

CHALLENGES AND SOLUTIONS FOR LIQUID HYDROGEN-POWERED UAVS: REGULATIONS AND CASE STUDY INSIGHTS

Baptiste LEGRAND[1] & Nikola GAVRILOVIC[1]

[1]Département Aérodynamique, Energie et Propulsion, ISAE-SUPAERO, Toulouse, F-31055, France

Abstract

Hydrogen fuel cells combined with liquid hydrogen storage offer a promising low carbon footprint solution for extending the endurance of unmanned aerial vehicles beyond batteries limitations. However, the integration of hydrogen technologies presents technical, operational, and safety challenges that are not yet fully addressed by existing UAV certification frameworks. This paper reviews the airworthiness scheme applicable to hydrogen-powered UAVs and discusses the main challenges associated with proton exchange membrane fuel cells and liquid hydrogen storage. Four major topics are addressed: the powertrain reliability, the thermal management and the environmental effects on fuel cell performance, overall hydrogen risk management, and safety while operating cryogenic fluids. Existing standards and certification frameworks are analyzed to identify the current limitations regarding LH2-powered UAVs. Solutions to several challenges are illustrated through the Mermoz project, an ultra-long-range UAV designed to operate using liquid hydrogen. Experimental results demonstrate the capability of the powertrain to deliver up to 2.5 kW during take-off. Cruise operation at 375 W are carried out solely with the FC, which in case of failure is replaced by the Li-ion battery. Combined with a 12 L LH2 tank, the system offers an estimated endurance exceeding 37 hours.

Keywords: UAV, fuel cell, hydrogen, hybrid, safety

1. Introduction

In the past decade the number and types of UAV operations significantly increased for all use cases (recreative, commercial and military). This need drove UAV manufacturers towards higher production rates and investments in existing and new technologies. Concurrent to this development, the cost of key UAV component (e.g., cameras and power electronic) significantly decreased. From this conjecture stem the current growth of the UAV market. All categories are affected at different scale depending on the aircraft size, mission type, capability and aero-structural configuration. In the past 10-15 years, micro (< 2 kg) and small (< 20 kg) UAVs went from expensive commercial usage to being available to general public.

Most of these UAVs are powered either by an electric powertrain or by a piston engine. While both solutions are feasible for small UAVs, some limitations remain. Piston engines dedicated to aircraft model are unreliable, requiring frequent overhaul or engine replacement. They convert gasoline in mechanical energy which is less efficient than other conversion processes like electric or electrochemical. Noise and pollutant emissions (COx, NOx, soots, etc.) are another drawback from gasoline use. However, in specific UAVs configurations, gasoline high energy density (11.8 kWh/kg) allows significant ranges for the aircraft. An electric propulsion using batteries solves the piston engine issues at the expense of the UAV autonomy and range. This issue scales with the size of the aircraft as power and energy density of batteries are limited to 2500 W/kg and 250 Wh/kg [1]. Lastly, batteries introduce a fire hazard as a result of thermal runaway [2]. This phenomenon is hard to predict and manage without oversizing the battery and its systems.

https://doi.org/10.71945/icas2026_0213

Hydrogen is seen as a new energy carrier enabling long range and zero-emission operations at high energy efficiencies. These specificity is enabled by the hydrogen high energy density (33.3 kWh/kg) and fuel cells (FC) efficiency. The electrochemical reaction of hydrogen and oxygen inside a FC, enable the production of electricity with hydrogen [3]. Electricity can then be used to propel the aircraft through an electric motor. Several FC technologies are available, Proton Exchange Membrane FC (PEMFC), Solid Oxide FC (SOFC), Alkaline FC (AFC), etc. [4]. Nowadays, UAV manufacturers usually turn toward PEMFC as it has it is already commercialized and its operation, mostly temperature and efficiency ranges, fits UAV requirements. PEMFCs are characterized by an efficiency ranging from 40% to 65%. However, such performance is highly dependent on the environmental conditions [5] and the FC auxiliaries [6]. As a FC provides electricity, it can be combined with other electric energy storage like batteries or capacitors [7]. These components provide flexibility in the use of UAV powertrain. They can act as a backup or provide power to follow low time-response (< 1 or 2 s) loads. Regarding hydrogen storage, several technologies are available. Hydrogen can be stored in a gaseous form in a pressurized vessel. It is usually pressurized between 250 and 700 bars. Another solution it to store hydrogen in solid components like metal hydrides [8]. Lastly, hydrogen can be liquefied and stored at 20 K. The aviation sector is especially interested in liquid hydrogen (LH2) for their high gravimetric index ($m_{H2}/(m_{H2}+m_{tank})$). State of art LH2 tank's gravimetric index can reach above 20% [9], while gaseous tanks are limited to 5.7% (Type IV) and solid tanks under 20% [10].
However, hydrogen entails a range of technical and operational issues for UAVs. Academic and industrial sectors have identified a number of these challenges through studies, proof of concepts and products developed for mobility and stationary applications. The research work presented hereafter addresses these challenges and highlights solutions from literature, regulation or experience. Section 2. is entitled to discussing the current UAV certification frameworks. Section 3. is dedicated to categorizing and detailing the challenges at hand. Section 4. showcases hazard management based on the Mermoz UAV use case.

2. UAV regulation

A pre-requisite to understanding hydrogen UAV risk management is understanding UAV regulation. It serves as a baseline that defines which operation can be carried under specific conditions. Operations involving flying over populated areas or critical infrastructure are subjected to stringent airworthiness requirements leading to a risk-adverse UAV design. Conversely, operations over deserted areas, airworthiness authorities will not require extensive demonstration of each component capabilities. However, they will require demonstration that the UAV does not fly outside of the region it is operated in, leading to a higher risk acceptance level for the UAV design. This section will highlight the necessary information to understand how UAV airworthiness is defined by the authorities.

2.1 EASA airworthiness framework

This section first provides an overview of the certification process of UAV defined by EASA. Its airworthiness framework is currently codified by the EU Regulation 2019/947 [11] for UAVs weighing under 25 kg. Depending on the operation the UAV falls into one of three categories: Open, Specific or Certified.

2.1.1 Open category

The Open category is intended for low-risk operations. It is divided into three subcategories (A1, A2 and A3), which refers to different risk levels. The open category is limited to 25kg drones with a flying height of 120 m. The drone has to be operated with Visual Line Of Sight (VLOS) and shall not fly directly above people, except for subcategory A1. Category A1 refers to drones lighter than 250 g. In this case, flying over uninvolved people is allowed but should remain minimal. However, flying over an assembly of people or inside a drone restriction area is still forbidden. Subcategory A1 can be extended to UAVs weighing up to 900 g if the operation is carried out by a qualified operator. A qualified operator is a mandatory requirement for the subcategories A2 and A3. Lastly, subcategory A2 (< 4 kg UAV) and A3 (< 25 kg UAV) respectively allow flying close to people and flying in deserted areas.

The Open Category provides an interesting framework for the prototyping and testing of liquid hydrogen powered UAVs. Provided that the operator complies with the Open category regulations, the sole requirement on the systems is conformity with the safety provision established by the EU directive on machinery [12]. The directive requires the system supplier to ensure the CE conformity certification. However, the Open category requires VLOS, leading to small operational regions. Moreover, it requires to use of Flight Termination System (FTS) or Geofencing to limit the flight area. While Geofencing works with copter-types UAV, it is not suited for fixed-wing aircraft, leading to FTS as the sole system limiting the UAV flight area. Today, most FTS trigger a controlled crash of the aircraft. These conditions appear rather counterproductive for the use of a LH2 powered UAV. However, they might be sufficient to showcase the UAV frame and systems (fuselage, wing, autopilote, etc.) resilience using a battery powertrain.

