

Physicochemical properties evolution of cathodic catalyst layer and cell performance improvement during PEMFC start-up with mitigation strategies

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International Society of Electrochemistry

FROM RESEARCH TO INDUSTRY

Physicochemical properties of cathodic catalyst layer and cell performance evolution during PEMFC start-up with mitigation strategies – 32nd ISE Topical Meeting

Timothee Drugeot[1,2], Fabrice Micoud[1], Eric Pinton[1], Jean-Phillippe Poirot-Crouvezier[1], Sébastien Rosini[1], Laure Guetaz[1], Lucas Poupin[1] and Yann Bultel[2]

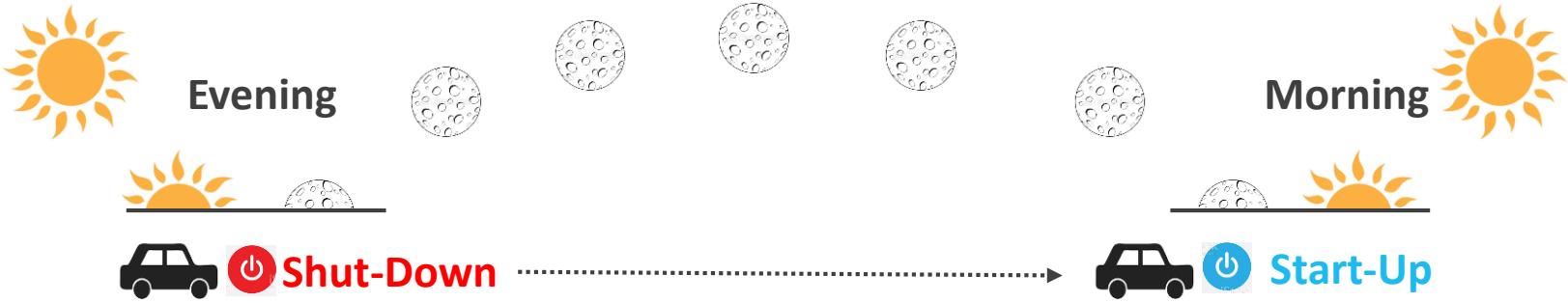
[1]*Univ. Grenoble Alpes, CEA, LITEN, DEHT 38000 Grenoble, France*

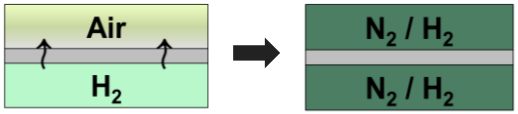
[2]*Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, Grenoble INP, LEPMI, 38000 Grenoble, France*

Email: timothee.drugeot@cea.fr

CONTEXT

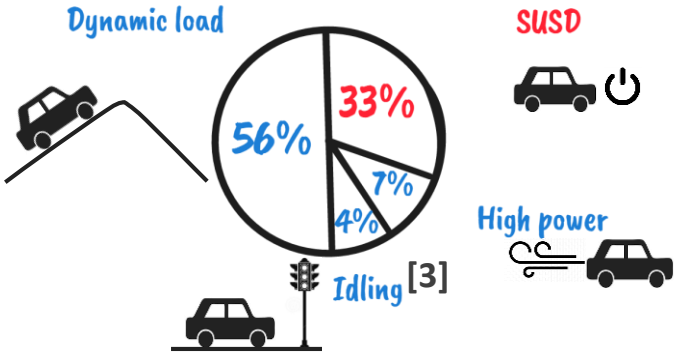
Shut-Down (SD) / Start-Up (SU) process





Oxygen consumption[1]

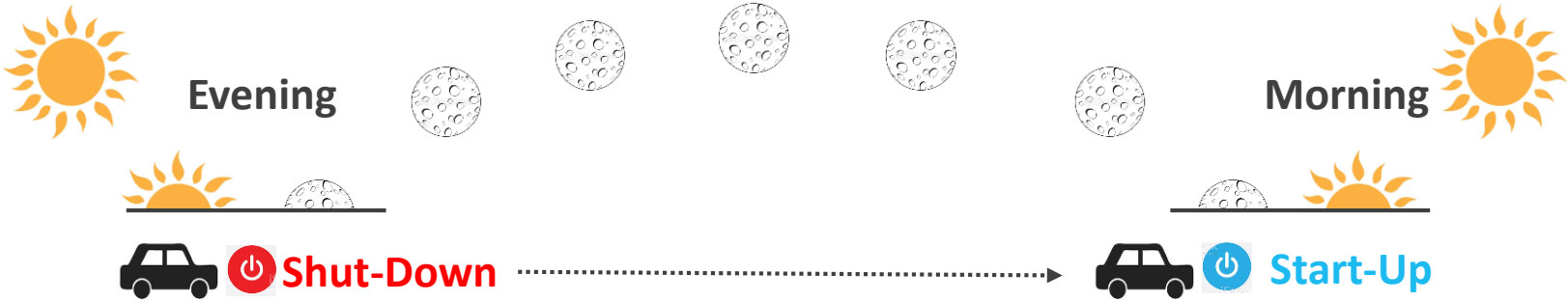
Estimation of performance losses [3]

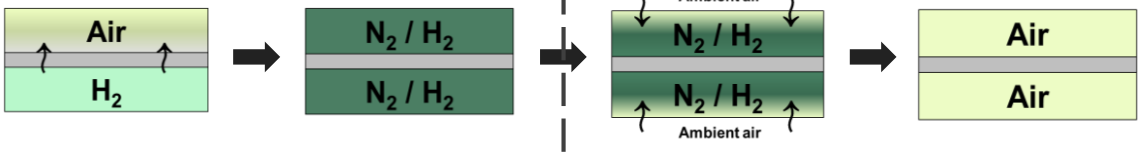


[1] Oyarce et al. "Comparing shut-down strategies for proton exchange membrane fuel cells" (2014)
[2] Reiser et al. "A Reverse-Current Decay Mechanism for Fuel Cells" (2005)
[3] Pei et al. « A quick evaluating method for automotive fuel cell lifetime"

CONTEXT

Shut-Down (SD) / Start-Up (SU) process

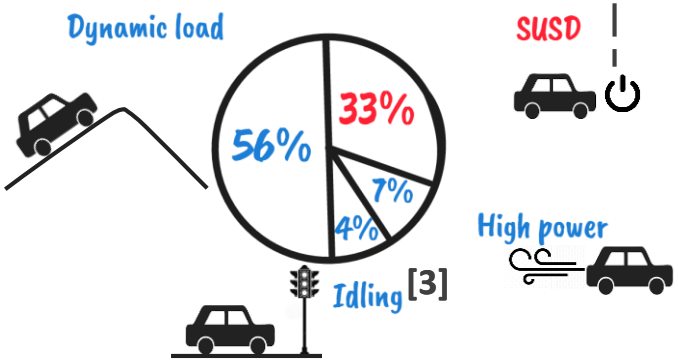




Oxygen consumption[1]

Ambient Air infiltration

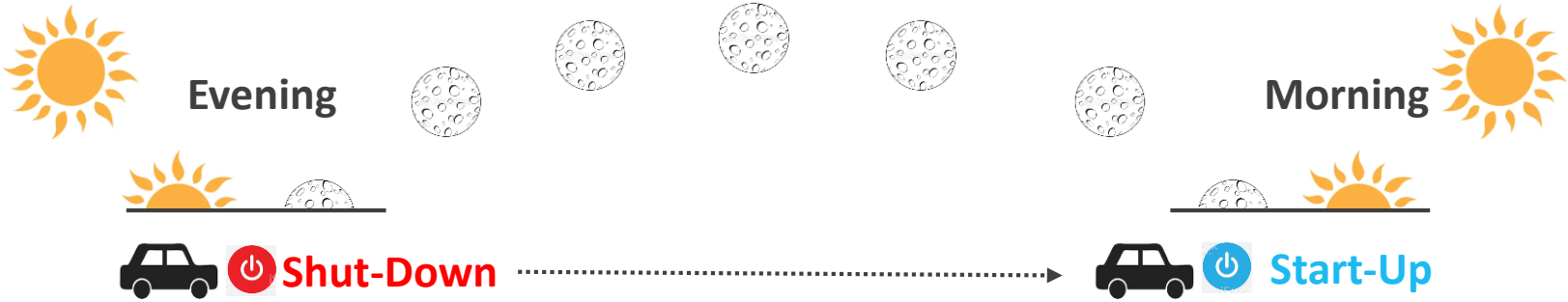
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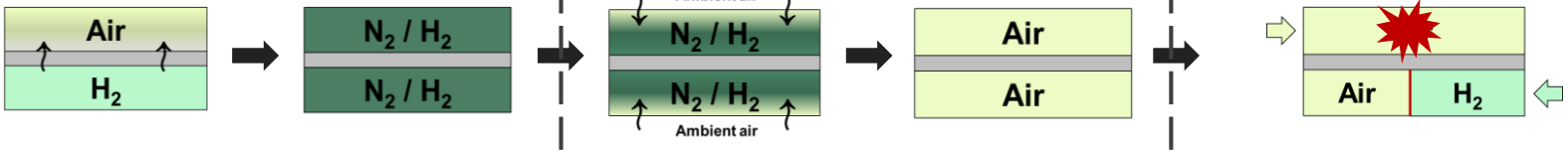


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CONTEXT

Shut-Down (SD) / Start-Up (SU) process





Oxygen consumption[1]

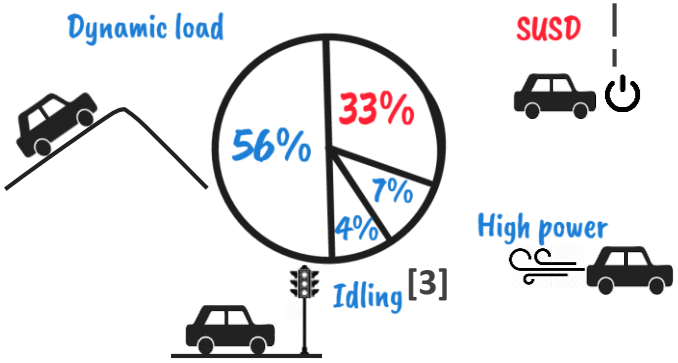
Ambient Air infiltration

Fuel injection = H_2|Air front

Reverse Current Decay mechanism[2]

Implementation of mitigation strategies on a system scale

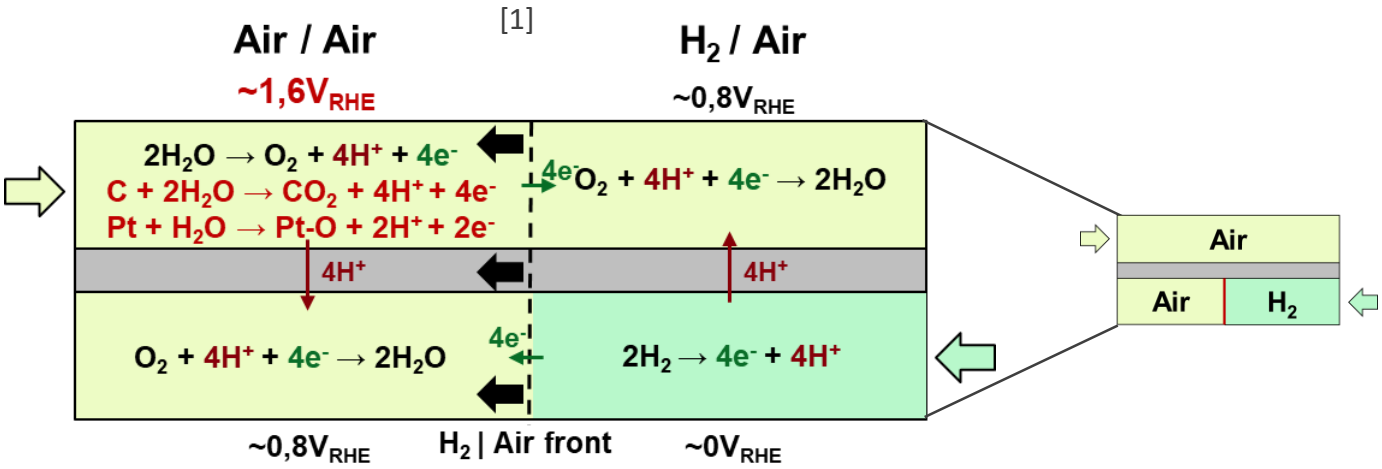
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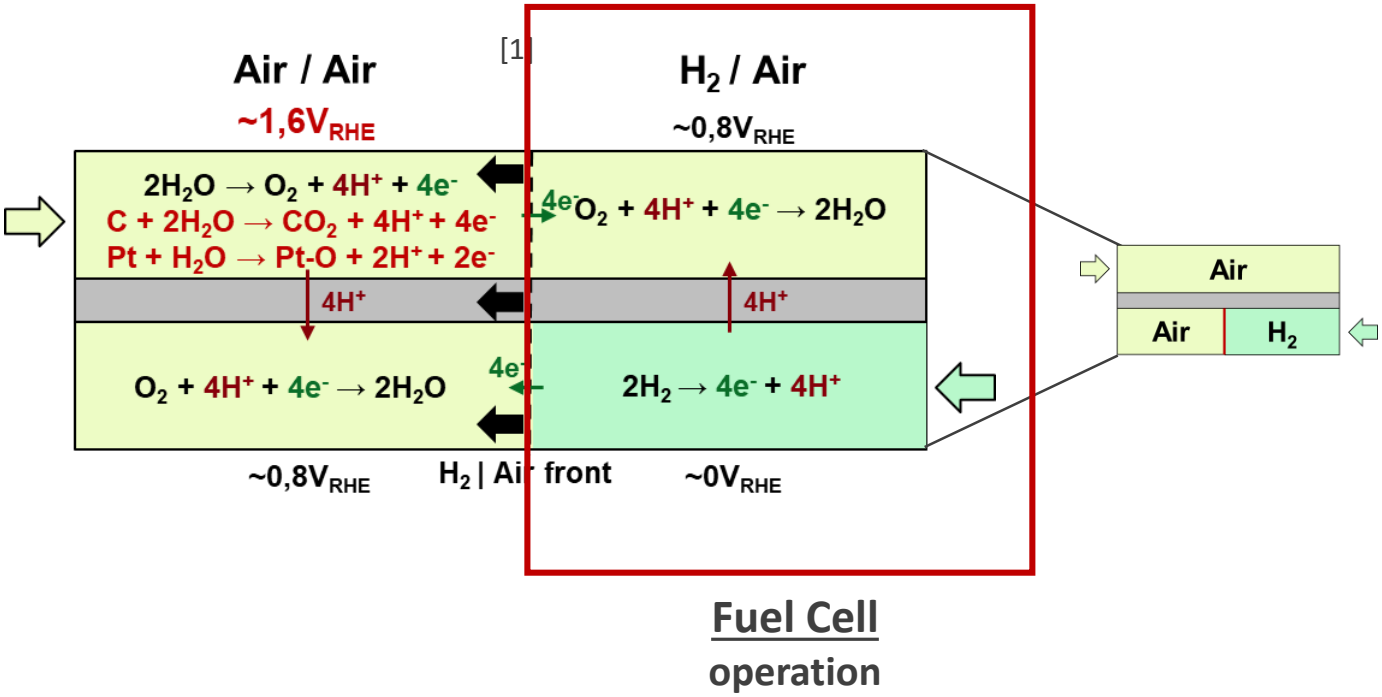
CONTEXT

