UK Civil Aviation Authority

UK CAA Hydrogen Challenge
CS-E Gap Analysis for a Hydrogen Engine

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Executive Summary

The certification specifications that are usually applicable to aircraft engines dedicated to CS-23, CS-25, CS-27, CS-29, and airships are contained in CS-E (Certification Specifications and Acceptable Means of Compliance for Engines).

An initial gap analysis has been conducted for CS-E in anticipation of the introduction of a Hydrogen Engine.

The gap analysis concludes that some updates to the current CS-E Airworthiness Requirements would be required to address the introduction of a Hydrogen Engine.

In addition, it would be an opportunity to include Electric Engines in the CS-E, which would be based on SC E-19 (Special Condition for Electric / Hybrid Propulsion System).

Based on a review of the latest CS-E Requirements at Amendment 7, the following changes have been identified and are summarised below:

Proposed Changes to CS-E Requirements:

Total number of **CS-E Requirements** – 90

Proposed changes to **CS-E Requirements** – 11 (Approximately 12%)

The proposed changes to CS-E requirements do not include the proposal to add a new Subpart for Electric Engines.

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

The change to the current CS-E Requirements (including 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 Engine could be applied to address a Type Certification (TC) application.

The proposed Special Condition would be based on the areas of the CS-E 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 Type Certification (TC) application for a Hydrogen Engine.

Definitions

The following are definitions of terms used in this document:

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) as described below.

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.

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.

Introduction

This document provides an initial gap analysis of Certification Specifications (CS-E) requirements for a Hydrogen Engine. The gap analysis looks at the potential changes that would be required to existing certification requirements to address the main airworthiness / safety considerations for a Hydrogen Engine and includes a review of the associated Acceptable Means of Compliance (AMC).

Based on developing technology, there is the possibility that a Hydrogen Engine will be used to provide the propulsion for a CS-23 / CS-25 aircraft.

It is important to identify the certification challenges and to properly identify any safety concerns that may result from the introduction of a Hydrogen Engine.

Scope of the gap analysis

A gap analysis using the Certification Specification, CS-E at Amendment 7, has been performed to identify specific requirements that may require an update to address a Hydrogen Engine stand-alone certification. This includes a review of the associated AMC material that is included in the CS-E requirements.

The gap analysis is the first step in understanding the gaps in current certification requirements for a Hydrogen Engine.

CS-E 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 CRIs/Special Conditions to address the shortfalls in the certification requirements.

The current certification requirements for a Piston / Turbine Engines are CS-E.

The Subparts within the CS-E requirements are as follows:

Subpart A — General

Subpart B — Piston Engines: Design and Construction

Subpart C — Piston Engines: Type Substantiation

Subpart D — Turbine Engines: Design and Construction

Subpart E — Turbine Engines: Type Substantiation

Subpart F — Turbine Engines: Environmental and Operational Design Requirements

The Gap Analysis for CS-E 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-E certification requirements / AMCs.

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

Next steps

The next steps in the gap analysis would be to perform a detailed assessment for each of the CS-E 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.

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 and Acceptable Means of Compliance for Engines (CS-E)

