

DEGRADATION MECHANISMS OF PEM FUEL CELLS

FREEZE START RELATED EXPERIMENTAL INVESTIGATIONS

BMW AG

CONTENT.

1. Introduction.

2. Method/Experiment.

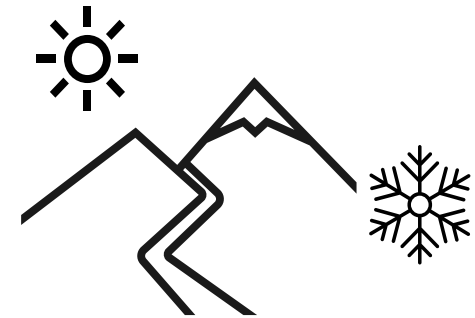
3. Results.

4. Outlook.

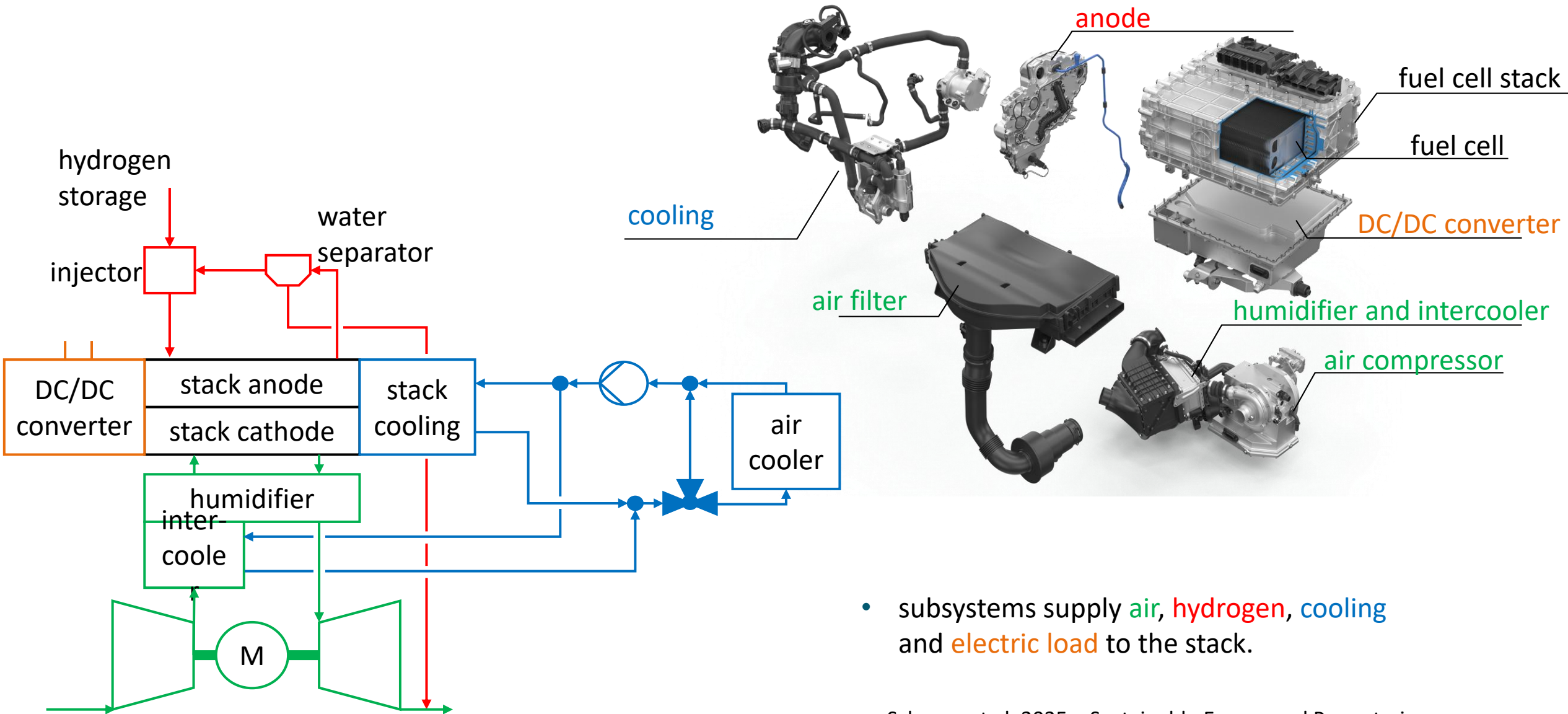


MOTIVATION.

- BMW Group follows the technology openness policy (offer of BEV, PHEV, ICE and FCEV).
- BMW ix5 Hydrogen will be offered as a series vehicle in 2028.
- Reliability and durability must be ensured under all environmental conditions (including winter operation).
- Further improvement of the freeze start strategy requires testing capacities.
- *How well can short-stack tests reproduce FCS freeze-start behavior and support durability investigations?*

