Accelerated stress tests impacts on short PEM fuel cell stacks

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***Abstract*— The durability and the reliability of fuel cells are key points to promote hydrogen. To increase the fuel cell system lifetime, diagnostic, prognostic and smart control approaches are developed by researchers. They allow detecting failures, forecasting the remaining useful lifetime and act on the system through sensors to face degradation. Nevertheless, as the ageing of the FC stack is slow, some long-term tests are needed. The aim is to develop accelerated stress tests to reduce expensive and time-consuming experiments to validate durability approaches. This paper is dedicated to studying three different experimental tests on proton exchange membrane fuel cells (PEMFC) and the degradation impact of two stress factors: the frequency and the magnitude**

I. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) have been extensively studied for several decades as hydrogen fuel is considered a promising alternative to fossil fuels [1]. PEMFCs can be used in both transportation and stationary applications [2]. However, large-scale deployment remains limited due to the restricted lifetime and reliability of PEMFC systems [3]. Therefore, ensuring better efficiency, reliability, and longer lifetime for these systems is essential and can be achieved through optimal operating conditions. Several studies have demonstrated how diagnostic approaches could help maintain nominal operating conditions by quickly detecting, isolating, and identifying faults affecting the fuel cell system and its ancillary components. The main causes of faults are linked to water, gas, and temperature management, leading to flooding, drying, fuel starvation, cooling failure, and CO poisoning [4–7]. These faults can be categorized into two groups: reversible and irreversible. Reversible faults refer to performance losses that can be recovered once the underlying issue is resolved. Conversely, irreversible losses correspond to permanent damage that deteriorates the performance of the fuel cell over time. Another approach to evaluating system degradation is prognostics. Prognostic algorithms aim to estimate the Remaining Useful Lifetime (RUL) of the fuel cell system [8–9]. Depending on the application, the Time to Failure (TTF) or the RUL varies. For transportation applications, the Fuel Cell Technical Team (FCTT), which defines goals and performance targets for automotive fuel cells, has set a durability target of 8,000 hours (equivalent to 150,000 miles or 240,000 km) for 2025, with less than 10% loss of performance [10]. This objective aims to make transportation fuel cell systems competitive with internal combustion engines (ICEs) and other alternative technologies. The target includes 17,000 start/stop cycles, 1,650 freeze cycles, and 1,200,000 load cycles [11]. Studying the reliability of PEMFCs requires long-term operation, commonly referred to as ageing tests. These test procedures are expensive, as they require fuel and continuous monitoring over prolonged periods. Two approaches are typically used for long-duration tests: operation under a constant load or under a dynamic load profile. Under constant load conditions, the steady-state degradation rate ranges from 2 to 10 µV/cell/h [12]. However, under dynamic load profiles, such as start/stop phases or load cycling, PEMFC degradation is significantly higher (25 µV/cell per start/stop cycle [12]). To address the high costs and time requirements of ageing tests, Accelerated Stress Tests (ASTs) have emerged as a viable alternative. ASTs provide a means to validate reliability and durability algorithms developed to extend fuel cell lifetime without requiring thousands of hours of operation. These tests are also beneficial for evaluating new materials for fuel cell components. In the context of ASTs, almost all degradation rates exceed 10 µV/cell/h [12].

The novelty of this work lies in the implementation of AST protocols at the stack level, rather than on single components, which remains rarely addressed in the literature. This study proposes a methodology to evaluate the collective impact of frequency and magnitude variations on short-stack degradation patterns, integrating system-level interactions between cell components. While standardized AST procedures for individual components (membrane, catalyst, gas diffusion layers) are established [10,13], few studies have extended these protocols to entire PEMFC stacks. This paper contributes to bridging that gap by examining degradation heterogeneity across multiple cells under dynamic load stressors. The development of standardized AST procedures at the stack level represents a significant challenge in PEMFC research. The US Department of Energy (DoE) [10] and the European Joint Research Centre (EU JRC) [13] are working on harmonized experimental procedures and standard AST protocols for PEMFCs. While standardized AST procedures for individual cell components already exist [10,13], the next step is to define AST protocols at the cell and stack levels.