Table 1 - Proposed changes to CS-E Requirements / AMCs

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A – GENERAL	**CS-E 10 Applicability**	1. New SUBPART to cover Electric Engines.	No change anticipated.
	CS-E-15 Terminology	1. Hydrogen embrittlement - means a form of stress-induced fracture, causing metal alloys to suddenly crack or fail under stress values below the yield stress and without prior signs of damage. The hydrogen accumulation rate inside materials because of being exposed to hydrogen flames must be kept below a critical threshold where hydrogen embrittlement could happen. In addition, hydrogen can affect other properties of superalloys, including creep and fatigue and evidence must be available to demonstrate the impact of H2 in the assumed material characteristics.	No change anticipated.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A – GENERAL	**CS-E 50 Engine Control System**	No Change Anticipated	AMC needs to consider the control systems and equipment specific to Hydrogen engines. This would include items such as fuel metering unit, pressure, temperature and flow rate control systems, hydrogen phase transitioning system, and heat exchangers.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A – GENERAL	**CS-E 70 Materials and Manufacturing Methods**	1, Hydrogen flame charged combustion chamber materials may be susceptible to hydrogen embrittlement and suitable tolerance to hydrogen must be stated in the material specification. 2. Manufacturing methods and processes must be such as to produce sound structure and mechanisms which retain the original mechanical properties under reasonable service conditions. Handling of material during assembly must be such that surface contamination with hydrogen is avoided to reduce variability in quality control metrics against hydrogen embrittlement or reduce the likelihood of prematurely promoting hydrogen embrittlement. In addition, Acceptable Means of compliance "AMC E 70 Castings, Forgings, Welded Structures and Welded Components" must be adapted to address manufacturing and material compliance methods of hydrogen combustion engines and demonstrate suitability of materials against hydrogen embrittlement.	New or revised AMC for new requirement.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A – GENERAL	**CS-E 80 Equipment**	The explosion proofness and prevention criteria needs to be highlighted for Hydrogen turbines due to the increased level of risk.	No change anticipated
	CS-E 90 Prevention of Corrosion and Deterioration	1. The maximum hydrogen absorption rate into materials must not exceed values that could promote hydrogen embrittlement under most severe operating conditions conforming to those established by satisfactory practice for the material involved. 2. Each engine component and each item of equipment that shows susceptibility to Hydrogen embrittlement must be protected from hydrogen absorption and deterioration in an approved manner.	No change anticipated.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A - GENERAL	**CS-E 100 Strength**	1. The stresses developed in the Engine must be correlated with the possible hydrogen absorption rates in combustion engine materials to identify critical stresses leading to Hydrogen embrittlement. 2. Apart from mapping critical operating conditions in CS-E 100 (b), evidence of how hydrogen may affect other mechanical properties must be available to demonstrate the impact of H2 in the assumed material characteristics. Maximum stress and hydrogen values must be defined conforming to those established by satisfactory practice for the material involved, due account being taken of the form of construction and the most severe operating conditions.	No change anticipated.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART A - GENERAL	**CS-E 130 Fire Protection**	To adequately address hydrogen-related threats, the current regulatory philosophy must be re-evaluated in line with fire and explosion prevention and protection at the aircraft level. While fire remains a concern, the risk of explosion must also be better considered. High pressure hydrogen leaks or explosions could become the sizing cases for engine and nacelle structures. Additional gaps are also identified about increased risk of torching flames due to pressurized hydrogen in gaseous form (which could extend beyond the currently addressed scenario of engine case burn-through), prevention of leaks and ignition, ventilation as mitigation means, and criteria to define hazardous quantities of hydrogen fuel.	New or revised AMC for new requirement.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART D – TURBINE ENGINES: DESIGN AND CONSTRUCTION	**CS-E 560 Fuel System**	Depending on design choices, hydrogen fuel conditioning and phase transition constraints may result in variations in engine–aircraft interfaces and necessitate the incorporation of new components, such as heat exchangers. These new elements introduce additional hazards that must be addressed. Among these are hydrogen leaks, which may require dedicated requirements or AMC for leak detection system calibration and venting systems. Furthermore, hydrogen's chemical properties introduce potential variability in the fuel's chemical composition in the tanks, particularly regarding the para/orthohydrogen proportion, with then a need to determine engine compatibility and impacts.	New or revised AMC for new requirement.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART E – TURBINE ENGINES: TYPE SUBSTANTIATION	**CS-E 780 Icing Conditions**	The requirement applies to atmospheric environmental conditions and is valid for hydrogen turbines. It is determined that exposure to hydrogen cryogenic conditions could lead, in normal or abnormal situations, to liquefaction or solidification of air, oxygen, water vapor, or any other fluid, thus leading to new safety concerns. These threats are not addressed in the requirement; a dedicated new requirement is probably needed to specifically account for these hydrogen-related cryogenic hazards.	New or revised AMC for new requirement.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART F – TURBINE ENGINES – ENVIRONMENTAL AND OPERATIONAL DESIGN REQUIREMENTS	**CS-E 1010 Fuel Venting**	The operation of hydrogen aircraft and engines introduces novel emissions: hydrogen emissions from boil-off, venting, leaks, or combustion; water vapor generated during combustion or as a by-product of fuel cell operation; and potentially inerting gases, if utilized as a preventive measure to mitigate the risk of flammable atmosphere build-up or during ground operations, especially refuelling. Consequently, a potential gap is identified in the environmental protection regulatory framework concerning the incorporation of those hydrogen-related emissions, the establishment of allowable criteria, and the definition of means of compliance.	New or revised AMC for new requirement.