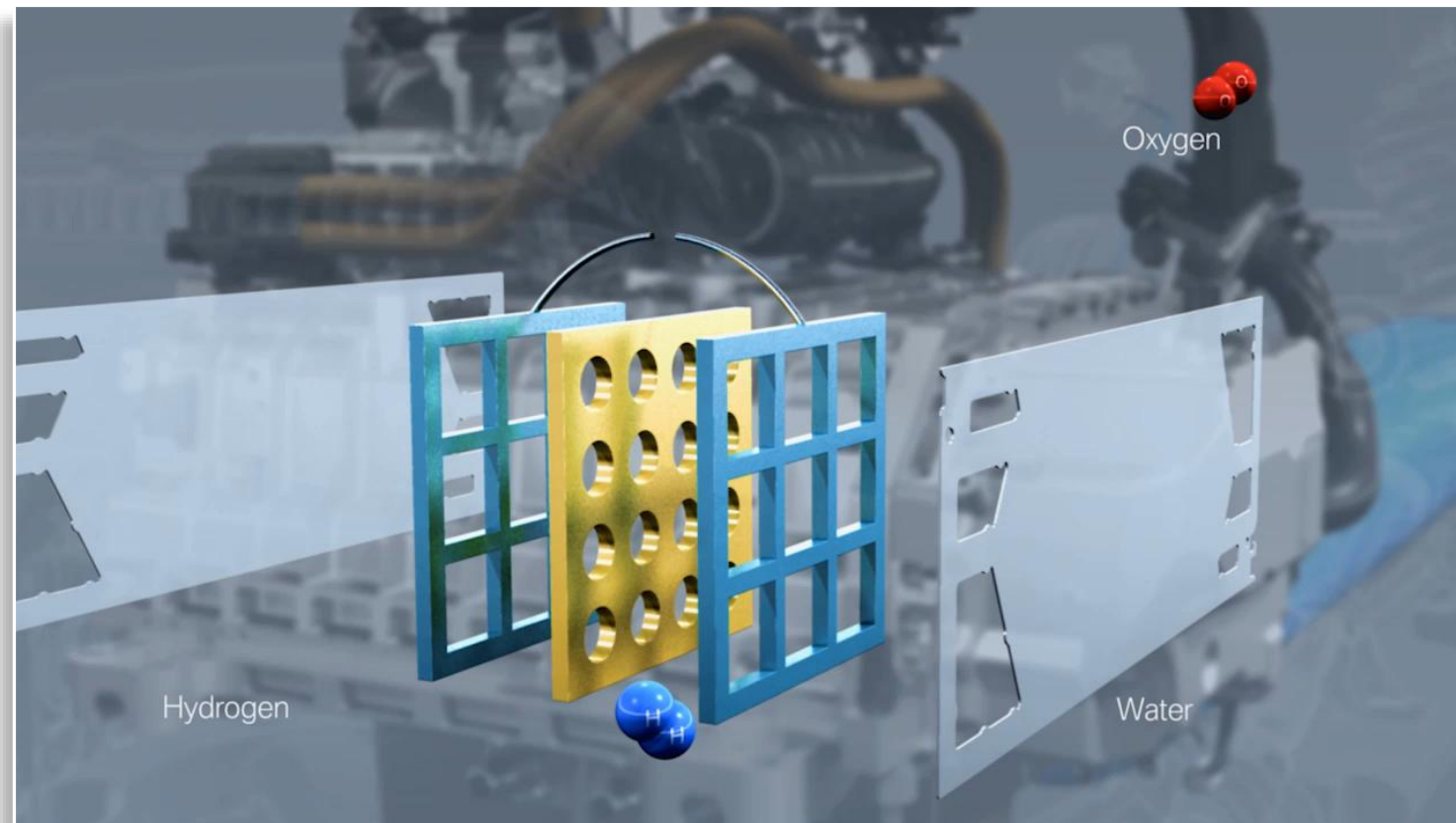


FUEL CELL SYSTEM (FCS)

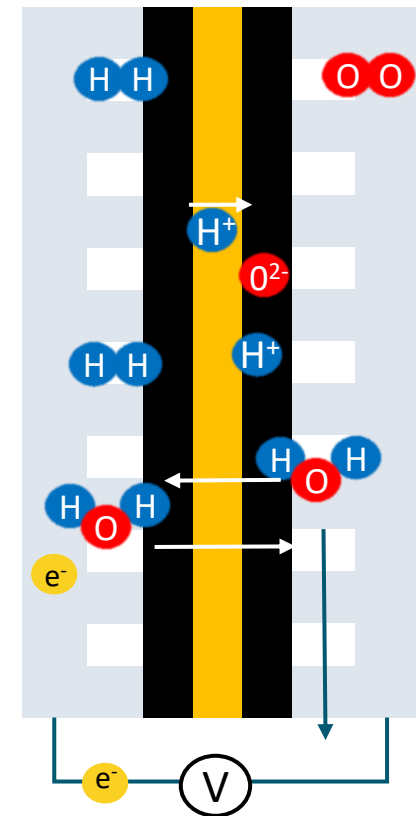


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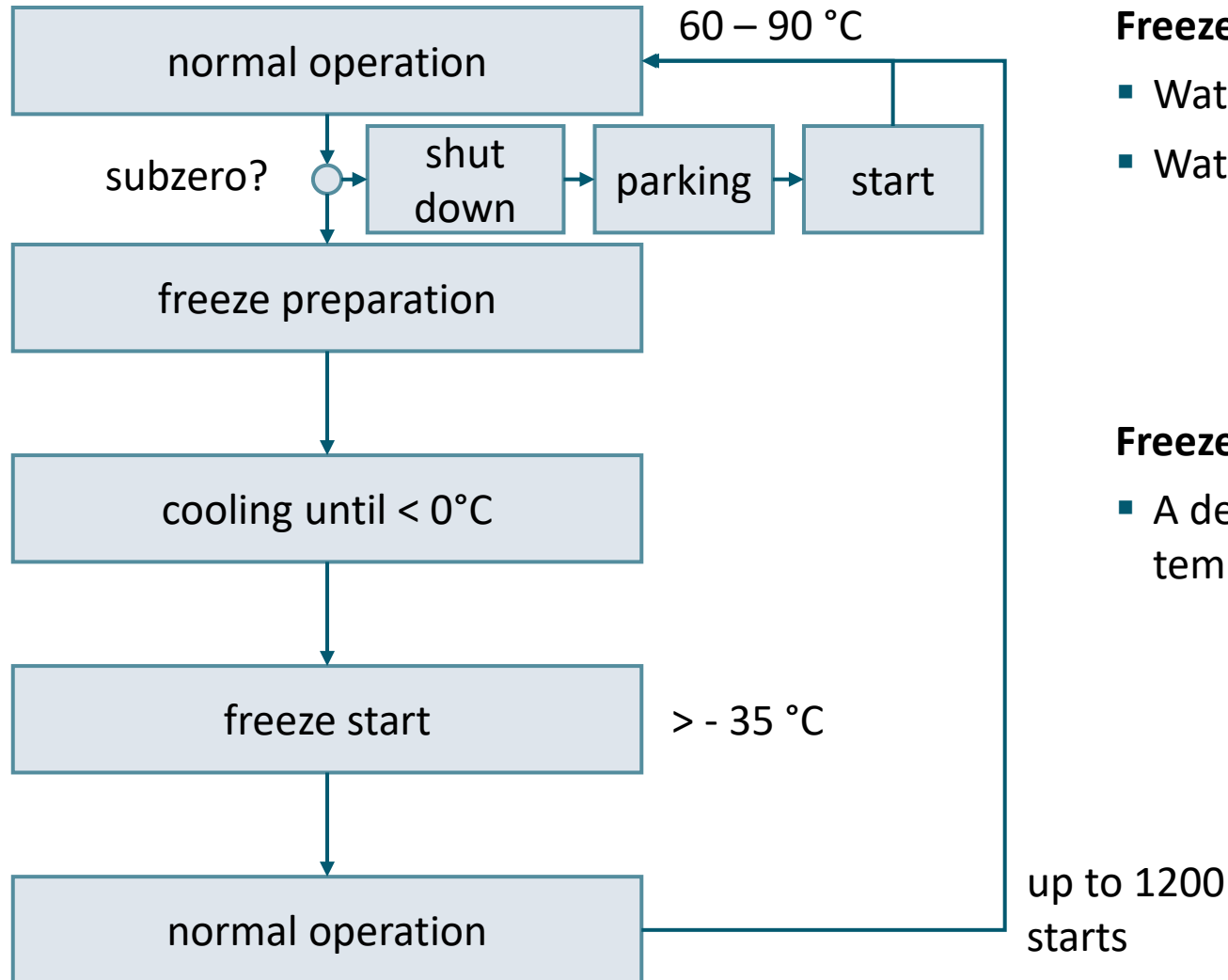
FUEL CELL AND CHEMICAL REACTION



