Grant agreement no.: 700127
Start date: 01.05.2016 – **Duration**: 36 months
Project Coordinator: Johnson Matthey plc

DELIVERABLE REPORT 6.6 – STACK HIGH LEVEL TEST REPORT ISSUED FOR GEN 2 & GEN 3

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Work Package	***WP 6***
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Date released by WP Leader	17/12/2019
Date released by Coordinator	19/12/2019

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NATURE OF THE DELIVERABLE		
R	*Report*	
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	***X***

SUMMARY	
Keywords	Testing Report, full-size-stack testing, MEA and BPP iterations,
Full Abstract (Confidential)	This deliverable report summarises the most important test results of the final two design generations of fuel cell hardware and three generations of MEA development in the INSPIRE project. The successful design methodology for Bipolar Plates (BPP) and Membrane Electrode Assemblies (MEAs) in compliance with INSPIRE operating conditions is shown within the full test reports (D6.3 and D6.5). Polarisation curves, current density distribution measurements as well as degradation analysis were performed using automotive single cell, short stacks and full stacks up to 170 kW electrical power. The final results show that the project target of 1.5 W/cm² was achieved in full-size-stack polarisation curve conditions.
Publishable Abstract (If different from above)	

REVISIONS			
Version	**Date**	**Changed by**	**Comments**
0.1	12.12.2019	Markus Perchthaler	First draft
0.2	16.12.2019	Jari Ihonen	Second draft
1.0	19.12.2019	S Buche, C Wayne	Final version

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1. Summary

In this report, performance, operational stability and durability testing for different stack generations are summarised.

The main issue observed during the development of the INSPIRE stack was anode flooding, which led to extremely poor durability. This issue affected the overall test program significantly. While anode flooding was a serious issue, MEA (membrane electrode assembly) performance could not be measured reliably in single cells or at stack level using metallic bipolar plates, as significant degradation was already taking place during the MEA break-in period. MEA performance could, however, be measured in small and full-size cells when graphite hardware was used, which enabled smooth development of the MEA while issues with anode flooding were solved.

This D6.6 report follows on from the work reported in public Deliverable 6.4 where the GEN 1.5 full-size stack performance showed that the interim power density target of 1.2 W/cm² was accomplished. The main area that needed resolution in order to be able to carry out the INSPIRE testing was the poor stability due to anode side flooding.

The work was performed using single cells (DESIGN 1, DESIGN 1*, DESIGN 2, graphite), short stacks (DESIGN 1, DESIGN 1*, DESIGN 2) and full-size stacks (DESIGN 2). In single cell measurements and in some 4-cell stack measurements, current density measurements as well as electrochemical impedance spectroscopy (EIS) were used as diagnostic tools.

The performance tests were carried out according to the test protocols defined in WP2 (Deliverables 2.1 and 2.3) at both short-stack and full-stack level. Polarisation curves were measured using both INSPIRE conditions and EU harmonised conditions.

Durability testing was carried out for all flow field types (DESIGN 1, DESIGN 1*, DESIGN 2, graphite) using an INSPIRE Dynamic Load Cycle (DLC).

The tests with the full-size stack (DESIGN 2) included parameter variations to determine the optimum performance within the fuel cell system limitations.

Post-mortem failure analysis of MEAs has been performed on components from several single cell and stack tests in order to better understand the degradation mechanisms. Together with cell voltage data, current distribution and electrochemical impedance spectroscopy, a clear picture of the degradation mechanisms occurring in bipolar plate and MEA generations was found and counter-measures were defined within the project, which helped to solve the remaining issues.

2. The test programs for GEN 2 and DESIGN 2 stacks

2.1 Objective and scope of the test and test procedure

The INSPIRE test points (operating modes) used in the measurements described in this report are shown in Figure 1. The measurement points at specific current densities wee chosen based on these points. The details for the points are presented in INSPIRE Deliverable 2.1.

