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CAA Hydrogen Challenge: Hydrogen Sandbox Summary Report

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Contents

1 Introduction

The Hydrogen Challenge project focuses on the key role that hydrogen is expected to play in the sustainability efforts of aviation at a global level but also at the national level of the UK. Since hydrogen aviation solutions are at an early stage of development, industry does not have yet a comprehensive understanding of the risks to aviation safety. To address these issues, the aim of the Hydrogen Challenge is to facilitate collaboration among the Civil Aviation Authority (CAA), the aviation industry and academia in order to enhance the understanding of hydrogen-related risks to aviation safety, identify gaps in CAA policies, and propose recommendations to develop new net-zero policies. One of the workstreams of the Hydrogen Challenge includes a number of sandbox projects that were selected to be part of our work.

In particular, the sandbox approach aims to make sure that regulation applicable to hydrogen in aviation is adapted and fit for purpose for this new fuel. This was done by using a controlled environment where organisations like the ones selected could test products and services in collaboration with the CAA. For the second round of the Hydrogen sandbox, we received preliminary applications from fifteen organisations that expressed an initial interest to participate in the sandbox. The applications were evaluated following a set of scoring criteria that were established by the Hydrogen Challenged team before receiving the applications.

Thirteen projects were selected initially from which eleven projects succeeded in working closely with the CAA to increase readiness of industry and the regulator for hydrogen fuel. Due to funding and other logistical constraints, two projects were not able to complete their projects within this second round of the sandbox. The work that these eleven organisations conducted within the sandbox in collaboration with the CAA's Hydrogen team is summarised in the following sections of this report. In addition to the summarised results presented below, the Hydrogen Challenge team has drafted a comprehensive technical report for each one of the projects describing at length the activities and tasks that these organisations completed as part of the sandbox.

2 Cranfield Aerospace Solutions (CAeS)

This section sets out the core roadmap across the five domains, with milestone codes appearing as:

- MT = Aircraft and Propulsion Systems
- ME = Energy
- MA = Aerodromes
- MO = Operations and Safety Management
- MF = Airspace and Flight Procedures

Each domain includes a 2050 end-state description, key dependencies, and the enabling activities that support safe progression through the three time periods.

Cranfield Aerospace Solutions is an aerospace technology company that specializes in aircraft conceptual designs and power and propulsion systems. Within the CAA's regulatory sandbox CAeS focused on its Stingray hydrogen-electric unmanned aircraft system (UAS) programme. Stingray is a hydrogen-electric, long-endurance unmanned aerial vehicle platform. Its aim is to explore the integration of hydrogen fuel-cell powertrains and to understand the performance, endurance, and zero-emissions potential of hydrogen-electric propulsion.

Following changes to their original Hydrogen Challenge sandbox application moving from a fixed wing hydrogen powered fuel cell aircraft to a hydrogen powered fuel cell UAV, the scope of the CAeS activities was reviewed and included the following:

- Fuel Cell Propulsion System (FCPS) design and validation including three independent sub-system modules and a control system.
- A case study to identify the two worse case failure scenarios for the Stingray 1 FCPS as installed in the airframe.
- FEMA with failure condition categorisation for Stingray 1 FCPS installed in an UAS and a Stingray 1 concept of operations (CONOPS).
- System Theoretic Process Analysis (STPA) process for a fuel cell and refuelling scenarios.
- FCPS cooling requirements, ramp up and shut down development during ground testing and performance development tests.
- Implications for certification.

A Fuel Cell Internal to a blended-wing UAS

The design of the UAS architecture is that the fuel cell stack is mounted internal to the blended wing aircraft and is air cooled. To investigate this aspect of the configuration, open circuit voltage at varied air flow conditions (built in fan speed variation) has been tested. During the test, the fan speed was varied to test for fuel cell over/undercooling, where overcooling was identified as an issue, leading to fuel cell degradation. The fan cools the fuel cell to a temperature below 40 C, but it cannot heat the fuel cell stack under cold ambient air intake conditions. All the above information has been derived from open-circuit voltage testing conducted under varying airflow conditions, both on the development bench and during on-aircraft ground testing. Insufficient cooling was found to cause permanent damage to the fuel cell; however, this damage could be repaired.

Ramifications for Certification

- *CS-E 745(a)(3) Engine Acceleration*

CAeS development ground testing has demonstrated that compliance against this requirement is most likely to be achieved by a hybrid battery and hydrogen fuel cell propulsive system, as opposed to pure battery or pure hydrogen fuel cell systems.

- *CS 23.77 (system level requirement at amendment 4) Bulked landing*

Similarly, compliance with this requirement can be achieved by a hybrid propulsive system.

- *CS 25.981 Fuel tank explosion prevention and Appendix N – Fuel Tank Flammability Exposure*

An issue is how to show that permanent fuel cell degradation can be avoided without the risk of developing an explosive mixture in the fuel cell stack. The power output threshold for overcooling, the appropriate cooling technology and sufficient ventilation to avoid accumulation of an explosive hydrogen/air mixture must also be considered.

STPA considerations

While CAeS applied the STPA approach to the Britten-Norman BN-2B Islander aircraft, the following considerations can be read across to their UAS project:

- UAV throttle control during a go-around shall be enough to ensure aircraft is capable to effectively clear a 50 ft obstacle.
- UAV throttle control during a Rejected Take-Off shall be enough to ensure that the aircraft is capable of stopping inside the runway.
- The Throttle Position Signal Controller (TPSC) shall send a signal to the Fuel Cell Propulsion System and report any internal Fault to the HMI, ensuring the human ground controller is situationally aware of Thrust status during critical phases of flight.
- The TPSC shall be supplied with a stable low voltage source, and this shall be available in emergency conditions.
- If the FCPS power status conflicts with throttle position, the HMI shall inform the human ground controller of the conflict.

- The TPSC shall not prevent high power demand from throttle control when low voltage source input is unstable in critical phases of flight in a go-around.
- If TPSC experiences loss of low voltage it shall inform the HMI for the human ground controller for immediate actions in critical phases of flight.

Project Challenges

Due to market forces and the UAS providing a wider opportunity and accelerated path to explore integrated platform and propulsion architectures, CAeS changed their original plans to retrofit a Britten-Norman BN-2B Islander aircraft with a hydrogen propulsion system and moved to a UAS platform as a test bed for the same propulsion system.

