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# Long-term tests duration reduction for PEMFC $\mu$ -CHP application

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**Abstract.** Proton exchange membrane fuel cells (PEMFC) are extremely promising devices. Nevertheless some technological constraints concerning system durability and reliability costs, still limit their large-scale production. In this framework lifetime prediction and durability enhancement studies are main concerned. To solve this issue, methods based on Prognostic and Health Management (PHM) are developed. It is worth noting that these methods usually require to establish a consistent database concerning the system ageing referring to specific mission profiles. To this purpose, long-term tests are commonly performed. Among different applications, this paper will focus on two micro-cogeneration ( $\mu$ -CHP) durability tests, based on the same load demand. The first test is realized in 1,000 hours while the second one is reduced to 500 hours resulting in a compressed profile. We observed that the respective global voltage degradation rates are similar. Consequently a reflection is proposed to support accelerated tests protocol development.

**Keywords:** PEM Fuel Cell ;  $\mu$ -CHP ; Durability ; Long-term tests ; Accelerated tests ; Prognostic and Health Management.

## 1. Introduction

Proton exchange membrane fuel cell (PEMFC) appears nowadays to be a promising energy device to face energy transition challenges. Nevertheless, high cost and low durability are still the main bottlenecks for their deployment. So, research activities mainly focus on ageing characterization to enhance the system lifetime.

In this framework, new approaches based on prognostic and health management (PHM) methods [1-3] are introduced to evaluate the remaining useful life (RUL). An example of RUL prediction is given in [2], where the performance of prediction of an echo state networks is analyzed on the voltage degradation. The main objective of the PHM is to reach the FC lifespan by improving the efficiency of the system control and by supporting maintenance and recovery actions. To develop PHM algorithms, several long duration tests are required resulting into extremely time consuming and very costly procedures. Then to reduce these constraints, the development of new accelerated stress test (AST) protocols to support lifetime prediction is an open question. The main contributions available in the literature are summed up in [4]. Authors reported the main stress factors influencing the PEMFC ageing that are commonly exploited to accelerate the degradation mechanisms. From this analysis, it results that high temperature condition is a common stress factor. Moreover, in the literature, different dynamic stress conditions like relative humidity (RH) cycles, improper start and stop and sudden load variations are also used to accelerate the degradation-failure modes [4]. Nevertheless,

to be consistent with the cell components ageing induced by real load conditions the main stressors must be opportunely increased. According to [4], load cycling is the simplest mode to induce ageing acceleration. In this framework, previous studies focused on load cycles effects can be found in Bae et al. [5] and Jeon et al. [6-7] works. These authors confirmed that increasing the load variation frequency can have a deep impact in FC ageing, especially for membrane degradation [6].

In this paper the ageing effects induced by a real load profile are underlined. Their impact on system durability is analyzed by comparing the results obtained by compressing the reference cycle profile. For this purpose a first long duration test was performed during 1,000 hours. Subsequently the same load profile was scaled to 500 hours. Experimental activity is presented in the next section (2), while tests results are presented in section 3. Results analysis and perspectives for future works aimed on stack ageing acceleration are proposed in section 4.

## 2. Context and Experimental Set-up

The proposed experimental activity has been done in the framework of the French ANR project PROPICE "Prognostics and Health Management of PEM Fuel Cell Systems" [8]. The project aims at establishing a robust prognostic approach for PEMFC in order to determine the Remaining Useful Lifetime (RUL). During this project, both micro-cogeneration ( $\mu$ -CHP) and transport profiles are tested. Tests durations are fixed to 1,000 hours. This paper focus on the  $\mu$ -CHP profile tests.

## 2.1. Test bench description

A high power test bench (10 kWe), which main characteristics are given in table 1, has been used for experimental activity.

Table 1: Specifications of the 10 kW test bench

Technical Specifications		Range
Cooling circuit		[20-80]°C
Inlet gas temperature *		[20-80]°C
Inlet gas humidification (RH)*		[0-100]%
Water flow rate		[0-20]l/min
Gas flow rate	Air	[0-500]l/min
	Hydrogen	[0-100]l/min
Gas pressure*		[0-2.5]bar
Current		[0-1000]A
*Both at anode and cathode sides		

A picture representing the considered 10 kWe test bench is proposed in figure 1. Both the inlet and outlet gas properties are controlled, such as their flow rate, pressure, temperature and humidification. All the operating variables concerning fluids (1), electrical (2) and thermal flows (3) are recorded at a 1 Hz acquisition frequency all along the test by National Instruments™ platform (3).

