyst materials mixture for the cathode side and the right gas diffusion layer as the support.

Textured electrode (with non-homogenous catalyst layers along the surface) were defined by analysing the results of the segmented cells on the reference homogeneous MEA, like the information on special MEA zones with different behaviour, particularly regarding sensitivity to drying or flooding. Data are used to determine the compositions of the inks corresponding to these different zones, mainly near inlets or outlets. The new inks are proposed to counter balance the trend observed, to increase performance and durability, by modifying the repartition of the current density.

Several types of textured MEAs could be delivered for the three designs. For the operation under air with hydrogen, pure or reformat, the modification of the electrodes was mainly based on new ink formulations with modification in the catalyst and ionomer composition for the cathode or both anode and cathode

catalyst layers. The advantage of modifying locally the two electrodes instead of only one to reach expected improvement was also an added value of these developments.

In addition to the formulation of the textured electrodes, another aim was to demonstrate the possibility to manufacture these textured electrodes in-line to show the applicability at larger scale. To confirm the feasibility of textured electrodes on the pilot line, the production of small series (more than 10) could be performed for the last version of textured MEAs, for the 3 industrial designs.

The principle of the fabrication process of textured electrodes on the pilot line is summarized as follows: deposition of the first ink, keeping the sufficient place for the deposition of the second ink between each electrode, winding of the gas diffusion layer (GDL) with the first ink at the end of the line, re-winding of the GDL with the first ink to print the second layer starting on the first electrode previously printed.

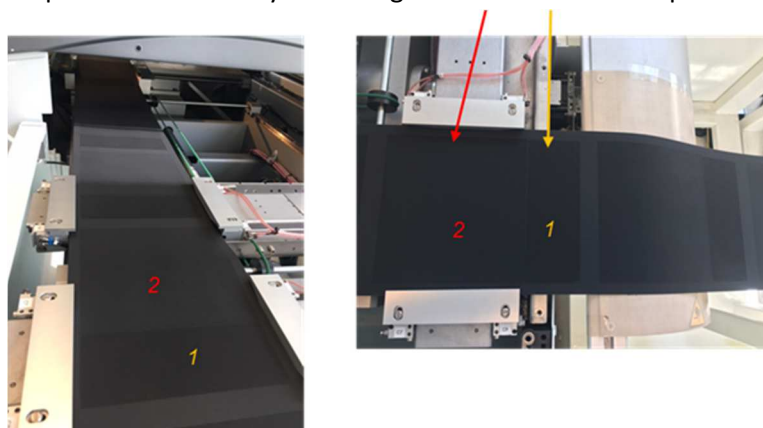


Figure 2: example of textured electrodes on the pilot line

3.1.2. MEA assembling

In parallel to the development work conducted on the formulation of specific inks and catalyst layers, another objective of the first period was to consider the development of the whole MEAs assembling, including the proposal and implementation of the anti-wicking technology and possible new gaskets.

For all the reference MEAs, the anti-wicking technology has been done for the 3 industrial partners that have tested the MEAs into stacks. Due to the requirements of the industrial partners, a work on the sub-gasket has been done. The 3 industrial partners were satisfied with the anti-wicking technology that aims to reduce the pollution and the degradation of the membrane that is not in contact with the liquid coolant, and to reduce membrane cost and waste because its surface is smaller. But, for Areva SE, the sub-gasket seems to involve an over thickness and an excess of mechanical constraint at the edge of the MEA, inducing a high electrical resistance between MEA and bipolar plates.

However, it was necessary to adapt the nature of the sub-gasket to avoid its delamination. The gasket is a part of the bipolar plate that is designed in function of the material and process used for the plate. Another way to improve the sealing of the stack is to deposit the gasket directly onto the MEA. The CEA developed a method to deposit directly onto the MEA by screen printing, allowing to adapt easily the design; and the bipolar plate can be reusable. The concept has been validated by a successful leak test.

For INHOUSE, the concept was interesting but work and time requested for gasket-on-MEA integration could not be affordable in the frame of MATISSE.

For Areva SE, important modification of the equipment and plate design would be needed; they consider

new sealing and anti-wicking solutions an open issue, not applicable in the short term but they intend to contribute to their definition.

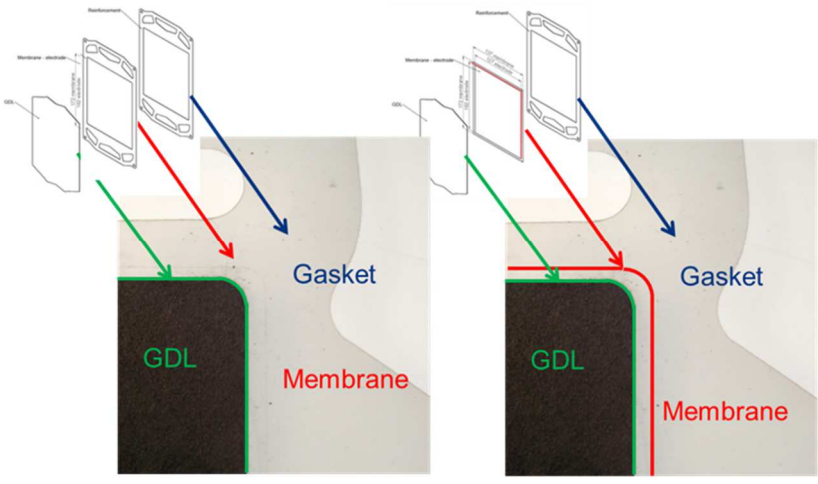


Figure 3: Anti-Wicking technology

Two types of assembling have been done during the project. First manual assembling for the small production of MEAs, and second with the automated assembling machine for the full stack. CEA was in charge of manufacturing the MEA in a fully automated system, already available for other MEA designs.



Figure 4: available automated MEA assembling machine (CEA)

The mains specificities of the equipment are the positioning of the components, the pressing, the pre-cutting and the final cutting.

The production rate is around 40 MEAs per day. Final geometrical characteristics are determined by tri-dimensional analysis.

For the automated assembling of the MATISSE MEAs, it has been necessary to adapt the machine to the 3 specific designs of the industrials. On the equipment, 5 tools had to be adapted for each design:

- One for the sub-gasket cutting
- One for the electrode cutting
- One for the storage of the electrode
- 2 tools for the hot pressing: one for the hot pressing of the electrode and the membrane and the second for the sticking of the sub-gasket

Different tools have thus been modified to adapt the machine for the three designs.

Before the assembling of the different components, it's necessary to cut the gas diffusion electrodes (GDE) (anode and cathode) and the membrane to the right design. The sub-gasket is cut to the design of the frame of membrane support.

The robot picks up the different components that are stored in different boxes. Detailed description is available in technical deliverables.

For one type of MEA, the type of GDL selected was without microporous layer, meaning higher porosity which prevented one step in the assembling process with the automatic equipment.

In total, 444 MEAs have been delivered with the three different industrial designs in the frame of the MATISSE project, including 241 completely made with automated processes: pilot line for the electrode and automated assembling for the MEA.

This number of MEAs (444) implies the manufacturing of around 1000 electrodes.

3.2. MEA and stack tests results with Areva SE design

3.2.1. Results of Matisse MEAs tested within Areva SE hardware

Operating conditions for assessment of MEAs designed for Areva SE application

The application targeted for the stacks developed here for ArevaSE is Smart Grid implementation using Hydrogen and Oxygen. It concerns the hydrogen-based energy storage system developed by Areva SE, by connecting a PV power plant with a PEM Water Electrolyzer (PEMWE), H₂ and O₂ storage tanks and a PEMFC power generation system. By connecting to the power grid, it aims to provide a solution to the problem of intermittency of renewable energy, to offer greater flexibility for grid operations and finally to integrate decentralized electricity from renewables into island power grids helping the grids more reliable.

Test protocols based on the application were defined with fixed current and standard operating conditions (70°C, 2 bars abs H₂/O₂) including current density and temperature distribution mapping (CDDM and TDM) recorded during measuring of polarization curves.

CDDM and TDM data have been processed with routine developed by ASE to generate a graphical view of current density and temperature profiles in 2D and 3D and statistical data distribution analyses. To perform the current and temperature mapping on short stack, a new device developed by the S++ Company has been implemented. It was specifically designed and fabricated to fit the design, mechanical and electrical constraints of AREVA SE fuel cell stack with 130 cm² active surface.

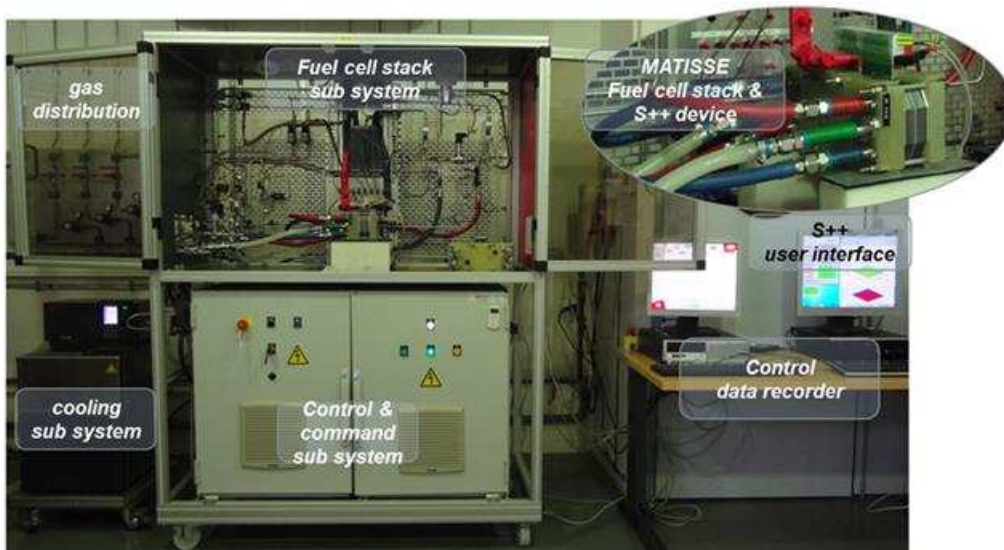


Figure 5: AREVA SE test bench dedicated for MATISSE project & S++ current and temperature mapping device

Comparison of Matisse MEAs' performance and behavior during tests in short-stacks

First objective was to define and validate homogeneous electrodes matching the expectation of the partner: performance similar to their commercial reference or lower but at lower cost, mainly lower noble catalyst loadings. Getting MEAs with expected performance was an issue during the period but this could be managed during the second period.

Results are presented for last stacks with better results obtained:

- Stack v4 comprising new electrode manufactured with a specific active layer ink formulation with low loading Pt Black to consider the specificity of H₂/O₂ operating conditions.
- Stack v5 comprising different GDLs (Toray Paper, SGL and Freudenberg) to assess the impact of the nature and the mechanical flexibility of GDL and its manufacturability using a continuous screen printing process.

Results showed comparison between the polarization curve of a new homogeneous MEA with commercial ASE MEA and different versions of MATISSE MEAs tested in short stacks (v1, v2 and v3).

One can see that the performance of the new homogenous reference MEA has been improved. It shows stable electrochemical performances reaching 0.70 V/cell at 1 A/cm² at nominal operating conditions 70°C; H₂/O₂ at 2 bar abs.

Between initial and last developed homogeneous MEAs, a real improvement in the performance of the new homogeneous reference MEA was observed knowing that the catalyst loading decreased significantly (Pt Black loading < 1mg/cm²). The performance of such MEAs reaches 0.70 V at 1 A/cm² in standard ASE operating conditions that is 70°C and H₂/O₂ at 2 bar abs

The current density and temperature distribution mapping (CDDM & TDM) for homogenous reference MEA at nominal conditions can be divided in two regions: low and high current densities. The low current is located at the O₂ outlet (H₂ inlet). It represents around 15% of the active area. The current density homogeneity represents more than 80% of active area. The current density standard deviation is equal to 0.25 A/cm². The temperature is slightly higher at the H₂ outlet. It represents less than 50% of active area. The temperature standard deviation is equal to 1°C.

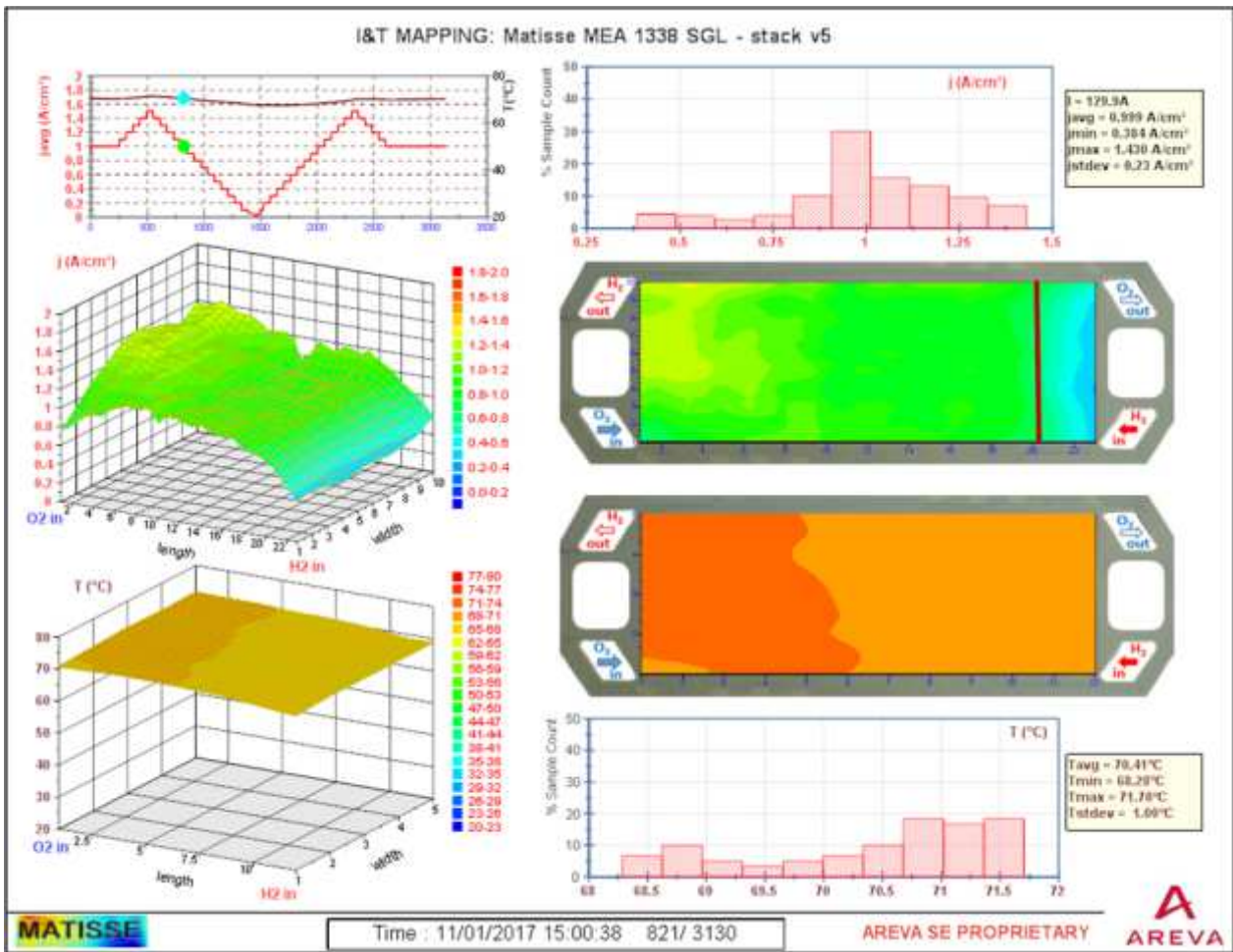
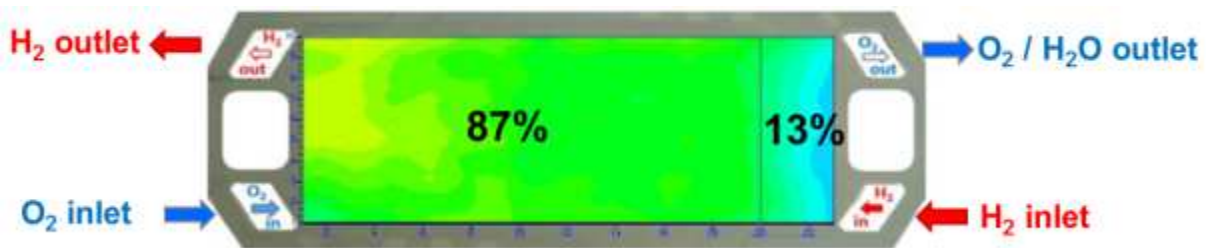


Figure 6: temperature and current density distribution 2D and 3D maps and histogram for one homogeneous reference MEA.