To move towards the development of accelerated tests for PEM fuel cells, it is essential to consider all their

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components (membrane, catalyst layer, gas diffusion layer, bipolar plates, and entire cells) as a whole rather than individually. When evaluating the entire fuel cell, individual component degradations are not entirely independent, and overall cell degradation cannot be viewed as a simple sum of single-component failures. Interactions between components and parameter variations must be accounted for, as degradation in one component can propagate to others. Some recent studies have investigated stress factors affecting voltage uniformity under dynamic loading [14], such as the number of cycle repetitions [15–16], variations in load frequency, and load step changes. However, these studies often focus on specific load profiles or single-cell tests, without addressing stack-level interactions or comparative protocol analysis. This study examines the influence of two critical stress factors—load profile frequency and magnitude—on PEMFC performance at the stack scale, using three distinct and reproducible experimental profiles. The originality of the work lies in its comparison of dynamic AST protocols using identical stack configurations and MEAs, allowing us to isolate the effects of each stressor on degradation behavior.

This paper is structured as follows: first, we outline the experimental setup and testing methodology employed to induce and monitor stress-related degradation. Next, we analyze the results obtained, highlighting critical degradation pathways and performance losses. Finally, we discuss the implications of our findings in the broader context of fuel cell diagnostics and lifetime enhancement strategies. By providing a comparative degradation assessment under different stress conditions, this work strengthens the rationale for stack-level AST standardization. It contributes to the development of more robust and cost-effective PEMFC systems for future clean energy applications.

II. EXPERIMENTAL TESTS CAMPAIGN

A. PEMFC specifications

Three PEMFC short-stacks are used to perform experimental data. They are each composed of 5-cells with a 100cm² active area. Nevertheless, the membrane-electrode assemblies (MEA) are not all the same. Stack 1 is a rainbow stack with 3 different types of MEA whereas stack 2 and 3 are 'classical' ones with only one type of MEA. The outlet temperature is set to 70°C. The objective of the experimental data plan is to observe the degradation of the fuel cell in response to a dedicated cycling profile. This will be followed by an observation of the degradation of the fuel cell with a higher cycling frequency and higher power amplitude. Anode and cathode gas are fed in counter-flow with the cooling flow in co-flow direction to cathode gas. The Table 1 presents stack specifications.

I. TABLE I PEMFC SHORT-STAKCS SPECIFICATIONS

	Stack 1	**Stack 2**	**Stack 3**
Cathode (gas and coolant inlets and outlets)			
Cell 5	MEA#1	MEA #3	MEA #1
Cell 4	MEA #2	MEA #3	MEA #1
Cell 3	MEA #3	MEA #3	MEA #1
Cell 2	MEA #3	MEA#3	MEA #1
Cell 1	MEA #3	MEA #3	MEA #1
Anode			

B. Reference test – Profile 1

Two experiments with the same operating conditions were performed to investigate the time-dependent behavior of stack performance. The operating conditions were derived from the operation of the combined heat and power system. The current density values are derived from a one-day profile of a stationary CHP system. For the duration test, two 5-cell stacks were operated with varying current densities and dwell times of some hours to reach quasi-stationary operation. The reference profile is based on a micro combined heat and power daily profile. The current load is based on the consumption of heat and power per hour (cf. Figure 1). Concerning the duration of the test, 2,000 hours are considered for all durability tests. This stack was cycled per day leading to less current, for a total duration of 2,155 hours, including cycling and in-situ characterizations.

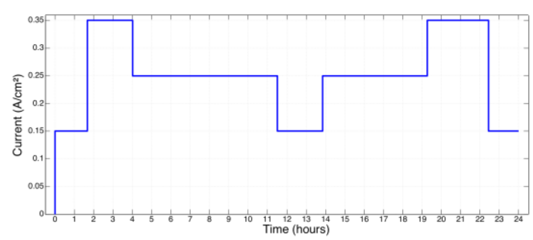


Figure 1: Current density profile of the reference test protocol

C. High frequency stress test – Profile 2

The second stack was cycled with 10 cycles per day (same cycle shape as defined for the reference profile) during 1,781 hours. The daily cycle is given in the Figure 2.

