The StasHH Size, Interface, and Testing Protocol Standards for Fuel Cell Modules in Heavy-Duty Applications

- Definition of an Industry-Driven Fuel Cell Module Standard -

K.J. Mrozewski [1)] A. Balaji [1)] C. Bekdemir [1)] R. Bouwman [2)] H. Lundkvist [3)]

1) TNO Powertrains, Helmond, The Netherlands

E-mail: kamil.mrozewski@tno.nl

2) VDL Enabling Transport Solutions, Helmond, The Netherlands

3) SINTEF Digital, Mathematics and Cybernetics, Trondheim, Norway

ABSTRACT: This paper describes an industry-driven standard for heavy-duty hydrogen fuel cell modules, defining their form factors, physical and digital interfaces as well as testing protocols. The standardized modules aim to serve diverse applications, including ships, trains, stationary generators, and heavy-duty vehicles. The objective of the standardized tests protocols is to provide an easily implementable framework for consistent validation and benchmarking of fuel cell module performance metrics, aligning with industry requirements. Currently, no unified standard exists for fuel cell module interchangeability and testing. Such a standard could consolidate markets, expedite development and deployment of hydrogen fuel cells in heavy-duty applications, foster competition among manufacturers, and lower the total cost of ownership. The StasHH project is addressing the lack of standardization of fuel cell modules by developing prototypes from seven major fuel cell manufacturers, with testing of eight fuel cell modules. The developed standards have been proposed to the IEC TC105 standardization committee for review, vote, and potential further work and adoption.

KEY WORDS: fuel cell, module, standard, size, interface, testing

1. INTRODUCTION

Standardizing fuel cell modules (FCM) is essential to accelerate deployment in the heavy-duty (HD) sector. Although fuel cell technology is applied across many HD applications, from buses and trucks to ships and trains, each project requires custom engineering between FCM manufacturers and Original Equipment Manufacturers (OEM), limiting scalability, reusability, and cross-compatibility. This tailor-made approach results in long development cycles, high costs, and limited competition, which hinder widespread adoption and economic feasibility. Standardization of FCMs can address these issues by creating a unified market across multiple HD applications, enabling modular, MW-scale units for broader applications, encouraging fair competition among FC suppliers, reducing development costs and lowering market entry barriers for OEMs, streamlining the supply chain for greater reliability and supporting automated mass production and lowering total cost of ownership.

The StasHH project, funded by the European Commission, unites seven FCM manufacturers, OEMs from various HD sectors, and Research and Technology Organisations. The aim of this industry-driven project is to define the size and interface standards for FCMs. An FCM includes a stack, balance-of-plant components, and optional DC/DC converters, excluding hydrogen storage and radiators. So far, standards bodies like IEC, ISO, and CEN did not focus on standards for FCM physical and digital interfaces. While size and interface definition represent important advances towards standardisation of FCMs, the lack of standardized testing protocols continues to impede reliable, consistent evaluation of FCM performance across various manufacturers and applications. Prior efforts have predominantly focused on standardizing cell- and stack-level protocols, which has provided valuable support for fundamental research, prototype and early product validation, and component-level development. The observed challenge was the lack of unified guidelines on the key performance metrics, consistent protocols on how to carry out tests and in which conditions, definition of terminology, and finally, data acquisition and post processing methods.

To ensure effective standardization within StasHH, it was deemed essential to establish testing protocols that enable consistent validation and benchmarking of FCMs, meeting industry needs for scalable performance assessments. This work aimed to define easily implementable and replicable test procedures to measure application-relevant FCM performance metrics. The StasHH protocols are intended to support the fuel cell community by providing a tool for validating high-TRL prototypes and products, aiding technology assessment and tracking progress across various suppliers, FCM sizes, and HD-sector applications. The StasHH project is addressing the lack of standardization of FCMs by developing prototypes from seven major fuel cell manufacturers, with testing of eight modules to validate the developed technology and testing protocols used for performance quantification. The outcome of this work has been submitted as a standard proposal to be reviewed by the IEC Technical Committee TC105 on "Fuel Cell Technologies".