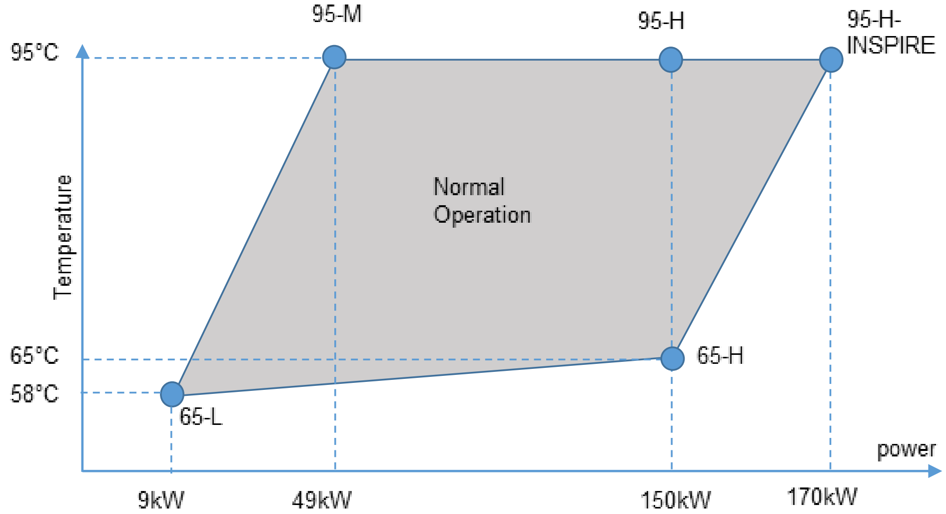


Figure 1. Operating conditions, power output versus stack outlet temperature (Temperature)

Figure 1, which is taken from Deliverable 2.1, gives insight into the system architecture of the INSPIRE fuel cell system. Within the grey marked area, stable fuel cell stack operation had to be ensured. A parameter set for fuel cell operating conditions was calculated and the focus was placed on the most demanding edge points shown in Figure 1.

2.2 Description of test objects (stacks and cells)

GEN 1 established the INSPIRE project baseline using a first iteration of bipolar plate (BPP) design with state-of-the-art benchmark MEAs. In GEN 1.5, single cells and short stacks were built using the same design of BPP as GEN 1 and the first new INSPIRE MEA iteration. One GEN 1.5 full-size stack was then assembled, using these components (reported in Deliverable 6.4).

Due to severe issues of anode flooding and other lessons learned, e.g. bypass, the GEN 2 stacks were modified to mitigate the excessive flow bypass as well as improving interfaces between stack components. Full-size stack measurements were not feasible due to anode flooding; therefore, single cells, short stacks and the developed graphite hardware were used to validate MEA components.

All the test results and lessons learned were used to design the GEN 3 stack concept. GEN 3 stacks incorporated re-designed BPPs with the bypass issue resolved. In addition to single cells, short stacks and full-size stacks, mid-size stacks (35 cells) were used for verifying the performance.

Table 1 shows the hardware designed in the INSPIRE project for different BPP designs and MEA iterations.

Table 1: Hardware designed in INSPIRE project for different BPP designs and MEA iterations

