GIANTLEAP

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Protocols for experiments and validation activities

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GIANTLEAP

Project acronym: GIANTLEAP

Project title: Giantleap Improves Automation of Non-polluting Transportation with Lifetime Extension of Automotive PEM fuel cells

Project number: 700101

Document date: July 10, 2017

Due date: January 31, 2017

Keywords: Proton Exchange Fuel Cells (PEMFCs); Fuel cell system; Operating conditions; testing protocols; Electrochemical impedance spectroscopy; cyclic voltammetry; Balance of plant components (BoP)

Abstract: The Giantleap FC system will be integrated by VDL into their buses and will be used as a range extender. This document presents a number of load cycles for both endurance and accelerated stress tests, as well as a set of reference operating conditions such as temperature, pressure, humidification, gas flow for this particular applications. Fuel cell stack and system durability will be evaluated through endurance testing by applying repetitive load profiles measuring performance degradation in terms of cell voltage decrease as function of operating hours. The tests are intended to be carried out in single cells, short stacks, as well as at system level. The report further contains a detailed description on how to perform the electrochemical characterization of stack and single cells, e. g. Polarization curves, electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV), as well as sampling parameters and rates. Finally, the document also contains a chapter on how AST of balance of plant (BoP) components is intended to be carried out with the Giantleap project.

Revision History

Date	Description	Author
19/01/2017	First draft	Alejandro Oyarce
22/02/2017	ElringKlinger draft	Stefan Hemmer
02/05/2017	Second draft	Alejandro Oyarce
01/07/2017	BEG draft	Uwe Braig

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1 Introduction

Proton Exchange Fuel Cells (PEMFCs) due to their high energy density, low operating temperature and high efficiency are considered to be very suitable for vehicle propulsion or as range extenders for electric vehicles. In order to address the challenges associated to fuel cell system cost, Giantleap focuses on using passenger-car fuel cell stacks and automotive balance of plant components in buses. Using the same technology as passenger cars will allow to leverage the economies of scale of fuel cell technology and leading to lower cost of ownership for fuel cell buses.

The Giantleap FC system will be integrated by VDL into their buses and will be used as a range extender. VDL's concept is a fuel-cell system encased in a trailer, a trailer that can be connect to any of the already operating battery buses by personnel with limited training. One range extender will be demonstrated with long-term and accelerated testing by BEG.

Fuel cell and fuel cell system testing within Giantleap shall reflect the conditions encountered in the real application. To assess the cell degradation rate, a dynamic load cycle for endurance testing is proposed based on previous experience of operating electric and fuel cell buses (VDL). The operating conditions of the stack and system, are based on Elringklingers previous knowledge of their technology that have already shown excellent durability.

This document presents load cycles and a set of reference operating conditions such as temperature, pressure, humidification, gas flow at the fuel and oxidant inlet representative for this particular applications so that they can be used in the rest of the project to ensure that results are comparable among the sites of experimental tests. Fuel cell durability is evaluated through endurance testing by applying a repetitive load profile to the cells and measuring performance degradation in terms of cell voltage decrease as function of operating hours. The tests will be carried out in both single cell, as well as in stacks.

The report further contains a detailed description on how to perform the electrochemical characterization of stack and single cells, e. g. Polarization curves, Electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV), as well as sampling rates.

Finally, there is also a chapter on balance of plant component testing and AST protocols for these.

2 Background for Giantleap protocols

2.1 Velocity profile FC 12m Intercity Transport Calculated from VLF

VDL has previously been involved in several hydrogen projects and have acquired both experience and data from these. Figure 1 shows the velocity profile, as well as the power requirements from the fuel cell stack and the state-of-charge (SOC) of the battery bus for a 12 m intercity bus. The intercity bus shows a high average velocity for the first part of the cycle. In addition, there are also several start and stops, in particular during city operation.

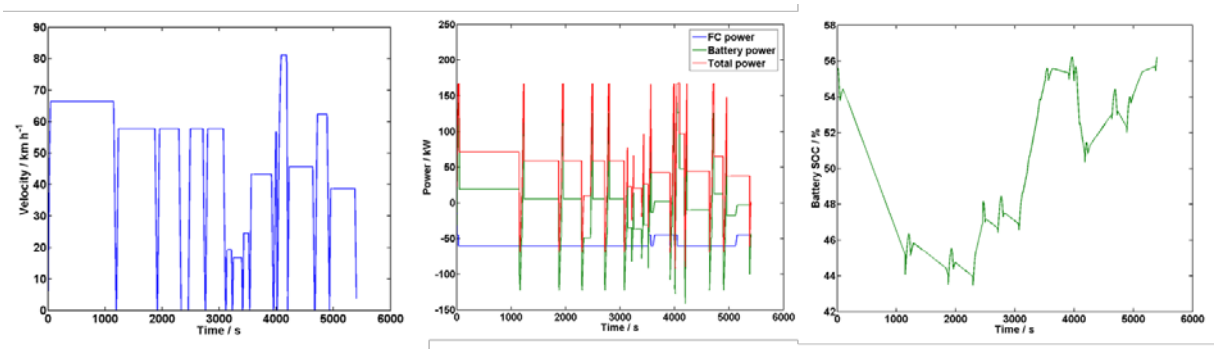

Figure 1 Velocity profile FC 12m Intercity Transport

From Figure 1 it is possible to observe that the fuel cell operates at a relatively constant power. During the 90 min cycle, the fuel cell is operated at a nominal power of 60 kW approximately 80 % of the time and only 20 % at high efficiency operation, with very few fuel cell transients. There is indeed some cycling of the fuel cell, which in theory could be avoided using a different hybridization strategy

2.2 Velocity profile FC 18m City-Transport Measured from VLF

Figure 2 shows the velocity profile, as well as the power requirements from the fuel cell stack and the state-of-charge (SOC) of the battery bus for one of four 18 m city fuel cell buses from VDL. In this cycle, the average speed is lower compared to the intercity bus (section 2.1). In addition, there are a much larger number of bus start and stops. Despite of the large number of transients for the total power requirement of the bus, it is possible to see that the fuel cell of these buses is still operated as a range extender, delivering a constant 50 kW power to the battery at all times.

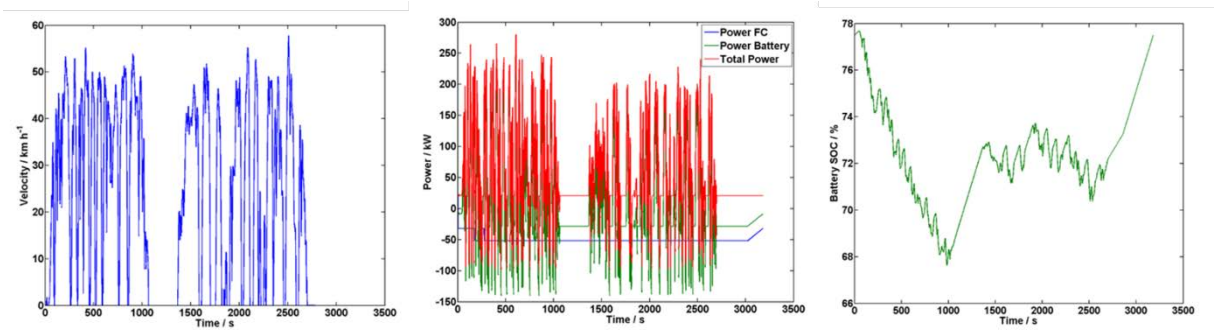

Figure 2 Velocity profile FC 18m city Transport

The bus data from VDL clearly show that these fuel cell systems are operated as range extenders providing power to the battery when required. It is therefore foreseen that the Giantleap fuel cell system will operate in a similar matter; hence, the testing protocols are designed accordingly.

3 Giantleap System

Figure 3 shows a schematic representation of the Giantleap fuel cell system. The system consist of two FCs stacks with the aim of delivering a combined nominal power of 80 kW. The combination of a large fuel cell system and a large battery pack may give a high degree of flexibility for hybridization, faster

charging of the battery pack if required and slow fuel cell transients if necessary. However, this may also result in the fuel cell system being forced to shut down when the battery pack is full, with a certain number of hours delivering zero power per day, also called idling periods. The exact operational strategy of the fuel cell system is still under development. However, fuel cell idling is indeed expected and is therefore included as part of testing protocols.

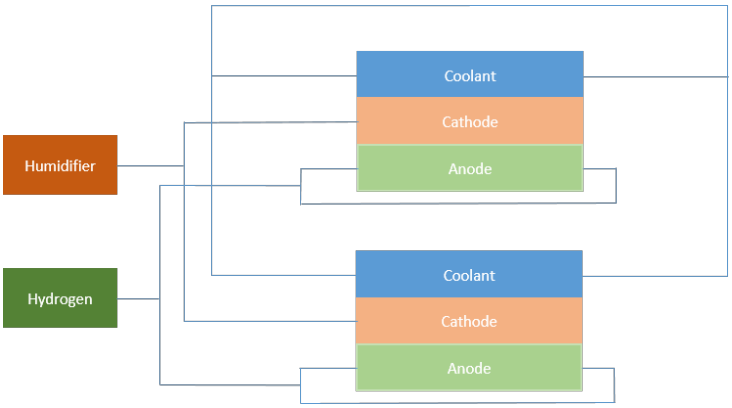

Figure 3 Schematic representation of the Giantleap fuel cell system

4 Giantleap operating conditions

The operation conditions in this rapport are specific for the fuel cell system intended to be use in the Giantleap project. The conditions were discussed between the stack manufacturer and system integrators. For readers outside the consortium, it is strongly recommended that the operating conditions are set according to their specific fuel cell technology and application.

4.1 Current and cell voltage

The limits of the Giantleap stack during normal operation have been set between 0.8 and 0.58 V per cell. However, standard operation have been estimated to be 0.6 V per cell (Nominal operation) and 0.7 V per cell (High efficiency operation). These set points are therefore used as set points in the Giantleap protocols.

4.2 Temperature and pressure

The Giantleap cooling system has been designed so that the fuel cells operated at 73 ^{o}C and 75 ^{o}C at high and low operating voltage, respectively. The absolute gas pressure at the cathode will be set to 130 kPa and 180 kPa at high and low voltage, respectively, and in any case not higher than 190 kPa at anode.