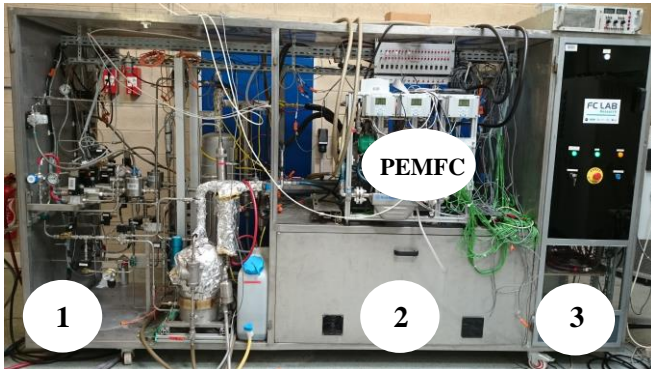


Figure 1: 10 kW test bench

The gas flows, the cooling system and the electrical connections are schematized in figure 2, together with the different sensors locations. For a better understanding the sensors' list is reported in table 2.

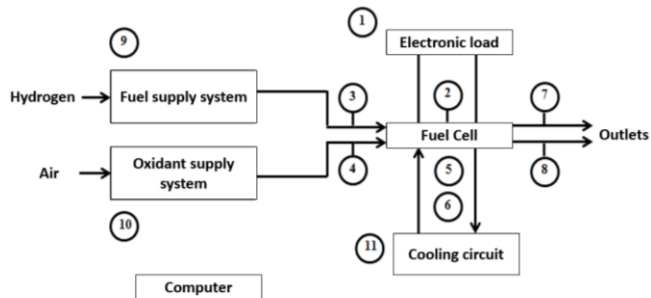


Figure 2: Locations of the different sensors on the test bench

Table 2: Sensor list

Measurements	Sensor
Current (I)	1
Stack voltage (V)	2
Cell voltages ( $V_n$ )	2
Stack temperature ( $T_{Seau}$ )	6
Hydrogen inlet temperature ( $TH_{2in}$ )	3
Hydrogen outlet temperature ( $TH_{2out}$ )	7
Air inlet temperature ( $T_{Airin}$ )	4
Air outlet temperature ( $T_{Airout}$ )	8
Hydrogen inlet relative humidity ( $HRH_{2in}$ )	3
Hydrogen outlet relative humidity ( $HRH_{2out}$ )	7
Air inlet relative humidity ( $HR_{Airin}$ )	4
Air outlet relative humidity ( $HR_{Airout}$ )	8
Hydrogen inlet pressure ( $PH_{2in}$ )	3
Hydrogen outlet pressure ( $PH_{2out}$ )	7
Air inlet pressure ( $P_{Airin}$ )	4
Air outlet pressure ( $P_{Airout}$ )	8
Pressure drop ( $\Delta P$ )	3-4
Hydrogen inlet flow rate ( $DH_{2in}$ )	3
Air inlet flow rate ( $D_{Airin}$ )	4
Water flow rate (Deau)	5

## 2.2. PEMFC Stack Specifications

Two 8-cells' PEMFC stacks of 1 kWe power are used for experimental activity; one for each test. The nominal specifications of the considered stacks are given in the table 3.

Table 3: 8-cell PEMFC nominal specifications

Specifications	Value
Active area	220 cm <sup>2</sup>
Dimensions	220 x 160x 186
Cooling (water) flow rate	2 l/min
Anode/cathode stoichiometry	1.5/2
Anode/cathode inlet pressure	150/150 kPa
Pressure drop *	30 kPa
Temperature	80°C
Relative humidity anode/cathode	50/50 %
Current density	0.5 A/cm <sup>2</sup>
*Both at anode and cathode sides	

## 2.3. Long duration (1,000 hours) test

The experimental profile proposed in this section and illustrated in figure 3 is based on on-field measurements performed within the framework of a demonstration project where, Electricity of France (EDF) was partner [9]. The reported  $\mu$ -CHP load profile simulates the behavior of a stationary PEMFC application during a complete year. Consequently the resulting load profile is obtained by combining in series 4 sub-period of 250 hours; one for each

1 season. The specific PEMFC utilization (power demand) is  
2 linked to each of them as reported below.