anode cathode



PREPARATION FOR SUBZERO AND START



Freeze Preparation:

- Water is removed from the stack.
- Water content of membrane decreases.

Freeze Start:

- A dedicated start-up procedure is required at subzero temperatures.

CONTENT.

1. Introduction.

2. Method/Experiment.

Method

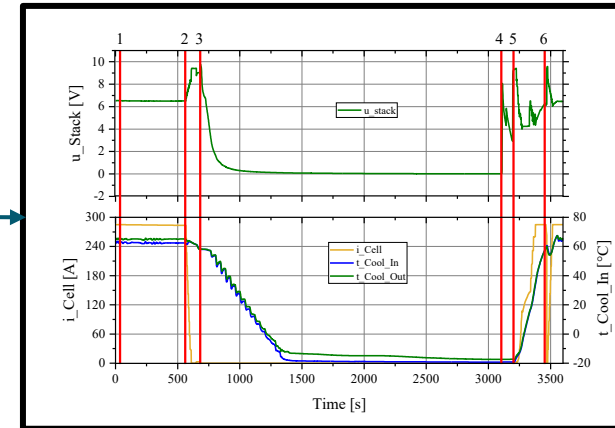
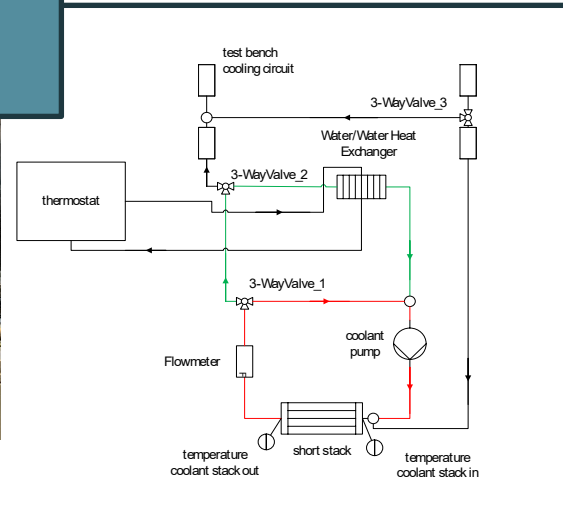
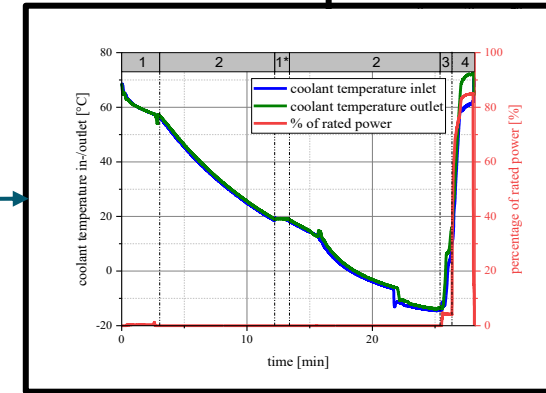
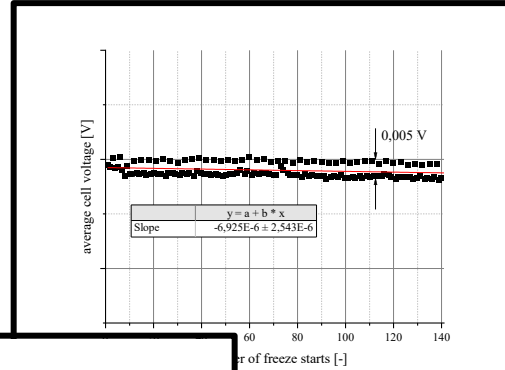
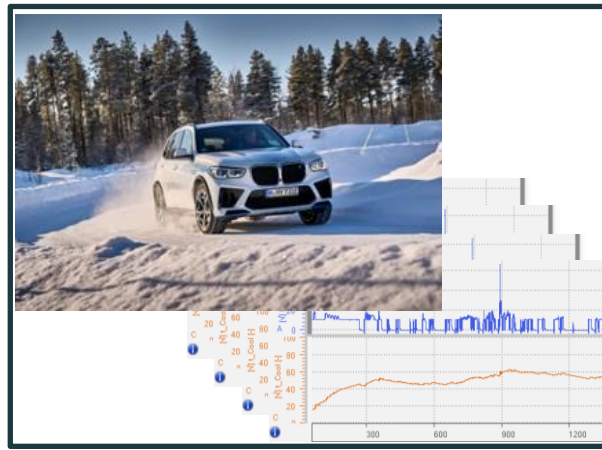
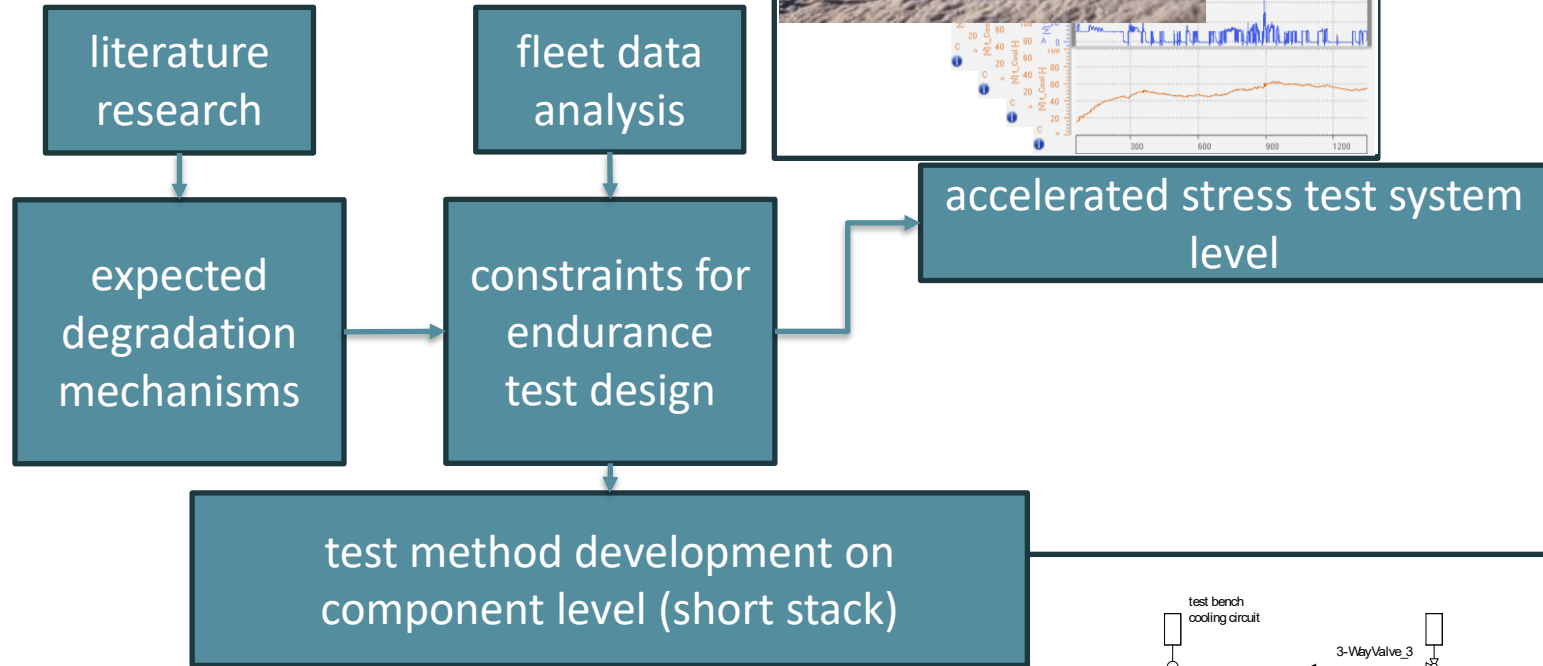
Experiment and test sequence