2. STANDARD SIZE AND INTERFACES

2.1 Standard Size

The StasHH standard dimensions are primarily determined by the space constraints of European trucks, one of the most challenging environments for FCM installation due to tight volume limits induced by EU-regulations(1). A maximum height of 680 mm and width of 700 mm is generally compatible with the diesel tank area and engine bays, while the length depends on the specific vehicle. For engine bays, an envelope size of 700×1360×1020 mm is acceptable for most manufacturers.

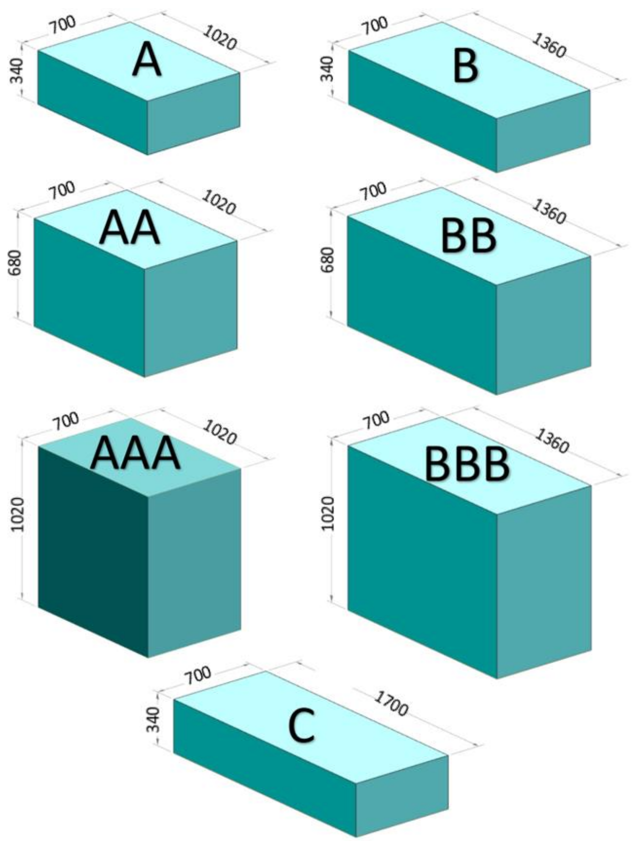

Figure 1. The StasHH FCM sizes (measurements in [mm]).

StasHH specifies three basic form factors with a width of 700 mm, height between 340 and 1020 mm, and variable lengths based on a unit length of 340 mm: Type A (3 units), Type B (4 units), and Type C (5 units). All dimensions have an acceptable tolerance of +0/-100 mm. These form factors are detailed in Table 1 and illustrated in Figure 1. The form factors are not power-specific but must support over 30 kW. Units can be stacked to form composite sizes, e.g. AA (two A units) and BBB (three B units). A more detailed discussion is available in StasHH project deliverables discussing the proposed standard(2), as well as its final update(3).

Table 1. The basic sizes and examples of composite sizes.

Type	Height [mm]	Width [mm]	Length [mm]	Volume [dm^3]
A	340	700	1020	243
B	340	700	1360	324
C	340	700	1700	405
AA	680	700	1020	486
BB	680	700	1360	647
AAA	1020	700	1020	729
BBB	1020	700	1360	971

All dimensions are tolerated with +0/-100mm.

2.2 Physical Interfaces

The StasHH standard specifies general areas for physical interfaces but leaves connector positioning, size, and shape to the manufacturers. This flexibility avoids significant design challenges, such as chassis modifications, as minor hose adjustments or adapters are not considered major obstacles.

Main hydraulic and pneumatic connections must not interfere vertically or horizontally to allow for manifold installations when stacking multiple FCMs. The standard defines acceptable inner diameters for hydrogen and air inlets, steam outlets, drains, and cooling, which scale with FCM power and include common metric and imperial sizes. Drain, ventilation, electric, and I/O connections can be placed anywhere within the form factor. High-voltage (HV) and low-voltage (LV) connector shapes are not specified. The interface standard also defines output voltage range and hydrogen input pressure, and environmental operating conditions requirements (3),(4).

