



# AEROSPACE INFORMATION REPORT

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## Considerations for Hydrogen Fuel Cells in Airborne Applications

### RATIONALE

Hydrogen is the most abundant chemical element. One of the most valuable uses of hydrogen is in the hydrogen fuel cell. A fuel cell is used to combine hydrogen and oxygen to produce electricity and water. This use of hydrogen is becoming increasingly important, given the imperative to store and use energy without producing any greenhouse gasses.

Fuel cells are being used in every sector of mobility (trains, cars, buses, ships, submarines, forklifts, even bicycles, etc.) except in civil aviation. Yet, fuel cells can be used to replace secondary power systems such as auxiliary power units and main engine-driven generators. Successful demonstrations of operating fuel cells in commercial airplanes and general aviation have already been performed.

The hydrogen fuel cell is a key technology for reaching the goals for climate change prevention and for energy security in several commercial sectors, including transport, industry, and power generation/distribution. In addition, connecting different hydrogen-using sectors with transmission and distribution networks will increase the operational flexibility of the future low carbon energy economy.

This SAE Aerospace Information Report will provide the needed comprehensive reference, background information, and potential benefits, aiming to promote the use of hydrogen-powered fuel cell systems in airborne applications.

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## 1. SCOPE

The scope of this joint EUROCAE/SAE report is to compile the considerations relating to airborne application of hydrogen fuel cells. This document provides a comprehensive analysis of the use of hydrogen as a fuel by describing its existing applications and the experience gained by exploiting fuel cells in sectors other than aviation. The use of hydrogen fuel cells in aircraft can help in meeting aviation environmental targets (including noise pollution) and can be vital to achieving efficient electrically propelled air vehicles. The experience gained with mature fuel cells in terrestrial applications and the handling of other gases in aviation, as presented herein, will help in alleviating safety concerns and in demystifying the usage of hydrogen in aviation.

## 2. REFERENCES

### 2.1 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

#### 2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel:877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), [www.sae.org](http://www.sae.org).

AIR6464 EUROCAE/SAE WG80/AE-7AFC Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines

AS6858 Installation of Fuel Cell Systems in Large Civil Aircraft

### 2.2 Acronyms and Symbols

|                |                                                                                  |
|----------------|----------------------------------------------------------------------------------|
| ARC            | Aviation Rulemaking Committee                                                    |
| C3H8           | Propane                                                                          |
| CGH2           | Compressed Gas of Hydrogen Molecules                                             |
| CH4            | Methane Gas                                                                      |
| CHP            | Combined Heat and Power                                                          |
| CNG            | Compressed Natural Gas                                                           |
| CO             | Carbon Monoxide                                                                  |
| CO2            | Carbon Dioxide                                                                   |
| DOE            | USA Department of Energy                                                         |
| FAA            | Federal Aviation Administration                                                  |
| FCEB           | Fuel Cell Electric Bus                                                           |
| FCEV           | Fuel Cell Electric Vehicle                                                       |
| H              | Hydrogen Atom                                                                    |
| H <sub>2</sub> | Hydrogen Molecule                                                                |
| H2FUTURE       | European project that analyze the use of H <sub>2</sub> to produce cleaner steel |
| HSP            | Hydrogen Safety Panel                                                            |
| KPMG           | International Consultant of the Global Business Community                        |
| LH2            | Liquid Hydrogen                                                                  |
| LOC            | Limiting Oxygen Concentration                                                    |
| MEA            | More Electric Aircraft                                                           |
| NASA           | National Aeronautics and Space Administration                                    |
| NEA            | Nitrogen-Enriched Air                                                            |
| OBIGGS         | On-Board Inert Gas Generation System                                             |
| ODA            | Oxygen-Depleted Air                                                              |
| OEM            | Original Equipment Manufacturer                                                  |
| PEM            | Proton Exchange Membrane                                                         |
| RAT            | Ram-Air Turbine                                                                  |
| SMR            | Steam Methane Reforming                                                          |
| SOFC           | Solid Oxide Fuel Cell                                                            |
| UAV            | Unmanned Aerial Vehicle                                                          |

### 3. INTRODUCTION TO HYDROGEN

#### 3.1 General

In many aircraft applications, hydrogen is becoming a relevant alternative to hydrocarbons as a high-quality energy carrier because hydrogen is abundant, non-polluting, renewable, and can be utilized efficiently. Hydrogen exists in a range of molecules which are readily available, including water and hydrocarbons, and the methods of isolating it from these molecules are well established.