4.3 Cathode stoichiometry, flow rates and humidity

The stoichiometry at the cathode will depend of the compressor map and operating point, the exact stoichiometries for the Giantleap system are at this time still not fixed. However, a limit of λ=1.7 at 0.6 V has been set. In addition, a constant flow rate, corresponding to 0.2 A cm^{-2} will be used as a minimum flow rate, e.g., when zero power is required from the fuel cell stacks. This value may also change in the final system as there is a particular "idling protocol" below a power density threshold.

A humidifier for the air will be used in the Giantleap system (see Figure 3) with the aim of increasing the lifetime of the stacks. On the other hand, the exact relative humidity (RH) of the incoming air, has at this point not been established. It is however, estimated that the RH will approximately be 75 %RH; a set point that will be used in these protocols.

4.4 Anode stoichiometry, flow rates and humidity

The fuel cell system also includes a passive hydrogen recirculation unit consisting of a Jet-Pump, a hydrogen injection valve, an overpressure valve and a pressure sensor. The hydrogen gas will therefore be humidified during operation. Due to space constrains of the loop and the difficulties to place sensors and flow meters, the exact humidity and mass flowrate in the loop will be unknown. It is however, estimated that the anode will have a humidity between 40-50 %RH and a hydrogen stoichiometry of around 1.5 and 2.5, at high efficiency and nominal operation, respectively. In these protocols a hydrogen RH of 45 % will be used. Table 1 summaries the operating conditions of the Giantleap protocols.

Table 1 Operating parameters of Giantleap

	Parameter	Symbol	Unit	Ref EU automotive conditions[1]	Giantleap conditions low current density	Giantleap conditions high current density
	Nominal cell operating temperature	T	oC	80	73	75
Anode	**Fuel gas inlet temperature**	T	oC	85	73	75
	Fuel gas inlet humidity	RH	%RH	50 (dpt 64oC)	45	45
	Fuel gas inlet pressure (absolute)	P	kpa	250	140	190
	Fuel stoichiometry	Stoich.		1,3	1.5	2.5
Cathode	**Oxidant gas inlet temperature**	T	oC	85	73	75
	Oxidant gas inlet humidity	RH	%RH	30 (dpt 53oC)	75	75
	Oxidant gas inlet pressure (absolute)	P	kpa	230	130	180
	Air stoichiometry	Stoich.		1,5	1.7	1.7
	Minimum current density for stoichiometry operation	Min gas flow	A/cm2	0,2	0.2*	0.2*

**This value is only recommended when performing polarization curves and low current density operation in general. For the Giantleap system a specific idling procedure is used when the power requirement is low.*

[1] *EU HARMONISED TEST PROTOCOLS FOR PEMFC MEA TESTING IN SINGLE CELL CONFIGURATION FOR AUTOMOTIVE APPLICATIONS, Georgios Tsotridis, Alberto Pilenga, Giancarlo De Marco, Thomas Malkow, 2015*

5 Giantleap protocols

5.1 Background

The purpose of a load cycles is to make a laboratory simulation of real driving conditions. In this view the load cycle is used to assess fuel cell durability during a relatively long period by exposing the cell to the same load cycle repetitively. Automotive PEMFC systems are usually subjected to different operation regimes including fast variations in load, prolonged OCV exposure as well as periods of steady state operation during their useful life. Regarding the Giantleap load profiles, this consortium considers that the protocols should resemble bus driving profiles as much as possible and that operating the stack and the system outside these operating points may results in degradation rates and phenomena not representative for the stack and the system. Therefore, existing load profiles such as the "New European Driving Cycle" (NEDC) will not be implemented in Giantleap. As described in Sections 2, the fuel cell system will be operated as a range extender providing power to the battery pack accordingly. In addition, a large battery pack will be used and will give flexibility to the system allowing it to operate at relatively moderate variations in load, as well as idling periods.

5.2 Endurance cycle

Figure 4 shows the endurance protocol suggested for the Giantleap project. As it is possible to observed from the figure, the primary cycle consist of a 2 h cycle starting with a short period of time at OCV's. A relatively slow ramp up rate is used 0.04 A cm^{-2} s^{-1} to reach high efficiency operation. A period of 650 s at high efficiency operation, followed by a longer period at steady state nominal operation (2500 s). In order to always ensure sufficient reactant flows, it is suggested that the gas flow rates are changed at least 3 s before ramping up the load and 3 s after ramping down the load. Furthermore, long periods at constant current may induce some degradation (reversible degradation). Therefore, a certain degree of dynamics is included in the protocol, going once again to high efficiency operation for 650 s and back to high power operation for another 2500 s. After the steady state periods, the stacks (or the cell in case of single cell testing), the power is ramp down at the same rate as the ramp-up rate. After a short period of 10 s at OCV, the stack is put into idling mode for 420 s. The cycle is calculated to generate a total of 127 kWh.

The relatively high nominal power of the stack, in combination with a large battery module will most probably allow for a relatively fast charging of the battery pack, therefore multiple idling periods per day at zero current are foreseen during real operation and thereby included this protocol. The idling consist of a bleed down of the stacks. The pressure of the anode is decreased, but not totally depressurized. It is vital for the idling procedure that hydrogen is present at the anode at all time. The cathode is completely closed (inlet and outlet), and the air flow is set to zero. After this, a small current is taken from the stack with the aim of consuming the residual oxygen at the cathode. This is carried out until the voltage of the individual cells decrease below 0.2 V. Finally, the endurance cycle ends with a start-up. This involves the opening of cathode and the use of a high air flow rates. Table 2 summarizes the Giantleap endurance cycle.

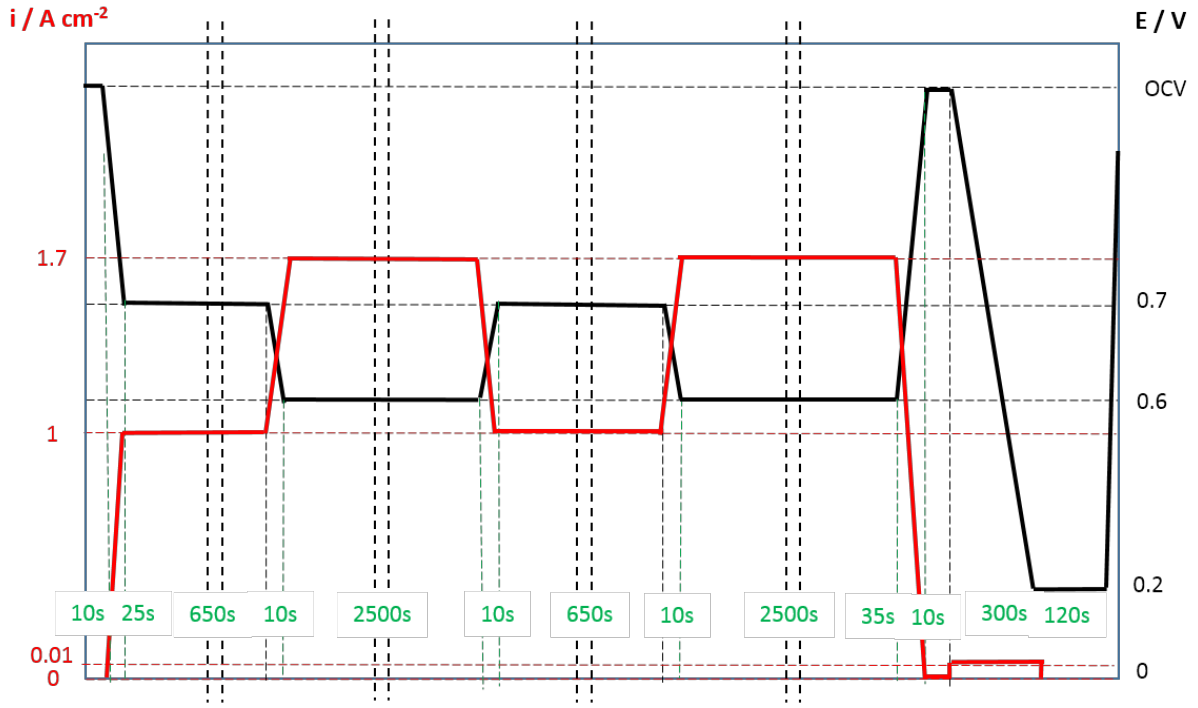

Figure 4 Giantleap endurance protocol

Table 2 Summary of the Giantleap endurance protocol

step	Voltage / V	Current density / A cm^{-2}	Ramp rate /A cm^{-2} s^{-1}	Duration /s	Temperature / °C	Air stoichiometry /λ	H2 stoichiometry /λ	Minimum flow at cathode/ l min^{-1} or A cm^{-2}	Minimum flow at anode/ l min^{-1} or A cm^{-2}
1	OCV	0	-	10	73	-	-	0.2 A cm^{-2}	0.2 A cm^{-2}
2	-	-	+0.04	25	73	1.7	1.5	-	-
3	0.7	1.0	-	650	73	1.7	1.5	-	-
4	-	-	+0.04	10	75	1.7	2.5	-	-
5	0.6	1.7	-	2500	75	1.7	2.5	-	
2	-	-	-0.04	10	73	1.7	2.5	-	-
3	0.7	1.0	-	650	73	1.7	1.5	-	-
4	-	-	+0.04	10	75	1.7	2.5	-	-
5	0.6	1.7	-	2500	75	1.7	2.5	-	-
6	-	-	-0.04	35	75	1.7	1.5	-	-
7	OCV	0	-	10	73	-	-	0.2 A cm^{-2}	0.2 A cm^{-2}
8	-	0.01	-	300**	73	-	-	-	0.2 A cm^{-2}
9	~0.2	0	-	120	73	-	-	-	0.2 A cm^{-2}
10	OCV	0	-	-	73			0.2 A cm^{-2}	0.2 A cm^{-2}
Sum				6810					

*** The current should be taken for 300 s or as until the stack/cell voltage is below 0.2 V.*

5.3 Endurance protocol

Each endurance test starts with the appropriate cell leak test, conditioning and break-in period, after which the protocol is performed according to the following 6 steps:

1. Set the test operating conditions at reference according to Table 1.
2. At the Beginning of Test (BoT), perform a polarization curve according to Table 6, section 6.1 and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2} (as suggested in the JRC protocols)[1].

