UK CAA Hydrogen Challenge

CS-23 Gap Analysis for a gaseous Hydrogen Fuel System

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Executive Summary

CS-23 (Certification specifications) provide the technical requirements for certification of small aeroplanes.

CS-23 is applicable to the certification in the normal category and applies to aeroplanes with a passenger seating configuration of 19 or less and a maximum certified take-off mass of 8618 kg (19000 pounds) or less.

An initial gap analysis has been conducted for CS-23 Airworthiness requirements in anticipation of the introduction of a Hydrogen Powered Aircraft (HPA).

This would include an aircraft with either a hydrogen gas turbine engine or an aircraft with a gaseous Hydrogen Fuel Cell (HFC) supplying an Electric Propulsion System (EPS).

The gap analysis concludes that a significant update of the current CS-23 requirements would be required to address the introduction of a Hydrogen Powered Aircraft (HPA).

Based on a review of the latest CS-23 requirements at Amendment 6 (AMC/GM Issue 4), the following changes have been identified and are summarised below:

Proposed Changes to CS-23 requirements:

Total number of **CS-23 requirements** – 70

Proposed changes to **CS-23 requirements** – 23 (Approximately 32%)

In addition, the associated Guidance Material (GM) and Acceptable Means of Compliance (AMC) will need revising where necessary.

The change to the current CS-23 requirements (including GM / AMC Material) will not be possible in the short-term due to the level of co-ordination and consultation with other National Aviation Authorities and the Public.

However, a Generic Special Condition or number of **Certification Review Items** (CRIs) for a Hydrogen Fuel System could be used to address a Type Certification (TC) or Supplemental Type Certification (STC) application.

The proposed **Special Condition** (SC) would be based on the highlighted areas of the CS-23 requirements that have been identified in the Gap Analysis, which are summarised in **Table 1** of this report.

The information in **Table 2** provides a list of proposed CRIs that could be used for a TC / STC application for a Hydrogen Powered Aircraft.

Additional Work:

It is considered that in addition to the CS-23 Gap Analysis, a similar analysis would be required for CS -E (Engines) to address the possibility of a Hydrogen Gas Combustion Engine.

The development of a **UKTSO** (UK Technical Standard Order) should also be considered to cover the requirements for a stand-alone approval of a Hydrogen Fuel Cell, as this would assist with the Certification process for a TC / STC application.

Definitions

Acceptable Means of Compliance (AMC) are non-binding. The AMC serves as a means by which the requirements contained in the Basic Regulation, and the IR, can be met. However, applicants may decide to show compliance with the requirements using other means. Both NAAs and organisations may propose alternative means of compliance. 'Alternative Means of Compliance' are those that propose an alternative to an existing AMC. Those Alternative Means of Compliance proposals must be accompanied by evidence of their ability to meet the intent of the IR. Use of an existing AMC gives the user the benefit of compliance with the IR.

Certification Specifications (CS) are non-binding technical standards adopted by the CAA to meet the essential requirements of the Basic Regulation. CSs are used to establish the certification basis (CB).

Certification Review Item (CRI) is a document describing an item that requires disposition prior to the issuance of Type Certificate (TC), change to TC approval or Supplemental Type Certificate (STC).

Guidance Material (GM) is non-binding explanatory and interpretation material on how to achieve the requirements contained in the Basic Regulation, the IRs, the AMCs and the CSs. It contains information, including examples, to assist the user in the interpretation and application of the Basic Regulation, its IRs, AMCs and the CSs.

Implementing Rules (IR) are binding in their entirety and used to specify a high and uniform level of safety and uniform conformity and compliance. The IRs are adopted by the European Commission in the form of Regulations.

Special Conditions (SC) are non-binding special detailed technical specifications determined by the NAA if the certification specifications established by the CAA are not adequate. Special Conditions, like Certification Specifications, become binding on an individual basis to the applicant as part of an agreed Certification Basis.