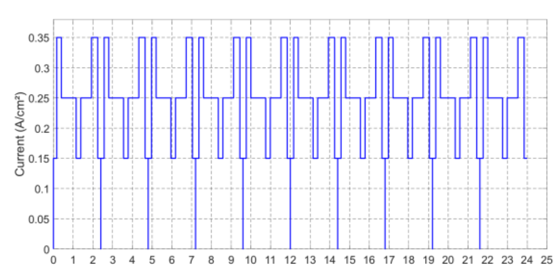


Figure 2: Current density profile of the high frequency stress test protocol

D. High frequency and amplitude stress test – Profile 3

The third stack was cycled with 10 cycles per day with all amplitudes multiplied by 2 during 800 hours. The main objective of this test is to evaluate the impact of amplitude combined with frequency on the fuel cell degradation. The daily cycle is given in the Figure 3.

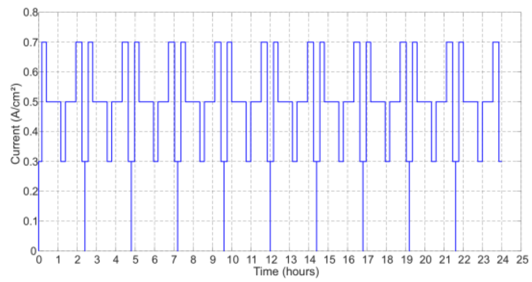


Figure 3: Current density profile of the high frequency and magnitude stress test protocol

The Figure 4 resumes the three load profiles tested on short 5-cell stacks with the effect that is studied.

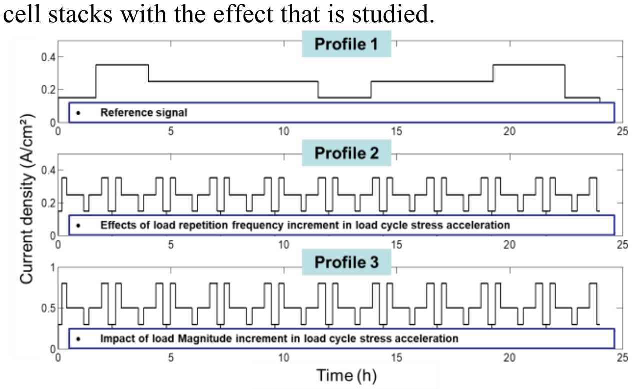


Figure 4: Three profiles tested on short-stacks

E. Characterizations

The characterization phase is composed of:

1. A polarization curve
2. EIS at the lowest current density: 0.15 A/cm² (profiles 1 & 2) or 0.30 A/cm² (profile 3)
3. EIS at the middle current density: 0.25 A/cm² (profiles 1 & 2) or 0.50 A/cm² (profile 3)
4. EIS at 0.35 A/cm² (profiles 1 & 2) or 0.70 A/cm² (profile 3)

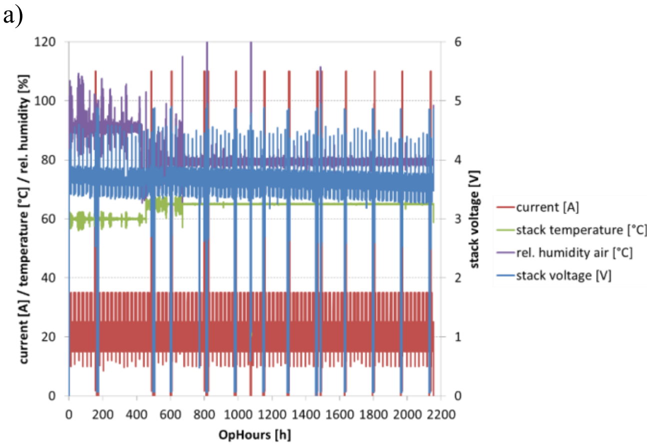
The characterization phase will be realized in one day between 8 AM and 7 PM every 7 days, the first one realized at t=0. For EIS, the frequency range considered is comprised between 5 kHz and 100 mHz. For the polarization curve, the step time is 15 minutes using a stability criterion of ±5 mV for the last 5 minutes based on the average cell voltage. At low current densities, under a minimum gas flow corresponding to 20% of nominal (0.66 A/cm²), the hold time is reduced to 1 minute to avoid stack damage by dry out and/or degradation. For the same purpose, OCV hold time should be reduced to 5 seconds. Subsequently, the current density is stepwise increased to the maximum to determine the ascending polarization curve measured with increasing electrical power output.