3 Exeter Airport

The Zero Carbon Turn (ZCT) Project was led by Exeter Airport, with support from Cranfield University, TUI, ULEMCo, Boeing and other industry partners. It focused on reducing ground-based emissions through the use of hydrogen in airport operations. After successful trials of GSE in April 2025, in this phase of the hydrogen sandbox, the project focused particularly on assessing the technical and safety implications of operating a **hybrid dual-fuel hydrogen ground power unit (HyGPU)** in winter conditions and during hours of darkness.

Therefore, a HyGPU Winter Operations Project Risk Assessment and Safety Case Development Workshop was held in December 2025, bringing together key project stakeholders to identify project risks and to inform the development of the safety case for winter HyGPU operations at Exeter Airport.

The purpose of the workshop and associated post-workshop activities was to support the development and submission of the CAP 791 assessment required for the HyGPU Winter Operations Project. Following the CAA's initial review of the CAP 791 application, a request was issued for clarification and additional supporting information. In response, the consortium submitted two further documents, along with a revised Airfield Safety Plan (see below). After reviewing the additional material, the CAA approved the CAP 791 application on 10th February 2026.

Trial findings

The HyGPU was positioned on the Aerodrome North Side on an area of hard standing adjacent to the Motor Transport workshop and the H2 MCP2 positioned in the same location to supply the GPU with the H2 (Hydrogen Gas).

Figure 1 Exeter Airport Trial Location

The trial was conducted over 5 operational days and the HyGPU was used on 33 separate occasions. However, on 17 occasions the HyGPU was either operational for too short a period (considered here as 0-5 minutes) to be realistic for the operation of a GPU, or key data points were missed from the data logger which left gaps in the dataset. Once the data had been cleaned and usable occurrences extracted, 15 separate operations were taken forward for analysis.

The analysis of those 15 operations shows that no direct, discernible impact of lower ambient temperatures on the technical operation or performance of the HyGPU was observed at the individual test level. However, it is noteworthy that on the two occasions where the HyGPU took longer to reach operating temperature and peak flow, testing was conducted early in the morning following overnight inactivity.

This suggests that periods of non-operation (i.e. the unit remaining dormant) have a greater influence on performance than ambient temperature alone. These effects may, however, be amplified under colder ambient conditions and when the unit is left inactive for longer periods.

Although the dataset remains modest, it represents one of the few examples of a hybrid hydrogen dual-fuel ground support equipment (GSE) operating in real-world conditions. The findings will help to inform decision-making and support the development of the business case for hydrogen adoption at airports, including forecasting hydrogen requirements for the operation of similar equipment.

Handling compliance requirements

It is important to note that the trial activities were guided by, and demonstrate compliance with, the following standards relating to the storage and handling of gaseous hydrogen:

- BS ISO 14687:2019 Hydrogen Fuel Quality
- NFPA 2 – Hydrogen codes, Ch7

- BCGA CP33. Bulk storage of gaseous hydrogen

Project Challenges

Due to financial constraints the initial application was rescoped to a winter trial developing a safety case taking into consideration environmental variables, including low ambient temperatures, wind, precipitation, and reduced lighting conditions during night-time operations.

4 Heathrow Airport

The Heathrow 601 hydrogen demonstration project was originally a 4-year project designed to advance the safe introduction of hydrogen-powered ground support equipment at a major international airport.

The project's Phase 1 - Refuelling Gaseous Hydrogen Ground Service Equipment (GSE) was scheduled for completion by the end of March 2026. This phase focused on assessing the feasibility of refuelling gaseous-hydrogen-powered GSE to support live aircraft turnaround operations and the development of a safety case.

A **HAZID workshop** on "Developing a Safety Case for a CAP 791 Submission" was held as part of the hydrogen sandbox. The purpose of this workshop was to establish a shared understanding of the high-level safety and environmental risks associated with Project 601 and to provide an overview of these risks to support further assessment, elimination, and mitigation activities.

The HAZID key discussion themes included the project's ConOps, the facility requirements, the supply of hydrogen to the airport and the management of the actions arising from the HAZID. A HAZID was fundamental for the CAP 791 submission because it:

- Meets regulatory expectations for systematic hazard identification.
- Forms the backbone of the safety case evidence.
- Supports ALARP demonstration.
- Ensures stakeholder participation and traceability.
- Captures risks associated with new and emerging technologies.
- Directly aligns with CAA safety case development guidance (CAP 760 and CAP 791).

Safety Case

The Safety Case Report was developed in support of CAP791 and contained the key elements expected of a report of this type. Dated February 2026, the document was prepared to complement the submission to Heathrow's internal compliance team and the subsequent UK CAA CAP791 submission. The Safety Case Report focused exclusively on the delivery of Phase 1 of the project and provided evidence that all credible hazards were identified, associated risks have been evaluated and reduced to a level that is ALARP.

COMAH and DSEAR assessments

An assessment was undertaken in November 2025 in alignment with the Control of Major Accident Hazards (COMAH) Regulations (SI 2015 No. 483), enacted under the Health and Safety at Work etc. Act 1974. The assessment confirmed that there is no safety interaction between existing COMAH sites and the P601 project.

In parallel, a DSEAR assessment was required under the *Dangerous Substances and Explosive Atmospheres Regulations 2002*. These regulations place duties on employers to assess, prevent, and control fire and explosion risks arising from dangerous substances, classify hazardous zones, implement emergency arrangements, and provide suitable information and training. The following requirements were derived for this project:

Parked Hydrogen Truck

- The hydrogen truck must maintain BCGA-recommended separation distances, with at least 8 m from nearby buildings, site huts, sheds, or workshops.
- During entry inspections at Stand 601, the truck must avoid confined areas and remain at least 5 m from ignition sources.
- A dedicated parking area should be marked out in Stand 601 using barriers and cones to maintain minimum safety distances.
- Because the hydrogen vents create an ATEX Zone 1 above the truck, the parking location must have no overhead obstructions (e.g., tree branches, canopies, lighting columns) and must not be indoors.