2.1.2 Specific category

The Specific category has been created as an in-between to Open and Certified categories. It allows a higher degree of operational risks while maintaining a manageable level of complexity compared to certified operations. To comply with the specific category, the manufacturer can either fill a Predefined Risk Assessment (PDRA) or a Specific Operations Risk Assessment (SORA) with the EASA or its national aviation authority. Upon validation by the competent authority, the operation of the UAV can be extended fly over populated areas or flight Beyond Visual Line Of Sight (BVLOS). Both methods require a specific assessment of the operation and the risks it exposes uninvolved population and critical infrastructure to. For example, with the SORA methodology, ground and air risks are assessed based on the aircraft characteristics and space populations. Risk can be mitigated under certain conditions like sheltering of uninvolved people inside buildings. The final overall risk assessment leads Operational Safety Objectives (OSO), which are requirements the UAV, its operation and its crew must abide to.

As the Specific category is significantly more permissive with the operation, it is also more suited to hydrogen powered UAVs. As BVLOS operations are allowed, the operation carried out can benefit from hydrogen UAVs range. In addition, the process remains lighter than the certified category and is therefore suited to organizations without airworthiness experts, such as research organizations, academia or small UAV manufacturers.

2.1.3 Certified category

Lastly, the Certified category is intended for high-risk operations. It requires a high level of safety and reliability to be able to fly over assemblies of people, transport people or carry dangerous goods. Moreover, the competent authority, EASA or national aviation authority, might require a drone certification when the risk evaluated with other methods is to high. EASA UAV certification framework is built around the EU Regulation 748/2012 [13]. This regulation lays down requirements as well as administrative procedures for the airworthiness of aircraft products and parts. As it stands, the EASA is currently working on amending current aviation regulations (CS23 and CS25) to account for specific UAV operations. For small UAVs, the CS-LUAS proposed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) can be applied. However, no definite guideline is being pushed by the safety agencies to certify an UAV.

Unlike the two first category which accept a certain degree of risk as long as population exposure remains within specific boundaries, the Certified category has a risk-adverse policy. It is required that the manufacturer test simple and in some occurrence combined failure cases. These tests are based on specific norms and standards. An example of such are the Direct Order (DO), like the DO-160 for system environmental test, the DO-178 for software or the DO-254 for electrical system design. As these tests are extensive, the UAV manufacturer shall carefully consider carrying out its operation as it stands. For research purposes, this framework shall be avoided, but might bring some insights on how systems shall be tested.

2.2 UAV hydrogen standards

As previously stated, operations falling into the Certified category shall be avoided. However, similarly than CS23, UAV airworthiness framework will call for specific standards. For hydrogen, these

standards might provide some information on how the UAV shall be design and tested to showcase a safe operation. Abiding to H2 UAV standard is invaluable to showcase a safe UAV design in Open or Specific categories. Currently, a sole aeronautical standard defined by the ASTM, ASTM F3547-24 [14], covers the use of hydrogen for an UAV. The standard introduces over 90 requirements split between 6 topics (battery, FC, fuel system, refueling, operation and test method). The four system at hand, refueling included, share 77 requirements on design, test, operation and certification.

2.2.1 Battery

Batteries, especially Li-ion technologies, are vastly used to power UAVs. These systems and their issues are known, and already subjected to specific ASTM standards like the ASTM F3005. The ASTM F3547 lists 9 requirements regarding the design, operation and management of Li-ion batteries coupled with a FC. These requirements are built to prevent a single hazard, the thermal runaway. Thermal runaway has different causes, such as over-temperature, over-charge and -discharge, or short-circuit. The three first causes listed here can be solved by monitoring the battery temperature and State of Charge (SOC). Short-circuit is harder to prevent as it has multiple causes.
Requirements of the ASTM F3547 are either oriented towards to sensing and protection devices (monitoring temperature, voltage, current, etc.) or towards the battery operability. The battery charging procedure using a FC is subjected to requirement in sections 5.2 and 5.3 of the standard. The system must provide a cell balancing procedure and the charging must remain within reasonable temperature range. Another requirement (5.4) states that the battery shall be actively monitored to prevent critical operations. Therefore, systems like battery management system (BMS) and circuit breaker shall be integrated and operated to limit the temperature and SOC range. The remaining requirements are discussing the way the battery is monitored by the ground station during flight.
While requirements 5.3 and 5.4 are common practice, requirement 5.2, advising a cell balancing strategy, is less common. Battery charging for power applications are usually carried out in three steps. At low SOC a constant current is applied, to quickly charge the battery. At higher SOC, a constant voltage phase brings the battery to a charge level corresponding to a given voltage [15]. While this procedure can charge cell at the full capacity voltage (4.2V/cell), most of the time, the voltage is kept below (4.05 to 4.1V/cell). After reaching 4.05V/cell, the third step is to apply a cell balancing procedures to ensure that all cells within the battery reach the same SOC. However, applying balancing procedures require specific hardware and a significant amount of time. If the hardware is not provided or supported by the fuel cell manufacturer, this requirement can be crippling. A more flexible approach would be to limit the charging voltage to a given value during operation. The procedure can be coupled with an on-ground cell balancing to limit cell voltage spread between operations. Such maintenance prevents overcharge during operation, limite additional hardware and mass and care for unbalanced cells on the ground.

2.2.2 Fuel cell

The ASTM F3547 requirements regarding the FC handle two critical hazards, partial or complete loss of power and hydrogen fire hazard resulting from fuel permeation or leaks. As the ASTM F3547 requires the FC to provide most of the energy during all flight phases, a total loss of the FC power is critical. Most of the requirements on the FC and battery hybridization stem from this specific case.
Five requirements from the ASTM F3547 can be demonstrated through various testing procedures. First, requirements 6.1.19 indicates that "The fuel cell shall provide rated power required by the aircraft with full rated payload in all stated conditions". A hybrid battery can support the fuel cell during peak loads and as stated in 6.1.14 and 6.1.15 be used as a back-up energy source in case of fuel cell failure. The transfer of the load from the fuel cell to the battery must be automatic, leading to specific design constraints. In addition, section 6.1.24 requires the fuel cell or another aircraft system to monitor fuel stored, used and leaked. While this requirement does not call for a specific test, each of the tests carried on the powertrain provide information on its fulfillment and the resilience of the system and its measurement. Other requirements are relevant to the FC operation such as FC preconditioning prior to the flight, monitoring operational parameters (temperature, fuel pressure, etc.), monitoring FC health indicators, etc.

The measure of the State of Health (SOH) shall be provided as per points 6.1.18. Most of the low power FC system (< 3 kW) are not provided with a SOH monitoring system. Testing procedures built to showcase fuel cell aging are usually time-extensive, even with Accelerated Stress Tests (AST) [16]. However, as research is extensive around this topic, it will be possible to implement a generic SOH model. Regarding hydrogen leakage detection, several solutions exist. Usually pressure sensors are placed at specific position over the hydrogen feeding line, which makes it possible to monitor pressure drop in the supply network and therefore leakage. Another solution relies on the tank hydrogen gauge and a flow meter before the fuel cell hydrogen inlet to compute hydrogen flows at both end of the network. As the mass quantity shall be conserved in the hydrogen network, a difference between both measurement will highlight leaks.

2.2.3 Fuel systems

The ASTM F3547 currently does not provide any guidance regarding operating a drone powered with LH2 as stated in section 7.2. As the FC cannot work under 0℃ (ice production), it is fed gaseous hydrogen through the supply line. Therefore, even with a liquid hydrogen storage, some gaseous hydrogen requirements can still be fulfilled.
The ASTM F3547 requirements 7.6 and its associated sub-requirements are significant design constraints. They state that: "the FC and hydrogen storage system shall be designed such that undue hazards are not presented [...] in cases of in-flight failure" [14]. This requirements accounts for hydrogen leaks as well as high energy debris that might result from a tank or fuel system breakage during an uncontrolled landing. Demonstrating such requirement can be done with either a controlled crash test of the UAV or through systems testing (e.g.: H2 tank drop test).