3. In addition, performed any other electrochemical characterization method available or possible, e. g. cyclic voltammetry or EIS (see section 6.2 and 6.3)
4. Operate the cell with the Giantleap endurance protocol for 50 consecutive cycles (50 cycles = 4 days).
5. At the end of one block, perform a polarization curve and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2} and any other of the electrochemical characterization methods performed in 2. Compare with measurements performed at BoT and observe the degradation rate in µV/hour.
6. Performance recovery/ prolonged shutdowns (see section 5.4.4)
7. back to 1 and repeat.

5.4 AST cycles

The aim of these AST protocols is to accelerate whatever degradation mechanism associated with the specific fuel cell operating conditions the system is subjected to in the real case (or during the endurance protocol). Any observed degradation and possible degradation mechanisms will be investigated and characterized through in-situ electrochemical characterization methods and post-mortem analysis of the components if possible.

5.4.1 AST-1 cycling

The AST-1 cycling protocol is carried out in an attempted to isolate the contribution of cycling the fuel cell stacks from near OCV to nominal operation on the degradation rates of the stacks. It consist of a 2 h cycle with multiple excursions to high voltage (OCV) representing the voltage cycling the stacks may experience. AST-1 do not involve any idling periods, however, the AST indeed involves 10 times more cycling up to OCV, compared to the endurance protocol and generates a total of 135 kWh.

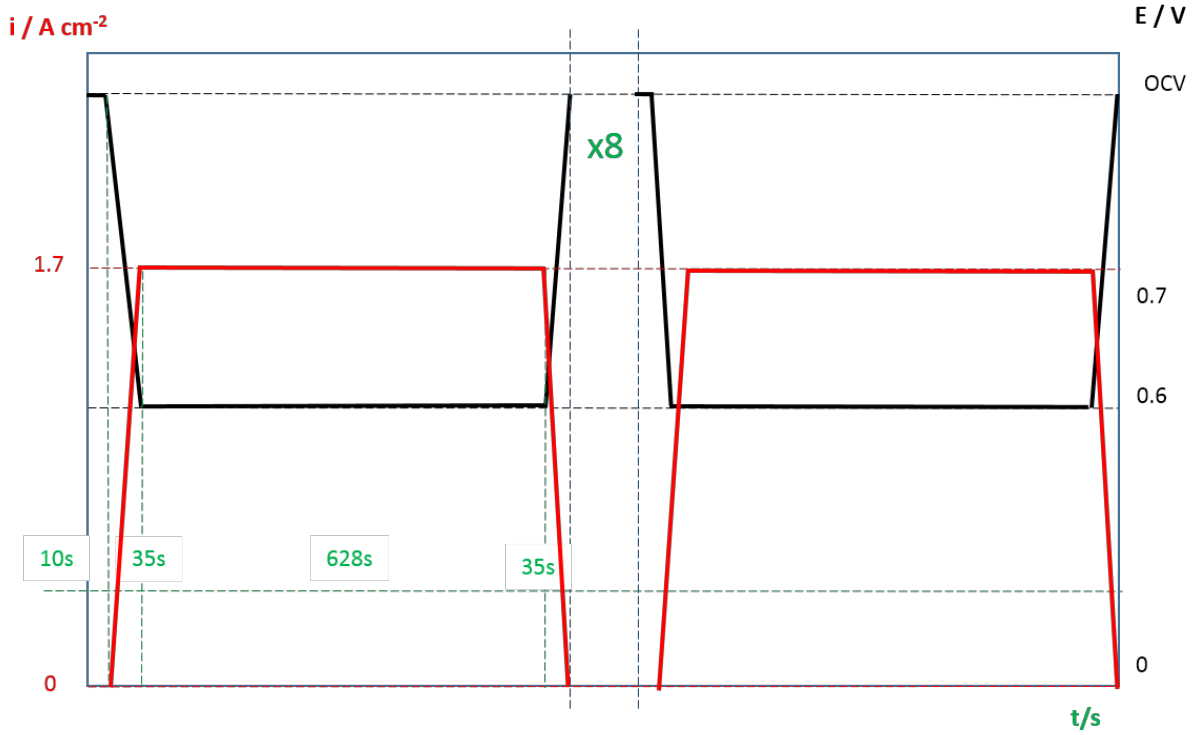

Figure 5 AST-1 cycling protocol

Table 3 Summary of the Giantleap AST-1 cycling protocol

step	Voltage / V	Current density / A cm-2	Ramp rate /A cm-2 s-1	Duration /s	Temperature/ oC	Air stoichiometry /λ	Minimum flow at cathode / l min-1 or A cm-2
1	OCV	0	-	10	75	-	0.2 A cm-2
2	-	-	+0.04	35	75	1.7	-
3	0.6	1.7	-	628	75	1.7	
4	-	-	-0.04	35	75	1.7	
5	OCV	-	-	10	75	-	0.2 A cm-2
6	-	-	+0.04	35	75	1.7	-
7	0.6	1.7	-	628	75	1.7	
8	-	-	-0.04	35	75	1.7	
9	OCV	-	-	10	75	-	0.2 A cm-2
10	-	-	+0.04	35	75	1.7	-
11	0.6	1.7	-	628	75	1.7	
12	-	-	-0.04	35	75	1.7	
13	OCV	-	-	10	75	-	0.2 A cm-2
14	-	-	+0.04	35	75	1.7	-
15	0.6	1.7	-	628	75	1.7	
16	-	-	-0.04	35	75	1.7	
17	OCV	-	-	10	75	-	0.2 A cm-2
18	-	-	+0.04	35	75	1.7	-
19	0.6	1.7	-	628	75	1.7	
20	-	-	-0.04	35	75	1.7	
21	OCV	-	-	10	75	-	0.2 A cm-2
22	-	-	+0.04	35	75	1.7	-
23	0.6	1.7	-	628	75	1.7	
24	-	-	-0.04	35	75	1.7	
25	OCV	-	-	10	75	-	0.2 A cm-2
26	-	-	+0.04	35	75	1.7	-
27	0.6	1.7	-	628	75	1.7	
28	-	-	-0.04	35	75	1.7	
29	OCV	-	-	10	75	-	0.2 A cm-2

30	-	-	+0.04	35	75	1.7	-
31	0.6	1.7	-	628	75	1.7	
32	-	-	-0.04	35	75	1.7	
33	OCV	-	-	10	75	-	0.2 A cm-2
34	-	-	+0.04	35	75	1.7	-
35	0.6	1.7	-	628	75	1.7	
36	-	-	-0.04	35	75	1.7	
37	OCV	-	-	10	75	-	0.2 A cm-2
38	-	-	+0.04	35	75	1.7	-
39	0.6	1.7	-	628	75	1.7	
40	-	-	-0.04	35	75	1.7	
41	OCV	-	-	10	75	-	0.2 A cm-2
42	-	-	+0.04	35	75	1.7	-
43	0.6	1.7	-	628	75	1.7	
44	-	-	-0.04	35	75	1.7	
sum				7080			

The AST-1 protocol starts with the appropriate cell leak test, conditioning and break-in period, after which the protocol is performed according to the following 6 steps:

1. Set the test operating conditions at reference according to Table 1.
2. At the Beginning of Test (BoT), perform a polarization curve according to Table 6, section 6.1 and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2}
3. In addition, performed any other electrochemical characterization method available or possible, e. g. cyclic voltammetry or EIS (s.ee section 6.2 and 6.3)
4. Operate the cell with the Giantleap endurance protocol for 50 consecutive cycles (50 cycles = 4 days).
5. At the end of one block perform a polarization curve and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2} and any other of the electrochemical characterization methods performed in 2. Compare with measurements performed at BoT and observe the degradation rate in µV/hour.
6. Performance recovery/ prolonged shutdowns (see section 5.4.4)
7. back to 1 and repeat.

5.4.2 AST-2 On-off

The AST-2 on-off protocol is carried out in an attempted to isolate the contribution of the on and off operation (idling) of the fuel cell stacks. After carrying out AST-1 it will be possible to calculate the degradation rate due to cycling, AST-2 will then be able to provide the information on the effects of idling and weather it has a negative impact on the degradation rate of the fuel cells. As in AST-1, AST-2 also consist of a 2 h cycle with multiple excursions to high voltage. However, it also contains multiple idling periods. In fact, 6 times more idling compared to the endurance protocol and generate a total of 87 kWh.