The results obtained with homogeneous reference MEAs have been used to define the textured MEAs formulation described in WP4. The textured design is formulated by CEA taking into account the blank current density distribution to evaluate water flooding or drying level.

The new design of textured MEA uses the same anode formulation as the homogenous anode MEA 1337 with SGL 24BA / GDE_17-014: 0.974 mg Pt/cm². The cathode textured design includes two regions with high and low Pt catalyst loading related to high and low current densities in order to improve the electrochemical performance in comparison to the homogeneous MEA. These regions correspond to 87% and 13 % of the active area respectively.



Six textured cathode GDEs with different GDLs material have been provided by CEA and tested in short stack v6. The following table summarizes the characteristics of these textured GDEs.

Data performance and CDDM corresponding to textured MEAs have been compared with those from homogeneous MEAs.

The polarization curves of stacks with textured Toray GDE vs homogeneous reference MEA with Toray GDE and textured MEAs with Freudenberg and Toray GDE are presented to compare their electrochemical performances.

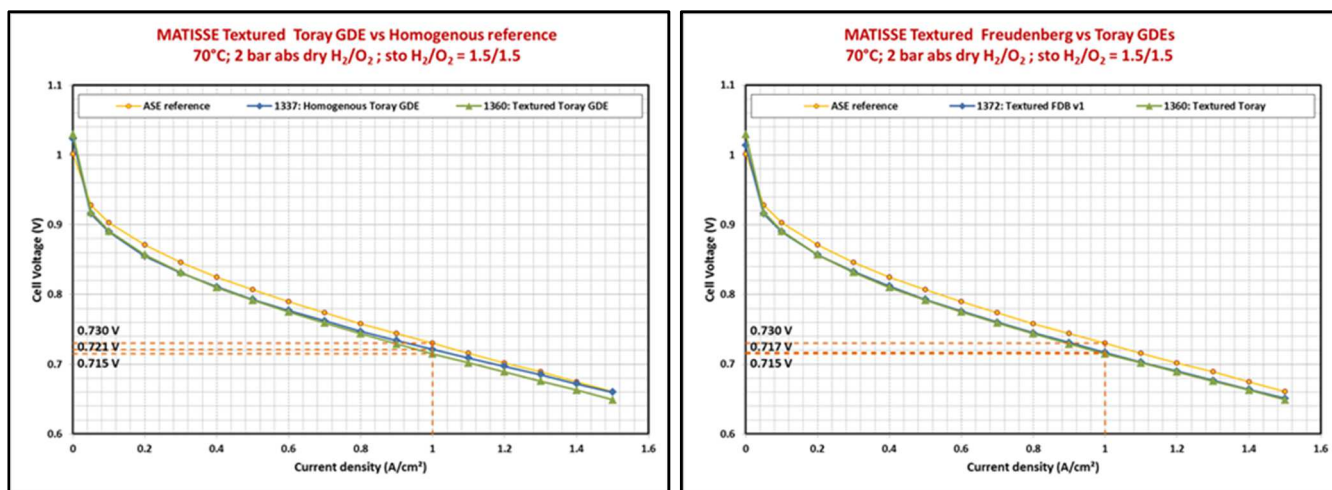


Figure 7: polarisation curves for two types of textured MEAs made with different gas diffusion layers.

The best electrochemical performance was obtained with homogeneous and textured Toray paper GDEs. The performance at high current density with textured GDE is slightly lower than homogeneous Toray GDE, 0.715 V vs 0.723 V/cell at 1 A/cm² respectively.

The textured MEAs performances with Freudenberg and Toray GDEs are quite similar demonstrating the suitability of Freudenberg GDL for the continuous screen printing and for automated manufacturing MEAs process. As mentioned above, Freudenberg GDL is softer and flexible than Toray and seems to be a more rollable GDL material.

Current density and temperature distribution mapping comparing homogeneous and textured MEAs are showing below. The low current region located at the O₂ outlet slightly decreases with textured GDE compare to the homogeneous ones. It can be correlated with the effect of the low catalyst loading formulation representing 13% of active area. In addition, with textured GDE, the high current and temperature distribution region are shifted at the H₂ outlet. At last statistics analysis of current density and temperature mapping indicate more centred data distribution with textured GDE.

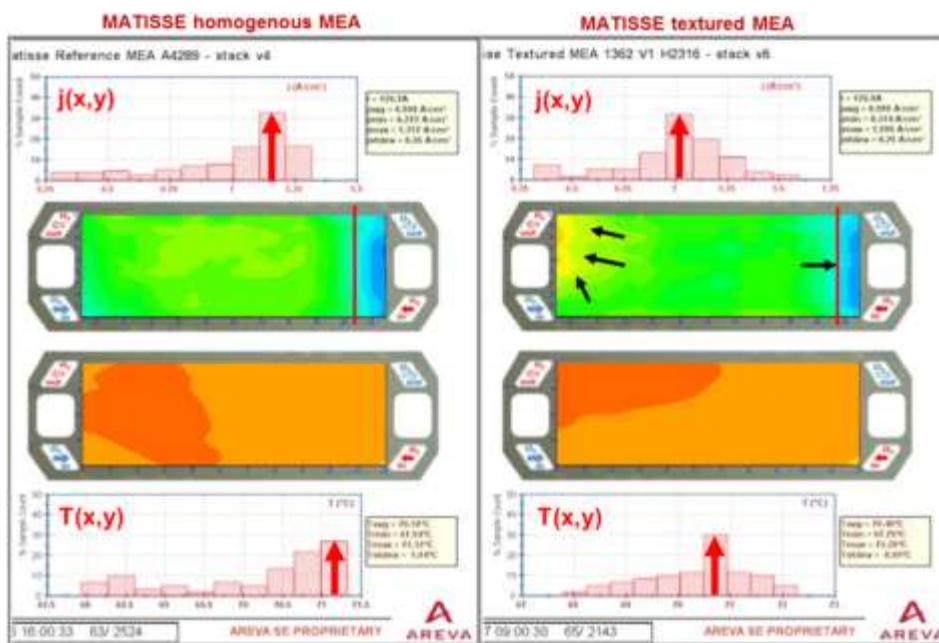


Figure 8: comparison of current density and temperature distributions for the homogeneous and textured Areva design MEAs.

In conclusion the new specific ink catalyst formulation with low Pt loading ($< 1 \text{ mg/cm}^2$) presents a good performance similar to commercial ASE MEA with high PtB loading.

In addition, different types of homogeneous and textured MEAs have been evaluated which mainly differ on GDLs used to support the active layer. MEAs with Toray paper present higher performance than those with Freudenberg and SGL GDLs.

However MEA with Freudenberg GDL present performance, up to 0.7 V at 1 A/cm^2 at nominal operating conditions, in good agreement with ASE specification. Moreover this Freudenberg GDL is suitable for a continuous screen printing and for automated manufacturing MEAs process. Texturing MEAs induce a slightly low electrochemical performance impact but durability issue has to be addressed to confirm its interest.

Additional tests of short stacks comprising specific homogeneous and textured MEAs with low Pt Black loading for H₂/O₂ operation mode were planned in order first to improve the interface control drawing & alignment then to validate the cathode and anode GDL structure to be used in the full stack with the new catalytic layer.

The first attempts in the MEA fabrication have demonstrated the need to reduce the gap between MEA components & gasket in order to obtain:

- Better sealing and mechanical protection
- Less chemical aggression
- Less premature membrane breakdown & degradation

After this first phase of optimisation of the manufacturing process, CEA supplied ASE with new MEAs for short-stack testing.

Results showed more stable electrochemical performance indicating a good homogeneity of the stack assembling, allowing an optimum compression of MEA on the bipolar plates (low ohmic losses), homogeneous gas distribution in the GDLs and sealing without any leakage.

The polarisation curves of all unit cells also show better performance for the textured electrodes in comparison to the homogeneous ones and for textured v3 vs textured v1 even if it is a slight increase. The result of the endurance test conducted on the stack 8 was 400h operating hours without any voltage decay. The test was stopped due to the membrane degradation allowing hydrogen permeation from anodic to cathodic side and potential short-circuit in the stack.

A last series of tests was conducted consisting in the characterisation of a short stack comprising homogeneous MEAs and dissymmetric GDLs:

- Homogeneous Anode: $\sim 0.882 \text{ mgPt/cm}^2$ _SGL24BA
- Homogeneous Cathode: $\sim 0.765 \text{ mgPt/cm}^2$ _Freudenberg H2315I6

The objective of these tests was the validation of such MEAs for the manufacture of the 100-cells stack for the performance evaluation at scale 1. The polarization curves indicate that dissymmetric GDLs are suitable for the final stack.

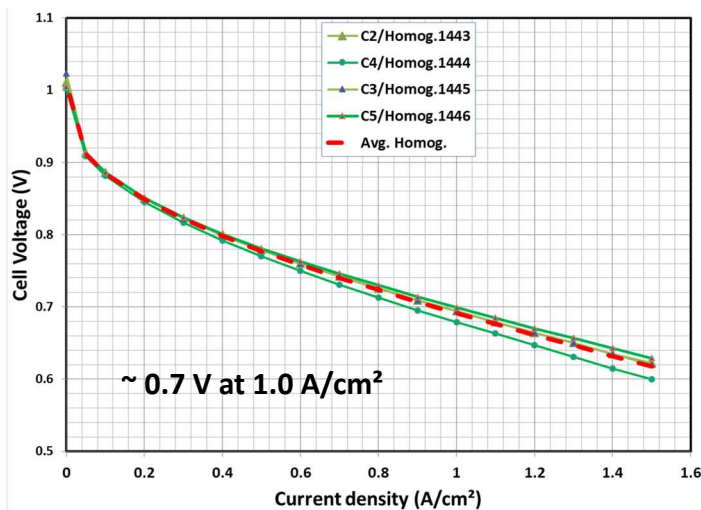


Figure 9 polarization curves of the cells with homogeneous MEAs in the Areva SE short stack for validation.

3.2.2. Full-stack test with Areva SE design automatically assembled MEA

As some difficulties were met in the automatic MEA assembling mainly due to the high porosity of the GDL selected for homogeneous electrodes for H₂/O₂ application prepared with the optimised ink formulation, it was decided to make H₂/Air MEAs in order to enable evaluating automated assembling also with this design. The composition of the electrode is slightly different from the homogeneous structure developed for the MATISSE project, as they were developed for the H₂/air application instead of the H₂/O₂ application initially planned (Cf. also WP4). So a set of 20 MEAs prepared on the automatic machine line was sent to ASE to be tested with the 130 cm² stack design in H₂/Air operating mode.

The first 10-cells stack was built without any problem and had internal and external tightness corresponding to our specifications. So it was tested on our test bench in the following operating conditions corresponding to our standard H₂/air mode: 60°C, 1,6 bars abs, Hydrogen and Air stoichiometry of 1,5 and 2,5, H₂/Air RH of 0% and 30%.

Results show the cells voltage evolution during the durability test under transient mode. The main conclusions are homogeneous cell performance with standard deviation to about 15 to 20mV, still lower

performance than ASE specification ($0,5\text{A}/\text{cm}^2$ - $0,68\text{V}$ instead of $0,72\text{V}$ at the BoL) and degradation rate of $35\ \mu\text{V}/\text{cell}$ per operating hour instead of $10\ \mu\text{V}/\text{cell}$.

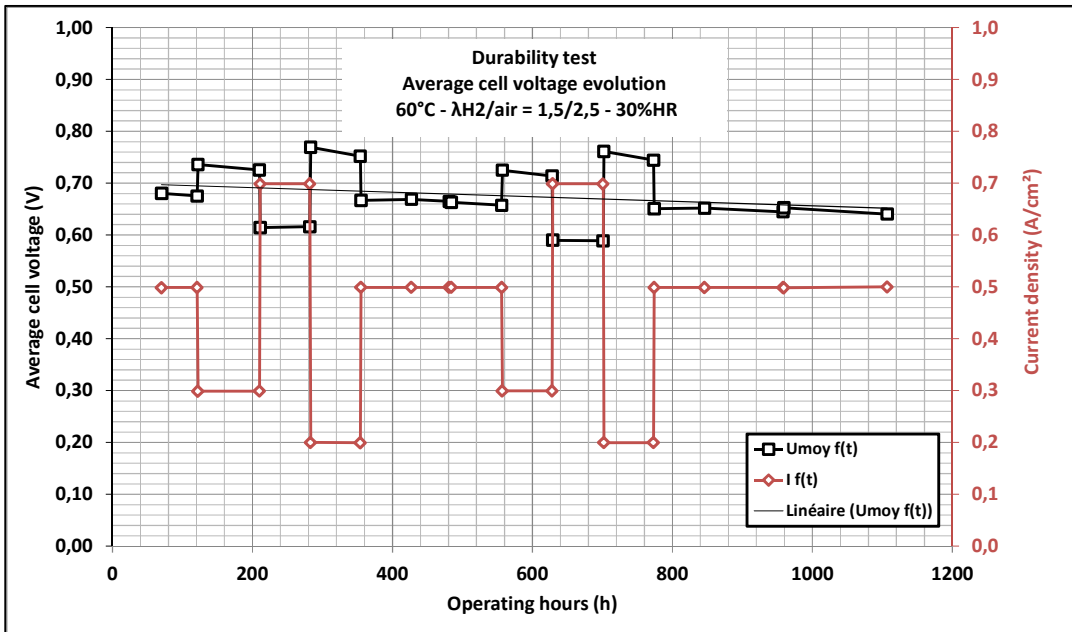


Figure 10: current and voltage evolution on Areva SE stack with automated MEAs (H_2/air conditions)

3.2.3. General conclusion about MATISSE MEAs in Areva SE hardware

The application H_2/O_2 of Areva was from beginning of the project challenging in terms of MEA- integration. Various tests with different GDLs and test parameters were performed. A final test-run with MEAs from automated production resulted in significantly higher degradation-rates and a lower initial cell performance compared to the commercial standard of Areva. But nevertheless significant improvements were made and results are promising due to a significantly lower catalyst-loading of the MATISSE-MEA compared to the commercial standard.

3.3. MEA and stack tests results with Nedstack design

3.3.1. Results of Matisse MEAs tested within Nedstack hardware

Specific AST protocol and conditions for assessment of MEAs designed for Nedstack application

The applications targeted by Nedstack are here backup-power or CHP systems (for large power plant) using Hydrogen and Air.

The general design of a protocol has been define to qualify the new MEAs. First stage concerns the receive and checking of the MEAs. In this stage the stack is also assembled before testing. The testing protocol includes the following steps: first break-in and polarisation curve, then electrochemical characterization, followed by two AST (Accelerated Stress Test) periods. The Accelerated Stress-Test (AST) - profile is a mixture of galvanostatic and potentiostatic mode. The low-load level is potentiostatic set to a fix average cell voltage (0,9-0,95V), the high-load step is galvanostatic-controlled by a fix current density (0.6A/cm²). After each AST period, polarisation curves and electrochemical characterizations are performed. To get the current density mapping, MEAs are placed in stacks with a size of 5-cell, with an S++ plate placed in the stack in between cells 2 and 3.

