



## INTEGRATION OF NOVEL STACK COMPONENTS FOR PERFORMANCE, IMPROVED DURABILITY AND LOWER COST

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### DELIVERABLE REPORT

#### **D4.4 – FINAL MEA DESIGN ACHIEVING TARGET PERFORMANCE (1.5 WCM<sup>2</sup>) AND DURABILITY**

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#### **NATURE OF THE DELIVERABLE**

<b>R</b>	Report	<b>X</b>
<b>P</b>	Prototype	
<b>D</b>	Demonstrator	
<b>O</b>	Other	

#### D4.4 – SUMMARY

<b>Keywords</b>	
<b>Full Abstract</b>	<p>This report outlines the GEN 3.0 MEA design produced during the INSPIRE project that has achieved <math>1.5 \text{ Wcm}^{-2}</math> beginning of life performance under the EU harmonised protocol conditions in a full-size stack of 383 cells, and a degradation rate of <math>22\text{-}29 \mu\text{Vhr}^{-1}</math> in an accelerated stress test. The work to develop the MEA incorporated the assessment of different membrane technologies and new cathode catalyst layer designs including the assessment of alloy catalysts from other work packages. Also included is the development of a new GDL material that has now been commercialised as SGL SIGRACET 22BB. Ultimately due to the high current densities targeted in this project, the alloy materials were not deemed suitable for use in the GEN 3.0 MEAs, and advanced cathode materials that were deemed suitable were not available in the required quantities for the three full size stacks to be tested. Further work would be required to progress the cathode developments identified in this work to allow the performance to be maintained or improved at reduced Pt loadings, and to further develop the stress test to incorporate recovery cycles and establish the acceleration factor compared to real-world operation.</p>

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## 1. INTRODUCTION

The purpose of the work described in this report was to develop an MEA (membrane electrode assembly) to work within the INSPIRE hardware also developed within this project (see D5.5), with a target power density of  $1.5 \text{ Wcm}^{-2}$  of  $0.6 \text{ V}$  at  $2.5 \text{ Acm}^{-2}$  under the target INSPIRE operating conditions (see D2.1 and D2.2). The durability requirement was that the stack should lose no more than 10% of its power output over 6000 hrs of operation. Several different aspects of the MEA needed to be optimised to enable achievement of these challenging project targets. Once the final MEA design had been defined, the aim was for it to be manufactured by high volume process routes to provide 1400 MEAs for three full-size stacks to evaluate the performance and degradation rates.

## 2. EXPERIMENTAL

### 2.1. SCREENER PERFORMANCE TESTING

The MEAs were tested under 3D single cell test conditions under a generic set of test conditions in Protocol 382 (detailed in the appendix) that probe a range of operating conditions and constant current holds at the stack operating points M1-5 as shown in the appendix. The cell used was a JMFC generic screener cell with an active area of  $50 \text{ cm}^2$ . The cell was run counter current flow. The test stands were Hydrogenics 2kW and the cell was compressed by an air piston to control the compressive load to 60 psi.

### 2.2. SCREENER 1D TESTING

The 1D cell testing used a Ballard STC cell masked down to  $11.25 \text{ cm}^2$  active area. This was run on an LAA Hydrogenics 12 kW test stand. The test protocol used for this testing was Protocol 402B detailed in the appendix, which was a slightly updated version from that presented in the D2.1 deliverable report in order to increase the testing throughput. The data produced represents the inlet, outlet and end cell outlet conditions of the INSPIRE stack at each of the M1-5 operating points. Also included at the end of the protocol was a limiting current test to determine the local mass transport losses associated with the cathode catalyst layer. This is similar to that presented by Nobuaki Nonoyama et al<sup>[1]</sup>. This test allows the determination of cathode catalyst layer mass transport resistances and separates them into a total mass transport resistance and a non-pressure dependence resistance. The non-pressure dependence resistance is further broken down into an oxygen permeability resistance and a Knudsen diffusivity resistance. Also, during this testing, EIS (Electrochemical Impedance Spectroscopy) data was collected during the oxygen polarisation tests at the relevant M1-5 conditions, allowing calculation of the ionic resistance of the catalyst layers.

### 2.3. DURABILITY TESTING

The durability testing of the membrane consisted of two tests to stress the membranes in different ways. The first was a combined OCV RH (Open Circuit Voltage Relative Humidity) cycling test as shown in Protocol 394 in the appendix. This test operates at OCV with the RH cycled between wet and dry gases, 45 s wet and 10 s dry, with the membrane resistance increasing by a factor of four at the dry condition over the wet condition. The diagnostics are carried out every 1000 RH cycles with an OCV pressure response test to determine any leak developing. This test is heavily mechanically biased with the OCV portion having little effect.

The second test was an OCV hold durability test, shown as Protocol 388 in the appendix. Here the membrane is held at OCV at 90 °C and 30 % RH, and diagnostics are carried out twice a week consisting of water collection for fluoride release rate, hydrogen permeation and electrical shorting tests. This test is heavily chemically biased and gives an indication of the chemical stability of the membrane and additive package.

#### 2.4. EX-SITU TESTING

A TA Instruments DMA (Dynamic Mechanical Analysis) Q800 with a relative humidity control unit was used to perform mechanical analyses on the membrane. 6 mm wide membrane samples were produced by a kiss-cutting method. These were clamped into the DMA to give a sample length of circa 16 mm and were tested in tensile mode.

Different experiments were devised to give different information about each membrane. The first such test equilibrated the sample under low stress to 80 °C and 90 % RH. After 2 hours, the stress was ramped at 0.2 MPa/min, while strain was measured. This experiment gives information about the Young's modulus of the membranes at conditions likely to be encountered during fuel cell operation.

#### 2.5. CRT TESTING METHOD

The cell reversal tolerance (CRT) was assessed in the 240 cm<sup>2</sup> active area cell hardware. The testing used a set of beginning of life diagnostics including anode nitrogen dilution during a polar curve to assess the losses caused by the reversal events. The reversal holds were conducted with pure N<sub>2</sub> at 100 % RH on the anode at 80 °C cell temperature and a current density of 200 mAcm<sup>-2</sup>. The holds were typically 6 seconds in duration, but more tolerant anodes used a 5-minute hold. After every hold, the beginning of life diagnostics were repeated, and the anode degradation assessed. The samples were deemed to have reached the end of life when either the cell voltage during the reversal hold dropped below -1.5 V or the anode diagnostics showed a nitrogen performance loss of 300 mV.

#### 2.6. STACK PERFORMANCE AND DURABILITY TESTING

The performance and durability testing were conducted in the INSPIRE stack hardware with 383 cells. The stack performance was assessed under the EU harmonised performance conditions and the INSPIRE operating conditions as described in the appendix. The stability and durability of the MEA was assessed with a dynamic load cycle shown in Figure 1 without any recovery cycles being conducted. The dynamic load cycle test was run for a total load time of 580 hrs with the load greater than 0.1 Acm<sup>-2</sup>.