Subpart	Section	Change to CS-E Requirements	Change to AMCs
SUBPART F – TURBINE ENGINES – ENVIRONMENTAL AND OPERATIONAL DESIGN REQUIREMENTS	**CS-E 1020 Engine Emissions**	The operation of hydrogen aircraft and engines introduces novel emissions: hydrogen emissions from boil-off, venting, leaks, or combustion; water vapor generated during combustion or as a by-product of fuel cell operation; and potentially inerting gases, if utilized as a preventive measure to mitigate the risk of flammable atmosphere build-up or during ground operations, especially refuelling. Consequently, a potential gap is identified in the environmental protection regulatory framework concerning the incorporation of those hydrogen-related emissions, the establishment of allowable criteria, and the definition of means of compliance.	New or revised AMC for new requirement.

Table 2 – Proposed Hydrogen Engine Special Condition or Certification Review Items (CRIs)

Subpart	Section	Statement of Issue
SUBPART A – GENERAL	**CS-E 10 Applicability**	Applicability to cover Electric Engines.
	CS-E 15 Terminology	Need to consider Hydrogen embrittlement.
	CS-E 50 Engine Control System	Need to consider the control systems and equipment specific to Hydrogen engines. This would include items such as fuel metering unit, pressure, temperature and flow rate control systems, hydrogen phase transitioning system, and heat exchangers.
	CS-E 70 Materials and Manufacturing Methods	Need to consider Hydrogen embrittlement.
	CS-E 80 Equipment	Need to consider the explosion proofness and prevention criteria for Hydrogen turbines due to the increased level of risk.

Subpart	Section	Statement of Issue
SUBPART A – GENERAL	**CS-E 90 Prevention of Corrosion and Deterioration**	1. Need to consider Hydrogen embrittlement under most severe operating conditions. 2. Each engine component and each item of equipment that shows susceptibility to Hydrogen embrittlement must be protected from hydrogen absorption and deterioration.
	CS-E 100 Strength	Stresses developed in the Engine must be correlated with the possible hydrogen absorption rates in combustion engine materials to identify critical stresses leading to Hydrogen embrittlement.
SUBPART D – TURBINE ENGINES: DESIGN AND CONSTRUCTION	**CS-E 560 Fuel System**	Depending on design choices, hydrogen fuel conditioning and phase transition constraints may result in variations in engine–aircraft interfaces and necessitate the incorporation of new components, such as heat exchangers, in E 560. These new elements introduce additional hazards that must be addressed. Among these are hydrogen leaks, which may require dedicated requirements or AMC for leak detection system calibration and venting systems. Furthermore, hydrogen's chemical properties introduce potential variability in the fuel's chemical composition in the tanks, particularly regarding the para/orthohydrogen proportion, with then a need to determine engine compatibility and impacts.

Subpart	Section	Statement of Issue
SUBPART E – TURBINE ENGINES: TYPE SUBSTANTIATION	**CS-E 780 Icing Conditions**	Need to specifically account for these hydrogen-related cryogenic hazards.
SUBPART F – TURBINE ENGINES – ENVIRONMENTAL AND OPERATIONAL DESIGN REQUIREMENTS	**CS-E 1010 Fuel Venting**	Potential gap is identified in the environmental protection regulatory framework concerning the incorporation of those hydrogen-related emissions, the establishment of allowable criteria, and the definition of means of compliance.
	CS-E 1020 Engine Emissions	Potential gap is identified in the environmental protection regulatory framework concerning the incorporation of those hydrogen-related emissions, the establishment of allowable criteria, and the definition of means of compliance.
NEW SUBPART FOR ELECTRIC ENGINE		Refer to SC E-19 (Electric / Hybrid Propulsion System)