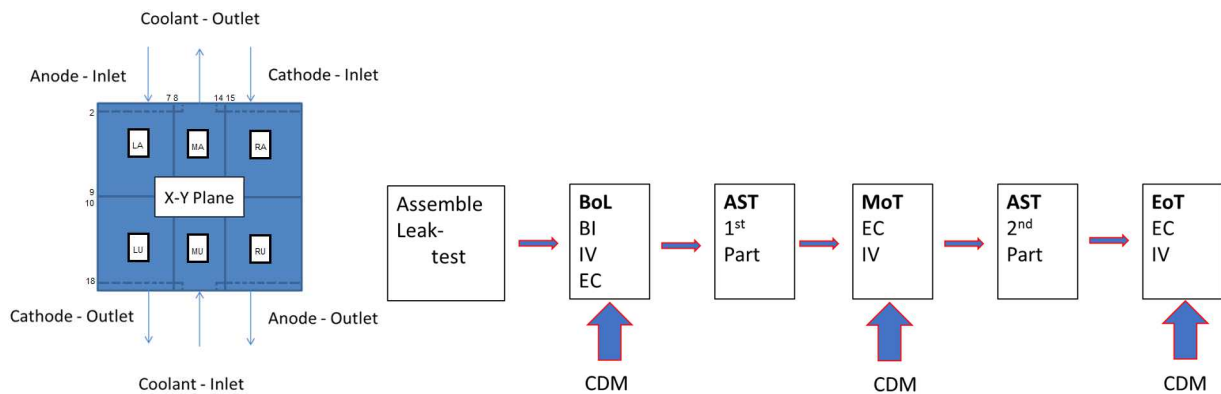


Figure 11 Orientation of segmented cell in Nedstack Hardware and typical Test Protocol at Nedstack

Tests were performed at Nedstack and ZSW to check the effect of the different test stands on stack behaviour. Nominal set of operating conditions applied for the tests in Nedstack hardware, as based on their system installed on the pilot plant were the following: pure hydrogen and air at about 1,2 bars, stack temperature of 65°C and relative humidity of 75%RH for both sides (anode/cathode). For a parametric study conducted in the last part of the project, two other sets of conditions were applied at 65°C but 40%RH (called “dry”) and at 75°C with 75%RH (called “hot”).

Concerning the operating conditions, one very important point noticed during the first period concerned the quality of the hydrogen used for the tests. A very strong decrease in cell voltage was observed during the AST protocol applied on a short stack made with one batch of MATISSE MEAs (first textured type). Because this issue was also observed with other stack made with for another purposes with commercial references, the cause for the strong performance decrease was investigated: it appeared that a lower hydrogen grade was used (“3.5” instead of the regular “5.2”). The effect of the low grade hydrogen noticed on the average voltage as well as on the CDM disappeared, when 5.2 grade was used again. The effect was reversible and mainly attributed to the presence of some contaminants, most probably carbon monoxide but dosage could be obtained from the provider. This issue is reported because it affected some data of this project and it confirms the importance of controlling the hydrogen quality for fuel cell testing and reporting.

Comparison of Matisse MEAs' performance and behavior during AST in short stack hardware

First batch of Matisse MEAs with homogeneous electrodes which was provided at the beginning of the project could be implemented in Nedstack-hardware with no particular issues, compared to some difficulties encountered with the two other designs and that had to be solved before going-on with the electrodes development process. In the case of Nedstack design, the initial MEAs and performance, despite a dispersion between the cell voltages, were validated as an acceptable basis to start with the development of textured electrodes. Main following efforts were thus put on proposing two major types of textured MEAs, with two batches for the second series.

The various Matisse MEAs, with homogeneous and textured electrodes have been tested following the overall AST protocol, and also compared to the commercial reference used by Nedstack. This was indeed suggested by the reviewers to add a Nedstack reference AST, based on Nedstack commercial MEA. The MEA is tested according to the same protocol, however at 150A, and with a start-stop protocol at 120A.

This section discusses the ageing of the homogenous as well as the textured MEAs. The ageing tests were performed according to the AST protocol. MEA discussed here are the first homogenous T1, and the textured MEAs T1, T2 and T2b.

By comparing commercial standard and the homogeneous Matisse-MEA (Stack S0301), it is obvious that the stability of the commercial standard-MEA is significantly higher, but both started at the same average load-level.

The first textured MEA that is discussed is "T1 textured". As the MEAs are built vertically in a stack, the cathode side of the MEA has two horizontally zones, where the emphasis of the upper part is more "dried" and the lower zone more "wet". GDL used is a Freudenberg type and the anode and cathode have a loading of 0.14 and 0.53mgPt/cm² (average both zones) respectively.

The follow-up, "T2 textured" included a change in GDL to SGL24BC and a change in the zones. The division of zones in this MEA is vertically with 40%/60% ratio, with a more active left side (higher Pt load) and a less active right side to prevent flooding. The anode Pt content was increased to 0.21mgPt/cm² and the cathode Pt was decreased to 0.47 mgPt/cm² (average). The last textured MEA, "T2b textured" included changes in GDL to SGL28BC and catalyst load of cathode side to 0.37mgPt/cm². Hereto the issues with catalyst underactivity (left) and flooding (right) were attempted to improve.

CDM charts of the various textured MEAs showed that the different texturations affected the current density profiles. Where the textured T1 MEA had a horizontal zoning of the MEA which resulted in a less active upper side of the MEA if compared to the improvement of the textured MEAs versions T2 and T2b. MEAs T2 and T2b have a somewhat less active left side and a more active right side in perspective of current formation.

There is a clear difference observed between version 2 and 2b with respect to current distribution. Especially just above cooling inlet a considerable area of apparent inactivity is observed. After disassembly of the stack, the cause of the inactive areas revealed itself and appeared to give an exact match with deposits found on the surface of the S++ tool. After cleaning of the complete surface area of the S++ tool, the current distribution for areas with this deposit improved, the areas without the deposit remained unchanged.

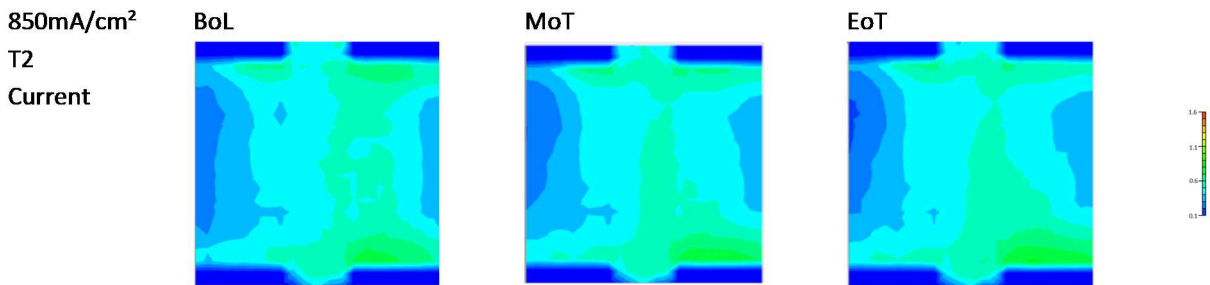


Figure 12 Excerpt of CDMs at 850mA/cm² at 40%RH for Cathode/Anode and Tstack of 65°C measured during an IV for MEA version 2 (textured) in Nedstack hardware

The discussion below summarizes results and conclusions about the textured MEAs compared to the reference regarding the AST protocol: it includes the results of textured MEAs includes T1, T2 and T2b, which were built in the following Nedstack stacks: S0315, S0340, S1558 and S1559. Besides the stack used at Nedstack laboratory facilities, one 5-cell stacks was shared with ZSW containing T2b textured MEAs. As with the stack with homogenous MEAs (S0316), the goal of the shared stack was to compare the results, evaluated in AST- test mode, when using the same operating procedures on different test stands.

First the results of the accelerated stress tests are discussed. After the AST results the different CDD results are shown to understand the effect of the test on the current and temperature distribution. The discussion of the results of these textured MEAs, measured at Nedstack, is finalized with electrochemical tests.

The AST curves measured during the second period are compared: they include commercial reference (ref S0327), and the textured MEAs T1 (ref S0315), T2 (ref S0340) and T2b (ref S1559).

There is clear improvement of the start voltage (from 0.65 to 0.7V) of the Matisse project MEAs tested in the 2nd period compared to the Nedstack commercial reference. The AST curves for T1 textured (S0315) MEA showed, as with the Nedstack reference discussed earlier, a strong voltage decay occurred during the first 150 hours attributed to low hydrogen quality, most likely containing CO (see note before). After approximately 110 hours the hydrogen quality was changed to the specified Nedstack quality and the stack performance recovered. The textured MEAs type T2 and T2b are clear improvement of the T1 textured MEA as with the Nedstack reference. Furthermore, at various points the AST curves show a spike shaped improvement. This improvement shows the reversible decay after intermittent tests.

Decay rates for the three types of MEAs were compared: the second type of textured MEAs showed the smallest decay, with a clear improvement compared to the first version. If the decay rates as a consequence of the applied AST protocol is studied, the improvement of the MEA design from horizontal to vertical, and change in GDL (Freudenberg => 24BC => 28BC respectively), shows a clear improvement (± 150 to ± 95 $\mu\text{V/hr}$).

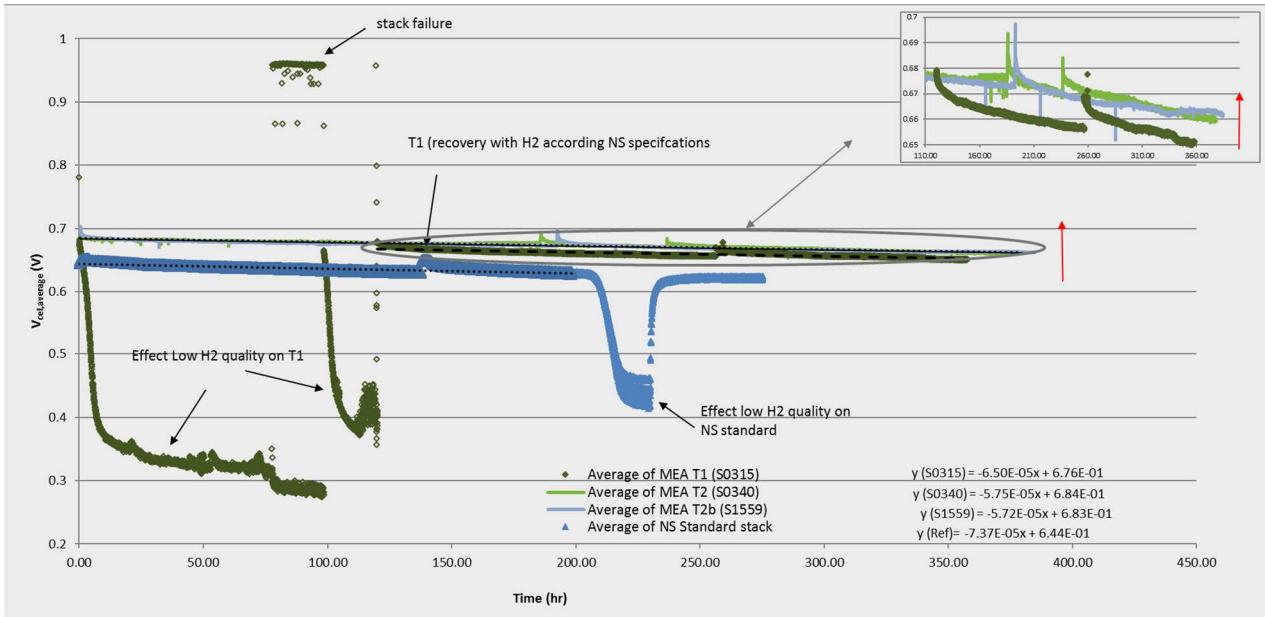


Figure 13 Results of stress protocol for textured MEAs T1, T2 and T2b with slope in V/hr.

Table 1 Slopes and decay rates for MATISSE MEAs

| | NS Reference S0267 ³⁾ | NS Reference S0327 ⁴⁾ | H1 homogenous S0301 | T1 textured S0315 | T2 textured S0340 | T2b textured S1559 | |
|--------------------------|-------------------------------------|-------------------------------------|------------------------|----------------------|----------------------|-----------------------|---------------|
| V_start | 0.64 | 0.65 | 0.66 | 0.70 | 0.70 | 0.70 | Volt |
| V_end | 0.60 | 0.62 | 0.47 | 0.65 | 0.66 | 0.66 | Volt |
| Change | -5.88 | -5.21 | -29.29 | -7.60 | -5.14 | -5.36 | % |
| Runtime | 1032.0 | 275.4 | 415.6 | 358.1 | 377.9 | 384.7 | hrs |
| Decay rate ¹⁾ | 36.6 | 123.5 | 463.9 | 149.6 | 94.5 | 97.5 | (μ V/hr) |
| Decay rate ²⁾ | -35.7 | -73.7 | -287.6 | -64.9 | -58.1 | 57.2 | (μ V/hr) |

1): Determined using the average of first 3 and the last 10 data points of the AST curve

2): Determined with MS Excel slope function over the AST curve

3): AST at 750mA/cm²

4): Start-stop test based

Considering the strong expected impact of operating conditions, a study has been conducted with two comparative tests with textured MEAs performed in parallel at Nedstack and ZSW. Here, the result evaluated at Nedstack is significantly more stable compared to the test at ZSW. Similar to the test with homogeneous MEA, the deviations of single cells extreme at ZSW and strongly dependent on operation conditions (reference – dry – hot).

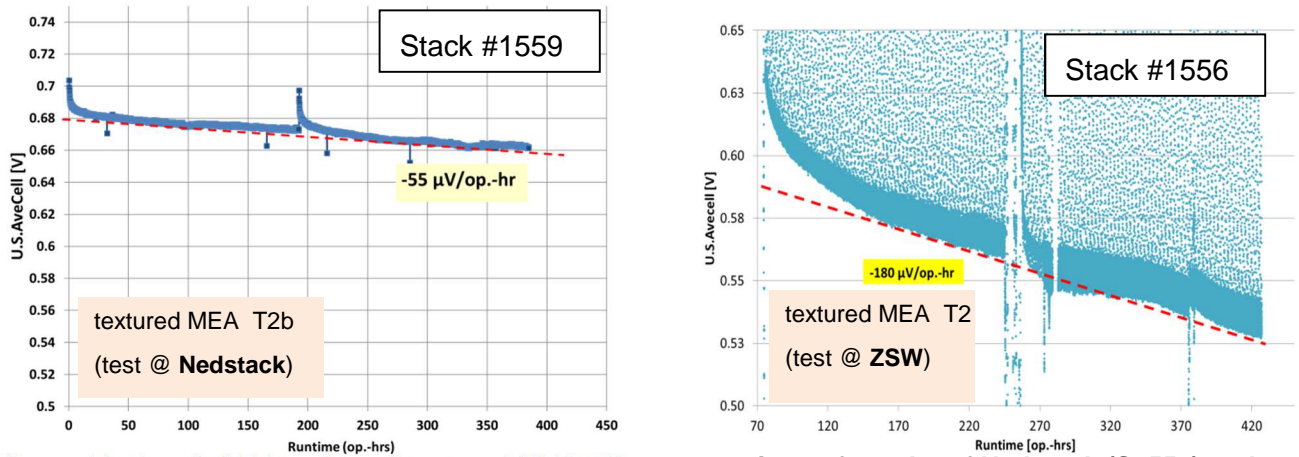


Figure 14: Result AST testing of textured MEA T2b – comparison of results of Nedstack (S1559) and ZSW (S1556)

During the intermittent periods of the ASTs polarization curves were recorded. In this section these polarization curves are discussed in perspective of the anode/cathode gas humidity and stack temperature conditions: 40%RH (anode/cathode) and 65°C (“dry”); 75%RH (anode/cathode) and 65°C (“reference”); 75%RH (anode/cathode) and 75°C (“hot”).

MEA improvements incorporated in the new textured designs resulted in better operation in more dry conditions of 40%RH. The adjustment and replacement of the different materials such as Pt loading and GDL, aids to performance improvement within every iteration.