3. Results.

4. Outlook.

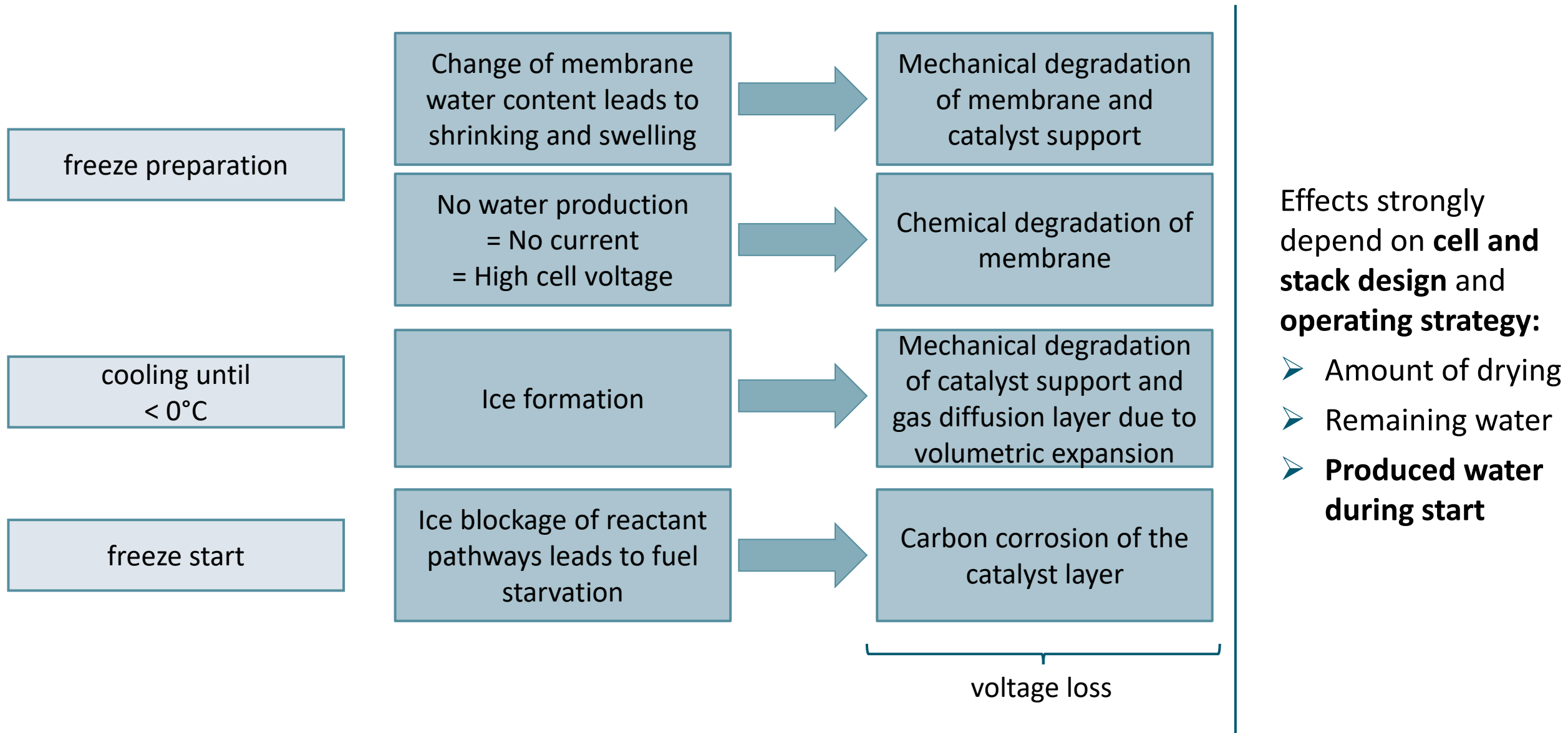


METHODOLOGY.



