Federal Aviation Administration

Hydrogen-Fueled Aircraft Safety and Certification Roadmap

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FAA Hydrogen-Fueled Aircraft Safety and Certification Roadmap

Foreword

The aviation industry is investing in hydrogen-powered aircraft as US companies are seeking to keep pace with significant investments in Europe and elsewhere to capitalize on the market for sustainable aircraft.

At the forefront of our efforts is aviation safety. We have developed this roadmap to outline the current knowledge, key research priorities, and collaborative efforts essential to enabling the safe use of hydrogen in civil aviation aircraft. This roadmap was developed in collaboration with several FAA offices and informed through a series of technical interchanges with other aviation regulators, government agencies, and industry. We plan to continue our collaboration with foreign civil aviation authorities to share perspectives and knowledge and harmonize our approaches to enable safe and efficient introduction of hydrogen in aviation.

As we look to the future, hydrogen has the potential to redefine aviation by enabling more sustainable flight. This roadmap is intended to serve as a step towards that future, where hydrogen-fueled aircraft is not only a possibility, but a reality. As we move forward, we will continue working both within and outside of our agency to set the course for a new era of sustainable aviation.

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Executive Summary

Consistent with 2050 decarbonization commitments[1], the aviation industry and research establishments are increasingly exploring the use of hydrogen as an alternative source of energy in aircraft. Technologies have been demonstrated whereby hydrogen can be burned in an aircraft engine for propulsion or auxiliary power or can be used in a fuel cell to generate electricity for propulsion and/or other aircraft systems, such as a galley, medivac, emergency, or auxiliary power.

The use of hydrogen on aircraft presents multiple potential hazards; key among them are fire and explosion resulting from uncontrolled leaks. These hazards must be fully understood and addressed in airworthiness standards and related guidance. In addition, essential aircraft systems, such as an engine, fuel cell, or thermal management systems must be shown to operate reliably using hydrogen. Appropriate regulations and guidance must be developed to assure the safety of initial projects and to provide a predictable path to obtaining airworthiness and operational approvals.

Existing FAA airworthiness standards did not envision fuel cells, nor the use of hydrogen to fuel an aircraft engine. This roadmap provides an overview of some of the technical challenges, safety concerns, and policy gaps that need to be addressed for the use of hydrogen as an alternative energy source in aircraft. It describes FAA's approach to work with industry in addressing those gaps, including a joint evaluation of the proposed application needs.

The roadmap focuses on the safety and certification of the use of hydrogen as an energy source in aircraft (e.g., title 14, Code of Federal Regulations (14 CFR) parts 21.17, 23, 25, 27, 29, and 33) and the operation and maintenance of such aircraft. Other areas of concern to the National Aerospace System (NAS), such as generation, transportation, storage, distribution at or near airports, rescue and firefighting efforts, etc. are outside the scope of this roadmap. They will, however, be coordinated with the relevant FAA organizations, government agencies, and other interested stakeholders.

Key elements of the roadmap include identifying industry application interests, the safety hazards associated with the use of hydrogen fuel, regulatory and guidance gaps, research needs, and defining a plan and timelines to address them. This roadmap will also be used to inform a research and development strategy on the safe use of hydrogen in civil aviation in accordance with the recently enacted 2024 FAA Reauthorization Bill[2] Section 1019, and a viable path for certification in accordance with Section 1109.

1.0 Purpose

The purpose of the Hydrogen Roadmap is to describe a plan for the FAA to identify and address the regulatory issues associated with safely and efficiently incorporating hydrogen as an energy source (fuel) in aircraft and acquire the information needed to address aircraft certification, operation, and maintenance issues. The roadmap aims to partially fulfill requirements of the recently enacted 2024 FAA Reauthorization Bill (Sections 1019 and 1109).

2.0 Technology Overview

Aviation decarbonization will require a concerted effort that includes higher efficiency aircraft, powerplants, airport and flight operations, as well as lower carbon intensity fuels such as (drop-in) Sustainable Aviation Fuel (SAF), hydrogen, or ammonia. Hydrogen is considered a potentially attractive alternative energy source for aircraft from an environmental perspective, as it eliminates carbon dioxide from aircraft emissions. However, the lifecycle emissions of hydrogen production, transportation, and liquefaction must be considered when evaluating hydrogen as a decarbonization pathway.

This roadmap is concerned with safe and efficient introduction of hydrogen in aircraft. A brief overview follows of technologies that will play a key role in this effort, as well as associated key hazards. A more in-depth description of hazards is provided in the Appendix 9.4 Known Hazards.

From a technology perspective, hydrogen-powered aircraft could look similar to current tube-and-wing design, with modified powerplants, fuel storage, and distribution systems. More ambitious proposals involve aircraft optimized to take advantage of the new fuel, such as thin, high Lift/Drag (L/D) wings, Blended Wing Body (BWB) fuselage, conformal tanks, distributed/embedded propulsion enabled by electrical motors powered by fuel cells, etc. Regardless of options pursued, common challenges exist due to the particular properties of hydrogen.

A key fuel property for aviation use is its specific energy content, that is, energy per unit mass or volume. Hydrogen's mass specific energy is ~3x higher than that of Jet fuel[3], which implies less fuel may be required for flight. Unfortunately, the volumetric specific energy of hydrogen is much lower than that of Jet fuel, at least 4x lower (even for liquid hydrogen - LH_2), which implies bigger fuel tanks. Large tanks result in weight and aerodynamic penalties, especially when mounted externally, and severely reduce the space available for passengers or cargo. Compressed gas tanks need to withstand high pressures (up to 850 bar) which implies structural reinforcement, thus additional weight. Cryogenic (LH_2) tanks must maintain extremely low temperatures (20K), which requires very good insulation/thermal management. To avoid over pressurization due to heating, cryogenic tanks need to be vented, a process commonly referred to as "boil-off." In addition, cryogenic tanks may have to maintain some LH_2 at most times to avoid extreme thermal cycling.

Hydrogen is exceptionally combustible. Compared to most other fuels hydrogen has much wider flammability limits, lower ignition energies, higher flame speeds, flame temperatures, and detonation potential[4]. Consequently, fire and explosion hazards are most significant. Uncontrolled leaks or improper venting can lead to fire, explosion, or detonation, especially in congested, confined spaces. Unlike vented jet fuel tanks whose ullage can become flammable requiring inerting or other flammability control methods, the pressurized hydrogen tank itself is extremely unlikely to experience a flammable mixture. However, oxygen could conceivably enter the tank during refueling, maintenance, or sloshing-induced pressure drop, which would create an explosion hazard. To our knowledge, there are currently no guidelines for acceptable O_2 ingestion in a hydrogen tank. While zero ingestion would be most desirable, it is difficult to achieve and verify.