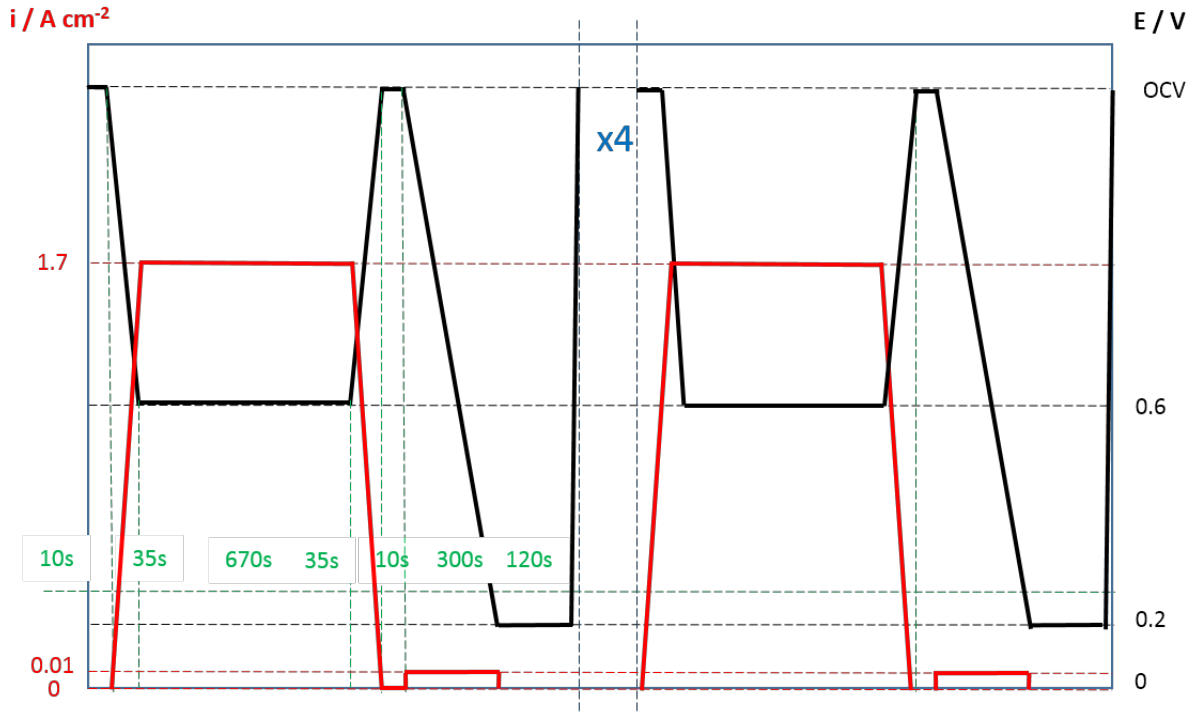

Figure 6 AST-2 on-off

Table 4 Summary of the Giantleap AST-2 on-off protocol

step	Voltage / V	Current density / A cm-2	Ramp rate /A cm-2 s-1	Duration /s	Temperature/ oC	Air stoichiometry /λ	Minimum flow at cathode / l min-1 or A cm-2
1	OCV	0	-	10	75	-	0.2 A cm-2
2	-	-	+0.04	35	75	1.7	-
3	0.6	1.7	-	670	75	1.7	
4	-	-	-0.04	35	75	1.7	
5	OCV	-	-	10	75	-	0.2 A cm-2
6	-	-	-	300	75	0	0
7	0	0	-	120	75	0	0
8	OCV	0	-	10	75	-	0.2 A cm-2
9	-	-	+0.04	35	75	1.7	-
10	0.6	1.7	-	670	75	1.7	
11	-	-	-0.04	35	75	1.7	
12	OCV	-	-	10	75	-	0.2 A cm-2
13	-	-	-	300	-	0	0
14	0	0	-	120	75	0	0
15	OCV	0	-	10	75	-	0.2 A cm-2
16	-	-	+0.04	35	75	1.7	-
17	0.6	1.7	-	670	75	1.7	
18	-	-	-0.04	35	75	1.7	
19	OCV	-	-	10	75	-	0.2 A cm-2
20	-	-	-	300	75	0	0
21	0	0	-	120	75	0	0
22	OCV	0	-	10	75	-	0.2 A cm-2
23	-	-	+0.04	35	75	1.7	-
24	0.6	1.7	-	670	75	1.7	
25	-	-	-0.04	35	75	1.7	
26	OCV	-	-	10	75	-	0.2 A cm-2
27	-	-	-	300	-	0	0
28	0	0	-	120	75	0	0
29	OCV	0	-	10	75	-	0.2 A cm-2
30	-	-	+0.04	35	75	1.7	-
31	0.6	1.7	-	670	75	1.7	

32	-	-	-0.04	35	75	1.7	
33	OCV	-	-	10	75	-	0.2 A cm-2
34	-	-	-	300	-	0	0
35	0	0	-	120	75	0	0
36	OCV	0	-	10	75	-	0.2 A cm-2
37	-	-	+0.04	35	75	1.7	-
38	0.6	1.7	-	670	75	1.7	
39	-	-	-0.04	35	75	1.7	
40	OCV	-	-	10	75	-	0.2 A cm-2
41	-	-	-	300	-	0	0
42	0	0	-	120	75	0	0
sum				7080			

The AST-2 protocol starts with the appropriate cell leak test, conditioning and break-in period, after which the protocol is performed according to the following 6 steps:

1. Set the test operating conditions at reference according to Table 1.
2. At the Beginning of Test (BoT), perform a polarization curve according to Table 6, section 6.1 and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2}
3. In addition, performed any other electrochemical characterization method available or possible, e. g. cyclic voltammetry or EIS (s.ee section 6.2 and 6.3)
4. Operate the cell with the Giantleap endurance protocol for 50 consecutive cycles (50 cycles = 4 days).
5. At the end of one block perform a polarization curve and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2} and any other of the electrochemical characterization methods performed in 2. Compare with measurements performed at BoT and observe the degradation rate in µV/hour.
6. Performance recovery/ prolonged shutdowns (see section 5.4.4)
7. back to 1 and repeat.

5.4.3 AST-3 Idling time

The AST-3 is also an on-off protocol. In this case, the protocol isolates the contribution of the idling time. AST-3 consist of a 2 h cycle with multiple excursions to high voltage. It also contains less idling compared to AST-2, but generate the same amount of energy, a total of 87 kWh. If both AST-2 and AST3 are performed and compared, it may be possible to answer the question of which operational strategy may provide longer lifetime: *i)* high efficiency operation with few idling periods, or *ii)* high power operation with more idling periods. This may be crucial information to the system developers when designing and choosing operational strategy.

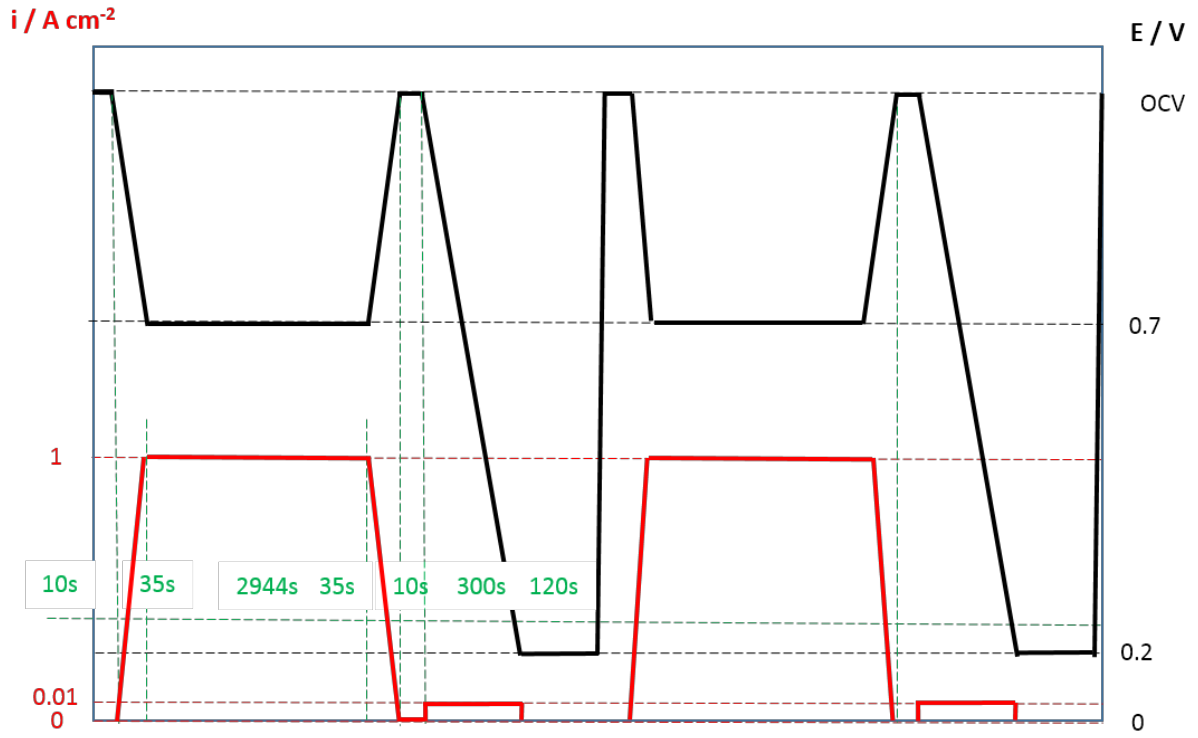

Figure 7 AST-3 Idling time

Table 5 Summary of the Giantleap AST-2 Idling time protocol

step	Voltage / V	Current density / A cm-2	Ramp rate /A cm-2 s-1	Duration /s	Temperature/ oC	Air stoichiometry /λ	Minimum flow at cathode / l min-1 or A cm-2
1	OCV	0	-	10	75	-	0.2 A cm-2
2	-	-	+0.04	35	75	1.7	-
3	0.7	1.0	-	2944	75	1.7	
4	-	-	-0.04	35	75	1.7	
5	OCV	-	-	10	75	-	0.2 A cm-2
6	-	-	-	300	75	0	0
7	0	0	-	120	75	0	0
8	OCV	0	-	10	75	-	0.2 A cm-2
9	-	-	+0.04	35	75	1.7	-
10	0.7	1.0	-	2944	75	1.7	
11	-	-	-0.04	35	75	1.7	
12	OCV	-	-	10	75	-	0.2 A cm-2
13	-	-	-	300	-	0	0
14	0	0	-	120	75	0	0
sum				7080			

The AST-3 protocol starts with the appropriate cell leak test, conditioning and break-in period, after which the protocol is performed according to the following 6 steps:

1. Set the test operating conditions at reference according to Table 1.
2. At the Beginning of Test (BoT), perform a polarization curve according to Table 6, section 6.1 and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2}
3. In addition, performed any other electrochemical characterization method available or possible, e. g. cyclic voltammetry or EIS (s.ee section 6.2 and 6.3)

4. Operate the cell with the Giantleap endurance protocol for 50 consecutive cycles (50 cycles = 4 days).
5. At the end of one block perform a polarization curve and/or record the cell voltage at 0.1, 0.8 and 1.8 A cm^{-2} and any other of the electrochemical characterization methods performed in 2. Compare with measurements performed at BoT and observe the degradation rate in µV/hour.
6. Performance recovery/ prolonged shutdowns (see section 5.4.4)
7. back to 1 and repeat.