Adapted from Schwarz et al. 2026 – TRA26

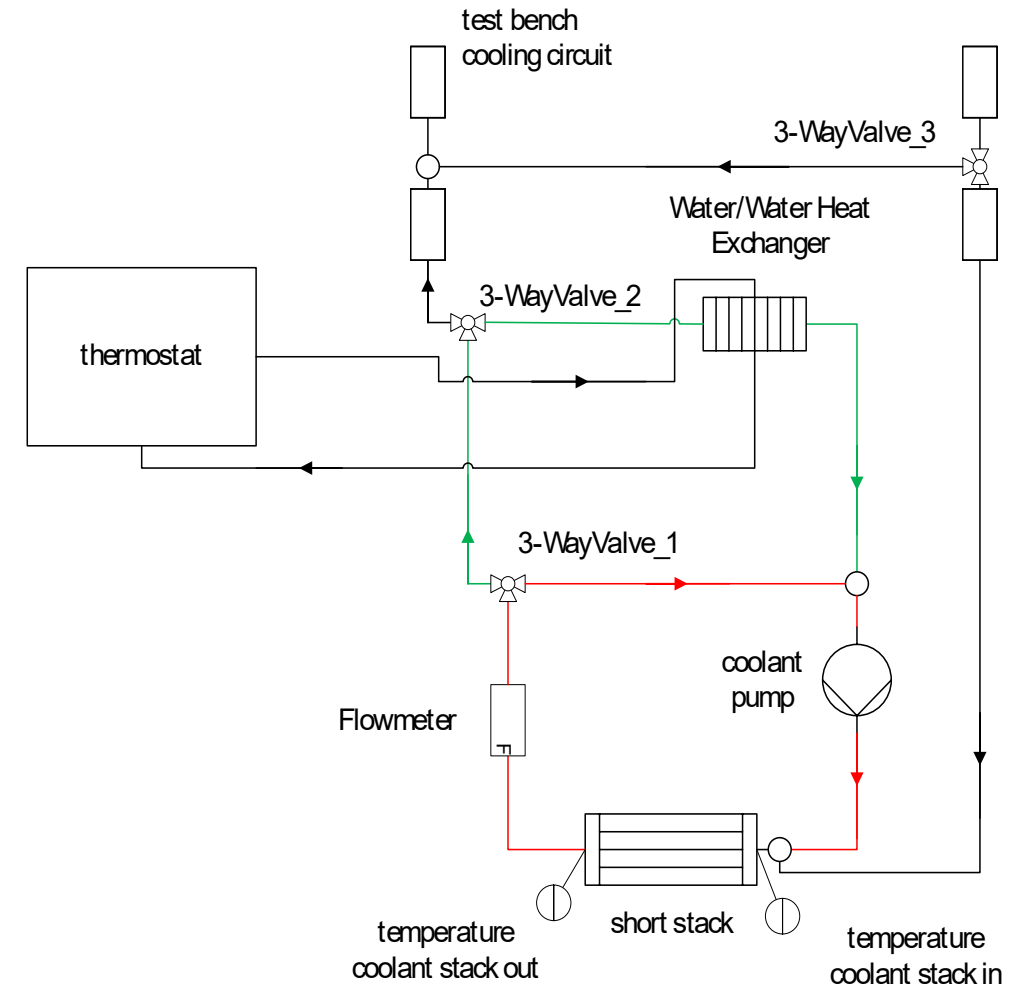
LINKED DEGRADATION MECHANISMS



Schwarz et al. 2025 – Sustainable Energy and Powertrains

EXPERIMENTAL SET-UP.

- 10-cell short stack with 285 cm² active area (early prototype).
- Big Short Stack Test bench: Horiba Fuel Con S005-LT.
- High Frequency Resistance: HIOKI BT3564-BATTERY-HiTester.
- Cooling circuit for active cooling and vehicle-like heat-up.
- Julabo FP55-SL circulation thermostat.

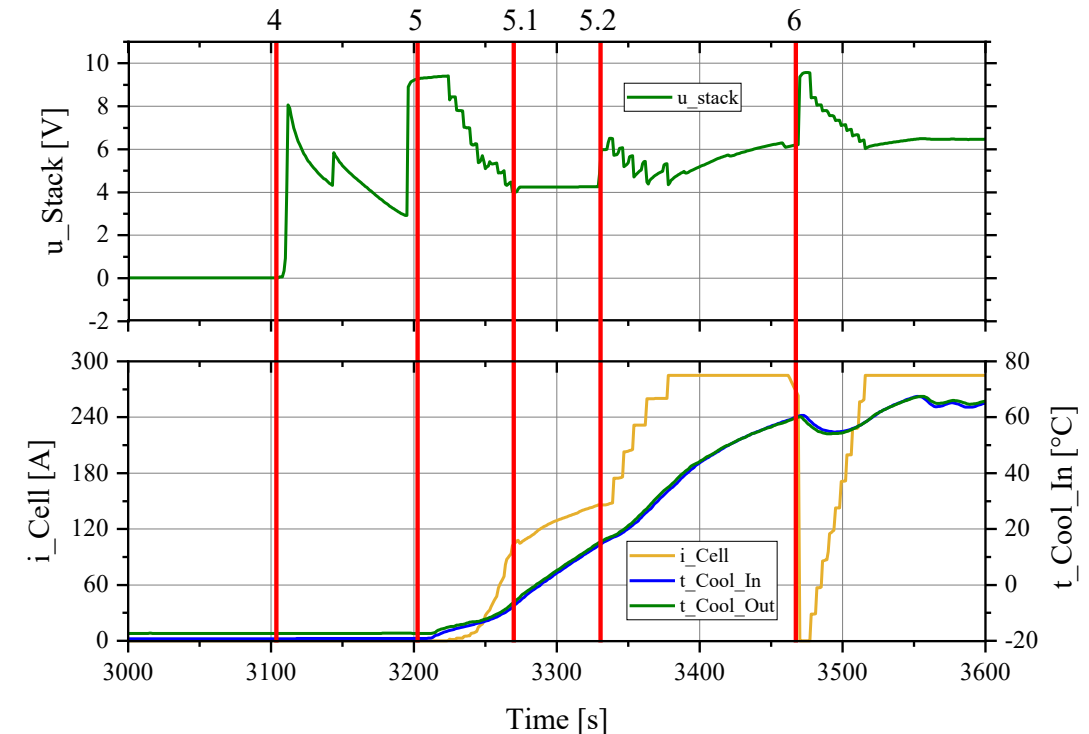
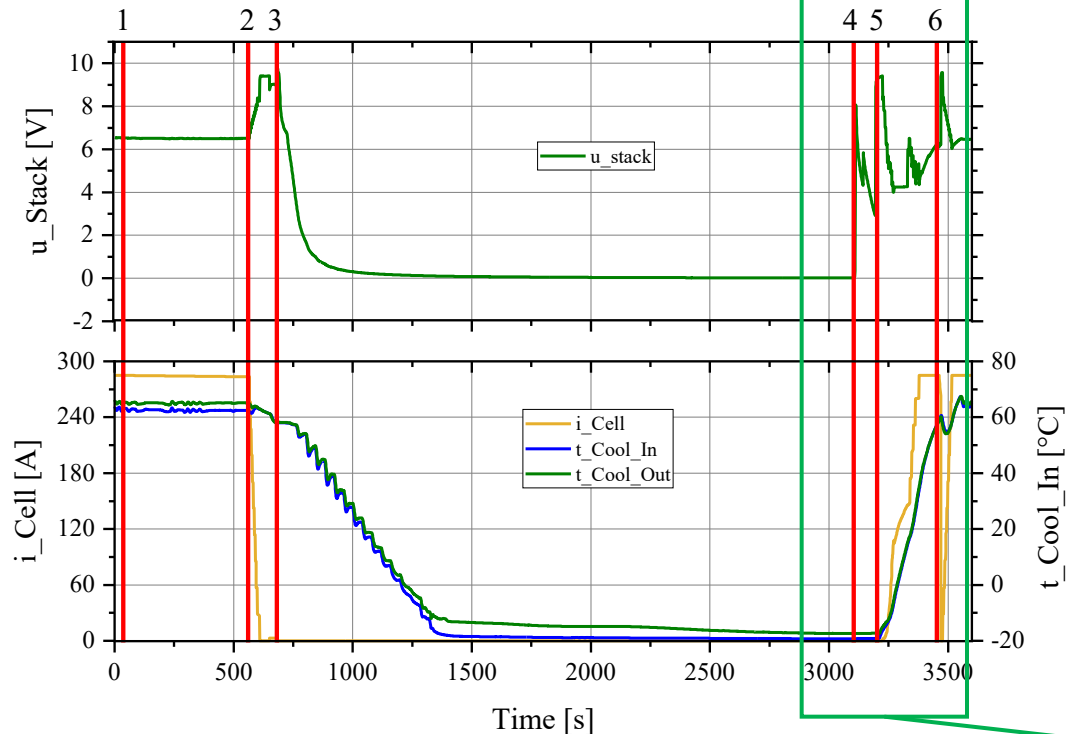