Other hazards are briefly mentioned but described in more detail in the Appendix. Material hazards primarily relate to high hydrogen diffusivity, including in metals[5], which leads to embrittlement that can affect tanks, conduits, and seals and may impact design-specific maintenance requirements. High pressures used with gaseous storage imply mechanical hazards, such as high velocity expelled fragments and failure of pressure relief devices. Fuel systems must be crashworthy, but the behavior upon a crash or emergency landing is not well characterized for large H_2 tanks, especially cryogenic. Physiological hazards include asphyxiation, exposure to toxic materials released by degassing, or combustion of aircraft materials, burns, or frostbite. Other generic hydrogen hazards include electrical, cryogenic operation, aircraft/powerplant interface (connection hazards). The operational fueling of an aircraft must be addressed. Fueling systems will need to mitigate the risk of hydrogen leakage or combustion during fueling.

Finally, it should be noted that additional risks exist outside the scope of the aircraft, such as those related to hydrogen production, storage, and distribution, for example at airports.

2.1 Hydrogen Fuel Cells

A hydrogen fuel cell is a device that converts the chemical energy of hydrogen and oxygen into electricity[6]. This electrical energy can then be conditioned and used for multiple purposes, such as powering an electric motor or galley.

Different technologies have been proposed for fuel cells; for aviation, it appears that Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cell (SOFC) technologies have the best potential. Low Temperature (LT) PEMs are a more mature technology, have high specific power and short start-up time even from freeze condition, with good load following. They need relatively pure hydrogen to function, however. LTs have moderate efficiency (typically 40-50%) and generally use expensive platinum group metal (PGM) catalysts. High Temperature (HT) PEMs are less mature than LT, offer lower power and efficiency, require longer warm-up, but are lighter (no need for membrane humidity management system) and more tolerant to contamination. SOFCs have high efficiency (60%), are fuel-flexible (can use methane, natural gas, ammonia, etc.), but need high temperatures (500-1000°C). SOFCs have more complex thermal management systems, longer start times, and higher susceptibility to corrosion. They also appear less reliable, although that may reflect their lower technology readiness level.

Fuel cell-based systems can provide a significantly better range than battery-based systems at the same overall weight, have higher efficiency than small engines, and can provide high quality electricity. Unlike batteries, fuel cells consume fuel so the aircraft gets lighter during the flight. Fueling an aircraft typically requires less time than charging/swapping batteries, providing a faster on-ground turnaround. Compared to traditional engines, fuel cells are heavier (system weight at same power), more expensive per unit power, and their reliability under aviation use is unproven. It is likely that fuel cells will be used in smaller aircraft in the near term.

Fuel cells present specific risks associated with their design and operability. Internal rupture could bring pressurized reactants into contact with potential for fire or explosion. Compressor systems required to pressurize the reactant supply may be subject to instabilities, such as surge/stall, with accompanying variation in pressure/flow rate and membrane integrity risks. The decrease in water boiling point with altitude could pose challenges to the system required to maintain membrane humidification. The high temperatures required by SOFC may provide ignition sources unless reactants are safely separated. The high voltage lines required for electrical propulsion create electrical hazards, including risks of ignition.

2.2 Hydrogen Engine Combustion

Hydrogen can be used directly as fuel and burned in a combustion engine like current hydrocarbon fuels. H_2 combustion would generate zero CO_2, zero carbonaceous (soot) particulate emissions, and could conceivably produce NOx emissions comparable with state-of-the art gas turbines. The exhaust of direct hydrogen combustion, while not containing soot, would contain greater water content than comparable hydrocarbon combustion exhaust. The effect of this unique exhaust on the formation and persistence of contrails and the resulting global warming impact from such contrails are not yet well-understood. Conventional gas turbine designs can be modified to use hydrogen instead of, or concurrent, with jet fuel or SAF. Aircraft areas affected will include materials, operability, combustion, thermal management, and engine controls. Direct combustion of hydrogen generates sufficient propulsion for medium and long-range transport and would require cryogenic tanks to achieve desired range.

Interesting concepts have been proposed that include water injection, condensation/recuperation, and advanced thermal management using LH_2 cryogenic properties. These concepts are currently at low technology readiness levels. A likelier entry point for hydrogen combustion might occur with lower pressure ratio engines, as already demonstrated by General Electric (GE) and Rolls Royce (RR). Reduced availability of H_2 at airports might restrict areas of operation or require multifuel engines, operating with Jet A/SAF and hydrogen, either as main fuel or reserve.

Similarly to fuel cells, hydrogen-powered combustion engines add risks specific to their design and operation. For example, engine start or relight could produce fire or even detonation internal to the engine. Fuel could leak into the cabin through the engine bleed system and may not be detected before reaching a flammable situation. Proposed cryogenic heat exchangers are susceptible to hydrogen leaking into the air channels, ice build-up on external surfaces open to environment, as well as flow blockage due to debris or ingestion of air.

2.3 Projects and Investments

In the United States, current hydrogen-fueled aviation efforts are focused on fuel cell-electric propulsion. Joby/H2FLY recently demonstrated a 523-mile flight of its hydrogen-electric concept aircraft, using both batteries and a cryogenic LH_2 tank supplying a fuel cell. Zero Avia is proposing compressed hydrogen used with fuel cells propelling twin electric engines on ATR72 or Q400 aircraft. Alakai Technologies is proposing a special class multicopter rotorcraft using cryogenic H_2 for use in fuel cell arrays to power six electric engine/rotor assemblies. Piasecki Aircraft is proposing compressed H_2 gas for use in multiple fuel cells driving a single main rotor and swiveling tail rotor. Of the three large US engine manufacturers, Pratt and Whitney (P&W) is developing a hydrogen combustor under Department of Energy (DOE) funding, while General Electric is involved in FAA-funded programs for their RISE engine that is planned to be hydrogen capable, as well as kerosene. To note, GE is also involved in Clean Aviation EU Programs, for example HYDEA (through its Avio subsidiary) and TROPHY (with its partner Safran).

The European Union has allocated almost $400M to hydrogen in aviation R&D in Phase I of its signature Clean Aviation program, with demonstrators to follow in Phase II. The largest participant, Airbus, has four developmental programs in hydrogen propulsion under the umbrella of the ZEROe project[7]: a 200-passenger single-aisle with two H_2-fueled turbofans, a 100-passenger turboprop with two H_2-fueled engines, both having LH_2 storage behind the rear pressure bulkhead, a 200-passenger BWB aircraft with two hybrid electric H_2-fueled turbofans, and a 100-passenger fuel cell electric regional with LH_2. Airbus is forecasting at least one hydrogen aircraft for Entry into Service by 2035. Other aspiring players in the EU include Conscious Aerospace[8] (LH_2-powered fuel cell 40 and 60 passengers), Fokker NextGen[9] (100-passenger class LH_2-powered turbofans), as well as several smaller start-ups. On the propulsion side, RR recently demonstrated hydrogen combustion on their Pearl 15 combustor; RR claims operability and emissions were obtained similar to kerosene with relatively minor modifications to the powerplant[10].