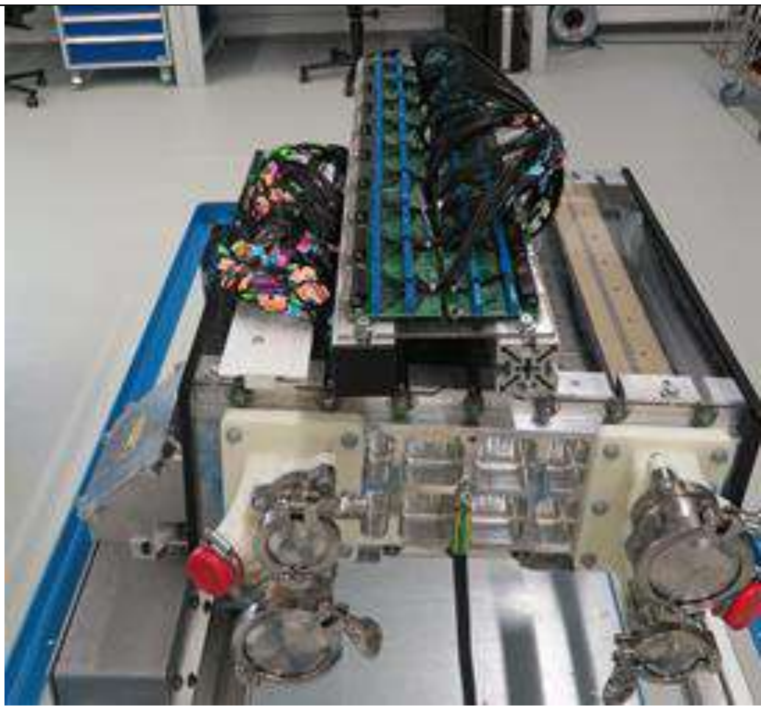
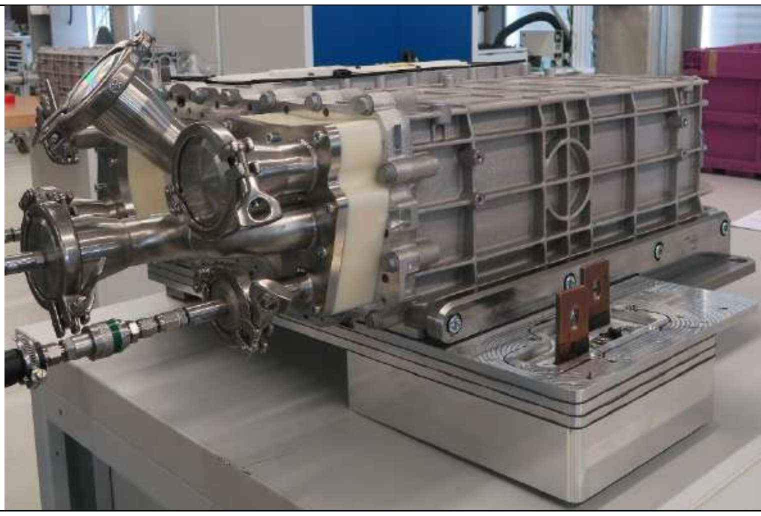
TP288 single cell with current density mapping device assembled in test rig – Testing of DESIGN 1 BPP with GEN 1.0 to GEN 2.5 MEAs	
GEN 1 full-size stack with DESIGN 1 BPP and GEN 1.5 MEA assembled in clean room environment at BMW	
GEN 3 full-size stack assembled with housing and test rig connectors in clean room environment at BMW – final leakage test	

Table 2 details the test items used to generate results for MEA Generations 1 and 1.5. In the original work plan it was intended that different generations of MEA and stack would be tested simultaneously; however, as the MEAs were ready first before the BPPs, they were also tested using cell and stack hardware of previous generations.

In Table 2 the measurements analysed in detail and reported in this deliverable are described. Overall, a significantly larger number of stacks and measurements were performed than originally planned.

Table 2: Stack testing definition for GEN 1.0 and 1.5

Generation	Stack Number	
TP288 – GEN 1 – GEN 1.5 MEAs	01	First assembly
	02	First single cell testing
	03	First single cell testing – graphitic BPP
	04	First single cell with current mapping device – GEN 1.5 MEA
	05	Single cell with current mapping device – GEN 1.0 MEA
	06	Single cell with current mapping device – GEN 1.5 MEA with subgasket improvements
	12	10 cell setup for testing at DANA
	13	First single cell with glue sheet bypass stopper (DESIGN 1* development)
	14	Single cell with current density mapping. Asymmetric GDL GEN 1.5 MEA (29BC Anode/22BB Cathode)

Table 3 describes the test objects which were characterised for MEA Generations 2 and 2.5.

Table 3 : Stack testing definition for GEN 2.0 and 2.5

Generation	Stack Number	
TP288 - GEN 2 – GEN 2.5 MEA	15	Single cell with current density mapping with GEN 2 MEA.
	23	GEN 1.5 10-cell short stack for degradation testing – shortcut at testing site due to bad compression
	25	GEN 2 MEA in graphitic single cell
	26	GEN 2.5 MEA in DESIGN 1* BPP
	27	Reference cell for post-mortem baseline characterisation
	28	4-cell short stack for degradation testing
	29	Graphitic single cell with GEN 2.5 MEA – insufficient compression
	30	10–cell short stack for durability testing
	31	ZBT elastomer bypass stopped BPP (DESIGN 1*) for 1100 hours degradation testing (TR_0444)
	32	Graphitic single cell with GEN 2.5 MEA
	33	Graphitic single cell for JMFC MEA optimisation

3. Results with final BPP design and MEA

The final results of the INSPIRE test program carried out with DESIGN 2 BPP and GEN 3 MEAs are reported in the following sections.

In summary, significant improvements compared to previous design generations were achieved and all technical project targets were met.