Refuelling Operations

- Refuelling must take place in a designated, open refuelling zone, well separated from personnel work areas, ignition sources, and flammable items, and clearly marked using barriers and cones.
- The refuelling area must be unenclosed and free from overhead obstructions due to potential hydrogen venting.
- Measures must prevent movement of the truck or tug during refuelling, although a breakaway coupling provides secondary.

Project Challenges

According to the original programme the Project 601 trial was scheduled to commence on 16 February 2026. However, progress was significantly impacted by challenges in engaging external stakeholders, most notably the onboarding of the airline. This delay subsequently affected the timeframe required to initiate engagement with the ground handling organisation. Additional delays arose from the time required to address and incorporate feedback from key stakeholders within Heathrow. These factors have contributed to the elongation of the project timeline beyond the initial plan. As a result and given that the revised timeline would likely enter an extremely busy period for aerodrome operations, a decision was taken to pause the project and revisit it in Q3 2026.

5 Qdot Technology

Qdot Technology

Qdot Technology (Qdot) specialises in advanced thermal management technologies for the aerospace, defence and energy sectors. Its current development activities focus on clean aerospace applications, including heat exchangers for hydrogen fuel cell powertrains and thermal management solutions for cryogenic hydrogen storage systems. Qdot has shared **two pieces of work** for this phase of the CAA Hydrogen Challenge:

1. The **Clean Hybrid Powertrain for Aviation (CHyPA) project** aimed to design, build, and integrate a hydrogen–battery hybrid propulsion system for a large VTOL UAV platform.

The CHyPA programme generated valuable technical, operational and organisational learning that informed the pace and direction of development. These insights have strengthened the team's understanding of hybrid-electric and hydrogen propulsion systems and will support the delivery of future programmes.
The fuel-cell subsystem work delivered a range of hydrogen-related components, including lightweight cooling elements, hydrogen regulation hardware, purge and venting mechanisms, suitable for aircraft-scale integration. The experience gained through the design, manufacture, integration and commissioning of these subsystems provides a strong platform for further innovation in hydrogen and thermal-management technologies.

Lessons Learnt

- Allocate sufficient programme time for controls implementation, system commissioning and iterative debugging under representative operating conditions.
- Include additional mass contingency in early system models to provide flexibility for evolving cooling and structural requirements.
- Enhance supply-chain resilience through multi-supplier strategies, early procurement and appropriate spare-parts provision.
- Increase subsystem modularity to simplify integration, testing and future system development.
- Strengthen battery safeguarding procedures during assembly and integration to maintain battery condition and prevent parasitic discharge.
- Incorporate appropriate schedule provision for safety assurance and approval activities, particularly where hydrogen systems require additional review and validation.

2. **Feasibility of Cryo-Compressed Hydrogen for Drones** project was a collaboration with the NCC (National Composites Centre) and concerned the

feasibility of Cryo-Compressed Hydrogen as a storage medium for general aviation and drone applications.


Not subject to export control

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Feasibility of Cryo-Compressed Hydrogen for Drones

Qdot Technologies

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Figure 2 NCC Feasibility Study

This report shows that Cryo-Compression of hydrogen has a number of **key advantages**:

- CcH2 permits a high volumetric density which is significantly greater than 700-bar compressed gas and is closer to liquid hydrogen density in some regimes.
- CcH2 also has reduced boil-off losses. This is because the pressure rise absorbs heat ingress and the hydrogen remains contained instead of venting.
- CcH2 can be refuelled with cryogenic liquid hydrogen, high-pressure gas hydrogen, or both, making it compatible with hybrid supply chains.

There are however some engineering **challenges** with CcH_2. Whilst promising, CcH_2 is technically demanding. Some of the key challenges with the CcH2 tank design are that it requires a combination of cryogenic insulation and high-pressure structural integrity. This in turn raises the question of materials compatibility, specifically with relation to hydrogen embrittlement and cryogenic fatigue. Finally, there is thermal-pressure management to contend with due to the coupled heat and mass transfer as hydrogen is consumed and then replenished.

Project challenges

As the programme progressed, Qdot refined the scope of its work packages in response to changes in partner funding and evolving commercial priorities. Development of the hydrogen-hybrid drone demonstrator was paused during this phase, enabling Qdot to focus its resources on advanced aerospace heat exchanger technologies, including solutions for hydrogen powertrains.

6 Intelligent Energy

Intelligent Energy

Intelligent Energy was part of the H2GEAR programme and was engaged in developing a state-of-the-art fuel cell-based ground demonstrator. The programme aimed to explore and validate the use of hydrogen fuel cells for aviation through extensive ground-based testing.

Intelligent Energy has identified several safety and reliability challenges in the introduction of hydrogen, as normally happens with any novel aircraft propulsion systems. These challenges include amongst others hydrogen leak detection, ventilation, fire suppression and handling of hydrogen in the propulsion system. To further explore some of these challenges within the hydrogen regulatory sandbox, the following programme of work was agreed between the CAA and Intelligent Energy:

Work Package 1: Technical Familiarization

Within this WP the CAA Hydrogen Challenge team examined the Intelligent Energy fuel cell stack system design and identified current challenges related to fuel cell powered aircraft.

Advanced fuel cell powered aircraft concepts have issues with the size of LT-PEM (Low Temperature Proton Exchange Membrane) fuel cell thermal management systems which are required to dissipate the low-grade heat generated from the fuel cells. However, the Intelligent Energy EC-HT solution uses proven commercial membrane technology combined with an improved thermal management system, providing a lower risk and viable aerospace solution. Hydrogen fuel cell research from Intelligent Energy, feature a new higher temperature heat rejection architecture delivering:

- Reduced heat exchanger size.
- Lower aerodynamic drag.
- High gravimetric power density as Intelligent Energy are delivering a higher heat rejection temperature, through compression of cathode exhaust fluid between the fuel cell stack and heat exchanger.