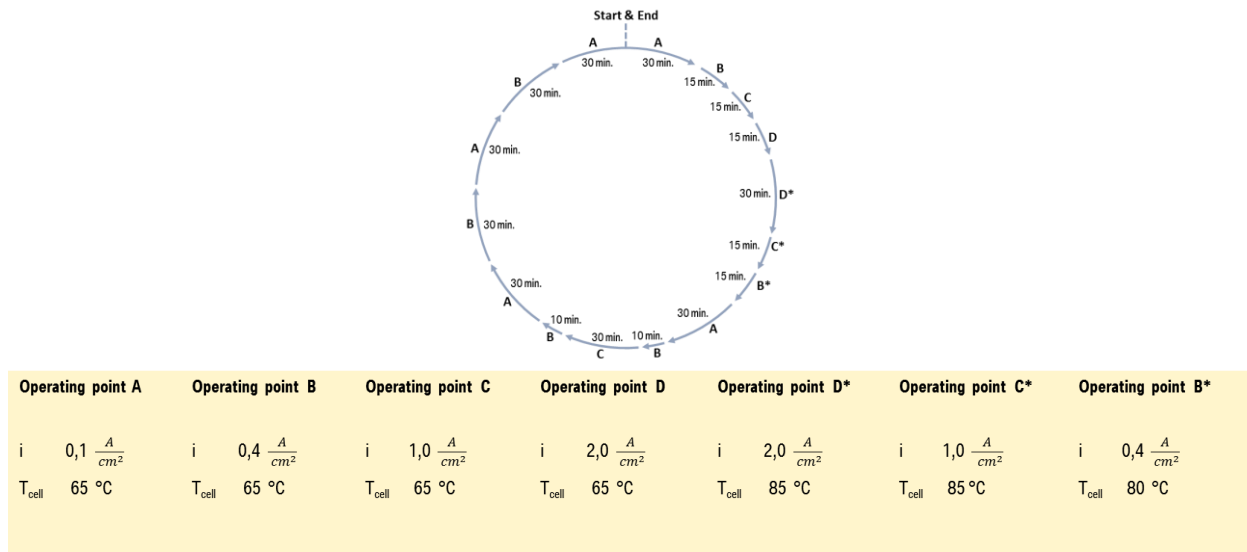


Figure 1: Schematic of the dynamic load cycle used to assess the MEA decay rates in the full stack GEN 3.0 MEA testing

### 3. RESULTS AND DISCUSSION

#### 3.1. FINAL MEA

The final INSPIRE MEA was the GEN 3.0 MEA as defined below in Table 1. To target the overall performance target in the project it was not feasible to thrift the MEA in the ways that had been envisaged at the start of the project, the reasons for which will be discussed in Section 3.4 of the report. The GEN 3.0 MEA was fabricated on roll-to-roll production equipment with over 1400 parts manufactured for the final stacks in the INSPIRE project.

Table 1: Summary of final GEN 3.0 MEA design

Component	Description
Anode	CRT capable anode with 0.05 mgPtcm <sup>-2</sup> and 0.043 mgIrcm <sup>-2</sup>
Membrane	15µm ePTFE reinforced membrane with chemical stabilisation additive package
Cathode	Performance optimised cathode with 0.4 mgPtcm <sup>-2</sup>
GDL	Asymmetric GDL design SGL29BC anode and SGL22BB cathode

#### 3.2. ANODE

For the final INSPIRE MEA, the anode design was selected based on a trade-off between performance and CRT capability. Table 2 shows the performance and CRT durability of the different options assessed. The first option was the benchmark anode with no CRT capability and a Pt loading of 0.08 mgPtcm<sup>-2</sup>. The second option had a CRT capability and a high surface area Pt catalyst at 0.05 mgPtcm<sup>-2</sup> and a total PGM loading of 0.093 mgcm<sup>-2</sup>. The final option evaluated was a CRT capable anode with a highly graphitised support material; however, this had a lower surface area and higher Pt loading compared to Anode 2, of

0.08 mgPtcm<sup>-2</sup> and a total PGM loading of 0.149 mgcm<sup>-2</sup>. The performance reported was measured during the 1D cell test at conditions to mimic the anode outlet of the cell, where the anode nitrogen dilution is highest. The CRT capability was measured as described in Section 2.5, with Anode 3 using an increased hold time under the reversal conditions for each cycle.

**Table 2: Anodes assessed for the GEN 3.0 MEA design**

Anode	HOR Catalyst loading [mgPtcm <sup>-2</sup> ]	OER Catalyst loading [mgIr <sub>0.5</sub> cm <sup>-2</sup> ]	M1 outlet performance at 2Acm <sup>-2</sup> [V]	M3 outlet performance at 2Acm <sup>-2</sup> [V]	Number of CRT cycles before failure (6s)	Total CRT time [min]
1	0.08	0	0.543	0.537	0	0
2	0.05	0.043	0.526	0.511	155	15
3	0.08	0.069	0.469	0.503	168 (5 min holds)	840

From the data in Table 2 it was decided to use Anode 2 as it gave a CRT capability without the significant downside of low performance when running with high nitrogen dilution at the anode outlet.

### 3.3. MEMBRANE

Within this project several membrane options were evaluated with the details further disclosed in D4.3. The final membrane chosen was a balance between the best performing membrane and one which provided good durability whilst minimising the risk to the final stack performance and durability. Table 3 shows the key membranes evaluated in the project.

**Table 3: Summary of membranes assessed for the GEN 3.0 MEA design**

Membrane	Thickness [μm]	Reinforcement	Chemical stabilisation	OCV hold degradation rate [μVhr <sup>-1</sup> ]	Combined OCV RH cycles	Performance at 2 Acm <sup>-2</sup> (100 kPa, 100 % RH) [mV]
Membrane 1	15	ePTFE	N	141	27000	573
Membrane 2	10	ePTFE	Y	15	21000	578
Membrane 3	15	ePTFE	Y	107	17000	574
Membrane 4	15	ePTFE	Y	62	40000	584
Membrane 5	15	PBI-X	Y	Under evaluation	41000	583

Membrane 1 was the benchmark membrane for the project, with excellent performance and mechanical stability but with no chemical stabilisation package. This led to a high OCV degradation rate of 141 μVhr<sup>-1</sup>. Membrane 2 was a thinner membrane of 10 μm thickness, and a high loading of chemical stabilisation additive to compensate for the increased gas crossover. This high level of additive gave an exceptional result in the OCV degradation test of 15 μVhr<sup>-1</sup>. The combined OCV RH test results showed a slightly worse result than the benchmark, and the performance was only slightly improved. Membrane 3 was a membrane developed by JM that incorporates a chemical stabilisation package with a reduced OCV degradation rate of 107 μVhr<sup>-1</sup>. The membrane had a good mechanical durability tolerance but was below that of the benchmark in the accelerated stress testing, and the performance was comparable.