The results obtained with the DESIGN 2 BPP and GEN 3 MEAs showed that the INSPIRE target was met only with a full-size stack and a 35-cell stack. The performances of these stacks were significantly (20-30 mV/cell) better that than those seen with single cells or a 10-cell short stack. This is an important observation for the stack development work: a minimum number of cells is needed before full stack performance can be predicted. In this project 35 cells was a sufficient number of cells.

For durability testing, the behaviour of the 10-cell stack was comparable to the full stack. This indicates that 10-cell stack measurements may be sufficient for durability testing for the stack developed in the INSPIRE project.

3.1 DESIGN 2 bipolar plate and GEN 3 MEA (TR0484) single cell

The initial measurements made with DESIGN 2 BPP and GEN 3 MEAs were polarisation curves at INSPIRE operating modes with modified conditions. The polarisation curve for a full-sized single cell at EU harmonised conditions is shown in Figure 2. Once the operation at all INSPIRE operating modes was considered to be stable in measurements with single cells, the work with short stacks and full-size stacks could be started.

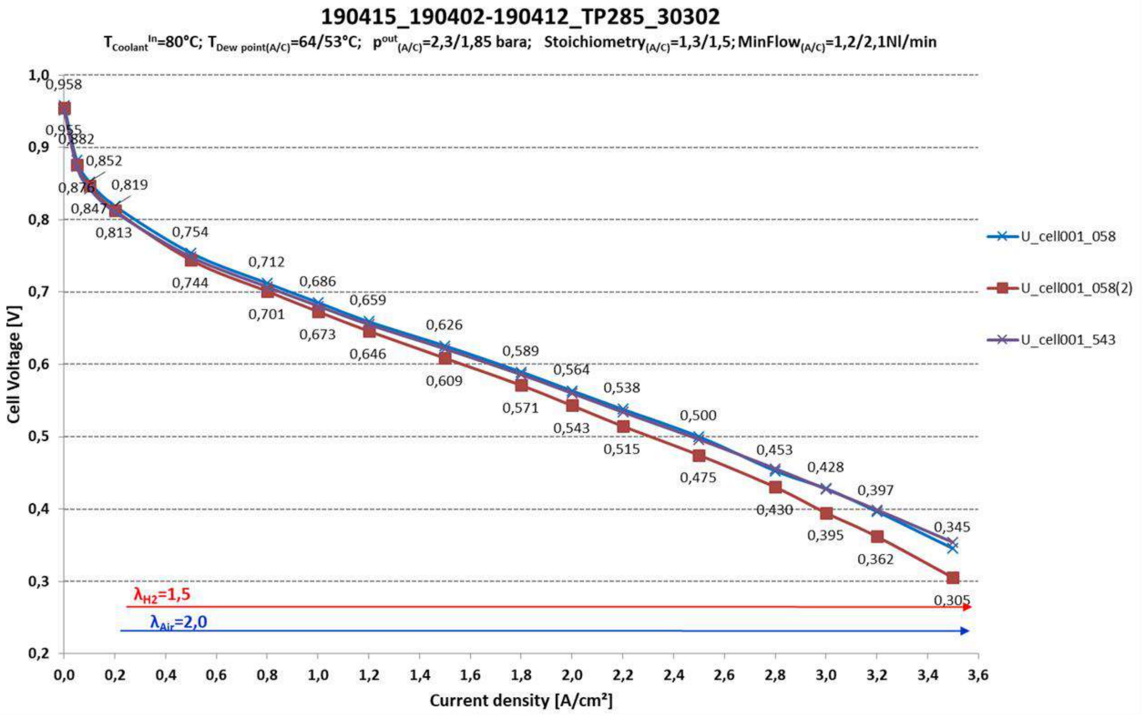


Figure 2. Polarisation curve for TR0484 single cell measured in EU harmonised conditions.

3.2 DESIGN 2 bipolar plate and GEN 3 MEA 35-cell mid-size stacks (TR0557)

The DESIGN 2 bipolar plate and GEN 3 MEA were also studied using mid-size stacks with 35 cells. It was observed that the performance and stability were very close to full-size stack behaviour. Mid-size stacks were characterised using polarisation curves and showed good performance.