Work Package 2: Route to Certification with Gap Analysis

Within this WP, the CAA Hydrogen Challenge team have provided Intelligent Energy with feedback on their design and safety requirements, as well as guidance on the best route to fuel cell system certification. This guidance was based on Intelligent Energy’s F300 Programme Certification Plan that was shared with the CAA with the aim of establishing a Certification Basis for the H_2 Fuel Cell based power plant, including special conditions, standards, and deviations. Some of the options to certification presented to Intelligent Energy included:

- Either developing a proposed Special Condition for a Hydrogen Fuel Cell or considering a Minimum Performance Standard for a Fuel Cell which could be used for a Technical Standard Order (TSO) authorisation.
- Developing guidance for certification through TSO Authorisation.
- Providing guidance for obtaining the necessary approvals related to a TSO, which would enable an application for a UK TSO application.
- Routes to certification through Means of Compliance 9 (MC9) Equipment Qualification.

Work Package 3: Hazard and Safety Analysis

Within this WP, a hazard and risk table with each top-level hazard created in the bow-tie format for publication was created. An example can be seen in the figure below.

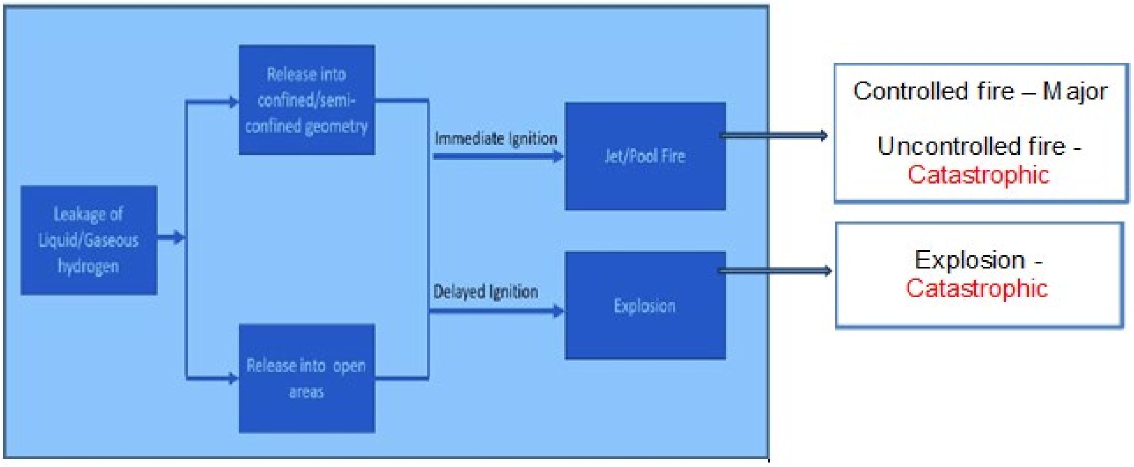

Figure 3 Fire Risks

Recommendations and Lessons Learned

The safety implications for critical technologies such as Hydrogen Fuel Cells technologies, need to be understood and airworthiness requirements (or special conditions) need to be developed to support future applications for aircraft installations.
The UK CAA need to ensure that the aviation policies, regulations, certification and operational requirements are addressed regarding the potential of future applications of a Hydrogen Fuel Cell in a hydrogen powered aircraft.
The UK CAA need to work with EASA and the FAA (and other Regulators) in developing specific approvals or changes to the current Certification Specifications (CS's) or Special Condition (SC) regarding a Hydrogen Fuel Cell either as a stand-alone approval (i.e. UK TSO or ETSO) or as an aircraft Type Certification or Supplemental Type Certificate using CS 25, CS 23 or CS E for example.

UK Civil Aviation Authority

7 World Mobile Stratospheric (WMS)

World Mobile Stratospheric (WMS) is developing Stratomast, a liquid hydrogen-powered, remotely piloted high-altitude aircraft capable of operating at approximately 18 km (60,000 ft). Stratomast is engineered to provide up to 15,000 km² of 5G coverage per aircraft using WMS's proprietary phased-array antenna system, which requires approximately 20 kW of power. WMS is also advancing a bespoke Liquid Hydrogen Fuel System (LHFS) capable of supporting safe, efficient, and continuous high-altitude operations.

Within the Hydrogen Regulatory Sandbox, the following programme of work was agreed between WMS and the CAA:

Work Package 1 - Gaps in certification requirements for a Liquid Hydrogen Fuel System for High-Altitude Platform.

The CAA Hydrogen Challenge Team has held a series of workshops with WMS which enabled a familiarisation with the high-level product design/concept and covered the following activities:

- Identifying the applicable Certification Specifications (e.g. CS-HAPS, CS-23, CS-ACNS, CS-E, CS-P) and any Special Conditions.
- Determining which requirements would be directly applicable, those which may require modification, and where there are potential gaps.

Furthermore, WMS provided the CAA with a detailed Excel Spreadsheet containing a Certification Compliance Checklist. The following proposed Certification Review Items (**CRIs**) were identified by WMS:

- CRI F-01 Hydrogen Fuel System.
- CRI F-02 Ground Support Equipment and Operations.
- CRI F-03 Emergency Power.
- CRI OPS-01, Platform certification requirements derived from Beyond Visual Line of Sight (**BVLOS**) operations in non-segregated airspace (including any necessary Detect and Avoid System).
- CRI G-01, Single Pilot oversight of multiple aircraft.
- CRI G-02, Aircraft control handover between Ground Stations.
- CRI G-03, Remote Pilot recognition of discrete source damage (*e.g. bird strike*).
- CRI G-04, RPAS Pre-flight checks and Ground Operations.
- CRI F-04, Equipment requirements for high altitude operations, covering equipment qualification and cosmic radiation.
- CRI E-01, Emissions and Venting requirements for hydrogen piston aircraft.

This sandbox activity supported the CAA in developing and shaping initial policy recommendations for the safe integration of liquid hydrogen fuel systems on high-altitude platforms.

Work Package 2 - Safety Risk Assessment for Liquid Hydrogen Fuelled HAPs

WMS provided a Functional Hazard Analysis (FHA) as an Excel Spreadsheet, which is available on the CAA collaboration SharePoint site. The objectives of the FHA were to assess functions at the LH2 fuel system top level and to identify failure conditions and their associated classifications, including both loss of functions and malfunctions. The FHA was shared with the Hydrogen Challenge Team; however, due to the Intellectual Property (IP) of the FHA information, the FHA output is not included in this report.