Membrane 4 was a developmental membrane based on an ePTFE reinforcement and a new lower EW ionomer material. The membrane also had an enhanced chemical stabilisation package, evidenced by the much reduced OCV degradation rate of  $62 \mu\text{Vhr}^{-1}$ , and significantly improved mechanical stability in the combined OCV/RH cycling test with an increased performance observed in the screener cell testing. The final membrane evaluated, Membrane 5, was a PBI-X reinforced membrane with the ionomer and stabilisation package otherwise used in Membrane 3. This showed improved performance and combined OCV/RH cycling results compared to Membrane 3. The improved result in the combined OCV RH cycling is due to the excellent strength of the PBI-X reinforcement at the cell operating temperatures. Figure 2 shows the strength of two PBI reinforced membranes compared to Membrane 3 at 80 °C and 90 % RH. At this date the OCV degradation rate testing has not yet been completed but we would expect it to be comparable to Membrane 3.

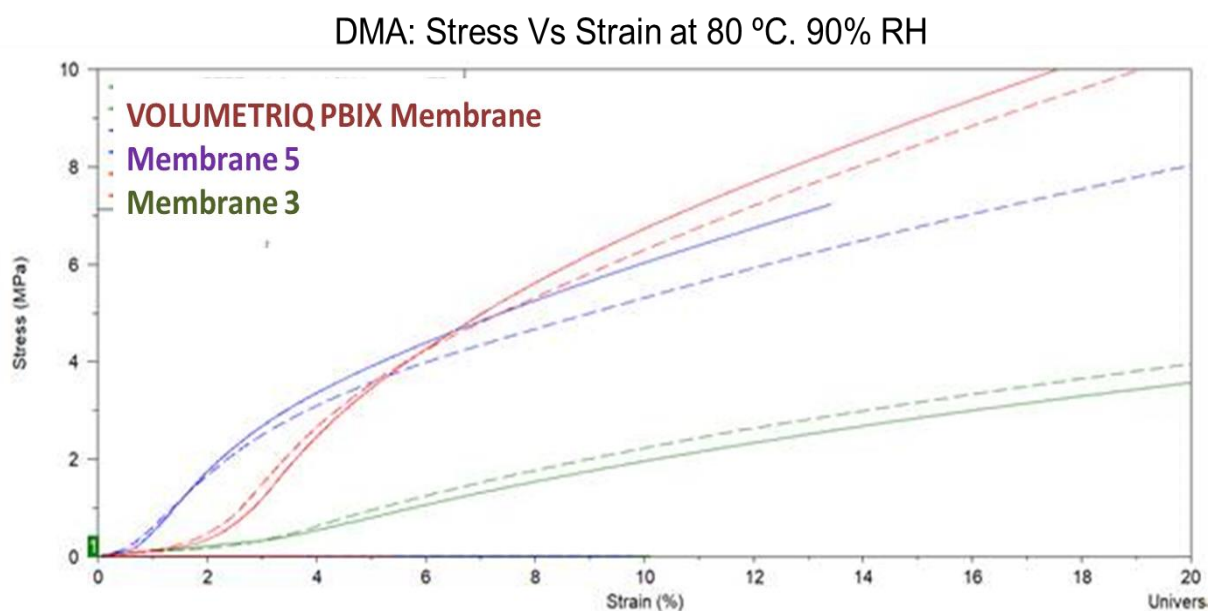


Figure 2: Stress vs. strain curves at 80 °C and 90 % RH for ePTFE and PBI-X reinforced membranes

For the final MEA generation it was decided to progress Membrane 3 as the favoured option, primarily due to its improved chemical stability over the benchmark membrane and its availability at a volume consistent with the required number of MEAs for the final stacks to be manufactured. Membranes 2,4 and 5 showed significant benefits in the testing; however, due to the developmental nature of the membranes only being made at small scale it was felt that the risks to the stack and project targets could not be sufficiently mitigated without further development and testing that was not possible within the project timelines.

### 3.4. CATHODE

In this project several cathode catalyst variants were assessed. One of the key activities was to progress advanced alloy catalysts from WP3 and optimise and assess them for the performance targets. As part of this work, alloy catalysts were developed and the layer optimised. The performance was increased within the project and the mass activity benefit realised.

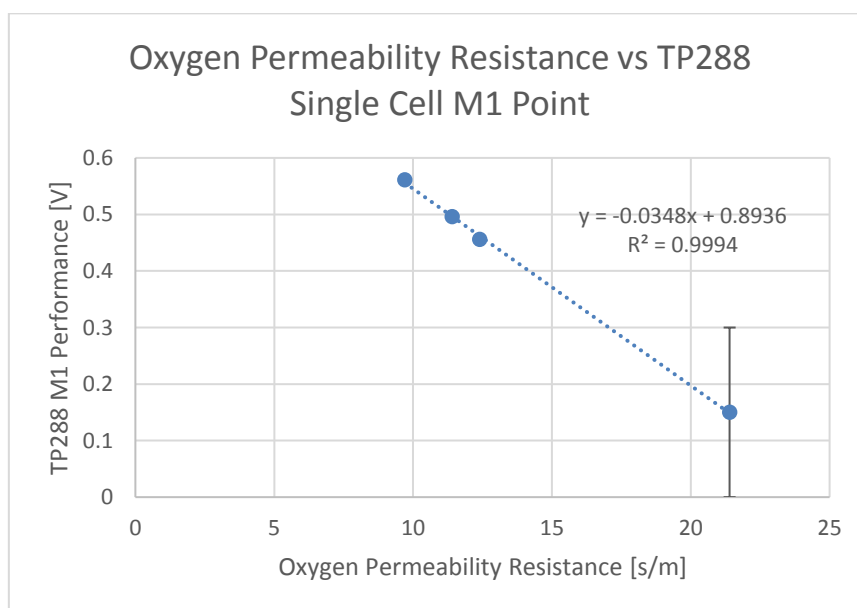


Table 4 shows the improvements made to the alloy layers over the course of the project.