UK Technical Standard Order (UKTSO) A UKTSO authorisation represents one way (and not the only way) to have parts and appliances approved. This is an optional step which ensures that a part or appliance complies with a minimum performance standard.

Introduction

This document provides an initial gap analysis of Certification Specifications (CS-23) requirements for a Hydrogen Powered Aircraft (HPA). The gap analysis looks at the potential changes required to existing Certification requirements to address the main airworthiness / safety considerations for a Hydrogen Powered Aircraft and includes a review of the associated Guidance Material (GM) and Acceptable Means of Compliance (AMCs).

Given the current technological developments, the CAA expect two potential hydrogen-based systems: (1) a Hydrogen Fuel Cell system which supplies electrical power to an Electric Propulsion System (EPS), or (2) a Hydrogen Combustion Engine (HCE) which uses hydrogen directly as a fuel.

The Hydrogen Fuel System would require Hydrogen Fuel Cells, a storage system for the gaseous Hydrogen, a distribution system for the connected systems and the necessary Control and Monitoring systems.

Hydrogen Fuel Systems will introduce safety hazards that are not adequately addressed by the current Certification Specifications (CS-23).

It is important to identify the Certification challenges and to properly identify any safety concerns that may result from the introduction of a Hydrogen Fuel System on an aircraft that will be certificated to CS-23 requirements.

Scope of the Gap Analysis

A gap analysis using the Certification Specification, CS-23 at Amendment 6, has been performed to identify any specific requirements that may require an update to address a Hydrogen Fuel System. This includes a review of associated GM and AMC material that are included in the CS-23 requirements.

The gap analysis aims to identify potential changes to the existing certification requirements for a Hydrogen Fuel System to ensure the expected level of safety and will enable the certification of a new or modified Hydrogen powered aircraft.

In the long term, it is expected that the CS Specifications will be updated to address these new or revised requirements. However, in the short term, it will be necessary provide requirements in the form of Special Conditions (SCs) or Certification Review Items (CRIs) to allow industry to proceed with TC / STC applications for Hydrogen powered aircraft.

CS-23 Gap Analysis Overview

There is a growing need to ensure that Certification requirements are updated to enable the safe certification of innovative technologies. A gap analysis is the first step to identify whether existing requirements are applicable to the innovative technologies.

For new and novel technologies, it is often necessary to adopt a CRIs / Special Conditions to address the shortfalls in the Certification requirements.

The current Certification requirements for a Normal Category Aeroplane is CS-23.

Subpart A — General

Subpart B — Flight

Subpart C — Structures

Subpart D — Design and Construction

Subpart E — Powerplant and Installation

Subpart F — Systems and Equipment

Subpart G — Flight Crew Interface and Other Information

The Gap Analysis for CS-23 is provided in Table 1 of this report and was based on current information from industry / academia. The table summarises the proposed changes to the current CS-23 Certification requirements / GM / AMC.

In addition, Table 2 provides the proposed Special Condition (SC) / Certification Review Items (CRIs) that may be necessary for the certification of a Hydrogen Powered Aircraft.

Next steps

The next steps in the gap analysis would be to perform a detailed assessment for each of the CS-23 Subparts. This could involve the various Subject Matter Experts from the departments in the UK CAA providing feedback and inputs into each Subpart.

A set of draft special condition or CRI's have been included in the report (Table 2).

Industry / EUROCAE Working Group could also be contacted to provide their feedback on the Gap Analysis. A comparison with industry Gap Analysis could then be performed.

It is understood that EUROCAE WG-80 Sub-Group has a Task to review the current CS-23 requirements and produce a gap analysis for a Hydrogen Powered Aircraft.

List of Abbreviations

AMC – Acceptable Means of Compliance

CS – Certification specifications

CRI – Certification Review Item

FCS – Fuel Cell System

H2 – Hydrogen

HEP – Hydrogen Electric Propulsion

HFCS – Hydrogen Fuel Cell System

HMS – Hydrogen Management System

HPA – Hydrogen Powered Aircraft

SC – Special Conditions

SME – Subject Matter Expert

STC – Supplemental Type Certification

TC – Type Certification

References

1. Certification Specifications for Normal-Category Aeroplanes (CS-23) and Acceptable Means of Compliance and Guidance Material to the Certification Specifications for Normal-Category Aeroplanes (AMC & GM to CS-23).