#### 3.2 Properties

Hydrogen (H) is non-toxic, non-polluting, colorless, odorless, and is not radioactive. Hydrogen is the simplest and smallest atom – two of which make the gas molecule ( $H_2$ ). Because of this, it has the lowest density of any gas (and of any fuel, as shown in Figure 1). For example, at sea level, 1 m<sup>3</sup> of air weights 1.3 kg, whereas 1 m<sup>3</sup> of hydrogen weighs 14 times less at 0.09 kg. This means that hydrogen rises and dissipates naturally - so it diffuses faster than any other gas should leakage occur. The risk of leaks into confined spaces can be mitigated in a number of ways, and these are discussed in Section 5. A table comparing the characteristics of hydrogen to those of other gaseous fuels is presented in Table A1 in Appendix A.

Hydrogen can release energy via oxidation, i.e., when combined with oxygen either through combustion (as in an internal-combustion engine) or through a controlled electro-chemical reaction (as in a fuel cell). The product of the hydrogen combustion is heat and water, while in a fuel cell, electrical energy is also produced together with heat and water.

Although hydrogen has the lowest density of any fuel, it has the highest energy content by mass. However, the volume required to store gaseous hydrogen is greater than for other liquid fuels. For example, it can be seen in Figure 1 that hydrogen has three times the energy content of jet fuel (kerosene) by mass but requires considerably more volume (both gaseous and liquid).

Hydrogen does not readily self-ignite because of its high auto-ignition temperature of 585 °C. Though hydrogen has a low ignition energy under ideal stoichiometric conditions, at low concentrations in air, it has similar ignition energy to other fuels. The flammability range of hydrogen is wide (from 4 to 75% by volume in air) though the opportunity for a fire to occur can be managed, as it is with any fuel. For instance, hydrogen is stored as a pure substance in its container – unlike jet fuel (kerosene), which is necessarily mixed with air. This eliminates the risk of combustion in the container itself. Safe and proper handling of hydrogen is described in detail in Section 5.