- 3 - *Winter*: Steady state operating conditions at the  
4 maximal power demand for a period of 250 hours.
- 5 - *Spring* : composed by 2 steps  
6 1. Load cycling [5 cycles; 1 cycle per day] by  
7 alternating maximal power and half power  
8 operating conditions.
- 9 2. Steady state operation at the half power  
10 demand for a period of 120 hours.
- 11 - *Summer*: Duty cycle [11 cycles; 1 cycle per day] of  
12 which 12 hours at half power and 12 hours at Open  
13 Circuit Voltage (OCV). During OCV, the current  
14 value is closed to zero and gases are supplied at low  
15 flow rates.
- 16 - *Autumn* : similar to spring but reversed  
17 1. Steady state at half power conditions.  
18 2. Load cycling [5 cycles; 1 cycle per day].

19 During the test, both the polarization curves and the  
20 electrochemical impedance spectra (EIS) at low, mean and  
21 high current values are measured once a week. The same  
22 measurements are performed at the beginning and at the  
23 end of the test.

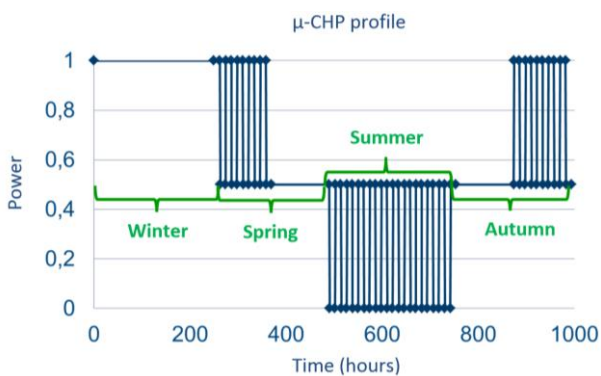


Figure 3:  $\mu$ -CHP profile given in power versus time

#### 28 2.4. Reduced (500 hours) test

29 The 500 hours ageing test is obtained by scaling in time  
30 domain the  $\mu$ -CHP load profile applied for long duration  
31 test. In the load profile compression procedure, the load  
32 variation conditions and, in particular the ramps assumed to  
33 switch the different load values are kept the same as in the  
34 original profile, accordingly to stack dynamic limitations.  
35 On the contrary the sub-periods related to the steady state  
36 conditions are reduced as reported below. The new  
37 compressed profile is still composed by four sub-periods  
38 (seasons).

- 39 - *Winter*: 125 hours at the maximal power.
- 40 - *Spring*: 5 cycles (2 per day) between the maximal  
41 power and the half power and 60 hours in steady state  
42 conditions at the half power value.
- 43 - *Summer*: 11 duty cycles (2 per day) with 6 hours at half  
44 power and 6 hours at OCV.

- 45 - *Autumn*: 60 hours at half power and 5 cycles between  
46 the half power and the maximal power.

47 During the test a new PEMFC stack of the same technology  
48 is used (c.f. table 3). Measurements are scheduled at the  
49 end of each sub-periods.

### 50 3. Experimental Results

51 To perform the experiments, the power demand profile  
52 shown in figure 3 is translated into a current density  
53 profile.

#### 54 3.1. Long-duration test results

55 The resulting load profile obtained for the 1,000h ageing  
56 test is shown in figure 4, while the corresponding stack  
57 voltage response is given in figure 5.