The mid-size stack TR0557 showed the best performance of all test objects (cells or stacks) studied within the INSPIRE project. When the polarisation curve was measured at INSPIRE conditions (60 °C inlet), the average cell voltage exceeded 0.6 V, at a current density of 2.5 A/cm², see Figure 3. This equals a power density of 1.5 W/cm² as required in the project target definition.

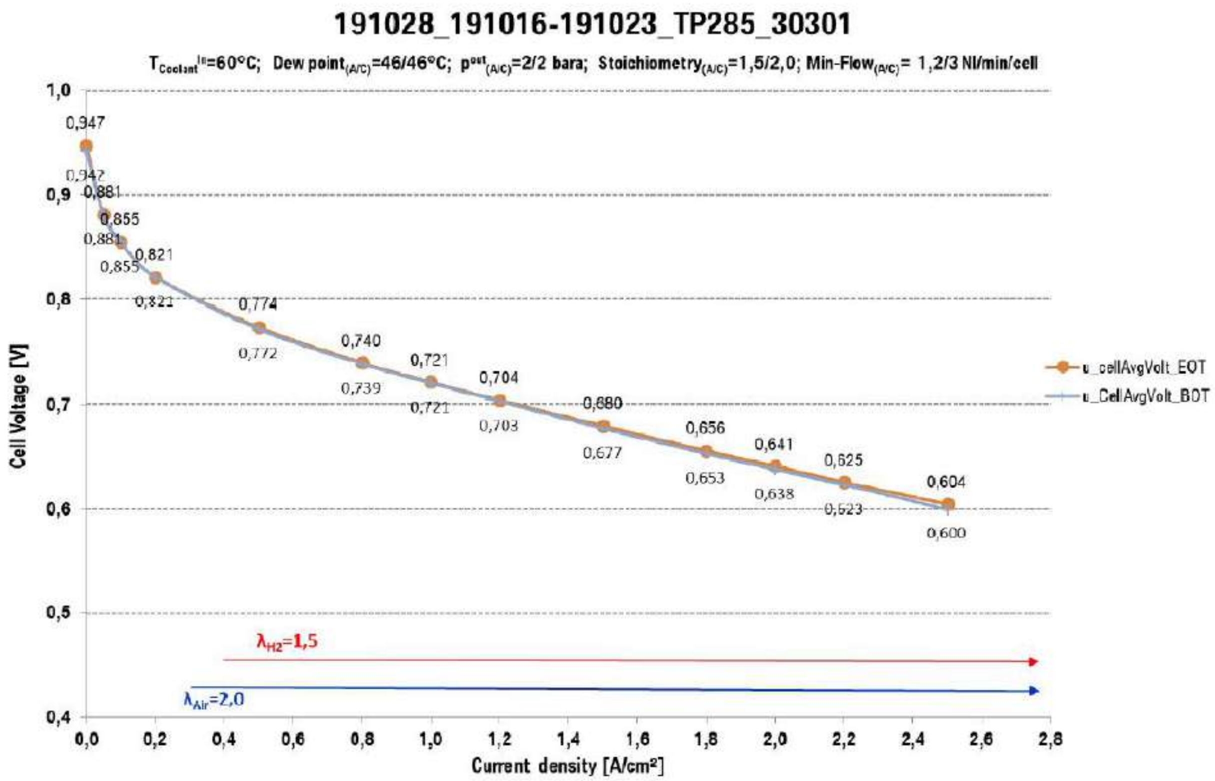


Figure 3. BoL and EoT polarisation curves for TR0557 measured at INSPIRE conditions.

In addition to excellent performance, the mid-size stack TR0557 had also excellent cell voltage distribution. When the performance was measured at adapted INSPIRE test point 95H-I*(highest current 2.5 A/cm^2), the difference between the worst and best cell was only 46 mV. This is an excellent result for a prototype stack with prototype MEAs. The difference between the worst and best cell at adapted INSPIRE test point 95M* (0.55 A/cm^2) was only 12 mV, see Figure 4b.