III. Durability tests results

A. Reference profile - Profile 1

Due to the regular current cycling the stack voltage is decreasing. For comparison of profiles, the degradation rate is calculated in two different ways. Firstly, the single cell voltage levels at a mid-current density (0.25 A/cm²) during duration profile are regarded. The reference time represents the cycling duration of 1,537h. Secondly, the decrease of voltages at a current density of 0.22 A/cm² (polarization curve set point) is calculated over the total experiment time. The characterization time is included in the second type of averaging. The first stack is a rainbow stack. The average degradation rate of cells including MEA#3 is 14.3 / 14.9 µV/h (calculated during duration profile / polarization curve respectively). The cell voltage with MEA#2 is decreasing more slowly. The cell including MEA#1 is decreasing faster, but still within the same magnitude. The voltage decays calculated using duration profile and polarization curve data are almost the same, as both operating conditions are comparable and overall non-degrading. On EIS (see Figure 5b), we observe that the high frequency resistance (HFR) changes insignificantly over the total experiment time. The low frequency resistance (LFR) shifts steadily to higher values. The LFR increases from 803h to 1,795h by 2.7-6%. Figure 5 presents the experimental results.

a)



b)

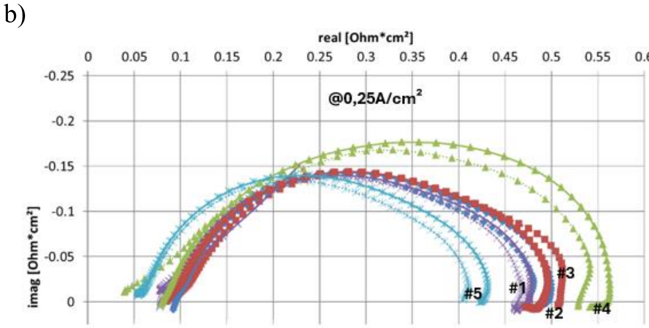


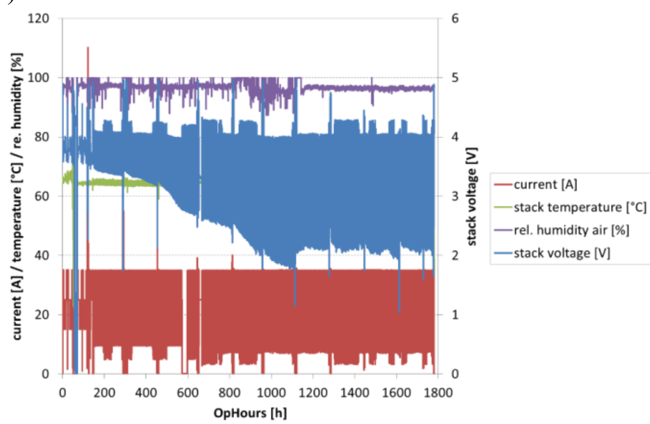
Figure 5: a) Long-term test results for the reference profile b) EIS results

B. High frequency stress test – Profile 2

Figure 6 shows the total duration of 1,781h excluding conditioning time. For the first 151 operating hours, the stack was cycled with one cycle per day as for the reference profile.

Then, the following 1,630 hours, it was cycled with a higher current frequency. The profile was 10 times more intensive. The performance of cell 5 decreased significantly with the first 650 operation hours. Cell 4 revealed the same performance loss within the first 1,000 operating hours. The degradation of cells 1 to 3 was less significant.

a)



b)