**Table 4: Table of PtNi alloy cathode catalyst layer iterations throughout the project at a reference loading of 0.2 mgPtcm<sup>-2</sup>**

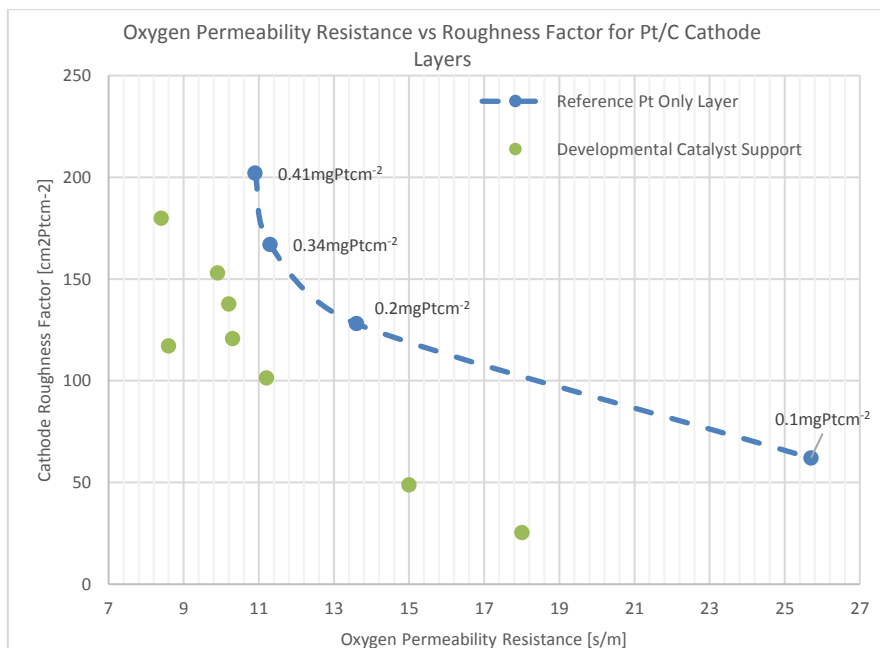
Layer	Mass Activity [A.mg <sub>Pt</sub> <sup>-1</sup> ] (96°C, a/c 2.34/1.86 bara, Dewpoint a/c 65/87 °C, H <sub>2</sub> /O <sub>2</sub> )	Local Transport Resistance [sm <sup>-1</sup> ]	Mass	Performance at 1 Acm <sup>-2</sup> [V] (100 % RH, 100 kPa, 80 °C)	Performance at 2 Acm <sup>-2</sup> [V] (100 % RH, 100 kPa, 80 °C)
Pt Reference	0.083	16.8		675	592
PtNi Iteration 1	0.102	33.8		670	544
PtNi Iteration 2	0.161	29.4		684	598
Scale-up Catalyst	0.13	28.2		693	571

Despite the improvements presented in Table 4, the catalyst could not provide the performance benefit at >2 Acm<sup>-2</sup> under the INSPIRE operating conditions due to the lower surface area of the catalyst materials used, although the performance benefit was shown at lower current densities. Figure 3 shows the performance of various MEA iterations in the INSPIRE GEN 1.0 plate design versus the measured oxygen permeability resistance from the 1D testing at JMFC. This shows a link between the high local oxygen transport resistance and the performance at the high current density operating points targeted in this work.



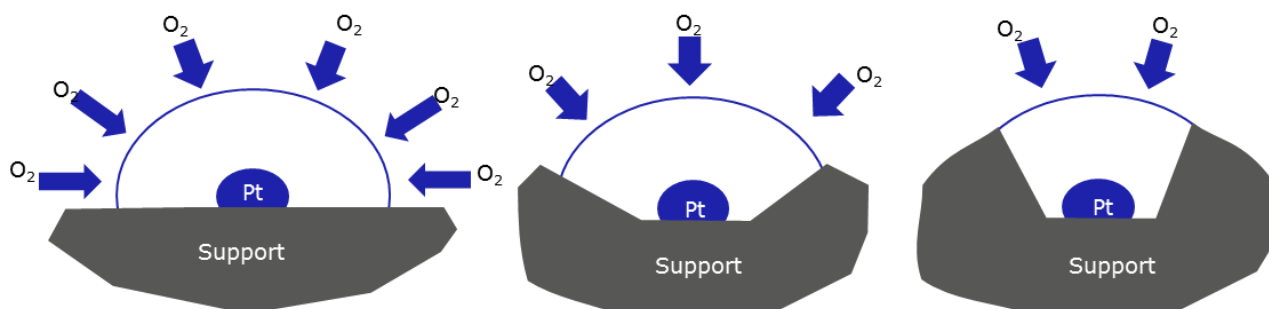
**Figure 3: Correlation of performance at 2 Acm<sup>-2</sup> in the INSPIRE GEN 1.0 hardware vs the oxygen permeability resistance measured in 1D liming current rests**

Several approaches were investigated to achieve a reduced oxygen permeability resistance, including its dependence upon Pt loading and new developmental catalyst support materials. Figure 4 shows the oxygen permeability resistance vs the cathode roughness factor for both the state-of-the-art materials and the new developmental carbon supports.



**Figure 4: Oxygen permeability resistance vs cathode roughness factor for reference state-of-the-art materials and developmental cathode carbon support materials**

The reference state-of-the-art materials shown in blue were assessed over a range of cathode loadings and, as can be seen, the local oxygen transport resistance increased significantly with decreased loading; from Figure 3 it can be seen at the operating point every  $1 \text{ s m}^{-1}$  increase in the oxygen permeability resistance was equivalent to almost 35 mV. The developmental catalyst support was a carbon specifically designed to have a porosity with fewer small pores  $< 2 \text{ nm}$  and more pores above  $4.5 \text{ nm}$ . Figure 5 shows a schematic of the principle employed by this support to reduce the oxygen permeability resistance. A Pt particle on a flat surface can access oxygen from a larger volume than those in either shallow or small pores. This led to a reduction in the measured oxygen permeability resistance of approximately  $4 \text{ s m}^{-1}$  at a comparable roughness factor for a  $0.2 \text{ mgPtcm}^{-2}$  loaded cathode.



**Figure 5: Schematic diagram of the hypothesised benefit from the developmental support material with the modified pore size distribution**

These new support materials were, however, developmental, and sufficient quantities were not available to be provided for the GEN 3.0 MEA and full stack assessment. Therefore, the state-of-the-art material at a loading of 0.4 mgPtcm<sup>-2</sup> was chosen to progress to the GEN 3.0 design although the developmental support materials show significant promise for future cathode catalyst layers.