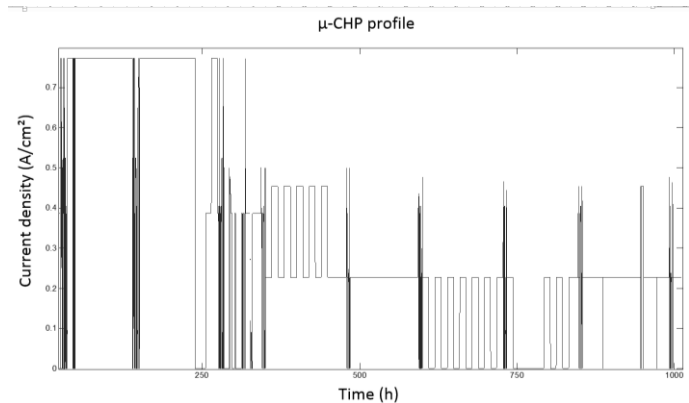


Figure 4: 1,000 hours  $\mu$ -CHP load profile

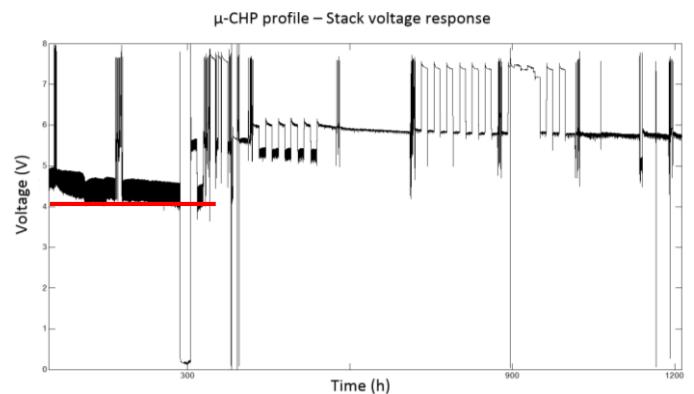
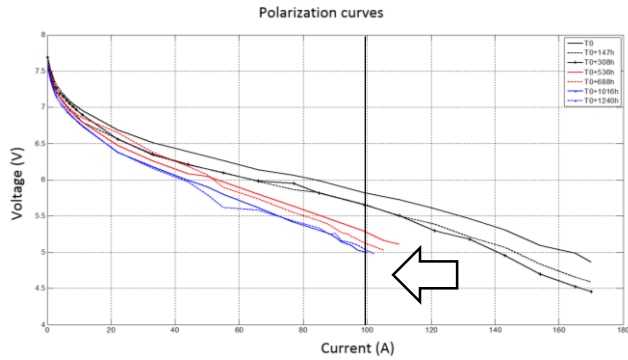


Figure 5: Stack voltage response (1,000h test)

62 It is possible to observe that the maximal power condition  
63 is associated to an initial current density value of 0.77  
64 A/cm<sup>2</sup>, while the half power state corresponds to 0.38  
65 A/cm<sup>2</sup>. As a first result, the maximal power operations  
66 severely affected the system performance during the winter  
67 sub-period, resulting in a stack critical voltage drop, as  
68 shown in figure 5. The stack voltage response decreases  
69 under the warning level (red line in figure 5).  
70 Consequently to perform the whole test, the current density  
71 values corresponding to the maximal and half load modes  
72 were changed. The new ones are fixed to 0.45A/cm<sup>2</sup> and  
73  
74  
75

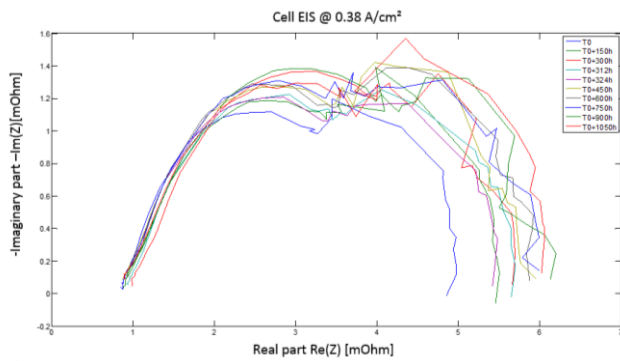
1 0.23 A/cm<sup>2</sup>, respectively. As a consequence, the limits for  
 2 the polarization curve measurements are changed as shown  
 3 in figure 6. Afterwards, the 3 reference values considered  
 4 to perform the EIS measurements are also changed,  
 5 resulting: 0.09, 0.23 and 0.38 A/cm<sup>2</sup>.

6 The impact of ageing on the polarization curves is  
 7 presented in figure 6, where their evolutions are reproduced  
 8 at different steps of the reference load profile.  
 9



10  
 11 Figure 6: Ageing impact on the polarization curves (1,000 hours  
 12 test)  
 13

14 Figure 7 represents the EIS curves evolution with ageing  
 15 for a current density value of 0.38 A/cm<sup>2</sup>. A frequency  
 16 range comprised between 5 kHz and 100 mHz is  
 17 considered for measurements. The spectra evolution  
 18 underline a sensible growth of both activation and diffusion  
 19 losses, in accordance with the polarization curves evolution  
 20 presented in figure 6.  
 21