3. Challenges of LH2 powertrains for UAVs

Several challenges must be addressed in order to safely design and operate a liquid hydrogen powered UAV. Some are addressed by standards like the ASTM F3547 while others are not currently accounted for. This section aims to complete regulations by assessing additional challenges that arise when designing and operating a LH2-powered UAV.

3.1 Hydrogen Proton Exchange Membrane Fuel Cell (PEMFC)

Currently, two PEMFC technologies are available on the market: open cathode FC and closed cathode FC. With open cathode FCs, air is directly fed to the cathode FC as a reactant and a coolant. With closed cathode FCs, air is conditioned before being fed as a reactant on the cathode side. In addition, cooling and reaction airflow are independent with closed cathode FCs. Figure 1 showcases an example of both technologies. On the left, the IE-S800 has a single air inlet for both coolant and reaction air. Air is drawn in the FC by two fans at the outlet. On the right, the Protium-1000 is provided with an air compressor at the inlet of FC cathode. The FC cells are enclosed and separated from the cooling system and the ambient environment. Air for cooling is drawn between two cells by the fans.
For light UAVs, the open cathode FCs are usually selected as they are lighter than closed cathode. However, as the air is not conditioned (filter, pressure, temperature), open cathodes are much more dependent on the environment in which they are operated. The environment influence on the FC performance is mainly due to three parameters: relative humidity, temperature and altitude. Fabian et al. [17] have shown that a 60% relative humidity variation can lead to voltage drop up to 16% at 40℃. Moreover, their study showcased a maximal voltage drop of 20% associated with a significant reduction of the maximal current density, from $0.75\mathrm{A/cm^2}$ to $0.5\mathrm{A/cm^2}$ while the temperature rise from 30℃ to 40℃. Another study conducted by Zhang et al. [18] highlighted the influence of the temperature on the FC Open-Circuit Voltage (OCV). As the FC temperature increases from 23℃ to 120℃, its theoretical OCV drops from 1.241 to 1.136. Further tests confirmed this tendency with minor corrections based on the FC membrane type. Deeper analysis showed extreme temperature (< 90℃) can significantly increase the FC ohmic resistance [19]. Such rise has been associated with the severe dehydration of the membrane and the catalyst layer. This reduces the water pressure and limits the number of active site were oxygen and hydrogen can react. The last challenge regarding temperature revolves around sub 0℃ conditions. This topic has been recurrent in research, especially for cold start [20]. Below 0℃ water freezes and blocks the mass transfer of the reactant at the

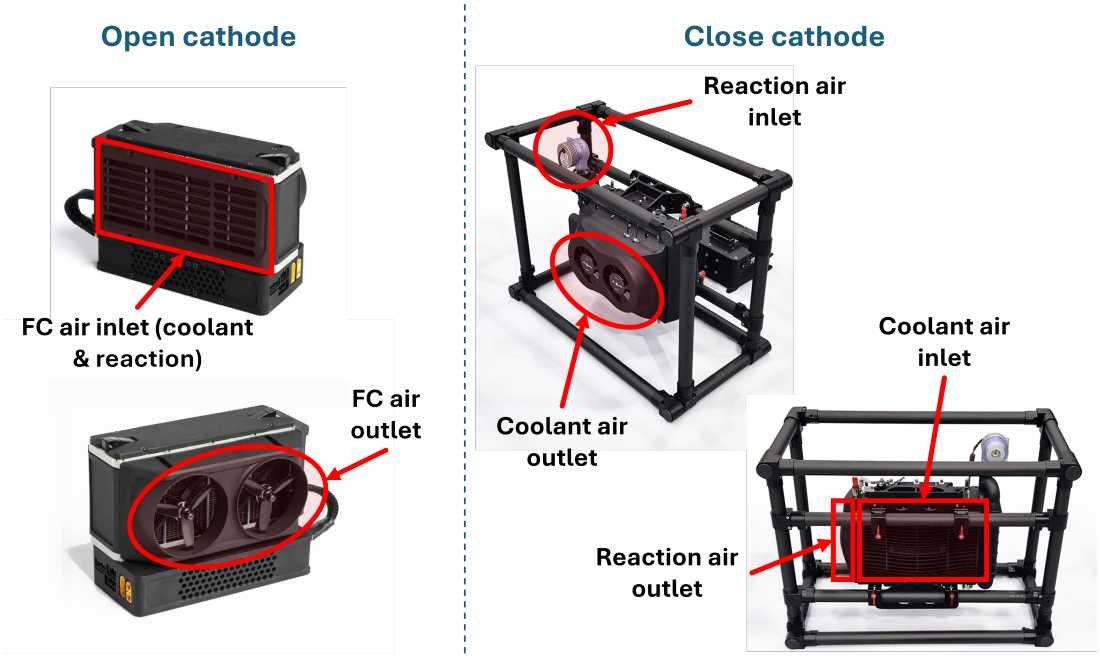


Figure 1 – Difference between open and close cathode air supply

anode, cathode and inside the membrane. Lastly, altitude has an effect on oxygen temperature and pressure. The reduction in the air pressure with the altitude limits the oxygen partial pressure entering an open cathode FC. This reduction hinders the oxygen mass transfer towards reaction site, lead to a lower FC voltage [3]. In addition, if a pressure difference between anode and cathode induces mechanical stress on the membrane. With a sufficient pressure differential and occurrence rate, the membrane are subjected to failure [21].

In addition to the previously discussed environmental conditions, open cathode FC are sensitive to the ingestion of contaminants from the atmosphere. Two compounds are concerning: sulfur-based (SO_2, H_2S) and nitrogen-based (NO_x) compounds [22]. Sulfur compounds in the atmosphere tend to bind with the platinum in the catalyst layer at the cathode, disabling reaction site available for oxygen reduction reaction. Nagahara et al. [23] showed that in sufficient concentration, in sufficient concentration, SO_2 and H_2S voltage decays can reach 38% of the nominal voltage at 1A/cm^2. They also showed that performance can be partially recovered through a procedure with high humidity levels. NO_x, especially NO_2 has shown to have an influence on the FC through several transformation. Mohtadi et al. [24] highlighted a reduction of the available current by 55% after a 12 h exposure time. Contrary to sulfur compounds which act on the catalyst layer, they believe that NO_2 competes with oxygen to produce NH_4, which is a ionomer pollutant. The introduction of carbon monoxide has also been studied. Pei et al. [25] shown that carbon monoxide has a significant influence on the FC performance when introduced at the anode side (mixed with hydrogen). However, its ingestion at the cathode does not significantly influence the FC performance as it is reduced by oxygen before reacting with the catalyst layer [26].

Mechanical stress like shocks and vibrations might hinder the FC performance as highlighted by Haji Hosseinloo et al. [27]. El-Emam et al. [28] conducted a study showcasing the effect of various angular vibrations. Their study ranges from 3 cm to 6 cm amplitude, 1.33 Hz to 3 Hz frequency and 9 starting angles. They showed that while most of the vibration patterns causes the FC voltage to drop, 1.33 Hz might improve the FC voltage at high loads. It appear that at high loads low amplitude and frequency improve the water drainage out of the FC Gas Diffusion Layer (GDL), limiting flooding conditions. They also hypothesized that the performance loss at high amplitude and frequency results from the formation of a water film inside the cathode GDL. This curtain limit the transport of oxygen inside the GDL, hindering the reduction reaction at the cathode. Regarding shocks which occurs during crash, literature tends to study larger FC, with 100 cells and above. Wu et al. [29] showed that cells can slip from one another with shocks parallel to the cell arrangement and above 30g. This

slippage might induce leaks as between disjointed cells. They also highlighted three key factors in the slippage magnitude: the impact acceleration, the clamping force of the FC cells and the friction coefficient between the cells.
Lastly, certification may require the FC system to comply with the environmental testing of the DO-160 [30]. According to the DO-160, 22 tests shall be carried out to show compliance of the system towards conditions it might work in. While research has extensively characterized some parameters in the DO-160 like temperature variation, humidity, ice or explosive atmosphere, significant work still remains for other parameters, like dust ingestion, electromagnetic fields or lightning.