If the results are studied for gas humidity of 75%RH and 65°C the differences between the individual MEAs are less apparent. Compared to the project reference (S0301) a clear improvement is obtained. The MEAs with Freudenberg (v1, S0315) and SGL24BC (T2, S0340) seem to maintain a more stable performance toward EoT. Compared to the Nedstack reference, especially MEA v1 and T2 are inline. MEA T2b lost somewhat more performance overtime.

At humidity levels of 75%RH (hot conditions 75°C) the T1 MEA with Freudenberg GDL performs less well if compared to T2 and T2b. Results of T2 and T2b are more-or-less inline. However, the ageing protocol seems to have less effect on T2b then T2. One notable effect is that EoT curve of MEA T2 is above the BoL curve. Most likely as consequence of improvement of performance during AST or damped flooding because the higher stack temperature has dried the MEA to some extent.

The results showed extreme dependency on operating conditions of the textured project MEA. Besides the strong degradation during the first test-period (BOT-MOT), no stable test conditions were obtained at EOT in the conditions 40-40-65 and 75-75-65; in reference conditions 75-75-65 even not at MOT.

The effect of humidity and temperature has been studied at 600mA/cm² because this current density is the standard operation value of the PEM power plant. The results show that at this current density the MEA show the smallest decay in perspective of the polarization curves. One notable result is that during the 2 week AST period, there was an improvement noted instead of a decay. A possible explanation of this improvement is that the EoL criteria is not reached after approximately 14 days.

Current and Temperature Distribution Measurements performed and analysed to get insight on the heterogeneities and their evolution during the AST and polarization curves allowed to conclude that the current distribution of T2b is more homogenous. It shows that the concept of texturation is an aid for more homogenous current MEA distribution. The polarization curves show that the textured MEA gives indeed an improved operation of the stack.

Main conclusion of ElectroChemical tests was that Textured MEA T2 and T2b (versions 2 and 2b) seem to be more sensitive to the ageing protocol than MEA T1 (first textured version). However, drop in ECSA for the T2 and T2B MEA observed at EoT, was not necessarily problematic as the polarization curves did not seem to be affected. Hydrogen crossover values were within the Nedstack boundary of 2 mA/cm², consistent with stack operation in e.g. power plant. The EIS data showed the ohmic part of the impedance was nearly unaffected by the AST protocol for all textured MEAs. This is in line with the results obtained for the polarization curves. However textured MEA T2 showed a strong deviation compared to the other MEAs, where the deviation in mass transfer is not related to the polarization curves; resistance for 'charge transfer' and 'mass transfer' have increased significantly. Considering the performance was still comparable judging by the polarization curves at EoT, it suggests that even further improvement is feasible by resolving the underlying issues now responsible for the resistance pattern.

Conclusion about performance, behaviour under AST and impact of conditions

It was successfully shown how the MEA configuration can be adjusted with textured electrodes to match the local operating conditions of the flow field plate. **The deliverable was the textured MEA T2b associated to the automated assembling which showed excellent performance exceeding the reference and good stability in line with the expected decay rate.**

In parallel to the test of MATISSE MEAs and to the project, we clearly showed that in addition to changing the MEA configuration, there is also benefit from improving the cell bipolar plate itself. The cell plate variations were designed to have a better interface with the GDL applied. Data showed the resistance improved for the different changed parameters. Interestingly, the lower resistance of the cell plate also caused a better 'definition' of the measurement method and the S++ plate appeared to show better resolution, giving the impression that current distribution was more diverse. It is counterintuitive considering the last section, to observe higher performance with a more distributed current pattern. However, it is logical that with a decreased absolute resistance, the overall performance is higher with lower resistance, independent of any variation of operating conditions across the flow plate.

In summary, we have shown that the fuel cell performance benefits directly from minimizing resistances, albeit contact resistance between plate//MEA, as well as keeping the MEA in optimum operation conditions across the entire plate and even patterning the MEA design accordingly.

The S++ analysis method has clearly proven itself to be a critical tool to identify the resulting current distribution and temperature distribution, enabling focused analysis of the issue at hand and directing development of improvements.

Finally, we should realize and accept the fact that the operating conditions change locally in the fuel cell, and only by selecting specific 'system' working points can we optimize the MEA and plate accordingly.

Long-term durability test at ZSW of textured MEA in a short Nedstack stack

Discussions about transfer of AST- results during the 1st project period led to a definition of a regular long-term test with regularly included stops, cold-soaks and start-ups, based on the test-program performed for inhouse engineering. For the textured MEA T2 an additional long-term test was performed including regular start-stop phases. This test was on the one hand defined to close the gap between AST- and system testing, on the other hand to apply the same test program to MEAs for different applications for comparative reasons. Steady-state-operation of 100 hrs on 0.6A/cm² (120A) are followed by polarization curves (in 3 different operating conditions), shutdown with and cold-soak \geq 4h, startup, polarization-curves and steady-state operation of 100h. The tests was stopped after an overall operating-time of about 2700 hrs. Here, no long-term data on stack-test level of reference-MEA is available.

Stack operating in reference operating conditions (based on D3.1) resulted in a strong, but mainly reversible degradation. Test operating conditions were changed after 700 hrs to higher stoichiometries and a low overpressure on the anode side. Test operation was much more stable there and an overall irreversible degradation rate (starting at 700 h) of $8 \mu\text{V/hr}$ could be evaluated. Here, the BOL- performance in that new operating-conditions is not available.

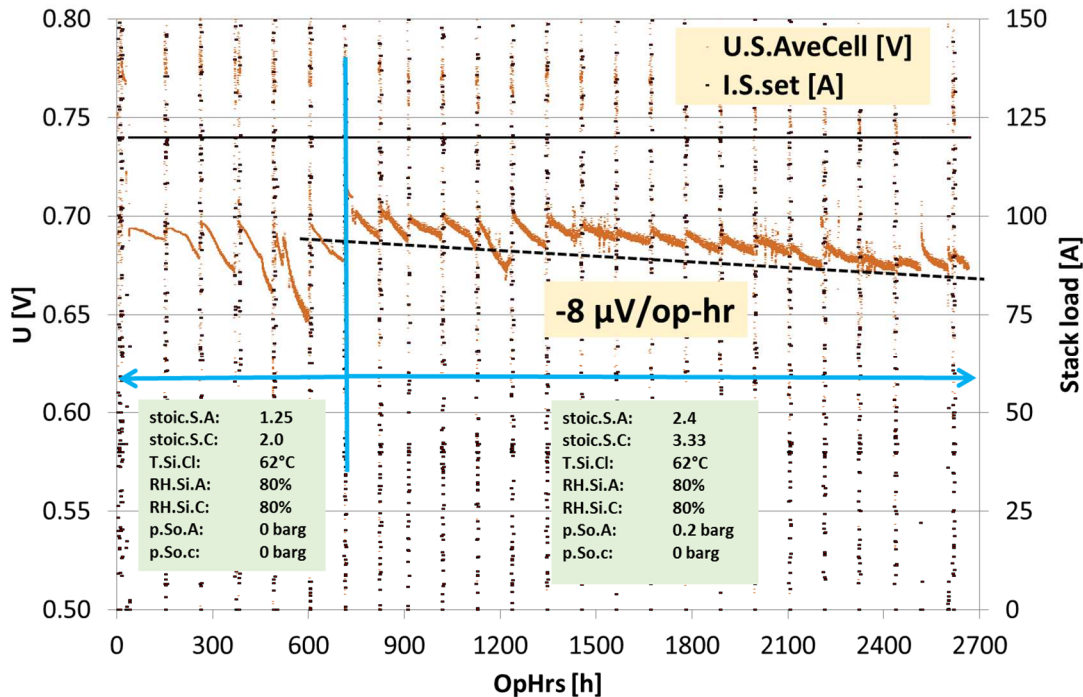


Figure 15: Long-time durability-test with textured MEA 2nd version, stack #1558 at ZSW (MEA T2b)

Analyzing results of performed polarization-curves in 3 different operating conditions (reference, dry and hot) gives a quite different picture:

| | | |
|-----------|-------------|--|
| Reference | (75-75-65): | -14 $\mu\text{V/op.-hr}$ |
| Hot | (75-75-75): | -6 $\mu\text{V/op.-hr}$ |
| Dry | (40-40-65): | -6 $\mu\text{V/op.-hr}$ |

There is a mismatch in polcurves in reference and those in hot and dry conditions. Hot and dry conditions are comparable and fit also to the overall fitted line during the test, if we consider the parameter change at op.-hr. 700.

Please consider that the durability-test is performed in different operating-conditions as the polcurves. The parameter-sets for polcurves stayed unchanged over the whole durability-test. So, deviations in degradation-rates evaluated by polcurves are purely resulting from the different polcurve-operating-conditions and not from the durability-test itself. A change of parameter-sensitivity over the 2700 op.-hrs due to aging-effects are probably having also an impact.

But nevertheless it can be concluded, the $6 \mu\text{V/op.-hr}$, already evaluated with the final textured (automated fabricated) inhouse-MEA, are also reproducible for the final textured (automated fabricated) Nedstack-MEA; if we consider the for the MEA-type not optimal operating-conditions for durability-testing.

Compared to the Nedstack-commercial reference, the final MATISSE textured MEA (T2b) can, even on this test level, compete both with the cell voltage performance and degradation.

CV-measurement Stack #1558 (only cathode-side) showed relatively uniform aging of the 15 cells, with reduction of active cathode catalyst area of about 25%.

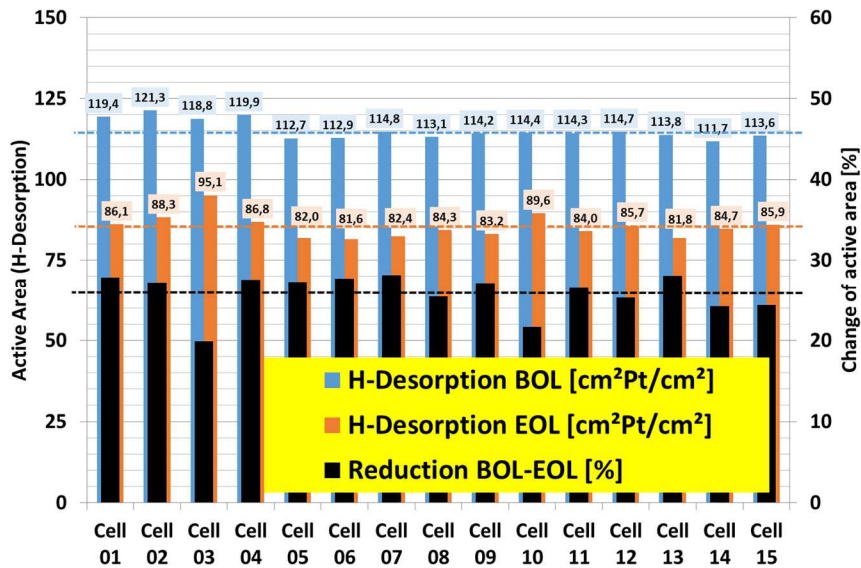


Figure 16: Result CV-measurement on cathode of stack #1558 BOL-EOL

Impedance-Spectroscopy of stack 1558 shows no increase in membrane-high frequency resistance (unclear for the anode here). Cathode charge transfer and mass transport impedance was slightly increased.

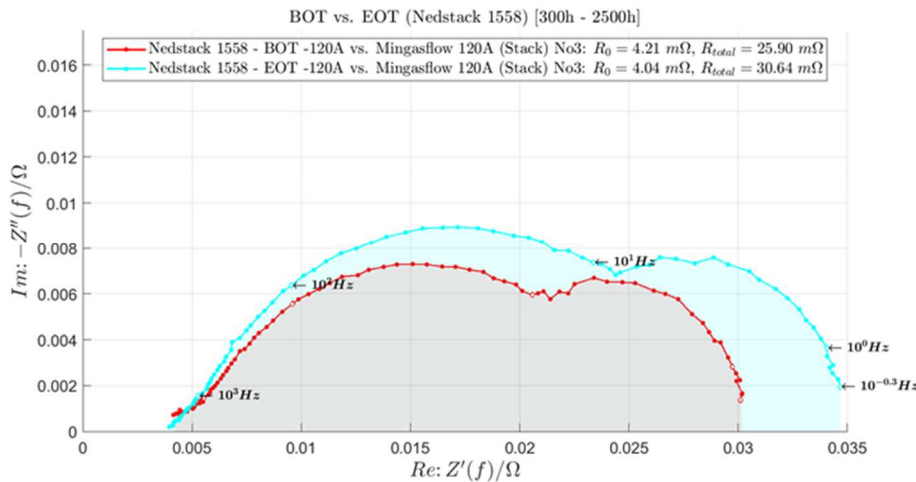


Figure 17: Result electrochemical impedance spectroscopy of stack #1558 BOL-EOL

So, during long-term testing the aging is more homogeneous, attributed both to a loss of active surface area and impedance increase. That's probably the main difference to AST- testing where one individual electrochemical issue was each affected overproportioned.

3.3.2. Full-stack test in the pilot plant with Nedstack design automatically assembled MEA

Validation of the MATISSE homogenous MEAs defined for Nedstack full stack

This section discusses the validation of the homogenous MEAs manufactured on the MEA pilot line at CEA. First MEAs were used for validation at Nedstack laboratory facilities, the following set was used to consider its results during long term durability tests in a pilot plant environment.

The task includes the discussion of the homogenous MEAs that were used to validate the MEA assembly line. Hereto three sets of MEAs were produced by CEA, first 2 MEAs to validate the Nedstack hardware geometry (without catalyst), then, secondly 5 MEAs were built in a 5-cell stack to verify if the required performance for the Nedstack PEM power plant is met, and finally a large batch of 75-cells for a full size stack for long-term durability testing.

Before the production of MEAs for a full size stack with 75 cells suitable for the Nedstack power plant, a small pre-batch of MEAs was produced by CEA. The first part was to check the geometry of the MEA and its alignment with Nedstack hardware. The MEA were checked and aligned with Nedstack hardware. No faults or other deficits were found that prohibited the use and hence suitable for the hardware.

The next step include a small batch to build a 5-cell stack for performance verification. The optimizations of the homogenous project MEA H1 with GDL 24BC: new GDL, changes in Pt-loading, gave a good improvement in performance as shown by the polarization curves for small scale stacks (5-cells). The new homogenous MEAs H1b with GDL 28BC and automatically assembled was compared with then Nedstack reference MEA (5-cell stack). The improvement resulted in a MEA design that has higher performance then the Nedstack reference. It was therefore considered as a suitable MEA for the next step: a full size stack.

Full stack test with MATISSE homogenous MEAs in Nedstack hardware on the pilot plant

The full size stack shows improved performance compared to the 5-cell stack, which is in-line with expectations. The Nedstack reference for a 75-cell stacks shows the same behaviour.

The stack with 75 MEAs of type homogenous reference (28BC) is placed in the Nedstack PEM Power plant environment in Delfzijl (NL). Typical operating conditions include humidity of 85%RH, with an average operation temperature of 62.5°C. Stoichiometric operation includes 2.4 on anode side and 3.33 on cathode side (air).

At the end of this report results were available over about 2000 hours. However, operation of the stack is continued until EoT is reached. Decay assessed on voltage data normalized at 120A shows the calculated slopes of the v1 homogenous MEA, but also the decay of the full stack with Nedstack reference MEAs. Average decay rates assessed up to 2000hrs are -48,5 μ /hrs for the Matisse final automated homogeneous MEAs compared to -27,5 or -39,0 assessed for the two Nedstack references. The decay thus showed to be twice as high as the Nedstack reference. Although the decay rates for the project MEAs were indeed higher than the Nedstack reference, the result showed that it is possible to apply a MEA produced on MEA pilot-line in PEM Power plant environment.