2.3 Digital Interfaces

Whereas no universal standard exists for FCM-to-application communication, the StasHH standard(3),(5) leverages established protocols. CAN bus, widely used in automotive applications, is chosen as the primary protocol, with CAN-FD as an option.

Ethernet is also supported for higher data capacity, larger networks, and to future-proof non-automotive applications like maritime.

The higher-level communication layer uses SAE J1939, mainly using Fuel Cell System standard messages that have recently been introduced by SAE and adapted in collaboration with the StasHH project. Safety and control requirements are based on an analysis of relevant regulations, addressing emergency stops (via hardwiring or CAN signals), high-voltage interlock loop (HVIL), cybersecurity and diagnostics. Six primary FCM states are defined, with the flexibility for manufacturers to add proprietary sub-states. To avoid vendor lock-in and allow application-specific adaptations, the standard does not mandate a specific connector but defines 5 required pins, 9 optional pins, and suggests 4 additional pins for future expansions.

2.4 General technical requirements

For the general technical requirements, the StasHH standard followed the Key Performance Indicators (KPI) as specified in the "Strategic Research and Innovation Agenda 2021-2027" formulated by the Clean Hydrogen Joint Undertaking of the European Commission[6]. Some of the key general requirements for systems using Polymer Electrolyte Membrane Fuel Cells (PEMFC) are given in Table 2.

Table 2. General technical requirements for PEMFC systems.

Parameter	Unit	Value
Service life	h	> 15,000
Low voltage	V_{DC}	24
Output voltage	V	160 - 850
Hydrogen input pressure	bar	6 - 22
Hydrogen Quality	-	ISO 14687(D), SAE J2719
Coolant conductivity	μS/cm	< 6 (ASTM D 1125)
Operating ambient temperature	°C	-25 to +45
Operating altitude	m	< 3,000 with derating
Ingress Protection class	-	> 54

3. STANDARD TESTING PROTOCOLS

3.1 State-of-the-art fuel cell testing protocols

A gap analysis was conducted to compare the existing testing protocols with those necessary for module-level testing required by the FCMs designed according to the StasHH standard. This process began with a thorough review of the state-of-the-art testing protocols, including references from IEC and ISO standards, UNECE Regulations, SAE technical papers, the Joint Research Centre (JRC) of the European Commission, the United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) Partnership (part of the U.S. Department of Energy), maritime classification rules and requirements (Lloyd's Register) and other key European projects. A review summary of the testing standards, norms, technical papers and references has been given in Table 3.

Table 3. Summary of the reviewed testing standards.

Source/Body	Name/number
IEC	62282-2-100; 62282-3-100; 62282-4-101; 63341
ISO	6469-3; 12619-2
UNECE	R10; R94; R95; R100; R134; R137; R153
SAE	J2615
JRC	EU harmonised test protocols for PEMFC MEA testing in single cell configuration for automotive applications
U.S. DRIVE	Cell Component Accelerated Stress Test Protocols for PEM Fuel Cells
EU Stack-Test	Development of PEM Fuel Cell Stack Reference Test Procedures for Industry Stack-Test
Lloyd's Register	Type Approval System Test Specification Number 1; Marine Fuel Cell Module Product Standard

Following the state-of-the-art review, an initial set consisting of 32 tests tailored to meet the needs of StasHH was drafted. However, making adjustments to this initial pool of tests was necessary to align with the project's agreed "black box" approach, which emphasizes modular testing without the investigation of components internal to the FCM. This ensures Intellectual Property Rights of each manufacturer are protected.