5.4.4 Performance recovery/ prolonged shutdowns

As part of the Giantleap protocol, a performance recovery/shut-down procedure will be used. This is a slightly modified version of what it is specified in the JRC protocols[1]. However, the aim is the same, namely consuming residual oxygen from the cathode side of the stack, similar to the idling procedure explained in Section 5.2. The main difference is a leak test (the Giantleap leak test is confidential), removal of the water from the cathode and a shutdown of the cooling system. The following steps are suggested:

1. **Disconnect the load.**
2. **Purge the cathode with dry air for 2 min**
3. **Leak test of the anode (constant pressure is expected)**
4. **Stop air flow to the cathode.**
5. **Shut off cathode exit.**
6. **Decrease the anode pressure, but make sure hydrogen is present at the anode**
7. **Take a small current from the stack until cell voltage reaches below 0.2 V**
8. **Close fuel supply**
9. **Shutoff the thermal system and let the cell to cool down to ambient temperature**
10. **Keep the cell under ambient conditions for at least 24 h hours**

5.4.5 Leak test

As mentioned above the leak test implemented in the Giantleap protocols is confidential. However, readers outside the consortium are recommended to follow the JRC leak test protocol[1].

Objectives:

- Measure leakage rate by pressure decrease in anode and cathode compartment;
- Assure gas tightness of cell and test station.

Procedure:

1. Start dry nitrogen flow in anodic and cathode compartment at minimum flow rate;
2. Pressurize the anode compartment to 320 kPa (abs) and the cathode compartment to 300 kPa (abs). The pressure difference between anode and cathode (20kPa) should be the same as for the reference operating conditions;
3. Reduce nitrogen flow to zero;
4. Keep cell at this state for minimum 10 minutes;
5. Measure pressure decrease in both compartments for minimum 10 minutes;

Data analysis:
Plot anode and cathode pressure versus test duration for both situations when no cell is used and when the cell is used to determine the influence of the test bench gas tightness. Acceptance criterion: the test is passed if the leak rate is lower than 0.3 kPa/min.

5.4.6 Cell break in

Unfortunately, the cell break in procedure is also confidential, this is due to confidentiality agreements with MEA manufactures. Therefore, the reader is referred to the cell break in procedure recommended by the JRC protocols[1], if specific instructions are not provided by the MEA manufacturer:

- Increase the cell temperature to 75°C, reactants inlets temperature to 77°C, RH to 100% (with respect to the cell temperature) and back pressure to 150 kPa (abs) on Anode and 130 kPa (abs) on Cathode, while avoiding the gas inlet dew points to exceed reactants inlets and cell temperatures.
- Increase the current density in steps of 100 mA/cm2 up to 800 mA/cm2 while keeping the cell voltage > 400 mV, and let the cell stabilize for 6 hours.
- Set the reactants RH to 50% and increase the current while keeping the cell voltage > 400 mV up to 1 A/cm2. Hold the cell in these conditions for at least 2 hours.
- Stability validation by 0.4 V to 0.8 V cycles with stoichiometric condition.
- At the 1.0 A/cm2 set point perform the reference 1 recording for 5 min, move to a high potential (0.8 V) and hold for 5 min. Subsequently move to a low potential (0.4 V) and hold for 5 min also. Repeat these jumps till three high voltage and two low voltage plateau measurements have been performed and hold for 0.5 h at the 1.0 A/cm2 set point to record the reference 2 for 5 min.

The recommended stability criterion is based on the cell voltage fluctuation and it is considered fulfilled when it is lower than ±5 mV in the reference 2 step. Additionally, the cell voltage fluctuation between the reference time frame 1 and 2 should be lower than ±10 mV. For higher fluctuation the whole or parts of the procedure have to be repeated till the targets are reached.

5.4.7 Cell conditioning

For cell conditioning, the reader is also referred to the procedures suggested in the JRC protocols[1].

The aim of the conditioning procedure is to assure that the cell voltage will be stable before the test initiation. A stability criterion is defined based on the difference between the cell voltages measured for a specified period. It is recommended that the variations in the cell voltage are lower than +/- 5 mV during the last hour before ending the conditioning step. Cell conditioning starts by setting the required operating conditions and maintain these conditions until the cell voltage is stable that is when it varies by not more than +/-5 mV during the last hour of conditioning procedure. In case no cell stability is obtained within 6 hours of operation a repetition of the break-in and conditioning could be reconsidered. If again the cell stability is not met troubleshooting actions shall take place.

6 Giantleap performance characterization

6.1 IV curves

The objective of performing polarization curve measurements is to determine the MEA performance in terms of cell voltage and power density against current density at specified operating conditions. The dwell time of each set point should be sufficient long enough to ensure that stabilization criteria of cell voltage of ±5 mV within 2 min but not longer than 15 min, except for the OCV which shall not exceed 1 min dwell time. The proposed set points are summarized in Table 6 which are the same set points suggested in the JRC protocols[1].

Table 6 Summary of Polarization curve.

Set point no	Current density (A cm-2)	Dwell time (s)	Data acquisition (s)
1	0.00	≤ 60	≥ 30
2	0.02	≤ 60	≥ 30
3	0.04	≤ 60	≥ 30
4	0.06	≤ 60	≥ 30
5	0.08	≤ 60	≥ 30
6	0.1	≤ 60	≥ 30
7	0.2	≥ 120	≥ 30
8	0.3	≥ 120	≥ 30
9	0.4	≥ 120	≥ 30
10	0.6	≥ 120	≥ 30
11	0.8	≥ 120	≥ 30
12	1	≥ 120	≥ 30
13	1.2	≥ 120	≥ 30
14	1.4	≥ 120	≥ 30
15	1.6	≥ 120	≥ 30
16	1.8	≥ 120	≥ 30
17	2	≥ 120	≥ 30
18	1.8	≥ 120	≥ 30
19	1.6	≥ 120	≥ 30
20	1.4	≥ 120	≥ 30
21	1.2	≥ 120	≥ 30
22	1	≥ 120	≥ 30
23	0.8	≥ 120	≥ 30
24	0.6	≥ 120	≥ 30
25	0.4	≥ 120	≥ 30
26	0.3	≥ 120	≥ 30
27	0.2	≥ 120	≥ 30
28	0.1	≤ 60	≥ 30
29	0.08	≤ 60	≥ 30
30	0.06	≤ 60	≥ 30
31	0.04	≤ 60	≥ 30
32	0.02	≤ 60	≥ 30
33	0.00	≤ 60	≥ 30

If the maximum current density of 2.0 A/cm-2 cannot be reached, the end point of the polarisation curve will be at the closest current setting giving a cell voltage of 0.4 V. If higher current density settings than 2.0 A/cm-2 are possible it is recommended to continue recording in 0.2 A/cm-2 steps until a cell voltage of 0.4 V is obtained. The measurements should be conducted in galvanostatic operation. For each current density set point the voltage is measured along the dwell time. The dwell time is composed by stabilisation time followed by data acquisition time. During the data acquisition time (ie 30 sec.) the cell voltage is sampled, recorded and all voltage sample (Vi) are then averaged. The averaged voltage (Vavg) is then used to determine the polarisation curve.

6.2 EIS

Electrochemical impedance spectroscopy (EIS) is regarded as a suitable electrochemical characterization technique for studying fuel cell performance. During these measurements a small sinusoidal current or voltage perturbation is applied at different frequencies which makes it possible to distinguish processes occurring at different time scales. However, in many situations a mathematical model is needed to increase the knowledge of the investigated system, especially when different processes with approximately the same time constants occur simultaneously.

In general, an EIS spectrum for a PEMFC shows one or several capacitive loops and in some situations an inductive loop at the lowest frequencies depending on the operating conditions and state of health of the fuel cell.

Figure 8 shows an example of an EIS spectra for a PEMFC single cell. In the high frequency region an intercept with the real axis occurs, defined as the high–frequency resistance (HFR) or ohmic cell resistance R. This high–frequency value is generally taken in the frequency range 1–10 kHz. Unfortunately, within this frequency range other contributors such as the anode kinetics and proton migration in the porous electrodes appear which may influence the value. At intermediate frequencies a capacitive loop appears with a 45◦ branch at the highest frequencies, which is associated to processes occurring in the cathode, kinetics and proton migration. In the low–frequency region around 10^{1} Hz down to 10^{-3} Hz one or several capacitive loops and in some situations an inductive loop may appear depending on the operating conditions. It is not the scope of this document to give a detailed review on these processes. However, these loops have been correlated to both transport processes in the channels, GDL and electrodes, as well as water transport (water drag and diffusion) in the membrane [2,3].

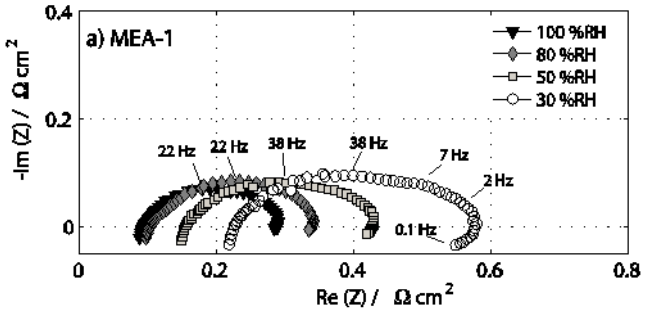

Figure 8 example of single cell EIS measurements at different RH.

6.2.1 Single cells

EIS is used as a standard electrochemical characterization and it is strongly recommended that this technique is applied within the Giantleap project in the laboratory in order to gather as much information as possible from tests.

- **Perform EIS in galvanostatic mode at 0.1, 0.8 and 1.8 A/cm2. Use the Giantleap operating parameter described in Table 1 and equilibrate the cell for at least 15 min before starting with the EIS.**

[2] *Nicklas Holmström, Katarina Wiezell, and Göran Lindbergh, Journal of The Electrochemical Society, 159 (8) F369-F378 (2012)*
[3] *I. A. Schneider, H.Kuhn,A.Wokaun, and G.G Scherer, J. Electrochem. Soc., 152(12), A2383 (2005).*

- **At the end of each current level recorded an impedance spectrum from 10 kHz down to 100 mHz for a H2/Air**
- **Record the impedance spectra using a sinusoidal ac current as possible to 5% of the dc current.**
- **In order to obtain good quality impedance data, it is recommended to perform the impedance measurements with 10 steps per decade, 10 measuring periods at frequencies above 66 Hz and 8 steps per decade and 4 measuring periods for frequencies below 66 Hz.**

It is also recommended to us a fixed value for the HFR, the real impedance at 5 kHz is suitable to use to determine the ohmic contribution of the cell.