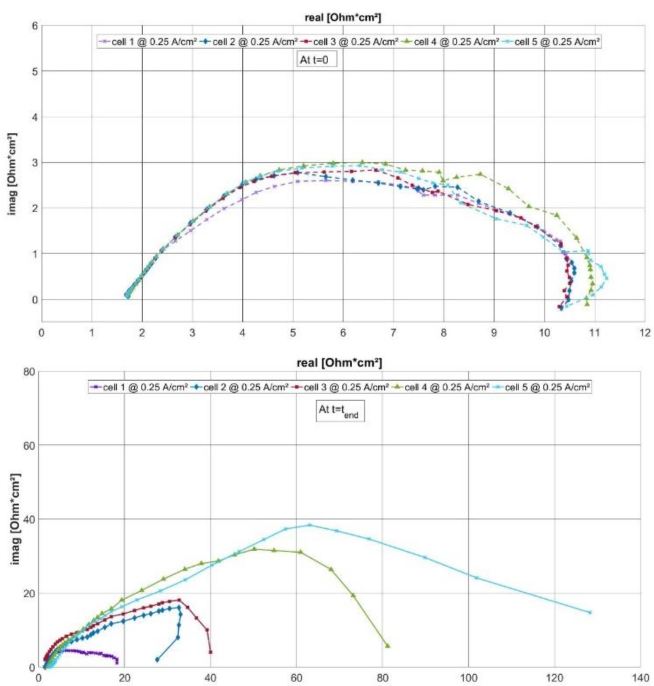


Figure 6: a)Long-term test results for the high frequency stress test b) EIS results

Two cells within the 5-cell stack showed a severe degradation leading to single cell voltage levels below normal operating performance. The voltage drops of cells 4 and 5 led to an unsteady operation with overall stable single cell voltage level. Cells 1 to 3 reveal a degradation rate to around 28.8 / 29.6 µV/h. The effect of degradation on the current cycling frequency is examined, and the results indicate that decoupling of load changes enhances the degradation by a factor of two, when considering only the three first cells. The degradation on the stack is increased by 4.5 / 3.35 µV/h. For EIS (see Figure 6b), the HFR is almost constant. The LFR largely increase until deform the impedance spectra, especially for the two last cells. This confirms the high degradation of cells 4 and 5.

C. High frequency and amplitude stress test – Profile 3

The test will show if fuel cell degradation is impacted by amplitude and if it can accelerate ageing. For this, all amplitudes are doubled. So, the 4 current densities levels considered are now: OCV, 0.3, 0.5 and 0.7 A/cm². The operating conditions are maintained similar than for two previous tests. Figure 7 presents the evolution of the stack voltage, the current and the temperature and Table 2 summarizes the degradation rates. We can note that the degradation is much higher for the two last cells (4 & 5).
Degradation of the fuel cell stack is largely heterogeneous with a mean degradation of 186.2 / 91.8 / 49.6 µV/h/cell under 0.7, 0.5 and 0.3 A/cm² respectively. Higher degradation is observed under higher current densities.

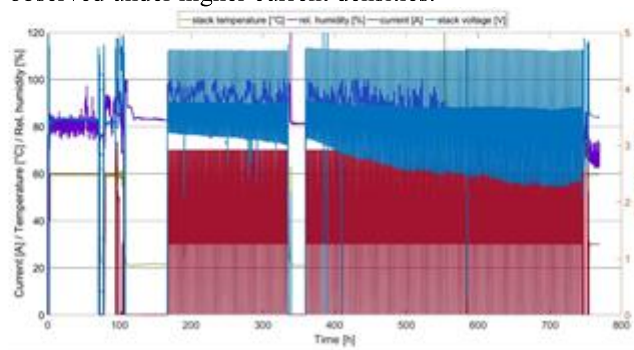


Figure 7: Long-term test results for the high frequency and amplitude stress test with conditioning phase (t=0 until t=180h)

TABLE II. DEGRADATIONS RATES FOR STACK 3

Cathode (gas and coolant inlets and outlets)	@ 0.7 A/cm²	@ 0.5 A/cm²	@ 0.3 A/cm²
Cell 5	-459 µV/h	-211 µV/h	-103 µV/h
Cell 4	-374 µV/h	-207 µV/h	-116 µV/h
Cell 3	-66 µV/h	-27 µV/h	-21 µV/h
Cell 2	-11 µV/h	-9 µV/h	-6 µV/h
Cell 1	-6 µV/h	-5 µV/h	-2 µV/h
Anode			

As presented in Table 2, the degradation is largely heterogeneous. The observed degradation disparities within a short-stack of five cells can be attributed to several factors:

- non-uniform reactant distribution: the reactant supply is not always uniform, leading to local differences in reactant availability and, therefore, varying operating conditions for the cells.
- temperature gradient: thermal management within a short-stack may be uneven, with some cells

experiencing higher temperatures, thereby accelerating their degradation.