3.2 StasHH fuel cell module testing protocols

The initial selection of tests was subsequently reviewed and refined through discussions with project partners and consultations with fuel cell experts at the JRC, integrating feedback, recommendations, and best practices from FCM manufacturers. From this process, a focused shortlist of six tests was identified as the most relevant, useful, and feasible to propose within the final StasHH testing protocol standard. These six tests are:

1. Start-up and shut-down duration
2. Ramp-up and ramp-down dynamics
3. Efficiency curve characterization
4. Dynamic load profile performance

5. Performance under static inclination
6. Performance with impaired cooling

The background and details of these testing protocols can be found in a StasHH project deliverable[7]. Additionally, a "glossary of terms" was proposed to ensure a shared understanding across all stakeholders. This glossary covers terminology definitions for FCM boundaries, inputs and outputs, test variables, measurement sampling locations, calculated performance metrics, and equations used for data processing. The following sub-sections provide more insight into the objective, protocol, and evaluation criteria of each of the proposed tests. The standardized test protocols were validated during an extensive campaign carried out in the StasHH project by testing seven PEM fuel cell modules from six manufacturers. A summary of the measured results is presented in another EVTeC 2025 article[8].

3.2.1 Start-up and shut-down duration

The ability of a FCM to realize a rapid, safe and efficient start-up to become ready to deliver power is an important performance factor, e.g. for mobility applications. The first goal of this test is to measure the duration and energy consumption of the start-up procedure, from the completely powered-off state, to the "Standby" state, such that the module can start producing output within a short time. The scope of this test covers two start-up scenarios, namely a cold-start (module is at ambient temperature 23 ±5 °C) and a hot-start (the module was producing power at nominal temperature, and was afterwards kept inactive for 300 seconds).

The second goal is to measure the duration and energy consumption of a normal shut-down sequence. The reason behind measuring energy consumption is to give insights into the proper dimensioning of the on-board energy buffer (e.g. battery). The two main references, based on which this test has been established, are the SAE J2615[9] and the protocol TMD-03 from the EU StackTest project[10].

The key performance indicators resulting from this test are the FCM start-up duration (both cold- and hot-start), shut-down duration measured in [s], and the needed electrical input energy measured in [kWh].

3.2.2 Ramp-up and ramp-down dynamics

The ability of a FCM to react quickly and safely to changing load demands is often a key performance criterium. In practice, the dynamic response times associated with the ramp-up and the ramp-down of FCM power can vary with the temperature of the system. The purpose of this test is to characterize the ramp-up and ramp-down dynamics of the FCM over its nominal power range, i.e. from minimal output power to nominal output power, and assess the impact of coolant temperature on these dynamics. The two main references, based on which this test has been established, are the IEC 62282-2-100 [11] and SAE J2615 [9].

Within the StasHH protocols, the dynamic response of the FCM is quantified by measuring the duration between the moment of initiation of a ramp-up or ramp-down request, and the moment in which the target power setpoint is reached. This is done at the nominal coolant temperature of the system. Two ramp-up and ramp-down cycles are performed to verify FCM stability and to verify if there is no unstable behavior. Afterwards, the coolant temperature is increased to the maximum operating value, specified by the manufacturer of the FCM, and the two ramp-up and ramp-down cycles are repeated. The complete test profile is shown on Figure 2.

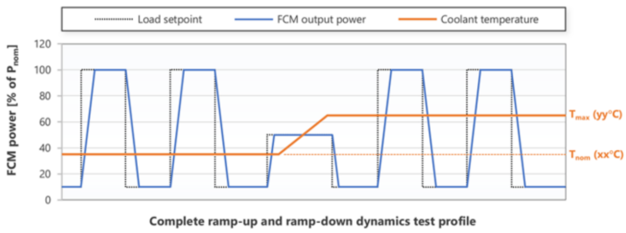

Figure 2. Ramp-up and ramp-down dynamics test profile.

A successful test result is achieved when the FCM performs the transients without a shutdown or permanent damage to the system. The KPI resulting from this test are the ramp-up and ramp-down dynamics, reported in [kW/s], at both the nominal and maximal operating temperature of the FCM.