3.0 Guiding Principles

The following key guiding principles apply to the development of this roadmap for safely enabling hydrogen-powered aircraft.

1. The focus of this Roadmap is aviation safety. The roadmap addresses the safe introduction into aircraft design, maintenance, and operation. There are many other important considerations that will need to be addressed to enable operations that would have a net-environmental benefit, such as production, transportation, and infrastructure.
2. Existing information will be utilized to the greatest extent, including regulations, industry standards, recommended practices, awareness of industry product developments, and research data. Significant work has been done to support the safe use of hydrogen in other applications, such as the chemical and space industries. While generated for different purposes, the results may have value in assessing safety for aviation. The roadmap will include efforts to identify gaps in knowledge and regulation related to safety hazards and changes that are necessary to address such gaps.
3. The roadmap proposes a performance-based approach to hydrogen safety rather than a prescriptive one. This approach should provide guidance for all aircraft categories that is proportional to the acceptable risk across the varying designs proposed for hydrogen technologies.
4. Type certification regulations (part 21.17, 23, 25, 27, 29, 33, and 35) will provide the base requirements for the aircraft. Special Conditions will likely be required to adapt hydrogen technologies to the specific aircraft type and system function. These Special Conditions

may require new or updated methods of compliance to implement them and achieve the intended level of safety for a given application. Maintenance and operation will be addressed through traditional methods such as instructions for continued airworthiness, maintenance manuals, and operating manuals.

4.0 Existing Standards

The Society of Automotive Engineers (SAE) and the European Organisation for Civil Aviation Equipment (EUROCAE) have a joint working group, AE-7AFC/WG-80, that developed a standard for hydrogen fuel cells for aviation use, AS6858. The standard is based on gaseous hydrogen and not focused on fuel cells used to generate power for propulsion. The joint committee is in the process of updating the standard to address propulsive power, as well as working on a standard for cryogenic storage of hydrogen, including refueling (AS6679). Each organization also has standards and recommended practices for non-aviation applications of hydrogen as in examples listed below. These standards have not been formally adopted by the FAA, nor other civil aviation authority, however the FAA is a full participant in the joint SAE/EUROCAE committees.

In addition, the joint committee has produced Information reports, such as AIR6464 Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines, AIR7765 Considerations for Hydrogen Fuel Cells in Airborne Applications, and recently, AIR8466 Hydrogen Fueling Stations for Airports, in Both Gaseous and Liquid Form which, although not standards, provide useful background information.

There are also a number of standards that have been developed for non-aviation applications. These may have some applicability or suggest where further research is necessary to adapt concepts to aviation. Some examples from relevant fuel cell standards (SAE/EUROCAE/NASA) include:

- J2578_201408 Recommended Practice for General Fuel Cell Vehicle
- J2579_201806 Standard for Fuel Systems in Fuel Cell and Other H_2 Vehicles
- J2601_202005 Fueling Protocols for Light Duty Gaseous H_2 Surface Vehicles
- J2719_202003 Hydrogen Fuel Quality for Fuel Cell Vehicles
- J1766_201401 Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing
- J2990_201907 Hybrid and EV First and Second Responder Recommended Practice
- NSS 1740.16 Safety Standard for Hydrogen and Hydrogen Systems

More broadly, the Department of Energy supports and maintains an extensive database of standards relevant to hydrogen safety for fuel cells[11]. While focused on ground based applications, such as fuel cell power generation or automotive, the database covers many Standards Developing Organizations (SDOs), both US-based (American Society of Mechanical Engineers-ASME, SAE, Compressed Gas Association-CGA, National Fire Protection Association-NFPA, Underwriters Laboratory-UL, etc.) and international (International Standards Organization-

ISO, International Maritime Organization-IMO, United Nations Global Regulations on Pollution and the Environment-UN- GRPE, etc.). Of interest to aviation are standards for storage, infrastructure, materials compatibility, detection, and test methods, including crash integrity. Finally, given the complexity of overlapping systems using or planning to use hydrogen in the US, various government agencies are responsible for oversight. In this regard, Sandia National Laboratory published a review of federal oversight for each component of the hydrogen supply value chain which includes production, storage, distribution, and use.[12]

5.0 Certification Readiness

The introduction of hydrogen in aviation requires an unprecedented effort in developing necessary technologies. Formidable challenges exist at every step. There are technologies to discover, architectures to explore, and new materials, coatings, and manufacturing methods to develop. Each of these must achieve an acceptable level of safety to gain approval and be used.

Like widely used technology maturity levels, the certification readiness of a technology or concept refers to the maturity of the requirements and methods of demonstrating the acceptable level of safety (Figure 1). In Discovery, potential risks and vulnerabilities of the technology are still being identified and assessed. In Application, sufficient insight has been developed to enable certification of individual projects, with some requirements or methods of compliance developed concurrent with the project. At the highest phase, Normalization, a predictable and repeatable set of requirements and means of compliance have been established that work for many projects.

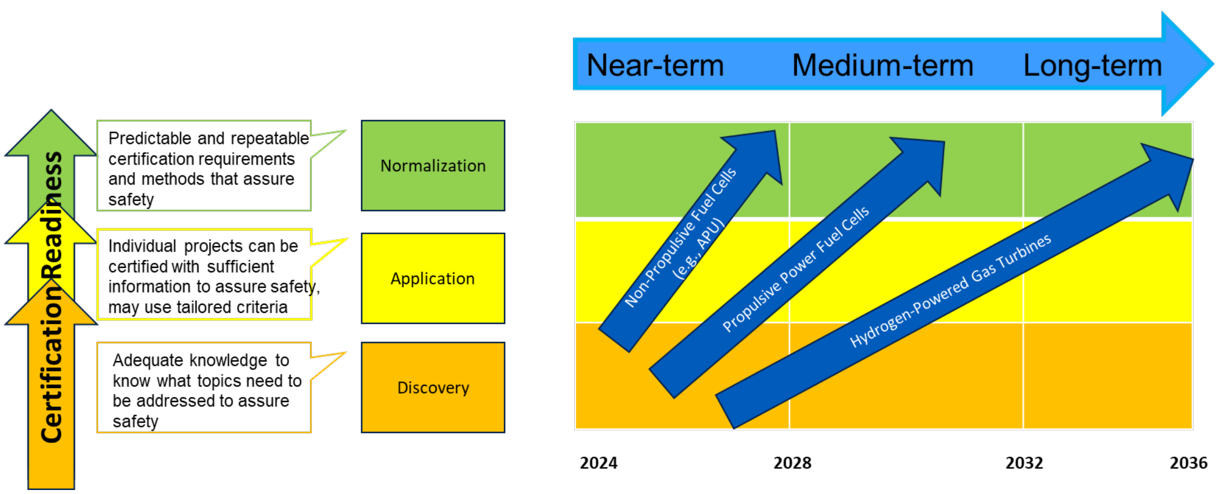


Figure 1 Certification Readiness

Figure 1 depicts the current certification readiness of the expected architectures for hydrogen on aircraft. To some extent, certification readiness parallels technology readiness. Fuel cells for non-propulsive application have been demonstrated for many years, starting with the space program; commercial ground uses of fuel cells are rather common (e.g., forklifts, buses, cars, emergency/supplemental power). Unsurprisingly, therefore, the most mature concept for commercial aviation is the use of hydrogen to generate electricity for non-propulsive uses, such as galley power, medevac, auxiliary/emergency power. A comprehensive Aviation Research

Committee (ARC) report was developed to provide recommendations for airworthiness standards and guidance on aircraft installation[6]. Larger systems with sufficient capacity to drive electric propulsion are expected to mature at a slower pace. The least mature concept (technologically, certification readiness, expected EIS) is the use of hydrogen in turbine engines.