6.2.2 Stacks

Performing EIS on stacks is a more complicated process than performing these measurements on a single cell level. Integral measurements of the whole stack do not provide information about single cells, therefore only the simultaneous impedance spectroscopy of individual cells in a stack is capable of evaluating the state of operation of these cells. Usually a Frequency Response Analyser (FRA), e. g. a Solartron 1254 equipped with multichannel extensions, is required in order to measure the individual impedance of cells. The current should be applied to the whole stack and special considerations should be taken if this technique should be used within the Giantleap project[4].

6.3 Cyclic voltammetry

Cyclic voltammetry is an electrochemical characterization technique commonly employed in fuel cell testing to assess the electrochemical active surface area (ECSA) of the Pt catalyst in fuel cell electrodes, an important performance metric that provides an estimate of catalyst utilisation and degradation.

6.3.1 Single cell

Cyclic voltammetry is an in-situ technique most commonly applied to single cells and it is well covered in the literature [5]. H_2 or diluted hydrogen (5% H_2 in Ar) is usually used on the anode side of the cell, while N_2 is flowed over the cathode. In this case, the N_2 electrode is connected as the working electrode and the H2 containing electrode functions as a pseudoreference electrode and connected as counter/reference electrode. Diluted H_2 is preferred in order to avoid high hydrogen crossover rates influencing the shape of the voltammogram. However, in this case, it is also important to consider the shifty in potential due to lower H_2 partial pressure and needs to be corrected according to the Nernst equation. Too high N2 flow rates on the working electrode, as well as dryness may underestimate the ECSA. In addition, repetitive cycling to high voltage may also degrade the working electrode. Therefore, it is important to limit the number of cycles as well as the higher potential limit while still being able to extract important information from these measurements. Table 7 shows a set of operating conditions, for the evaluation of small area single cells (50 cm2).

[4] *W. Merida, D.A. Harrington, J.M. Le Canut, G. McLean, Journal of Power Sources 161 (2006) 264–274*
[5] *Rakel Wreland Lindström, Katrin Kortsdottir, Maria Wesselmark, Alejandro Oyarce, Carina Lagergren, and Göran Lindbergh, Journal of The Electrochemical Society, 157 (12) B1795-B1801 (2010)*

Table 7 Summary of conditions to be used for cyclic voltammetry measurements.

	Parameter	Symbol	Unit	Giantleap conditions
	Nominal cell operating temperature	T	oC	75
Counter/reference	**Fuel gas inlet temperature**	T	oC	73
	Fuel gas inlet humidity	RH	%RH	45
	Fuel gas inlet pressure (absolute)	p	kpa	20
	H2 flow rate	NL min-1		0.5
Working	**Oxidant gas inlet temperature**	T	oC	73
	Oxidant gas inlet humidity	RH	%RH	75
	Oxidant gas inlet pressure (absolute)	p	kpa	20
	N2 flow rate	NL min-1		0.4

1. **Flow H2 over the counter/reference electrode and N2 over the working electrode for 20 min and make sure the voltage of the cell is below 0.5 V vs. SHE.**
2. **Cycle the voltage at 100 mV/s between 0.05 V and 0.8 V vs SHE for 20 times**
3. **Cycle the voltage at 50 mV/s between 0.05 V and 0.8 V vs SHE for 10 times**
4. **Cycle the voltage at 10 mV/s between 0.05 V and 0.8 V vs SHE for 3 times**

Using this method, protons present in the polymer electrolyte are reduced to form a monolayer of electro-adsorbed hydrogen on the platinum surface. The Pt-H species formed, so-called underpotential deposited hydrogen (Hupd), is distinct from the intermediate involved in the hydrogen evolution reaction, which is driven by application of an overpotential.

$$Pt_{surface} + H_3O^+ + e^- \rightleftharpoons Pt - H_{upd} + H_2O \quad (1)$$

The reaction in Eq. (1) involves a range of adsorption energies due to the polycrystalline nature of the platinum catalyst and so the potential at which this occurs ranges from 0.05 to 0.40 V vs. the standard hydrogen electrode (SHE). The measurement of ECSA by this method is based on the assumption that each proton is able to occupy one site on the available platinum surface, and that all sites that are active and accessible are occupied during the measurement.

The surface area is estimated using a conversion factor determined from smooth crystalline platinum surfaces, which is known to be about 210 µC cm-2 for H adsorption. The ECSA of the electrode in units of m^2g^{-1} is then calculated using the following formula:

$$ECSA = \frac{Q}{\Gamma L}$$

where Q is the integrated charge density (C cm^{-2}), Γ is the specific charge required to oxidise/reduce a monolayer of the adsorbed species (i.e. 210 µC cm^{-2}), and L is the platinum loading of the electrode (g m^{-2}). The technique can also be used to measure the surface area of platinum per unit geometrical

area of the electrode, or roughness factor, without requiring knowledge of the platinum loading L. This value is usually given in units cm^2 (Pt) cm^{-2}(electrode).

6.3.2 Stacks

As mentioned above, the evaluation of the ECSA of fuel cell electrodes inside single cells is most easily carried out by performing cyclic voltammetry. On the other hand, the assessment of the ECSA inside fuel cell stacks is much more complicated. The use of the conventional technique for ECSA measurement in single cells requires potentiodynamic control of the cell. This is impractical in a fuel cell stack, firstly because the potential of individual cells cannot be controlled independently due to the electrical connections between them and secondly because of the prohibitively long time required to measure the ECSA of each individual cell in sequence, particularly for large stacks.

Brightman et al.[6] from National Physical Laboratory (NPL) has recently reported a novel galvanostatic technique for measurement of ECSA in fuel cell stacks. The stack tests involves H2 reduction rather than H oxidation, i.e. a small negative current is applied to the fuel cell stack when N2 is flowing over the cathode and H2 flowing over the anode (100% or diluted), such that the cell potentials drift from high to low.

A short summary of this measurement technique and suggested operating parameters are presented here. However, it is strongly recommended to see the detail in the publication.

- **Stack conditioned by running the fuel cell stack at 500 mA cm-2 in H2:Air using Giantleap operating conditions (see Table 1)**
- **Turn off the load and switch the gas supply on the cathode from air to N2. Before the voltage of any cell dropped below 0.8 V, apply a fixed negative current of 5 mA cm-2 to the stack using a potentiostat and record each cell voltages with ≤ 1 s intervals.**
- **The test is complete when the voltage on all cells had dropped to 0.1 V. The charge passed in forming a monolayer of adsorbed H_{upd} is then calculated from the time taken for the cell voltage to drop from 0.4 V to 0.1 V. The accuracy of this measurement is limited by the time resolution of the stack testing equipment used.**

The magnitude of the negative current applied during the measurement is important and may significantly overestimate the ECSA value if too lower current densities are used. According to the study a current density between 2-6 mA cm^{-2}.

The potential transients obtained in the galvanostatic tests may be converted to pseudo-CV form using numerical differentiation of the potential with respect to time to give (ΔV/Δt). This is then used to calculate differential capacity (dQ/dV) using the following relationship:

$$\left(\frac{dQ}{dV}\right) \approx \frac{\Delta Q}{\Delta V} = \frac{I\Delta t}{\Delta V} \quad (2)$$

where I is the galvanostatic current density. When plotted against cell potential, a pseudo-CV is obtained which can be directly compared to a conventionally measured potentiodynamic CV (see Figure 9).

[6] *E. Brightman, G. Hinds, R. O'Malley , Journal of Power Sources 242 (2013) 244-254*

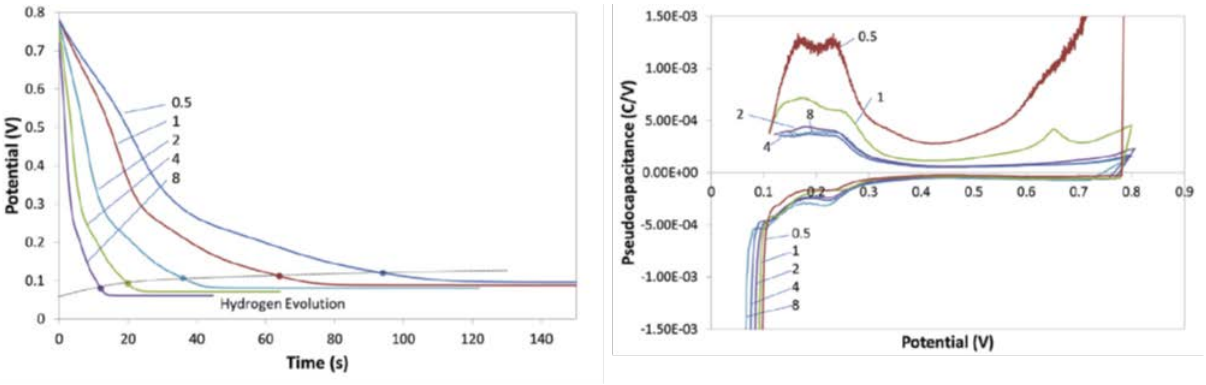

Figure 9 In-situ active area quantification on stacks [5].

6.4 Characterization of reversible vs. irreversible losses

As often reported, part of the overall voltage loss observed during cell operation, under steady state or load cycling, may be recovered upon cell shutdown and consecutive restart. It has also been reported that such an operation may lead to reduced overall degradation rate, as compared to uninterrupted (steady or dynamic) operation. This suggests that the overall voltage degradation of the cell is composed of reversible and irreversible contributions.

The recoverable part of the overall voltage loss is called reversible voltage loss ΔVrev. According to the JRC protocols[1], a fuel cell operated at (steady or dynamic operation) for a time Δti between a start-up and a shut-down, the reversible voltage loss ΔVrev,i can be calculated as the difference between the cell voltage V(ti+1) at the starting time ti+1 of the test block i+1 and the voltage V(ti+ &ti) at the ending time ti + &ti of the test block i as follows:

$$\Delta V_{rev,i} = V(t_{i+1}) - V(t_i + \Delta t_i) \quad (3)$$

The irreversible (non-recoverable) part of the voltage loss due to a test block i can be defined as the difference between the cell voltage V(ti) at starting time ti of the test block i and the voltage V(ti+1) at the ending time ti+1 of the recovery period &tri (i.e. the voltage at starting time ti+1 of test block i+1) as follows:

$$\Delta V_{irrrev,i} = V(t_i) - V(t_{i+1}) \quad (3)$$

A graphical description of reversible and irreversible contributions is given in Figure 10.

