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| Public Abstract |
|---|
| <p>This deliverable summarizes the experimental conditions and protocols that will be used during the tests on stacks and systems. The tests will be carried out under nominal and faulty operating conditions as agreed between the manufacturer (BPSE) and the testing partners (UBFC & EIFER). Several faulty conditions will be tested during the test campaign:</p> <ul style="list-style-type: none"> - Cathode contamination - Fuel / Air starvation - Drying in stand-by mode - Damage cell(s) within the stack |



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INTRODUCTION

The RUBY approach is based on the use of the EIS technique as a tool for diagnosis in fuel cells. For this project, 4 major fault's families are tested:

- Drying in standby mode
- Cathode contamination
- Fuel starvation
- Oxidant Starvation
- Damaged cell within the stack

These faults are chosen to simulate system components failures (malfunction of air filter/polluted oxidant, dry oxidant)., A diagnosis algorithm will be developed to detect these faults, using data acquired during EIS measurement. This document proposes a test protocol for PEMFC stacks in order to create valuable data for algorithms development and validation.

1 INTRODUCTION TO PROTOCOLS

The supplied stacks will run in a continuous mode respecting supplier's indication. They will be characterized by I-V curves in non-faulty conditions and EIS either in faulty or nominal conditions. The procedure to process I-V curves is proposed in section 2.5.

The following figures represent the sequence to be followed to characterize the stacks via EIS measurements.

First of all, a stack characterization will be performed to check and define the stack operating conditions limits, which means defining the operational conditions resulting in visible, but not destructive, effect of the faults: this will allow detecting a fault as soon as it appears, even at low intensity and so, increasing the lifetime and availability of the stack/system.

2 PROCEDURES & PROTOCOLS

2.1 Global procedure

The figure below shows the global procedure followed for experimental tests.

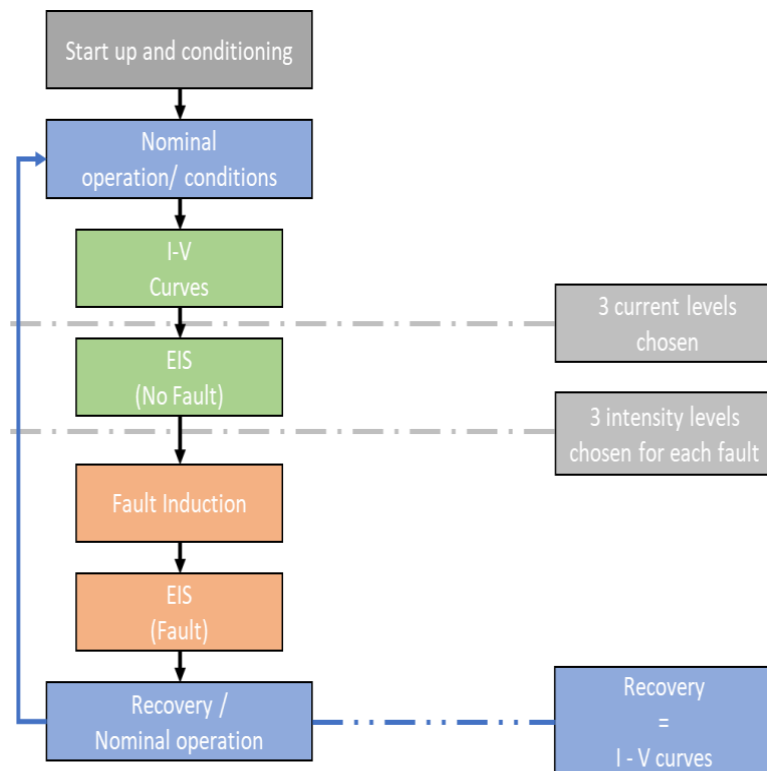


Fig. 1. Global procedure for experimental tests

2.2 Normal procedure details

The following steps describe the procedure of the Ballard manual [1]. This procedure is altered for the fault generation.

2.2.1 Start-up

In the first step, the fan is started before the start-up purge to give fan the time to reach a sufficient airflow and to dilute the startup purge.

Secondly, the anode gas needs to be exchanged with hydrogen before the stack can deliver power (supply and purge valve are open). For that reason, a startup purge is done. The applied current



during this purge is approximately 15 A at BOL and should be reduced at EOL. Once the startup purge is done, the fan speed is reduced to allow the start of the warmup procedure.