6.0 Required Aviation Safety Research

The ultimate objective of safety research is to inform criteria necessary for the safe and efficient incorporation of hydrogen propulsion technologies into aircraft. Hydrogen (primarily gaseous) is already being used safely at massive scale in the refining and chemical industries (95Mt in 2022), as well as some transportation areas (fuel cell powered vehicles and forklifts). Its use in aerospace, however, is limited to applications (rockets, demonstrators) with a higher risk tolerance than civil aircraft operations. Aviation should leverage that experience, recognizing that some of the safety requirements imposed in space operations may not be entirely adequate, nor practical for use in commercial aviation.

To create an effective research strategy and plan for hydrogen safety requires adequate knowledge of the technologies and existing regulations and means of compliance. Initial areas of research are identified in the following paragraphs and will be updated as technology options and products become better defined, and a related regulatory gap analysis is complete.

PEM fuel cells using gaseous hydrogen are farthest along in technology development, with prototypes tested in flight and several companies in the process of application. At the same time, regulatory and means of compliance gaps for certain applications have been investigated already[6]. Fuel cells are, consequently, also most advanced in terms of certification readiness, between Discovery and Application (Fig. 1). Fuel cell APUs (for aviation) are expected to demo in the 2028 timeframe; normalization readiness should be achieved prior to that. Propulsive applications for fuel cells are not far behind, although options and architectures have yet to be solidified. Personal aviation to commuter may see the first real applications, with some expecting entry into service (EIS) before 2030s[13].

As indicated earlier, the most significant (and common across technologies) risk for hydrogen is fire and explosion. Hydrogen fire and explosion characteristics will need to be defined and guidance materials developed for industry to certify hydrogen-combustion engine and propulsion system components. This research effort will be similar to previous jet fuel fire test research efforts which resulted in today’s FAA AC 20-135 fire test guidance material for certification of transport aircraft engines and propulsion systems. As with the use of natural gas in homes, consideration should be given to requiring an additive (color and odor) be used when in aerospace applications. A burning hydrogen flame is also colorless, thereby making it difficult to detect. When adding a dye, it should identify the flame, as well as the fuel source. However, dyes may not be compatible with LH2 and research may be required to characterize additive compatibility with fuel cells.

For fuel cell systems, areas that require research common to both non-propulsive and propulsive installations include fast and accurate leak detection, characterization/dispersion, and control.

Tank location, proximity to high temperature “hot points” or electrical devices, cabin penetration, etc., are some of the concerns to address in selecting sensor types as well as best locations for detection. Mitigation strategies, such as ventilation, inerting, and fuel shut-off need to be devised and implemented in a safe manner. Structural requirements for the entire system, comprised of tanks, distribution system, and fuel cells with balance of plant systems will need to be revisited and updated. A particular case involves rupture of the electrolyte membrane which might bring pressurized hydrogen and oxygen into direct contact, thus creating a fire hazard. Contributing mechanisms (e.g., manufacturing defects, aging, compressor instabilities, loss of humidification with altitude) need better understanding.

Propulsive fuel cell applications imply much larger scale, thus aircraft-level implications. Thermal management systems (radiators, for example) can be subject to foreign object damage, as well as loss of performance due to accumulation of debris. Leaks need to be detected with identification of the correct fuel supply circuit; full system shutdown would cause loss of propulsion. Research is needed for rapid, accurate leak source identification methods, e.g., using sensor networks or dispersion models, preferably self-calibrating. Hydrogen leaks may not only result in hydrogen flames; leaks impinging on other surfaces can also affect the combustion characteristics of flammable materials (e.g., faster, stronger heat release). Better information is needed on quantifying such impact and devising appropriate test protocols, as well as fire extinguishing/fireproofing methods.

Cryogenic tanks will likely be used in propulsive applications to achieve desired range. Such tanks pose additional crashworthiness challenges. Research is needed to address adequacy of current structural guidelines for fuel tanks, safety factors, test methodologies, inspection, and maintenance procedures. Thin-walled spherical tanks are desirable for gravimetric efficiency, however, they may not be adequate from a crashworthiness perspective. Liquid hydrogen lines will require purge during connection, maintenance, or refuel. Space operations use helium as a purge gas; however, prodigious amounts would be required of this non-renewable resource to enable safe operation at airports and aircraft. Nitrogen could not be used alone due to freezing in contact with LH_2 followed by clogging of filters, regulators, and other components. Alternative methods, e.g., nitrogen purging in combination with gaseous hydrogen need to be researched and evaluated to ensure safety of operations. Liquid hydrogen is extremely cold (20K) when released rapidly or in the case of a leak, instantly freezing even surrounding oxygen, which could subsequently enable detonation upon ignition. Shielding requirements should be developed to avoid frost bite or other injuries associated with proximity to a rapid hydrogen leak or simply performing necessary maintenance.

Venting, both emergency and boil-off, needs to be managed not only from a safety perspective, but also as an environmental concern. Research is needed to investigate the feasibility of minimal, preferably zero boil-off systems, their response/operability especially during transients. A concern may be the potential for pressure collapse[14]; tanks are much less resistant to negative pressure gradients, while fluctuating fuel supply could impact the fuel cell power generation ability, hence, thrust. Research is needed to identify the potential for such events, as well as mitigation strategies, such as rapid pressurization. Refueling and tank pressure variation could cause ingestion of O_2 into the tanks. Research is needed to understand the acceptable O_2 limits (if any), provide accurate detection methods and control strategies. Manufacturers of equipment, components and plumbing associated with the distribution of hydrogen aboard aircraft will need to be aware of the long-term effects hydrogen has on components, such as embrittlement and/or change in mechanical properties. Such changes could impact structural viability, for example should a significant leak develop in a tank that doubles as fuselage.

Hydrogen combustion gas turbine technologies are least advanced from a readiness perspective, several engine demos and early flight experiences notwithstanding. Planned medium range aircraft flight demos appear to prioritize fuel cell installations, although enabling a gas turbine to operate on hydrogen might be less complex. Adoption at the medium and large transport levels, however, cannot occur without hydrogen being available (safely and at scale) at airports. A new engine program is a very large commitment that OEMs would be reluctant to engage in without clear market (i.e., airlines) pull.

