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IMPROVED LIFETIME STACKS FOR HEAVY DUTY TRUCKS THROUGH ULTRA-DURABLE COMPONENTS

Grant agreement no.: 101006641
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Project Coordinator: D. J. Jones, CNRS

DELIVERABLE REPORT

D2.4: FINAL PROTOCOL DEFINITION FOR HEAVY-DUTY ACCELERATED STRESS TESTS AND LOAD PROFILE TESTS	
Due Date	30. June 2023
Author (s)	Thilo Lehre, Thomas Mittermeier, Nina Schelter, Jonas Gutmann
Workpackage	WP 2, Heavy-duty stack degradation assessment and lifetime prediction
Workpackage Leader	Bosch
Lead Beneficiary	Bosch
Date released by WP leader	25.07.2023
Date released by Coordinator	25.07.2023

DISSEMINATION LEVEL		
PU	*Public*	***X***
PP	*Restricted to other programme participants (including the Commission Services)*	
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NATURE OF THE DELIVERABLE		
R	*Report*	***X***
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	

SUMMARY	
Keywords	*heavy-duty accelerated stress test, heavy-duty load profile test*
Abstract	*Work package 2 of the IMMORTAL project aims to define and perform a set of stack and laboratory cell ageing tests, accelerated and load profile tests, which reflect real heavy-duty truck operation. In this deliverable a final definition of accelerated stress tests (ASTs) and load profile tests (LPTs) is presented. The single cell ASTs are identical to the ASTs defined in IMMORTAL deliverable report D2.1. The definition of the LPT includes load cycling, short stop, cold soak, characterization, and short stop to high load.*
Public abstract for confidential deliverables	*As above*

REVISIONS			
Version	**Date**	**Changed by**	**Comments**
0.1	20.07.2023	Thilo Lehre	

D2.4: FINAL PROTOCOL DEFINITION FOR HEAVY-DUTY ACCELERATED STRESS TESTS AND LOAD PROFILE TESTS

CONTENTS

1 INTRODUCTION

IMMORTAL aims to develop exceptionally durable and high-power density membrane electrode assemblies (MEAs) well beyond the current state of the art up to TRL4 by building on understanding of fuel cell degradation pathways specific to heavy-duty truck operation and developing lifetime prediction models from extensive real-life stack operation, accelerated stress test and load profile cycles on short stacks. IMMORTAL encompasses OEMs, tier 1 suppliers, and leading industrial and academic/research organisation partners with long expertise in fuel cell science and technology. Work package 2 of the project aims to define and perform a set of stack and laboratory cell ageing tests, accelerated and load profile tests, which reflect real heavy-duty truck operation.
In this deliverable a final definition of accelerated stress tests (ASTs) and load profile tests (LPTs) is presented. For that purpose, protocols have been harmonized among the project partners.

2 ACCELERATED STRESS TESTING (AST)

During the first 30 months of project IMMORTAL a set of accelerated stress tests has been performed as well as a sensitivity analysis of ageing rates against load parameters such as upper and lower cycling voltages, hold times, ramp rates, cell temperature and inlet humidity with the IMMORTAL baseline MEA. This same MEA was also tested in initial heavy-duty relevant LPT, see D2.1. In both AST and LPT a strong correlation between loss of electrochemical surface area and performance loss was found. End of Test analytics of catalyst coated membranes (CCM) were done with CCM from ASTs and LPTs. These analytics did not reveal any degradation mechanism beyond the well-known Platinum particle coarsening effect. Therefore, the partners concluded it is feasible to keep the AST protocols as published in D2.1 for characterization of final IMMORTAL MEA.