Table 1 - Proposed Changes to CS-23 requirements / GM / AMC

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart B – Flight	**CS-23.2100 Mass and centre of gravity**	The definition of "empty weight" will change for an HPA aircraft, based on the necessity of retaining hydrogen pressure in the tank and to avoid the ingress of air. The definition of Zero Fuel Weight (ZFW) would also need to be renamed / redefined.	New or revised AMC to be added.
	CS-23.2105 Performance Data	Fuel cell temperature and qualification for operation at altitude.	New or revised AMC to be added.
	CS-23.2115 Take-off Performance	Definition to be added for HPA aircraft for critical loss of thrust. Additional considerations for HPA such as a H2 onboard dump, H2 storage failure modes reducing take off distance. Loss of Power Control (LOPC) definition needed.	New or revised AMC to be added.
	CS-23.2120 Climb requirements	Critical loss of thrust needs to be considered based on a Hydrogen / Electric system where redundancy in the electrical side of the HPA (multiple motor windings, inverters) need to be considered with a critical loss of thrust.	New or revised AMC to be added.
	CS-23.2125 Climb information	Loss of Power Control (LOPC) for H2 / Electric engines needs to be defined, critical loss of thrust needs redefining vs existing consideration of redundancy in the electrical side of the HPA (multiple motor windings, inverters) could be considered when considering critical loss of thrust.	New or revised AMC to be added.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart C — Structures	**CS-23.2200 Structural design envelope**	Hydrogen storage conditions, distribution and consumption needs to be considered for weight distribution and structural implications.	New or revised AMC to be added.
	CS-23.2205 Interaction of systems and structures	1. With the introduction of H2 storage and Hydrogen Fuel Cells, there will need to be a modified structural performance. 2. HEP (Hydrogen Electric Propulsion) control failures may introduce additional structural loads e.g. Electric Motor mechanical failure.	New or revised AMC to added.
	CS-23.2215 Flight load conditions	Flight loads introduced by HEP failures.	New or revised AMC to added.
	CS-23.2225 Component loading conditions	1. Structural design loads will differ with HEP. 2. HEP failures may introduce additional structural loads into the installation.	New or revised AMC to added.
	CS-23.2240 Structural durability	1. Inspections and continued airworthiness will change in an HPA with electric propulsion. The causes will need more expanding due to H2 related failures such as embrittlement. 2. Embrittlement related structural damage needs to be taken into consideration. 3. Propeller, electric motor rotor and other engine fragments to be considered.	New or revised AMC to be added.
	CS-23.2255 Protection of Structure	Ventilation of Hydrogen to be considered.	New or revised AMC to be added.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart C — Structures	**CS-23.2260 Materials and processes**	Hydrogen embrittlement to be taken into consideration.	New or revised AMC to be added.
	CS-23.2265 Special Factors of Safety	Hydrogen embrittlement to be taken into consideration.	New or revised AMC to be added.
	CS-23.2270 Emergency conditions	1. H2 storage leakage and explosion need to be considered in the event of an emergency landing. 2. Impact of other systems such as landing gear on the H2 system to be assessed (Use CS-25 as guidance). 3. Emergency landing conditions to also consider H2 storage system related concerns. 4. Design of H2 storage to provide protection to occupants in case of crash. Crash worthiness to be added. 5. Fire zone reclassification due to H2 with respect to the baggage area.	New or revised AMC to be added.