22  
 23 Figure 7: Ageing impact on the EIS measurements (1,000 hours)  
 24

25 For a better evaluation of the voltage degradation, the  
 26 voltage drop is given depending on the time, in table 4.  
 27 Values are evaluated at the same current density value of  
 28 0.38 A/cm<sup>2</sup>. After 1,016h of operation a global voltage  
 29 degradation rate of 597 μV/h is observed for the whole  
 30 stack, corresponding to 75 μV/h/cell. The partial  
 31 information at 147, 308, 536 and 688h are also reported to  
 32 compare the voltage degradation rate during the different  
 33 sub-periods.  
 34

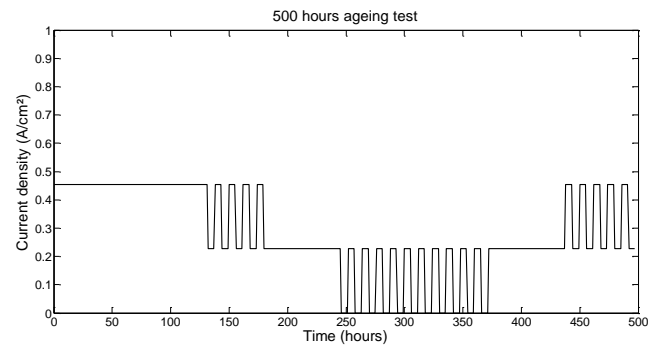
35 Table 4: Degradations of the 8-cell stack @ 0.38A/cm<sup>2</sup>

Time	Degradation (μV/cell/h)
[T0 ; T0+147h]	170
[T0 ; T0+308h]	81
[T0 ; T0+536h]	116
[T0 ; T0+688h]	109
[T0 ; Tend]	75

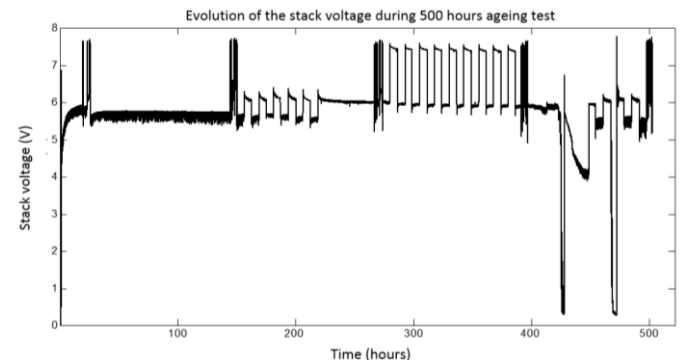
36

### 37 3.2.Reduced test results

38 The current density profile of the 500 hours experiment is  
 39 reported in figure 8, while the corresponding stack voltage  
 40 is given in figure 9. A maximal current density of 0.45  
 41 A/cm<sup>2</sup> is considered and a value of 0.23 A/cm<sup>2</sup> is  
 42 considered for the half load conditions. So it is worth  
 43 underlining that the current densities values considered in  
 44 both 1,000 hours and 500 hours profiles are the same,  
 45 except for the winter steady state conditions. Finally, the  
 46 same metrics proposed in the previous paragraph are  
 47 considered.  
 48



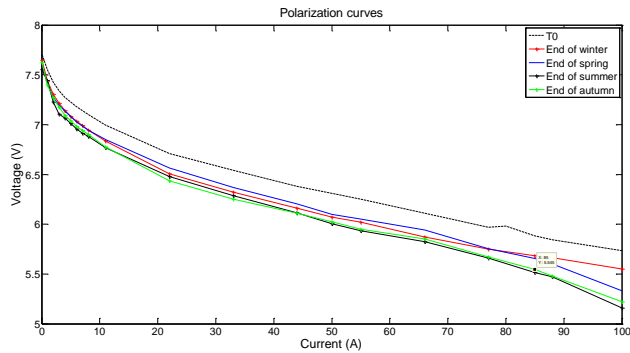
49  
 50 Figure 8: 500 hours μ-CHP load profile  
 51