2.2.2 Warmup & Run

The warmup procedure brings up the temperature in the stack and hydrates the membrane. This step enables the stack to deliver a rated power., the stack can be air-starved or current pulsed to improve the performance of the catalyst. A current ramp should be defined to increase the current step by step over the time while maintaining the minimum stack voltage above 0.5 V/cell and the current under 75 A.

During the warmup and the run procedure, a purge is done. In addition, the fan operates to maintain the stack temperature at the temperature optimum presented in section III.

2.2.3 Post Shutdown

Once shutdown is finished (load switch off), all H₂ is consumed through diffusion across the membrane. After the anode pressure has dropped and once all H₂ has been consumed, the air diffuses into the membrane and the pressure equilibrates at atmospheric pressure.

2.2.4 Standby

During the stand-by, the stack does not consume reactants and it should be in a state where it can deliver power after a start-up procedure. When the stack is in stand-by mode, it should be maintained at a temperature greater than -10°C.

2.3 Stack testing

2.3.1 Dry out in standby (SB) mode

Generation of the fault

The Procedure to infer the fault is shown in the diagram below. The drying out characterization will be achieved mainly by EIS characterization.

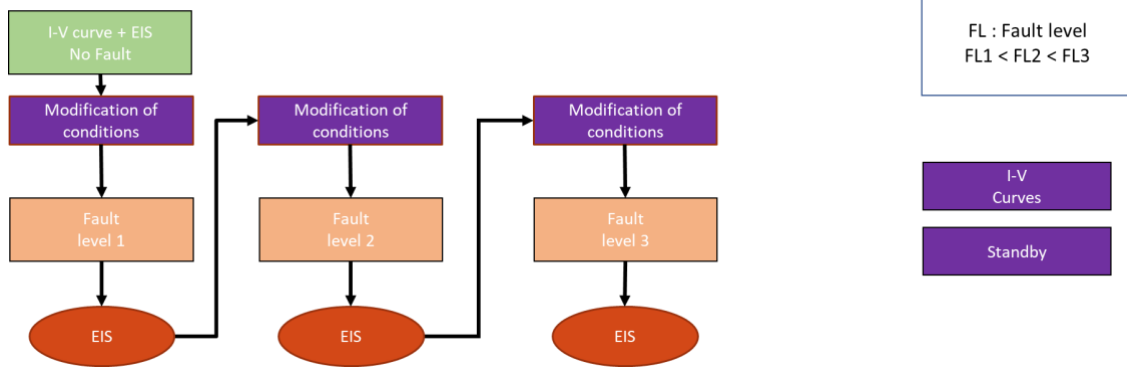


Fig. 2. Proposed procedure to process EIS in Drying out in standby mode fault

The EIS will be done at a lowest current level selected (I_{min}), and the different levels of air flow are to be defined by EIFER after preliminary testing.

Table 1. Selected Flow conditions to infer drying out in standby mode

| | Level 1 | Level 2 | Level 3 |
|---------------------------------------|------------------|------------------|------------------|
| Air Flow for drying in SB mode [slpm] | tbd ¹ | tbd ¹ | tbd ¹ |

Recovery procedure

To recover the inferred fault once an EIS in faulty condition done, the proposed procedure consists of doing an IV curve in the decreasing and increasing direction.

2.3.2 Cathode Contamination

Two contaminants are selected to create gas contamination fault. The contamination faults differ significantly in their effect from the other faults. They are cumulative, which means their impact on the stack conditions is a function of intensity and time. A long, small intensity contamination can lead to the same picture as short, high intensity contamination. If the introduced contamination is not reversible, like for Sulfur, all following experiments are started from a new condition of the stack and the analysis might be not so straightforward.

¹ Values will be set during test campaign



Due to the cumulative effect, it is necessary to start with low level of contaminations and from CO; as soon as the effect is visible on the voltage, the contamination of the stack will be stopped and the EIS will be performed.

Moreover, the second level of contamination can be introduced from a sort of static state; this will happen also in real field.

Generation of the fault

Carbon Monoxide Contamination

About carbon monoxide contamination, the interest is to simulate the proximity of a farming and urban environments. A proposed concentration to start with will be set during the test campaign according to the behavior of the stack, but it could be increased if the impact is not visible on EIS. The impact depends on the exposition time and the concentration value.

The stack is run with the contaminated air flow at current². Once effect of poisoning is visible, EIS are done at operational points.

Apparatus description: To simulate the air contamination at stack level a specific apparatus is to be set up.