Work Package 4 – System Theoretic Process Analysis (STPA)

WMS have participated in several CAA/Stakeholder STPA workshops, they have provided the architecture for the proposed Liquid Hydrogen Fuel System (figure below) and have produced schematics for the Fuel Cell Power System and an Internal Combustion Engine.

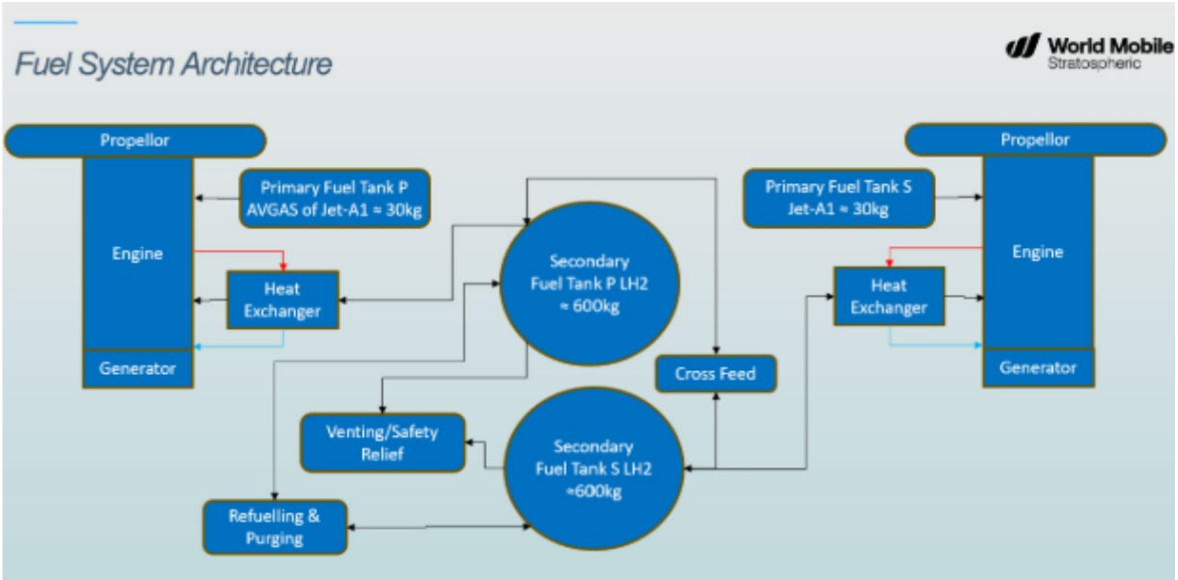

Figure 2 WMS Fuel System Architecture

Project Challenges

WMS has undergone organisational restructuring during the summer of 2025, resulting in delays to the testing programme (**Work Package 3**); flight testing is now planned to resume from July 2026.

8 Swift Aircraft

Swift Aircraft Limited is a British aerospace manufacturer that specialises in designing aerobatic training aircraft. They are currently developing a hydrogen-hybrid electric aircraft for General Aviation (GA) and Advanced Air Mobility (AAM). The goal is to achieve a 90% reduction in carbon dioxide emissions, leveraging a hydrogen/Lithium-ion (Li-ion) hybrid system that addresses both power and energy demands.

Within the Hydrogen Regulatory Sandbox, it has been agreed between the CAA and Swift Aircraft to **identify potential Certification Review Items (CRI) for CS 23 and CS 25 for electrical hybrid hydrogen propelled aircraft.** The main points of this exercise are summarized below.

Regarding **subpart B Flight**, there is a need to consider the impact of the gaseous hydrogen tank weight, reduction in the difference between Maximum Take Off Weight and Maximum Landing Weight and maintaining an adequate static margin for longitudinal stability. Critical loss of thrust needs to be defined for a hybrid hydrogen electric propulsion system, while redundancy in the electrical side of the hybrid hydrogen electric propulsion system as well as partial loss of thrust during climb need to be considered.

In relation to gaps in **Subpart C – Structure**, it has been proposed to verify impact on compliance issues caused by differences on the mass distribution for gaseous hydrogen fuel systems through flight testing (MC 6) and not just analysis (MC2). **Structure Durability** might be an issue since aircraft Structure may be susceptible to hydrogen embrittlement. Additionally, a hydrogen propulsion system may introduce new sources of discrete damage such as release of electric motor rotors or compressor blades supplying fuel cells with oxidant. A relevant AMC could comprise of continual post flight inspections that monitor any specific potential damage areas.

Since **hydrogen storage tanks** will be heavier than their kerosene counterparts, hydrogen storage conditions, distribution and consumption need to be considered for weight distribution. Also, the aircraft's **structural performance** will need to be modified for the introduction of hydrogen storage and fuel cells and hydrogen storage leakage, fire and explosion will need to be considered in the event of an **emergency landing**. The impact of other systems, such as detached landing gear, on the hydrogen system will need to be assessed.

Regarding gaps in **Subpart D – Design and Construction**, it was noted that any high-pressure gaseous hydrogen system installed in or near the passenger cabin must ensure the safety of the occupants. In the event of a fire materials such as high-voltage cabling, hydrogen pipelines, hydrogen quick connects, fuel cell system packaging must be self-extinguished once the hydrogen supply has been shut-off. The possible presence of permeated or leaked hydrogen should be taken into consideration when designating fire zones.

In relation to **Subpart E Powerplant Installation**, it should be considered that hydrogen fuel cell propulsion systems may be susceptible to fuel cell "poisoning" by contaminates in the inducted oxidant (air) and un-oxidised hydrogen in the fuel cell exhaust that might represent a fire hazard. Installation of a hybrid hydrogen-electric propulsion system needs to include additional criteria for high-voltage installations and address the hazards of battery fires, as well as those associated with hydrogen installations, including asphyxiation risks.

Finally, regarding **Subpart F Systems and Equipment,** a gap in AMC2 of CS23 has been identified as it only provides burst and proof pressure specifications for hydraulic, pneumatic, and oxygen systems. Furthermore, no AMC in CS23 gives provision for pressurised fuel systems.