Reverse Current Decay mechanism



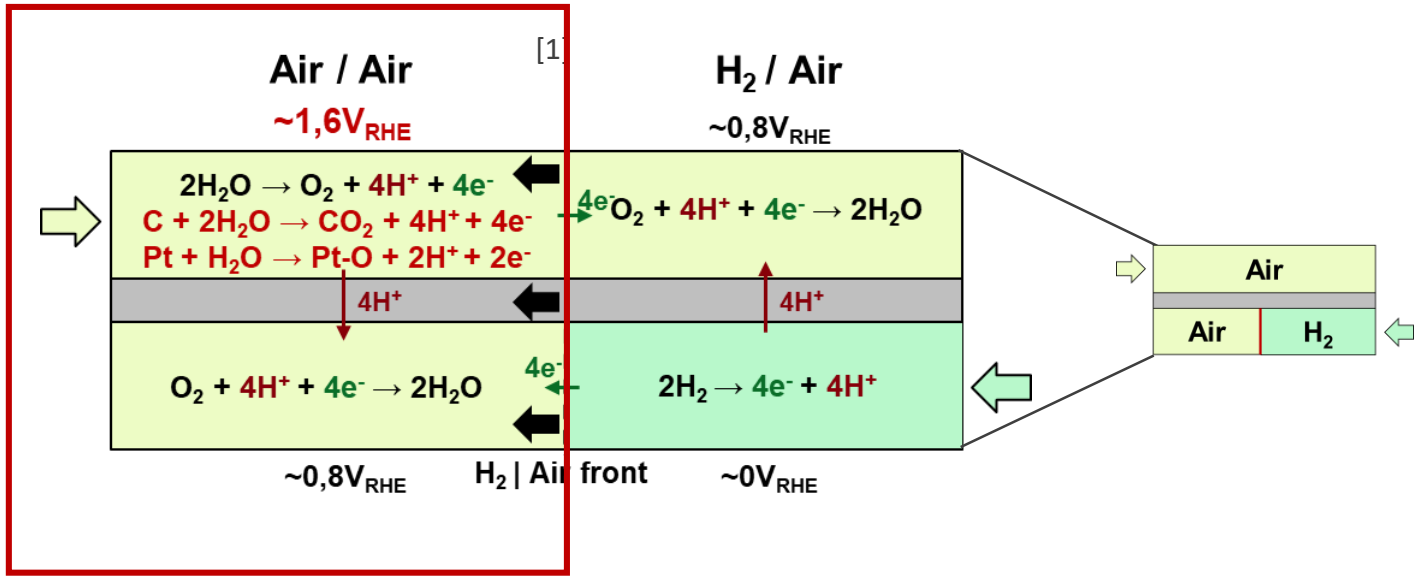
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Reverse Current Decay mechanism



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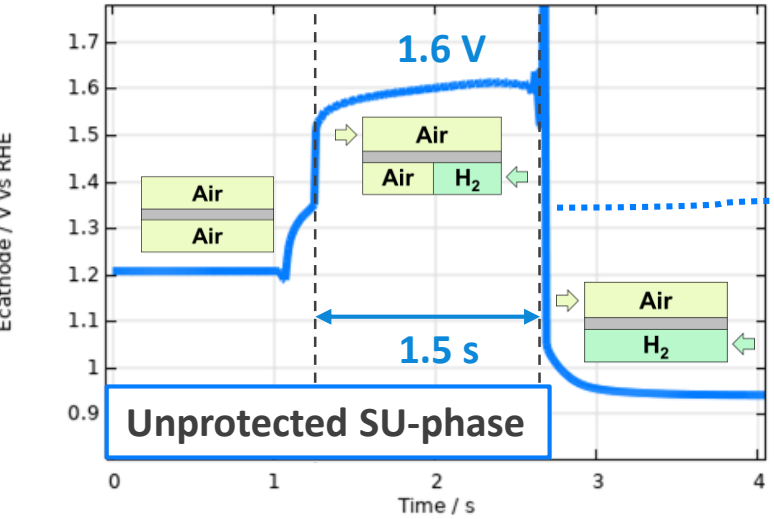


Electrolysis operation

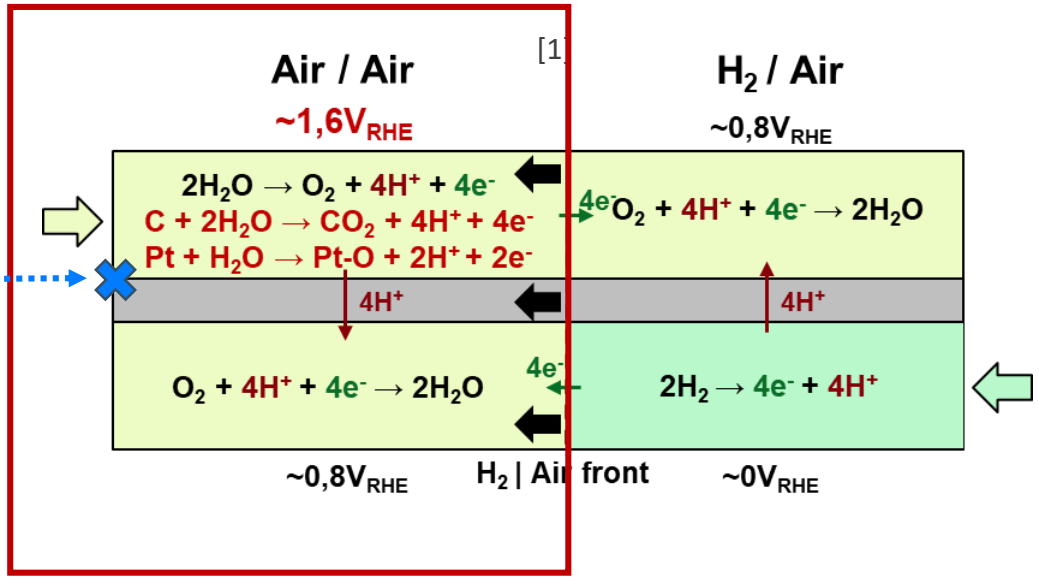
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Reverse Current Decay mechanism

Simulated SU phase potential profile



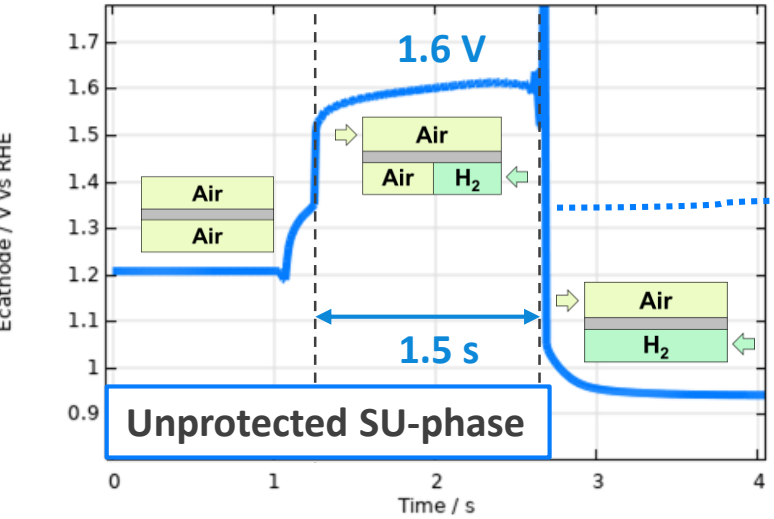
Cathode electrode potential (input) when the H2/Air front passes through the anode side (CEA model) [2]



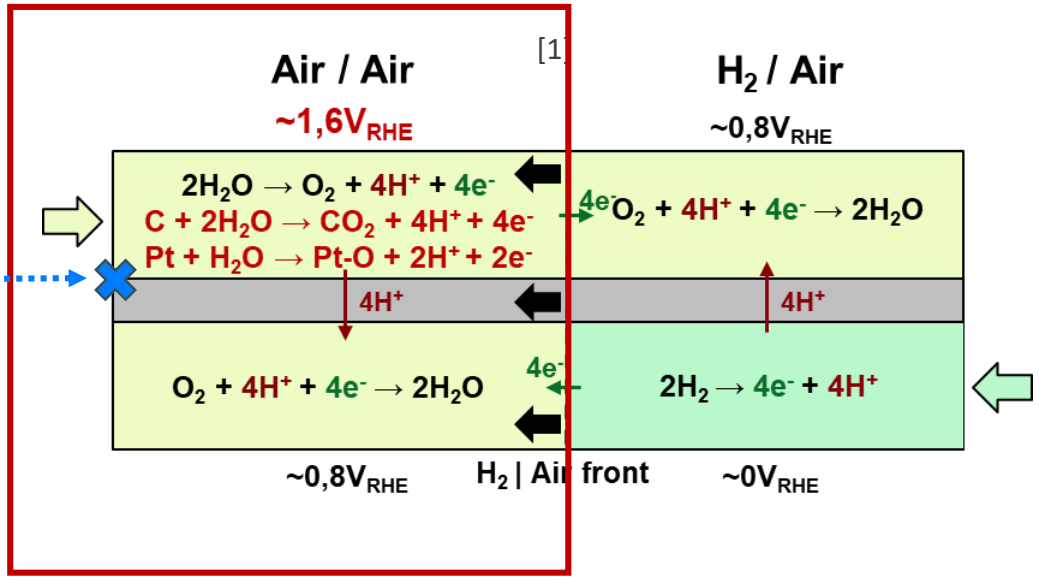
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Simulated SU phase potential profile



Cathode electrode potential (input) when the H2/Air front passes through the anode side (CEA model) [2]



Electrolysis operation

Cathod Catalyst Layer (CCL) degradation:

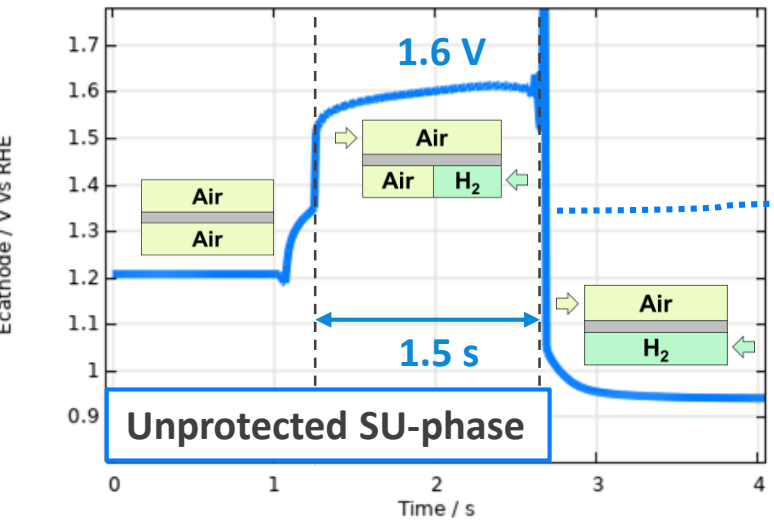
- **Carbon Support Corrosion (CSC)**
- **Pt Dissolution/redeposition**

IRREVERSIBLE loss of cell performance

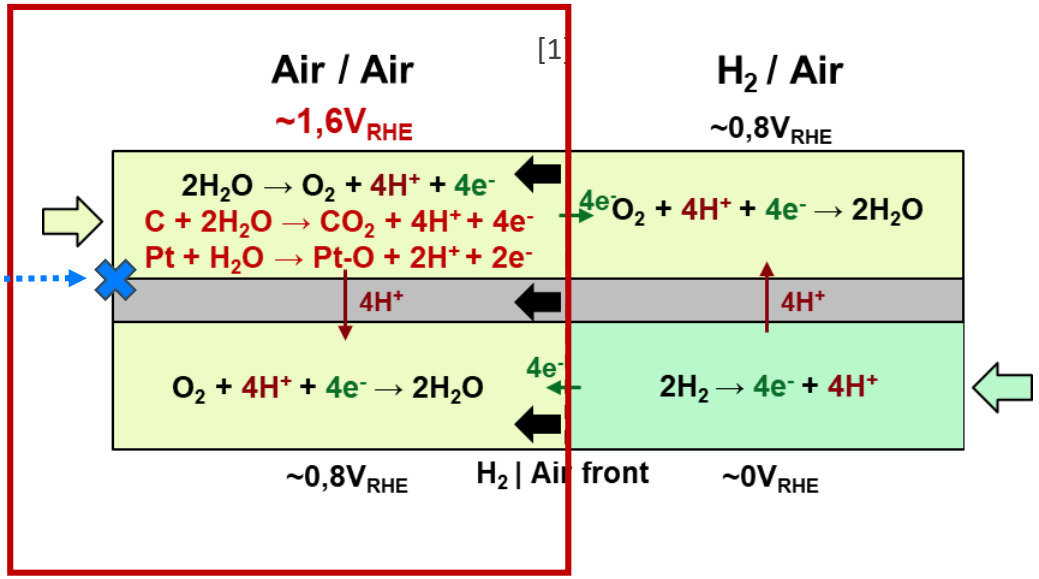
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Reverse Current Decay mechanism

Simulated SU phase potential profile



Cathode electrode potential (input) when the H2/Air front passes through the anode side (CEA model) [2]



Electrolysis operation

Cathod Catalyst Layer (CCL) degradation:

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- **Pt Dissolution/redeposition**

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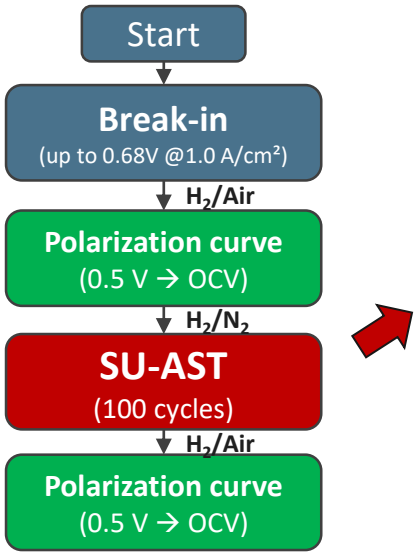
Objectives

1. **Better understanding of RCD mechanism** and impact on cell performance decay by **sizing of an Accelerated Stress Test** mimicking SU-phase
2. Evaluate **the most impactful mitigating parameters** by coupling several monitoring *in-situ* and *post-mortem* techniques

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In-situ SU-AST protocol

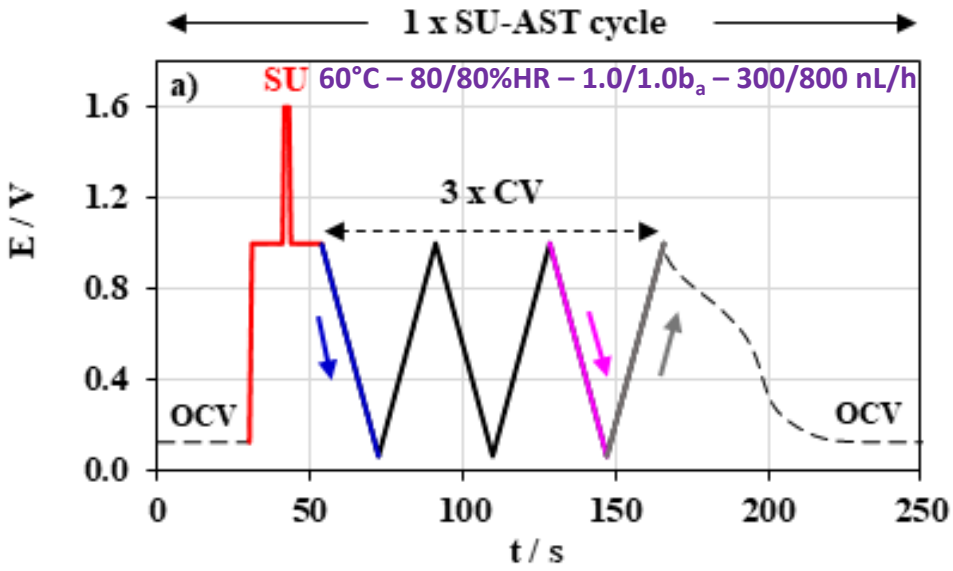
Emulation of realistic cathode potential profile