### 3.5. GDL

Since the INSPIRE MEA target power densities were above 1 Watt per cm<sup>2</sup>, the cathode GDL in particular makes an important contribution to the attainment of the cell/stack performance targets. At the beginning of the project, the interactions of the GDL with the BPP and CCM materials to be used in INSPIRE were not fully understood. Hence, the INSPIRE GEN 1.0 GDL was based on SGL's latest generation of commercially available SIGRACET automotive grade gas diffusion layer technology (carbon papers with uncompressed thickness of 240 μm). The grade selection was made based on single cell performance of various GDL (combinations) according to the harmonised automotive testing protocol developed by JRC in cooperation with automotive OEMs<sup>2</sup>. Three candidate materials with total GDL thicknesses of 130 μm (#1), 200 μm (#2) and 215 μm (#4) were investigated during the initial phase, differing in carbon substrates and MPL (microporous layer). The thin GDL type (#1) was discarded since the mechanical properties were not satisfactory for upscaling and subsequent processes. Hence emphasis was placed on the GDL Type #3 which is based on an improved MPL type on a robust carbon fibre backing substrate. A new MPL ink was developed which used a lower amount of polymeric binders. This new MPL formulation had a lower viscosity and hence allowed for a lower MPL loading (< 3 mg cm<sup>-2</sup>) without compromising homogeneity of the MPL coating. A comparison of the properties of the GEN 1.0 and GEN 1.5/2/3 GDL is shown in Table 5.

**Table 5: Comparison of material properties of GEN 1 and GEN 1.5/GEN 2.0/GEN 3.0 GDLs**

<b>GDL Generation</b>	<b>1</b>	<b>1.5 / 2 / 3</b>
Total GDL thickness (μm)	235	215
Carbon paper backing thickness (μm)	190	190
PTFE loading of backing (wt %)	5	5
Carbon paper backing porosity (%)	88 - 89	88 - 89
MPL PTFE content (wt %)	23	25
MPL loading (mg/cm <sup>2</sup> )	4 - 5	2.5 - 3.1
Area-specific resistance (mΩcm <sup>2</sup> ) @ 1 MPa	< 10	< 8
Total GDL porosity (%)	73	75
Bending stiffness X/Y (N mm)	2.1 / 1.5	1.9 / 1.4
MPL roughness R <sub>a</sub> (μm)	< 10	< 10

The GEN 1.5/2/3 GDL has recently been introduced by SGL as a new GDL grade with the nomenclature SIGRACET GDL 22 BB. Comparisons of the gas transport and porosities of coated GDL suggest it produces a less compact packing of the carbon particulates of the MPL, see Figure 6.

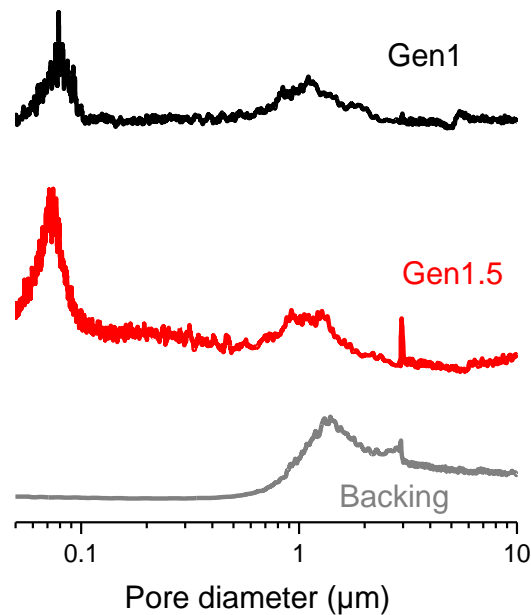


Figure 6. Pore size distribution of GEN 1 and GEN 1.5/2/3 GDL (MPL/interface region) determined by mercury intrusion.

For integration into MEAs and single cells, the GDL behaviour upon compression was studied. Figure 7 shows the compression behaviour of the GEN 1.0 and GEN 1.5/2/3 GDLs including area-specific resistance (ASR) and the in-plane gas permeability. Multiple compression curves were conducted to determine the ratio between elastic (reversible) and plastic (irreversible) deformation up to 3 different loads (0.6, 1.0 and 1.5 MPa).

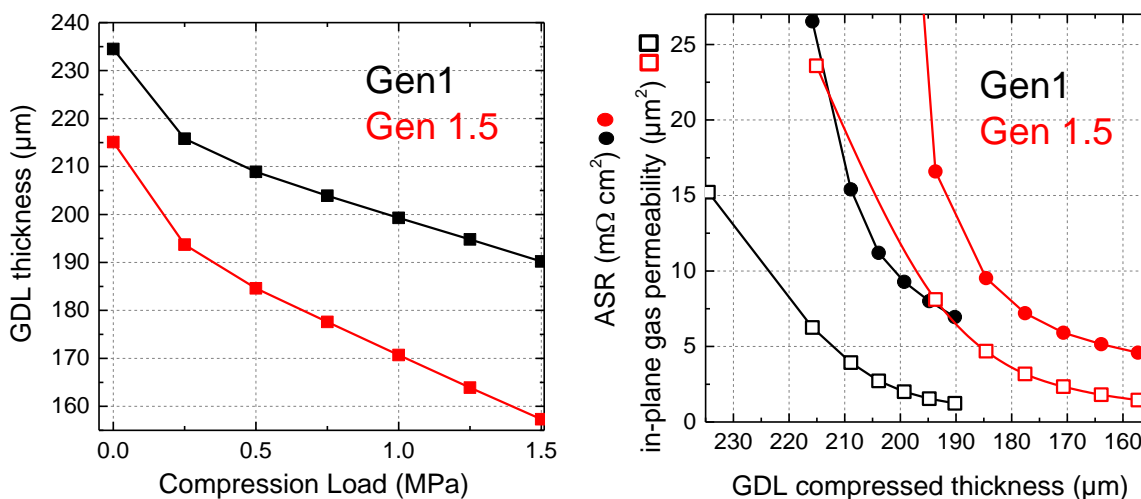
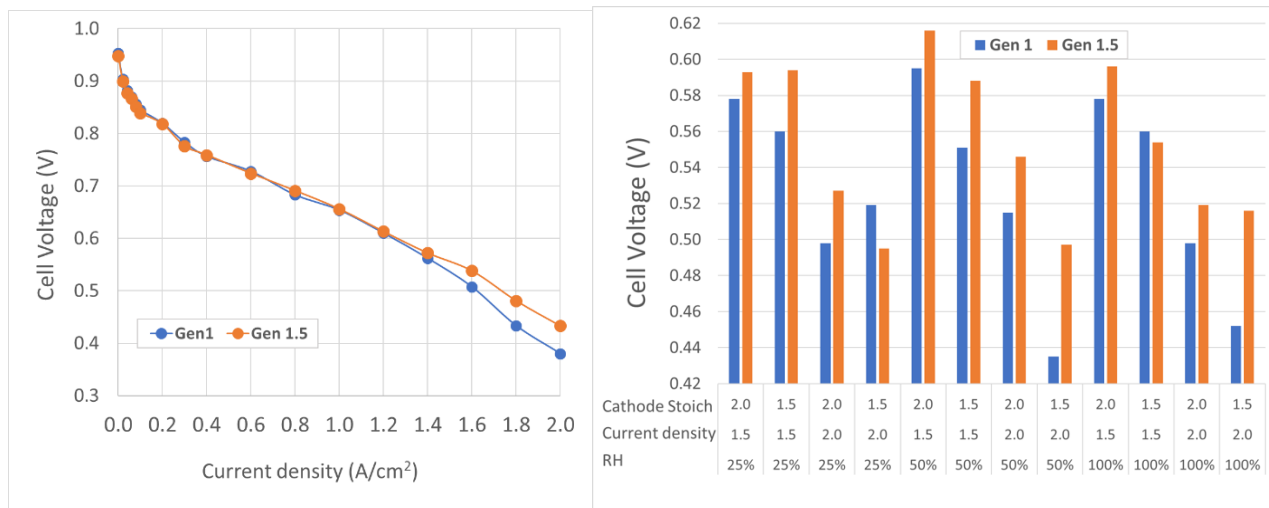