Schwarz et al. 2026 – TRA26

TEST PROCEDURE - FREEZE START ON SHORT STACK.

1. Operating Point
2. Freeze Preparation
3. Shut Down + N₂/ N₂-Purge
4. N₂/ N₂-Purge

5. OCV (H₂/Air)
- 5.1 desired voltage for heat-up
- 5.2 $t_{\text{stack}} > 15\text{ }^{\circ}\text{C}$? galvanostatic mode
6. $t_{\text{stack}} > 59\text{ }^{\circ}\text{C}$? humidified operation



Adapted from Schwarz et al. 2026 – ETRR

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3. Results.

Variation of Freeze Preparation.

Variation of Freeze Start Strategy.

Comparison – Short Stack vs. FCS.

4. Outlook.

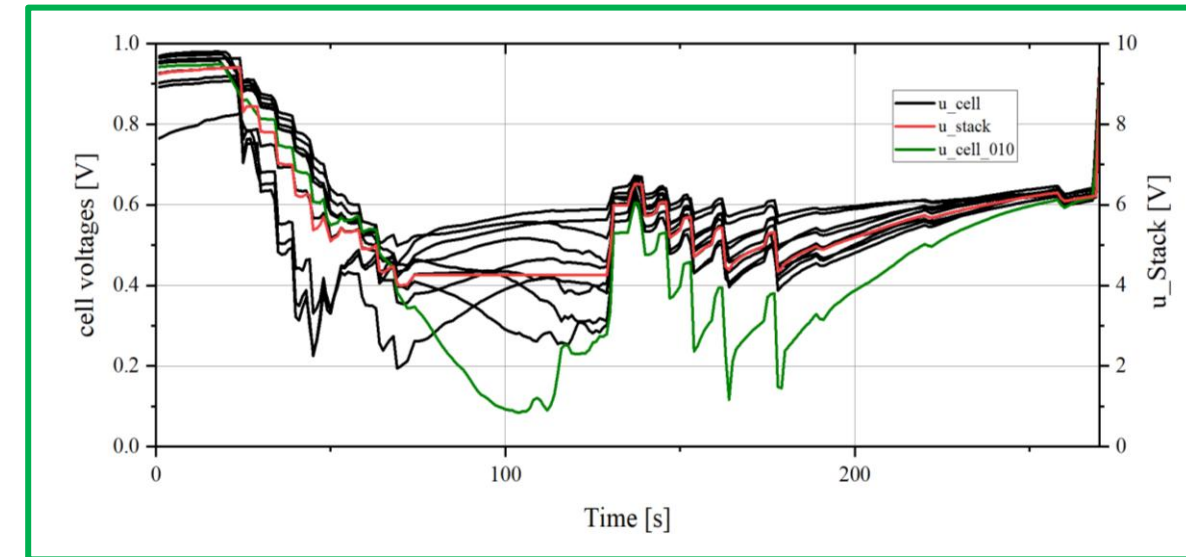
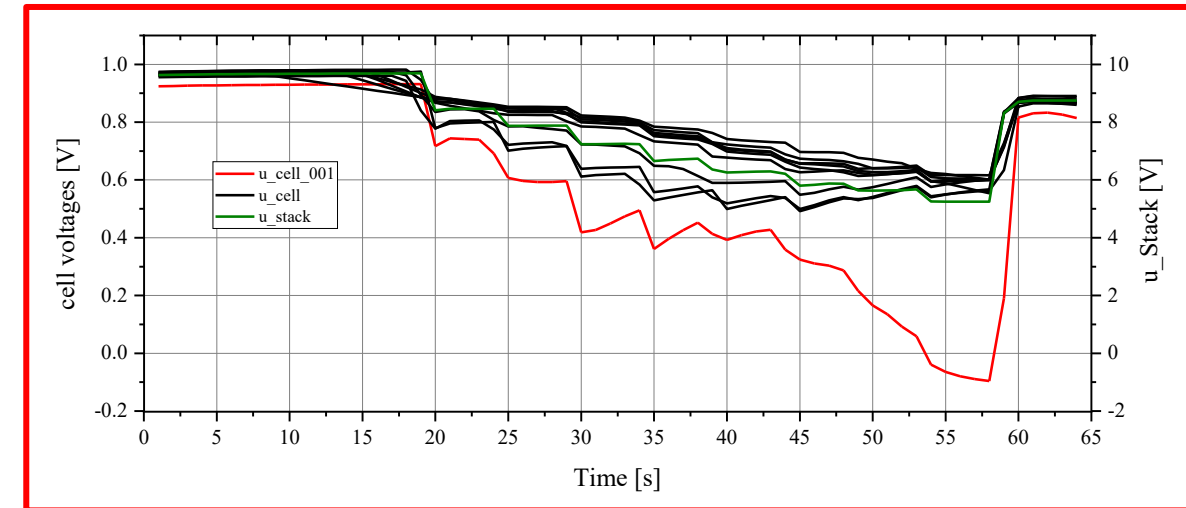