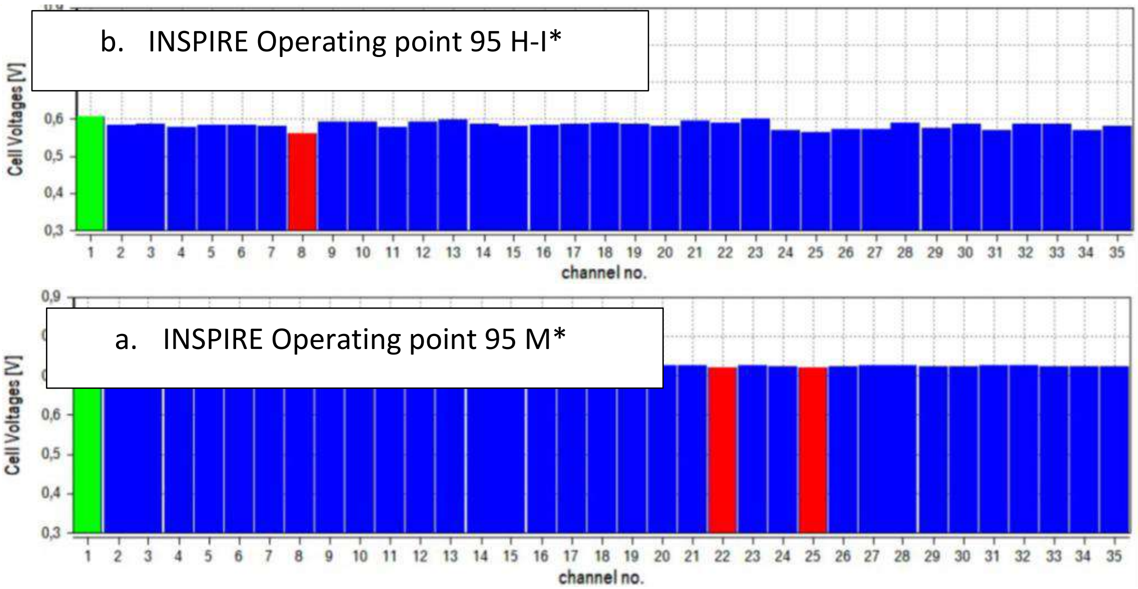


Figure 4. Cell voltage distribution for TR0557 at adapted INSPIRE test point a. 95H-I* and b.95M*.

5.4 DESIGN 2 bipolar plate and GEN 3 MEA full-size stack

As soon as full stacks became available, they were tested. Results from the short stack were used to modify the operating conditions in order to enhance the power output and operational stability.

The initial performance of the full-size stack measured during site acceptance testing at BMW is shown in Figure 5. At 80 °C (EU harmonised conditions) the polarisation curve shows that the average cell voltage was 50 mV higher than a single cell at 2.0 A/cm² and 25-30 mV higher than a 4-cell stack.

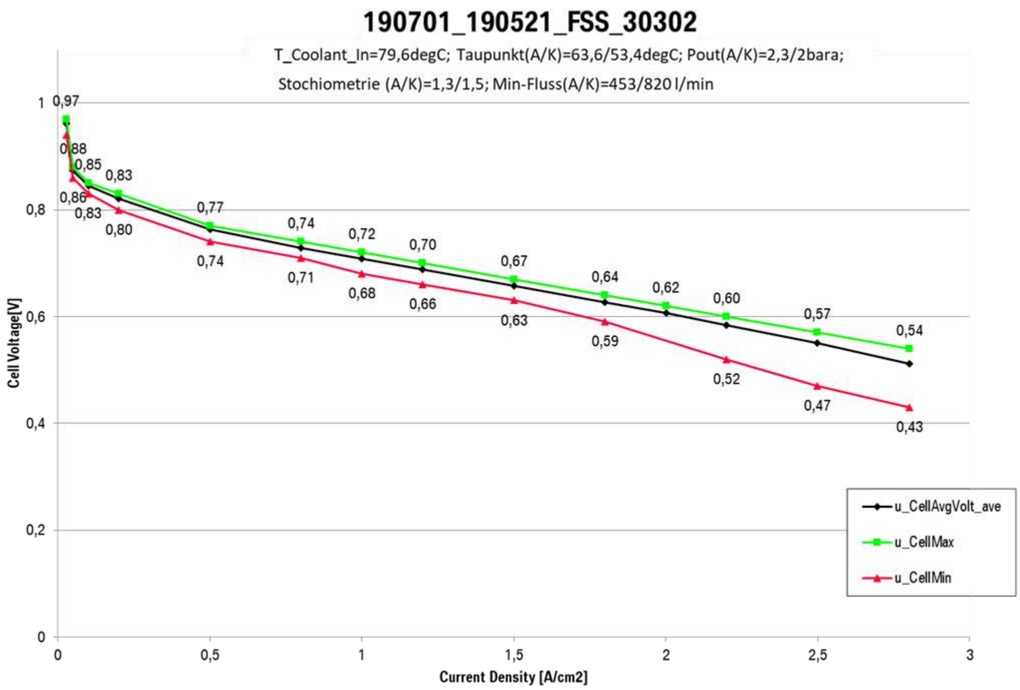


Figure 5. Polarisation curve for GEN 3 full-size stack measured at EU harmonized conditions after break-in.