Coupling monitoring techniques

- **Cell performance decay** (polarization)
- **ECSA losses** along AST (CV)
- **CO_2 emission rate** along AST

SU-AST potential profile



x100

In-situ SU-AST protocol

Emulation of realistic cathode potential profile

Start

Break-in
(up to 0.68V @1.0 A/cm²)

H_2/Air

Polarization curve
(0.5 V → OCV)

H_2/N_2

SU-AST
(100 cycles)

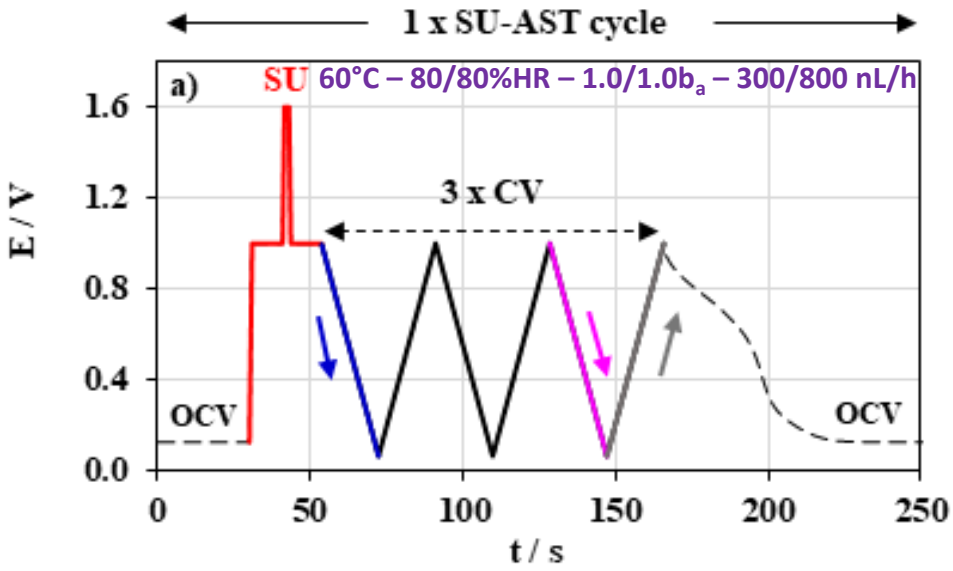
H_2/Air

Polarization curve
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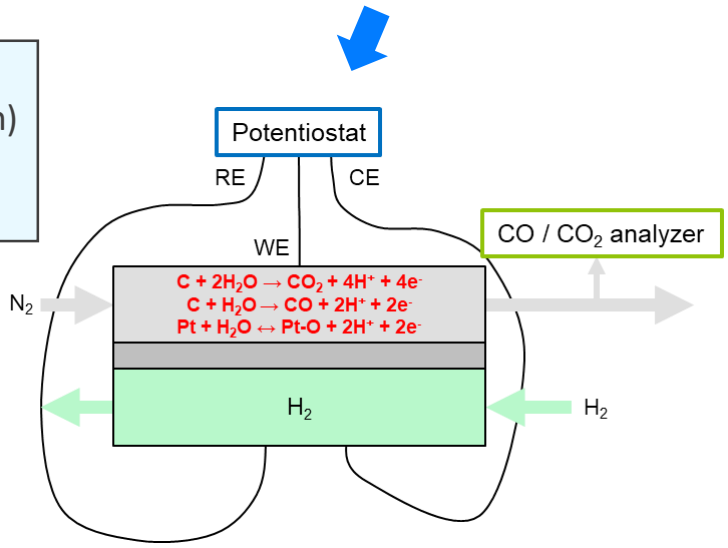
Coupling monitoring techniques

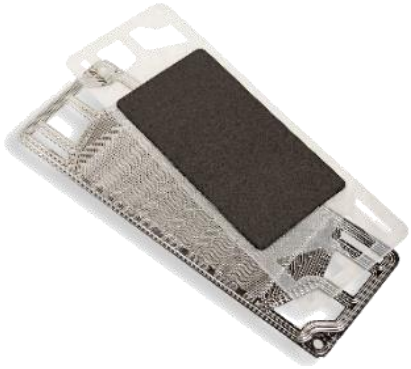
- **Cell performance decay** (polarization)
- **ECSA losses** along AST (CV)
- **CO_2 emission rate** along AST

SU-AST potential profile



x100

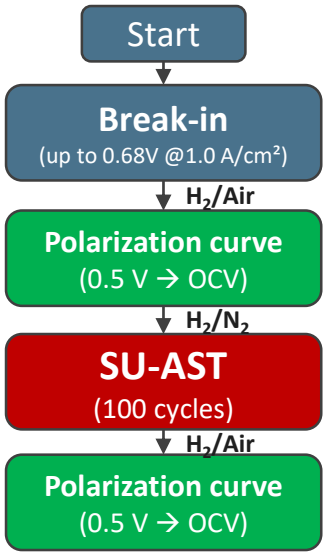


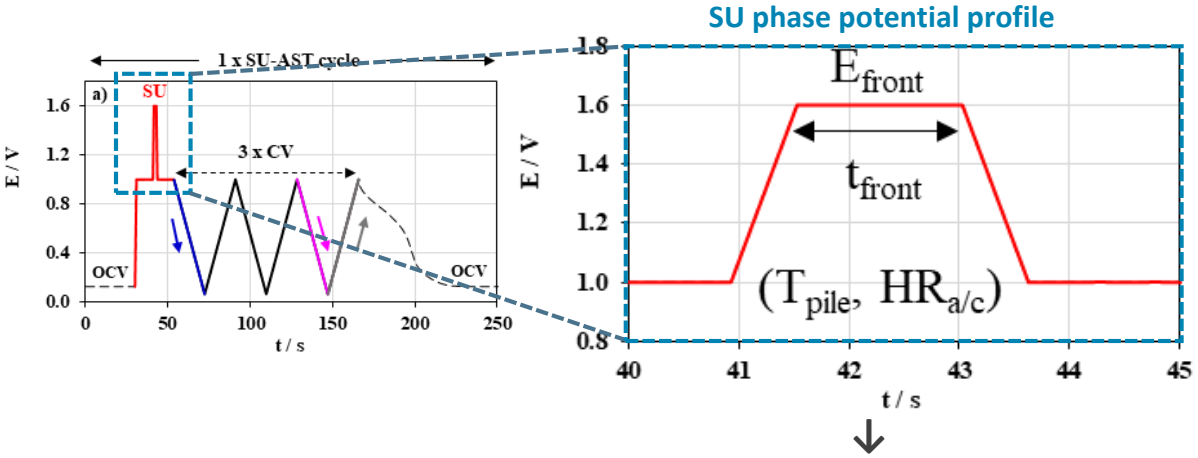


Real stack flow-field design
100 cm² MEA single cell

In-situ SU-AST protocol

Parametric study





- **E_{front} (1.6 → 1.0 V)**

relative to electrcial current by-passing strategy

- **1.6V** – 1.5s – 80/80%HR – 60°C **(Ref)**
  - **1.4V** – 1.5s – 80/80%RH – 60°C
  - **1.2V** – 1.5s – 80/80%RH – 60°C
  - **1.0V** – 1.5s – 80/80%RH – 60°C
  - 1.6V – **1.0s** – 80/80%RH – 60°C
  - 1.6V – **0.5s** – 80/80%RH – 60°C
  - 1.6V – 1.5s – **80/50%RH** – 60°C
  - 1.6V – 1.5s – **50/50%RH** – 60°C
  - 1.6V – 1.5s – **80/95%RH** – 60°C
  - 1.6V – 1.5s – 80/80%RH – **45°C**
  - 1.6V – 1.5s – 80/80%RH – **30°C**

- **t_{front} (1.5 → 0.5s)**

relative accelerating H_2 injection in Air-filled anode

- **$RH_{a/c}$ (95 → 50%)**

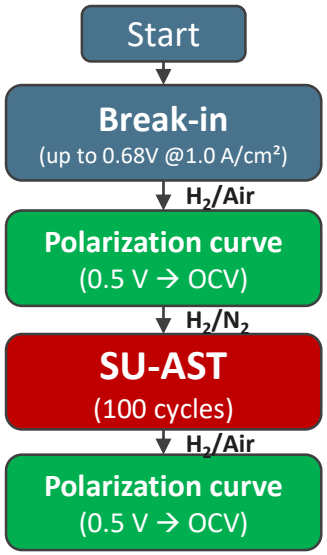
relative to water evaporated at the gas inlet

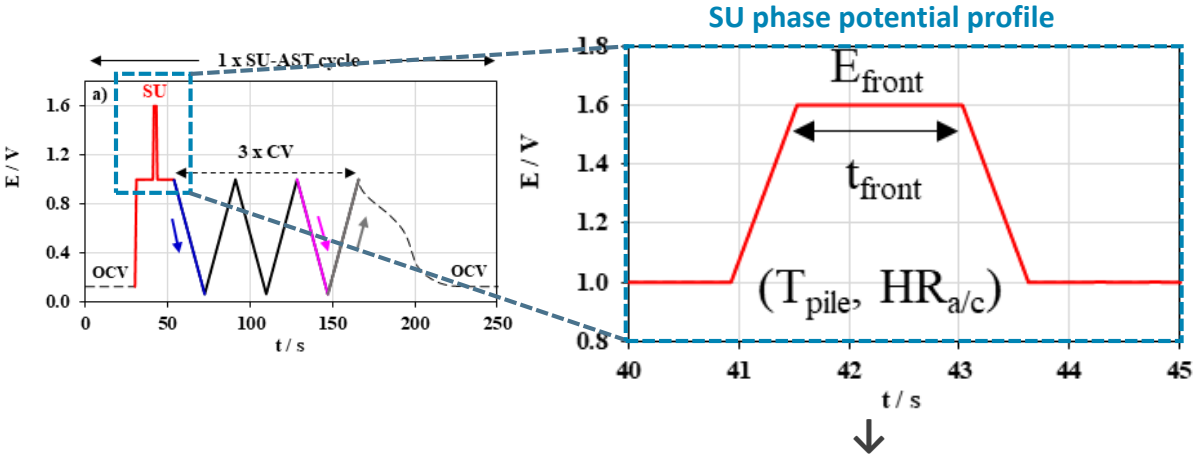
- **T_{cell} (60 → 30°C)**

relative to internal cell temperature

In-situ SU-AST protocol

Parametric study





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relative to electrcial current by-passing strategy

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  - 1.6V – 1.5s – **50/50%RH** – 60°C
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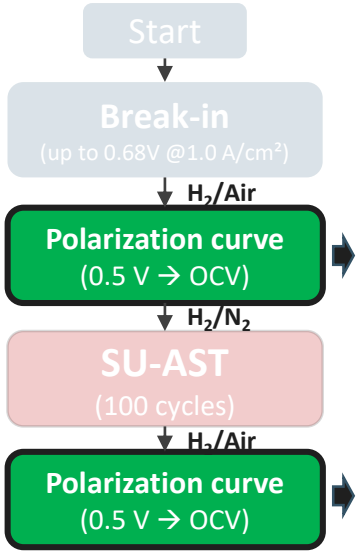
relative to water evaporated at the gas inlet

- **T_{cell} (60 → 30°C)**

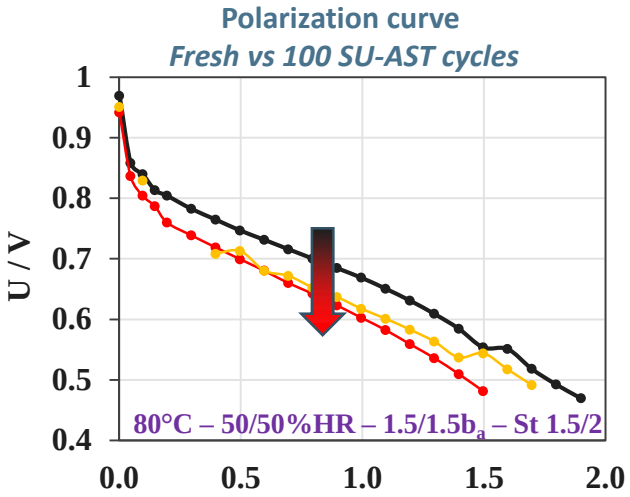
relative to internal cell temperature

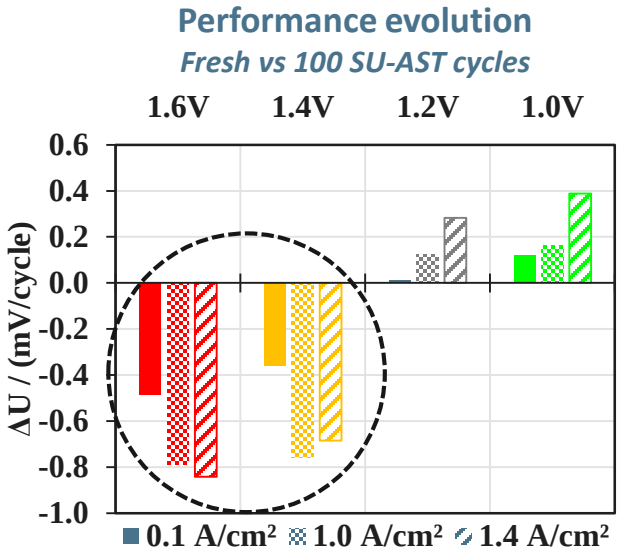
In-situ SU-AST results

E_{front} investigation – Cell voltage evolution



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V



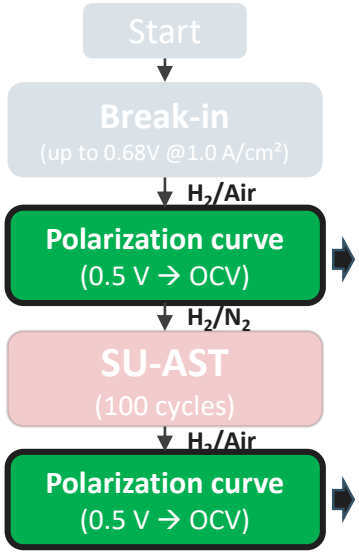


1.4 – 1.6 V range

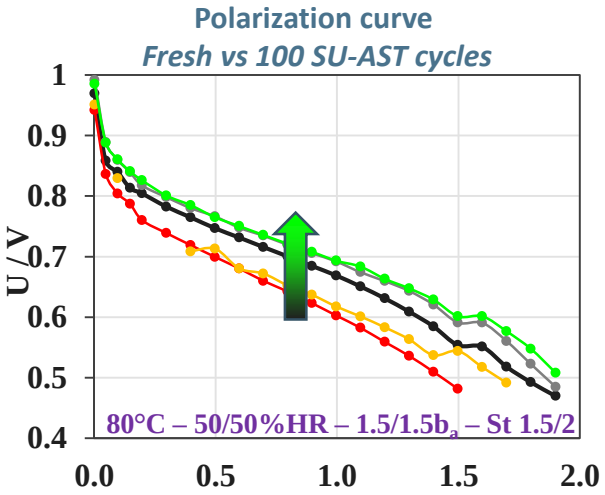
- **Harsh voltage loss** along overall polarization curve