Subpart D — Design and Construction	**23.2320 Occupant physical environment**	Design requirements need to consider a H2 pressurized systems if stored in fuselage or near passenger cabin.	New or revised AMC to be added.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart D — Design and Construction	**CS-23.2325 Fire protection**	1. More materials to be added to be self-extinguishing such as HV cabling, H2 pipelines, H2 quick connects, Fuel Cell System packaging etc. 2. Fire zone classification for H2 to be added to AMC. 3. H2 fire protection. AIR 8466 may provide the basis for low, medium and high leakage scenarios into ventilated areas. The case of hydrogen accumulation in the passenger cabin, well below the Lower Flammability Limit also needs to be addressed in the context of accelerating a cabin fire. 4. H2 fires and extinguishing and detection Refer AIR8466. H2 zones need to be specified. 5. Hydrogen leakage to be included here with ignition sources and mitigations against the accumulation of explosive hydrogen/air mixtures.	New or revised AMC to be added.
	23.2330 Fire protection in designated fire zones and adjacent areas	1. Needs interpretation for H2 electric engine if different parts of engine are in different areas such as electric propulsion on nacelle, fuel cell in fuselage. 2. Need to address HV cables, H2 Supplies / tube lines / hoses.	New or revised AMC to be added.
Subpart E – Powerplant Installation	**23.2400 Powerplant installation**	1. Not clear what the engine approach is for H2 electric aircraft. Key words are "applicable to the specific design". 2. Needs to include additional criteria for High Voltage for H2. 3. Needs to include H2, gases due to HV batteries fire, asphyxiation due to H2.	New or revised AMC to be added.
	CS-23.2405 Automatic power or thrust control systems	Automatic power, thrust control to be redefined if any major changes to powerplant functioning vs standard fixed wing. suggest that power failure to the electric motor, transient negative thrust while the propeller feathers and back EMF is the case to consider.	New or revised AMC to be added.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart E – Powerplant Installation	**CS-23.2425 Powerplant operational characteristics.**	1. Addition of H2 fuel cell definitions of normal, emergency operation, operating envelopes. 2. Stop and restart of powerplant needs more definition for H2 electric.	New or revised AMC to be added.
	23.2430 Fuel system	1. Develop similar requirement which is specific to Hydrogen system. 2. It would depend on the specific design - location of vents and tanks in relation to lightning attachment zones. Indirect effects might result in induced voltages on elements of the fuel system. 3. This may need to change for hydrogen. Retaining fuel in all scenarios may not be applicable See long comment against Emergency conditions above. 4. Timing may need to change. We would need to identify how the 30min of fuel was determined. 5. May not be applicable. Is there a safety case in which jettison is required? 6. Certain procedures within the Refuelling CONOPS might have to be approved.	New or revised AMC to be added.
Subpart E – Powerplant Installation	**CS-23.2435 Powerplant induction and exhaust systems.**	No change anticipated.	1. AMC to be added specific to fuel cell air system and ingestion of material detrimental to the PEM. 2. With excess H2O from fuel cells, any additional considerations to be taken into account.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
	23.2440 Powerplant fire protection	1. H2 fire zone to be added. 2. H2 detection to be included. 3. H2 fire detection requires other methods than visual so may need a special condition. The buoyant nature of hydrogen flames might also exclude the use of fire wires. Other than shutting off the hydrogen supply hydrogen fires are difficult to extinguish. 4. H2 fire extinguishers or fighting fires by the crew need reconsideration vs standard jet fuel / Av gas. The Buoyant nature of hydrogen flames might also exclude the use of fire wires. Other than shutting off the hydrogen supply hydrogen fires are difficult to extinguish, and UV tuned cameras to replace the pilot's view.	New or Revised AMC to be added.
Subpart F – Systems and Equipment	**23.2500 Airplane level system requirements**	No change anticipated.	Any changes to Subpart F depend on what part of the H2 electric powertrain is defined as 'Equipment'.
	23.2525 System power generation, storage and distribution	This would need to change dependent on definition of power generation, storage for hydrogen. Clarification is needed to distinguish between power for essential loads and power for HPA.	New or Revised AMC to be added.