3.2.3 Efficiency curve characterization

This test is carried out to trace the efficiency curve of the FCM as a function of the net electrical power output, measured at steady state within the entire power output range of the FCM. It is one of the most common and relevant methods to characterize fuel cell performance, as it highly impacts multiple techno-economic features, such as system operating costs or sizing of auxiliary systems and their components, e.g. cooling/HVAC, and helps OEMs in defining a correct hybridization strategy for their application. The two main references, based on which this test has been established, are the SAE J2615[9] and IEC 62282-2-100 [11].

Within the StasHH protocols, it is advised to measure the performance of the FCM at defined power setpoints, from 20% to

100% of nominal output power, including two other characteristic design points of the fuel cell, which are minimal output power, and power output corresponding to maximal efficiency. The test profile is illustrated in Figure 3. Test start conditions are prescribed to ensure result repeatability and comparability. In the case of the efficiency curve test, a preconditioning procedure shall be conducted, which consists of operating the FCM for at least 30 minutes at 60% of nominal power and allow it to reach thermal steady state. Thermal steady state of the FCM is achieved when the average coolant temperature of two consecutive intervals of 60 seconds do not differ by more than ±2°C in relation to the setpoint.

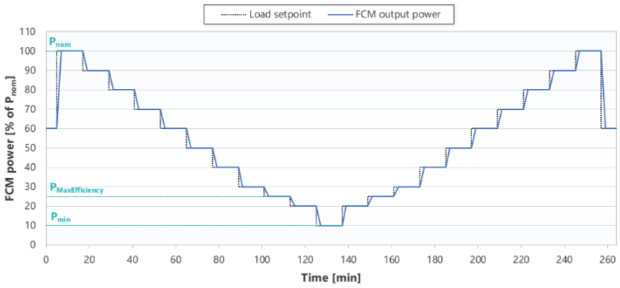

Figure 3. Efficiency curve test load profile.

The KPI resulting from this test is the FCM electrical efficiency (η_{FCM}) quantified as a function of net power output, reported in [%]. The FCM energy conversion efficiency accounts for fuel and electric input and the electrical output at steady state. It is the ratio of the net electric power output minus the sum of input DC power, to the lower heating value of hydrogen fuel supplied to the FCM, as given by the equation (1):

$$\eta_{FCM} = \frac{P_{eOut} - P_{eIn}}{\dot{m}_{H2} \cdot LHV_{H2}} \qquad \text{Eq. (1)}$$

FCM efficiency is calculated relative to the lower heating value of hydrogen, LHV_{H2} = 241.8 kJ/mol at standard conditions (25°C, 101.325 kPa). A successful result is achieved when the FCM performs without a shutdown or permanent damage to the system, and when the performance acceptance criteria are met.

3.2.4 Dynamic load profile performance

Considering that the FCM is expected to operate under dynamic load conditions, it is essential to assess its performance and robustness in response to variable power demand. The objectives of these tests are to measure the overall energy conversion efficiency of the FCM over repeated cycles, monitor its dynamic behavior and assess its power stability during stationary phases. Similarly to efforts taken in regulating internal combustion engine exhaust emissions and measuring fuel economy, a common standard cycle definition is needed to benchmark the FCMs against. To this end, the StasHH project proposed using three dynamic load profiles.

In practice, fuel cells are typically hybridized with batteries or supercapacitors, which buffer power fluctuations by handling sudden ramp-up demands, peak loads, and surplus electricity (e.g., during regenerative braking). This reduces the exposition of the FCM to high load dynamics. Given this fact, it is unlikely that a fuel cell will directly experience a fully transient load profile, such as the World Harmonized Transient Cycle (WHTC), defined by the Global Technical Regulation (GTR) No. 4[12]. To account for the effect of hybridization, semi-transient load profiles with lower dynamics are proposed. The first is based on the World Harmonized Stationary Cycle (WHSC)[12], a ramped steady-state test cycle with defined power levels and ramp transitions. The profile assumes an idle power equal to 10% of nominal power of the FCM, and 20s ramp times, as illustrated on Figure 4.

