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Federal Aviation Administration
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Energy Supply Device Aviation Rulemaking Committee

April 2019

Final Report

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U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Energy Supply Device Aviation Rulemaking Committee

Final Report to:

Federal Aviation Administration

Executive Director, Aircraft Certification Service
and
Executive Director, Office of Rulemaking

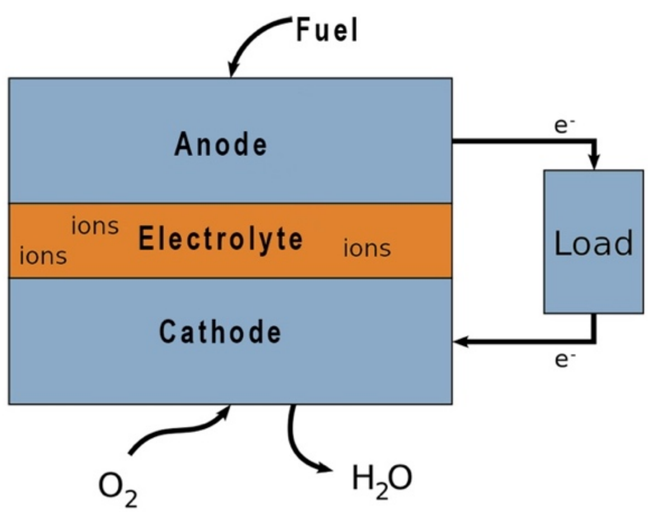
December 8, 2017

Executive Summary

This report contains the findings and recommendations of the Energy Supply Device Aviation Rulemaking Committee (ESD ARC). The ESD ARC (the Committee) was charted by the Federal Aviation Administration (FAA) on April 15, 2015 to provide recommendations that may be used to develop appropriate airworthiness standards and guidance material for energy supply device installations on transport airplanes and other types of aircraft, with a focus on hydrogen fuel cells.

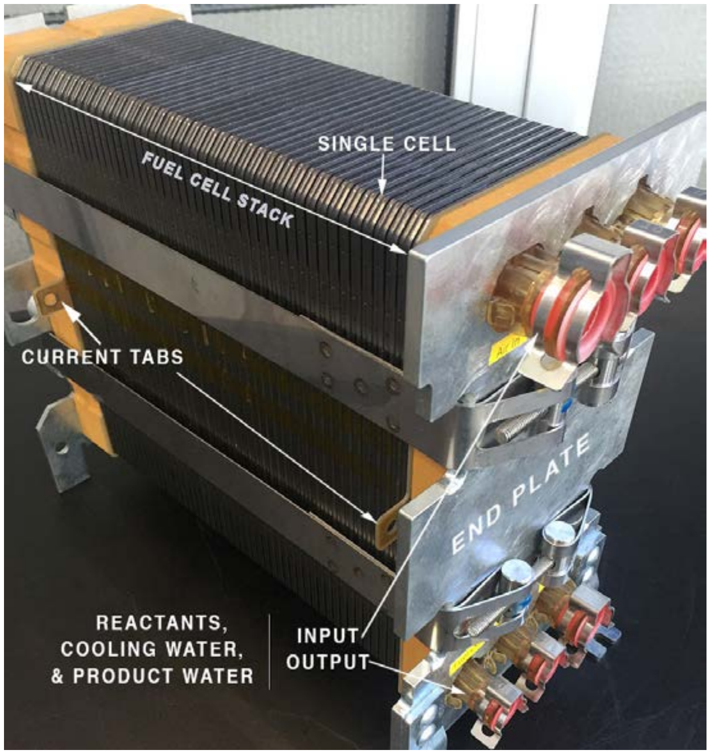
Hydrogen fuel cells[1] are electrochemical devices that convert chemical energy of a fuel (typically hydrogen) and an oxidant (oxygen) directly into electrical energy. This electrical energy can then be conditioned and used for multiple purposes. Below is a typical simplified fuel cell (FC) diagram. Each fuel cell produces approximately 0.6 volts of direct current. Placing each individual fuel cell with other individual fuel cells makes a fuel cell stack and this increases the amount of voltage produced. The more fuel cells in a stack, the higher the voltage output. The surface area of each individual cell controls the amount of current (i.e., amperage) available. Larger surface area equal higher current levels. A mock-up of a 46-cell fuel cell stack is shown in Figure 2. The reactants, product water and cooling water are fed though the manifold fittings on the end. Current is tapped off the two tabs just under the end plates.