Subpart	Section	Change to CS-23 requirements	Change to GM / AMC
Subpart F – Systems and Equipment	**23.2545 Pressurised system elements**	H2 storage systems would fit under this category. This would need more additions. CS 25.1453 Protection of oxygen equipment from rupture could be used as guidance, in particular, the proof and burst factors given in Table I for various component types? The factors in Table 1 are applied to MAWP of the oxygen system. Therapeutic medial oxygen cylinders are pressurised to 200 bar and industrial oxygen cylinders up to 300 Bar. CS 25.1453 also states: “The maximum working pressure must include the maximum normal operating pressure, the transient and surge pressures, tolerances of any pressure limiting means and possible pressure variations in the normal operating modes. Transient or surge pressures need not be considered except where these exceed the maximum normal operating pressure multiplied by 1.10.” EU 134 hydrogen fuelled vehicles provides specifications of the compressed hydrogen system. It defines a maximum Normal Working Pressure (NWP) of 70 MPa (700 bar), burst pressure is defined as 2.25 x NWP, increasing to 3.5 x NWP for a glass-fibre tank. There is no specific mention of a composite/carbon fibre tank. The burst factor of 2.25 seems consistent with the factor of 2.0 given by CS 25.1453. The higher CS 25.1453 factors for hoses, pipes and couplings needs putting into context. These components should only experience a transient pressure rise under failure conditions. The pressure surge release valve operation will mitigate against over-pressurisation of components.	New or Revised AMC to be added.

Table 2 – Hydrogen Powered Aircraft (HPA) – Proposed Special Condition (SC) / Certification Review Items (CRIs)

Subpart	Section	Statement of Issue
Subpart B - Flight	**23.2100 Weight and centre of gravity**	Need to consider the impact of the gaseous hydrogen tank weight, reduction in the difference between Maximum Take Off Weight (MTOW) and Maximum Landing Weight (MLW) and maintaining an adequate static margin for longitudinal stability.
	CS-23.2115 Take-off Performance	Definition to be added for HPA aircraft for critical loss of thrust. Additional considerations for HPA such as a H2 onboard dump, H2 storage failure modes reducing take off distance. Loss of Power Control (LOPC) definition needed.
	23.2120 Climb requirements	Critical loss of thrust needs to be considered based on a Hydrogen / Electric system where redundancy in the electrical side of the HPA (multiple motor windings, inverters) need to be considered with a critical Loss of thrust.
	23.2120(b) Climb requirements and 23.2125(b) Climb information	LOPC for H2 electric engines needs to be defined, critical loss of thrust needs redefining vs existing consideration of redundancy in the electrical side of the HPA (multiple motor windings, inverters) could be considered when considering critical loss of thrust.
Subpart C - Structure	**23.2200 Structural design envelope**	Hydrogen storage conditions, distribution and consumption needs to be considered for weight distribution.
	23.2205 Interaction of Systems and Structure	1. With the introduction of H2 storage and Hydrogen Fuel Cells, there will need to be a modified structural performance. 2. Control failures of HEP may lead to additional structural loads e.g. electric motor mechanical failure / seizure.
	23.2215 Flight load conditions.	Additional flight loads resulting from a HEP failure need to be considered.

Subpart	Section	Statement of Issue
Subpart C - Structure	**23.2225 Component loading conditions.**	Structural design loads will differ with H2 / Electric Propulsion aircraft.
	23.2240 Structural durability.	1. Inspections and continued airworthiness will change in an HPA with electric propulsion. The causes will need more expanding due to H2 related failures such as embrittlement. 2. Embrittlement related structural damage needs to be taken into consideration. 3. Propeller, electric motor rotor and other engine fragments to be considered
	CS-23.2255 Protection of Structure	Ventilation of Hydrogen to be considered.
	23.2260 Materials and processes.	Hydrogen embrittlement to be considered.
	CS-23.2265 Special Factors of Safety	Hydrogen embrittlement to be considered.
	23.2270 Emergency conditions.	1. H2 storage leakage and explosion need to be considered in the event of an emergency landing. 2. Impact of other systems such as landing gear on the H2 system to be assessed (Use CS-25 as guidance). 3. Emergency landing conditions to also consider H2 storage system related concerns. 4. Design of H2 storage to provide protection to occupants in case of crash. Crash worthiness to be added. 5. Fire zone reclassification due to H2 with respect to the baggage area.
Subpart D – Design and Construction	**23.2320 Occupant physical environment**	Design requirements need to consider a H2 pressurized systems if stored in fuselage or near passenger cabin.

