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Hydrogen Aircraft Certification: Determination of Regulatory Gaps

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Abstract

Hydrogen is an energy vector identified as a promising candidate to replace fossil fuel on aircraft, used in a gaseous or cryogenic liquid form, either through direct combustion or through reaction in fuel cells. Hydrogen comes with intrinsic properties that lead to hazards and safety risks. The objective of this work, conducted under the Clean Aviation CONCERTO research project, is to perform a regulatory gap analysis and a risk assessment to prepare future rulemaking activities for the timely certification of hydrogen-powered aircraft. The existing EASA certification regulation will be evaluated to determine its relevancy for hydrogen aircraft architecture and the adaptations that will be needed. Firstly, a synthesis of hazards is determined from hydrogen properties and related research. Through a proposed methodology, a gap analysis is then conducted to cross-evaluate hydrogen hazards, generic concepts of hydrogen aircraft and existing certification regulations. The preliminary results of this analysis show that multiple requirements related to fire protection and cabin safety/emergency evacuation are affected due to the flammability properties of hydrogen. It can be concluded that hydrogen hazards challenge some existing certification assumptions, and that further regulatory evolutions will be needed, with a still on-going analysis that raises significant gaps in existing requirements and means of compliance.

Introduction

In the European Union roadmap to decarbonize the aviation sector, hydrogen, as a carbon-free energy vector with valuable energetic properties, is identified as a promising candidate to replace fossil fuel [1]. Hydrogen can be used on a hydrogen-powered aircraft (HPA), in a liquid or gaseous form, either through direct combustion in turbines or thermal machines, or through electro-chemical reaction in fuel cells. Recent research or industrial developments of HPA show that a large design space is considered, on small to large airplanes.

For a timely entry into service of those disruptive technologies and products expected in 2035, the European Union Clean Aviation Strategic Research and Innovation Agenda [1] identifies that safety standards and certification requirements are key-enablers to foster those developments. Therefore, it is of importance to anticipate the certification challenges and to properly identify the safety concerns resulting from those novelties, as they have the potential to introduce new hazards.

Hydrogen as a fuel or as a source of electrical power is not a new concept in aviation but has not been achieved to the scale of kerosene. Since 1950s, various research projects and experiments, including flight tests on the Tupolev TU-155, have been carried out [2] [3]. Those studies included to some extent initial safety assessments mainly focused on leak and fire detection, crash hazards and passenger exposure to cryogenic fuel [3]. In 2000-2003, as part of the Cryoplane European project, a partial analysis of risks related to liquid hydrogen concluded in the certifiability of a HPA and in the need to amend certification regulations, without further publicly available data [4]. A step forward is needed to thoroughly investigate the safety of hydrogen aircraft and to pave the way for rulemaking tasks to prepare the relevant aircraft and engine certification requirements to be issued by aviation safety authorities and the relevant means of compliance.

For this purpose, within the Clean Aviation CONCERTO (Construction Of Novel CERTification methOds and means of compliance for disruptive technologies) research project, one pillar is dedicated to HPA. This paper synthesizes the initial outcomes of this project, focusing on certification requirements issued the European Union Aviation Safety Agency (EASA)

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Section 1 presents the key principles of certification and what is at stake for HPA. Section 2 synthesizes key properties of hydrogen and resulting hazards. Section 3 describes the methodology developed for this regulatory analysis in CONCERTO. The initial results are then discussed in Section 4.

1. Certification of innovative aircraft and technologies

Airworthiness is a measure of aeronautical products suitability for safe flight, defined as the status of an aircraft, an engine, a propeller, or a part, that grants it the ability to be operated while ensuring safety objectives for persons on-board, third parties, third persons, other aircraft, and overflown persons and territories. Certification of the initial airworthiness is necessary before entry-into-service of any new or modified product.

1.1 Principles of aircraft certification

The process applicable for certification is ruled by aviation safety authorities. It basically involves the organization responsible for the design of a product and the competent authority that has jurisdiction over this organization. In Europe, the EASA is the competent authority, responsible for products certification and for establishing procedures, organizational and technical requirements applicable for the purpose of certification.