- current distribution: due to variations in contact and differences in internal resistance between cells, the current distribution can be heterogeneous, creating more severe loading conditions for cells.
- Fuel cell edge effects and cooling flow heterogeneity: cells located near the gas and coolant inlet and outlet connections may experience more severe conditions compared to those located in the center of the stack.
- degradation propagation: a degraded component in one cell (e.g., a damaged membrane or weakened catalyst layer) can influence the performance of adjacent cells, thereby amplifying the aging discrepancies.

By combining these factors, a better understanding of why some cells degraded faster, especially those closer to the gas and cooling inlets, undergo more rapid degradation than others.

Figure 8 gives a subsequent examination of the voltage evolution for the three experiments and four current densities (red: OCV, green: low, blue: mid, black: high). It reveals a uniform evolution, suggesting a consistent degradation of behavior over time. This outcome is of particular interest, as the objective of accelerated stress testing is to observe the same natural ageing process, but over a shorter time. For each current density, the evolution of profile 3 (including accelerated frequency and amplitude) is consistently situated between the evolution of profile 1 (reference) and profile 2 (frequency stressor). The voltage results of profile 2 appear more severe than those observed in all other experiments. Finally, profile 1 (reference one) is the less severe with FC degradation as expected.

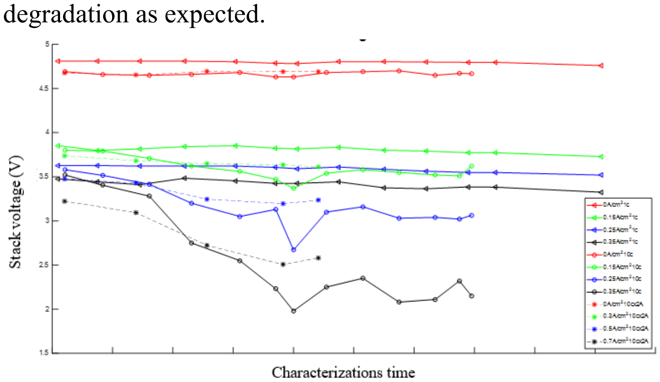


Figure 8: Stack voltage evolution trend with time

IV. Conclusion

In all experimental conditions, cells 4 and 5, located on the cathode side, exhibit systematically higher degradation rates compared to cells positioned further from the gas and coolant inlets.

Among the tested configurations, Stack 2, composed of five MEA#3s, presents the highest mean degradation rate at 65.5 $\mu V \cdot h^{-1} \cdot cell^{-1}$, followed by Stack 3 (MEA#2) at 49.5 $\mu V \cdot h^{-1} \cdot cell^{-1}$, and the rainbow stack at 14.4 $\mu V \cdot h^{-1} \cdot cell^{-1}$.

When comparing identical MEAs at equivalent locations within the stack (e.g., cells 1 to 3 in Stacks 1 and 2), the degradation rate doubles under Profile 2, which includes a frequency stressor, relative to Profile 1. More notably, for Cell 1 in Stacks 1 and 3, the degradation rate under Profile 3 (combining frequency and amplitude stressors) is ten times greater than that observed under Profile 1.

These findings emphasize the significant influence of frequency as a degradation-driving stressor, independent of amplitude. Moreover, despite a twofold reduction in test duration between Profiles 1 and 3, the observed degradation in Profile 3 is three times higher, revealing a nonlinear degradation behavior and substantial cell-to-cell heterogeneity.

Collectively, these results highlight the necessity of further investigations to define robust and representative accelerated stress test (AST) protocols for PEM fuel cells, and to ensure the reproducibility and relevance of such approaches under real-world operating conditions.