EASA Special Condition Ballistic Recovery System for CS-VLA

As the Swift Aircraft includes a ballistic recovery system, the EASA special condition could perhaps be adopted with the additional considerations of:

- Minimum altitude and maximum air speed for deployment.
- Loads encountered by the aircraft from the parachute's opening shock.
- Aircraft weight and descent rate once the parachute was deployed.
- Risk of the parachute and its line entangling with the aircraft, leading to partial or complete failure to inflate.
- Consequences of the aircraft becoming ballistic should the parachute fail to deploy.
- Pilot's ability to visually check the deployment of the parachute.

Gaps Identified in CS23 Guidance Material

CS-23 Amendment 6 sets out a performance-based framework supported by system-level guidance from Amendment 4 through AMC2. As AMC material is non-binding, it allows applicants flexibility in how compliance is demonstrated, including the use of alternative means where appropriate. In collaboration with Swift, a number of gaps in AMC2s have been identified and should be taken into account in the discussion of the Certification Review Items summarized above. These gaps should be addressed to improve clarity and consistency, with engagement between the CAA and industry supporting the development of practical and effective means of compliance.

Project Challenges

During this sandbox project, Swift was not able to acquire the funding required to proceed with their aircraft development and potential trials.

9 Ultima Forma

Ultima Forma develops platform technologies for application across a range of advanced engineering sectors. The Multi-functional Electroformed Fuel System Vacuum Structure (MEFSVS) project is developing a secondary outer shell for aircraft LH2 tanks, replacing traditional aluminium or stainless-steel shells with a hybrid CFRP + electroformed metal barrier to provide vacuum insulation.

The component under consideration is a hybrid material system consisting of carbon fibre composite (CFRP) and electroformed metal permeation barrier that replaces an all-metal structure of the outer casing of a vacuum containment system. The **LH2 secondary containment vessel** is designed to:

- Contain an inner LH2 tank with a vacuum for thermal insulation.
- Replace heavier metals with CFRP + electroformed copper for weight saving and reduced hydrogen / air impermeability.
- Facilitate sensor integration for pressure, temperature, and strain monitoring.

Coupon testing

Ultima Forma shared with the CAA the results of their coupon testing to gather data on mechanical properties of their vessel. They tested for tensile loading, interlaminar shear, adhesive bonding shear joints, thermal expansion coefficients, emissivity/outgassing. Test results to date are shown below.

Material	Test	Property	Test Temp /°C	Data sheet value	Ave	Units	CoV %
CFRP laminate	Tensile	Strength	RT		1197	MPa	1.7
			-196		1015	MPa	-
		Elastic modulus	RT	86.0	98.2	GPa	2.1
			-196	91.5	107.3	GPa	4.1
	ILSS	Strength	RT	57.0	56.1	MPa	6.4
			-196	199	105.2	MPa	8.2
CFRP laminate to copper electroform	Single Overlap Shear	Strength	RT		20.4	MPa	6.2
			-150		25.4	MPa	19.6
			-196		34.3	MPa	8.8
CFRP laminate 0 degrees	Thermal expansion	Coefficient of thermal expansion vs temperature	-196 to 0	2.5	-4.0	10^{-6}/K	1.4
			0 to 170	-1.5	0.5	10^{-6}/K	3.8
CFRP laminate 90 degrees			-196 to 0	18	11.3	10^{-6}/K	-11.3
			0 to 170	45	16.2	10^{-6}/K	-
Copper electroform			-196 to 0		10.6	10^{-6}/K	12.7
			0 to 170	16.7 (RT)	17.0	10^{-6}/K	16.5

Figure 3 Coupon Testing Results

Comparison to CAA's CS-25 Gap Analysis and Certification Requirements

CAP3124 that was published by the CAA conducts a gap analysis of CS-25 considering changes required for hydrogen powered aircraft. In general, this analysis considers combustion of hydrogen or fuel cells as potential power generator with hydrogen gaseous or liquid as the fuel system. Within this project, the following observations were made in relation to this gap analysis and to route to certification for Ultima Forma:

- Vacuum insulation of the liquid fuel now becomes a new consideration for CS-25.
- Specifications for fuel tanks in CS-25.951 / .952 / .961 / .963 assume a carbon-based liquid fuel, close to room temperature, which may expand or generate vapour pressure on heating – this can be vented on the ground. The situation is very different for LH2, where the cryogenic temperature must be maintained at all times, and vapour boil-off pressure managed – since LH2 is always in a state of equilibrium between liquid and vapour.
- Systems to detect and manage vacuum loss need to be included in CS-25.9**
- CS-25.571 probably needs consideration of the effects of damage on vacuum insulation loss. This may also require a change to the relevant AMC.
- Ultima Forma's contribution to a future type certification could be in providing a Declaration of Design and Performance in response to the customer's Purchase Technical Specification.
- Ultima Forma has to establish a dialogue with the airframer as regards compliance with CS 25.571 Damage tolerance and fatigue evaluation of structure, CS 25.603 Materials and CS 25.605 Fabrication methods.

Next steps

The process of component design and testing is, in general, covered by existing design codes and acceptable means of compliance processes. There are a couple of issues that differ from current practice and will have to be answered with further research:

- What constitutes a failure (no longer fit for purpose), or partial failure (not functioning at intended performance?
- Consequences of failure cases, including loss of vacuum integrity, require careful consideration and are not currently covered by CS-25 part 1 & 2.
- Failure mechanisms of this component need to be considered in relation to other aircraft systems and aircraft operations, since these are different to current (hydrocarbon) fuel operations.

UK Civil Aviation Authority

10 ZeroAvia

ZeroAvia specialises in the development of Hydrogen Fuel Cell Electric Propulsion Systems for Aviation. This project focuses on the development, design & testing of a powertrain, which consists of an electrical power system (EPS), a power generation system (PGS) a hydrogen fuel cell installation and a power distribution system (PDS) that connects the PGS to the external power unit (EPU) and provides interface points for ground and aircraft electrical systems. For Phase 1 (2025–2026) of the Hydrogen Challenge Sandbox, the work programme has been split into two work packages focusing on the one hand on **high temperature fuel cells** and on the other on **laboratory and ground testing** of the propulsion system.