3 LOAD PROFILE TESTING (LPT)

The IMMORTAL project, funded by EU's Clean Hydrogen Partnership targets 30 000 h durability, which is defined by 10 % voltage loss from the beginning of life (BOL) performance target of 0.675 V at 1.78 A/cm² for heavy-duty proton exchange membrane fuel cell (HD-PEMFC) membrane electrode assemblies (MEAs). However, the project's testing focus lies on accelerated stress tests (ASTs) and load profile tests (LPTs) with much shorter duration (typically less than hundreds of hours for ASTs and between one and two thousand hours for LPTs). Therefore, it is necessary to predict degradation over 30 000 h from much shorter measurements. To do so, one of the IMMORTAL project targets is to establish a lifetime prediction method. Such a method needs

- validation against aging rates from realistic profiles
- model training from AST data and realistic load profiles

Both bullets above require the application of realistic LPTs to MEAs in subscale single cells, as well as short stacks up to 20 cells, in the IMMORTAL project.
The approach here is to derive realistic load profiles from simulated input data from project partner FPT Industrial (FPT) and derive testable modal load profiles. Details were reported by FPT in D6.1. A short overview is given in the following paragraphs.

FPT simulations were based on

- FPT road missions: urban, regional, long haul
- Gross vehicle weight from 25 t to 44 t
- Battery capacity and type adapted to corresponding mission and vehicle

- Nominal current density from 1.1 A/cm² to 1.78 A/cm² (IMMORTAL BOL target is 1.2 W/cm² at 0.675 V)
- Operating temperatures between ~ 65 °C and 75 °C
- Absolute pressures at stack inlet: 1.5 bar, 2.2 bar and 2.5 bar (equal pressure between anode and cathode considered)

Figure 1 indicates the simulation toolchain used to derive cell load profiles at FPT.

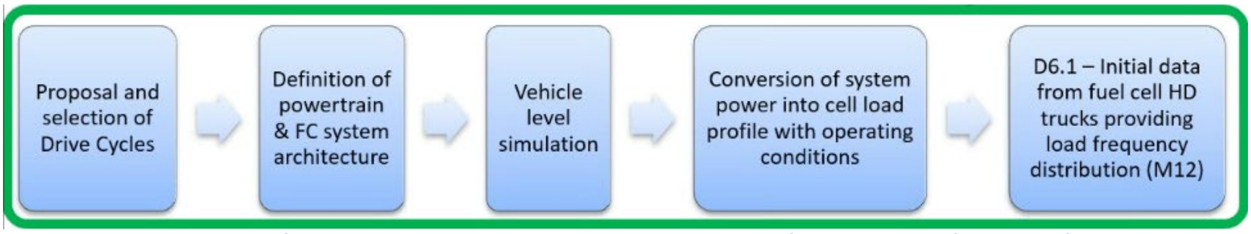

Figure 1. Workflow used at FPT resulting in simulated load profiles as a basis for LPT definition

Table 2 shows combinations of missions, ambient conditions, powertrain controls and FCS configurations, resulting in a total number of 450 profiles simulated by FPT.

Table 1. Combinations of mission profiles used with variations of ambient conditions, powertrain controls and fuel cell system configurations by FPT. All possible combinations were simulated, resulting in a total number of 450 simulation runs.

Road missions, vehicles, and e-powertrain architectures	Ambient conditions	Powertrain control strategies	Fuel cell system configurations	Total test runs
6	5	3	5	**450**

A down selection of the 4 most relevant profiles was done, according to the following criteria:

- Case RUN282 that had the maximum cell voltage and current density normalised dynamic throughput.
- Cases RUN197 and RUN241 with maximum current density mode.
- Cases RUN003 presenting maximum mean cell voltage.

To derive testable modal load profiles from simulated load profiles, the simulated profiles need to be discretized and statistically analysed for hold time and transition distribution. The result of the analysis of simulated load profiles with a Markov chain-like approach is shown in Figure 2. It can be observed that:

- RUN003:
  - Concentration at low current, low share at high current
  - Highly dynamic → "Passenger Car like"
- RUN197:
  - High current dominates
  - On/Off characteristics → "Range Extender like"
- RUN241:
  - Similar to #003, less dynamic
- RUN282:
  - High share of high and low current