The performance before and after 500 hours DLC is shown in Figure 6. This result is proof that when operating conditions are stable and both hydrogen starvation and flooding can be avoided, the degradation rate is approaching acceptable values.

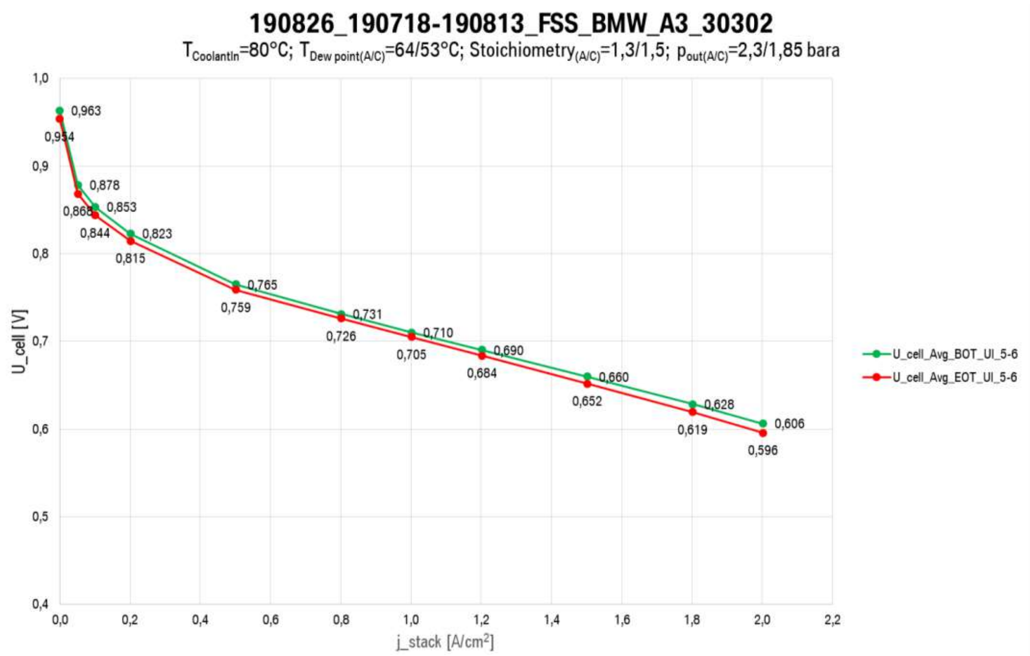


Figure 6: Full-size stack polarisation curve before and after degradation testing. Measured at EU harmonised conditions.

While the result is very promising at high current densities (10 mV degradation), it should be noted that at low current density (0.1 A/cm²) the voltage loss is already 9 mV. The performance at all INSPIRE operating modes for the beginning of the test and end of test is shown in Figure 7. From Figure 7 it can also be concluded that there is already some degradation (15 mV) at low current density (65-L). However, the decrease of resistance probably compensates for this, so that only 9 mV decrease in cell voltage decay is measurable.