Figure 7: Comparison of the behaviour of GDL GEN 1 and GEN 1.5/2/3 upon compression. Left: Thickness as a function of compression load. Right: Area-specific resistance and in-plane gas permeability as a function of compressed GDL thickness.

The values found for the compression hysteresis (Table 6) reflect the different MPL loadings as the MPL is less compressible than the backing materials.

**Table 6: Compression hysteresis (plastic thickness reduction) of GDLs after flat compression with different loads.**

GDL	0.6 MPa	1 MPa	1.5 MPa
Backing	15 $\mu\text{m}$	21 $\mu\text{m}$	31 $\mu\text{m}$
GEN 1	11 $\mu\text{m}$	15 $\mu\text{m}$	19 $\mu\text{m}$
GEN 1.5/2/3	14 $\mu\text{m}$	21 $\mu\text{m}$	27 $\mu\text{m}$



**Figure 8: Comparison of the single cell performance of both GDL types.**

Single cell tests (25 cm<sup>2</sup>) of GEN 1 and GEN 1.5/2/3. Left: Polarisation curve (JRC harmonised automotive conditions, MEA compression load 1 MPa, graphite serpentine plates). Right: Steady-state behaviour at different RH and cathode stoichiometry (H<sub>2</sub>/air 1.5 bar, 80°C, anode stoich = 1.5)

The improved performance of the GDL used for GEN 1.5/2/3 can be attributed to its higher oxygen diffusion at high water saturation levels. This is confirmed by steady-state measurements with variable RH and air stoichiometry where the thin MPL of GEN 1.5/2/3 shows better performance under flooding conditions (Figure 8 right).

### 3.6. GEN 3.0 PERFORMANCE

Single cell testing was unable to accurately replicate the performance seen in large stack testing. Therefore, the performance shown in Figure 9 is from the first full-size stack tested with GEN 3.0 MEAs. The performance achieved showed 1.5 Wcm<sup>-2</sup> under the EU harmonised protocol conditions at 2.8 Acm<sup>-2</sup>.

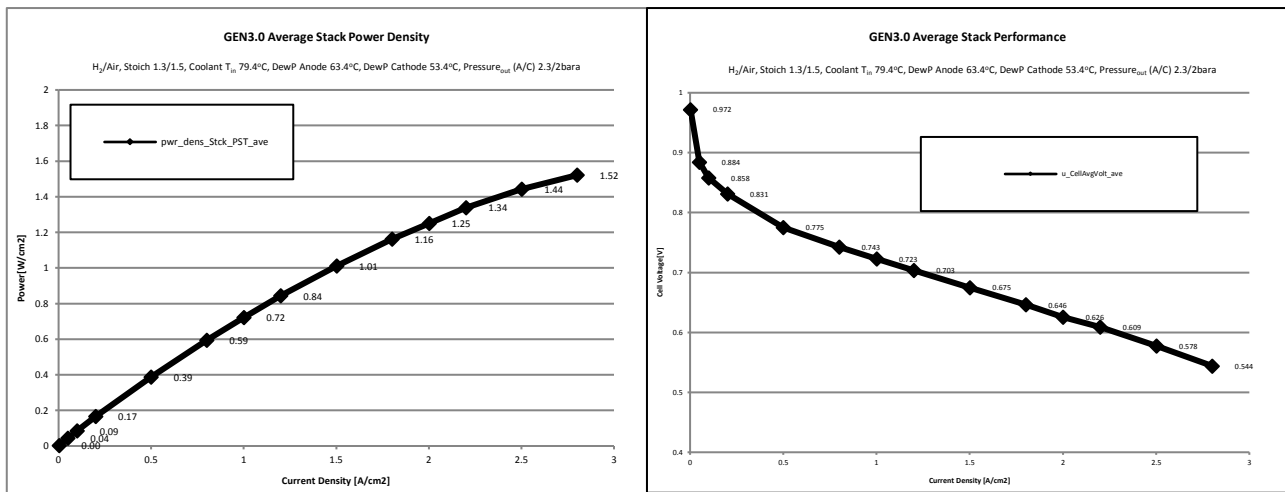


Figure 9: Full size stack power density (left), and stack average polar curve under EU harmonised protocol conditions (right)

The performance degradation from an accelerated durability protocol described in Section 2.6 is shown in Figure 10 as the beginning of life and end of test performance at the INSPIRE operating points, and gives a value of 22-29  $\mu\text{Vhr}^{-1}$  over 580 load hours  $>0.1 \text{ Acm}^{-2}$  of testing for the INSPIRE operating points. The M3 operation point that showed an increase in performance was due to the stack operating temperature being approximately 2 °C cooler than the target and hence the performance being slightly improved. The acceleration factor of this test is not yet fully known. The target degradation rate to achieve the 10% performance loss over 6000 hrs would need to be 10  $\mu\text{Vhr}^{-1}$ , of real operation. This test did not have any recovery cycle so it is reasonable to assume that the degradation rate would be lower than that measured if recovery cycles were used.