In addition to areas mentioned above for fuel cells, research specific to H_2 gas turbines will be needed to address the operability and safety of a more complex fueling system, possibly cryogenic heat exchangers, fire protection of nacelles. Risks also need to be addressed arising from requirements of engine start-up and altitude relight whereupon hydrogen could ignite uncontrollably within the propulsion system and result in engine damage. H_2-initiated residual fires may have different characteristics than jet fuel-initiated fires.

7.0 Roadmap Plan

The plan describes the elements necessary to enable the safe and efficient introduction of hydrogen propulsion in aircraft. AVS will use a phased, accelerated approach, comprised of near and mid-term actions to develop and implement the hydrogen roadmap. The FAA will coordinate with other Civil Aviation Authorities and industry to refine the roadmap and pursue harmonized criteria for hydrogen use, especially in transport aircraft.

7.1 Near-Term Actions (2023-2028)

Near term key objectives are to complete the hazards, regulations, and Means of Compliance gap analyses, to define mitigation strategies, and to fulfill the mandates of the FAA Reauthorization Bill, of which the current roadmap is an integral part. To this extent, an FAA/EASA Certification Oversight Board (COB) Hydrogen Technologies Working Group has been initiated (October 2023). The group is tasked with creating harmonized recommendations for developing airworthiness requirements for both liquid and gaseous hydrogen use in aircraft propulsion systems (fuel cells and gas turbines). In addition, a Hydrogen Fire and Explosion Research Steering Group has been established with broad FAA, EASA, industry, and academia participation to focus on knowledge gaps specific to fire and explosion, as mentioned earlier the principal risk for hydrogen introduction into aviation. The effort of these groups will enable achievement of Normalization stage for Non-Propulsive Fuel Cells (APUs, galleys, medevac, emergency power, etc.) and Application stage for Propulsive Fuel Cells implementations Certification Readiness. At same time, output from both groups will inform the creation and commence the execution of a research plan to address key safety risks and provide regulatory guidance, as exemplified in previous section.

During the same period, the FAA will continue to support existing and near-term applicants through Special Conditions Projects and §21.17(b) airworthiness requirements. The FAA will participate in hydrogen-related SDO groups, such as the SAE AE-7F and EUROCAE WG 80. FAA's Aircraft Certification Service (AIR) will coordinate research requirements and plans with the FAA Energy and Environment Office (AEE), Flight Standards Service (AFS), Office of NexGen (ANG) and Office of Airports (ARP), NASA, DOE/ARPA-E, DOD. In this regard, a multi-agency working group is being established under the Hydrogen Interagency Task Force at DOE tasked to respond to the requirements of Sections 1019 and 1109 in the FAA Reauthorization Bill.

During the same period, the FAA will establish collaboration with Foreign CAA's, research Institutions, and Universities to help guide research on implementation of hydrogen-enabling technologies for aviation. Finally, the FAA will create and present Hot Topics/webinars, participate in panels and invited presentations at key aviation conferences and other public information sessions on hydrogen hazards and certification requirements.

7.2 Medium-Term Actions (2028-2032)

The main objectives for medium-term actions are to complete FAA and partner organizations R&D defined during the earlier period (referenced in prior section) and to achieve Normalization certification readiness for Propulsive Fuel Cells, as well as Application readiness for H_2-powered gas turbine aircraft, including electrical hybridization. To this extent, the FAA will review results from previous efforts and update research plans as appropriate. The FAA will publish formal engine and aircraft regulations and related guidance, as well as Policy, Guidance, and Orders/safety procedures addressing differences from petroleum fuel. The FAA will develop and deliver formal FAA and Designee, for example, Designated Engineering Representative (DER) training modules.

8.0 Workforce

Applicants are planning to incorporate hydrogen into aircraft and engines at a rapid pace. FAA requirements, guidance, processes, technical training on hazards associated with hydrogen, and procedures must be put in place timely to ensure the safe certification, operation, and maintenance of these aircraft.

8.1 Collaboration

Ongoing collaboration across the agency is essential for executing an effective and timely path to certification. The FAA is also working with foreign civil aviation authorities to share ideas and experience with a goal of harmonizing.

8.2 Skills Development

AVS should train and assign sufficient personnel to address hydrogen-related safety and certification issues in the short, medium, and long term.

- Collaborate with government agencies, foreign civil aviation authorities (CAA's), industry and academia to understand completed and in progress research on implementation of hydrogen-enabling technologies for aviation.
- Keep the workforce informed, via, for example, Hot Topics/webinars, etc., on hydrogen hazards and certification requirements.
- Develop formal FAA and Designee training modules.

Task	**Description**	**Schedule (CY Start)**
CAA Harmonization	Joint workshops, COB meetings, coordination of research	Ongoing
FAA Webinars	Familiarization with key hydrogen technologies and hazards, regulatory changes and Means of Compliance (MoC)	CY26
Government (NASA) Training	Coordination of research plans, resources (staff, facilities), results sharing	CY27
Industry Training	Certification guidance, consensus standards, Designee training	CY28

9.0 Appendix: Technology Review

9.1 Hydrogen as Aviation Fuel

Aviation currently produces ~2-3% of overall anthropogenic CO_2 emissions (800Mt or 2.17% in 2022[15]), yet its impact on global warming might be significantly higher if considering all other emissions, such as water, NOx, and particulates. Sustained aviation growth may result in an increase in aviation's share of global CO2 emissions and overall global warming impact, especially if other sectors of the economy successfully decarbonize. While introduction of renewable energy sources could result in a significant decrease of CO_2 emissions from other transportation sectors, aviation remains hard to decarbonize primarily because of the high cost and weight/volume of available options. Continued efficiency improvements at the historical ~2% per year rate would still result in a significant (>60%) increase in aviation emissions by 2050 (Figure 2), due to continued traffic growth[16].

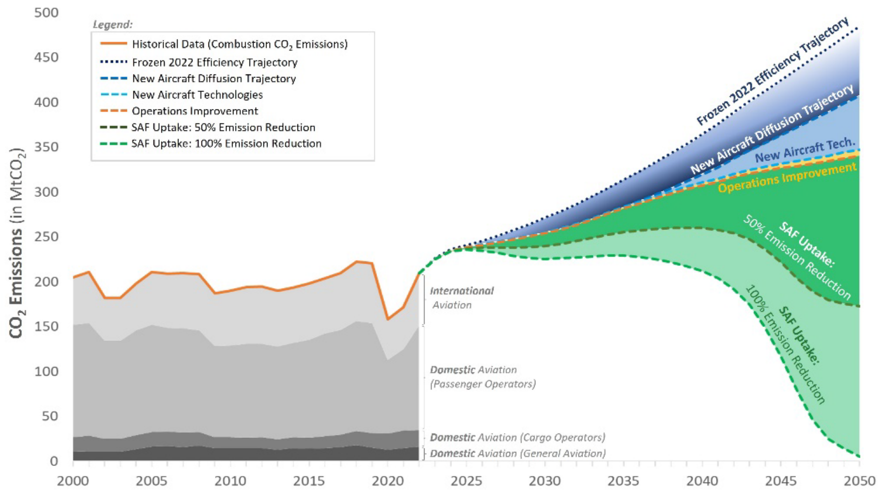


Figure 2 Global CO2 Emissions[1]

There are complementary government investments to achieve net zero emissions by 2050, including development and application of aircraft technologies, operational enhancements, and sustainable aviation fuels. Key to the U.S. strategy is a focus on drop-in Sustainable Aviation Fuels (SAF) made from renewable and waste resources, estimating that SAF production can be scaled up to satisfy 100% demand by 2050[1,17], while the EU and UK see SAF production constrained by availability of feedstocks or cost of green Power-to-Liquids (PtL) process, and therefore invest heavily in other avenues, such as hydrogen and electrified propulsion[18, 19].