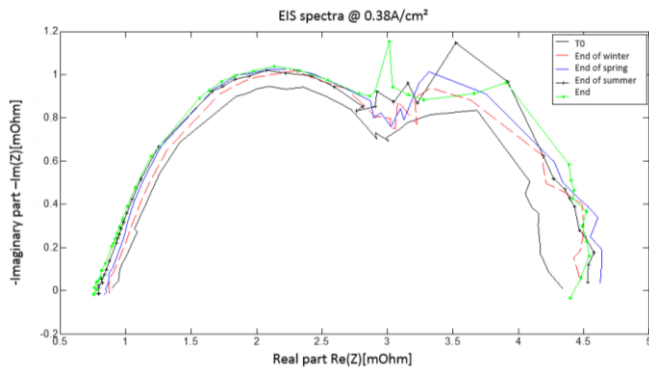
52  
 53 Figure 9: Stack voltage response (500 hours test)  
 54

55 Figure 10 illustrates the evolution of polarization curves  
 56 during the 500 hours, while EIS evolutions at 0.38 A/cm<sup>2</sup>  
 57 are shown in figure 11. Comparing figure 6 and 10, we  
 58 observe that the polarization curve obtained at 500 hours  
 59 in the case of the long duration test (red curve in fig.6) is  
 60 quite similar to the polarization curve measured at the end  
 61 of the 500 hours test (green curve in fig.10). While  
 62 considering the impedance spectra acquired at 0.38 A/cm<sup>2</sup>  
 63 both in long-duration and reduced test (fig. 7 and 11), we

1 observe that the same performance losses (activation and  
 2 diffusion) are influenced. Losses intensity are lower in case  
 3 of the reduced duration test, but this comportment can be  
 4 due to the fact that comparing the first spectra at T0 the  
 5 second stack shows the best behavior.  
 6



7  
 8 Figure 10: Ageing impact on the polarization curves obtained  
 9 during the reduced test (500 hours)



11  
 12 Figure 11: Ageing impact on the EIS measurements  
 13

14 As for long duration test, the voltage drop versus time is  
 15 reported in table 5. After 500 hours of operations, a voltage  
 16 degradation rate of 611  $\mu\text{V/h}$  is observed for the whole  
 17 stack, corresponding to 76  $\mu\text{V/h/cell}$ . The information at  
 18 the end of each season are also reported to compare the  
 19 voltage rate variation during the different sub-periods. The  
 20 global voltage degradation rate in both the tests is similar.  
 21 This point is consistent with the polarization curve  
 22 similitude at 500 hours. For more details, a deeper analysis  
 23 is presented in the next section.  
 24

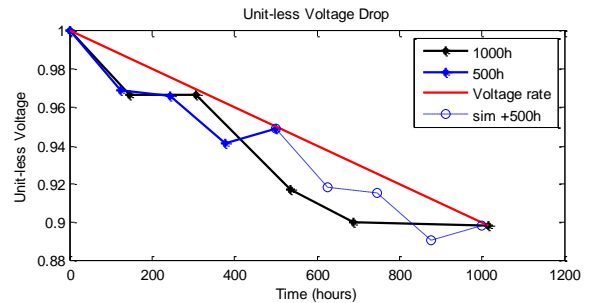
25 Table 5: Degradations of the 8-cell stack @ 0.38A/cm<sup>2</sup>

Time	Degradation ( $\mu\text{V/cell/h}$ )
[T0 ; T0+125h]	184
[T0 ; T0+245h]	103
[T0 ; T0+377h]	116
[T0 ; Tend]	76

## 28 4. Results Analysis and Suggestions

29 Results reported in paragraphs 3.1 and 3.2 exhibit the  
 30 impact of load cycle profile in system ageing. Tests  
 31 performed both at 1,000 and 500 hours mainly show that  
 32 even if the test duration is reduced, the global voltage  
 33 degradation rate is the same.