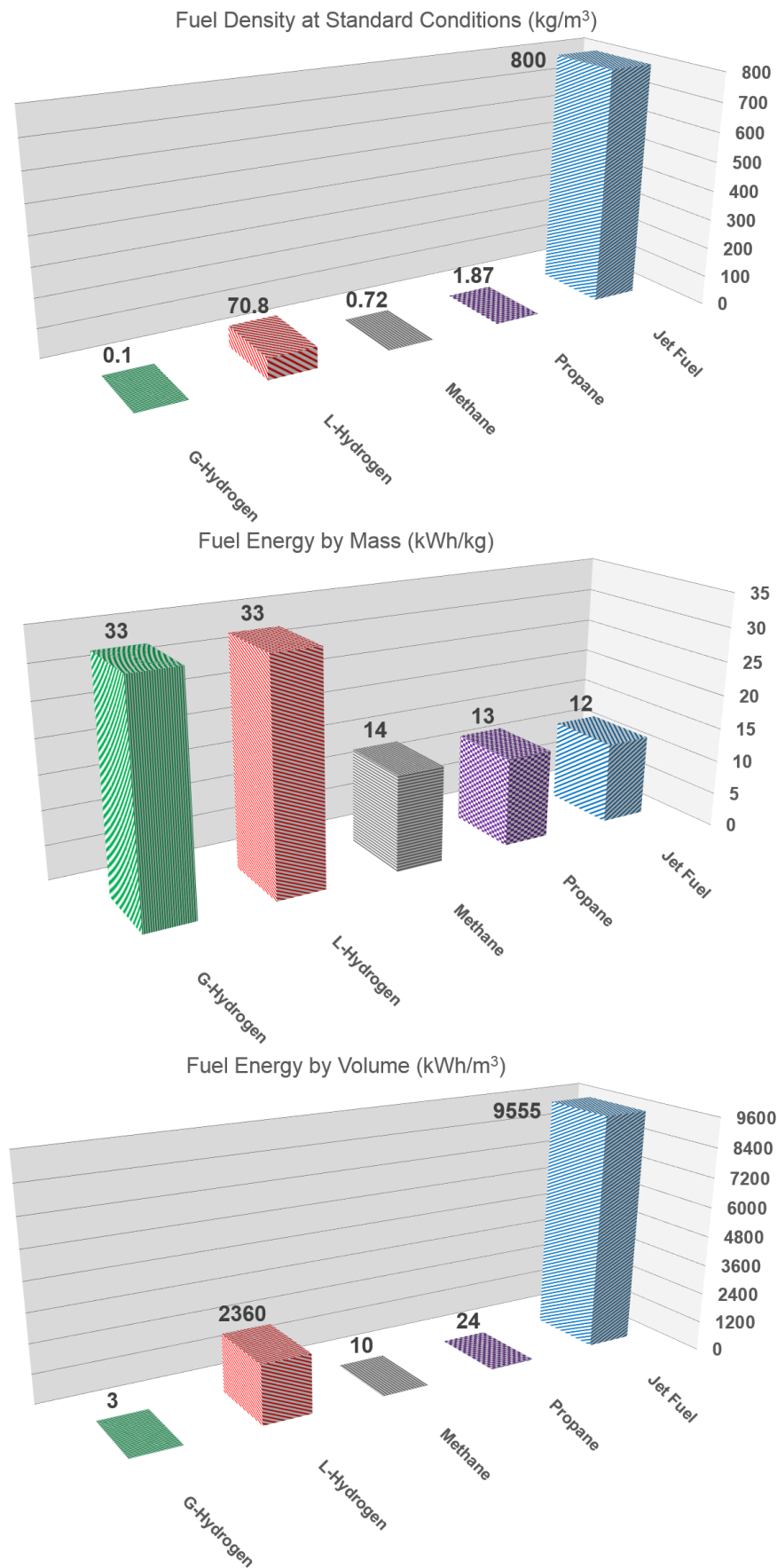


Figure 1 - Comparison of hydrogen properties to other fuels



### 3.3 From Hydrogen Production to Fuel Cell Energy

#### 3.3.1 Production

Currently, most hydrogen is generated by hydrocarbon reforming – mainly steam methane reforming (SMR). Hydrogen may also be produced through electrolysis of water, which may be accomplished using clean electricity sources such as wind, solar, and hydro. Hydrogen production by electrolysis is likely to rise as more surplus clean electricity becomes available globally. Biological hydrogen production is an emerging technology that will further increase availability of the gas.

#### 3.3.2 Conditioning

Hydrogen produced through electrolysis of water does not require any purification for use in fuel cells, whereas hydrogen produced by other methods often requires removal of sulphur and carbon monoxide for proper use in fuel cells.

#### 3.3.3 Transportation and Storage

When not produced locally at the point of use, hydrogen is readily transported by pipeline or by surface modes, such as truck, rail, and ship. Depending on the application, a combination of several transportation modes can be utilized.

Hydrogen is transported via surface modes either as a compressed gas (CGH<sub>2</sub>) at up to 500 bar or in the low pressure liquid state (LH<sub>2</sub>). Tube trailers regularly transport up to 500 kg of compressed hydrogen while insulated trailers can transport up to 3000 kg of liquid hydrogen. Figure 2 shows both tanker models.

Pipelines also transport gaseous hydrogen at up to 100 bar. Pipelines require higher initial investment but are generally preferred for transportation of large amounts of hydrogen. More than 4500 km of hydrogen pipelines already exist worldwide<sup>1</sup>, mainly to serve industrial requirements.



**Figure 2 - Hydrogen road transport: left, gaseous high pressure tube tanker; right, insulated tanker for low pressure liquid**

<sup>1</sup> [h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines](https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines)

### 3.3.4 Distribution for Use in Fuel Cells

Hydrogen is used in many different industries, and hydrogen systems are being implemented increasingly in mobile applications, especially cars. More countries are planning to develop a hydrogen refueling infrastructure following the initiatives of Japan, California, and Germany. The aviation industry can benefit from hydrogen's current and growing availability around the world.

### 3.4 Cost

As of 2018, the cost of hydrogen to the owner of a hydrogen-fuel-cell-powered car, for a given range, is the same as for gasoline<sup>2</sup>, while hydrogen remains un-taxed. When new taxes come into place, it is expected that the cost will remain competitive as the efficiency of the fuel cells increase and the price of the hydrogen drops as the quantity and efficiency of production increase.

### 3.5 Public Perception and How It is Changing

Gases are sometimes perceived as being more dangerous than solid materials since they cannot be seen or touched. The Hindenburg airship, which used hydrogen as a lifting gas, and the hydrogen bomb have also obscured hydrogen's valuable use as an energy carrier. However, the risks associated with hydrogen use can be well controlled. In fact, hydrogen is already widely used as an energy carrier in stationary fuel cells, fuel cell cars, submarines, and even spacecraft. Unlike petroleum products, hydrogen does not require exploration or mining, and it can be generated from numerous resources.