Work Package 1 – High Temperature Fuel Cells

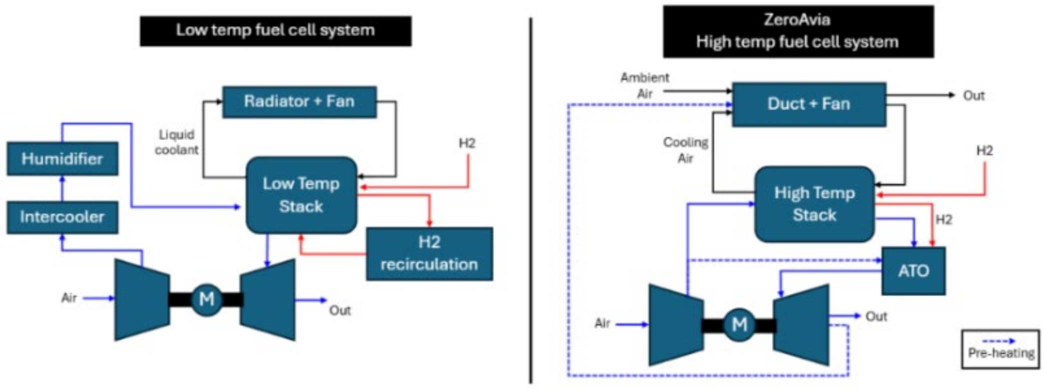

Figure 4 Difference between low and high temperature fuel cell systems

Guidance material for the ZA602 certification basis might emphasize the importance of the ambient air intake not being blocked or damaged by:

- ZA602-HEPS.270 Rain Conditions
- ZA602-HEPS.280 Icing and Snowing Conditions
- ZA602-HEPS.290 Bird, Hail Strike and Impact of Foreign Matter
- ZA602-HEPS.320 Cooling System is applicable to both low and high temperature stacks.
- ZA602-HEPS.940 HEPS Initiating System

Guidance material for the ZA602 certification basis, which is assumed to be SC E-19 with CRIs to address the use of hydrogen, might emphasize the importance of the ambient air intake not being blocked or damaged by:

- EHPS.270 Rain Conditions
- EHPS.280 Icing and Snowing Conditions
- EHPS.290 Bird, Hail Strike and Impact of Foreign Matter
- EHPS.320 Cooling System is applicable to both low and high temperature stacks.
- EHPS.340 HEPS Ignition System

CS 23.909 Turbo Charger System (amendment 4) could form the basis for developing Means of Compliance (MOC) and demonstrating that the ATO can safely boost the enthalpy of the stack exhaust gases. One point to note is that the exhaust from the ATO must be sufficiently hot to avoid water condensing on the compressor's turbine blades.

No specific guidance for HTFCs currently exists. Currently, guidance on the installation of fuel cells on an aircraft is only generalised and does not differentiate between low and high temperature PEM fuel cells.

The conclusions from DOT/FAA/TC-16/24 Abusive Testing of PEM fuel cells remain valid for high temperature stacks – monitoring reactant gas supply pressures, coolant exit temperatures, stack surface temperature or stack output voltage and current will still detect stack failures in a timely fashion. In addition, provisions should be made to monitor the stack's environment for any increases in temperature or hydrogen gas concentration.

Work Package 2 – Laboratory Testing

This Work Package has focused on what can be learnt from ZeroAvia's experimental Liquid Hydrogen Management System (LHMS) laboratory bench testing and low power propeller spin ground testing as guidance material for future certification compliance. Three requirements from the proposed ZeroAvia certification basis (ZA 602) have been considered as regards using these insights as guidance for means of compliance MC4 Laboratory testing:

- EHPS.350 Electrical Hydrogen Propulsion System (EHPS) Control System.
- EHPS.460 Operational Demonstration.
- EHPS.100 Fire Protection.

During the testing, the following failures were noted:

- Tank heater controller circuit board broken and subsequently replaced.
- Software update to remove "extraction mode" as proving to be problematic.
- New software was introduced to communicate with the Mass Flow Regulator to address issues with high flow rates.
- Heater runaway observed while bringing pressure down to 6.3 bar in withdraw mode.
- A loose electrical connection caused the Ground Support Equipment alarm to sound and a small pressure dip.
- Electromagnetic interference on the tank controller.

Lessons learnt

The experimental LHMS bench test results are a good starting point for evaluating possible stratification across the entire flight envelope. Stratification during "starting mode" needs further investigation to establish compliance with EHPS.460 Operational Demonstration. Guidance could also be provided for future testing to ensure that pressure signal sampling rates are sufficiently fast to catch a true view of any possible Taconis pressure oscillations in the LHMS and the ramifications for EHPS.350 Control System compliance. Finally, large amounts of liquid oxygen (LOX) were formed during depressurisation test runs. Although oxygen itself does not burn, it is a powerful oxidizer.

11 Rolls Royce

The Hydrogen Challenge Sandbox programme included a collaboration with Rolls Royce and easyJet to accelerate the understanding, readiness, and safe integration of hydrogen propulsion technologies for future aviation. Rolls Royce and EasyJet's project objective was to demonstrate hydrogen combustion capability through an empirical test programme based on a Pearl 15 donor engine that has conducted a series of tests and evaluation activities using hydrogen as the only fuel source. These activities aimed to build understanding and confidence in the behaviour, performance, and control of hydrogen within a gas turbine, while collecting foundational data that could assist with the creation of policy recommendations for a certification pathway for a hydrogen combustion engine.

Alongside engine testing activities, easyJet examined the key operational role of airline operations, outlining aircraft operations, ground handling process and route-network for hydrogen adoption. This included a concept of operations evaluating how hydrogen fuelled aircraft could be integrated into airline operations, assessing the requirements for turnaround procedures and understanding the impact on scheduling, pilot licencing, maintenance and safety considerations on the airport ramp for ground operations staff.