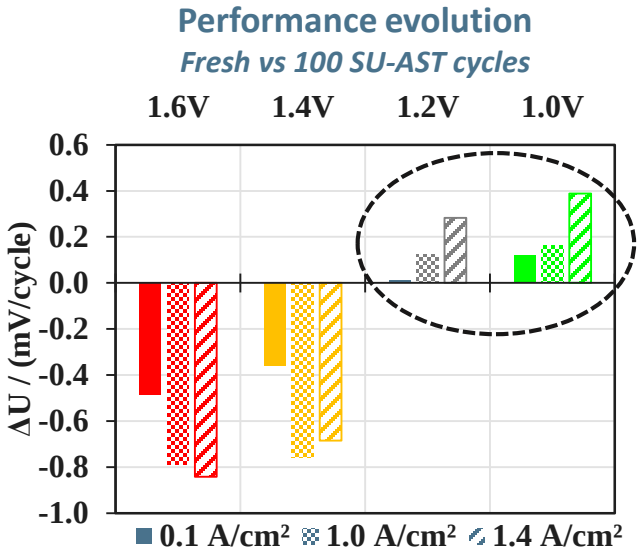
In-situ SU-AST results

E_{front} investigation – Cell voltage evolution



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V





1.0 – 1.2 V range

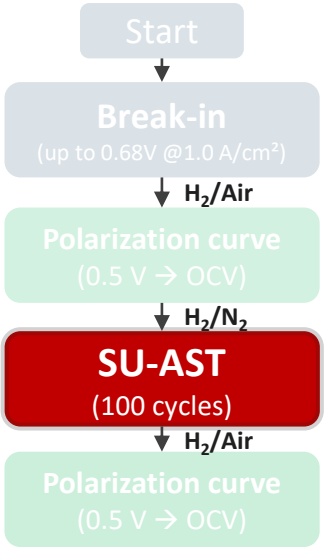
- Unexpected **improvement of cell performance** (even after 100 cycles)

1.4 – 1.6 V range

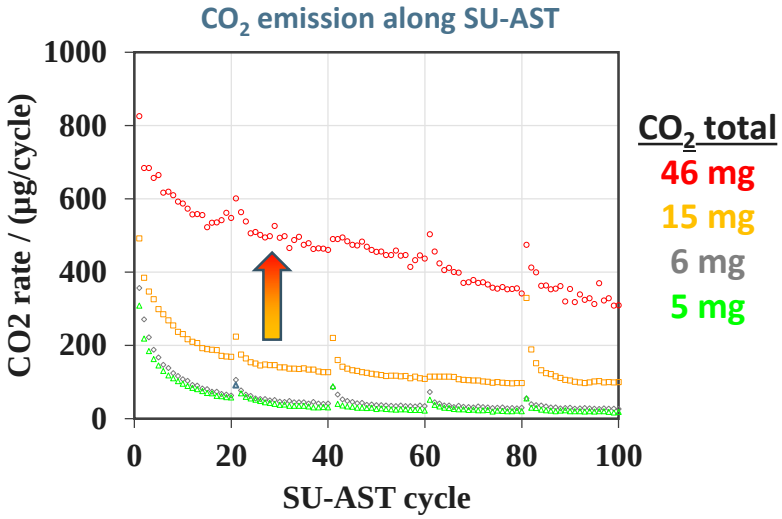
- **Harsh voltage loss** along overall polarization curve

In-situ SU-AST results

E_{front} investigation – CO_2 measurements



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V



1.0 – 1.2 V range

- Unexpected **improvement of cell performance**
- **Low CO_2 emission rate** expected during the first 20 cycles

1.4 – 1.6 V range

- **Harsh voltage loss** along overall polarization curve
- **Higher CO_2 emission** rate for 1.6 V case along cycles

In-situ SU-AST results

E_{front} investigation – CO_2 measurments

Start

↓

Break-in
(up to 0.68V @1.0 A/cm²)

↓ H_2/Air

Polarization curve
(0.5 V → OCV)

↓ H_2/N_2

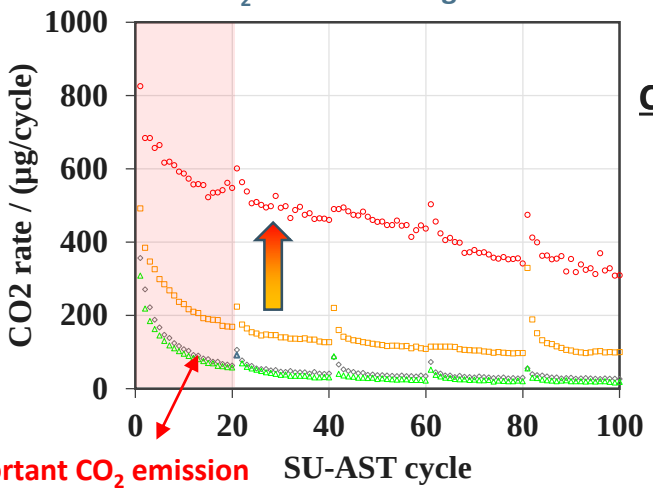
SU-AST
(100 cycles)

↓ H_2/Air

Polarization curve
(0.5 V → OCV)

Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V

CO_2 emission along SU-AST



CO_2 total
46 mg
15 mg
6 mg
5 mg

Important CO_2 emission during the first cycles

1.0 – 1.2 V range

- Unexpected **improvement of cell performance**
- **Low CO_2 emission rate** expected during the first 20 cycles

→ **CSC of only poorly ordered domains**

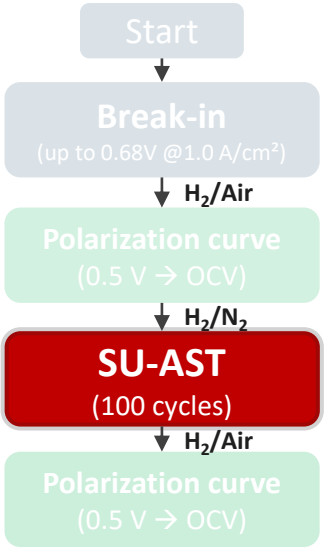
1.4 – 1.6 V range

- **Harsh voltage loss** along overall polarization curve
- **Higher CO_2 emission rate** for 1.6 V case along cycles

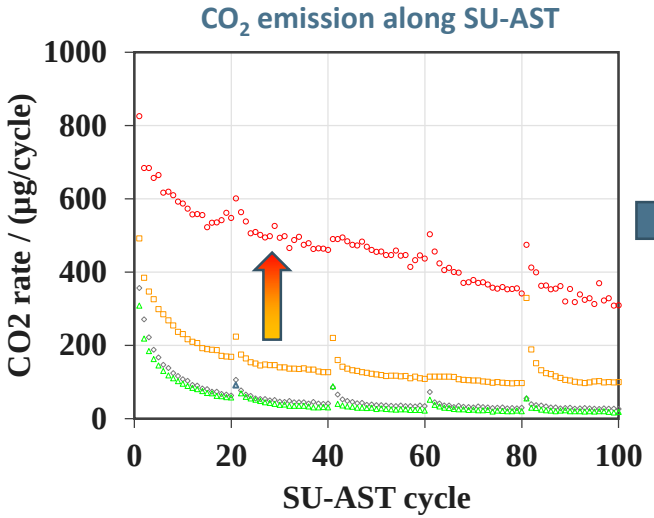
→ **CSC of poorly and more ordered domains**

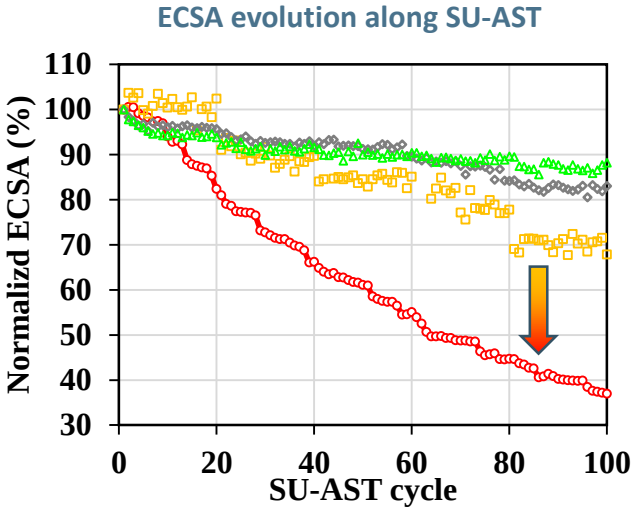
In-situ SU-AST results

E_{front} investigation – CV evolution



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V





1.0 – 1.2 V range

- Unexpected **improvement of cell performance**
- **Low CO_2 emission rate** expected during the first 20 cycles

→ **CSC of poorly ordered domains**
→ **Pt Dissolution/redeposition**

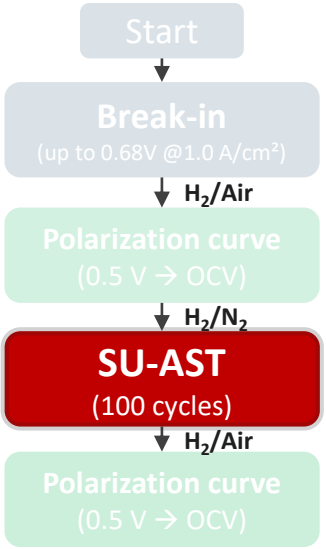
1.4 – 1.6 V range

- **Harsh voltage loss** along overall polarization curve
- **Higher CO_2 emission rate** for 1.6 V case along cycles

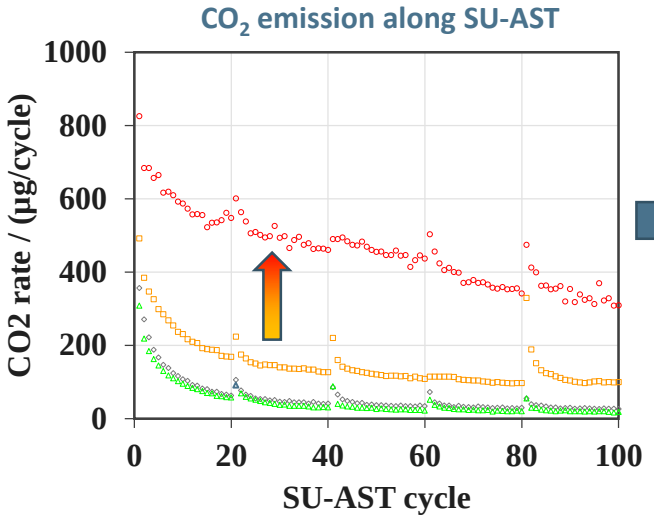
→ **CSC of poorly and more ordered domains [1]**
→ **Pt dissolution/reposition +**
Pt detachement/agglomeration (linked to CSC)

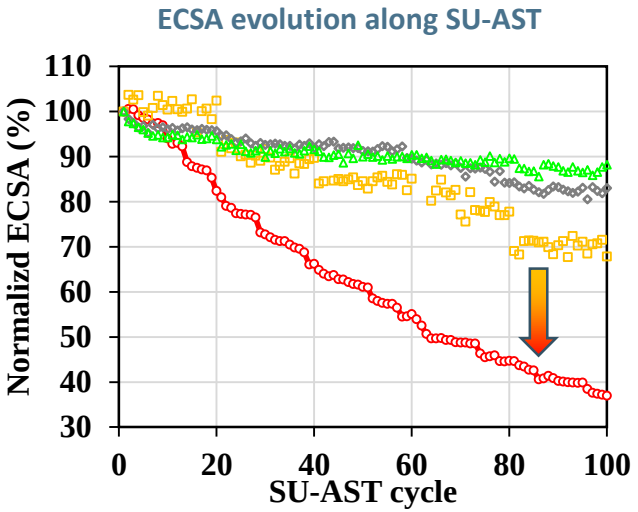
In-situ SU-AST results

E_{front} investigation – Conclusion



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V





1.0 – 1.2 V range

- Unexpected **improvement of cell performance**
- **Low CO_2 emission rate** expected during the first 20 cycles

→ **CSC of poorly ordered domains**
→ **Pt Dissolution/redeposition**

1.4 – 1.6 V range

- **Harsh voltage loss** along overall polarization curve
- **Higher CO_2 emission rate** for 1.6 V case along cycles

→ **CSC of poorly and more ordered domains [1]**
→ **Pt dissolution/reposition +**
Pt detachement/agglomeration (linked to CSC)

→ Validation & Quantification of the **mitigation of performance decay by lowering E_{front} potential**
→ Further insights on degradation mechanisms through a ***post-mortem* study**

Post-mortem Protocol

In-situ AST

Start

Break-in
(up to 0.68V @1.0 A/cm²)

H_2/Air

Polarization curve
(0.5 V → OCV)

H_2/N_2

SU-AST
(100 cycles)

H_2/Air

Polarization curve
(0.5 V → OCV)

Post-mortem AST

X3 operating conditions
↓
80°C - 50%HR*
80°C - 80%HR*
80°C - 100%HR*

Polarization curve
@0.1 V → OCV

PEIS (H_2/Air)
@0.85 – 0.675 – 0.5 V

H_2/N_2

CV @50 $mV.s^{-1}$
(0.065 → 1.0 V)

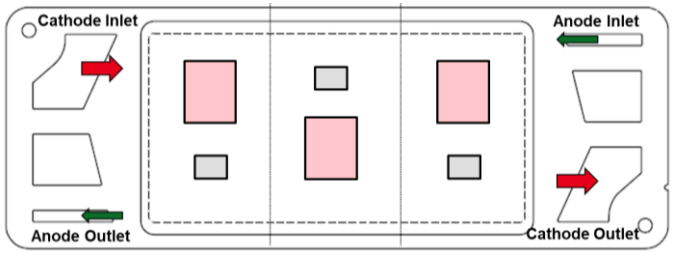
PEIS (H_2/N_2)
@0.4 V

SEM

End

*1.5/1.5 bar_a – St 50/50

Cutting sample of fresh / aged MEA



Post-mortem Protocol

In-situ AST

Start

Break-in
(up to 0.68V @1.0 A/cm²)

H_2/Air

Polarization curve
(0.5 V → OCV)

H_2/N_2

SU-AST
(100 cycles)

H_2/Air

Polarization curve
(0.5 V → OCV)

Post-mortem AST

X3 operating conditions
↓
80°C - 50%HR*
80°C - 80%HR*
80°C - 100%HR*

Polarization curve
@0.1 V → OCV

PEIS (H_2/Air)
@0.85 – 0.675 – 0.5 V

H_2/N_2

CV @50 $mV.s^{-1}$
(0.065 → 1.0 V)

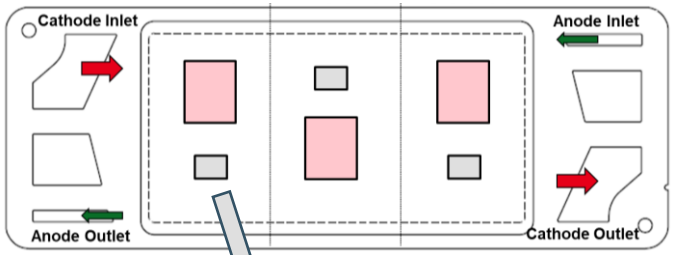
PEIS (H_2/N_2)
@0.4 V

SEM

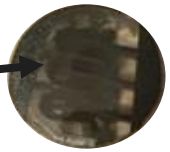
End

*1.5/1.5 bar_a – St 50/50

Cutting sample of fresh / aged MEA



7-layer MEA (side view)



Local structural analysis
By
Scanning Electron Microscopy (SEM)