VARIATION OF FREEZE PREPARATION STRATEGIES.

- Vary flow rates.
- Vary HFR thresholds.
- Successful start: no negative cell voltages

Name	Anode Flow [g/s]	Cathode Flow [g/s]	HFR threshold [Ohm*cm ² /cell]	Min. possible Start Temperature [°C]
FP1	0.07	1.18	0.20	-10 °C
FP2	0.07	2.37	0.20	-10 °C
FP3	0.07	1.94	0.25	-10 °C
FP4	0.07	1.94	0.4	-15 °C
FP5	0.07	2.37	0.6	-18 °C

Result: Among the tested strategies, FP5 achieved the lowest start temperature (−18 °C).



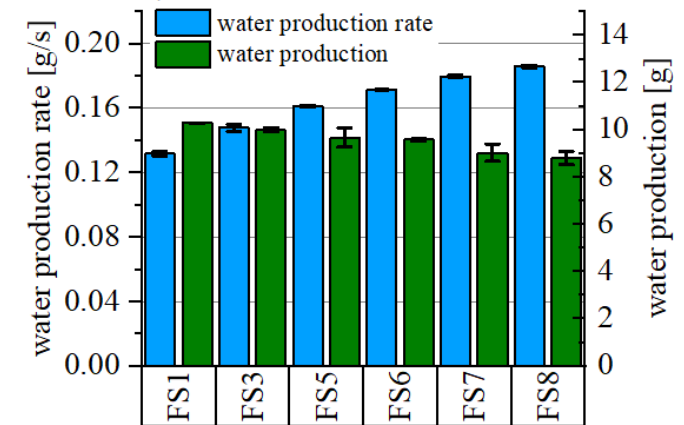
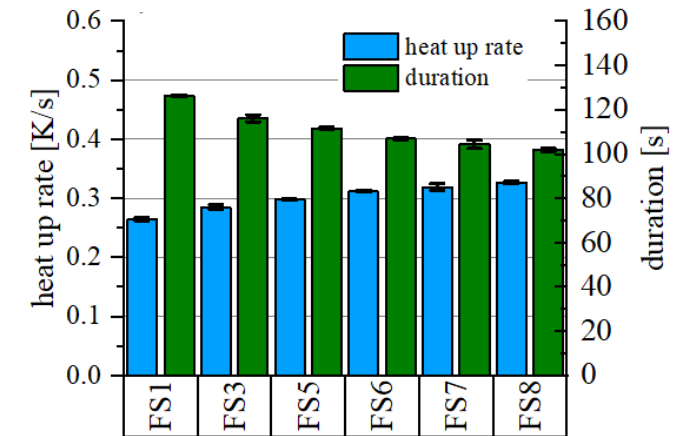
Adapted from Schwarz et al. 2026 – TRA26

VARIATION OF FREEZE START STRATEGIES.

Name	Anode Stoichiometry [-]	Cathode Flow [g/s]	Stack Voltage [V]
FS1 – 5.25 V	1.5	0.75	5.25
FS3 – 4.75 V	1.5	0.75	4.75
FS5 – 4.25 V	1.5	0.75	4.25
FS6 – 3.75 V	1.5	0.75	3.75
FS7 – 3.25 V	1.5	0.75	3.25
FS8 – 2.75 V	1.5	0.75	2.75

- Stack voltage has a big influence on the duration of the freeze start and produced water.
- Poorer efficiency leads to more heat and less electric power.

Result: Lowest Stack Voltage leads to highest heat up rates and lowest overall water production.