3.2 Liquid hydrogen

As stated in section 2., the use of liquid hydrogen is not oversight by any certification process, norm or standard for UAVs. Therefore, assessing this fuel safety in a regulated framework cannot be achieved. This sub-section provides insight on the current challenges associated with cryogenic storage of hydrogen based on literature and previous experience (ground tests).
Regardless of the operation, cryogenic hydrogen can be fed to a FC using one of the two following methods, a cryo-pump or the boil-off pressure differential. While cryo-pumps are active systems that require energy, a control scheme and maintenance, boil-off feeding can occur naturally. Boil-off occurs when hydrogen is heated inside the tank due external factors (e.g.: thermal bridges) or internal ones (e.g.: heating resistor). Part of the liquid hydrogen is vaporized leading to the formation a gaseous phase in the tank. As the quantity of vaporized hydrogen increases, the gaseous phase pressure increases as well. If the tank thermal specifications are accurately selected for the UAV design, boil-off pressure build-up can be stabilized to the FC operating hydrogen pressure and flow rate [9]. Most of the UAVs currently designed are using boil-off differential pressure while cryo-pumps are expensive, heavy, rather inefficient and have a short life span [31].
Using boil-off to fed hydrogen might lead to several technical constraints. First, boil-off pressure shall be balanced using the FC. If the pressure is to low, the FC performance decreases, until it is shut down. A pressure to high lead to degradation of the FC. In worst case scenario, overpressure can compromise the integrity of the FC, as it leads to tearing in the membrane, and the tank, as some safety pressure valves remain open after being used. This can be solved by adding a pressure relief valve to the LH2 tank. Second, the thermal management of the tank (insulation and boil-off management) should be thought of during design. On one hand, if the tank insulation is too efficient, the hydrogen gaseous phase pressure will be low and will not feed enough reactant to the FC. Depending on the FC control system, under-stoichiometry could induce irreversible losses [32] or shutdown the system to protect the FC stack. On the other hand, if the tank insulation is not sufficient, pressure rises and a significant quantity of the hydrogen will be lost through the pressure relief valve. Previous work also highlighted that ambient temperature modifies the tank boil-off rate by $\pm$ 2% for a 20 ℃ difference close to ambient temperature [9]. Third, fuel sloshing might be hazardous for the operation. During sloshing, the liquid and gaseous phases of the hydrogen mix together. As a consequence, temperature is homogenized and part of the gaseous hydrogen is liquefied [33]. The sudden liquefaction of the gaseous phase leads to a rapid loss of pressure in the tank that might cut the hydrogen supply. Fourth, liquid hydrogen temperature might present a safety issue. When fed to the FC, hydrogen lowers the pipe environment temperature. If this environment is cold enough, oxygen and nitrogen in the air liquefies and can even solidify [34]. An environment rich in oxygen or in nitrogen might be produced depending on the temperature. While the oxygen rich environment leads to a fire hazard, the nitrogen one leads to a risk of hypoxia or anoxia for the nearby operators. Lastly, operating a FC below 0 ℃ is complex, especially during start up. As the temperature drops, water freezes inside the FC which hinder chemical mass transport [20]. As hydrogen is at cryogenic conditions inside the tank (-253 ℃), a poor design can fed hydrogen below 0 ℃ to the FC. Thermal management of the hydrogen feeding line shall be careful thought of to limit such operation. During previous work, the FC cooling exhaust was used to heat up hydrogen feeding line [34, 9, 35]. Such experiment showed that the temperature of the hydrogen exiting the tubing can rise from around 0 ℃ up to 22 ℃. This method also helped reduced icing from air humidity around the pipes. As hydrogen shall be heat up, is can also act as a heat sink for systems, like FCs [36], electric motors [37], power converters or even batteries [38].

4. Mermoz LH2 UAV framework

Mermoz challenge is a specific use case that require to overcome several challenges associated with LH2 powertrains. This section presents the case study of Mermoz LH2 challenge. Firstly, the concept is introduced in the context previously exposed. Secondly, the UAV testing framework is provided from on the ground component testing up to flight tests using LH2. Thirdly, safety and performance concerns will be discussed.

4.1 UAV design

The objective of the Mermoz project is to develop an UAV capable of crossing the Atlantic ocean from Dakar to Natal. To this end, the UAV should be able to fly for more than 3000 km without refueling. Useing liquid hydrogen is key to reach this goal [39]. By design, 8 kg are allocated to Mermoz UAV powertrain. Such mass allocation enables 485 km with batteries, 1135 km with gaseous hydrogen and 3270 km with LH2. As LH2 enables the range requirement, this solution was selected for the UAV final version. Another stringent requirement is to take-off and land from hard and soft runaway without landing gear. Take-off can be either operated using a trolley or a catapult. The latter operation requires a clear identification of the sloshing effects when the tank is subjected to a longitudinal acceleration. Landing requires specific wearing parts as the aircraft land on its belly. In order to incrementally test systems, the aircraft undergo several versions. The first version are based on a Calvados aircraft model frame. The powertrain and systems are integrated in a designated pod assembled to the Calvados fuselage. With the first Mermoz UAV versions, the pod tail is left open for maintenance and safety purposes. The final version of Mermoz UAV uses the Calvados aircraft wing, while the fuselage is designed based on the tested pod. Figure 2 showcase the intermediate version with an open pod (in blue). The air inlet and outlet at colored in light blue, while the Calvados fuselage is in light gray. An interface part (in orange) is assembled below the pod, to serve as a wearing part and setup the guide rail of the catapult.

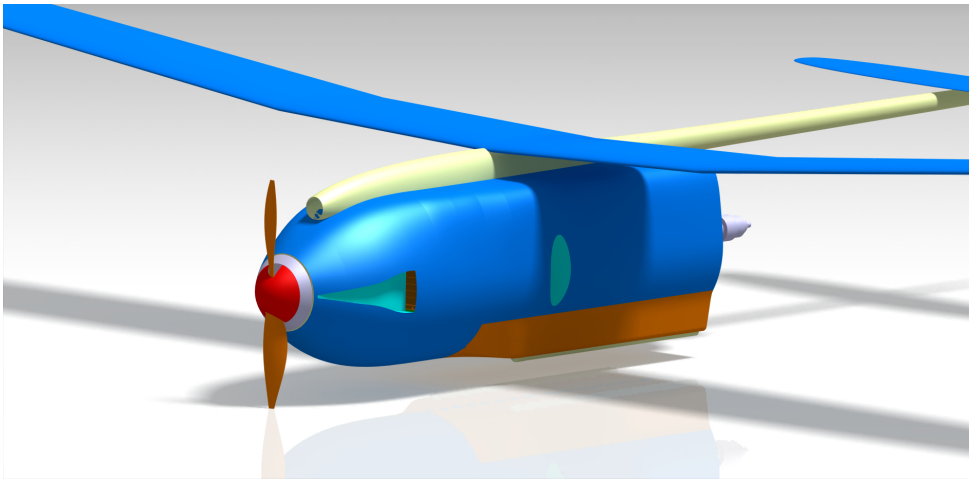


Figure 2 – Mermoz UAV intermediate version rendering

The internal layout of the hydrogen systems for the final version is presented in Figure 3. Air is fed to the systems through an expansion chamber after the air inlet. Hot air exiting the FC is guided to the outlet to limit recirculation of air and hydrogen inside the fuselage. However, before exiting the fuselage, this hot air is blown over the LH2 heat exchanger. To this extent, specific air outlet guides and LH2 heat exchanger have to be designed. Lastly, the LH2 tank is enclosed in a compartment separated from the rest of the powertrain. This enable a finer thermal management of the tank environment and the aircraft systems. In addition, this compartment is slightly vented to limit cold atmosphere as well as accumulating hydrogen resulting from a leak.
Regarding its characteristics, the UAV has a wingspan of 4.355 m, for a wing area of 0.933 m^2. In its intermediate version, (cf. Figure 2), the length of UAV fuselage is 1.935 m. Such characteristics enable an aircraft MTOM up to 13 kg for the given mission profile. The mission profile consists of a take-off, followed by a climb to the cruise height (100 m). After achieving its mission, the UAV