² Value will be set during test campaign

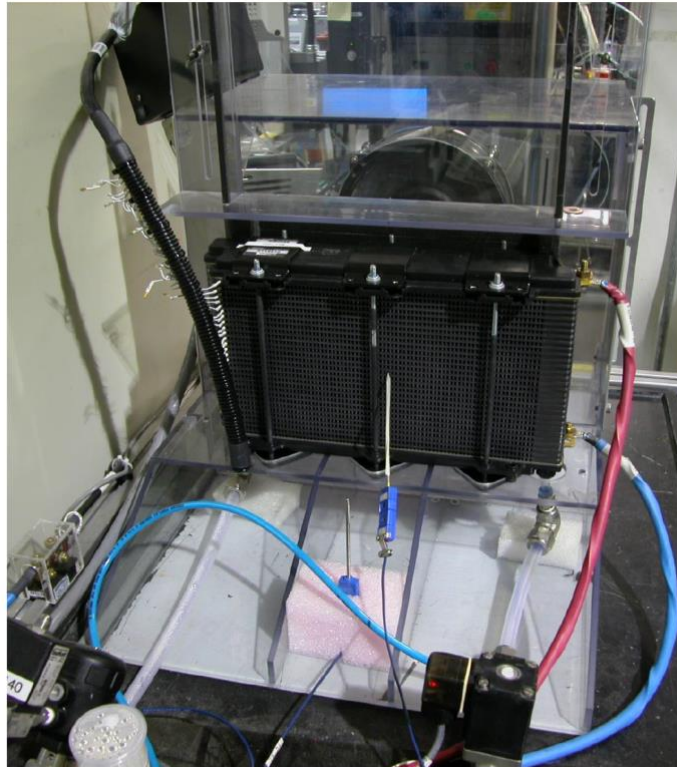


Fig. 3. EIFER apparatus to simulate air contamination

The air box for the inlet air, will be connected to a N₂ gas line in order to reduce the quantity of air reaching the cathode. The different fault levels will be set with different flows of N₂ and checking the effect on the stack voltage. The same apparatus will be used for contaminants test following the same principle.

Sulfur Contamination (SO₂)

About sulfur contamination, the interest is to simulate the proximity of a farming and urban environments. Objectives is to show the impact of a low sulfur concentration during a long-time test. The lowest concentration achievable, considering the capabilities of the facilities is used to start, but it could be increased if the impact is not visible on EIS. The impact depends on the exposition time and the concentration value. Procedure detailed is the following:



The stack is run with the contaminated air flow at current³. Once effect of poisoning is visible, EIS are done at operational points.

Recovery procedure

- No recovery possible for sulfur poisoning
- Partial Recovery possible for CO by increasing temperature.

2.3.3 Air/Fuel Starvation

Two types of starvation are tested:

- Air starvation
- anode starvation

Generation of the fault

Procedure proposed is the same that these proposed for cathode contamination.