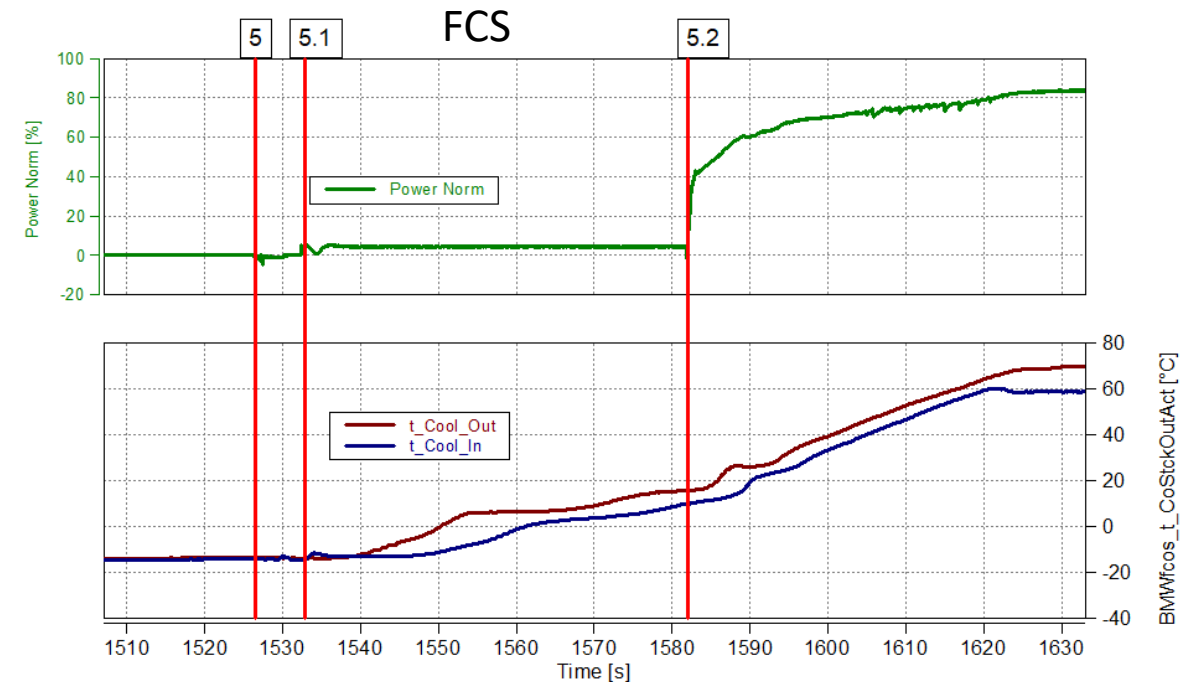
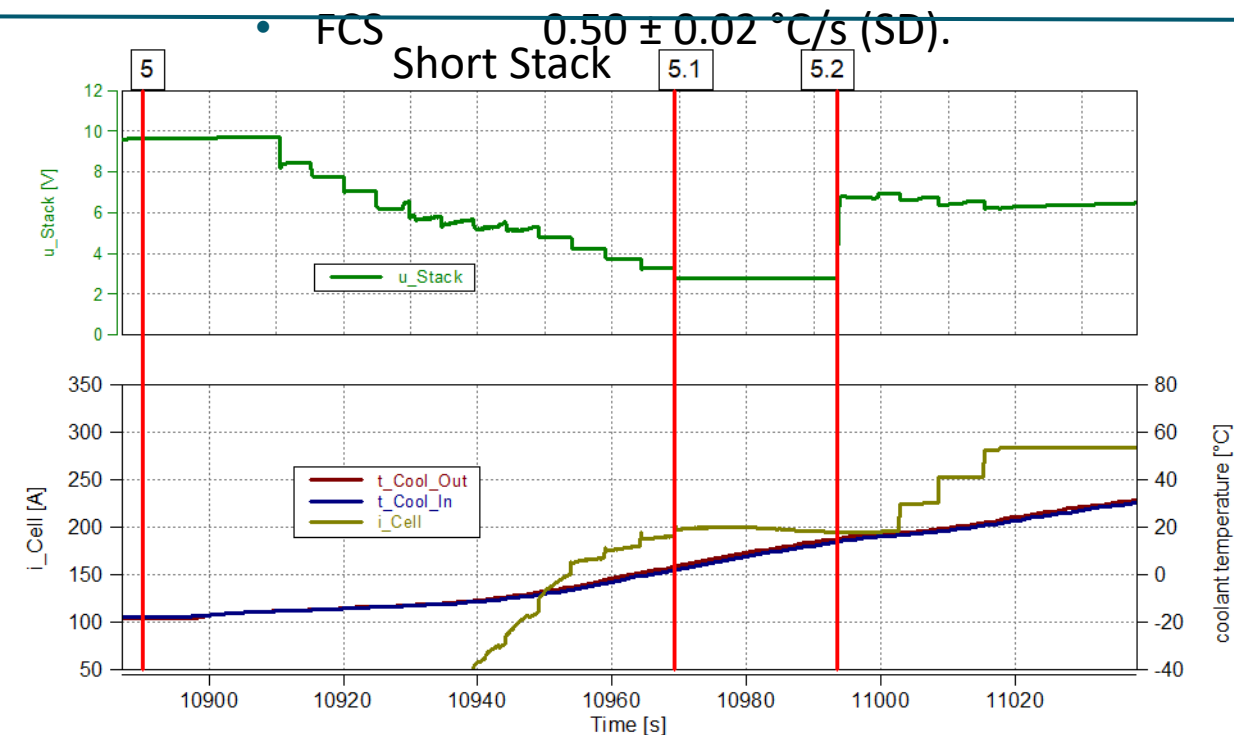
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COMPARISON OF TEST SEQUENCE BETWEEN FCS AND SHORT STACK.

- Slow ramp-down of u_{cell} (5 to 5.1) for short stack.
- Comparable heat-up rate between 5.1 and 5.2.
 - Short Stack $0.49 \pm 0.01 \text{ } ^\circ\text{C/s}$ (SD).
 - FCS $0.50 \pm 0.02 \text{ } ^\circ\text{C/s}$ (SD).



- Faster ramp-down can be implemented with more robust cells.
- Test sequence of short stack can be close to FCS



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CONCLUSION AND OUTLOOK.

Key findings:

- Similar thermal behavior for Short Stack and FCS can be achieved.
- Cheaper and earlier insights into freeze start behavior of a cell design.
- Early parameterization of simulation models possible.

Constraints:

- Qualitative and quantitative comparability of degradation behavior between short stack and FCS remains to be demonstrated.
- Vehicle-level testing remains necessary to validate freeze-start strategies.

Outlook:

- Perform freeze-start durability tests on short stack and FCS using the same cell design and operating strategy.

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Faculty of Mechanical Engineering, RWTH Aachen University, 52062 Aachen, Germany

LITERATURE

This presentation draws in part on the following publications:

Conference Contributions:

Schwarz, M. et al. (25.11.2025) “Development of an Accelerated Stress Test for Fuel Cell Freeze Start Durability Validation Using Real-World Driving Data of Light-Duty FCEVs” [Conference Contribution], Sustainable Energy & Powertrains, Stuttgart, Germany

Schwarz, M. et al. (21.05.2026) “Freeze start strategies for fuel cell electric vehicles: Balancing durability, reliability and practicability – an experimental approach on automotive-sized short stacks” [Conference Contribution], TRA26 , Budapest, Hungary

Journal Paper:

Schwarz, Markus, Albert Albert, und Rüdiger-A. Eichel. “Development of an Accelerated Stress Test for Fuel Cell Freeze Start Durability Validation Using Real-World Driving Data of Light-Duty FCEVs”. *SAE Int. J. Adv. & Curr. Prac. in Mobility* 8(3):1081-1089, 2026, <https://doi.org/10.4271/2025-01-0526>.

Schwarz, Markus, Albert Albert, und Rüdiger-A. Eichel. “Freeze Start Strategies for Fuel Cell Electric Vehicles: Balancing Durability, Reliability and Practicability – an Experimental Approach on Automotive-Sized Short Stacks”. *European Transport Research Review* 18, Nr. 1 (2026): 83. <https://doi.org/10.1186/s12544-026-00845-x>.