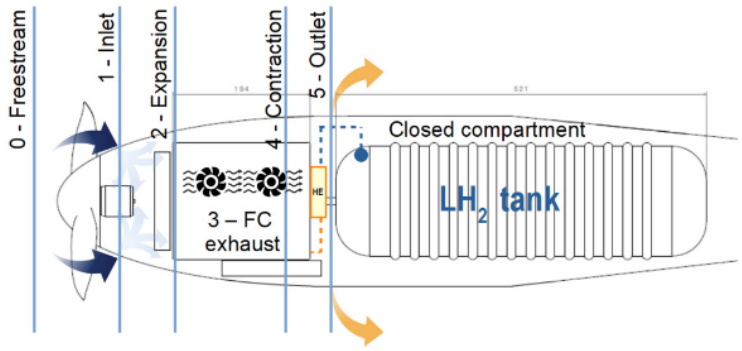


Figure 3 – FC and LH2 tank integration inside the UAV. HE is the heat exchanger

descends and land. By design, the aircraft stalls at 15 m/s without flaps. Adding the flaps enables a lower stall speed, below 10 m/s. Cruise is carried out at 23 m/s, while first flight tests showcased a maximal speed between 43 and 44 m/s (during a descent with power). Such design enable the UAV to work with rather low power levels. Cruise requires the electrical network to provide between 350 W and 400 W, while take-off ranges from 1500 W to 1700 W.

Three electrical networks were designed to enable a safe approach to aircraft control. The first network is the powertrain. As showcased in figure 4, it consists of 8 main components for Mermoz UAV. The hydrogen tank stores LH2 and provides gaseous hydrogen to the FC. It is equipped with a safety boil-off valve that opens at 2.75 bars. Hydrogen is fed to the FC through the second component, the heat exchanger. As the temperature differential and tubing section are small, the heat exchanger doesn't require fins or extensive length to supply hydrogen above 0 °C. The third component is the FC. It is an IE-S800 provided by Intelligent Energy. The FC alone can provide 800 W to the powertrain. The FC is the main energy supplier throughout the mission. It is associated with the fourth component the power module (provided by Intelligent Energy). This system controls the current drawn from the FC using a DCDC converter. It also acts as a charger for the battery when it is depleted. The battery is a 12S 3.25 Ah Li-ion battery. It provides power when the requirement exceeds what the FC can provide and serves as a voltage source. The latter is set between 50.4 V and 38 V depending on the battery SOC and the applied load. The drivetrain consists of the last three components, the Electronic Speed Controller (ESC), the electric motor and the propeller. All three were selected to provide the traction requirement during take-off and minimize energy consumption during cruise.

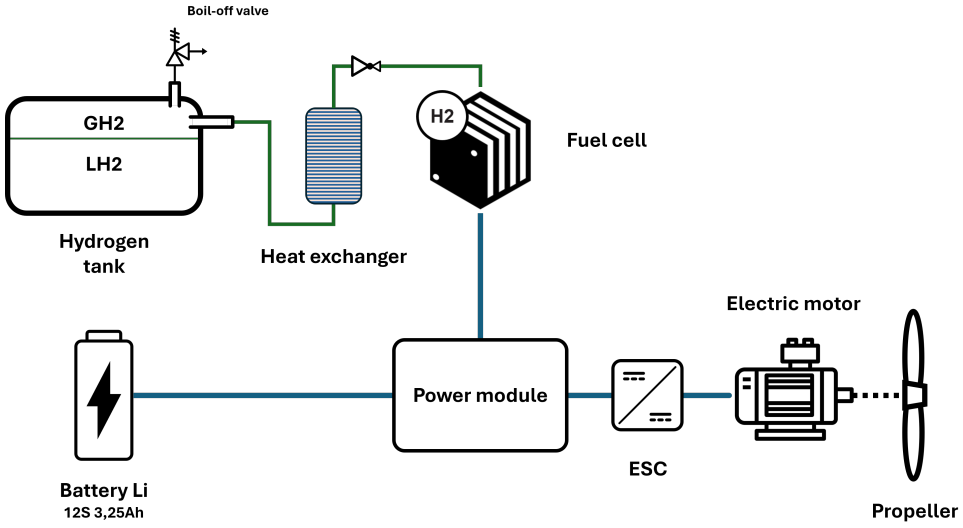


Figure 4 – Powertrain network

The second electrical network is the data acquisition network. It is based on a Teensy 4.0 micro-

processor as the architecture centerpiece. The Teensy board provides energy to the measurement probes while collecting their data. The following information are collected by the sensor probes: position (using GNSS), speed and acceleration (inertial measurement unit), temperatures, currents, voltages, hydrogen pressure and flow rate. Data is sent to the ground station using an XBee RF module. The network is powered by a dedicated Li-ion battery. The third electrical network is the aircraft aerodynamic surface control. For the intermediate design, this network is split from the other network to that a loss of aircraft power does not hinder its control by the remote pilot. The remote control receiver is powered by a another dedicated Li-ion battery. Upon command, the receiver directly controls the servo control setting the aerodynamic control surfaces accordingly. The batteries powering the two last network shall be separated from the powertrain systems. They can be placed in a dedicated vented compartment to limit thermal exchange with other systems.
The aircraft requires 3 Li-ion batteries. At least one temperature and voltage probe monitor each battery. They provide information to the remote pilot and test engineer on how the remaining SOC and battery temperature. The powertrain battery has an additional current sensor to enable a finer monitoring of power management. Each battery is tested before and after the operation. If needed, they are charged and the cells are balanced with a charger on the ground.
As depicted in this section, by design the aircraft accounts for several challenges. During nominal operation, hydrogen FC purges are evacuated using the cooling air outlets. Hydrogen leaks resulting from system failures should not create explosive atmospheres as every compartments is vented. Moreover, electrical networks and batteries are mostly segregated from hydrogen compartment to limit the number of potential ignition sources. Lastly, powertrain and aircraft control surfaces systems are split to limit a combined loss of power and aircraft control.

4.2 Testing procedures

In spite of stringent design requirements, components still need to be tested to confirm that the previously stated challenges are overcome. As the powertrain is this research main concern, only testing related to it will be introduced. For Mermoz use case, system testing is split as such: drivetrain testing, FC and battery testing and LH2 tank testing. As drivetrain testing is common [40, 41], it will not be presented here.
During Mermoz challenge, two main FC test campaigns are carried out. The first characterizes the FC, battery and their hybridization in open air conditions. The objective of this test campaign is to show compliance with the requirements of the ASTM F3547 and define the system performance limitations in a controlled environment. Testing the FC alone shall demonstrate at least the component nominal performance, through a polarization curve, and the maximal applicable load. In addition, simple FC transient electrical states can be identified to fine tune FC preconditioning prior to other tests. Battery testing shall demonstrate its capabilities regarding loads over short periods (5-10 s) and longer periods (3-5 min). Short periods will showcase the capacity of the battery to answer high power requirements such as take-off or go-around with an nonoperational FC. Long timescales will showcase the battery capability to maintain cruise requirement in case of FC failure. In addition to single component test, the whole system operation shall be demonstrated. For the IE-S800, it consists of characterizing the charging procedure of the battery using the FC and showcasing the system dynamic capabilities. The latter is demonstrated by subjecting the system to load power levels comparable to climb or take-off requirements. The second campaign characterizes the influence of the powertrain integration on the system performance. Several environmental conditions can be tested as well. The objective of this campaign is to characterize how the compartmentalization of the systems inside the UAV modifies the behavior of the FC and battery. Similar protocol to the open air can be carried out, such as building a polarization curve, evaluating FC electric transient, etc. Building a test bench enabling air flow rate, temperature, humidity and pressure control is pertinent for these tests. It will provide a finer characterization of the system when subjected to several environmental conditions. In the case of Mermoz challenge, air flow rate and temperature is controlled. As the UAV flies close to sea level, pressure does not significantly changes. Moreover, days were the UAV flies can be selected, to keep the relative humidity in a specific range.
LH2 tank testing is complementary to the FC test campaign. To this extent, the tests carried out shall demonstrate concordance between the boil-off rate and the fuel cell hydrogen supply over the