Fuel cell systems using hydrogen may not yet be fully recognized by the public as eco-friendly while purely battery powered systems, such as electric cars, are. However, when considering the complete energy balance including production and recycling, hydrogen fed fuel cells exhibit many ecological benefits when all life cycle elements are considered<sup>3</sup> (no harmful emission at the point of use is an example).

Moreover, because hydrogen is a clean, flexible and versatile energy vector, it is being established in Europe as an essential lever to achieve the decarbonized energy system required to combat climate change. Hydrogen provides a way to decarbonize segments in power, transport, buildings and industry, which would otherwise be difficult to decarbonize, by integrating and balancing the renewable energies.

Therefore, it is essential to have factual information on hydrogen, its benefits, and its related risks in order to properly evaluate the use of hydrogen-fed fuel cells on-board aircraft:

- Hydrogen has been safely used for decades as energy carrier (residential use under various environmental conditions and in back-up power supplies)
- Eco-friendly production and reaction products
- Can be safely:
  - Generated (water electrolysis from solar or hydro-power electricity)
  - Transported (e.g., by pipelines and trucks)
  - Stored (gas and liquid)
  - Distributed (by fueling station)
  - Consumed (in a vehicle)

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<sup>2</sup> [cafc.org/content/cost-refill](https://cafc.org/content/cost-refill)  
<sup>3</sup> <https://blog.ballard.com/benefits-of-fuel-cells>  
<https://waste-management-world.com/a/1-the-lithium-battery-recycling-challenge>

Although some public perception of hydrogen may be affected by historical events, the use of hydrogen based fuel cell technology is increasing significantly through industrial uses, domestic uses (such as hydrogen portable power devices<sup>4</sup> to recharge batteries or emergency power or home heating), and mobile uses (such as trucks, trains, buses, and cars), which are accessible to the general public. It is this ongoing, increasing, and safe use of hydrogen and fuel cells that will change public perception most effectively since it is through their personal experience.

#### 4. HYDROGEN USAGE

##### 4.1 History of Hydrogen Use

##### 4.1.1 Buoyancy

The element hydrogen was discovered in the late 18th century, and its varied use began shortly thereafter. Initially, hydrogen was used for its buoyancy in the development of balloons as an alternative to hot air. The first hydrogen balloons were developed in 1783 and progressed to the point that by the early 1900s there were flight contests and regularly scheduled flights with hydrogen-filled airships.

Just like any aircraft, airships have had accidents<sup>5</sup>, and regardless of how they were inflated, with either hydrogen or helium (USS Akron, which used helium, was the deadliest ever), it was hydrogen's reputation that suffered the most, mainly due to the Hindenburg accident<sup>6</sup>.

With the rise of more capable "heavier-than-air" aircraft, airships as a whole became restricted to specific uses where the ability to hover for extended periods are more important than speed and maneuverability such as for advertising, tourism and camera platforms.



**Figure 3 - First hydrogen balloon in 1783; "number 5" circles eiffel tower in 1901; first hydrogen blimp over the english channel in 1910**

<sup>4</sup> <http://www.fccea.org/portable>

<sup>5</sup> [en.wikipedia.org/wiki/Airship](http://en.wikipedia.org/wiki/Airship)

<sup>6</sup> International Journal of Hydrogen Energy, Vol.24, No.5, 399-403, 1999 - The Hindenburg tragedy revisited: the fatal flaw found - Bain A, Van Vorst WD

#### 4.1.2 Energy Content

There were other nascent uses of hydrogen. For example, in cities such as Paris and London, hydrogen was utilized for public lighting and domestic heating from the 1830s until the 1960s when its use was supplanted by readily available natural gas.



**Figure 4 - Town gas (hydrogen) lamp in 1833 and stove in 1868**

The ability to use hydrogen for electrical generation was discovered as early as 1838 with the initial development of the fuel cell. Development continued over the years and by the 1950s a number of experimental applications highlighting the utility of hydrogen fuel cells in mobile applications were implemented: a farm tractor in 1959, on cars since 1966, NASA's Gemini and Apollo space programs since 1962, and submarines since the 1980s.



**Figure 5 - First ever hydrogen fuel cell vehicle in 1959; NASA's gemini spacecraft fuel cell in 1962**

In the 1990s, advances in PEM (proton exchange membrane) technology allowed this innovation to be more broadly applied to cars and has become the preferred technology for fuel cells. Continued innovation and other concerns such as emissions has seen the increasing use of stationary fuel cell systems in co-generation power plants for hospitals, universities, and large office buildings.