Table 2 Decay rate for fullsize stacks with Matisse MEA H1b homogenous (28BC) and Nedstack Reference MEAs

| | H1b homogenous | Nedstack reference 1 | Nedstack reference 2 |
|---|----------------|----------------------|----------------------|
| Slope ($\mu\text{V/hr}$) | -46.1 | -23.2 | -24.7 |
| Operation hours | ± 2150 | ± 2000 | ± 2200 |
| Start voltage | 717 | 686 | 703 |
| End voltage | 637 | 631 | 598 |
| Voltage at 2000 hrs | 620 | 631 | 625 |
| Averaged degradation up to 2000hrs ($\mu\text{V}/\text{hrs}$) | -48.5 | -27.5 | -39.0 |

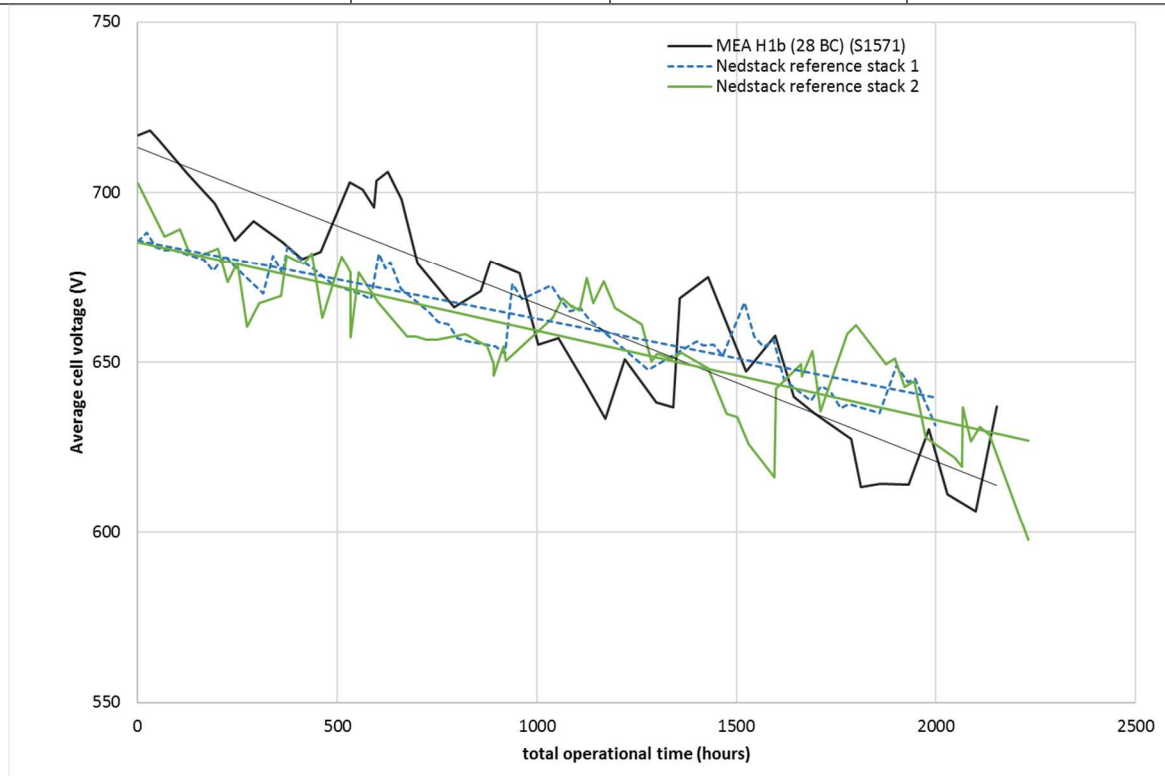


Figure 18 Decay of H1b homogenous (28BC) in and Nedstack reference in Pilot Plant Environment normalized to 120A

3.3.3. General conclusion about MATISSE MEAs in Nedstack hardware

Concerning last selected textured MEAs for Nedstack design, no corresponding long-term results from system-testing are available due to used homogeneous MEAs on the system-site. For the automated homogeneous MEAs, the degradation-rate on system-site is behind the commercial Nedstack-reference. However, results of the long-term test on test-bench-level and also partly on AST-test bench-level of the final textured MEA are very promising and can clearly compete with the commercial Nedstack standard-MEA in terms of performance and durability; but that still has to be proven on real system-site and is above the Matisse-timeframe.

3.4. MEA and stack tests results with inhouse design

3.4.1. Results of Matisse MEAs tested within inhouse hardware

Specific protocol and conditions for assessment of MEAs designed for inhouse application

The main application targeted is μ -CHP-systems using reformat hydrogen and Air (inhouse engineering)
The 24h- load profile from inhouse engineering is defined by fix current density steps (0.2 and 0.4 A/cm² steps of few hours each with regular 1 hour load off) and 2 (warm) stops and starts a day. Reversible performance loss within a durability test can be determined by observing the average cell voltage within the load profile in fix steps (points 1 – 8). The irreversible performance loss within a long-term durability test can additionally be determined by defined intermediate polarization curves directly after the start-up-phases. In addition to initial performance and durability in nominal conditions (75%H₂, 25%CO₂, 65°C, fuel and air dew points 60°C, with stoichiometric ratios 1.3/2.0 and atmospheric back-pressure), extensive tests were performed about the sensitivity to operating parameters, like mainly stoichiometry and relative humidity. In the frame of MATISSE INHOUSE used its own Current Density Distribution Measurement (CDDM) Device. The CDDM device consists of a sensor plate, an electronic evaluation processor unit and software for visualization and data logging developed by Otto-von-Guericke-University of Magdeburg, Germany supported by inhouse engineering GmbH.

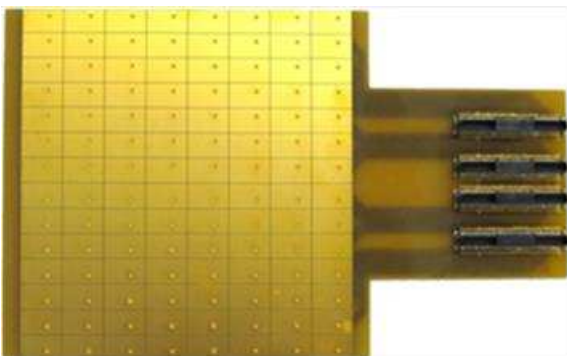


Figure 19: Left: Sensor plate, Right: Electronic evaluation processor unit

Many of the tests were conducted with a segmented plate or two implemented in the short stacks. For evaluation and advanced visualization of current-density-mapping data's ZSW developed a Matlab-based software-tool allowing to get 3D and 2D views, or videos enabling to identify the zones and moments of interest for deeper analyses. This software-tool initially used for inhouse-datas, but could also be adapted to different CDDM-plates (e.g. S++).

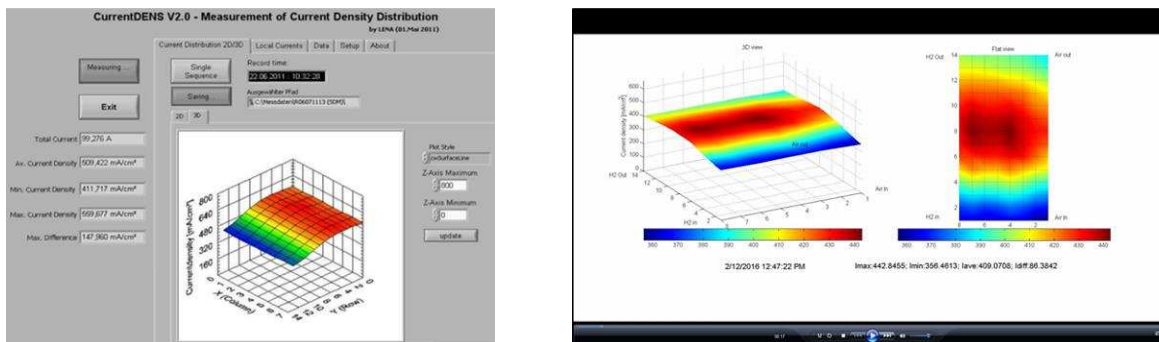


Figure 20: screenshot of software for visualization and data logging and CDDM video made by ZSW

In addition to current mapping, inhouse discussed the integration of their temperature mapping tool into their hardware with CEA reference MEAs. Inhouse successfully implemented their tool into a stack and obtained relevant temperature mapping results.

Performance and Current Density Distribution profiles for assessment of MEAs designed for inhouse application

During the first period, first aim was to implement and validate homogeneous as Matisse reference MEAs. Several 6-cells stacks were assembled and tested on inhouse and ZSW test benches to extensively evaluate reference homogeneous MEAs. First step identified as a priority at the beginning of the project, was the integration of CEA MEAs into the inhouse stack design: the integration was finally successful, but took more time as initially estimated. The anti-wicking-technology was implemented standard wise at inhouse and tests were performed with two gasket-types: glued and none-glued. The non-glued showed poor performance but the glued-versions reached the performance demands. Satisfying results could be obtained thus validating the Matisse reference for inhouse design during the first period.

In the course of the project, 3 iterations of textured MEA designed for steam reformate application have been tested by ZSW, INHOUSE and CEA within 4 short stacks with cell number of 6 to 10.

Texturation T1: Texturation of cathode electrode, anode electrode was equal to reference MEA

Texturation T2: Texturation of anode and cathode electrodes

Texturation T3: Texturation of anode electrode, cathode electrode was equal to reference MEA

The development of texturation was done by CEA using first manual assembling (Reference MEA, Texturation 1 and Texturation 2).

In a downstream step the production of the MEA was transferred from manual to automated production (Reference MEA, Texturation 2 and Texturation 3) by CEA with production of MEAs for a 90-cell full stack as well as 2 short stacks. The shift from manual to automated production has affected the cell performance in a positive way but with reduced comparability between all 3 texturations. However, several tests could be compared to conclude on these various formulations.

Below, most important comparative results of texturations 1-3 with reference MEA are given. In addition selected results of parameter screening of texturation 2 (MATISSE stack #5) are shown as well as and some observations regarding long term stability of the current density profile (stack #4 and #5).

Comparison of texturation 1-3 with reference MEA at Beginning of Test (test at inhouse)

The full polarization curves of all short stacks including the different MEA types as well as the commercial stack of INHOUSE were compared. All values come from Begin-of-Life polarization curves which have been carried out by INHOUSE during function test of the stacks and very close after break-in of the stacks.

Already the Reference MEAs from manual production deliver higher cell voltages (0.709mV/0.705mV) than the commercial MEA of INHOUSE (0.696mV). The texturation 1 is more or less in the same range (0.711V) like the reference MEAs – with minimal improvement. A stronger improvement was reached by manually made texturation 2 with 0.718mV cell voltage which is 9 to 13 mV higher than handmade reference MEA. The shift from manual to automated production affected the cell performance in a positive way. In general the cell voltages of all automatically produced MEA types are approximately 10mV higher than identical manually made MEAs. Automatically produced reference MEA delivers 0.719mV, texturation 2 delivers 0.728mV and texturation 3 delivers 0.718mV.

The specific power during MATISSE project for handmade texturation 2 reached 297mW/cm² which is ~2% higher than handmade reference and ~4.5% higher than commercial MEA. The final automatically assembled texturation 2 reached a specific power of 301mW/cm².

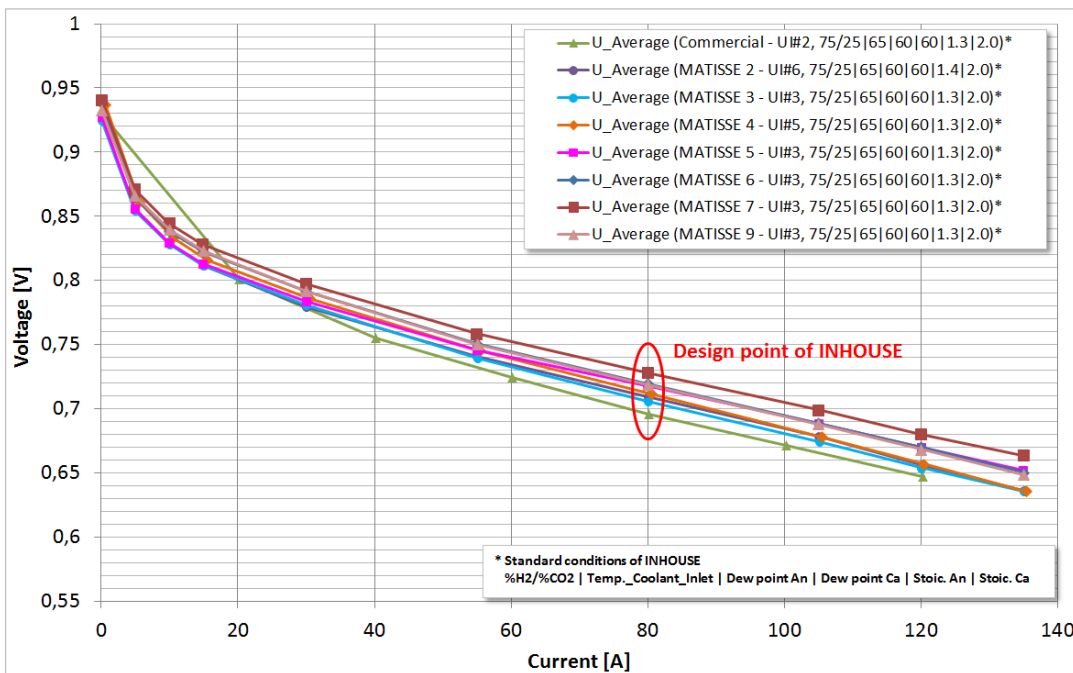


Figure 21: Begin-of-Life polarization curves

Commercial stack if INHOUSE

Reference MEA, manual production by CEA (MATISSE stack #2 & #3)

Texturation 1, manual production by CEA (MATISSE stack #4)

Texturation 2, manual production by CEA (MATISSE stack #5)

Reference MEA, automated production by CEA (MATISSE stack #6)

Texturation 2, automated production by CEA (MATISSE stack #7)

Texturation 3, automated production by CEA (MATISSE stack #9)

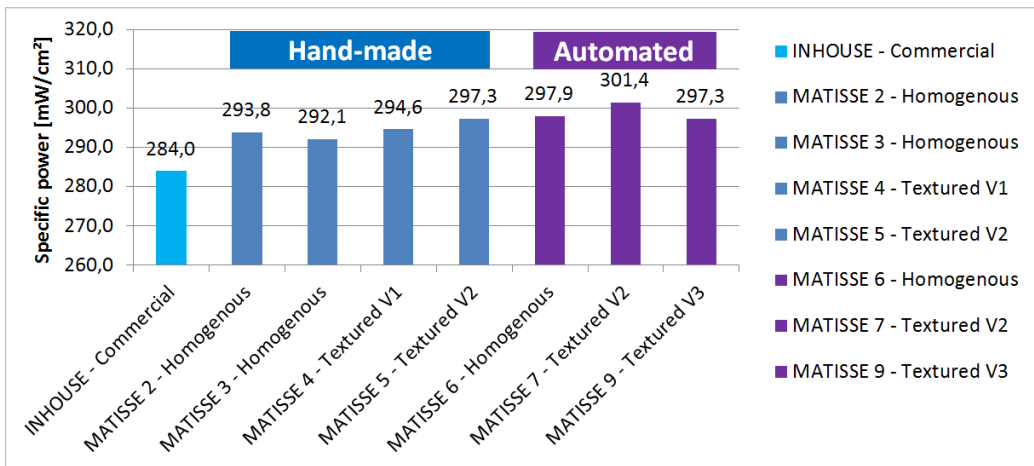


Figure 22: Average cell specific power at design point of 80A (0.41A/cm²)

Gas composition An/Ca: 75%H₂ + 25%CO₂ / Air

Temperature coolant inlet/outlet: 65°C/68°C

Temperature gas inlet An/Ca: 61°C/61°C

Stoichiometry An/Ca: 1.3/2.0

Dew point An/Ca: 60°C/60°C

Coolant: DI-Water

From the first half of the project it was known that CDDM profile of reference MEA has minimum current production at the gas inlet region and a maximum current production in the middle of inlet and outlet (~60% away from inlet). Furthermore it was known that it is a more or less monotone profile with quite similar 2D-profiles of each CDDM segment column between inlet and outlet.