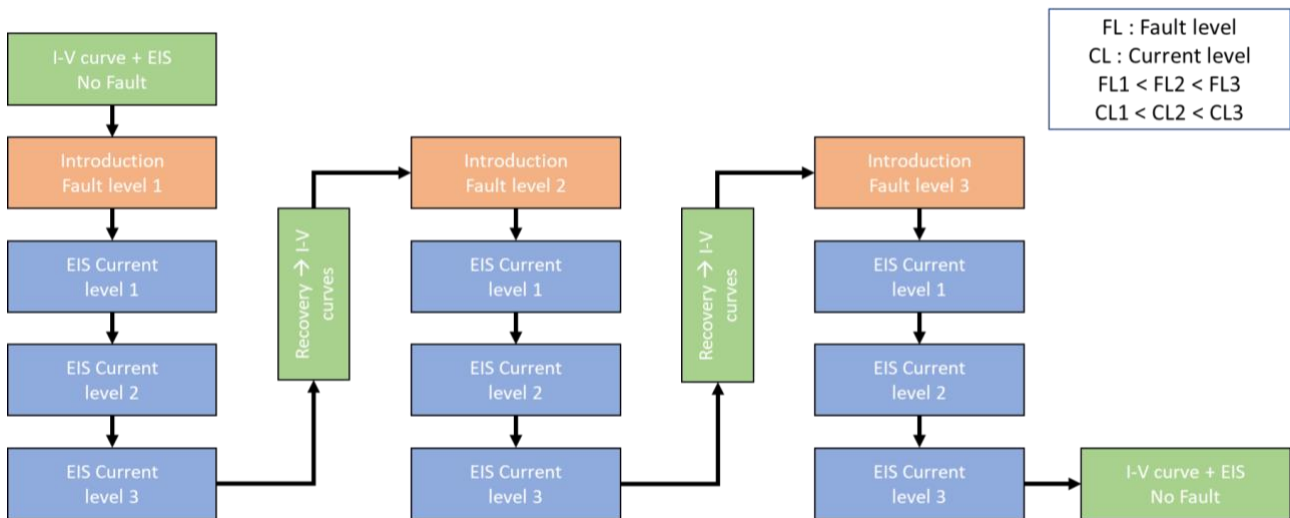


Fig. 4. Proposed procedure to process EIS in Fuel/Air Starvation fault

Values proposed for experimental tests

Table 2. Current levels selected to process EIS in Starvation condition

³ Value will be set during test campaign



| | Level 1 | Level 2 | Level 3 |
|-------------|-----------------|-----------------|-----------------|
| Current [A] | 15 ⁴ | 35 ⁴ | 70 ⁴ |

Air Starvation

Since we are in open Cathode stack, the way to generate air starvation is to dilute air with Nitrogen. The air box for the inlet air will be connected to a N2 gas line in order to reduce the quantity of air reaching the cathode. The different fault levels will be set with different flows of N2 and checking the effect on the stack voltage. If possible, an indicative stoichiometry will be evaluated.

Table 3. Air stoichiometry values selected to infer starvation fault levels

| | Level 1 | Level 2 | Level 3 |
|-------------------|-------------------|-----------------|-----------------|
| Air Stoichiometry | > 50 ⁴ | 50 ⁴ | 10 ⁴ |

$$\text{Airflow} = 0.0166 * I * n * \text{stoichiometry} [\text{slpm}] [1]$$

where I = Current [A], N = number of cells

Fuel Starvation

Table 4. Hydrogen stoichiometry values selected to infer hydrogen starvation fault levels

| | Level 1 | Level 2 | Level 3 |
|------------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|
| H2 Stoichiometry [barg] [Stoic] | 0.3 ⁴ tbd ⁵ | 0.22 ⁴ tbd ⁵ | 0.16 ⁴ tbd ⁵ |

$$\text{H2 flow} = 0.00696 * I * n * \text{stoichiometry} [\text{slpm}] [1]$$

⁴ Values can be adjusted during the test campaign.

⁵ Values will be set during test campaign

where I = Current [A], N = number of cells

Monitoring of the ageing

To track the possible ageing caused by the fault generation IV curves will be done between two fault levels.

2.3.4 Damaged cells

The considered damaged cells will be the ones with a degraded membrane (pin hole).