mission. This usually consists of a natural boil-off test and a mission profile test using the FC. For the natural boil-off test, the hydrogen tank is setup and slowly filled with LH2. Upon reaching the required LH2 quantity inside the tank, supply is cut and hydrogen is naturally vented to the atmosphere. For the second test, the hydrogen tank is plug to a hydrogen feeding line and a FC. Using an electric load, the FC is subjected to operating conditions similar to the flight. The tank shall be tested at several ambient temperature. Lastly, as Mermoz UAV is catapulted, a sloshing test representative of the take-off conditions shall be carried out. As previously stated, sloshing mixes liquid and gaseous hydrogen within the tank. This operation redistributes the temperatures, liquefies part of the gaseous hydrogen and can lead to significant pressure drops inside the tank. Therefore, sloshing test strives to defining if the hydrogen supply remains within the FC boundaries in terms of pressure and flow rate.

To this date, Mermoz systems have been subjected to two of the three test campaigns previously presented. The open air FC system test campaign has been successfully carried out. The limits of the FC, the battery and the overall system are summed up in table 1. This table presents the power limitations, times responses and overall achievable times at specific operating power. Moreover, the hydrogen flow rate results represents the requirement for the boil-off testing which has been validated in a previous study [42]. FC and system time response are especially interesting. They showed that the system is able to provide 950 W under 200 ms, while the FC requires 1.5 s to reach similar power level. In between, the power requirement was achieved using the battery. Similar behavior was showed going from high power to low power, and the battery was recharged. Such operation requires to manage the battery SOC, to limit over-discharge and over-charge. Lastly, the battery has showed that it can provide alone 600 W during 5 min. Such operation highlight that the battery can provide enough power to sustain cruise and climb for 5 minutes in case of FC failure.

Table 1 – FC, battery and FC system general limitations

General limitations		
Characteristic	Operating point	Value
Hydrogen flow rate	375 W / 800 W / Purge	4.5 / 10 / 23 NL/min
FC response time	0 to 1000 W	1.5 s
FC response time	1000 to 0 W	0.5 s
System response time	0 to 950 W	< 200 ms
Maximal system power	< 10 s	2500 W
Time constraints		
System tested	Operating power	Time
Battery (maximal continuous)	600 W	5 min
Battery (take-off)	1250 W + 1700 W	5 s + 5 s
FC	850 W	continuous

The fuel cell efficiency and hydrogen flow rate are presented in figure 5. The maximal efficiency is achieved when the FC provides 250 W. At 375 W, representing the rapide cruise conditions, the FC efficiency is 53.3% and it consumes 4.4 NL of hydrogen per minute.

Previous LH2 test campaigns [34, 9, 42] for Mermoz UAV showcased several requirements. The latest [42], illustrated the tank behavior subjected to several flight profiles one after another over 7 hours. The LH2 was supplied in accordance with FC requirements. Under take-off requirement load, the minimal pressure reached was around 1.5 bars. As the tank was provided with a heating resistor, its influence on the tank feeding pressure was characterized as well. Associating a controller with the heater limited the tank pressure range from 1.8 bars to 2 bars. Regarding performance, the tests showed that cruise requirement lead the tank pressure to 1.5 bars for 5 NL/min. During this test, the battery was recharged as well, explaining the higher hydrogen flow rate. In addition, it appeared that despite significant temperature variation at the tank outlet, the hydrogen temperature remains around 20°C at the FC inlet. Over the test span, the lowest tank outlet temperature was -130°C. At such temperature condition, air molecules (N2 or O2) are not liquefied, disabling the production of

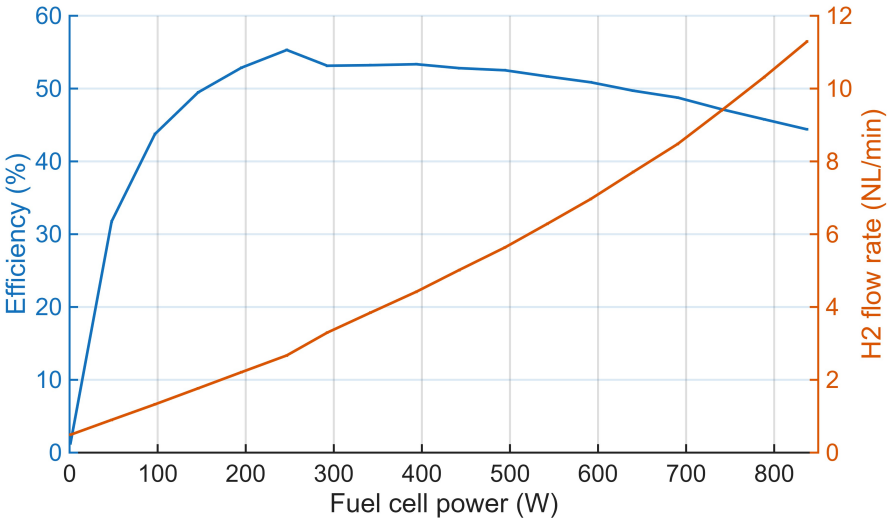


Figure 5 – Fuel cell efficiency and hydrogen flow rate

nitrogen or oxygen rich atmospheres. Lastly, these tests were carried out using a 12L LH2 tank. With such volume and consumption, the UAV has up to 34 h 20 min (up to 37 h 30 min with 4.5ÑL/min). Sloshing tests have not been performed yet.

4.3 Discussions on the safety approach

Mermoz UAV is a technological demonstrator. As the UAV must showcase long range capabilities with a powertrain system unconventional by authority standards, flight tests must be carried out in a specific setting. This setting limits the UAV operational volume to low population density areas. Getting out of this volume first triggers warning and then a controlled crash. Such safety features enable Mermoz to flight either in Open or Specific categories. The SORA framework is build to highlight the safety features and how they fit the operation at hand. While testing presented in the previous section demonstrates the systems capabilities, the SORA method is build to minimize risk associated with the UAV operation. The SORA framework assesses how ground and aerial population are exposed to the UAV inherent risks. Then the initial risk evaluation can be mitigated through specific means (shielded population, restricting access to flight areas, limiting crash area and energy, etc.). Based on the mitigated risks, the SORA assessment details a list of Operational Safety Objectives (OSO) which is a list of requirements the UAV, the operation and the crew must abide to.

Adding to the operational limits and safety features, safety procedures tailored to the UAV and the use of hydrogen were build as part of the SORA OSO. As some tests have not yet been carried out regarding LH2, these procedures might still evolve. They account for: nominal use, hydrogen tank refill and handling, radio frequency (RF) and GPS signal loss, motor power loss, fly away, accidental fire and UAV crash. Losses of RF, GPS or motor power requires an immediate landing. If the UAV reaches the end of its flight area with such failure, a controlled crash is initiated. In the case of fire or crash, the procedure priorities rescuing the injured. From the UAV landing or crash, a 10 minute observation period shall be accounted for before approaching the UAV. This period as been deemed sufficient to let hydrogen escape or burn out of the tank. As a precaution, approaching the UAV requires the operator to probe for remaining hydrogen and abnormal temperatures as hydrogen flame might not be visible in specific settings [43].