It can be seen that the CDD profiles of both reference stacks (#2, #3) are quite similar with its minimum current production at the gas inlet region and a maximum current production in the middle of inlet and outlet (~50% away from inlet).

The idea of MEA improvement was to improve the inlet area for dry conditions – which have been assumed – to reach a higher current production at the inlet region. In a first step of texturation the cathode electrode was modified and the anode electrode was homogenous. The stack equipped with textured MEAs (Texturation 1) gives profiles similar to the reference stacks (2nd stack, 3rd stack) but with small displacement of the maximum current production in the direction of the outlet. The amplitude of the shape is a little bit smaller than for reference stacks. The outlet region produces more current than before with reference MEA. The CDDM profile of textured MEA (Texturation 2 within 5th stack) is more different with strong increase of current density at the inlet region and a strong decrease at the outlet. As targeted the current production at the inlet could be improved now by this texturation 2. Compared with the reference MEA the maximum current production is slightly moved to the inlet. It was agreed to transfer this texturation 2 to the serial production and to use it in the full stack.

In a final development step texturation 3 was realized and tested in a short stack (9th stack). The profile is quite close to the reference profiles (2nd, 3rd). So from this test it could be seen that both – Anode and Cathode – must be textured to influence the shape of the profile in the targeted way.

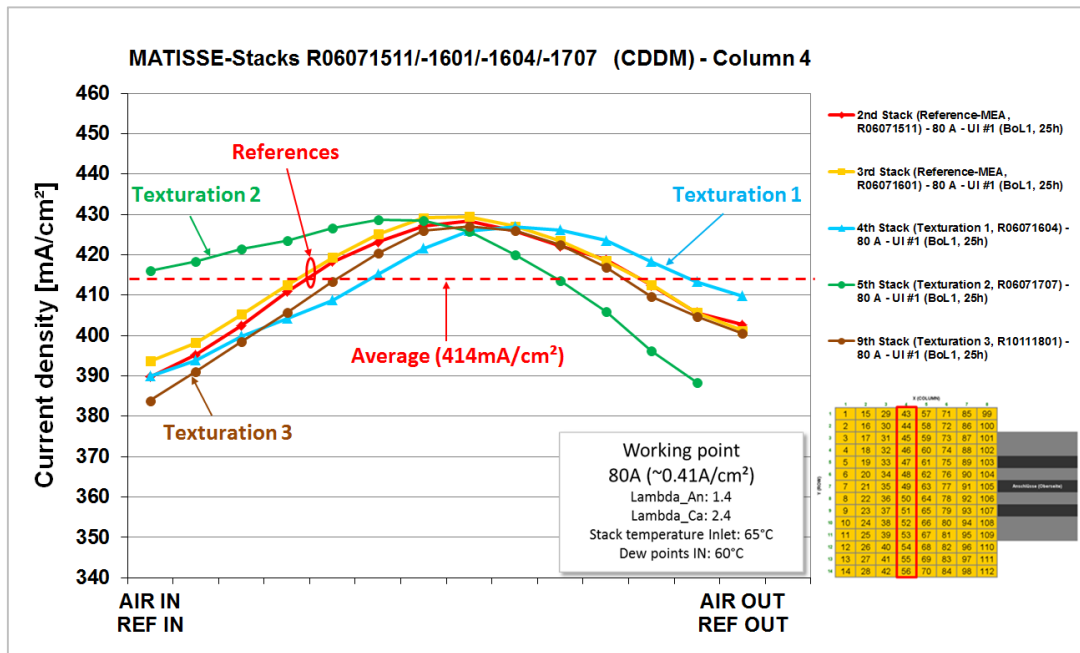


Figure 23 2D profiles (column 4) of reference stacks #2, #3 and stacks #4, #5, #9 with textured MEAs

Conclusion on Current Density Distribution of inhouse texturations 1-3 compared with the reference MEA

The test programs of short stacks with textured MEAs – stability tests included – have shown that the shape of the CDDM profile is more stable during real operation but it is strongly influenced by stop and restart. The original reached improvement of the dry inlet area in case of second texturation type could not be kept high over the long term after break-in and some start-stops.

Texturation 2 is the most promising texturation because of its highest cell voltage compared to the other texturations as well as to the reference and to commercial MEA of INHOUSE.

Conclusion on parameter screening of texturation 2

By increasing the dew point at cathode inlet:

- the current production of the inlet region increases
- the current production of the outlet region decreases
- the position of maximum current production moves towards the inlet

Conclusion on CO sensitivity of reference and textured MEAs 2 and 3

When comparing to pure hydrogen operation, CO affected the CDD profiles of reference homogeneous MEAs and also of the third type of textured MEAs (with only the anodes inlet modified) while no modification of the CDD profiles was observed when testing the impact of reformat with CO in similar conditions (during durability test) with the second type of textured MEA (both anodes and cathodes modified at inlets). However, CO tests were conducted during long term testing for reference and second texturation whereas only near beginning of test for the third texturation type. Still exact effect of fuel conditions (like composition and back-pressure) as well as of ageing should be clarified; however it could be confirmed that electrodes composition has an impact on the CO contamination process and on related current profiles variations, allowing to expect an impact on durability when ageing would be conducted under reformat with CO traces like it can occur in the system.

Conclusion on long term stability of texturation 1 and 2

The Max-Min difference for texturation 1 was at start comparable to the reference and kept on increasing during the operation time. For stack #5 the Max-Min difference initially increased, but kept constant up to EoT.

Durability tests in inhouse short-stacks of reference and selected textured MEAs

The texturation 2 MEAs (hand-made), which was the most promising texturation, has been tested for a long term period at inhouse (stack#5) for a total duration of about 2500 hrs, equivalent to long term test conducted on reference MEAs with homogeneous electrodes.

The overall irreversible average degradation rate of MEAs with texturation 2 (hand-made) based on BoL and EoL polarization curves, was evaluated to 17 $\mu\text{V}/\text{op.}\text{-hr}$, based on 2500 h operating hours within stack #5 and at design point of 80A (0.41A/cm²). The evolution of the degradation rate for each cell of the 6-cell stack shows general information is the same as for the average degradation rate but it is visible that there were differences between the single cells, which became smaller with increasing operating time.

This degradation rate of texturation 2 MEA (manually assembled) was similar to reference MEA tested on the long term in similar conditions.

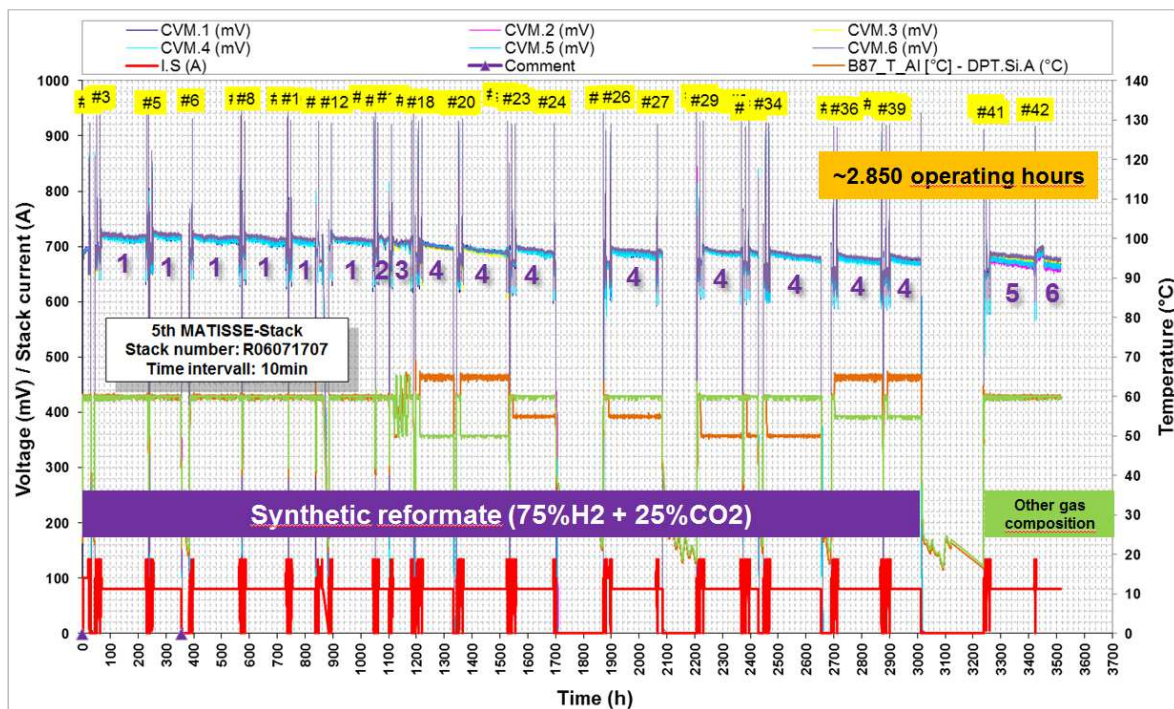


Figure 24 Stack test history of 5th MATISSE stack (R06071707) - Whole stack test history of MATISSE stack #5. Polarization curves are numbered in yellow. Special test protocols are numbered with 1 – 6.

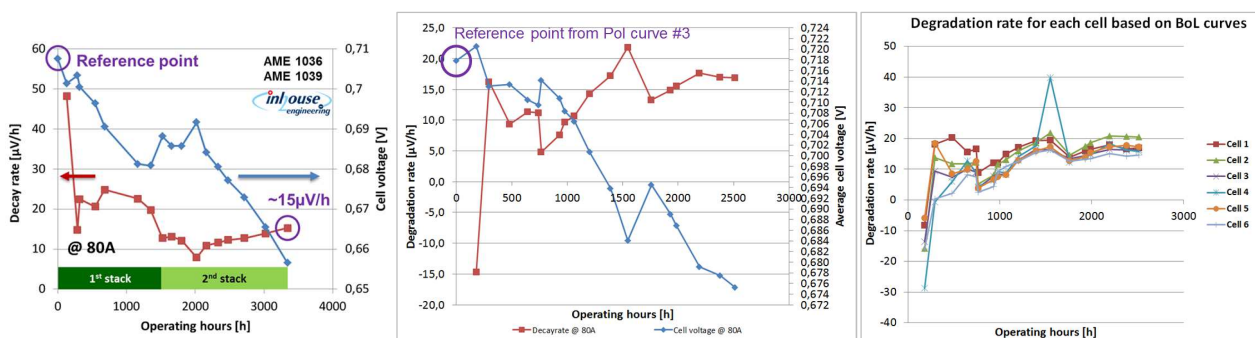


Figure 25: Development of average degradation rate of inhouse 1-2 (reference MEAs) and 5th (textured v2 MEAs) MATISSE stacks - degradation rates of each cell of 5th MATISSE stack

The degradation rate of 17 $\mu\text{V}/\text{op.-hr}$ after 2500 hours is quite good for project MEA but should be further decreased down to 5 $\mu\text{V}/\text{op.-hr}$ and lower. The degradation rate in the time range up to 1000 hours shows the potential of the texturation 2. After 930 hours cell 6 has a rate of 4.3 $\mu\text{V}/\text{op.-hr}$. Without the subsequent parameter screening the probability is high that the degradation rate would be lower than 17 $\mu\text{V}/\text{op.-hr}$.

In stack #7 of INHOUSE the texturation 2 MEA (automated produced) has been tested for a long term period at ZSW. Special test protocols have been applied along with polarization curves. After meaningful operating time the impact of CO contamination up to 20ppm CO in synthetic reformat (75% H₂ + 25% CO₂) was investigated.

The direct comparison of cell voltage evolution of stack #3 and #7 tested on the same test bench at ZSW, applying the same test program with texturation 2 (automated MEA assembling) showed that the 7th stack run more robust in an enhanced cell voltage level- and with significantly lower degradation rate than the 3rd stack with reference (hand-made) MEA. The degradation rate of automated produced texturation 2 is with its 6 $\mu\text{V}/\text{op.-hr}$. approximately 62% lower as for hand-made reference with 16 $\mu\text{V}/\text{op.-hr}$.

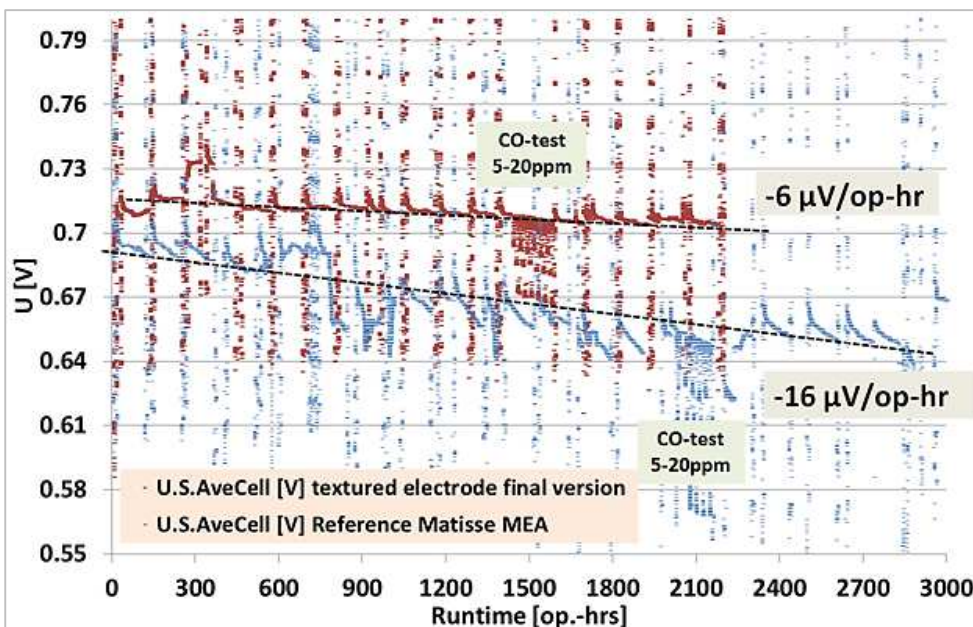


Figure 26: Whole stack test histories of 3rd and 7th MATISSE stack (tests at ZSW)

Degradation rate was also confirmed by calculating it from polarization curves at begin of stack operation at ZSW and at the end. Using an operating time of 2200 hours between both polarization curves a degradation rate of ~6 $\mu\text{V}/\text{h}$ was also evaluated.

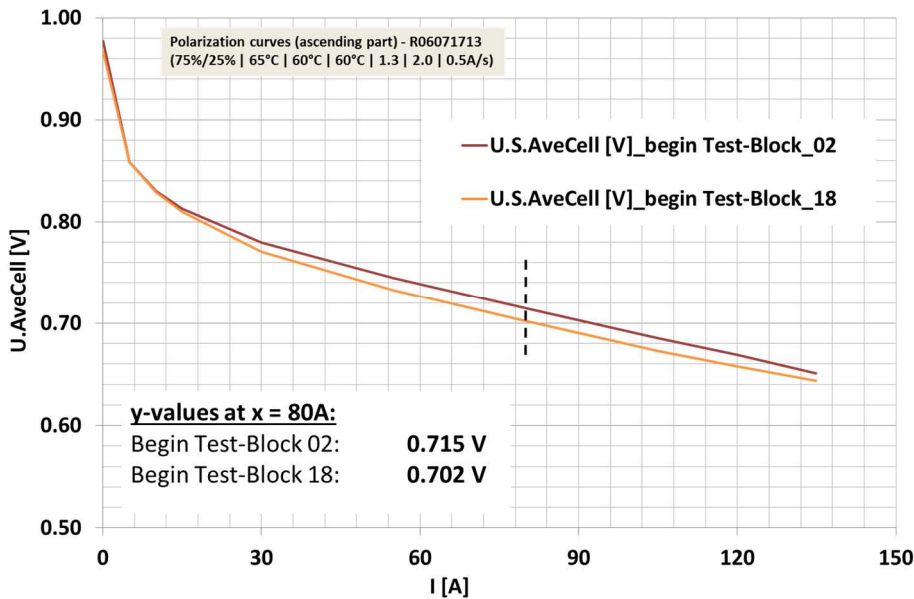


Figure 27: Polarization curves at begin of test and end of test (outlet pressures 50 mbar)

CO tests performed by ZSW during ageing tests were done at constant load of 80A ($\sim 0.41 \text{ A/cm}^2$) at standard conditions of INHOUSE with synthetic reformat consisting of 75% H₂ + 25% CO₂ + x ppm CO. Starting with 0ppm CO concentrations of 5ppm, 10ppm and 20ppm have been set for 4 hours each. With increasing CO content the average cell voltage goes down with $\sim 1.794 \text{ mV}$ per ppm CO. After each CO contamination step the average cell voltage came back to initial value before the contamination step. The CO contamination was fully reversible.