Hydrogen may be used for SAF production or as direct fuel for fuel cell/electric propulsion systems and combustion engines (piston and turbine). Such aircraft will need to be certified, which requires understanding, quantification, and mitigation of specific risks, as well as an efficient certification procedure[20] and harmonized rulemaking. To note, the FAA already has TC/STC applicants that plan to use hydrogen fuel cells.

At 120 MJ/kg liquid hydrogen is about three times higher mass-specific energy than Jet A (43.2 MJ/kg), but unfortunately also more than 4 times lower volumetric energy (8.5MJ/L vs. 34.9 MJ/L for Jet A), as can be seen in Figure 3.

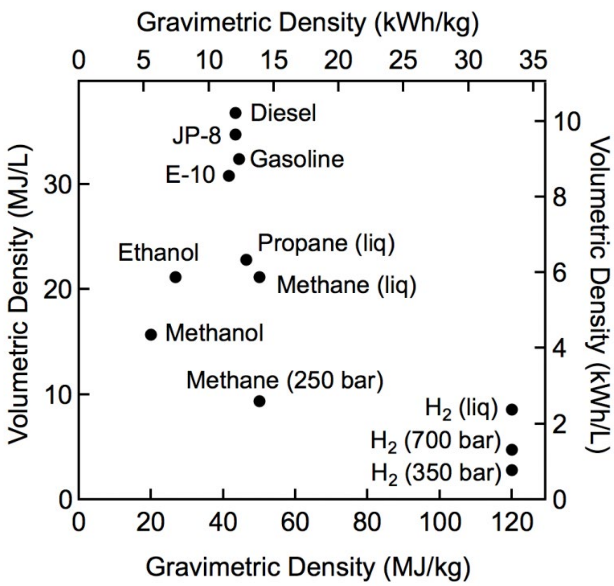


Figure 3 Comparison of specific energies for different fuels[3]

While actual (mass) fuel consumption might be lower with H_2, onboard storage will require a much higher volume than using Jet fuel, with corresponding weight and aerodynamic penalties. Storage in compressed form (350 or 700 bar) will require stronger tanks, which further adds weight. As such, the use of gaseous hydrogen will likely remain limited to applications whose total energy could be feasibly carried in high pressure tanks, such as supplemental (electrical) power and propulsion, from short-haul small to moderate size aircraft.

For large passenger transport, only liquid storage could provide sufficient range[16]. Unfortunately, liquid hydrogen needs to be stored at -423ºF (20K). This, in turn, requires tank shape optimization for minimal heat loss (spherical preferred), insulation (adding weight and volume), and management of boil-off (0.1% of H_2 total weight per hour seems typical). Therefore, hydrogen cannot be stored in a traditional wet wing design. The large hydrogen tanks must be located elsewhere, such as in the fuselage or lobes above the cabin. Long term, aircraft designs may be optimized for hydrogen, for example using conformal (perhaps integral) tanks in Blended Wing Body (BWB) aircraft[21].

Hydrogen is easier to ignite (minimum ignition energy order of magnitude lower than kerosene[6]), burns faster, hotter, and remains flammable in air in a much wider concentration range (in particular, very high Upper Flammability Limit) than hydrocarbons (except, perhaps, acetylene)[22]. Its explosion and ignition behaviors are unique among fuels, displaying non-monotonic change with pressure and temperature (three limit behavior)[23]. Hydrogen flammability characteristics under varying altitudes and temperatures need better characterization[24]. It appears they widen with lower pressures and increased temperatures, albeit not significantly[25]. Hydrogen has a much greater propensity to detonate and can undergo a transition from deflagration to detonation under a wide range of circumstances and fuel/air ratios[4].

Key hazards with hydrogen use are fire and explosion, especially through leaks into confined volumes. Naturally colorless and odorless, hydrogen diffuses order of magnitude faster than other fuels. An uncontrolled leak in the fuel lines or incorrect engine start-up/relight could have catastrophic consequences for the engine, nacelle, or worse, the fuselage. Once initiated, a hydrogen fire may only be safely extinguished by shutting off the fuel supply. Inerting (reducing the O_2 concentration) or ventilation (reducing the H_2 concentration) would require large, sudden discharges of inert gases or air, because required limiting concentrations are so low (either O_2 or H_2 ~4-5% v/v[26]).

Studies conducted in the 1980s[27, 28] examined crash fire hazards associated with LH_2 under scenarios ranging from abnormal landing causing fuel leak to catastrophic crash followed by massive leak and pool fire/explosion. They concluded LH_2 was safer than alternatives (Liquefied Methane - LCH_4 or Jet fuel) because (a) LH_2 tanks will be designed to withstand higher pressures, (b) in the event of a rupture the LH_2 pool would evaporate rapidly, and (c) the resulting pool fire would burn out quickly with much lower (12x) radiative load and shorter safe distances than Jet fuel. Nevertheless, such studies were preliminary and did not address confined/congested leaks (which could lead to rapid detonation); needs for improvement were identified in modeling pool vaporization, cloud dispersion, heavy gas behavior. A large hydrogen leak (or tank venting) can produce a solid flammable mixture by preferentially solidifying the lower boiling point O_2; such mixture could subsequently explode or detonate[29].

9.2 Hydrogen Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of a fuel and oxidant (usually hydrogen and oxygen) directly into electrical energy (Figure 4). When individual fuel cells are placed together, the fuel cells are called a fuel cell stack. A complete fuel cell system will include: a gas management system to provide adequate fuel and oxidizer flow at all conditions, a water management system to condition the stacks, store and/or dispose of the produced water, a power conditioning system, and a thermal management system to ensure stable and efficient operation.