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References

1. F. Barbir. PEM Fuel Cells (Second Edition), 2013, pp. 518.
2. K. Javed, R. Gouriveau, N. Zerhouni, D. Hissel. Prognostics of Proton Exchange Membrane Fuel Cells stack using an ensemble of constraints based connectionist networks, Journal of Power Sources, vol. 234, 2016, pp. 745-757.
3. M. Jouin, R. Gouriveau, D. Hissel, M.-C. Péra, N. Zerhouni. PEMFC aging modeling for prognostics and health assessment, 9th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes SAFEPROCESS 2015, 48, 21, 2015, 790-795
4. E. Dijoux, N. Yousfi-Steiner, M. Benne, M.C. Péra, B. Grondin-Perez. A review of fault tolerant control strategies applied to proton exchange membrane fuel cell systems, Journal of Power Sources, vol. 359, 2017, pp. 119-133.
5. E. Pahon, N. Yousfi-Steiner, S. Jemei, D. Hissel, P. Moçotéguy. A non-intrusive signal-based method for a Proton Exchange Membrane Fuel Cell fault diagnosis, Fuel Cells vol. 17, issue 2, 2017, pp. 238-246.
6. C. Jeppesen, S. S. Araya, S. L. Sahlin, S. Thomas, S. J. Andreasen, S. K. Kær. Fault detection and isolation of high temperature proton exchange membrane fuel cell stack under the influence of degradation, Journal of Power Sources vol. 359, 2017, pp. 37-47.
7.] G. De Moor, N. Charvin, C. Bas, N. Caqué, E. Rossinot, L. Flandin. In Situ Quantification of Electronic Short Circuits in PEM Fuel Cell Stacks, IEEE Transactions on Industrial Electronics vol. 62, issue 8, 2015, pp. 5275-5282.
8. T. Sutharssana, D. Montalvaoc , Y. K. Chen, W. C. Wang, C. Pisac , H. Elemara. A review on prognostics and health monitoring of proton exchange membrane fuel cell, Renewable and Sustainable Energy Reviews vol. 75, 2017, pp. 440–450.
9. H. Chen, P. Pei, M. Song. Lifetime prediction and the economic lifetime of Proton Exchange Membrane fuel cells, Applied Energy vol. 142, 2015, pp. 154–163.
10. DOE Hydrogen 2017. Fuel cell Technical Team Roadmap 2017, pp. 1-38.
11. P. Urchaga, T. Kadyk S. G Rinaldo, A. O Pistono, J. Hu, W. Lee, C. Richards, M. H. Eikerling, C. A. Rice. Catalyst Degradation in Fuel

Cell Electrodes: Accelerated Stress Tests and Model-based Analysis, Electrochimica Acta vol. 176, 2015, pp. 1500–1510.
12. C. Lorenzo, D. Bouquain, S. Hibon, D. Hissel. Synthesis of degradation mechanisms and their impacts on degradation rates on proton-exchange membrane fuel cells and lithium-ion nickel-maganese-cobalt batteries in hybrid transport applications,Reliability Engineering & Systel Safety, vol. 212, 2021, 107369..
13. G. Tsotridis, A. Pilenga, G. De Marco, T. Malkow. EU harmonized test protocols for PEMFC-MEA testing in single cell – Configuration for automotive applications, 2015.
14. Y. Li, X. Zhao, Z. Liu, Y. Li, W. Chen, Q. Li. Experimental study on the voltage uniformity for dynamic loading of a PEM fuel cell stack, International Journal of Hydrogen Energy, vol. 40, 2015, pp. 7361-7369.
15. R. Petrone, D. Hissel, M.C. Péra, D. Chamagne, R. Gouriveau. Accelerated stress test procedures for PEM fuel cells under actual load constraints: State-of-art and proposals, International Journal of Hydrogen Energy vol. 40, 2015, pp. 12489-12505.
16. E. Pahon, S. Morando, R. Petrone, M.C. Péra, D. Hissel, N. Yousfi-Steiner, S. Jemei, R. Gouriveau, D. Chamagne, P. Moçotéguy, N. Zerhouni. Long-term tests duration reduction for PEMFC μ-CHP application, International Journal of Hydrogen Energy, vol. 42, issue 2, 2017, pp. 1527-1533.

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