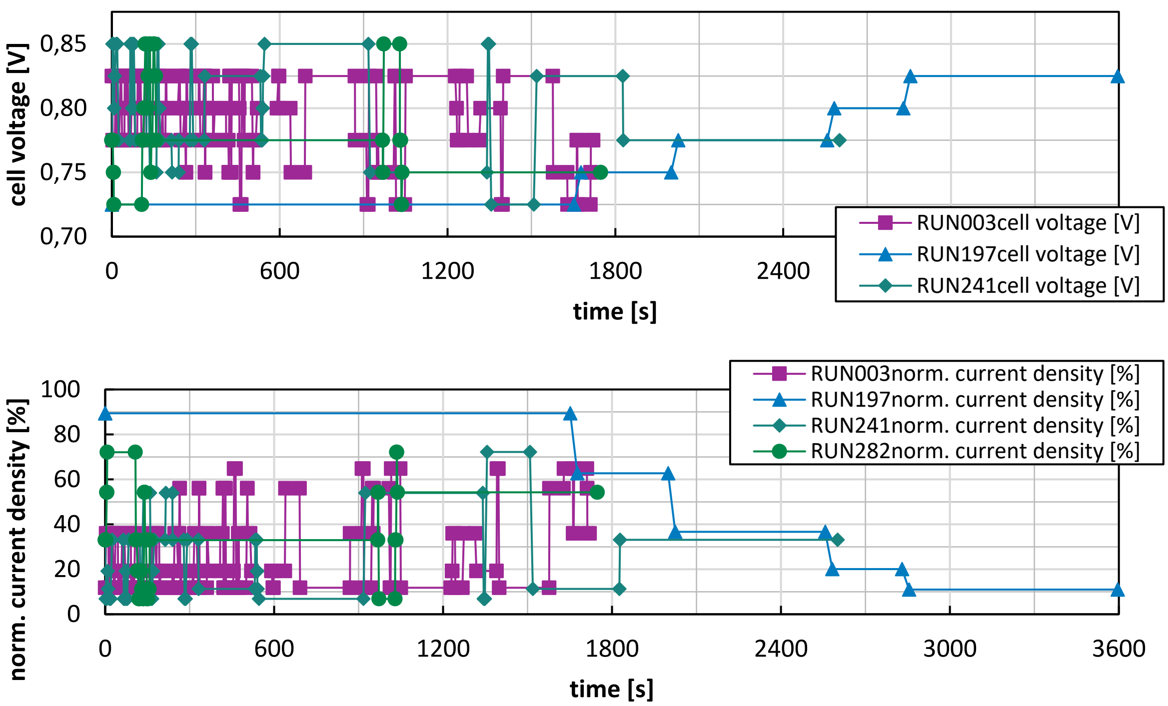

Figure 2. Individual load profiles as determined from statistical analysis of simulated load data from FPT.

Table 3. Expected relative occurrence of the four simulated mission profiles provided by FPT.

RUN#	Relative frequency
003	5.80 %
197	11.68 %
241	5.80 %
282	76.72 %
	100.00 %

Table 3 gives the relative occurrence of the four simulated mission profiles as provided by FPT. For a translation from FPT's simulated to a real current density of a Bosch stack with IMMORTAL-MEAs, first a normalization of current was done, i.e., the highest current occurring was defined as 100 %, which occurred at RUN197 at 0.735 V, corresponding to 1.514 A/cm² (cf., Table 3). Relative humidity and pressure show a strong correlation with current density; empirical correlation functions are used to interpolate operating conditions in the later deduced LPT, see Table 4.

Compared to the transition gradients in Figure 2, the available stack testbench dynamics are limited, especially in the case of pressure gradients. Transients with decreasing pressure are generally dynamically unproblematic, while fast increasing transients can lead to a temporary undersupply of reactants. It was therefore necessary to restrict positive transients to an equivalent of 20 mbar/s, therefore slowing down the fastest transitions (which would otherwise have shown transients up to >1000 mbar/s). Other quantities' transients during these transitions (e.g., of current, flows, etc.) were adapted to give equivalent transient times as the so restricted pressure gradients. Further, to make the profiles testable on a stack testbench, additional delays were incorporated into the transients between load modes:

- 1.5 s between flows and pressure (each direction)
- 4.0 s between pressure and current (only current increase)

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These additional delays result in overall times for each profile being longer than initially determined. Table 5 shows the course of the final LPT, where the individual profiles are to be repeated with different frequencies, according to Table 3. Other elements and occurrence were carried over from the initial IMMORTAL LPT (s. public report D2.1). The two columns on the right compare initially determined times of the individual profiles with measured values during 20-cell short stack tests at Bosch. As a result, the overall number of repetitions in the highest level was increased from initially planned 12 cycles to 17 cycles.