As part of its initial airworthiness demonstration, the design of a product shall be approved through a type certificate issued by the competent authority [5]. This type certificate attests that the design is compliant with its certification basis that consists of the airworthiness, environmental protection and operational suitability data applicable requirements. The certification process thus consists in demonstrating, verifying, and attesting this compliance. The requirements are compiled in a coherent manner in Certification Specifications (CS), documents issued by the EASA. For example, CS-25, CS-23, and CS-E defines the airworthiness requirements respectively for large airplanes, for normal-category airplanes, and for engines. Furthermore, each CS includes, or refers to, Acceptable Means of Compliance (AMC) that are means recognized by the authority as acceptable to demonstrate compliance with certification requirements. The certification basis is then made of the CSs that are applicable to the product to certify, and that are effective at the starting date of the certification process, completed as necessary by additional requirements specified by the authority.

1.2 Certification of novel technologies

When those CSs do not contain adequate or appropriate requirements, Special Condition (SC) is the regular regulatory means used by the EASA to prescribe technical specifications in addition to, or in replacement of, requirements from the applicable CSs. Use of SC is typically well adapted to cover situations where novel or unusual design features existing in the design of a product to certify are not covered by existing CSs. A SC usually addresses specific technical topics. But it can also have a wider scope, up to the definition of a full set of requirements for the certification of a novel product. That way, the special condition SC-VTOL defines the requirements applicable for the certification of small Vertical Take Off and Landing (VTOL) aircraft, and the special condition SC-EHPS prescribes the certification requirements for electric and/or hybrid propulsion systems (EHPS).

Furthermore, CS are regularly updated and can be amended to introduce requirements addressing novelties.

Thus, the European regulatory framework is flexible to enable the certification of novel technologies and aircraft concepts. The regulatory means to establish a certification basis for novel products are existing, provided that the technical requirements to prescribe are properly defined to provide the level of safety expected from those products.

1.3 The case of hydrogen powered aircraft certification

Certification requirements build-up along the years to address safety issues, to improve the level of safety, and to support industrial developments. Some requirements and means of compliance are based on technical assumptions. A significant one is the main on-board source of energy. Fossil aviation fuel, and recently electrical power, are currently considered in the regulation and requirements to address hazards and failure conditions from those sources. As of existing CSs, hydrogen, as a novel source of energy, is not considered. Therefore, with the goal of certifying a HPA with a level of safety equivalent to the one expected today, an overall evaluation of the existing certification regulatory framework is needed, to assess its relevancy for hydrogen solutions, to determine the needed adjustments, and to identify critical safety areas. For this purpose, a certification gap analysis described in this paper is then conducted, that combines the hazards introduced by hydrogen technologies with existing certification requirements and means of compliance.

It shall be noted that standardization and rulemaking efforts are on-going for hydrogen fuel cells as auxiliary energy supply devices, with some published standards and proposed regulation [6] that are considered in this study.

2. Hydrogen properties and related hazards

Hydrogen comes with properties that may lead to specific hazard and safety risks when used on an aircraft. Some of those properties related to safety risks are synthesized hereafter.

2.1 Physical properties

Hydrogen is a low-density chemical element, which makes it necessary to store it in a compressed or liquefied form. Its storage on aircraft however requiring, for the same amount of energy, significantly more volume than fossil aviation fuel [7].

Due to weak intermolecular forces, hydrogen presents extremely low melting and boiling points (respectively -259°C and -252,8°C at 1013,25 hPa), thus eventually requiring cryogenic conditions for storage, distribution, and use. Due to these weak forces and a very low density compared to air, gaseous hydrogen is highly diffusive and highly buoyant, so it is able to mix with air rapidly upon release. In case of leakage, this property can present favorable safety effect for flammable mixture build-up in unconfined areas, but unfavorable in confined areas where hydrogen can accumulate [6] [7].