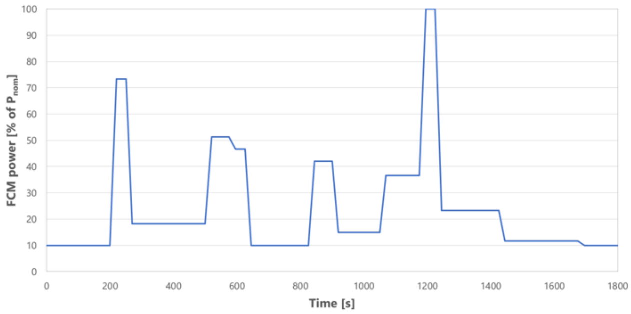

Figure 4. Semi-transient load profile based on the WHSC.

The second semi-transient profile is based on the ISO 8178[13], which is an international standard for exhaust emission certification and/or type approval testing for a number of non-road engine applications. For the purpose of StasHH, the type E3 (for propeller-law-operated main and propeller-law-operated auxiliary engines) is used, and is given in Figure 5.

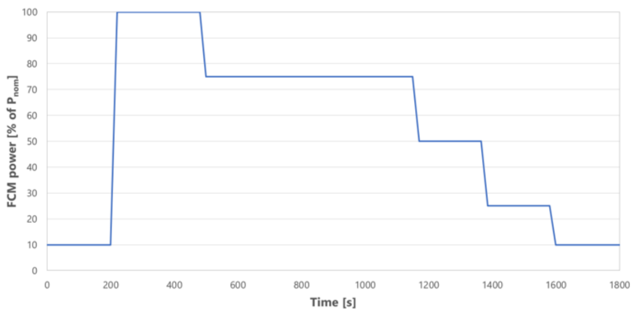

Figure 5. Semi-transient load profile based on ISO 8178 E3.

In addition to the load profiles inspired by WHSC and ISO 8178, the third profile was introduced by the StasHH project, and is visualized on Figure 6. The profile is not derived from a specific HD application, but was designed to gradually explore the dynamics of the full power range of the FCM. It consists of a 120 second-long plateaus, with interweaved load variations from 100% nominal power down to minimal power in 10% decrements, each lasting 60 seconds (therefore the requested ramp rate is variable).

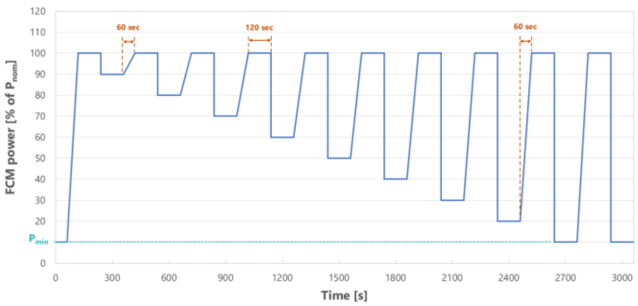

Figure 6. Semi-transient custom load profile.

The test profiles are to be repeated at least 2 times to assess the stability of the FCM. Additional cycle repetitions should be considered if the FCM behavior appears unstable, indicated by deviations exceeding a predefined threshold, e.g., more than 5% variance in hydrogen consumption between cycles, module temperature instability exceeding ±10°C from the setpoint. A successful result is achieved when the FCM performs the transients without a shutdown or permanent damage to the system. The KPI resulting from this test are the average hydrogen consumption per duty cycle, reported in [g/h].

In addition to the aforementioned sources, this test has been based on the protocol TMD-02 from the EU StackTest project(10) and PEMFC test protocols developed by the JRC(14).

3.2.5 Performance under static inclination

Due to the intended versatility of the FCMs, the system needs to be suitable for operation under inclination. Steep operating angles might lead to internal water management issues, which can render efficient operation much more difficult, resulting e.g. in sub-optimal electricity generation capabilities. This test simulates road gradients seen in automotive applications and roll scenarios encountered in maritime, and it was based on the protocol TMP-09 from the EU StackTest project(10), on the IEC 60092-504(15), and DNV-CG-0339(16).