Cryogenic conditions bring specific safety concerns regarding temperatures and chemical species management. Refilling and handling of LH2 tanks are especially sensitive operations. LH2 production requires dedicated liquefaction units that are usually stationary. Procedures are required to refill a small LH2 tank, such as Mermoz's, using these liquefaction units. First, certain void level shall be obtain between the LH2 tank inner and outer layer, usually close to 10^{-5} Torr. Then the LH2 tank inner volume has to be cooled down prior to filling it with LH2. To this extent, three chemical species are commonly used. Either hydrogen from the liquefaction unit (in gaseous or liquid form), liquid nitrogen

of liquid helium. While liquid helium is expensive, liquid nitrogen solidifies at a higher temperature than hydrogen liquefaction point. Therefore, nitrogen can solidify in the piping or tank when LH2 is fed to the tank, leading to a significant safety hazard. Lastly, using hydrogen from the liquefaction unit is cost effective but rather inefficient regarding energy consumption. Handling of LH2 tank is also critical. To achieve the required mass constraints, the LH2 tank inner and outer envelopes are build to fulfill the UAV structural constraints. Therefore, shocks or falls can significantly damage the tank outer layer which could in turn lead to a rupture of the void in the tank. When filled with LH2, a rupture in the insulation leads to significant boil-off rate and a rapid pressure increase inside the tank. If the safety valve is not accurately designed to vent the hydrogen out, pressure rises until the tank bursts [44]. Lastly, handling of cryogenic systems subjects people to cold burn hazards. The operator shall be especially wary of surfaces made of good thermal conductors such as metals.

5. Conclusion

This paper presents the challenges associated with LH2-powered UAVs. As presented in section 2., airworthiness authorities considerations towards hydrogen-powered UAV is limited to gaseous hydrogen with specific operational constraints. This section also introduced the main differences in managing the safety of the UAV based on the category they are operated in. Open and Specific categories manage risks by identifying the UAV limits for a given operation. Following such constraints, a component in the UAV is allowed to fail and lead to a controlled crash. However, procedures and systems must be built to limit the UAV wandering area and its potential effects on uninvolved population. Certified category does not allow system failure leading to a total loss of the UAV control. Such risk aversion leads to stringent requirements for the components and the UAV. Section 3. provides insight on technical challenges regarding FC and LH2 that are not tackled by the current regulation. As it stands, thermal management of the FC and LH2 system appears to be a significant challenge. On one hand, FC cooling requirements are stringent for at a low temperature. At high temperatures, above 90 °C, FC OCV decreases (-5%), while its internal resistances increase, especially in low humidity conditions. On the other hand, using LH2 requires a controlled heat flux to the hydrogen as its temperature shall rise above 0 °C when fed to the FC. In addition, hazardous conditions can arise due to liquefaction or solidification of air molecules (N2 and O2). The last section 4. provides insights on how airworthiness is approached on several levels throughout Mermoz challenge. The objective of Mermoz current operation is to fall either in the Open or Specific categories. Requirements associated with these categories add constraints at the UAV and operational levels. However, as hydrogen and LH2 are new, Mermoz UAV underwent several system level testing. These tests are carried out on the ground. They showed that the powertrain can provide up to 2500 W for 10 seconds during take-off without accounting for system failure. The FC is the sole energy provider for cruise with 375 W. In addition, failure cases were also studied. The battery is able to provide most of the take-off power requirement for 5 seconds, as well as the cruise power requirement for 5 minutes. The latter also proved that during these 5 minutes, the UAV retains part of its climb capabilities. Lastly, LH2 tank testing showed compliance with the FC cruise hydrogen flow rate requirement of 4.5 NL/min. With a 12L LH2 tank, such consumption leads to a 37 h 30 min use. In addition, the hydrogen is supplied at temperatures above 0 °C with a specific heat exchanger placement.
Experience built around Mermoz UAV for several years helps to build a framework around the technical challenges associated with LH2 powertrains. The intermediate version of Mermoz UAV required new operations and test infrastructure in order to showcase its long range feasibility. From this experience, the following recommendations are formulated :

- Define one typical operation as early as possible during the UAV design stage. The operation requirements shall be declined in the form of an operational flight volume at specific airspeeds. It shall serve as a baseline to start the usually time-intensive airworthiness procedures.
- Design the aircraft with at least one FTS that lead to either a controlled crash or a recovery attempt (e.g.: parachute). These systems will be required to constrain the aircraft wandering capabilities under failures conditions (e.g.: loss of RF or GPS).

- Ground testing is an effective method to highlight compliance of the UAV powertrain with performance requirements before flight tests. An effective test planing shall be done as soon as possible during the UAV design stage.

References

[1] K. A. Vishnumurthy and K. H. Girish. A comprehensive review of battery technology for E-mobility. *Journal of the Indian Chemical Society*, 98(10):100173, 2021.

[2] W.H. Yan, W.X. Huang, Y. Yang, Z.W. Wei, H.S. Zhen, and Y. Lin. Research on overcharge mitigations and thermal runaway risk of 18650 lithium-ion batteries. *Journal of Energy Storage*, 120:116372, June 2025.

[3] J. Larminie, A. Dicks, and M. S. McDonald. *Fuel Cell Systems Explained*, volume 2. J. Wiley Chichester, UK, 2003.

[4] Mehdi Soleymani, Vahid Mostafavi, Marie Hebert, Sousso Kelouwani, and Loïc Boulon. Hydrogen propulsion systems for aircraft, a review on recent advances and ongoing challenges. *International Journal of Hydrogen Energy*, 91:137–171, November 2024.

[5] Robert W. Atkinson, Matthew W. Hazard, Joseph A. Rodgers, Richard O. Stroman, and Benjamin D. Gould. An Open-Cathode Fuel Cell for Atmospheric Flight. *Journal of The Electrochemical Society*, 164(2):F46–F54, 2017.

[6] K. Stutenberg. Toyota Mirai Testing. Technical report, Argonne National Laboratory, 9700 South Cass Ave.Lemont, IL 60439, September 2018.

[7] Emre Özbek, Gorkem Yalin, Selcuk Ekici, and T. Hikmet Karakoc. Evaluation of design methodology, limitations, and iterations of a hydrogen fuelled hybrid fuel cell mini UAV. *Energy*, 213:118757, December 2020.

[8] H. Barthelemy, M. Weber, and F. Barbier. Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, 42(11):7254–7262, 2017.

[9] Nikola Gavrilovic, Sofia Mertika, Jean-Marc Moschetta, Joshua Schimpf, Gyeongbae Park, and Seo Young Kim. Experimental Study on a Liquid Hydrogen Tank for Unmanned Aerial Vehicle Applications. *Journal of Aircraft*, 61(6):1805–1816, November 2024.

[10] Abdisa Sisay Mekonnin, Krzysztof Wacławiak, Muhammad Humayun, Shaowei Zhang, and Habib Ullah. Hydrogen Storage Technology, and Its Challenges: A Review. *Catalysts*, 15(3):260, March 2025.

[11] Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft (Text with EEA relevance.), May 2019.

[12] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) (Text with EEA relevance), May 2006.

[13] Commission Regulation (EU) No 748/2012 of 3 August 2012 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations (recast) Text with EEA relevance, August 2012.

[14] ASTM F3547-24 : Standard Specification for Fuel Cell Power Systems for Use in Small Unmanned Aircraft Systems (sUAS), June 2024.

[15] Sheng Shui Zhang. The effect of the charging protocol on the cycle life of a Li-ion battery. *Journal of Power Sources*, 161(2):1385–1391, October 2006.