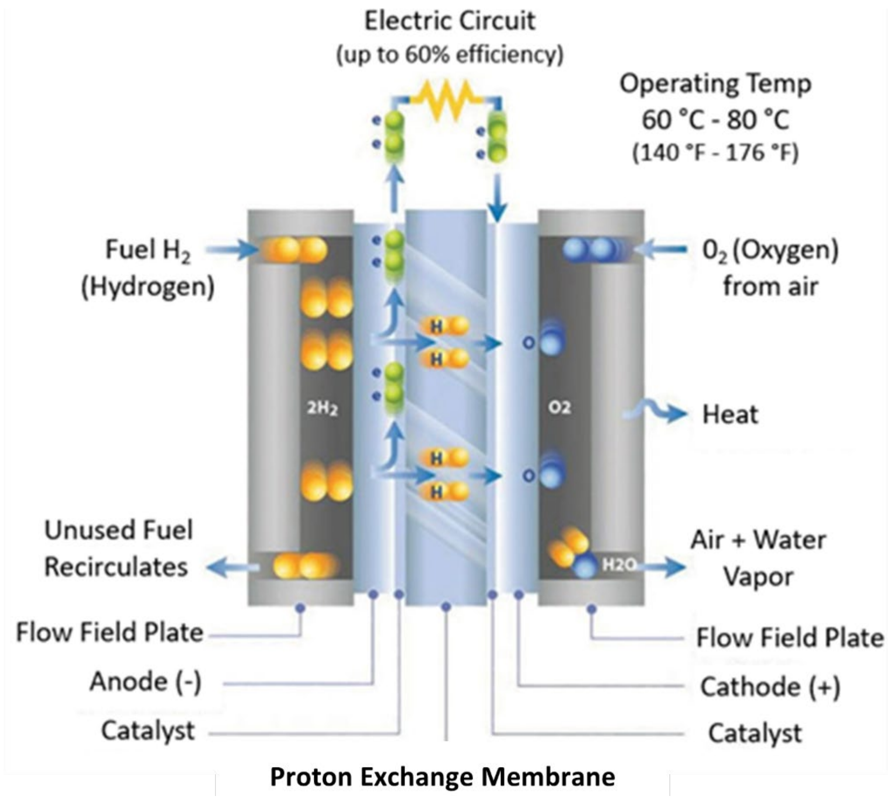


Figure 4 PEM (Individual) Fuel Cell Operation[6]

The most proposed fuel cell designs for aviation are PEM and SOFC. There are two versions of PEMs, based on different cell membrane technology.

Low Temperature (LT) PEMs are typically limited to less than 120°C due to stability of the thin membrane. LTs have been in operation longest, have high specific power and short start-up time even from freeze condition, with good load following. They need relatively pure hydrogen to function, have moderate efficiency (40-50%, 60% in research) and generally use expensive, platinum group metal (PGM) catalysts. Water must be managed to keep the membrane wet for ionic conduction, but not flooded. They are also prone to catalyst contamination, especially with CO that might result from reformed fuels. High Temperature (HT) PEMs may use a phosphoric acid doped polybenzimidazole (PBI) membrane instead of liquid water, therefore no water management is needed; the cells operate at temperatures in the 120-180°C range, even up to 220°C. They are less mature than LT, offer lower power and efficiency, require longer warm-up but have simpler, smaller balance of plant systems. They are also more tolerant to pollutants, hence better suited to use with onboard reforming.

SOFCs are high efficiency, fuel-flexible (can use methane, natural gas, ammonia, etc.), but need high temperatures (500-1000°C), have more complex thermal management systems, longer start times, and susceptibility to corrosion. SOFCs also appear less reliable (fewer allowable shutdowns). One advantage of the SOFCs is that they hold the additional promise of reversibility, producing H_2 and O_2 while consuming electricity.

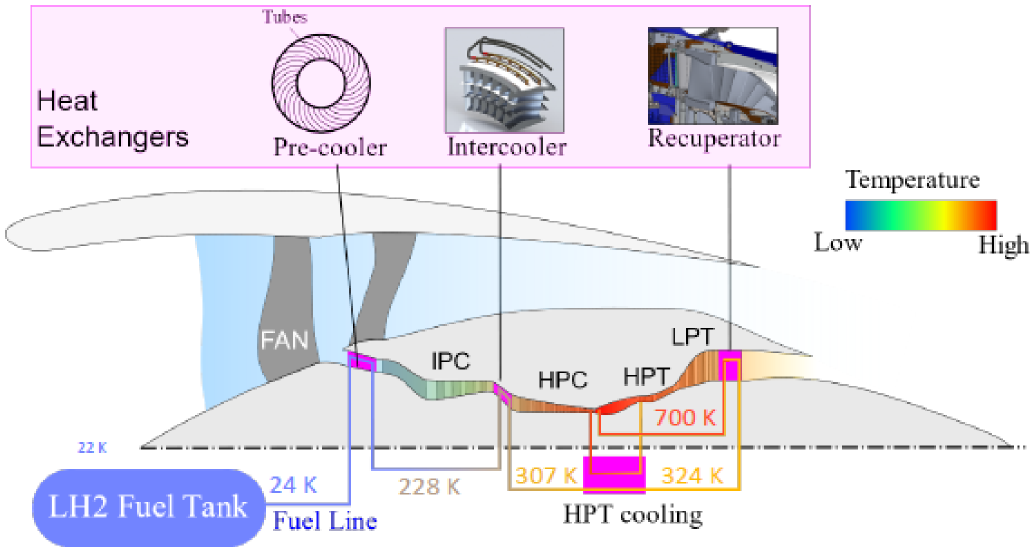
Fuel cell technology has been advancing rapidly over the past decade. Once confined to niche applications such as spacecraft or warehouse forklifts and occasional, short-lived demos on buses or back-up power, fuel cells are increasingly being considered for automotive uses, as well as a variety of electric mobility aircraft, up to regional/medium range transport aircraft. Fuel cell-based systems can provide (much) higher range than battery-based systems at comparable weight[16], have higher efficiency than small engines, and can provide high quality electricity. Unlike batteries, fuel cells consume fuel, which means the aircraft gets lighter during the flight, thus requiring less propulsive power. Fueling tanks typically requires less time than charging/swapping batteries, hence fuel cells can enable faster on-ground turnaround.

Compared to traditional engines, however, fuel cells remain more expensive per unit power, heavier, and their reliability is unproven. Hydrogen tanks and fueling systems require additional development. The power density of fuel cells is at present 0.6-0.75kW/kg (system). Even at projected 3kW/kg by 2035[16] fuel cells may be best suited for aircraft carrying fewer than 75 passengers and short-haul flights. For long range transport, fuel cell systems of hundreds MWh energy would have to be produced (the largest current ones for aircraft are in 250kWh range); this would also require separate development of electronic DC-AC converters and circuit breakers capable of handling several MW, as well as electric motors[16] of tens of MW. It appears likely that near term their main applicability will be smaller aircraft applications.