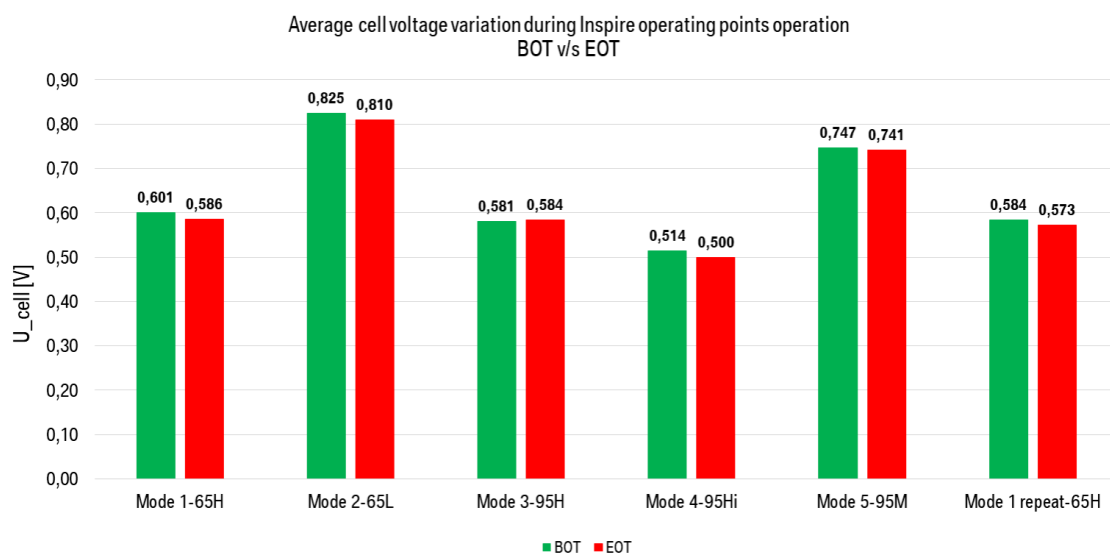


Figure 10: Performance of INSPIRE operating points in the full-size stack at beginning of life and after 580 hrs of accelerated dynamic load cycling

## 4. CONCLUSIONS

The performance target of  $1.5 \text{ Wcm}^{-2}$  was achieved at the beginning of life with the GEN 3.0 MEA design under the EU harmonised protocol conditions. To achieve this during the project lifetime, the cathode loading had to be maintained at  $0.4 \text{ mgPtcm}^{-2}$ ; however, within the development work for this MEA, options have been identified for future designs to achieve this at a reduced Pt loading. The durability of the MEAs showed degradation rates in an accelerated stress test without any recovery cycles of  $22\text{--}29 \mu\text{Vhr}^{-1}$  with a real-world target rate of  $10 \mu\text{Vhr}^{-1}$ . At this point the acceleration factor of the accelerated stress test compared to real-world operation is not clear and further work is needed to establish this value.

## 5. RECOMMENDATIONS AND FUTURE WORK

The cathode developments identified in this work should be progressed further to allow the performance achieved to be maintained or improved at reduced Pt loadings.

The acceleration factor of the stress test should be further defined and should incorporate recovery cycles such as cold soaks to better replicate the expected usage of the stack in a vehicle.

## 6. REFERENCES

- 1 Nobuaki Nonoyama, Shinobu Okazaki, Adam Z. Weber, Yoshihiro Ikogi and Toshihiko Yoshida (2011). Analysis of Oxygen Transport Diffusion Resistance in Proton Exchange Membrane Fuel Cells, *Journal of the Electrochemical Society*, 158 (4) B416-B423 (2011)
- 2 Source: G. Tsotridis, A. Pilenga, G. De Marco, T. Malkow; *EU HARMONISED TEST PROTOCOLS FOR PEMFC MEA TESTING IN SINGLE CELL CONFIGURATION FOR AUTOMOTIVE APPLICATIONS*; JRC Science for Policy report, 2015; EUR 27632 EN; doi 10.2790/54653

## 7. APPENDIX

	Unit	Mode 1: Full Screener Cell Operating Conditions Case 65-High: $\lambda_{H2} = 1,38$ ; $\lambda_{air} = 1,6$	Mode 2: Full Screener Cell Operating Conditions Case 65-L: $\lambda_{H2} = 1,33$ ; $\lambda_{air} = 1,6$	Mode 3: Full Screener Cell Operating Conditions Case 95-L: $\lambda_{H2} = 1,25$ ; $\lambda_{air} = 1,4$	Mode 4: Full Screener Cell Operating Conditions Case 95-H-I - INSPIRE: $\lambda_{H2} = 1,25$ ; $\lambda_{air} = 1,4$	Mode 5: Full Screener Cell Operating Conditions Case 95-M-I: $\lambda_{H2} = 1,25$ ; $\lambda_{air} = 1,4$
Current density	Acm <sup>-2</sup>	2	0.1	2	2.5	0.55
Cell temperature Inlet	°C	65	55	87	87	86
<b>Anode</b>						
Pressure anode inlet	bara	2.03	1.49	2.24	2.28	2.34
H2 concentration anode (dry)	mol%	91.6	86.3	89.7	89.7	83.7
N2 concentration anode (dry)	mol%	8.4	13.7	10.3	10.3	16.3
Dew point anode inlet	°C	45	45	65	65	65
<b>Cathode</b>						
Pressure cathode inlet	bara	2	1.13	2.18	2.26	1.93
O2 concentration cathode (dry)	mol%	21	21	21	21	21
N2 concentration cathode (dry)	mol%	79	79	79	79	79
Dew point cathode inlet	°C	45	45	65	65	65

### Protocol 382 – Screener cell test protocol for INSPIRE membranes

Test	Anode Gas Composition	Anode Stoich	Cathode Gas Composition	Cathode Stoich	% RHA	% RHC	Anode Inlet P (kPag)	Cathode Inlet P (kPag)	Cell Temperature (deg C)	Current Density (mAcm <sup>-2</sup> )	Duration (hrs)
Conditioning	H2	1.5	Air	2.0	100	100	100	100	80	500	16
3Way Ox 100kPa	H2	1.5	Air/Helox/Oxygen	2/2/10	100	100	100	100	80	OCV-2000	4
5hr Reconditioning	H2	1.5	Air	2.0	50 (64DP)	50 (64DP)	Amb	Amb	80	500	5
3 Way Ox	H2	1.5	Air/Helox/Oxygen	2/2/10	50 (64DP)	50 (64DP)	Amb	Amb	80	OCV-2000	4
5hr Reconditioning	H2	1.5	Air	2.0	25.7 (50DP)	25.7 (50DP)	Amb	Amb	80	500	5
3 Way Ox	H2	1.5	Air/Helox/Oxygen	2/2/10	25.7 (50DP)	25.7 (50DP)	Amb	Amb	80	OCV-2000	4
3hr Reconditioning	H2	1.5	Air	2.0	100(50DP)	100(50DP)	Amb	Amb	50	1200	3
Temperature Sweep + Water balance	H2	1.5	Air/O2	2.0/10.0	50DP	50DP	Amb	Amb	40-90	1200	5



**Protocol 388 – OCV membrane durability test protocol**

Test	Anode Gas Composition	Anode Stoich	Cathode Gas Composition	Cathode Stoich	% RHA	% RHC	Anode Inlet P (kPag)	Cathode Inlet P (kPag)	Cell Temperature (deg C)	Current Density (mAcm <sup>-2</sup> )	Duration (hrs)
Conditioning	H2	1.5	Air	2.0	100	100	100	100	80	500	16
OCV Hold	H2	142cc/min	Air	310cc/min	30	30	50	50	90	0	48-72
H2 Permeation	H2	100cc/min	N2	100cc/min	50	50	0	0	80	N/A	
Leak test	-	-	-	-	-	-	-	-	-	-	-
Repeat OCV hold until; leak rate >5cc/min											