Then, known as material embrittlement, hydrogen can cause a deterioration of mechanical properties of some metals or alloys, under a combination of hydrogen environment, applied stress, and material type. This implies a careful selection of airframe materials.

Finally, being a very small molecule, in its gaseous form hydrogen presents a high permeation rate, meaning it can diffuse through materials more readily than other gases requiring an attention to micro-leakages and hydrogen accumulation in a hydrogen system.

2.2 Chemical and combustion properties

A selection of relevant chemical properties of hydrogen, compared to a fossil fuel commonly in service on large airplanes, are presented in Table 1.

	H_2 (1)	Jet-A (2)
Lower heating value [MJ/kg]	119.96	42.8
Flammability limit range in air [vol%]	4.0 - 75	0.6 - 4.7
Minimum ignition energy in air [mJ]	0.017	0.25
Minimum autoignition temperature [K]	858	>500
Adiabatic flame temperature in air [K]	2318	2200
Maximum burning velocity [m/s]	3.46	<0.5

Table 1: Comparison of H2 and Jet-A chemical properties - (1) at normal temperature and pressure conditions, from [8] [9] – (2) typical values, from [10]

From this table, key safety conclusions can be derived. First, the amount of heat released during hydrogen combustion is more important and the flame temperature is higher than for Jet-A, which can be a hazard in case of fire. Then, the flammability limit range of gaseous hydrogen-air mixture is very large, meaning that the mixing of hydrogen with air in case of leak is very likely to result in the creation of a flammable atmosphere. When combined with the very low minimum ignition energy (MIE), a flammable hydrogen environment can be more susceptible to lead to a fire hazard than with Jet-A vapors. The burning velocity of hydrogen flame implies that overpressure, deflagration or detonation can occur following an initial fire.

Without being exhaustive, this comparison shows that hydrogen flammability is a major safety hazard to consider, but with little relevant available data about hydrogen behavior in altitude.

2.3 Hazards

As a result of the analysis of hydrogen intrinsic properties and related hazards, the following categorization of aircraft-level hazards, adapted from [8] and [11], is retained for this gap analysis: Fire & Explosion, Chemical, Leak & Spill, Mechanical, Structural, Impact, Physiological, Thermal, Electrical & Control, Environmental, Flight loads (effects of aircraft motion). Failure modes, their effects and the related

safety objectives are then evaluated with respect to this categorization.
Furthermore, this analysis has identified new phenomena which are not covered by existing aviation safety processes, or which are not covered to the extent of what is required by hydrogen properties. These are likely to constitute new behaviors, failure scenarios or hazards to be accounted for in the gap analysis (*e.g.* explosive atmosphere, blast wave, boiling liquid expanding vapor explosion, deflagration, detonation, liquid lock-up, permeation, flame quenching).

3. Methodology for certification gap analysis

The analysis aims at determining and quantifying gaps in the existing certification regulations that may prevent the future certification of a HPA. It thus helps to reach a certification readiness level that allows to prepare and prioritize forthcoming rulemaking activities to adapt, as necessary, CSs and to anticipate the developments of relevant AMC or standards.

The methodology developed in CONCERTO project to carry out this analysis is summarized in Fig. 1. It consists in gathering a set of relevant data for three inputs that go through an in-depth cross-analysis, organized per certification panels as defined by the EASA, to derive outputs.

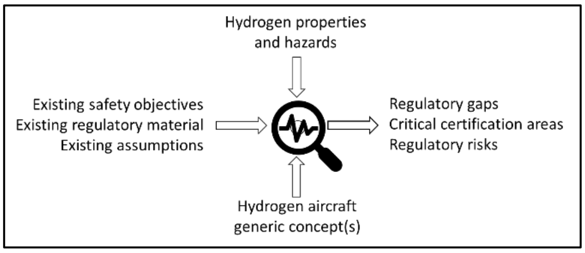

Fig. 1: Overview of the gap analysis methodology

The first input data contains generic concept(s) of HPA and their operations. It consists in defining the aircraft architecture to investigate, its technologies, systems and integration solutions, and its concept of operations with identification of expected nominal, off-nominal and emergency conditions.