Post-mortem Protocol

In-situ AST

Start

Break-in
(up to 0.68V @1.0 A/cm²)

H_2/Air

Polarization curve
(0.5 V → OCV)

H_2/N_2

SU-AST
(100 cycles)

H_2/Air

Polarization curve
(0.5 V → OCV)

Post-mortem AST

X3 operating conditions
↓
80°C - 50%HR*
80°C - 80%HR*
80°C - 100%HR*

Polarization curve
@0.1 V → OCV

PEIS (H_2/Air)
@0.85 – 0.675 – 0.5 V

H_2/N_2

CV @50 $mV.s^{-1}$
(0.065 → 1.0 V)

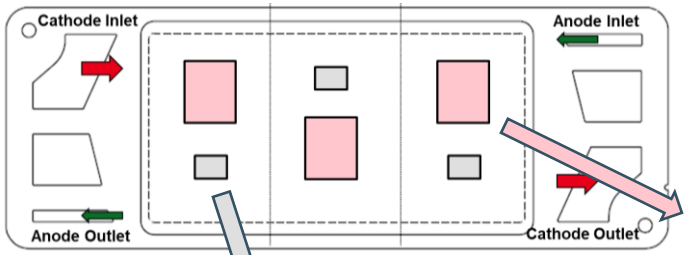
PEIS (H_2/N_2)
@0.4 V

SEM

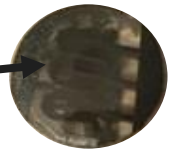
End

*1.5/1.5 bar_a – St 50/50

Cutting sample of fresh / aged MEA



7-layer MEA (side view)



7-layer MEA (front view)



1.8 cm² MEA sample

Local structural analysis
By
Scanning Electron Microscopy (SEM)

Local EC analysis
By
- **Polarization**
- **CV**
- **Impedance Spectroscopy (PEIS)**

Post-mortem Protocol

In-situ AST

Start

Break-in
(up to 0.68V @1.0 A/cm²)

H_2/Air

Polarization curve
(0.5 V → OCV)

H_2/N_2

SU-AST
(100 cycles)

H_2/Air

Polarization curve
(0.5 V → OCV)

Post-mortem AST

X3 operating conditions
↓
80°C - 50%HR*
80°C - 80%HR*
80°C - 100%HR*

Polarization curve
@0.1 V → OCV

PEIS (H_2/Air)
@0.85 – 0.675 – 0.5 V

H_2/N_2

CV @50 mV.s^{-1}
(0.065 → 1.0 V)

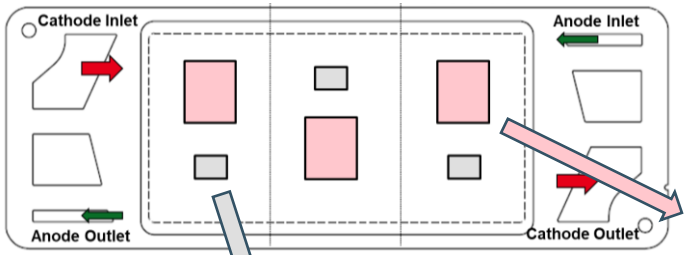
PEIS (H_2/N_2)
@0.4 V

SEM

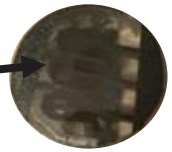
End

*1.5/1.5 bar$_a$ – St 50/50

Cutting sample of fresh / aged MEA



7-layer MEA (side view)



7-layer MEA (front view)



1.8 cm² MEA sample

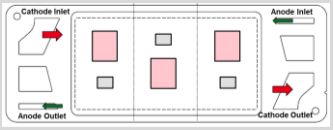
Local structural analysis
By
Scanning Electron Microscopy (SEM)

Local EC analysis
By
- **Polarization**
- **CV**
- **Impedance Spectroscopy (PEIS)**

- ***Reproducibility on fresh MEA ✓***
- ***Homogeneity (inlet – middle – outlet) on aged MEA @1.6 – 1.4 V ✓***

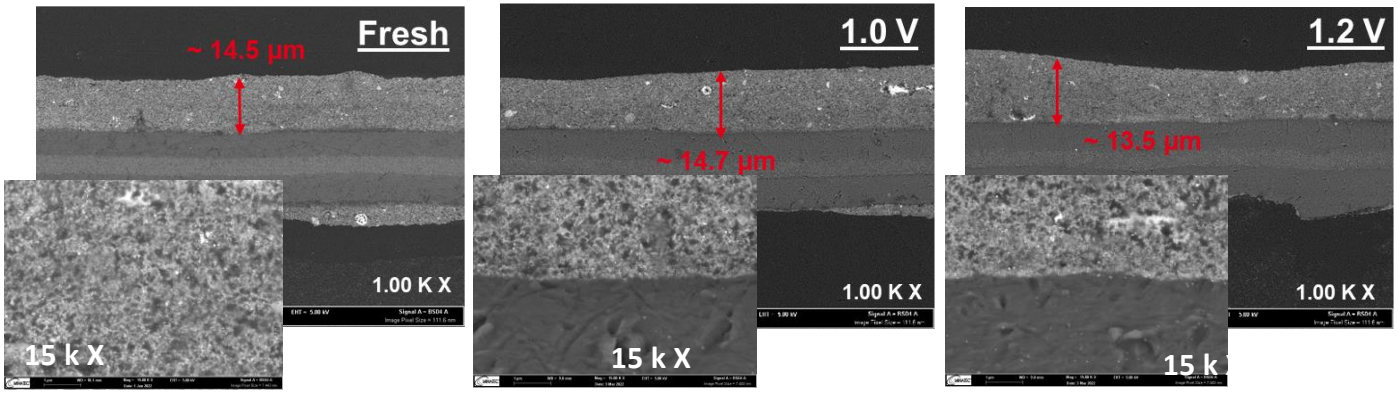
Post-mortem RESULTS

SEM observation



Low thinning from fresh to 1.2 V aged commercial MEA

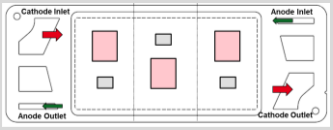
Fresh **1.0 V** **1.2 V**



- **No CCL structural modification** from fresh to aged MEA at 1.2 V

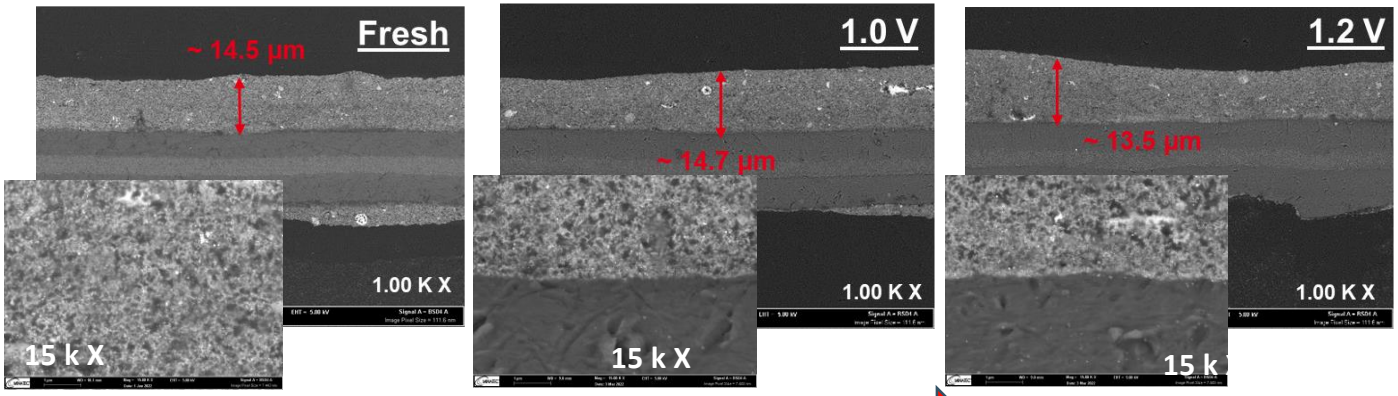
Post-mortem RESULTS

SEM observation



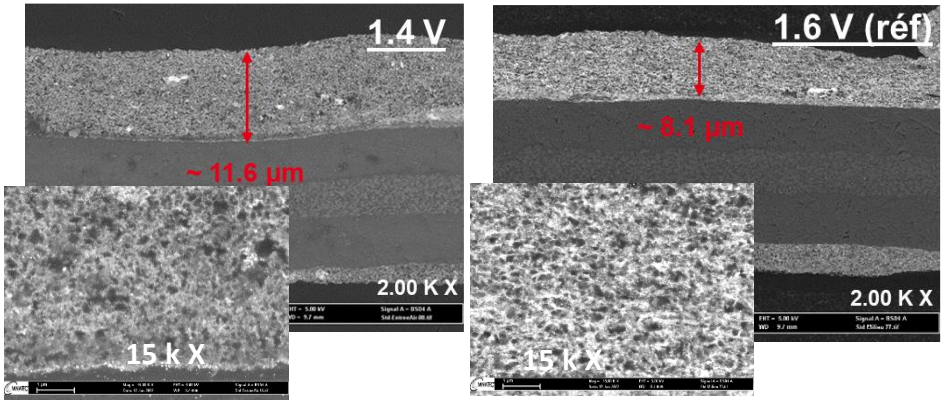
Low thinning from fresh to 1.2 V aged commercial MEA

Fresh | **1.0 V** | **1.2 V**

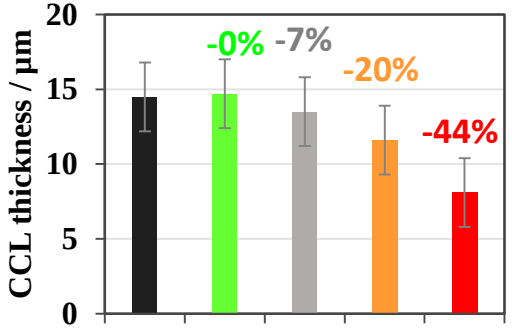


High thinning beyond 1.4 V

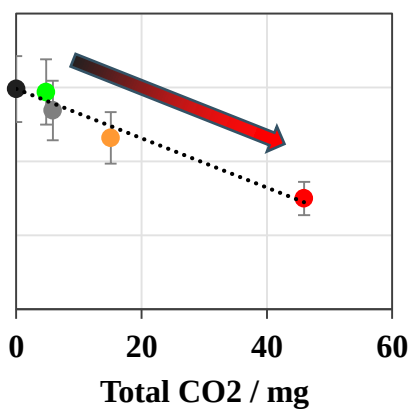
1.4 V | **1.6 V**



Estimated CCL thickness



CCL thickness VS CO_2

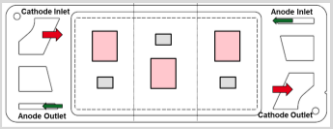


- **No CCL structural modification** from fresh to aged MEA at 1.2 V
- **Low compaction of CCL and densification of Pt nanoparticles** at 1.4 V and **harsher at 1.6 V**

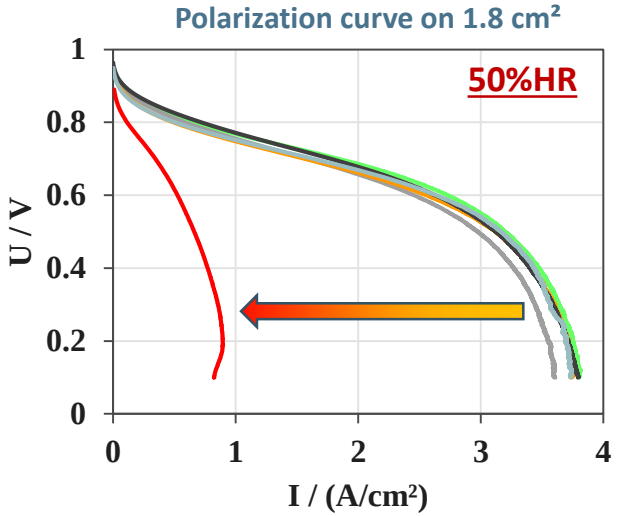
→ **Linear correlation with CSC mechanisms**

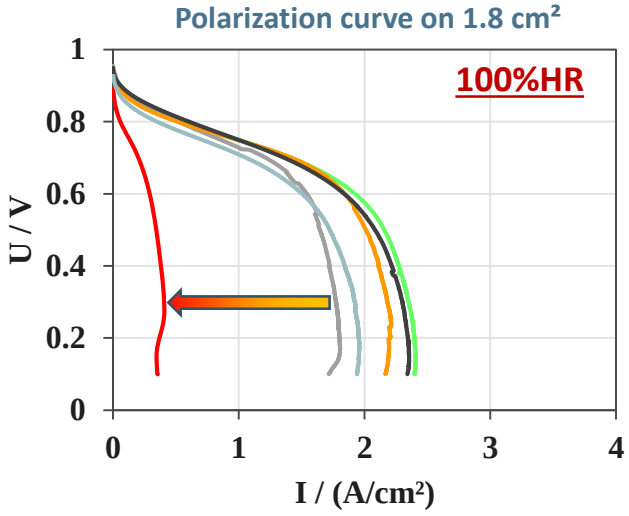
Post-mortem RESULTS

Local polarization curve



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V



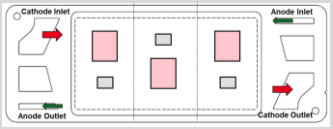


- **At 50 %HR** : No performance decay excepted for 1.6 V case

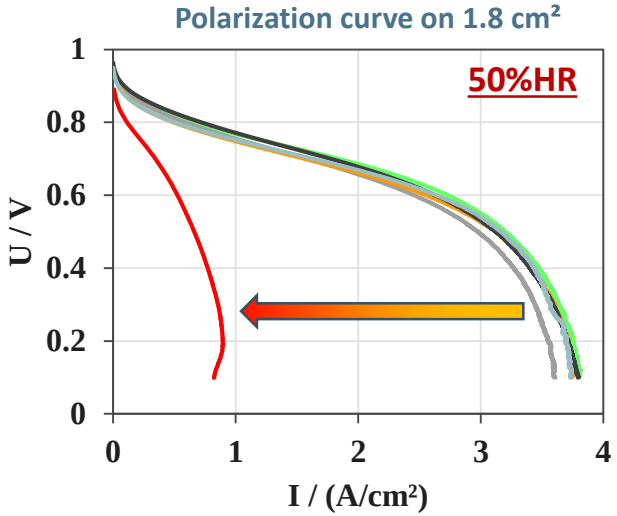
  ↓
- **At 100 %HR** : Emergence of progressive performance decay

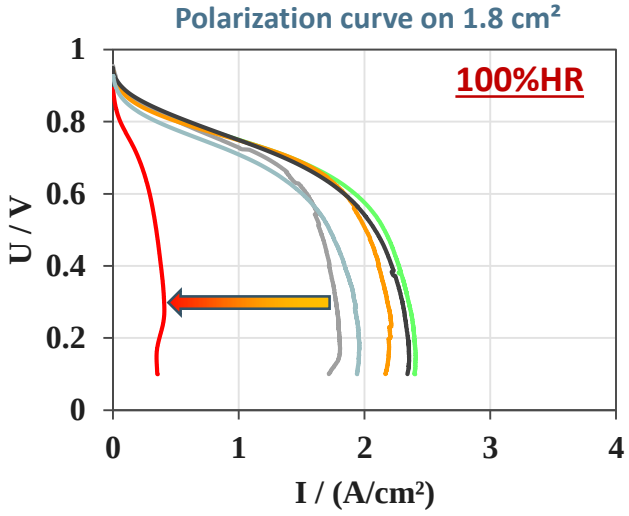
Post-mortem RESULTS

Local polarization curve



Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V





- **At 50 %HR** : No performance decay excepted for 1.6 V case

↓

- **At 100 %HR** : Emergence of progressive performance decay

- **Improvement of performance for 1.0 V** case similar as in previous in-situ SU-AST (98 cm²)