Proposition of the sequence of tests

For the case of a damage cell, a method to process EIS is proposed below

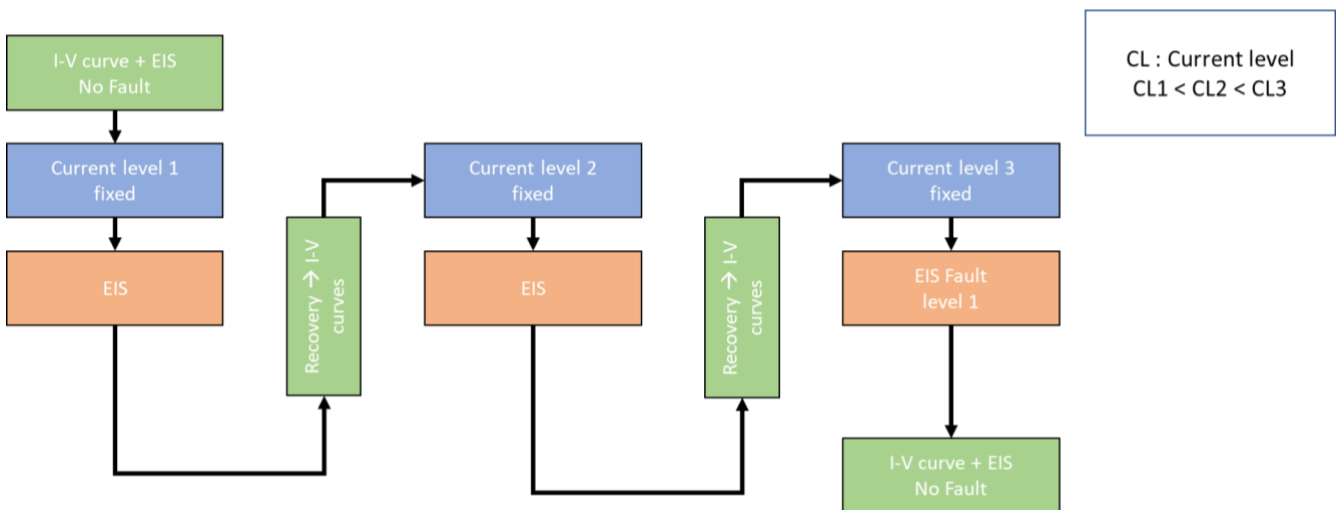


Fig. 5. Proposed procedure to process EIS in damaged cell fault

In this case, they are not fault levels because objective is to detect a disfunction in the FC stack. EIS will be made.

At system level, it will be equipped by single cell monitoring.

Table 5. Current levels selected to process EIS in damaged cell condition

| | Low | Medium | High |
|-------------|-----------------|-----------------|-----------------|
| Current [A] | 15 ⁶ | 35 ⁶ | 70 ⁶ |

⁶ Values can be adjusted during the test campaign



2.4 System testing Protocols

Two methods are possible to observe a faulty condition in a FC system.

- First, monitoring an operating system and wait for the occurrence of a faulty condition
- Second, introducing a control bias to change systems' parameters (for instance the speed of the fan, etc.). This second option depends on the accessibility to the control unit.

2.4.1 Starvation

A possible method to control the starvation phenomena at system level is to control the current signal sent to the FC system control. If a false signal is sent to the compressor or hydrogen regulator for a constant current, the flow feeding the FC can be modified

Another possibility for hydrogen starvation is to dilute it with nitrogen in bottle.

It is more difficult to use the same procedure at system level for air starvation. Therefore, this fault will not be considered at system level.

UBFC checked the possibilities to install the same apparatus proposed by EIFER, but this is not feasible in the lab. Therefore, air starvation fault will not be simulated at system level.

For fuel starvation, a possible solution is to use diluted h₂ at the inlet.

The operating conditions for fuel starvation at system level will be based on the ones defined at stack level.

2.4.2 Drying in stand-by mode

One possible way to generate drying of the fuel cell in stand-by mode is to control the compressor and inject a high air mass flow at the cathode to dry the membrane.

The operating conditions for drying out at system level will be based on the ones defined at stack level.

2.4.3 Cathode Poisoning

It is required to modify the intake of air in the system to inject contaminated air without poisoning the atmosphere of the test room. Therefore, this fault will not be considered at system level.

2.4.4 Damaged cell(s)

the system will be operated with a stack which includes a damaged cell (supplied by Ballard). The system is equipped with Single Cell Voltage monitoring.



2.5 Polarization curves specifications

A procedure for I-V curves is important for a good replicability of the tests. This procedure represents the different steps necessary for polarization curves. Ballard presents in the document [1] a I-V curves procedure.

Table 6. Proposed I-V curve protocol

Values can be adjusted during the test campaign

| Current [A] | Time [min] |
|-------------|------------|
| 60 | 15 |
| 50 | 15 |
| 20 | 15 |

This protocol should be done in descending and then in ascending direction.

The minimum reactant flow has been defined by the supplier to ensure comparable stoichiometric values and humidity levels in the first part of the polarization curve dominated by activation losses.

- All relevant TIPs and TOPs must be monitored and recorded.
- The stability of the TOCs has to be assured during the entire test. Thereby, all parameters likely to affect the stack humidification level should be monitored carefully due to their high impact on stack performance.
- The basic safety limits regarding minimum cell voltage must be considered.

2.6 EIS Specifications

One input parameter of EIS is the AC signal's perturbation frequency, f . It is controlled by the AC generator attached to the fuel cell stack. Other inputs are the AC value, the signal sampling time, and the number of injected periods at a given frequency. These ones are controlled by the AC analyzer and are usually linked to f . Table below gives the details of the three variable inputs.

Table 7. Specification about EIS

| Input | Value for Lab Test |
|-----------|---|
| Frequency | [2000 – 0.05 ⁷ Hz] log scale |

⁷ Value can be adjusted during test campaign



| | |
|-----------------------------|------------------------------------|
| Current value [A,ac] | +, -1 A,ac |
| Number of periods | 10 |
| Sampling frequency | To be defined during test campaign |

3 REFERENCES

- [1] Ballard, "Integrating the 1020ACS into a System," p. 147, 2016.