34 The results reported in tables 4 and 5 underline that steady  
 35 state conditions at high current density have an initial deep  
 36 impact on voltage degradation. Nevertheless this effect  
 37 seems to be partially recovered during the spring sub-  
 38 period. It is important to notice that data presented in tables  
 39 4 and 5 are obtained for the same current density value of  
 40 0.38 A/cm<sup>2</sup>. This can explain the similar voltage rate values  
 41 obtained in case of high load condition in both the tests.  
 42 Indeed, if long duration test response showed a critical  
 43 voltage drop (see fig. 5), this phenomenon was mainly due  
 44 to the high current density impact on voltage degradation.  
 45 Nevertheless, this effect was mainly reversible and then, it  
 46 was recovered by performing the polarization curve.  
 47 Consequently a similar voltage degradation rate can be  
 48 observed at 0.38 A/cm<sup>2</sup> in both tests. Moreover by  
 49 analyzing the voltage rate behavior during the different  
 50 seasons' sub-periods it is possible to state that summer load  
 51 variations (between OCV and half load values) also have  
 52 an important impact, while during spring and autumn sub-  
 53 periods a partial recovery is observed. To have a better  
 54 understanding, the unit-less voltage drops evaluated at 0.38  
 55 A/cm<sup>2</sup> are presented in figure 12. The voltage drop values  
 56 are normalized with respect to the reference voltage value  
 57 measured at  $j=0.38 \text{ A/cm}^2$  and  $t=T_0$ . The red line in figure  
 58 12 represents the global voltage degradation rate. We can  
 59 observe that at the end of both tests, the related voltage  
 60 drops are closed to this line. The voltage degradation rate  
 61 increasing and partial recovery are represented by the black  
 62 (1,000h) and blue (500 hours) full-lines' slope variations.  
 63 The light blue circled-line indicates the probable  
 64 (simulated) voltage degradations obtained in case of the  
 65 500 hours profile repetition. This line is proposed to  
 66 underline the voltage rate conservation. Indeed in case of  
 67 real ageing the effects induced by adding a second 500  
 68 hours cycle could not be linear, inducing a global voltage  
 69 rate variation.  
 70



71  
 72 Figure 12: Unit-less voltage drop and degradations' rate  
 73 comparison for 1,000h and 500 hours tests  
 74

1 For a long duration test of 1,000 hours, the stack operates  
 2 at quite long stationary conditions. These operations induce  
 3 both irreversible and recoverable voltage losses. In case of  
 4 500 hours test, the steady state conditions durations are  
 5 reduced, while the load variation are kept the same. This  
 6 procedure seems to conserve the global voltage degradation  
 7 rate, suggesting that load variations and OCV conditions  
 8 are the main stressing factors for irreversible degradations.  
 9 Nevertheless, accelerating the cell ageing means increasing  
 10 the voltage degradation rate. Consequently, the results  
 11 presented in this work do not represent an accelerated test  
 12 but characterize an important support in AST procedure  
 13 development.

14 For a better understanding, future studies will be oriented  
 15 to check the real impact of stationary conditions duration in  
 16 voltage degradation with respect to the load dynamics.  
 17 Only quantifying this contribution will be possible to  
 18 evaluate if in case of load variations, the steady state  
 19 duration can be neglected in voltage degradation rate  
 20 evaluation. This information will be fundamental in AST  
 21 procedure development, indicating the limit conditions to  
 22 respect in steady state duration reduction during the test.  
 23 Subsequently the ageing acceleration and then the voltage  
 24 degradation rate growth will be induced stressing the load  
 25 variation conditions. For this purpose, a first suggestion is  
 26 to increase the number of load variation repetitions  
 27 proportionally to the reference cycle dynamics. This  
 28 procedure can be also implemented by increasing the  
 29 reference load cycle frequency, which means accelerating  
 30 the real load dynamics. These considerations are in  
 31 accordance with AST works presented in [4-7]. These  
 32 proposals will allow the development of a suitable AST  
 33 procedure able to link accelerated and real ageing  
 34 consistently with real load profile dynamics. Therefore it  
 35 will be finally possible to reduce the actual test duration  
 36 and costs for durability analysis and lifetime prediction  
 37 application.

## 38 5. Conclusion

39 This paper presents French ANR project PROPICE  
 40 experimental results. Two ageing tests are proposed. The  
 41 first one is a long duration test of 1,000 hours, developed  
 42 for simulating a  $\mu$ -CHP load demand profile for a complete  
 43 year. Effects of long duration stationary conditions, OCV  
 44 operations and sudden load variations are analyzed. The  
 45 second test of 500 hours reproduces the same load profile  
 46 scaled in time domain. The effects of the long-term test  
 47 duration reduction on voltage decay are then analyzed. A  
 48 similar voltage degradation rate is observed at the test end  
 49 in both cases. Moreover, the partial voltage drops analysis  
 50 suggests that it is possible to induce similar voltage decays  
 51 by reducing the steady-state operations' duration and  
 52 considering the same load variations. These results are then  
 53 assumed to be a key point to propose new methods to  
 54 reduce long duration tests by increasing the real load cycle  
 55 frequency.

56  
 57

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 61 *realization of this work and the corresponding*  
 62 *experimental campaigns.*

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