The second input data contains a state-of-the-art on hydrogen intrinsic properties and hazards, and related aircraft installation hazards, as summarized in Section 2.

The third input data contains existing relevant regulatory material to be scrutinized (CS, AMC, advisory material) and commonly accepted assumptions that may be invalidated by HPA.

The proposed methodology for gap analysis then consists in evaluating the following items for the concept(s) described in the first input, with respect to hydrogen hazards described in the second input, and for each existing requirement or means of compliance from the third input:

1- Relevancy of the safety intent(s) of a requirement/means of compliance: are the intent(s) still valid for HPA?
2- Validity of the underlying assumptions of a requirement/means of compliance: are the assumptions still valid for HPA?
3- Validity of means of mitigation used in a requirement/means of compliance: are those means still relevant for HPA?
4- Adequacy of a requirement/means of compliance to properly address hydrogen risks
5- Identification and substantiation of regulatory gaps, and of missing requirements

Finally, the output data contains identification of regulations that would be mainly affected, identification of those that would need to be amended/developed in priority, identification of critical certification areas that will require in-depth investigation (*e.g.* unknown phenomena, insufficiently well-characterized behavior, insufficient data, lack of scientific knowledge).

4. Initial results

As a first step, the methodology is applied to a generic liquid hydrogen-powered airplane with H2-direct combustion turbine engine and cryogenic storage in tanks located in the rear part of the fuselage. A generic fuel distribution system from tanks to engine in liquid form, through isolated pipes, is considered.

The EASA CSs at stake are CS-25, CS-23, CS-E. It is determined that the main impacted certification panels, and main impacted areas within each panel, are:

- Propulsion: turbine engine
- Powerplant Installation and Fuel Systems: engine installation, fuel systems, fuel tank inerting, fire protection, thermal management
- Structure and Material: proof of structure, fatigue and damage tolerance, materials, crashworthiness, impact conditions

- Cabin Safety: fire protection, emergency evacuation
- Electrical Systems: electrical wiring and interconnection system, fuel cells, thermal management, electromagnetic compatibility, high-intensity radiated field effects, lightning effects
- Instructions for Continued Airworthiness: development of scheduled maintenance tasks
- Development Assurance & Safety Assessment: safety assessment methodology (with a potential need for new Particular Risk Analysis)

Initial results are presented for 2 sets of requirements, and for competence development within organizations.

4.1 Fire and Explosion

Hydrogen properties identified in Section 2 exhibit that leaks and spills will rapidly create gaseous flammable atmosphere especially in confined aeras *e.g.*closed volume surrounding a distribution pipe or a tank. The low hydrogen MIE implies that ignition sources will be more numerous and various than the ones identified for fossil fuel, typically electrical, electromagnetic, mechanical, and thermal sources [6]. Therefore, new potential hazards are likely to occur following a leak, with subsequent risks of fire or explosion. The level of risk is escalated by the currently documented lack of efficient fire extinguishing solutions other than stopping hydrogen supply [6].

Fire mitigation strategy in the existing regulation for fossil fuel is based on 2 principles. First is prevention, to minimize the probability of occurence of ignition, with means of mitigation including drainage and ventilation, potential ignition sources elimination, flammable fluids and ignition sources segregation, inerting systems,. Second is protection, to reduce the consequence of fire occurence with means of mitigation such as fire and smoke detection, extinguishing agent, shielding and protective insulation, fire resistance and fire proofness. The gap analysis determines that those assumptions valid for fossil fuel are challenged by hydrogen fuel. Even if the safety intents of the existing requirements remain valid for hydrogen fuel, it is determined that hydrogen properties and hazards lead to differently appreciate the efficiency of fire detection system, fire suppression system, structural protection against fire, hydrogen fuel system inerting, ventilation solutions and isolation systems (such as shut-off valves to interrupt hydrogen supply) as means of mitigation. Therefore identification of new means of mitigation or development of new certification approaches to meet the intents of certification requirements and safety objectives are needed. Furthemore, as presented in Section 2, an hydrogen fire may develop in an explosion, under some physical (*e.g.* dimensions of a volume) and chemical conditions that still require further investigation and characterization when applied to aircraft environment to conclude on the gap analysis.