Table 4. Top: Current density normalization. Bottom: empirical correlation models for cathode pressure at stack inlet and relative humidity (cathode, anode RH) referenced to coolant temperature at stack inlet.

current normalization	current density [A/cm²]	normalized current density x [%]	100 % current at voltage [V]	
	1.514	100.0	0.716	
pressure polynomial	p [bara] = B0+B1*x+B2*x^2+B3*x^3+B4*x^4+B5*x^5+B6*x^6			
	RUN003	**RUN197**	**RUN241**	**RUN282**
B0	1.02E+00	9.25E-01	8.80E-01	8.73E-01
B1	4.09E-02	2.00E-02	4.83E-02	5.05E-02
B2	-5.62E-03	-1.14E-03	-4.46E-03	-4.65E-03
B3	3.12E-04	5.42E-05	1.95E-04	2.03E-04
B4	-7.34E-06	-1.03E-06	-3.81E-06	-3.96E-06
B5	7.81E-08	8.85E-09	3.41E-08	3.57E-08
B6	-3.13E-10	-2.92E-11	-1.16E-10	-1.21E-10
valid from x [%] (const. below)	16.2	9.1	6.8	6.8
to x [%] (const. above)	64.5	100.0	77.5	77.6
RH exponential	RH [%] = a*x^b			
	RUN003	**RUN197**	**RUN241**	**RUN282**
a	164	148	157	157
b	-35.4	-29.9	-32.9	-33.0
valid from x [%] (const. below)	6.6	6.6	6.6	6.6
to x [%] (const. above)	64.5	100.0	77.5	77.6

Other operation parameters were chosen as specified in Table 5. These were based on a published set of operation condition already used in the initial IMMORTAL LPT, see D2.1.

Table 2. Additional chosen test parameters. FR_Si_CL and T_SI_CL are coolant flow per cell and temperature at stack inlet, respectively; p_Si_A and p_Si_C are anode and cathode pressure at stack inlet, p_Si_C as in table 4; T_Si_A and T_Si_C are anode and cathode gas temperatures at stack inlet. DPT_A and DPT_C are anode and cathode dew points at stack inlet, calculated from the relative humidities referenced to T_Si_CL, see table 4; STC_A and STC_C are anode and cathode stoichiometries. At currents below 0.5 A/cm², constant flow according to 0.5 A/cm² flows were applied. CMP_A is the dry gas-based fraction of H_2 in a H_2 + N_2 mixture supplied to the stack (i.e., 10 % N_2 on a dry gas base).

Coolant		Anode					Cathode			
FR_Si_CL	**T_Si_CL**	**p_Si_A**	**T_Si_A**	**DPT_A**	**STC_A**	**CMP_A**	**p_Si_C**	**T_Si_C**	**DPT_C**	**STC_C**
[l/min/cell]	[°C]	[bara]	[°C]	[°C]	[-]	[%]	[bara]	[°C]	[°C]	[-]
0.6	65	p_SI_C + 0.2	70	Calc. from rel. hum. & T_Si_CL	1.5 at ≥0.7 A/cm² 1.7 at ≥0.5 A/cm²	90	see Table 4	70	Calc. from rel. hum. & T_Si_CL	1.6 at ≥0.5 A/cm²

Table 5. Final IMMORTAL LPT procedure.