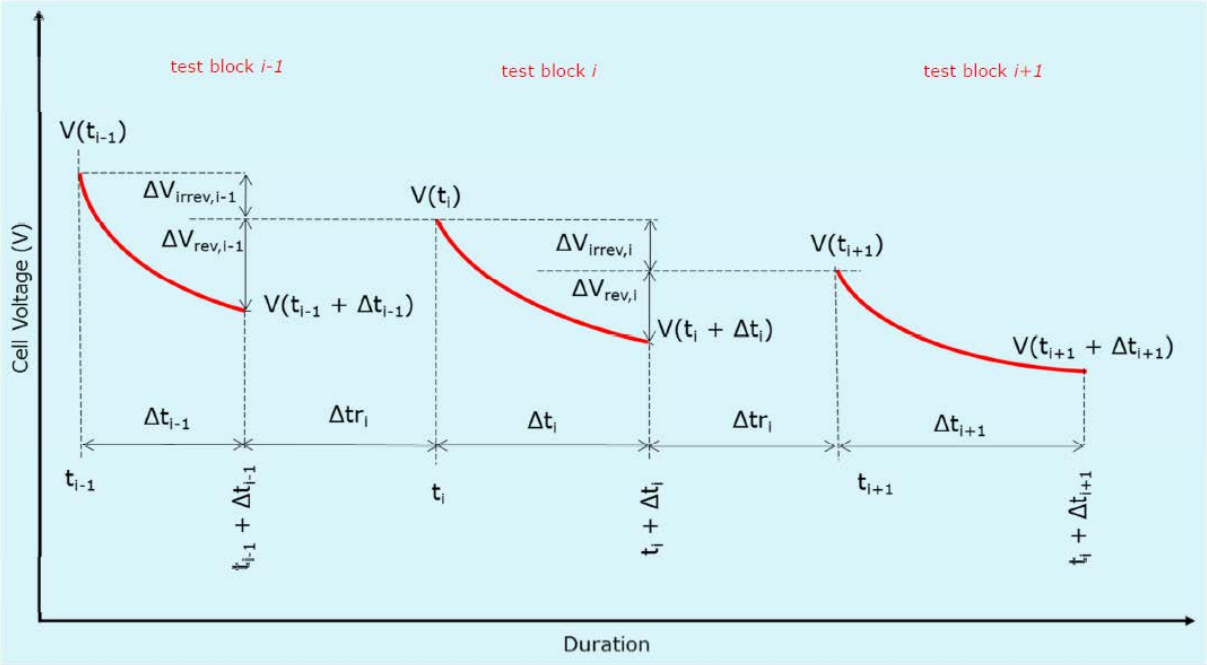

Figure 10 Quantification of reversible and irreversible fuel cell degradation according to JRC[1].

The total irreversible voltage loss ΔVirrev,1→N at EoT upon performing N test blocks in total expressed in µV is the sum of all irreversible voltage losses as follows:

$$\Delta V_{irrrev,1\to N} = \sum_{i=1}^{N} \Delta V_{irrrev,i} = V(t_i) - V(t_N)$$

The total irreversible voltage loss (degradation) rate) $V_{irr,1\to N}$ of all N test blocks can be expressed in µV per hour. It is the ratio of ΔVirrev,1→N to the sum of the duration of all N test blocks as follows:

$$\Delta V_{irrrev,1\to N} = \frac{\Delta V_{irrrev,1\to N}}{\sum_{i=1}^{N} \Delta t_i}$$

6.5 Data acquisition and sampling frequency

Table 3 shows a detailed description of all data that will be acquired, including the sampling rate during the Giantleap system testing.

Table 3: Summary of fuel cell system data sampling rates.

	Component	Internal FCCU parameter name	Description of parameter	Sampling rate [ms]
Air system	Air mass flow meter	AFS_dm	Current air mass flow	10
		HfcCoor_dmAirDes	Desired air mass flow	10
	Air compressor	AirCmpr_r	Desired air compressor ratio	10
		AirCECU_ratAirSplyAct	Current air compressor ratio	10
		AirCECU_nCmprAirSply	Current air compressor speed	10

	System components	AirPOut_p	Air pressure outlet	10
		AitTOut_t	Air temperature outlet	100
		EnvT_t	Environment temperature	100
		EnvP_p	Environment pressure	100
		AirSysBypVlv_r	Bypass valve ratio	10
		ThrVlv_r	Throttle valve ratio	10
		PurgVlv_stAct	Purge valve status	10
		DrainVlv_stAct	Drain valve status	10
	Safety	HLeakMtgtnAfs_dm	Mitigation air mass flow	100
		HLeakMtgtnBlowr_rAct	Current mitigation fan ratio	100
H2 system	System components	HTankP_p	Current H2 tank pressure	10
		HTankT_t	Current H2 tank temperature	100
		HTankVlv_r	High pressure tank valve ratio	100
		HMedPVlv_r	Medium pressure tank valve ratio	100
		HPOutPrr_p	Medium pressure	10
		HPIn_p	Current H2 inlet pressure	10
		HPOut_p	Current H2 outlet pressure	10
		HfcCoor_pHDes	Desired H2 inlet pressure	10
	HGI	Hgi_r	Desired HGI ratio stack 1	10
		Hgi2_r	Desired HGI ratio stack 2	10
	H2 concentration	H2 Env1 (CAN)	H2 concentration stack housing 1	10
		H2 Env2 (CAN)	H2 concentration stack housing 2	10
		H2 Env3 (CAN)	H2 concentration hydrogen storage compartment	10
		H2 Cathode (CAN)	H2 concentration at cathode end	10
Cooling system	System components	CooltPIn_p	Cooling pressure inlet	100
		CooltTIn1_t	Cooling temperature inlet stack 1	100
		CooltTIn2_t	Cooling temperature inlet stack 2	100
		CooltPOut_p	Cooling pressure outlet	10
		CooltTOut_t	Cooling temperature outlet	100
		AuxCoolgP_p	Cooling pressure E/E system	10
		AuxCoolgT_t	Cooling temperature E/E system	100
	Fan	Fan1_r	Fan ratio	10
		AuxCoolgFan_r	Fan ratio E/E system (optional)	10
	Water pump	CooltPmpHvB_r	Cooling pump ratio	10
		AuxCoolgPmp_r	Cooling pump ratio E/Esystem	10
	3 way valve	ERClntVlv_r	3-way-valve ratio	10
Electrical system	Low volt system	T15_st	T15 signal	10
		SftyCircIn1_stAct	Emergencency shut down input signal	10
		SftyCircOut1_stAct	Emergencency shut down output signal	10
		BattU_u	LV battery voltage	100
	High volt system	EemEcu_iStckAct	Current stack current	10
		EemEcu_uStckAct	Current stack voltage	10
		HfcCoor_pwrStckAct	Current stack power	10
Status	FCCU	HfcCoor_st	Status of the fuel cell system	10

7 Giantleap BoP component testing

The characterization of degradation patterns in critical BoP components (air compressor, air humidifier and hydrogen injection valves) will be done in later deliverable 1.3. As an early result, the procedure how to obtain the degradation pattern as well as the test procedure for the accelerated lifetime testing, the next steps are described in this deliverable 1.2 in the following chapters.

Planned working steps:

- Step 1: Analysis of components and identification of aging and failure mechanisms
- Step 2: Definition of test setup and stress profile (e.g. DIN EN 62506:2014)
- Step 3: Performance of aging and failure tests
- Step 4: Correlation to real operating conditions

7.1 Time schedule for BoP component testing

In consideration of the test bench utilization the BoP component lifetime testing for the air supply system (compressor and humidifier) is planned according to time schedule in Fig 11. The lifetime testing of the hydrogen injection valve (HGI) has already been made in recent projects.

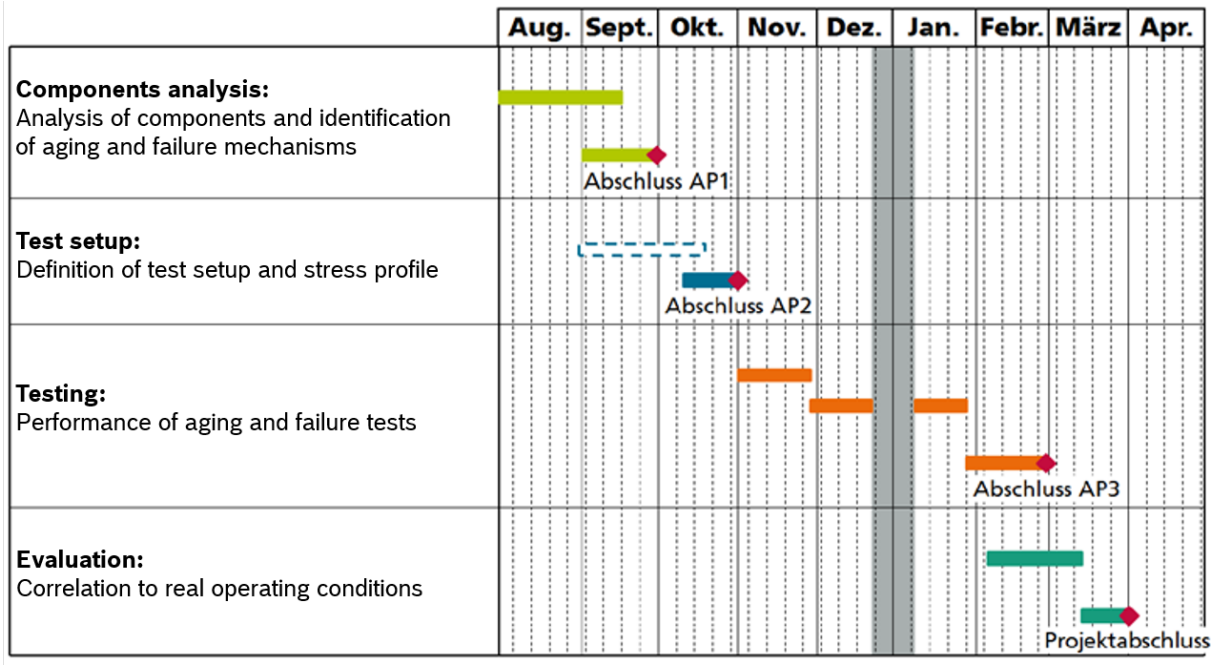

Figure 11: Time schedule for BOP component lifetime testing (air supply system)

7.2 Generic test procedures for accelerated life tests

There are different possible test methods for different phases during the product lifecycle.