→ **Mass transport limitation is more pronounced At higher RH**

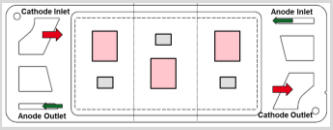
↓

→ **Water management is altered** due to **CCL chemical and/or electrochemical modifications**:

i. Loss of hydrophobicity
ii. Modification of carbon surface properties
iii. Higher Pt/C loading ratio due to carbon support corrosion

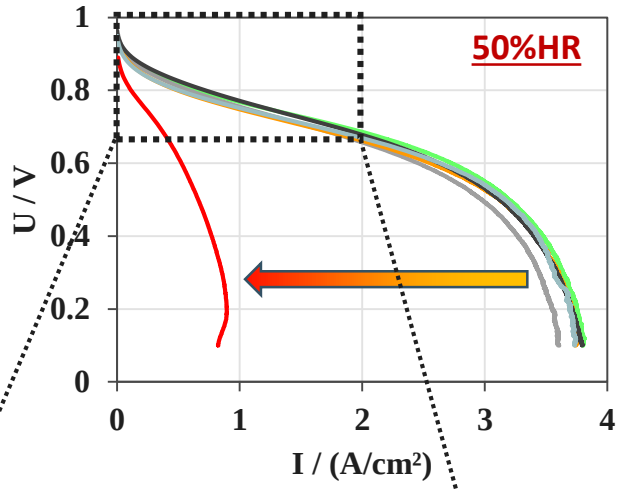
Post-mortem RESULTS

Local polarization curve

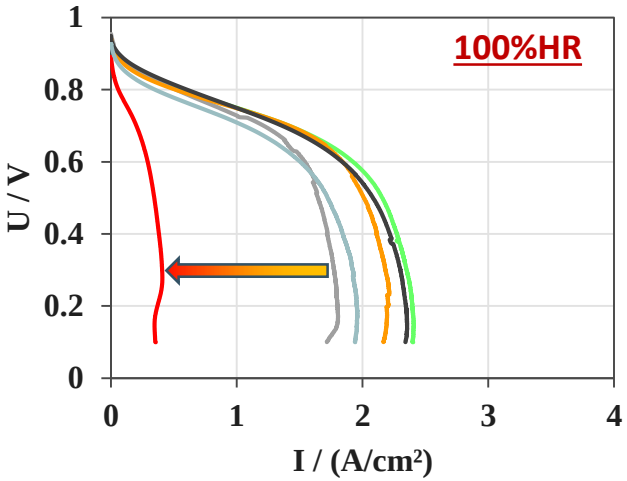


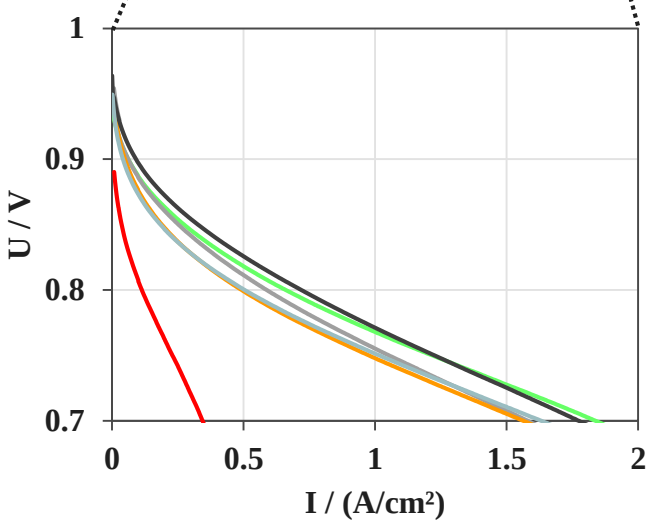
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V

Polarization curve on 1.8 cm²



Polarization curve on 1.8 cm²

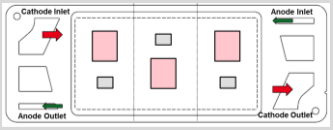




- By zooming in **low current density region** (< 2 A/cm²)
  - → **Loss of cell performance** for every case
  - → **Probably linked to Pt ECSA decrease**

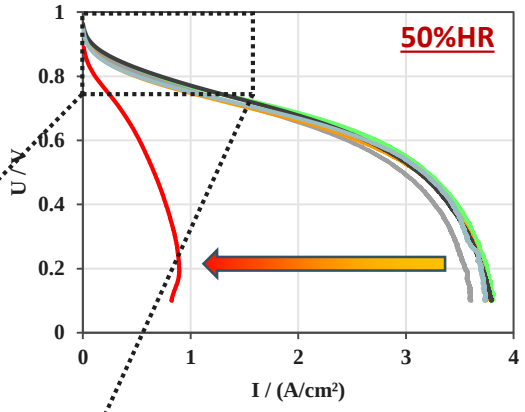
Post-mortem RESULTS

PEIS (H_2/Air) @0.85 V

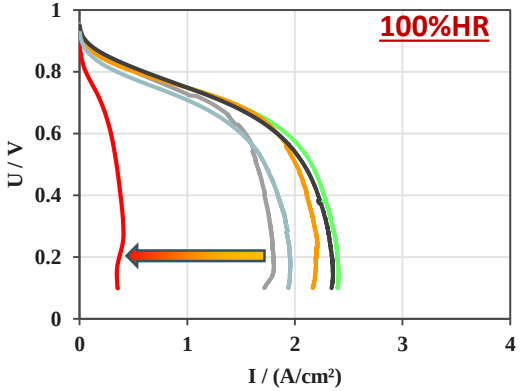


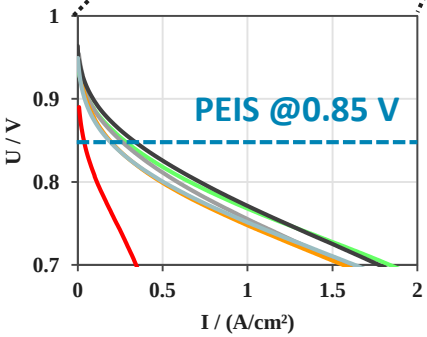
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

Polarization curve on 1.8 cm²



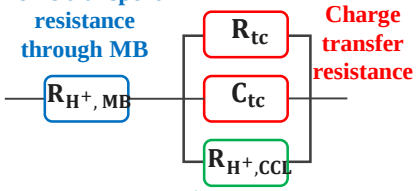
Polarization curve on 1.8 cm²





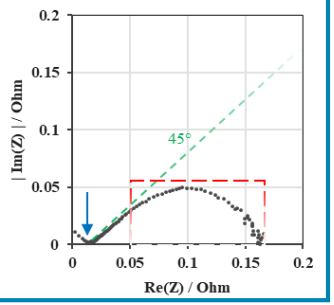
PEIS model (H_2/Air)

Ionic transport resistance through MB



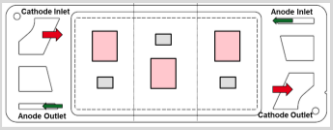
Charge transfer resistance

Ionic transport resistance through CCL



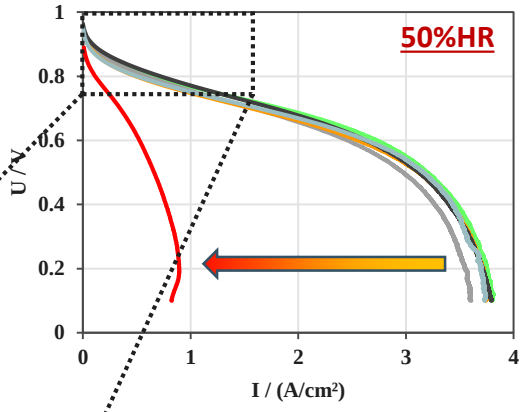
Post-mortem RESULTS

PEIS (H_2/Air) @0.85 V

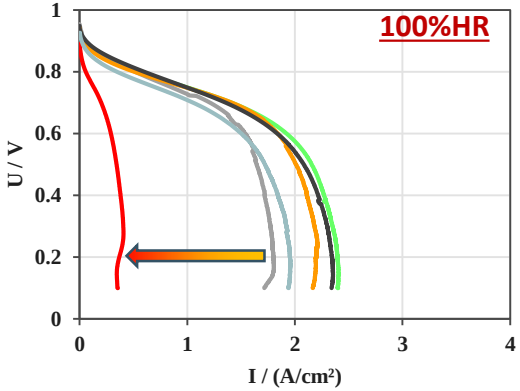


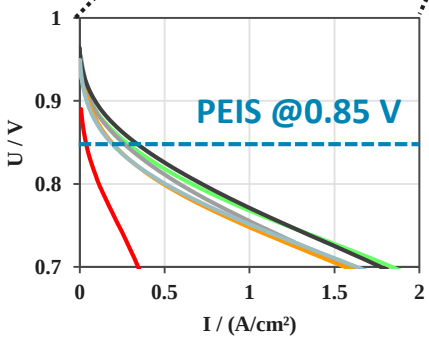
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

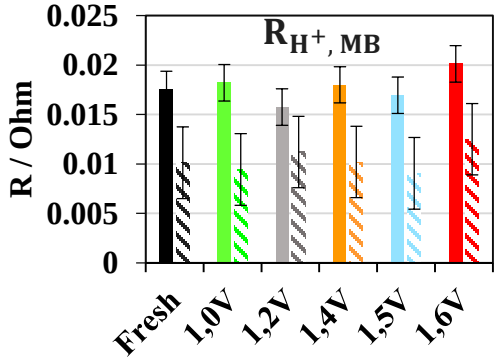
Polarization curve on 1.8 cm²



Polarization curve on 1.8 cm²







■ @50/50%RH
▨ @100/100%RH

PEIS model (H_2/Air)

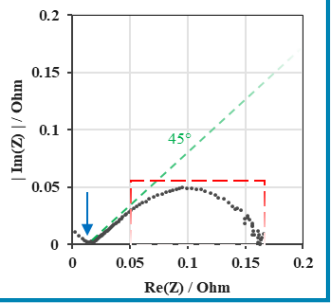
Ionic transport resistance through MB

$R_{H^+, MB}$

R_{tc} | C_{tc} | $R_{H^+,CCL}$

Charge transfer resistance

Ionic transport resistance through CCL

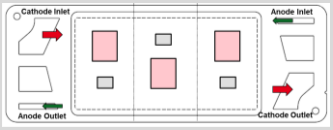


No high frequency resistance variation

→ **Protonic conductivity of the membrane is conserved during SU-AST**

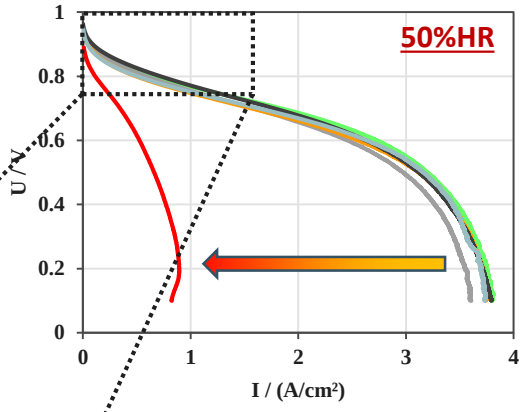
Post-mortem RESULTS

PEIS (H_2/Air) @0.85 V

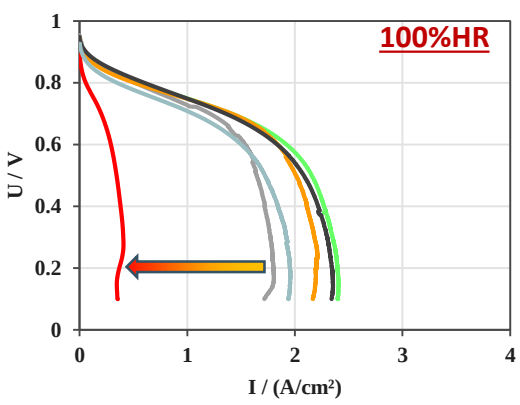


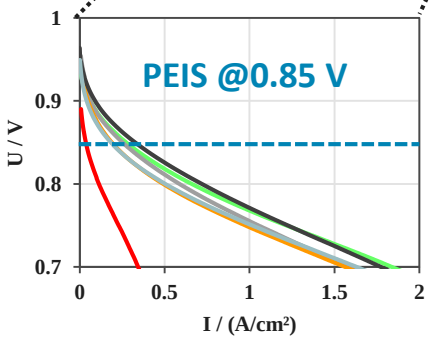
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

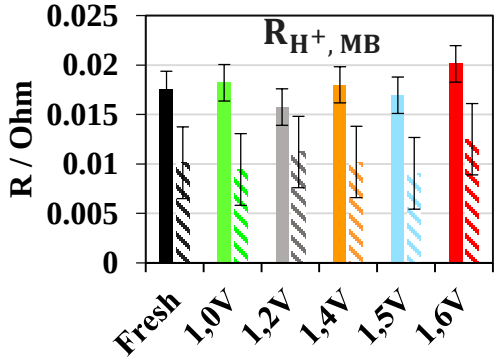
Polarization curve on 1.8 cm²

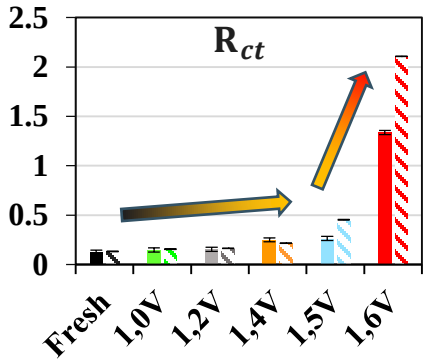


Polarization curve on 1.8 cm²







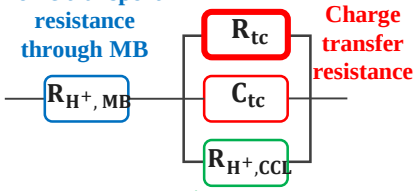


@50/50%RH

@100/100%RH

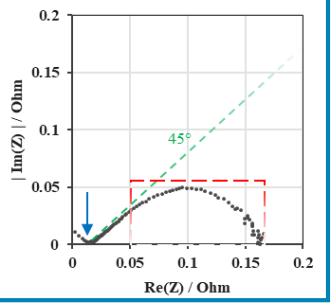
PEIS model (H_2/Air)

Ionic transport resistance through MB



Charge transfer resistance

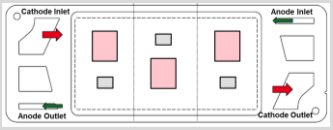
Ionic transport resistance through CCL



- **Slight increase of charge transfer resistance** from fresh up to aged MEA at 1.4 V
- **High increase of R_{ct} value above 1.5 V**