Major impacts are then identified for CS-25 fire requirements such as, but not limited to, 25.981 Fuel tank explosion prevention, 25.863 – Flammable fluid fire protection (fire zoning, ignition sources requirements), 25.1187 – Drainage and ventilation of fire zones. Various existing requirements on fire resistance and proofness, based on fossil fuel flame properties, need to be revisited to reflect hydrogen flame characteristics, chemistry and speed, and to specify appropriate protection against hydrogen flame. The variation of material flammability properties when exposed to hydrogen environment described in the literature needs also to be characterized in the regulation.

4.2 Occupant protection and evacuation

The presence of liquid hydrogen tanks in the fuselage results in gaps with current certification requirements. To address in-flight fire, gaps are identified related to fire extinguishing (25.851), where the envisioned extinguishing solutions could require the definition of new means of mitigation or of a new approach to fire protection in the cabin, to address the aircraft-level hazards. Flame penetration and propagation requirements (25.855, 25.856) also require an update of flame characterization as mentioned earlier.

The gap analysis also identifies that post-crash pool fire resulting from massive hydrogen leak may require evolutions in the regulation concerning emergency evacuation and prevention of outside fire to penetrate the fuselage. Simulations conclude that a hydrogen pool fire is less impacting than a kerosene pool fire [9], but additional characterization of the behavior of pool fires is needed for a conclusive gap analysis.

4.3 Competencies maturity within organizations

Throughout the regulatory gap analysis of those two sets of technical requirements, it is determined that the evaluation of novel technologies certifiability such as HPA requires an appropriate scientific and technological knowledge.

As per EASA Part-21 implementing rule for airworthiness and environmental certification [12], technical competence is currently already recognized as one key element within a design organization for its capability demonstration. When dealing with innovative design, reaching the certification readiness level expected after a gap analysis implies that a sufficient product design maturity is met, and that the relevant competencies about new technologies are available in a timely manner within the design organization and within the authority. Roadmaps and gates on a maturity scale towards needed rulemaking activities and establishment of certification basis for hydrogen aircraft have then to duly consider skills development. This can be achieved for example through training programs, data exchange between design organizations and authority with an early involvement of the authority, or research & technology programs involving the authority.

Maturity of technical competence within organizations, as early as a certifiability evaluation, is then identified as a cornerstone in the development of appropriate regulation for innovative technologies. Existing EASA Part-21 requires a design organization to demonstrate the competence of its staff (knowledge, background, experience) and doesn't need to be updated.

Conclusion

Hydrogen-powered aircraft presents new hazards not adequately consider in the existing certification regulations, thus leading to rulemaking activities for future certification of such a disruptive aircraft configuration.

The regulatory gap analysis methodology presented in this paper is in place within the Clean Aviation CONCERTO project. The first outputs of the analysis on a limited scope demonstrate that existing certification regulation presents some gaps that will require the definition of adapted requirements and means of compliance. Then, the development of competence, within design organizations and authority, about novel technologies to certify is a key gate on a maturity scale towards the development of future certification regulations.

In addition, those first results exhibit that phenomenology data, needed for better hazards and means of mitigation characterization, and then for appropriate requirements definition, are missing. This resulting compilation of missing data is essential to push on the critical research for derisking certification.

The overall regulatory analysis is in progress, along with a definition of hydrogen aircraft generic concepts, aiming at preparing future regulations, and at identifying technical risks with respect to certification and regulatory risks that may prevent the certification regulation to be available on time..

Acknowledgment

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