9.3 Hydrogen Engine Combustion

Hydrogen can be used directly as fuel for combustion with air and burned in a combustion engine. H_2 combustion would be truly zero CO_2 and soot emissions and could conceivably be burned to produce NOx emissions similar or lower than state-of-the art gas turbines. Absence of soot nuclei coupled with (much) higher water content might result in larger ice crystals that fall and do not create contrails. Using hydrogen directly would imply lower energy wasted compared to SAF obtained via Power-to-Liquids (PtL) pathway (since substantial additional energy is required to go from electrolyzed H_2 to liquid fuels). H_2 is widely used in industry already, mainly for fertilizers and refineries, therefore a substantial experience base exists for its safe production, storage, transportation, and distribution. Only a very small fraction (0.1%), however, is currently produced using “green” (renewable energy) methods. To realize environmental benefits at scale will require a massive change in production pathways.

Conventional gas turbine designs could likely be modified to use hydrogen instead of (or even concurrent with) jet fuel or SAF. Areas affected will include materials, operability, combustion, thermal management, and engine controls. More ambitious designs might include water recovery and cryogenic cooling of parts, avionics, and high voltage transmission lines. Hydrogen fueled aircraft have already been demonstrated in the US and the Soviet Union, during the 50s (project Suntan in the US) and 80s (TU-155 in the former USSR), but efforts were halted due to changing priorities (missiles preferred to bombers) and onboard fuel storage challenges.



Modern large turbofan engines (Figure 5) used in a majority of medium and long-range flights operate at overall pressure ratios (OPR) exceeding 40-50. Yet higher OPRs are being proposed for advanced designs, because of resulting increased thermal efficiency. Resulting pressures and temperatures prior to H_2 injection are too high to prevent flashback, flame stabilization in the injector, and autoignition right upon injection. Compared to kerosene, hydrogen has much wider flammability limits, higher adiabatic flame temperature, higher flame speed (laminar and turbulent), lower non-premixed ignition temperatures, and an order of magnitude higher diffusivity in gas phase. The very high content of water in the combustor exhaust (20% vol. or higher with water reinjection vs. <8% with kerosene) might pose significant coatings and base metal issues throughout the hot section[30]. Despite the previously mentioned challenges, combustion of hydrogen has several properties that make it both a promising fuel (lower Green House Gas emissions, better altitude relight, uniform temperature radial distribution, improved combustor liner durability), as well as a non-trivial solution to implement.

9.4 Known Hazards

9.4.1 Hydrogen Fire and Explosion Hazards

The fire and explosion hazards of hydrogen are discussed throughout this roadmap and are generally regarded as the most significant safety issues for which current aviation standards are inadequate. The characteristics (wide flammability range, low ignition energy and propensity to leak) that drive the safety concerns require a full evaluation. Design methods should ensure separation of hydrogen and any oxidizer, prevent the accumulation of flammable mixtures, provide effective leak detection preferably coupled with flame detection, fuel shut-off with sufficient remaining propulsive power. Another significant aircraft safety concern that must be addressed is an uncontrolled hydrogen engine fire or explosion scenario. This will require development and certification of effective and reliable aircraft / engine hydrogen detection and shut-off means, as the means to extinguish a hydrogen engine fire may not be available. More detailed recommendations for these hazards can be found in the ARC report[6].

9.4.2 Materials Hazards

Hydrogen can be absorbed by certain metals, notably steel and titanium, and cause a significant deterioration in the mechanical properties of metals through loss of ductility. This effect is referred to as hydrogen embrittlement.

In addition, hydrogen can penetrate and diffuse through materials and seals more readily that other gases including helium and nitrogen; consequently, the possibility of diffusion because of permeation or material porosity must be evaluated for a hydrogen system.

9.4.3 Mechanical Hazards

The principal concern is with stored gaseous hydrogen where the pressures involved are much higher than other stored gas systems. Therefore, the consequences of a failure are amplified due both to the nature of hydrogen as a flammable gas, and the additional stored energy in the storage vessel due to the higher pressure. Rupture of tanks or other pressurized systems can lead to high energy fragments impacting other systems. Presence of other gases such as air in cryogenic lines can lead to solid deposits which could block flow systems, such as valves, pumps, heat exchangers. Malfunctioning pressure relief devices could lead to catastrophic tank failure.

9.4.4 Crashworthiness

Fuel system (including fuel tanks) crashworthiness is an existing requirement; however, the means of compliance may require significant reassessment with hydrogen. The main differences are the difficulty in evaluating whether the system would allow leakage after a crash, since there are not readily available surrogates for hydrogen itself, and the fact that hydrogen is very easy to ignite should it leak or should air be drawn into the tank. This also could amplify some of the physiological hazards discussed below.

9.4.5 Physiological Hazards

Personnel exposed to hydrogen leaks, fires or explosions can incur several types of injury.

Hydrogen is odorless and colorless, so there is risk of asphyxiation should hydrogen displace the air, diluting the oxygen below 19.5% by volume. Although this is addressed by §25.831 for the crew and passenger compartments, the means of assuring compliance may be more challenging due to the buoyancy of hydrogen and the challenges with dealing with normal leakage.

Burns can result from exposure to a hydrogen fire or contact with a surface heated by such. Frostbite can result from contact with a cold fluid or surface. Blast (overpressure) can result from a detonation, deflagration, or unconfined rapid expansion of a compressed gas. Fragments can be created when a hydrogen explosion acts on a container or other items in proximity. Noxious gases can be generated in case of combustion or degassing of materials exposed to a hydrogen fire.

9.4.6 Cryogenic Hydrogen Hazards

An essential safety concern of liquid hydrogen's low temperature is that, except for helium, all gases exposed to such cryogenic temperatures will change their state to liquid form or even to solid form depending on the individual physical properties of the gas. Since the liquid hydrogen will have to be converted to gaseous hydrogen to be usable, whether in a fuel cell or for combustion, and likely warmed in the process to above cryogenic temperatures, system architecture will have to allow for both deliberate and inadvertent contact with cryogenic hydrogen. Heating of cryogenic tanks can cause over pressurization while intense sloshing could result in ullage condensation followed by pressure collapse and possible structural damage or ingestion of oxygen into the tank.

9.4.7 Electrical Hazards

Due to the low ignition energy of hydrogen, protection from lightning and electrical faults is especially important, particularly considering the potential for hydrogen leakage and the location of fuel tanks. The degree to which protection will need to exceed what is done currently is not known.

9.4.8 Airplane/Engine Interface Hazards

A significant hazard resulting from the need to transfer hydrogen from its storage vessel to the engine is leakage. Hydrogen leakage is virtually unavoidable when there are fittings, couplings, joints etc. As noted above, the characteristics of hydrogen regarding its flammability and potential for physiological injury make leakage a significant safety concern.

9.4.9 Hazards Outside the Scope of the Aircraft and its Operation

The fire and explosion hazards, as well as hazards to personnel will also be present for the production, distribution and fueling process. Different models for fueling are being considered, including having fuel tanks filled remotely and installed on the airplane before flight, traditional fueling with a hydrogen fuel farm and a combination of on-airport, but remote fueling under controlled conditions. The approach taken will influence aircraft design and consequently some of the safety features required.

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