3.4.2. Full-stack test with inhouse design automatically assembled MEA

Validation of the full stack with various MATISSE MEAs on the inhouse test bench

In the last third of the project the decision was made – based on short stack results – how to realize the full stack with 5kW electrical power suitable for CHP application of INHOUSE. In the following the design of the full stack is explained as well as results are given for test bench operation with synthetic gases and CHP operation with real steam reformat.

The 5kW full stack was realized as described in the following specification:

- „Rainbow stack“ with overall cell quantity of 88 cells
- 20 cells (cells 11-30) with T2 textured MEAs (Version 2) (produced with automated process)
- 68 cells (cells 1-10 & 31-88) with H4 Reference MEAs (produced with automated process)
- CDDM sensor plate 1 between cell 20 and 21 (CDD profile of texturation)
- CDDM sensor plate 2 between cell 40 and 41 (CDD profile of reference)



Figure 28: Full stack (MATISSE-Stack #8, R88891714) - connected with test bench (right side)

The mix of the MEA types in one stack offered the opportunity of direct comparison of MEA behavior. The MEAs have been arranged in the way that there were reference MEAs (cells 1-10, cell 1 is on upper side of the stack) followed by a 20 cells block (cells 11-30) of texturation 2 MEAs with 1st CDDM sensor plate in the middle of the cell block. The block of textured MEAs was then followed by 58 cells with reference MEAs. The 2nd CDDM sensor plate was also placed in the middle of a comparable 20 cells block (cells 31-50) of reference MEAs.

At first the full stack was connected with 5kW test bench of INHOUSE with a special connection needed due to the CDDM sensor plates.

Following tests have been performed with synthetic gases: Function test; Activation of catalysts (break-in); Performing of 3 Begin-of-Life polarization curves.

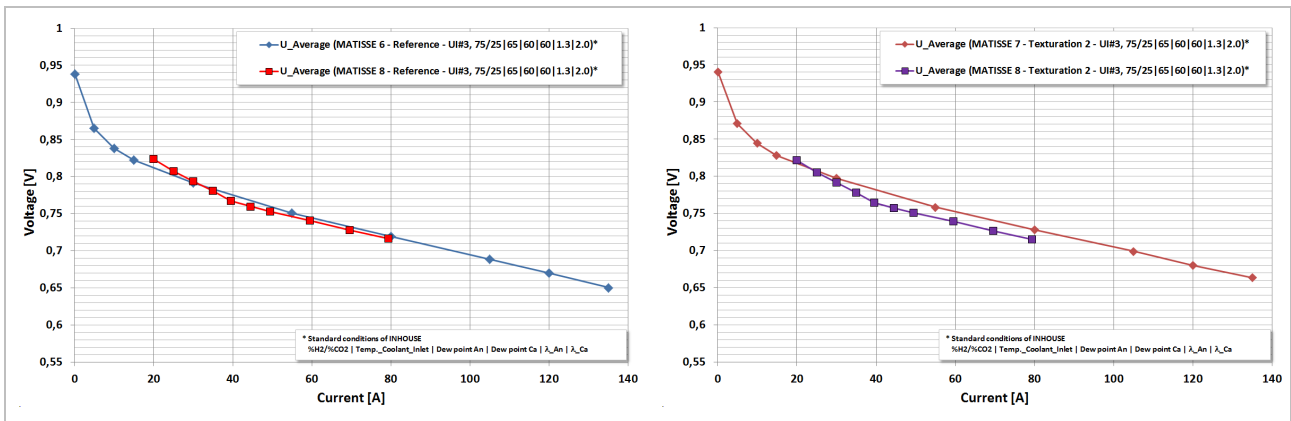
From the function test it was observed that the stack has shown a very stable cell voltage behavior with small deviations between the single cells ($\Delta U_{\text{Texturation 2 (cells 11-30)}} = 21\text{mV}$; $\Delta U_{\text{Reference (cells 1-10, 51-88)}} = 13\text{mV}$). One reference cell (cell #56) has shown much lower cell voltage ($\sim 100\text{mV}$ lower) than all other cells. Because the cell was stable it was decided not to exchange the MEA of that cell also due to the time pressure at the end of the project. All analyses and visualizations were done by comparing a 20 cell block of texturation 2 MEAs (cells 11-30) with a 20 cell block of reference MEA (cells 31-50). Both cell blocks have been equipped with CDDM sensor plate in the middle of each cell block.

Begin-of-Life polarization curve (UI curve #3) for both cell blocks delivered quite equal performance. This was opposite to the expectations based on short stack results. Approximately 10mV higher cell voltage of the textured MEAs was expected.

From the comparisons of Begin-of-Life polarization curves with related short stacks MATISSE #6 (Reference MEA from automated production) and MATISSE #7 (Texturation 2 MEAs from automated production), it was observed that the polarization curve of the full stack (stack #8) was quite equal to the short stack (stack #6) curve. For the texturation 2 MEAs a small deviation between full stack (stack #8) and short stack (stack #7) was visible with lower performance of the full stack MEAs. At the design point of 80A the textured full stack MEAs are $\sim 12\text{mV}$ lower than the textured short stack MEAs.

The comparisons of Begin-of-Life current density profiles with related short stacks MATISSE #6 (Reference MEA from automated production) and MATISSE #7 (Texturation 2 MEAs from automated production)

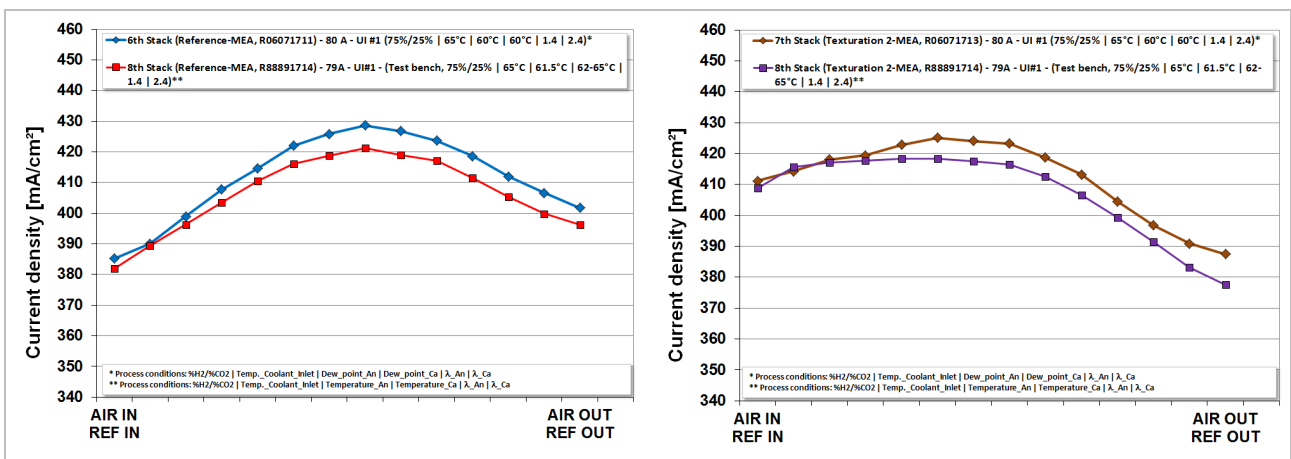
showed that for both MEA types of the full stack the current density profiles are very reproducible with respect to related short stacks.



a) Reference MEA

b) Texturation 2 MEA

Figure 29: Comparison of polarization curves of full stack (MATISSE stack #8) with related short stacks (MATISSE stacks #6, #7)



a) Reference MEA

b) Texturation 2 MEA

Figure 30: Comparison of current density profiles of full stack (MATISSE stack #8) with related short stacks (MATISSE stacks #6, #7)

Test of the full stack with various MATISSE MEAs on inhouse CHP system

After the test on test bench with synthetic gases the full stack was integrated into the CHP system “inhouse5000+”. The CHP system allowed the operation of the stack with real reformat coming from a natural gas driven steam reformer module.

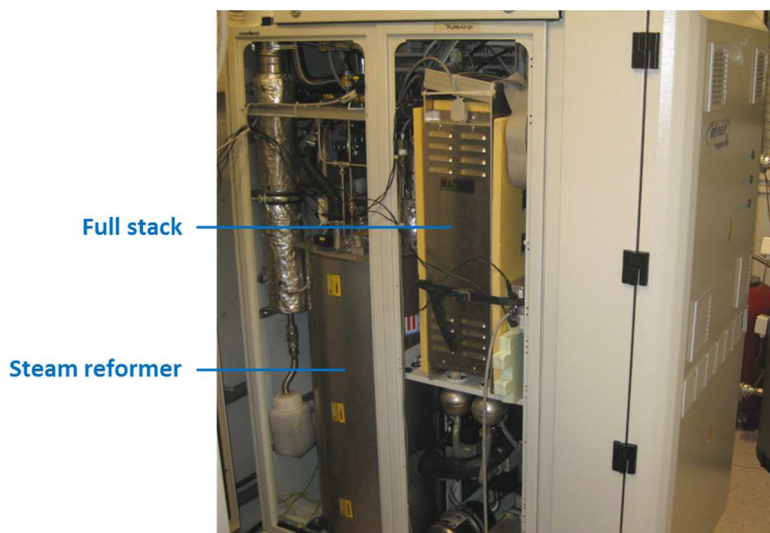


Figure 31: Full stack (MATISSE-Stack #8, R88891714) mounted in CHP system “inhouse5000+”

Following tests have been performed with real steam reformat: Performing of polarization curves; Short stability tests at constant load ($\sim 80\text{A}$) over $\sim 8\text{h}$ with daily start stop; Long stability tests at constant load ($\sim 80\text{A}$) over 100-140h; Air bleed test.

The direct comparison of BoT polarization curves (UI curve #5) from CHP operation with real reformat (dashed lines) with BoL polarization curves (UI curve #3) from test bench with synthetic gases (solid lines) shows lower cell voltages for CHP operation. For the reference MEA the difference was $\sim 22\text{mV}$ and for the texturation 2 MEAs it was $\sim 15\text{mV}$.

The reasons for that cell voltage difference could be: fuel (real reformat instead of synthetic gas mixture with 2 components); perhaps the presence of carbon monoxide in real reformat; different process parameters of CHP especially slightly lower inlet dew points.

Furthermore it was observed that the CHP polarization curves of both MEA types are quite equal but with a small advantage of the textured MEAs in the higher load range (e.g. $\Delta U_{\text{Texturation-Reference}} \sim 6\text{mV}$ @ 80A). The electrical power of the stack at Begin-of-Test within CHP system was 4.9kW .

The whole stack test history (real operating time) until completion of this report reaches operating time of ~ 1000 hours. The most time the CHP system run under full load with some part load sections and polarization curves. Cell voltage degradation was calculated using polarization curves UI#5 and UI#11 with CHP operating time of ~ 881 hours in-between. At 80A the degradation rate for the reference MEA was $\sim 46.5 \mu\text{V/h}$ and for the texturation 2 MEAs $\sim 43.2 \mu\text{V/h}$. Both MEA types are gradually drifting apart with small advantage for textured MEA. For reformat application an operating time of ~ 1000 hours is too low for determining a meaningful degradation rate. To reach meaningful degradation rate a minimum of 3000 to 5000 operating hours are necessary. INHOUSE is going to continue the operation of MATISSE stack #8 after finishing the MATISSE project to collect and share more data.

In the frame of CHP test a short air bleed test was carried out by inhouse to find out the influence. It could be observed that the cell voltages increased on average by 4mV with air bleed of 1-2%. Using CO dependency determined by CO test at ZSW a CO concentration of 2-3 ppm can be assumed for steam reformat which is a common value.

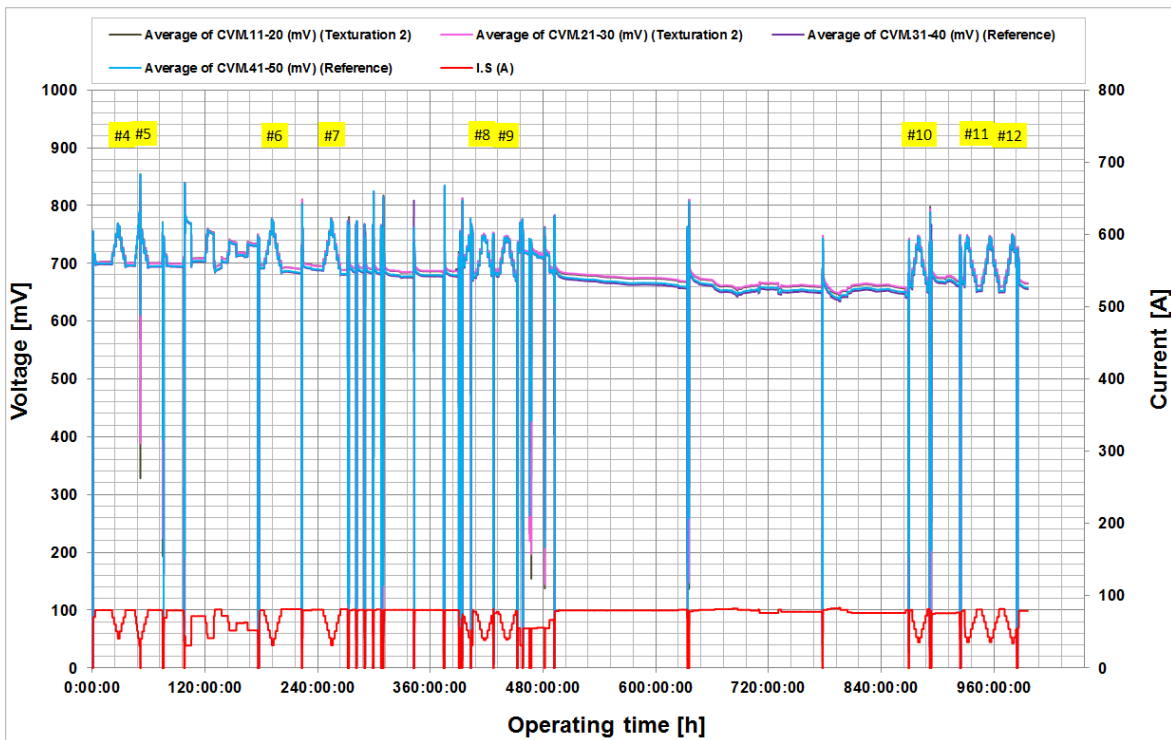


Figure 32: Whole stack test history (operating time) of CHP operation with real reformat

3.4.3. General conclusion about MATISSE MEAs in inhouse hardware

Compared to the internal commercial reference of inhouse, this final project-MEA has a better cell performance and can also compete in terms of durability. Based on that results, inhouse has a clear interest on exploitation of the final Matisse-MEA.

3.5. Post-mortem analyses

Applied techniques for analysis of aging-effects were microscope (surface), Scanning Electron Microscopy SEM (surface and cross-sections), goniometer (surface, contact angle) and Transmission-Electron-Microscopy TEM (cross-sections).