In Q1 of 2026, Rolls-Royce tested an GH2 engine outdoors, in the US, at a NASA / Rolls-Royce facility in Stennis. Rolls-Royce chose to work with NASA due to the availability of significant quantities of liquid and gaseous hydrogen and nitrogen and to learn and benefit from the skill and experience of the NASA team from decades of working with hydrogen to assure a safe test programme. An outcome of this test campaign is summarised below:

- Demonstration of all control states necessary for hydrogen - Purge, prime, light-up-fuel-flow, ignition, running and shutdown, purge and maintenance purge.
- Thermal paint of high-pressure-turbine and nozzle guide vane along with combustor thermocouples to correlate engine running to rig. Combustor rumble mapping.
- Validation of thermo-liquid system.
- Running to maximum design fuel-flow to max-take-off rating.
- Slam acceleration and slam deceleration from idle to max and intermediate.
- Flight cycle demonstration (taxi, take-off, climb, cruise, descent, thrust reverse, taxi).
- Outdoor acoustic noise characterisation.
- Sub-idle mapping – helps kerosene understanding as well as hydrogen.
- Failed ignitor testing and GH2 supply pressure mapping.
- Observed no ignited hydrogen releases and no gross hydrogen leakages.

- Trial of maintenance and safe working practices around a hydrogen gas turbine.

Without a pre-existing set of rules and regulations to define our basis-of-safety, a range of sources were used to define Rolls-Royce's approach for the testing:

1. CS-E certification specifications
2. Industrial standards
3. National Health and Safety standards
4. Rolls-Royce safety policies, internal design methods and design standards
5. Expert consultancy and experience from practical users such as the HS&E and NASA and other industry experts

An initial view of the Concept of Operations (CONOPS) introducing hydrogen-powered aircraft was prepared by EasyJet. Key operational impacts are summarized on the table below.

Table 2: Impact of hydrogen propulsion on airport operations

	Type of Impact	
Aircraft preparation procedures	• To be redesigned in light of new operational requirements, and be performed at different times	• Possibly longer turnaround due to restrictions on parallel operations during refuelling • Possible restrictions on how an a/c can be approached multiple hours after refuelling due to hydrogen boil-off and associated venting issues
Push-back procedures	• Slight changes in procedures	• More complex a/c systems • Possibly different engine start timing
Taxi procedures	• Wider safety distance to be maintained between taxiing a/c	• A/C may vent at any time (safety risks for following a/c)
Take-off procedures	• Slight changes in procedures	• Possible minor changes in take-off performance
Climb procedures	• Slight changes in procedures	• Possible minor changes in climb performance
Cruise procedures	• Slight changes in procedures • Fewer step climbs	• Need to minimize the formation of contrails and aviation-induced cirrus clouds • Optimum cruising altitude remains mainly unchanged due to lower weight variation in flight

Approach Procedures	• Different a/c handling	• Higher approach speeds caused by heavier a/c (due to the extra weight of the LH2 tanks)
Landing Procedures	• Having to select higher autobrake settings and reverse thrust	• Higher landing speeds caused by heavier a/c (due to the extra weight of the LH2 tanks

(Reference: Impact of emerging sustainable aircraft technologies on the existing operating ecosystem - ScienceDirect)

12 HyFive Project

In collaboration with UK CAA's Hydrogen Challenge the HyFive project was selected to participate in the Hydrogen Challenge Sandbox. The HyFive project aimed to design and verify a modular and scalable hydrogen fuel system architecture capable of supporting multiple aircraft classes. The architecture was intended to be compatible with both hydrogen electric and hydrogen combustion powertrains and to be deployable across customer applications.

Marshall, GKN Aerospace, Parker Meggitt, Manchester University, University of Bath and Cardiff University formed the project consortium that aimed to design and verify a modular and scalable hydrogen fuel system architecture capable of supporting multiple aircraft classes.

The project worked towards collaboratively advancing the capabilities and enabling technologies required to deliver intelligent, connected hydrogen fuel systems for the emerging zero-emissions aviation market. A core objective was to increase technology readiness from TRL 3 to TRL 5 through ground-based demonstrations of a fully integrated fuel system, including storage, conveyance, indication, venting, and fuelling functions, with a defined pathway towards TRL 6.

The scope of the project was redefined in mid-2025 to focus on Subsystem and Component Technology Development including requirements and design and system architecture maturation. The revised scope included a review of certification gaps and maintenance considerations for a fuel cell system architecture. The HyFive project completed in December 2025.

Gap Analysis

HyFive conducted a review of the CAA's CS-25 Gap Analysis for a Hydrogen Fuel System CAP 3124 against their aims of developing a certifiable Liquid Hydrogen (LH2) fuel system for different aircraft types, including hydrogen-electric and hydrogen combustion powertrains. Through this analysis it was identified by HyFive that both the certification basis and means of compliance would need to be updated to accommodate the 'novel' aspect of LH2.

To understand the gaps in the certification basis the certification requirements were categorised as:

- Applicable (or Not Applicable) - The certification requirement is applicable (or not) to the notional aircraft platform.

- Affected (or Not Affected) - The certification requirement is affected by, or affects, (or not) the liquid hydrogen fuel system

A Red-Amber-Green (RAG) status was applied to each requirement of CS-25, to identify the level of risk (of changes required) associated with these requirements when considering a novel liquid hydrogen aircraft and fuel system design. The RAG status assessment applied is defined below:

- Green - The requirement and compliance to the requirement is sufficiently similar to a kerosene aircraft application; conventional approach to compliance is expected.

- Amber - The requirement is sufficient/valid, but the means of compliance or necessary data for compliance is different to that of a kerosene aircraft certification programme. Therefore, new AMC's or an alternative approach to compliance may need to be developed, with associated pre-requisite data generation.

- Red - The requirement is insufficient or not valid for a liquid hydrogen aircraft, and new regulations or Special Conditions (SCs) will need to be created to close these gaps.

On completion of the gap analysis 91 Amber and 90 Red risks/changes were identified in relation to CS25 Requirements affecting the fuel system. Also, it has been outlined in the table below where differences have been identified when undertaking this activity between CAA's and HyFive's review.

Nature of Difference	Number of Requirements
CAA have identified a gap, HyFive have not	27
HyFive have identified a gap, CAA have not	32
Both organisations have identified gaps, but disagree about the nature of the gap (Requirement vs AMC)	17

Through this process HyFive identified broad themes grouped into seven topic areas to enable technical understanding, safety analysis and design/analysis mitigation. These seven topic areas are:

1. Fire, Flammability/ Explosion
2. Electrical Systems / Lightning & Bonding
3. Crash worthiness & Ditching
4. Structures & Materials
5. Testing & Analysis
6. Fuel System Management
7. Boil