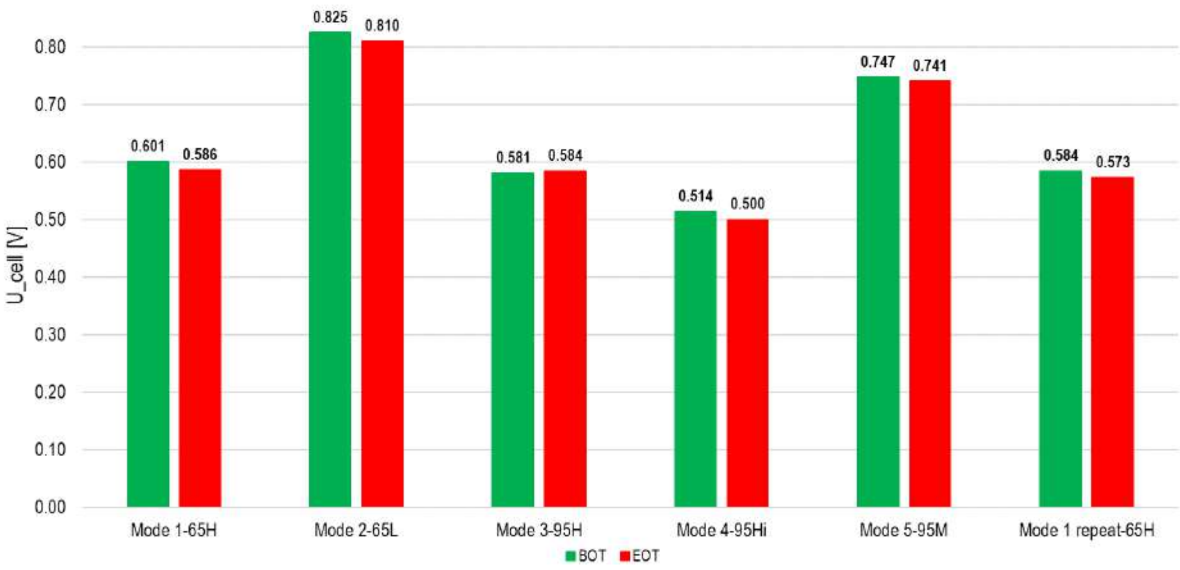


Figure 7: Average cell voltage BoL in comparison to EOT of DESIGN 2 Full-Size-Stack

4. Conclusions

Extensive stack performance measurements were carried out in the second half of the INSPIRE project with more than 20 short stacks in total. Once the test hardware was operating in a stable enough manner, 500 hours and up to 1000 hours of durability tests were completed. Post-mortem failure analysis of MEAs was performed on components from several single-cell and stack tests in order to better understand the degradation mechanisms. Together with cell voltage data, current distribution and electrochemical impedance spectroscopy, a clear picture of the degradation mechanisms occurring in bipolar plate and MEA generations was found and counter-measures were defined within the project, which helped to solve the remaining issues.

The milestone target of 1.5 W/cm^2 was achieved in full stack testing in the INSPIRE GEN 3.0 hardware. While initial testing in the full-size stack under the INSPIRE operating conditions yielded a power density of 1.3 W/cm^2, the stack was very sensitive to changes in the operating conditions, and running the EU harmonised protocol conditions (which are not too dissimilar to the INSPIRE operating points, with slightly increased stoichiometries) allowed the target of 1.5 W/cm^2 to be achieved at 2.8 A/cm^2 and 535 mV average stack performance. The power density milestone was, however, met under the INSPIRE test conditions at the short stack level, in a 35-cell stack, with no adjustments to the operating conditions, achieving 1.5 W/cm^2 under peak power conditions (95 H-I mode). The short stack performance was very close to that of the full stack and ongoing testing beyond the project end will enable the INSPIRE team to further assess the short and full stack performance under the full range of INSPIRE testing conditions.

The degradation rate observed was between 22-29 µV/hr, but the test does not yet reflect real operating conditions. In addition, durability was difficult to assess due to some test stand issues and interruptions in testing. Moreover, the test hardware itself, including the coated copper current collectors, tubes and hoses, is affecting the observed degradation rate. Durability assessment will continue beyond the end of the project. It is predicted that improvements to the test protocol will enable the target of 10 µV/hr of real operation to be met.

5. Recommendations regarding test methods

- Improvements and topics for further study
    - Test station shut-down should not have an impact for durability testing
        - This was a problem especially with the DESIGN 2 short stack.
    - A “real life mimicking” recovery cycle (H_2 soak, cool down) could be added for FC-DLC testing.
    - Stability range (until anode flooding is detected) for the stack should be defined. Anode flooding and the resulting catastrophic degradation of the cathode catalyst layer is a fundamental issue and should have highest priority, even if full stack DLC testing was successful.
    - A better MEA reproducibility would be needed for revealing the full performance of the GEN 3 design.
    - A short-stack hardware should be studied (and further developed) to see how many cells are needed to represent full-stack behaviour, as full-stack testing itself is too expensive.