On selected aged samples, it can be pointed out that:

- Cracks on catalyst-surfaces predominantly observed at MEAs from manual production are significantly reduced on MEAs from automated production line (proved on inhouse-MEAs). This gives a strong indication for a significant contribution to durability-properties.
- Analysed textured MEAs have more homogeneous thicknesses of catalyst-layers compared to initial batch of reference-MEAs. That's probably also one of the contributions to durability-properties.
- For inhouse, drop-shape analysis on GDL-side of reference-MEAs gave a quite clear trend towards lower contact angles with increased lifetimes. Lower contact-angle means a loss of hydrophobicity, assessed as an aging-indicator. A loss of hydrophobicity over time results in a change of optimal test parameters which can have a serious impact to durability-issues. Without having the certainty of statistical relevance, analysed textured MEAs are more stable over lifetime resulting in stable operating-conditions and stack-performance over long time.

- Results of detailed TEM-analysis of samples of a long-term durability-test performed on reference-MEA gave numbers of aging-effects of the alloy-catalyst:
 - o i) At the cathode side, there is probably a slight Pt₃Co nanoparticle size increase due to the electrochemical Ostwald ripening mechanism. This mechanism involves small Pt₃Co nanoparticle dissolution following by the Pt redeposition on larger nanoparticles whereas Co ions remain within the electrolyte due to the negative Co²⁺/Co standard potential. These Co ions is a source of ionomer contamination that can reduce its proton conductivity. In the aged cathodes, the electrochemical Ostwald ripening mechanism is highlighted on one hand by a Pt shell surrounding the Pt₃Co, that is thicker (thicker than 1 nm) than the thin (0.6 nm) Pt shell observed for the fresh cathode Pt+Co nanoparticles and on the other hand by the neighbouring nanoparticle sintering.
 - o ii) At the anode side, Ru is dissolved from the PtRu catalyst and after their migration toward the membrane, Ru ions are reduced within the membrane by the H₂ crossover. These Ru rich precipitates mainly formed on the initial Pt/C that were present in the fresh MEA and that probably played a catalyst role for the Ru reduction. In addition, a precipitation band richer in Pt appears between the initial Pt/C, the Pt coming from the cathode catalyst dissolution. The Ru dissolution seems to be more severe in the Air Inlet zone, where the lowest current density was recorded and could suggest a more severe anode degradation in this zone.

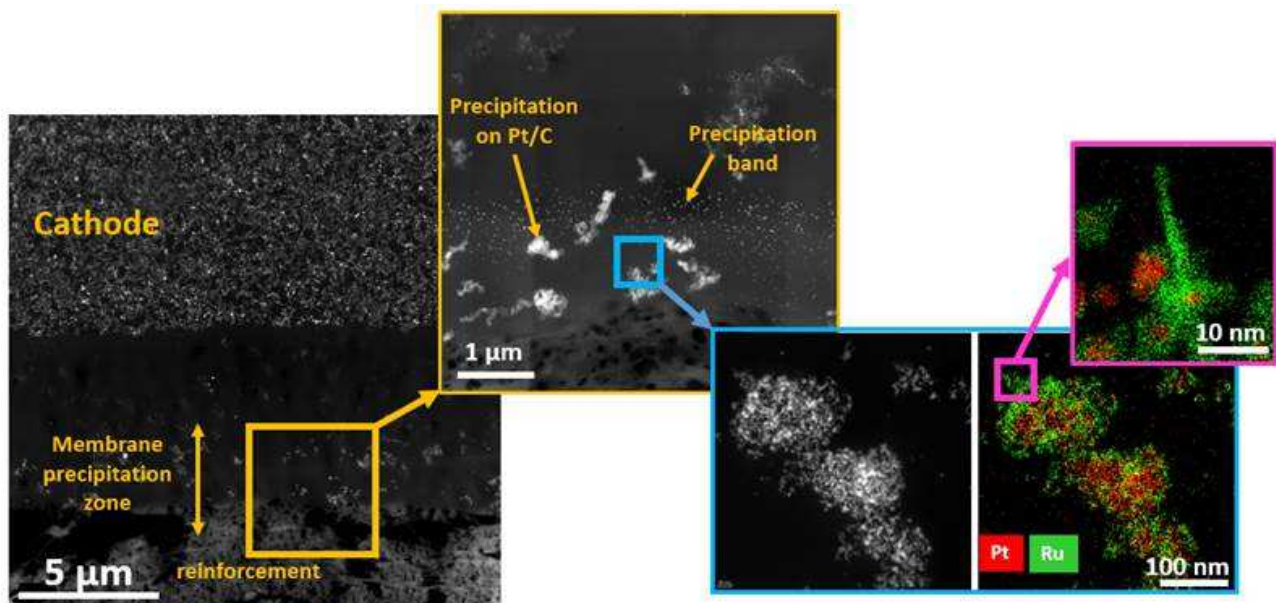


Figure 33: PtRu precipitates within the membrane after ageing due to Ru dissolution at the anode side

3.6. Cost assessment data

The PEMFC cost model developed internally by CEA and adapted to the project, was described in detail with its set of hypothesis and input data collected from partners for the assessment on the reference MEAs. The impact of production scale and automation on cost was studied. It demonstrated that according to the process step, it could be cost effective to invest early in automated tool even at low running time or to prioritize the externalization, as illustrate by the example of the MEA assembly and shape process step.

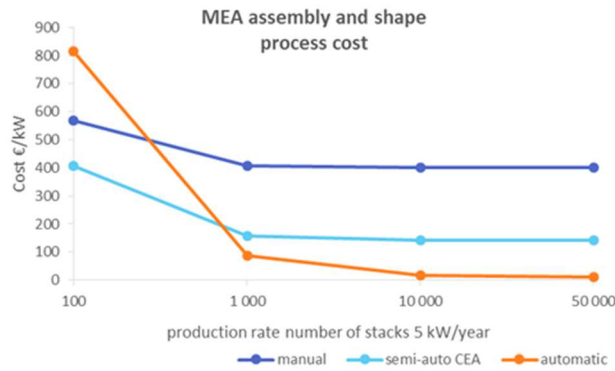


Figure 34: Cost of stack assembly according to production rate

Secondly, the cost analysis focused on the 3 applications in order to demonstrate the financial value of the improvements proposed within the framework of the project. For each case, the cost of the 3 commercial, homogeneous and textured MEAs were calculated using the same set of parameters and cost model, complemented by a sensitivity study to outline the influence of the key cost drivers.

Comparative assessment was done considering a mature market and a production rate of 10,000 systems of 5 kW per year.

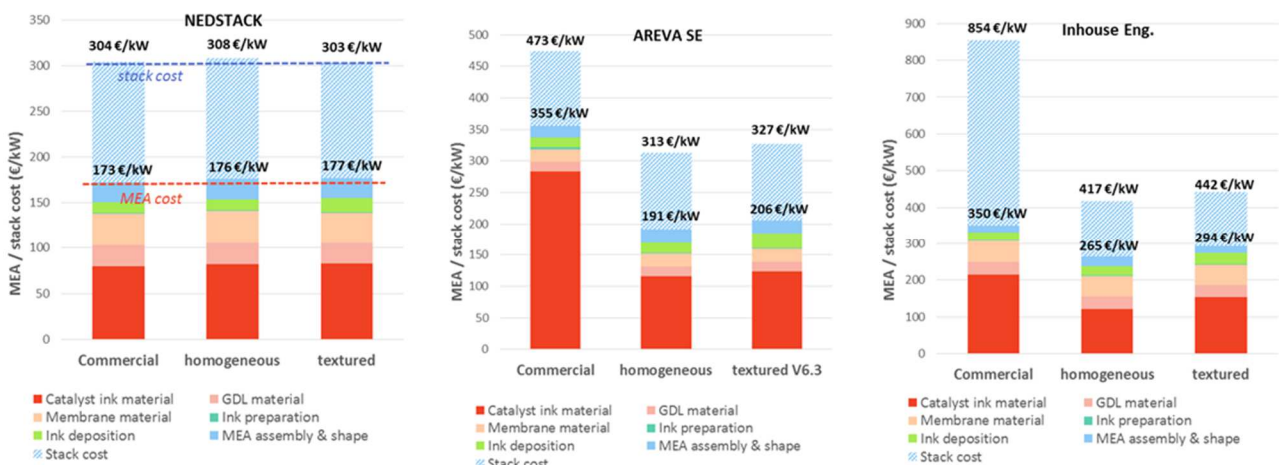


Figure 35: Cost breakdown of the stacks with the 3 MEAs

At this stage, the study was not able to clearly demonstrate the cost benefit of textured MEA compared to homogeneous, due to difference in design parameters like Pt loading and its partial approach not including degradation criteria.

If the conclusions were very dependent on the application cases, they globally demonstrated that the MEAs developed in the timeframe of the project reached equivalent and even better performance, with similar and in some cases far cheaper production cost.

Finally, improvements on assembling aspects like innovative gasket and anti-wicking solutions, were analyzed and provided encouraging results on anti-wicking solution that would conducted to a cost saving of 3% on MEA.

Cost assessment has shown that the costs of stacks with textured MEAs are similar (NEDSTACK) or lower (AREVA, INHOUSE) as for commercial MEAs.

4. Potential impact and main dissemination activities and exploitation results

4.1.1. Summary of dissemination

The external website was installed and available under: <http://matisse.zsw-bw.de>

During the 2nd project-phase the webpage was basically updated with more and detailed information about the individual work-packages.

Interested people can get quickly an overview about the general goals and the WP-specific activities.

Active dissemination of project results was during scientific workshops (e.g. EFCF in Luzern) or the electrochemical talks (Ulm).

- “Ulmer Electrochemical Talks (UECT) 2016 in Blaubeuren, Germany (Expert committee for batteries and fuel cells) - Poster presentation
- “7th International Conference on “Fundamentals & Development of Fuel Cells” in Stuttgart, January 31-February 2 2017 - Poster presentation
- EFCF Luzern (02.-07.07.2017): Overall project-presentation (publication see attachment); Poster presentation

Due to reasonable results with textured MEAs during the 2nd project phase no active publications are already submitted, but planned beyond the Matisse-project. Topics are identified such as the analysis, understanding

From scientific point of view that success of influencing current density distribution profile and cell performance came quite late in the project as to show solid project results on an expert workshop. At the end of the project – including extension – a lot of effort was necessary to realize full stacks for each application and to operate them in real application surroundings and no workforce was available to organize or to attend a workshop in this project phase.

From commercial point of view it was similar. Due to late achievement of relevant impact caused by texturation the dissemination and announcement of future fuel cell stack products based on advanced MEA was not really driven forward and dissemination was reduced to scientific dissemination and publication.

A MATISSE poster presentation with very first relevant results was done during Hannover Fair 2017 by ZSW as scientific project member.

4.1.2. Summary of exploitation



Table 3: Table of planned exploitation foreground

| Type of exploitable foreground | Description of exploitable foreground FC techno FC system FC components Specific Application | Confidential | Foreseen Embargo date | Exploitable products or means | Sectors of application | Timetable for commercial use (licenses) | Patents or other IPR | Owners (other beneficiaries) |
|---|--|--------------|-----------------------|--|---|--|----------------------|---|
| General advancement of knowledge for MEA and Stack integration of MEA | The detailed analysis of the MEAs in stacks can be exploited in terms of improved operation strategies, break-in strategies | yes | 2022 | LT-PEM fuel cell stack | Stationary power supply with CHP system | Duration for commercial use 3-5 years R&D: pre-dominantly effect of life-time on operation: 1-2 years Demonstration/ Qualification of the product: 1-2 years Product introduction: 1year | No patents | inhouse |
| Commercial exploitation of R&D results | The enhanced knowledge of improved components like the textures MEA can be in future exploited in the commercial product inhouse5000+ a CHP system | yes | 2022 | LT_PEM fuel cell stack wit 5 kW electrical power | Stationary power supply with CHP system with 5 kW electrical power | Duration for commercial use 3-5 years R&D: pre-dominantly effect of life-time on operation: 1-2 years Demonstration/ Qualification of the product: 1-2 years Product introduction: 1year | No patents | inhouse Technology of textured MEA belongs to Partner CEA |
| General advancement of knowledge | The detailed analysis of the MEAs in stacks can be exploited in terms of improved recommended operation strategies | yes | | Nedstack commercial stack range | Automotive, stationary (Fuel cell power plants), CHP or telecom application | R&D: pre-dominantly effect of life-time on operation: 1-2 years Demonstration/ Qualification of the product: 1-2 years Product introduction: 1year | No Patents | Nedstack (With ZSW and CEA for specific operating conditions and MATISSE electrodes or MEA composition) |

| | | | | | | | | |
|--|---|---|------|--|---|---|------------|--|
| Commercial exploitation of R&D results | The enhanced knowledge of improved components (MEAs) can be exploited in the commercial product (PEMFC stack or system) | yes | | Nedstack commercial stack range | Automotive, stationary (Fuel cell power plants), CHP or telecom application | Duration for commercial use 3-5 years R&D: pre-dominantly effect of life-time on operation: 1-2 years Demonstration/ Qualification of the product: 1-2 years Product introduction: 1year | No Patents | Nedstack With CEA for MATISSE electrodes or MEA composition |
| Low cost homogeneous or textured MEA with low Pt Black loading | Manufacture and integration of low cost MEA in stack for specific stationary applications operating in H2/O2 mode | yes | 2022 | High power stationary fuel cell | Power supply Backup power Off-Grid | 4-5 years | No patents | AREVA SE (With CEA for MATISSE electrodes or MEA composition(|
| Automated stack assembling protocols | Industrialisation of stack manufacturing to reach the targeted production level | yes | 2021 | High power stationary fuel cell | Power supply Backup power Off-Grid | 4-5 years | No patents | AREVA SE (with CEA when CEA equipment's' technology involved) |
| Application oriented research as basic for follow-up projects | Direct comparison of results evaluated on different test levels (test bench (AST, long-term test, system test). Better classification of results gained on test bench level possible. | yes | open | Input for European Standardization efforts (e.g. Durability, IEC 62282-X) | Tests of LT-PEM Fuel Cell Stacks | Not for ZSW | No patents | Open Mainly ZSW and CEA |
| Advanced in-situ and Post-Mortem Analysing Methods | Basic research was linked to application-specific tests. | No (anonymized research results, to be confirmed by project partners) | None | Application of specific techniques in other research and industrial projects | LT-PEM Fuel Cells | Not for ZSW | No patents | Open Mainly ZSW and CEA |

5. Conclusion

Both homogeneous reference and textured electrodes could thus be defined, made automatically on the screen-printing pilot-line and validated with respect to two main criteria which were respectively, reaching at least similar level as commercial reference for the reference and demonstrating improved performance and/or durability thanks to selected textured electrodes and automated manufacturing of MEAs.

Indeed, better performance or similar level with lower catalyst loading were achieved for all MATISSE reference MEAs while selected new MATISSE MEAs actually demonstrated clear impact onto the current density profiles allowing to improve local or overall performance for specific conditions as well as positive effect on stability with reduced degradation rates thanks to the implementation of textured electrodes, made by adapting in one zone near gases inlet or outlet the catalyst layer composition in noble metal and/or ionomer, and of automatically assembled MEAs.

It could be demonstrated that MEAs developed on the pilot-line scale could be implemented in full stacks and tested in real operating conditions respectively in a pilot plant or in a system with a reformer.

Long term endurance tests could be conducted for different stacks allowing particularly to reach about 2700 hours and 2100 hours with low degradation rates of respectively 8 and 6 $\mu\text{V}/\text{hrs}$ with textured and automatically assembled MEAs developed for operation under H_2/air and reformat e/air .

In addition, information acquired thanks to MATISSE achievements have been analysed to try and define recommendations for further system operation or developments. Means to adapt systems operating conditions to stack components have been proposed with respect to specific results achieved particularly during parametric studies performed on short stacks or from systems.

Cost assessment has been done for the three stack designs and fuel cell technologies using first the reference data with commercial components and then the new data with MATISSE MEAs and results for each case.

The final outcomes such as particularly improved MEA components and proposal of adapted operating conditions are envisioned for further stack or system developments by the 3 industry partners for their applications.