**Protocol 394 – Combined OCV / RH cycling membrane AST**

Test	Anode Gas Composition	Anode Stoich	Cathode Gas Composition	Cathode Stoich	% RHA	% RHC	Anode Inlet P (kPag)	Cathode Inlet P (kPag)	Cell Temperature (deg C)	Current Density (mAcm <sup>-2</sup> )	Duration (hrs)
Initial Conditioning (Startup)	H2	1.5	Air	2	100	100	100	100	80	500	10
Cycling Through Steps Below until 20000 cycles											
1000 RH Cycles	H2	2000sccpm	Air	2000sccpm			0	0	90	0	6
Diagnostics Step 1	N2	2000sccpm	N2	2000sccpm	100	100	0	0	90	0	2mins
Diagnostics Step 2	N/A	300sccpm	Air	2000sccpm	100	100	0	0	90	0	15mins
Diagnostics Step 3	N2	2000sccpm	N2	2000sccpm	100	100	0	0	90	0	2mins
Diagnostics Step 4	H2	2000sccpm	N/A	300sccpm	100	100	0	0	90	0	10mins
Diagnostics Step 5	H2	2000sccpm	Air	2000sccpm	100	100	0	0	90	0	2mins
Diagnostics Step 6	H2	300sccpm	Air	300sccpm	100	100	50/50/0	50/0/0	90	0	10mins
Back To 1000 RH Cycles											

Note: RH cycles are done with 10s dry gas and 45s wet gas.

**Protocol 402B – 1D**

Test	Anode Gas Composition	Anode Stoich	Cathode Gas Composition	Cathode Stoich	RHA (Dew point C)	RHC (dew point C)	Anode Inlet P (kPag)	Cathode Inlet P (kPag)	Cell Temperature (deg C)	Current Density (mAcm <sup>-2</sup> )	Duration (hrs)
Conditioning	H2	10	Air	10	80	80	100	100	80	1000	16
Test point M1 End cell Out	91.6%H2/8.4%N2	10	9% O2/ 91%N2	10	45	65	103	56	57	2000	1
Test point M1 End cell Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	45	65	103	56	57	25,50,100,200	1.2
Test point M2 End cell Out	86.3% H2/ 13.7% N2	10	9% O2 / 91%N2	10	45	65	49	ambient	55	100	1
Test point M2 End cell Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	45	65	49	ambient	55	25,50,100,200	1.2
Test point M1 Out	91.6%H2/8.4%N2	10	9% O2/ 91%N2	10	45	65	103	56	67	2000	1
Test point M1 Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	45	65	103	56	67	25,50,100,200	1.2
Test point M2 Out	86.3% H2/ 13.7% N2	10	9% O2 / 91%N2	10	45	65	49	ambient	58	100	1
Test point M2 Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	45	65	49	ambient	58	25,50,100,200	1.2
Test point M1 In	74.7%H2/25.3% N2	10	Air	10	65	45	91	100	57	2000	1

Test point M1 In ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	65	45	91	100	57	25,50,100,200	1.2
Test point M2 In	60% H2/ 40% N2	10	Air	10	65	45	48	amb	55	100	1
Test point M2 In ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	65	45	48	amb	55	25,50,100,200	1.2
Test point M3 End cell Out	89.7% H2 / 10.3% N2	10	7.1% O2 / 92.9% N2	10	65	85	124	77	87	2000	1
Test point M3 End cell Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	65	85	124	77	87	25,50,100,200	1.2
Test point M4 End cell Out	89.7% H2 / 10.3% N2	10	7.1% O2 / 92.9% N2	10	65	85	128	76	87	2500	1
Test point M4 End cell Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	65	85	128	76	87	25,50,100,200	1.2
Test point M3 Out	89.7% H2 / 10.3% N2	10	7.1% O2 / 92.9% N2	10	60	79	124	77	91	2000	1
Test point M3 Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	60	79	124	77	91	25,50,100,200	1.2
Test point M4 Out	89.7% H2 / 10.3% N2	10	7.1% O2 / 92.9% N2	10	60	79	128	76	91	2500	1
Test point M4 Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	60	79	128	76	91	25,50,100,200	1.2
Test point M5 End cell Out	83.7% H2/ 16.3% N2	10	7.1% O2 / 92.9% N2	10	65	87	134	86	86	550	1
Test point M5 End cell Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	65	87	134	86	86	25,50,100,200	1.2
Test point M5 Out	83.7% H2/ 16.3% N2	10	7.1% O2 / 92.9% N2	10	61	80	134	86	91	550	1
Test point M5 Out ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	61	80	134	86	91	25,50,100,200	1.2
Test point M4 In	65% H2 / 35% N2	10	Air	10	85	65	111	126	87	2500	1
Test point M4 In ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	85	65	111	126	87	25,50,100,200	1.2
Test point M3 In	63.2% H2/ 36.8% N2	10	Air	10	88	65	111	118	87	2000	1
Test point M3 In ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	88	65	111	118	87	25,50,100,200	1.2
Test point M5 In	48.9% H2 / 52.1% N2	10	Air	10	88	65	130	93	86	550	1
Test point M5 In ionic conductivity measurement	H2	Fixed flow	O2	Fixed flow	88	65	130	93	86	25,50,100,200	1.2
45C Point Limiting current	H2	Fixed flow	0.5%-2%O2 in N2	Fixed flow	75%	75%	40-250	40-250	45	Potential hold 0.2 - 0.15 - 0.1 and 0.05V	38
55C Point Limiting current	H2	Fixed flow	0.5%-2%O2 in N2	Fixed flow	75%	75%	40-250	40-250	55	Potential hold 0.2 - 0.15 - 0.1 and 0.05V	
68C Point Limiting Current	H2	Fixed flow	0.5%-2%O2 in N2	Fixed flow	75%	75%	40-250	40-250	68	Potential hold 0.2 - 0.15 - 0.1 and 0.05V	
80C Point Limiting Current	H2	Fixed flow	0.5%-2%O2 in N2	Fixed flow	75%	75%	40-250	40-250	80	Potential hold 0.2 - 0.15 - 0.1 and 0.05V	
90C Point limiting current	H2	Fixed flow	0.5%-2%O2 in N2	Fixed flow	75%	75%	40-250	40-250	90	Potential hold 0.2 - 0.15 - 0.1 and 0.05V	
Cathode CV	H2	Fixed flow	N2	Fixed Flow	80%	80	100	100	80	N/A	