The objective is to assess the impact of static inclination on the operability, performance and stability of the FCMs at steady state. Given that some FCM designs are optimized for road conditions and not for maritime use, each individual FCM manufacturer is free to select test angles that follow performance standards relevant in the target field of application. A minimal limit of 5° inclination is recommended. Figure 7 gives an example of an FCM load profile tested fist at a 0° angle, and afterwards under static maritime inclination conditions of positive and negative 22.5° in both pitch and roll dimensions of the FCM. The KPI resulting from this test is the average efficiency of the FCM, reported in [%], at 50% load and at nominal load for each tested inclination scenario.

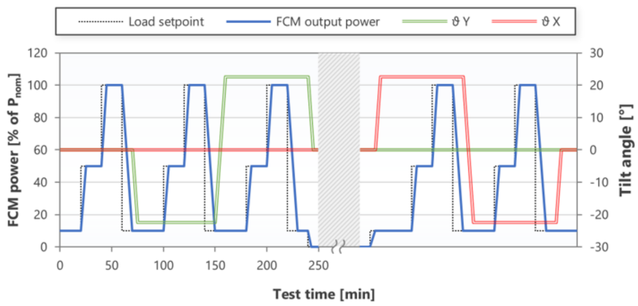

Figure 7. Performance under static inclination example profile.

3.2.6 Performance with impaired cooling

The FCM operating temperature depends on the thermal management system, including external components like coolant pumps, heat sinks, and vehicle HVAC systems. In case of cooling system failure, the FCM must either enter a safety mode or shut down automatically. This test evaluates the response of the FCM to impaired cooling, simulating reduced coolant flow or increased coolant temperature. To prevent irreversible damages of the FCM, testing the scenario of total coolant loss is not considered. The references used in formulating this test are based on the protocol TMS-05 from the EU StackTest project(10) and the IEC 62282-2-100(11).

The protocol includes an initial leakage rate test, operating under nominal load, increasing the coolant temperature and operating the FCM for 30 minutes, checking for the time to trigger alarms and/or FCM shut-down. Afterwards, once the FCM is shut-down, a leakage test is performed to check for correct tightness of gas and coolant circuits. If the FCM tightness quality has not decreased and is within safe limits, a restart is carried out, and the FCM is requested to operate under nominal load to check for any performance decrease. The test profile is illustrated on Figure 8.

Compared to the previous tests aimed primarily at quantifying performance, this test is focused on safety. A successful test result is achieved when the FCM maintains operation during the test or when the safety-related control function initiates the transfer of the FCM into a safe state (e.g. shut-down). To validate if the FCM has not incurred any permanent damage, a leakage rate test and a normal restart will be done at nominal coolant temperature.

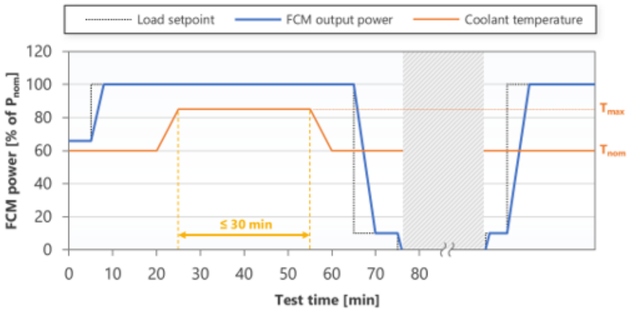

Figure 8. Performance with impaired cooling test profile.

4. CONCLUSIONS AND OUTLOOK

StasHH, in collaboration with leading fuel cell suppliers and key heavy-duty OEMs, has developed a practical FCM standard for fuel cell module form factors, physical and digital interfaces, and test protocols. The StasHH testing protocols have been successfully applied and validated on seven PEM fuel cell modules from six manufacturers, using different testing equipment and present a replicable framework for consistent validation and benchmarking of fuel cell module performance. The developed standards have been submitted to the IEC TC105 standardization committee for further review, voting and potential adoption.