Subpart	Section	Statement of Issue
Subpart D – Design and Construction	**23.2325 Fire Protection**	1. More materials to be added to be self-extinguishing such as HV cabling, H2 pipelines, H2 quick connects, Fuel Cell System packaging etc. 2. Fire zone classification for H2 to be added to AMC. 3. H2 fire protection. AIR 8466 may provide the basis for low, medium and high leakage scenarios into ventilated areas. The case of hydrogen accumulation in the passenger cabin, well below the Lower Flammability Limit also needs to be addressed in the context of accelerating a cabin fire. 4. H2 fires and extinguishing and detection Refer AIR8466. H2 zones need to be specified. 5. Hydrogen leakage to be included here with ignition sources and mitigations against the accumulation of explosive hydrogen/air mixtures.
	23.2330 Fire protection in designated fire zones and adjacent areas	1. Needs interpretation for H2 electric engine if different parts of engine are in different areas such as electric propulsion on nacelle, fuel cell in fuselage. 2. Need to address HV cables, H2 Supplies / tube lines / hoses.
Subpart E – Powerplant Installation	**23.2400 Powerplant installation**	1. Not clear what the engine approach is for H2 electric aircraft. Key words are "applicable to the specific design". 2. Needs to include additional criteria for High Voltage for H2. 3. Needs to include H2, gases due to HV batteries fire, asphyxiation due to H2.
	CS-23.2405 Automatic power or thrust control systems	Automatic power, thrust control to be redefined if any major changes to powerplant functioning vs standard fixed wing. suggest that power failure to the electric motor, transient negative thrust while the propeller feathers and back EMF is the case to consider.
	CS-23.2425 Powerplant operational characteristics.	1. Addition of H2 fuel cell definitions of normal, emergency operation, operating envelopes. 2. Stop and restart of powerplant needs more definition for H2 electric.
	CS 2430 Fuel system	Develop a similar requirement which is specific to Hydrogen system – CS-23.XXXX.

Subpart	Section	Statement of Issue
Subpart E – Powerplant Installation	**CS-23.2435 Powerplant induction and exhaust systems.**	1. AMC to be added specific to fuel cell air system and ingestion of material detrimental to the PEM (Proton Exchange Membrane). 2. With excess H_2O from fuel cells, any additional considerations to be considered.
	23.2440 Powerplant fire protection	1. H2 fire zone to be added. 2. H2 detection to be included. 3. H2 fire detection requires other methods than visual so may need a special condition. The buoyant nature of hydrogen flames might also exclude the use of fire wires. Other than shutting off the hydrogen supply hydrogen fires are difficult to extinguish. 4. H2 fire extinguishers or fighting fires by the crew need reconsideration vs standard jet fuel / Av gas. The Buoyant nature of hydrogen flames might also exclude the use of fire wires. Other than shutting off the hydrogen supply hydrogen fires are difficult to extinguish, and UV tuned cameras to replace the pilot's view.
Subpart F – Systems and Equipment	**23.2500 Airplane level system requirements**	Any changes to subpart F depend on what part of the H2 electric powertrain is defined as 'Equipment'.
	23.2525 System power generation, storage and distribution	This would need to change dependent on definition of power generation, storage for hydrogen. clarification is needed to distinguish between power for essential loads and power for HPA.
	23.2545 Pressurised system elements	H2 storage systems would fit under this category. This would need more additions. CS 25.1453 - Protection of oxygen equipment from rupture could be used as guidance material, in particular, the proof and burst factors given in Table I for various component types?