[16] Paul Thiele, Yue Yang, Steffen Dirkes, Maximilian Wick, and Stefan Pischinger. Realistic accelerated stress tests for PEM fuel cells: Test procedure development based on standardized automotive driving cycles. *International Journal of Hydrogen Energy*, 52:1065–1080, January 2024.

[17] Tibor Fabian, Jonathan D. Posner, Ryan O'Hayre, Suk-Won Cha, John K. Eaton, Fritz B. Prinz, and Juan G. Santiago. The role of ambient conditions on the performance of a planar, air-breathing hydrogen PEM fuel cell. *Journal of Power Sources*, 161(1):168–182, October 2006.

[18] Jianlu Zhang, Yanghua Tang, Chaojie Song, Jiujun Zhang, and Haijiang Wang. PEM fuel cell open circuit voltage (OCV) in the temperature range of 23°C to 120°C. *Journal of Power Sources*, 163(1):532–537, December 2006.

[19] Dongfang Chen, Taoheng Yin, Yuan Yang, Xianqi Song, Xiaohua Yang, Tong Hu, Jie Liu, Song Hu, Xiaoming Xu, and Pucheng Pei. High-temperature performance and degradation mechanisms of proton exchange membrane fuel cells: Experimental investigation at 95–105 °C. *Applied Thermal Engineering*, 280:128341, December 2025.

[20] Zhongmin Wan, Huawei Chang, Shuiming Shu, Yongxiang Wang, and Haolin Tang. A Review on Cold

Start of Proton Exchange Membrane Fuel Cells. *Energies*, 7(5):3179–3203, May 2014.

[21] Mohsen Mazrouei Sebdani and Erik Kjeang. In-situ pressure differential-accelerated mechanical fatigue testing and modeling of a reinforced fuel cell membrane. *Polymer Testing*, 136:108482, July 2024.

[22] Xuan Cheng, Zheng Shi, Nancy Glass, Lu Zhang, Jiujun Zhang, Datong Song, Zhong-Sheng Liu, Haijiang Wang, and Jun Shen. A review of PEM hydrogen fuel cell contamination: Impacts, mechanisms, and mitigation. *Journal of Power Sources*, 165(2):739–756, March 2007.

[23] Yoshiki Nagahara, Seiho Sugawara, and Kazuhiko Shinohara. The impact of air contaminants on PEMFC performance and durability. *Journal of Power Sources*, 182(2):422–428, August 2008.

[24] R. Mohtadi, W.-k. Lee, and J.W. Van Zee. Assessing durability of cathodes exposed to common air impurities. *Journal of Power Sources*, 138(1-2):216–225, November 2004.

[25] Pucheng Pei, Yiming Xu, Mingkai Wang, and Peng Ren. Effects of carbon monoxide on proton exchange membrane fuel cells and elimination techniques. *International Journal of Hydrogen Energy*, 69:1287–1304, June 2024.

[26] Valérie Parry, Grégory Berthomé, Jean-Charles Joud, Olivier Lemaire, and Alejandro A. Franco. XPS investigations of the proton exchange membrane fuel cell active layers aging: Characterization of the mitigating role of an anodic CO contamination on cathode degradation. *Journal of Power Sources*, 196(5):2530–2538, March 2011.

[27] Ashkan Haji Hosseinloo and Mohsen Mousavi Ehteshami. Shock and vibration effects on performance reliability and mechanical integrity of proton exchange membrane fuel cells: A critical review and discussion. *Journal of Power Sources*, 364:367–373, October 2017.

[28] Salah H. El-Emam, Ahmed A. Mousa, and Mahmoud M. Awad. Effects of stack orientation and vibration on the performance of PEM fuel cell. *International Journal of Energy Research*, 39(1):75–83, January 2015.

[29] C.-W. Wu, B. Liu, M.-Y. Wei, and W. Zhang. Mechanical Response of a Large Fuel Cell Stack to Impact: A Numerical Analysis. *Fuel Cells*, 15(2):344–351, April 2015.

[30] RTCA DO-160: Environmental Conditions and test Procedures for Airborne Equipment, December 2014.

[31] Guillaume Petitpas and Salvador M. Aceves. Liquid hydrogen pump performance and durability testing through repeated cryogenic vessel filling to 700 bar. *International Journal of Hydrogen Energy*, 43(39):18403–18420, September 2018.

[32] Kai Meng, Ben Chen, Haoran Zhou, Jun Shen, and Zhengkai Tu. Experimental investigation on voltage response characteristics of hydrogen-oxygen proton exchange membrane fuel cells under gas starvation. *Energy Conversion and Management*, 268:115973, September 2022.

[33] J. Lacapere, B. Vieille, and B. Legrand. Experimental and numerical results of sloshing with cryogenic fluids. In *Progress in Propulsion Physics*, pages 267–278, Brussels, Belgium, 2009. EDP Sciences.

[34] Sofia Mertika, Joshua Schimpf, Seo Young Kim, Jean-Marc Moschetta, and Christophe Turpin. Modeling and experimental testing of a UAV liquid hydrogen propulsion set. *International Journal of Hydrogen Energy*, 88:1398–1409, October 2024.

[35] Nikola Gavrilovic, Yuchen Leng, and Jean-Marc Moschetta. Thermal control of a hydrogen-powered uncrewed aerial vehicle for crossing the Atlantic Ocean. *Aerospace Science and Technology*, 155:109667, December 2024.

[36] Magnus Lenger, Steffen Heinke, Wilhelm Tegethoff, and Jürgen Köhler. Synergies of fuel cell system thermal management and cryogenic hydrogen exergy utilization. *Scientific Reports*, 12(1):22065, December 2022.

[37] Gi-Dong Nam, Hae-Jin Sung, Dong-Woo Ha, Hyun-Woo No, Tea-Hyung Koo, Rock-Kil Ko, and Minwon Park. Design and Analysis of Cryogenic Cooling System for Electric Propulsion System Using Liquid Hydrogen. *Energies*, 16(1):527, January 2023.

[38] Shirui Li, Jiaying Yu, Wei Xiao, Shanlin Liu, Huan Liu, Wei Chen, Xiaoqing Zhang, Xiao Ma, and Shijin Shuai. Thermal management for batteries and motors in a liquid hydrogen-fueled hybrid propulsion system. *Applied Thermal Engineering*, 281:128519, December 2025.

[39] Nikola Gavrilovic, Jean-Marc Moschetta, and Quentin Barascud. Development of a Hydrogen-powered UAV System for Crossing the Atlantic Ocean. In *AIAA SCITECH 2023 Forum*, National Harbor, MD & Online, January 2023. American Institute of Aeronautics and Astronautics.

[40] Fabrizio Marignetti, Damiano D'Aguanno, and Giuseppe Volpe. Design and experiments of a test equipment for hybrid and electric vehicle drivetrains. In *2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, pages 1–6, Monte-Carlo, Monaco, April 2017. IEEE.

[41] Andrew Gong, Rens MacNeill, and Dries Verstraete. Performance Testing and Modeling of a Brushless DC Motor, Electronic Speed Controller and Propeller for a Small UAV Application. In *2018 Joint*

Propulsion Conference, Cincinnati, Ohio, July 2018. American Institute of Aeronautics and Astronautics.

[42] Nikola Gavrilovic, Xavier Carbonneau, Jean-Marc Moschetta, Ritesh Prakash, Joshua Schimpf, and Seo Young Kim. Ground testing and analysis of a liquid-hydrogen propulsion system for UAVs. *International Journal of Hydrogen Energy*, 187:151960, November 2025.

[43] R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, and T.B. Settersten. Visible emission of hydrogen flames. *Combustion and Flame*, 156(6):1234–1241, June 2009.

[44] Karl Verfondern. Safety consideration on liquid hydrogen. December 2008.

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.