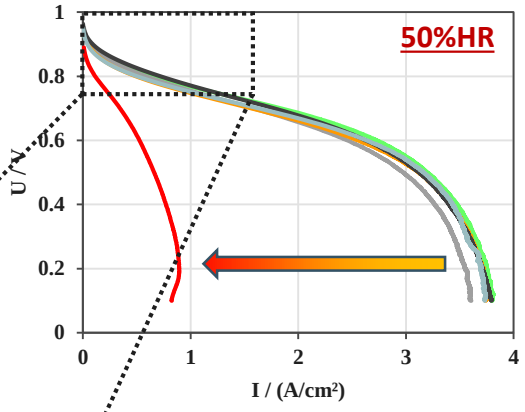
Post-mortem RESULTS

PEIS (H_2/Air) @0.85 V vs ECSA

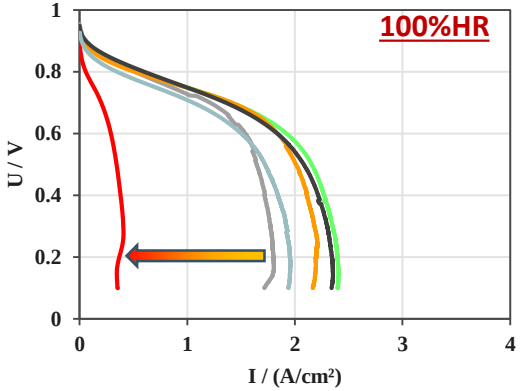


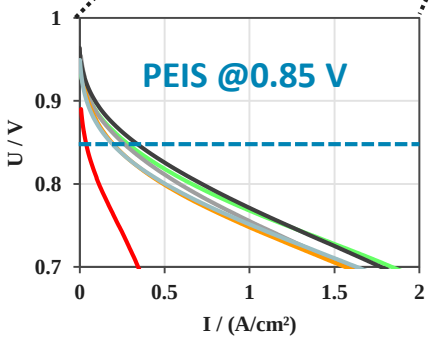
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

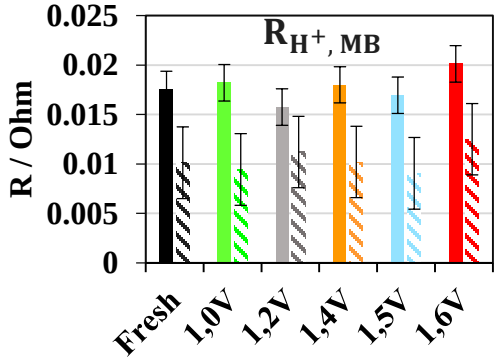
Polarization curve on 1.8 cm²

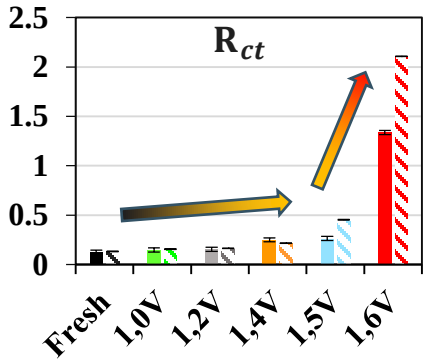


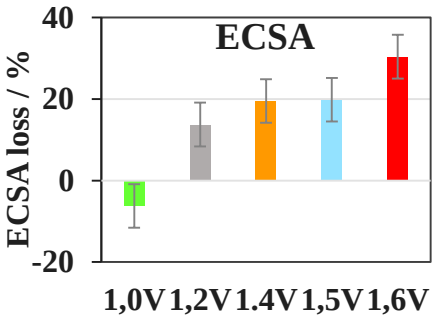
Polarization curve on 1.8 cm²









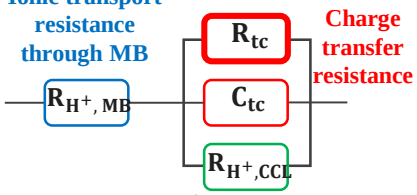


■ @50/50%RH

▨ @100/100%RH

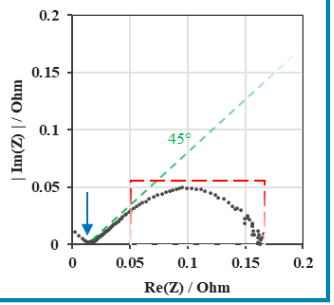
PEIS model (H_2/Air)

Ionic transport resistance through MB



Charge transfer resistance

Ionic transport resistance through CCL

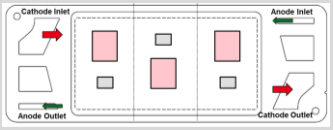


→ R_{ct} evolution cannot be fully linked to ECSA loss and thus Pt degradations

→ Other limiting mechanisms above 1.5 V

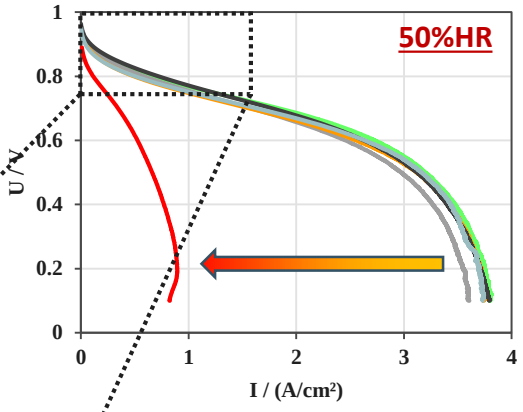
Post-mortem RESULTS

PEIS (H_2/Air) @0.85 V

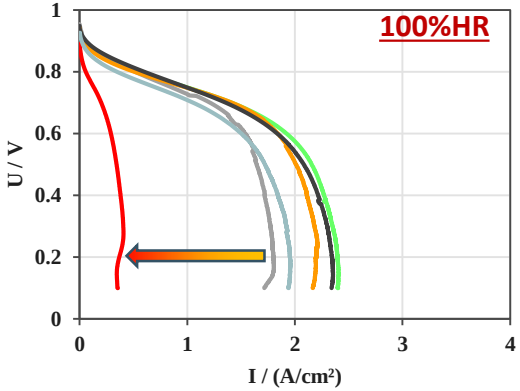


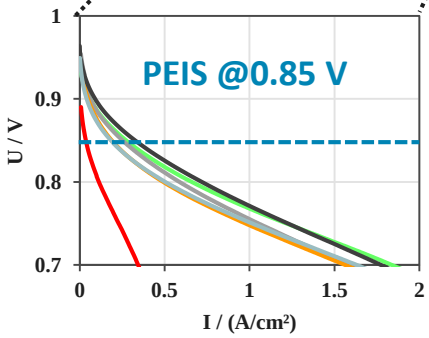
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

Polarization curve on 1.8 cm²



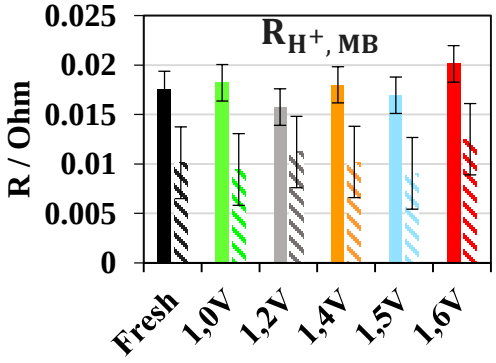
Polarization curve on 1.8 cm²

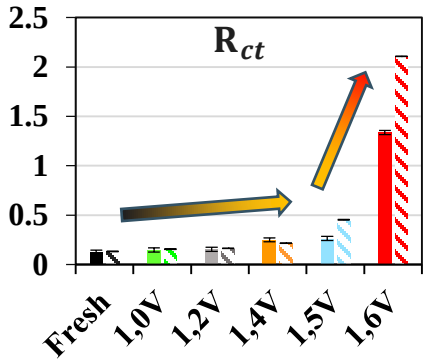


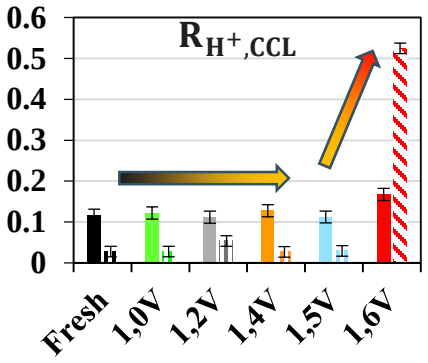


■ @50/50%RH

▨ @100/100%RH

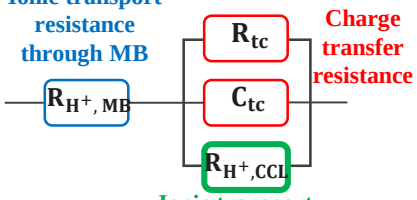






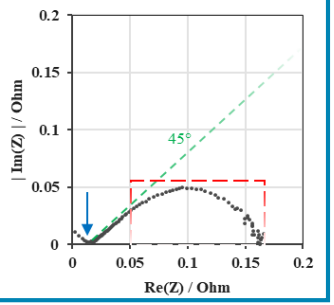
PEIS model (H_2/Air)

Ionic transport resistance through MB



Charge transfer resistance

Ionic transport resistance through CCL

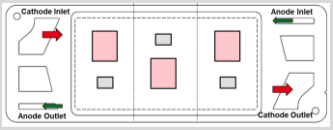


- **No significant variation for CCL protonic transport resistance** from fresh up to aged MEA at 1.5 V
- Drastic $R_{H^+,CCL}$ increase for 1.6 V case in FC operation

→ **Modification of proton transport properties in CCL due to carbon support collapse ?**

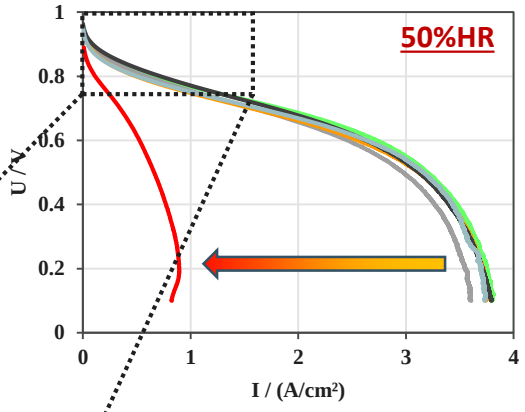
Post-mortem RESULTS

PEIS (H_2/N_2) @0.4 V

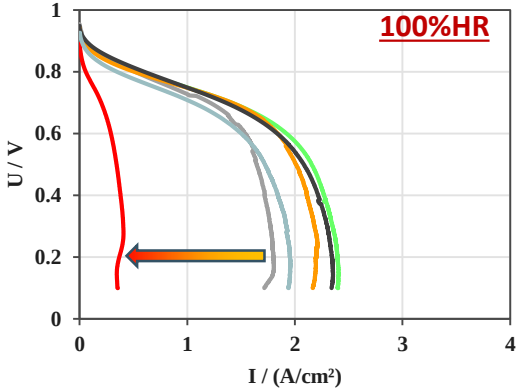


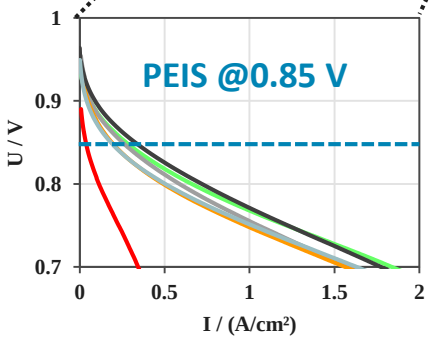
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)

Polarization curve on 1.8 cm²



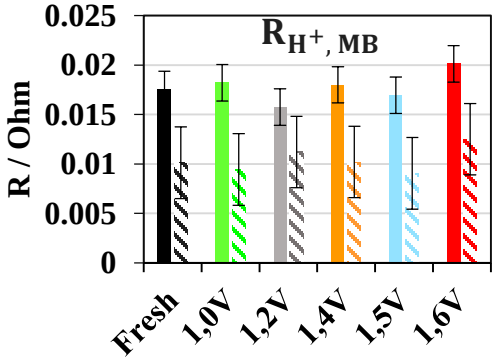
Polarization curve on 1.8 cm²

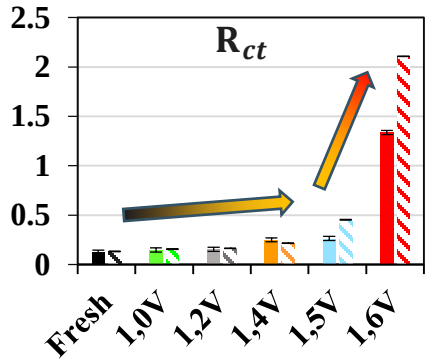


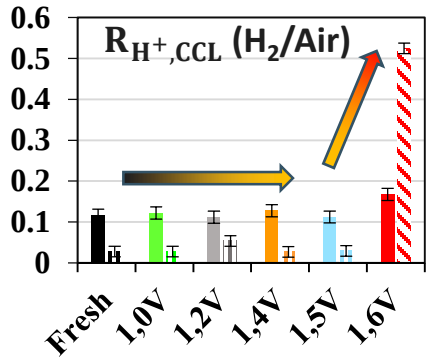


@50/50%RH

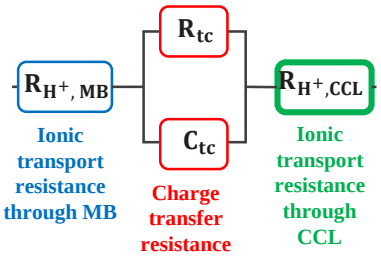
@100/100%RH

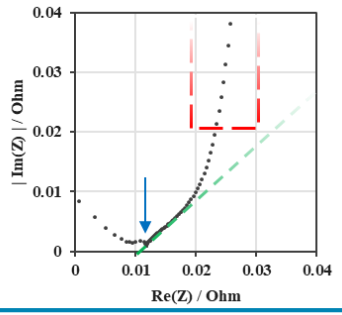






PEIS model (H_2/N_2)

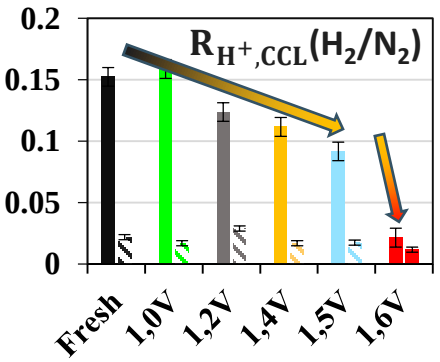




- Progressive reduction R_{H+} in CCL under N_2 when E_{front} is increased
- Drastic decrease in proton resistance at 1.6 V at 50%RH

→ Higher water retention in damaged CCL ?