In the products prototype phase typically a **HALT (Highly Accelerated Life Test)** is performed. The HALT determines a product's operating limits, identifies design weaknesses, and identifies weak

components. Figure 12 shows the assumed probability of failure for different stress factors during HALT testing of electromechanical components.

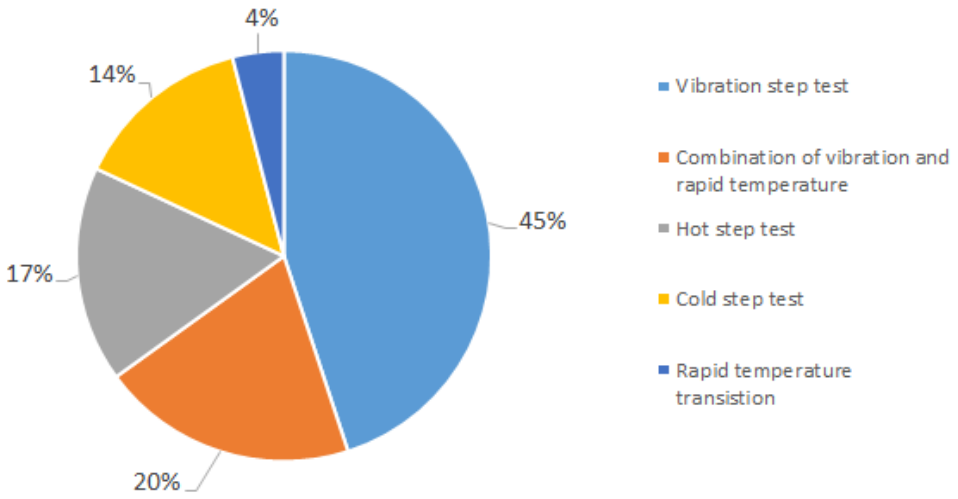

Figure 12: Assumed probabilities of failure for electromechanical components in HALT

During the manufacturing phase, typically a **HASS (Highly Accelerated Stress Screen)** is performed. The HASS is a post-production process that can be performed in a partial sample or on 100 % of the produced units. Figure 13 shows the assumed probability of failure for different stress factors during HASS testing of electromechanical components.

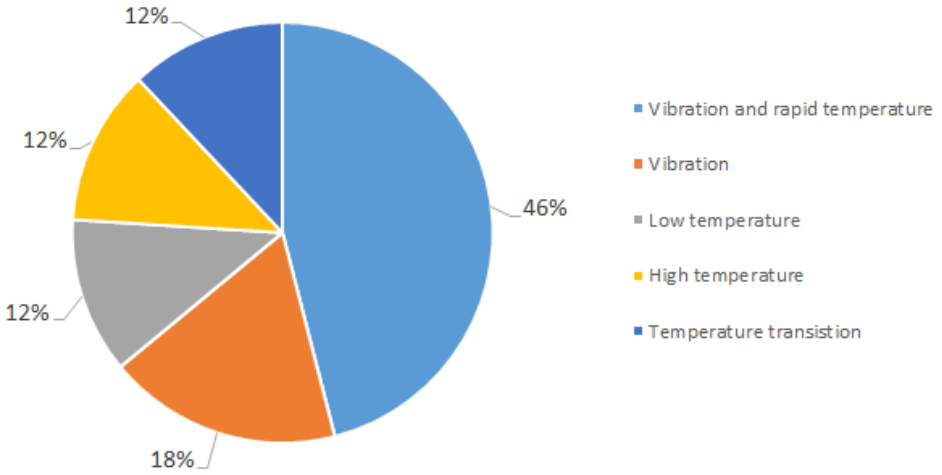

Figure 13: Assumed probabilities of failure for electromechanical components in HASS

7.3 Degradation stress factors

A first assessment and ranking of the degradation stress factor derived from the experience in component development and HALT and HASS testing for electromechanical units is shown in Figure 14. A more detailed understanding of the main degradation patterns and the most suitable stress test profile will result by the evaluation of the BoP components for deliverable 1.3.

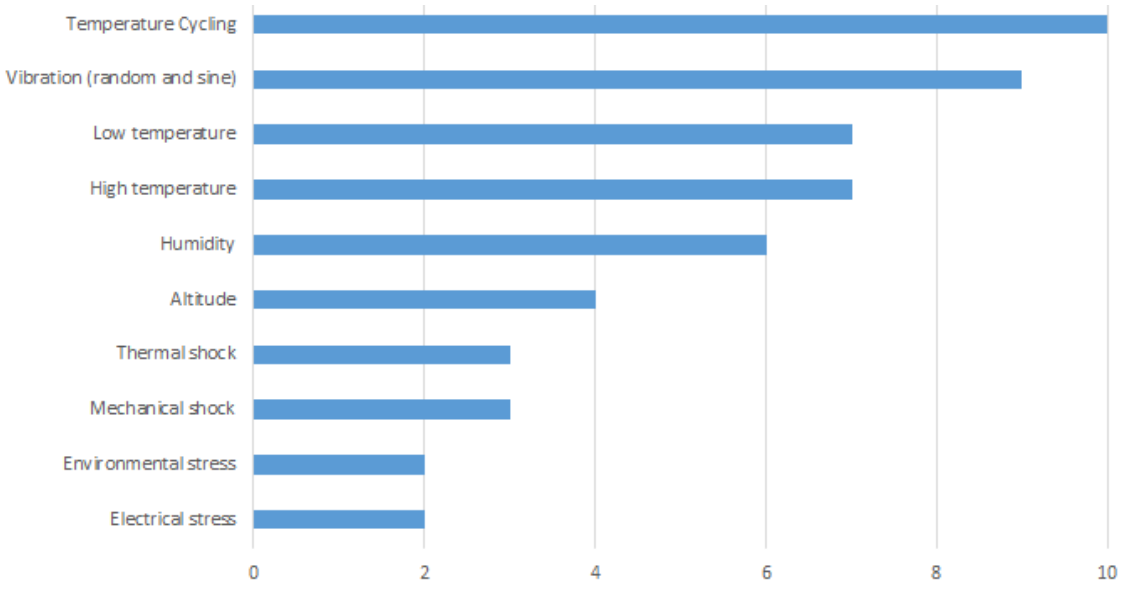

Figure 14: Ranking of expected stress factors for air supply system

7.4 Test setup for BoP component testing

In addition, a first test setup proposal for accelerated lifetime testing of the air supply system (mainly air compressor and humidifier) is shown in Figure 15. This will be further worked out in the AP2 (see time schedule Fig 11).

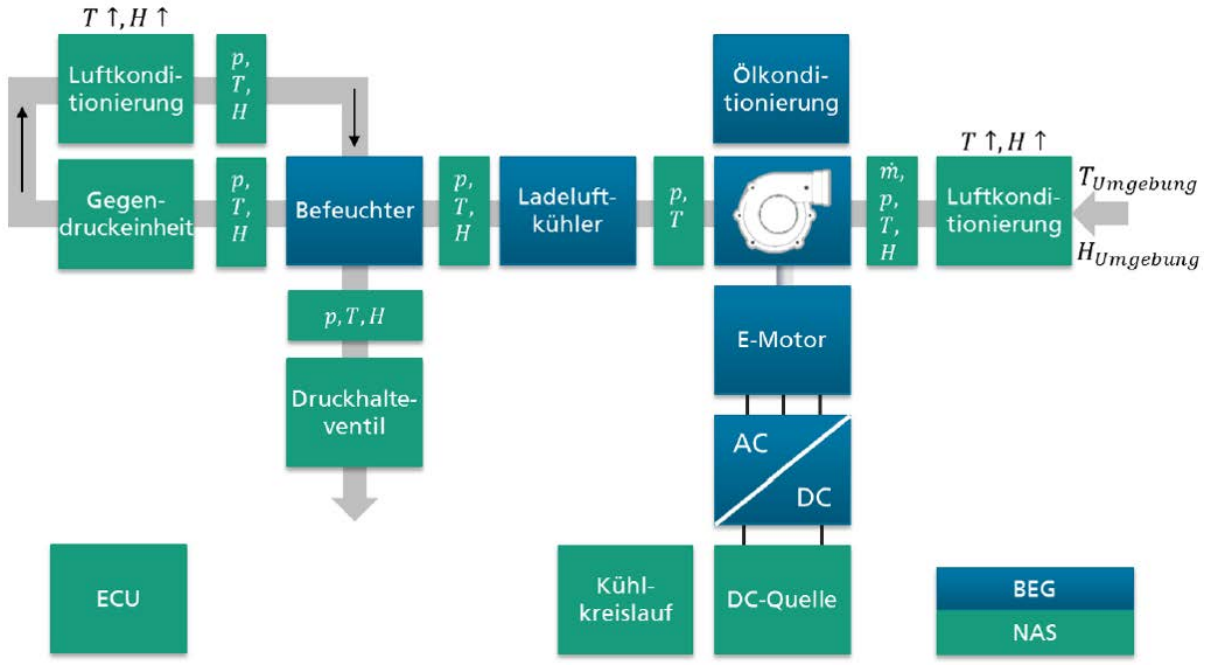

Figure 15: Test configuration for air supply system

7.5 Applicable standards, methods

The following standards – with a focus on the DIN EN 62506:2014 – will be evaluated and if applicable further considered for the definition of the stress test profile and test setup for the accelerated lifetime testing:

- DIN EN 62506:2014: Verfahren für beschleunigte Produktprüfungen
- EIA/JEDEC JESD22-A110: Highly-Accelerated Temperature and Humidity Stress Test (HAST)
- DIN EN 60749-4: Feuchte Wärme, konstant, Prüfung mit hochbeschleunigter Wirkung (HAST)
- DIN EN 60749-24: Beschleunigte Verfahren für Feuchtebeständigkeit – Hochbeschleunigte Wirkung (HAST) ohne elektrische Beanspruchung
- DIN EN 60068-2-66: Prüfung Cx: Feuchte Wärme, konstant (ungesättigter Druckdampf)