The adoption of testing protocols can promote benchmarking a key part of standardization, ensuring comparability and scalability across the fuel cell industry. It has the potential to facilitate comparative assessments, information exchange, and help bridge the gap in module-level standards for HD applications. Insights from this work highlight the need for ongoing collaboration and can guide future FCM standardization efforts.

Future efforts should focus on remaining standardization gaps. Firstly, harmonization of electrical power output should be prioritized, including the introduction of a universal connector system and standardized voltage ranges. Secondly, defining unified dynamic load cycles is essential, as the application base in the HD sector is broad and continues to grow. Thirdly, further effort should be put in the development of unified methods for data processing, which can improve inter-laboratory comparability and objective benchmarking across diverse FCMs. Lastly, expanding stakeholder engagement and OEM alignment in order to avoid an excessive number of requests for tailor-made or customization requests and promoting standard adoption. By doing so, the industry can foster a more unified and efficient pathway toward the large-scale adoption of FC technologies in HD applications.

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REFERENCES

(1) F. Zenith, R. Bouwman, H. Lundkvist, The StasHH Fuel-Cell Module Standard, IEEE VPPC 2022, DOI: 10.1109/VPPC55846.2022.10003465.

(2) R. Bouwman, "Standard Size Definition", StasHH deliverable D3.2, 2022, https://stashh.eu/stashh-standard.

(3) R. Bouwman, H. Lundkvist, "Standard Update", StasHH deliverable D3.5, 2024, https://stashh.eu/stashh-standard.

(4) R. Bouwman, "Standard Interface Definition", StasHH deliverable D3.3, 2022, https://stashh.eu/stashh-standard.

(5) H. Lundkvist, "Standard API Definition", StasHH deliverable D3.4, 2022, https://stashh.eu/stashh-standard.

(6) Clean Hydrogen Joint Partnership of the European Commission, "Strategic Research and Innovation Agenda 2021-2027", https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en.

(7) K. Mrozewski, C. Bekdemir, "Test Protocols", StasHH deliverable D5.6, 2024, https://stashh.eu/stashh-standard.

(8) A. Balaji, K.J. Mrozewski, C. Bekdemir, Y. Wang, E. Havret, Evaluation of Standardized Testing Protocols for Fuel Cell Modules in Heavy-Duty Applications, Submitted to EVTeC 2025.

(9) Society of Automotive Engineers Surface Vehicle Recommended Practice SAE J2615, Testing Performance of Fuel Cell Systems for Automotive Applications, 2011.

(10) European "StackTest" project, (Development of PEM Fuel Cell Stack Reference Test Procedures for Industry), Grant

ID: 303445, http://stacktest.zsw-bw.de/general-information.html.

(11) International Standard IEC 62282-2-100:2020, Fuel cell technologies - Part 2-100: Fuel cell modules – Safety, 2020.

(12) United Nations Economic Commission for Europe (UNECE), UN Global Technical Regulation No. 4 - Amendment 4, Geneva, Switzerland, 2021.

(13) International Organization for Standardization, Reciprocating internal combustion engines — Exhaust emission measurement Part 4: Steady-state and transient test cycles for different engine applications, ISO 8178-4:2020, 2020.

(14) G. Tsotridis, A. Pilenga, G. De Marco, T. Malkow, EU harmonised test protocols for PEMFC MEA testing in single cell configuration for automotive applications, Joint Research Center of the European Commission, Publications Office of the European Union, 2015, https://data.europa.eu/doi/10.2790/54653.

(15) International Standard IEC 60092-504:2016, Electrical installations in ships - Part 504: Automation, control and instrumentation, 2016.

(16) DNV Class Guideline DNV-CG-0339, Environmental test specification for electrical, electronic and programmable equipment and systems, August 2021.