→ To be confirmed by additional tenchiques



CONCLUSION & PERSPECTIVES

- **Validation of complete *in-situ* & *post-mortem* investigation by:**
  - Electrochemical and physico-chemical analysis on large (98 cm^2) and localized small (1.8 cm^2) MEA areas

- **Mitigating parameters confirmed and quantified** with represented potential profile in real flow field design:
  - E_{front}: **Lowering cathode potential** by by-passing electrical current through dummy load
  - t_{front}: **Lowering exposure time** by accelerating H_2 injection in Air-filled anode
  - $RH_{a/c}$: **Flushing cell with dry gas** before H_2 injection
  - T_{cell}: **Lowering stack temperature** before H_2 injection

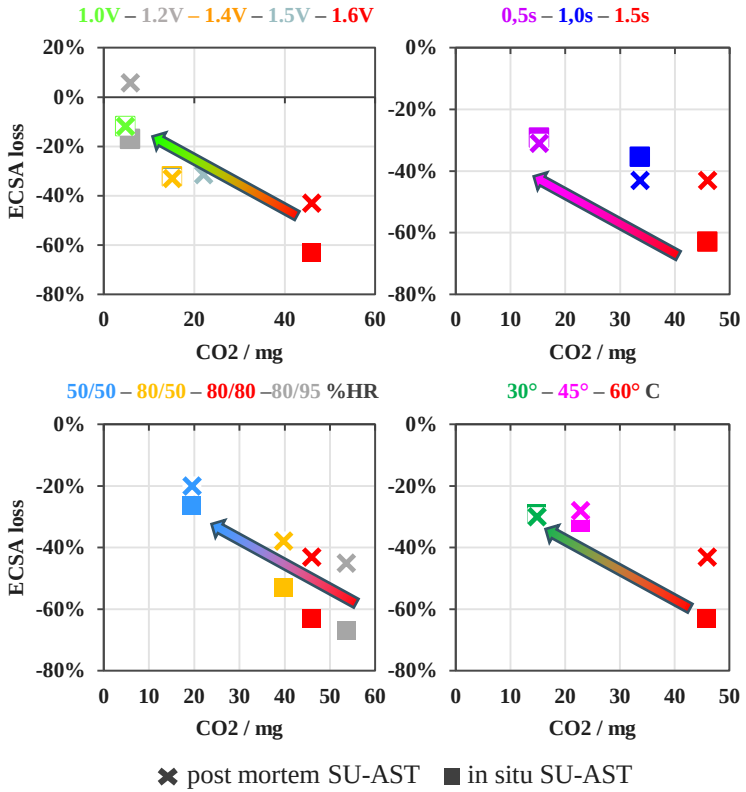
- **Complex degradation mechanism revealed:**
  - Weaker water management for damaged MEA in our SU-AST beyond 1.4 V
  - Better cell performance for damaged MEA at 1.0 V
  - Further insights on degradation mechanisms by using:
    - **Water sorption measurements**
    - **Raman spectroscopy** → Investigation of amorphous and graphitized domains into CCL
    - **XPS technique** →Investigation of functional groups onto carbon surface



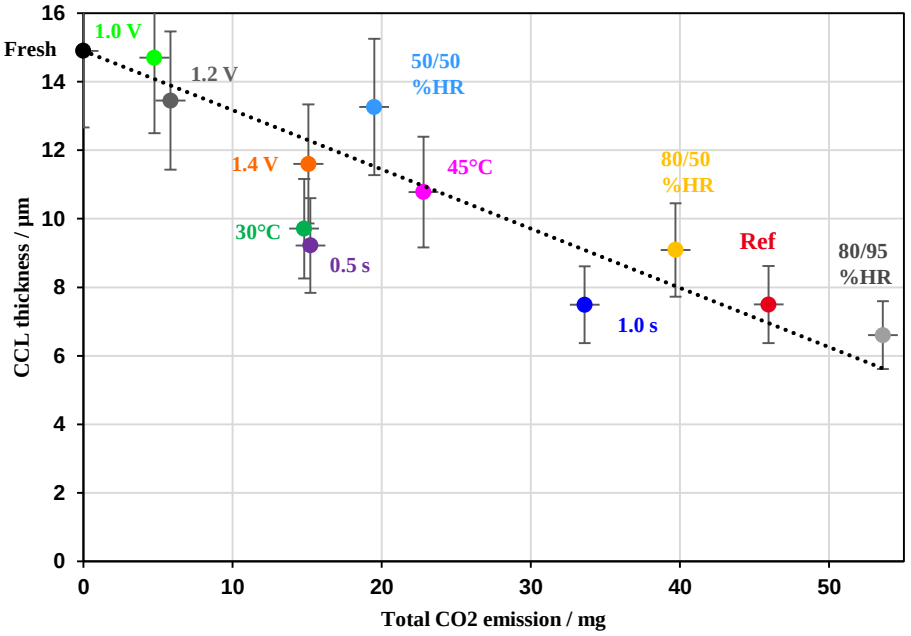
Thank for your attention

Timothée DRUGEOT

ECSA loss VS CO_2 emission



CCL thickness VS CO_2 emission



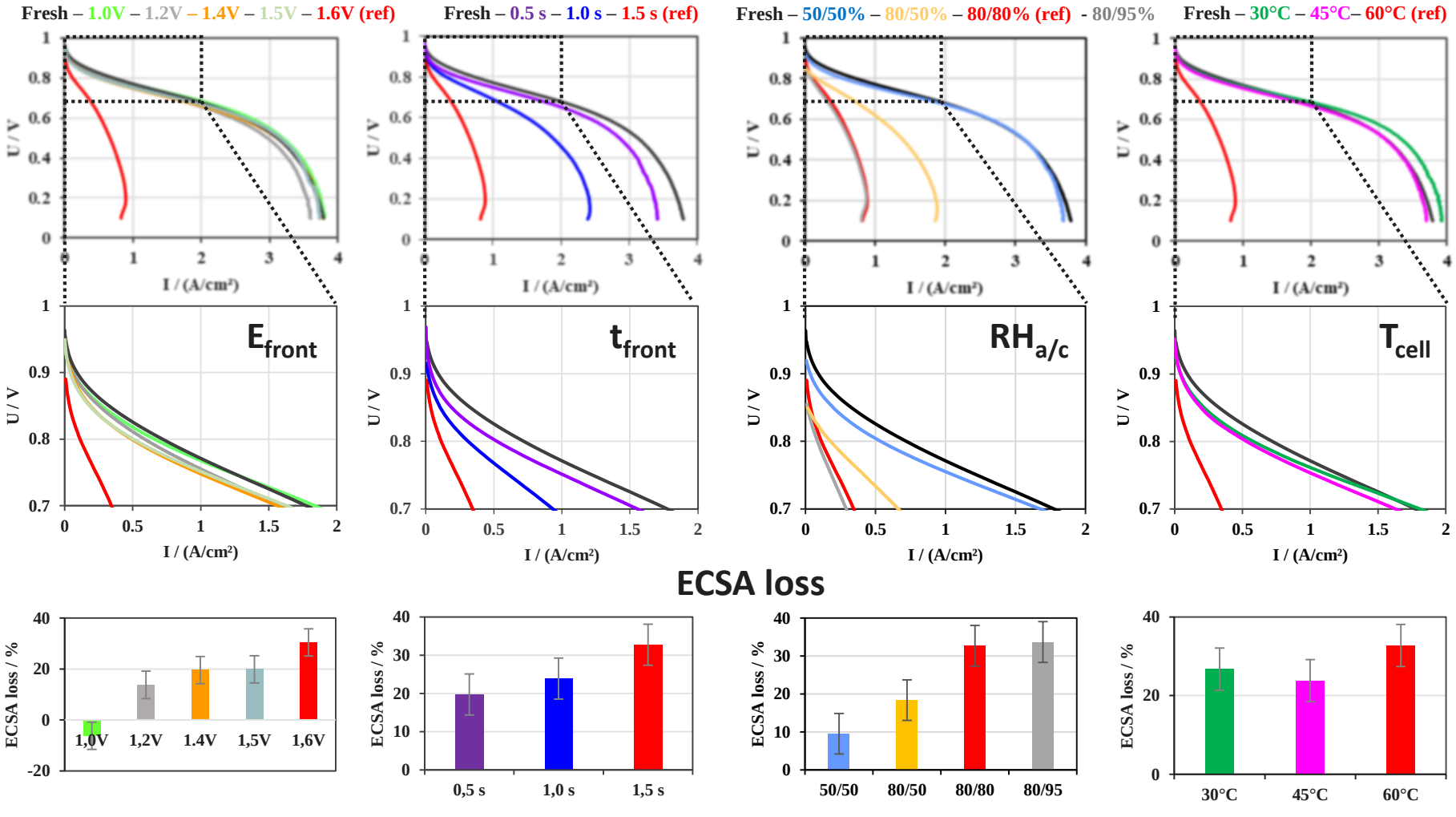
Lowering E_{front} / t_{front} / HR / T_{cell}

→ **Reduce CSC mechanism and Pt degradations**

→ **Reduce CCL thinning and thus loss of porosity**

→ **Require additional post-mortem analysis to validate water retention and degradation mechanisms**

80°C – 50/50%HR – 1.5/1.5b$_a$ – St 50/50

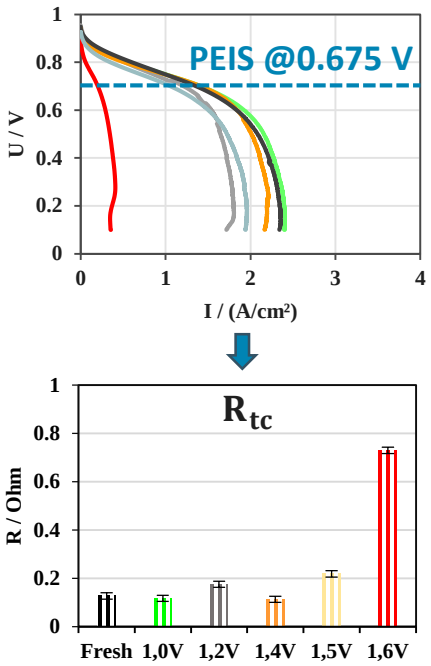


Post-mortem RESULTS

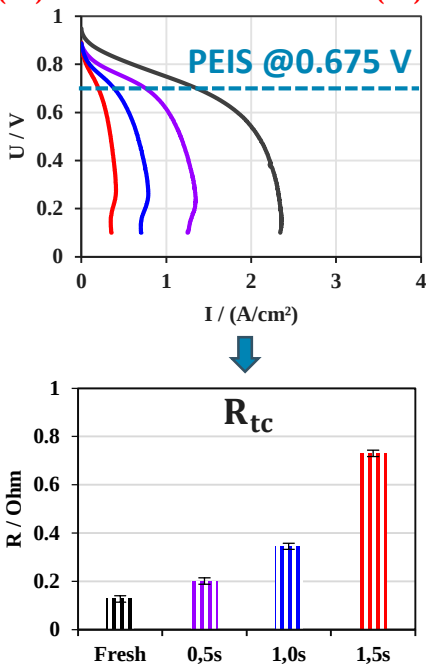
PEIS (H_2/Air) at high RH

80°C – 95/95%HR – 1.5/1.5b_a – St 50/50

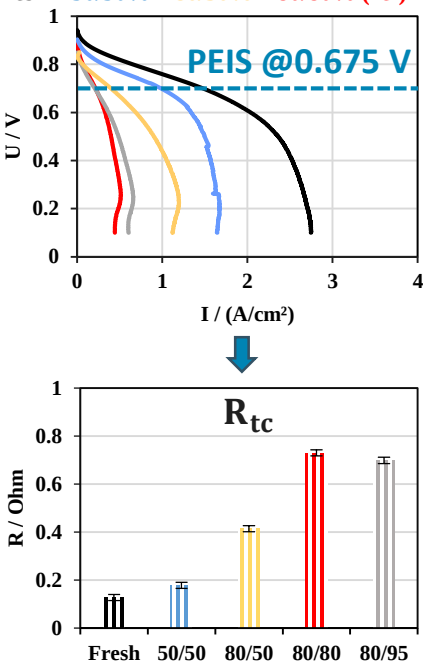
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)



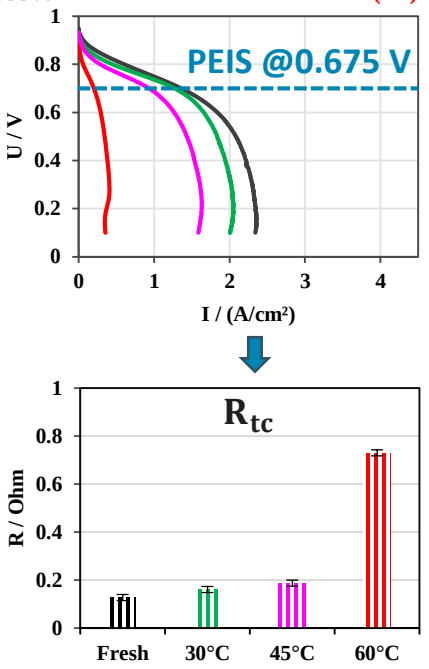
Fresh – 0.5 s – 1.0 s – 1.5 s (ref)



Fresh – 50/50% – 80/50% – 80/80% (ref) - 80/95%



Fresh – 30°C – 45°C– 60°C (ref)



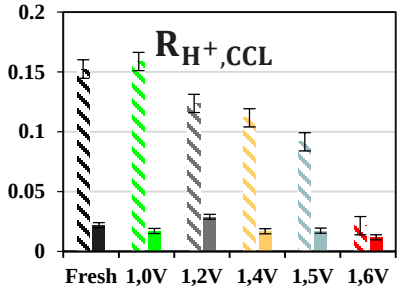
Post-mortem RESULTS

PEIS (H_2/N_2) at low and high RH : « Fresh » vs « Aged » MEA

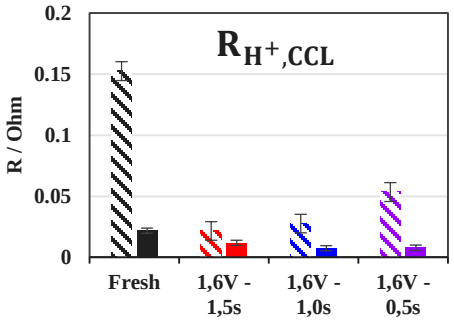
80°C – 1.5/1.5b_a – St 50/50

@50/50%RH **@100/100%RH**

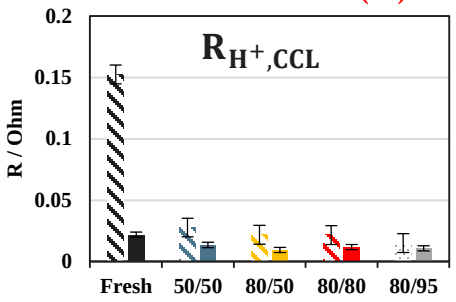
Fresh – 1.0V – 1.2V – 1.4V – 1.5V – 1.6V (ref)



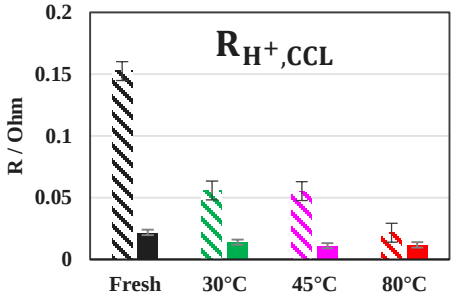
Fresh – 0.5 s – 1.0 s – 1.5 s (ref)

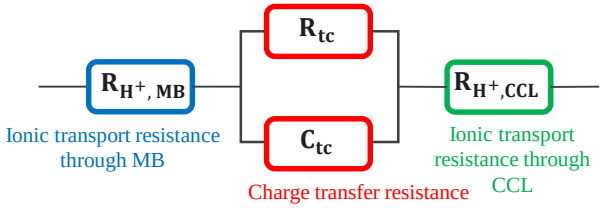


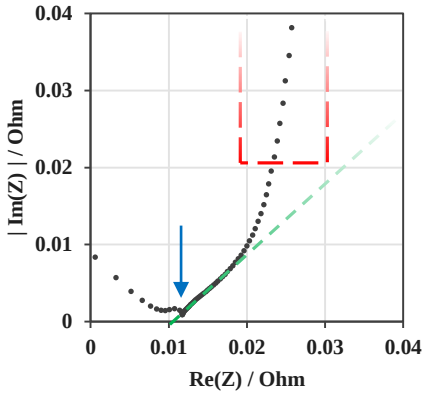
Fresh – 50/50% – 80/50% – 80/80% (ref) - 80/95%



Fresh – 30°C – 45°C– 60°C (ref)







PEIS at high HR condition (95/95% HR)

- Lower resistance with higher RH was excepted
- Lower resistance for more degraded CCL could be explained by :
  - A structural modification of ionomer phases with the carbon support collapse
  - A lower water removal abilities due to loss of hydrophobicity

→ Requires additional analysis (water sorption, Raman spectroscopy…)