repeats						**procedure**	**approx. time [h]**	**measured time [h]**
		1	x	1	x	cold soak	4.00	4.90
		1	x	1	x	Membrane state of health check	0.42	0.67
		1	x	1	x	Air starves (~2 h / 10 cycles)	2.00	1.90
		1	x	1	x	characterization	9.24	11.0
		1	x	1	x	short stop	0.25	0.20
				8	x	282	8.00	4.48
				1	x	short stop	0.25	0.20
				4	x	282	4.00	2.24
				2	x	197	2.00	2.08
		7	x	1	x	3	1.00	0.69
				1	x	241	1.00	0.82
				1	x	short stop	0.25	0.20
						SUM (single)	16.5	10.7
						total:	116	75.0
~~12~~	~~x~~	~~(intended)~~		-	-	~~**total:**~~	~~**1577**~~	
17	x	(adjusted)				**total:**		**1592**

Figure 3 shows an exemplary excerpt of a sequence of 8 individual cycles of the here defined RUN282 profile, followed by a short stop, further 4 repetitions of the RUN282 profile and 2 RUN197 profiles, one RUN003 profile and one RUN241 profile.

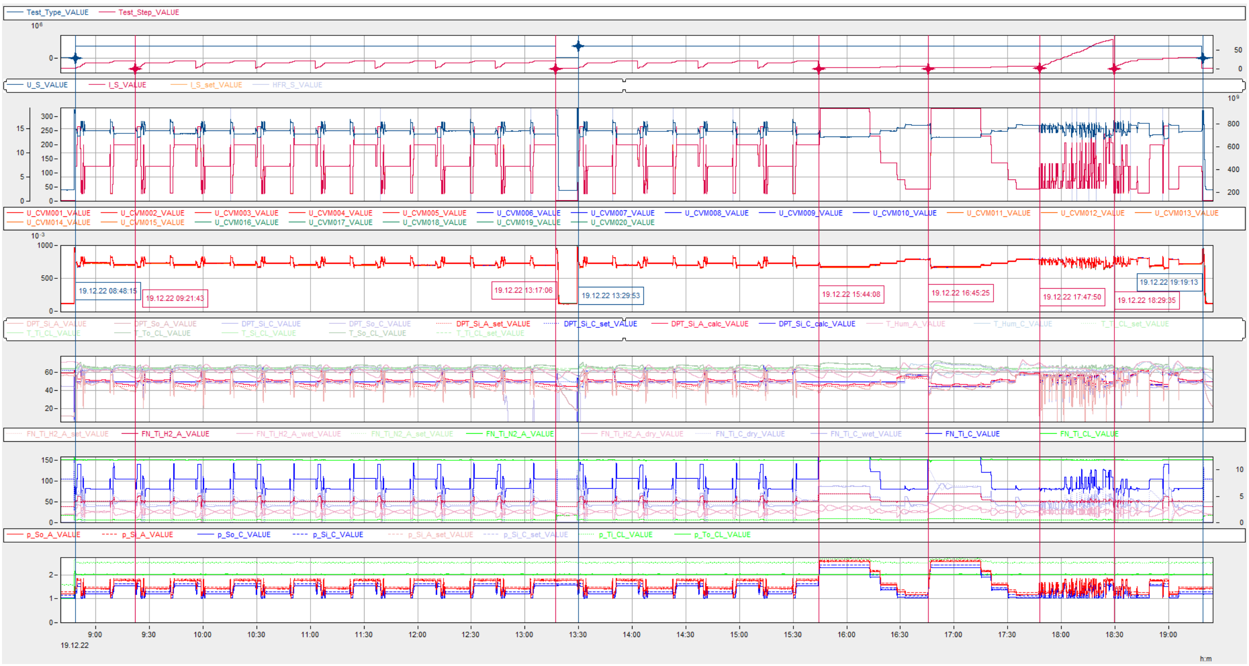

Figure 3. Raw data from test run of inner loop, which is to be repeated 7 times according to Table 5.

4 CONCLUSIONS AND FUTURE WORK

The final IMMORTAL LPT protocol is synthesized from various simulated heavy-duty relevant load profiles, implemented and ready to use at Bosch and will be applied to characterize the aging of the final IMMORTAL MEA.

5 References

IMMORTAL deliverable report D6.1 - Initial data from fuel cell heavy duty trucks providing load frequency distribution