Figure 1. Simplified Fuel Cell Diagram (Typical)



[1] "Hydrogen fuel cells" in this report are herein afterwards referred to as "fuel cells."

Figure 2. Mock-Up of a Fuel Cell Stack Composed of 46 Individual Fuel Cells



Fuel cells have become increasingly important as alternative sources of power, offering the potential for a reduction in emissions in particulate matter, nitrogen oxides, and carbon dioxide. In addition, they offer quieter operation than a combustion engine, more efficient use of the fuel energy compared to combustion engines, and offer more flexible energy storage density compared to batteries. Apart from emissions reduction and thermal efficiency, fuel cell technology can constitute distributed power systems; enabling locating the power near the point of use and also reducing the power draw from the engines. The main by-products of a fuel cell are water and heat. Both of these by-products can be discarded; however, they also have the potential to provide potable water and heat for use by other airplane systems. Another by-product is oxygen depleted air that could be used for fuel tank inerting. Thus, potentially negating the need for a nitrogen inerting system.

The main body of the report summarizes the findings and recommendations of the committee. Details of those findings and recommendations are contained in the report's appendices. The appendices are presented in a logical order that begins with a comparison of fuel cells with other energy supply devices technologies. It discusses fuel cell benefits and compares FCs to batteries and combustion systems. The appendices then progress by presenting various FC technology options (i.e., different types of FCs), and then focuses on the technology options that are best suited for use in an aviation environment. Next is a discussion about all of the components that are required to enable the FC to produce electricity, deliver it to a load (e.g., galley power), and dispose of the by-products. The FC itself, along with these components, comprise a fuel cell system (FCS). A detailed discussion of the FCS is presented, as is a discussion of various sources and storage options for hydrogen and oxygen. For example, pure hydrogen can be stored in various forms, including a pressurized gaseous state. However, it can also be derived from jet fuel through a process known as reforming. Various reforming methods are discussed as well.

Then airborne applications for fuel cells are discussed. Applications discussed are galley power, stand-alone power, medivac system power, auxiliary power, emergency power systems, and unmanned aerial system propulsion. These applications are the ones most likely to take advantage of the benefits that a fuel cell can offer using today's fuel cell technology. The installation and use of a FCS for one of these applications requires some level of integration with other airplane systems. While some FC applications will require minimal modifications to install (e.g., self-contained medevac), others will require extensive modifications (e.g., emergency power system, auxiliary power). A discussion of fuel cell integration with aircraft systems is therefore provided in the application appendix as well.

Following the applications discussion, fuel cell systems hazards are discussed. Fuel cell use as a source of power is becoming more common for ground based solutions. As examples; fuel cell powered forklifts are used in warehouses, fuel cell powered city busses are in use many countries, and Toyota sells a fuel cell powered passenger sedan. However, fuel cell use in airborne applications is in its infancy (the exception is the use of fuel cells in NASA's Gemini and Space Shuttle programs). While hazards associated with hydrogen, whether used in ground based or in airborne applications, might not be new in themselves, they are not currently well addressed in the airworthiness requirements. Use in an airborne environment demands that potential hazards associated with fuel cell systems be fully understood. Therefore, the hazards appendix discusses a multitude of potential hazards and their mitigation means. This includes hydrogen fire and explosion hazards, mechanical and material hazards, physiological hazards, cryogenic hazards, non-hydrogen fuel and oxygen hazards, and electrical hazards.

Following the discussion on hazards, the next appendix presents recommendations for regulatory standards and advisory material. After developing the information on various types of fuel cell technologies, their possible aircraft applications, their potential hazards, and the review of existing part 25 and operational regulatory requirements, it was decided to: 1) recommend the development of one new part 25 regulation, known as the fuel cell system safety baseline regulation; 2) recommend revisions to existing part 25 regulatory standards to accommodate fuel cell systems; 3) identify existing part 25 regulations that are applicable to fuel cell systems, but do not require any revision; and 4) identify operational regulations in parts 43, 91, 121, 125, and 129 that are applicable to fuel cell systems. With the exception of the operational requirements, the recommendations apply to both 14 CFR part 25 and EASA's CS 25. Any differences between the two sets of standards is noted in the recommendation's appendix.

Although the committee does not provide recommendations for regulatory requirements for CFR / CS parts 23, 27, and 29 airworthiness standards, the same concerns would apply with the typical differences between the different product types. The committee therefore recommends when a rulemaking group is created, this group will amend the different airworthiness standards based on the conclusions presented in this report.

Also included in the recommendation's appendix is a recommendation for more general regulation that would be applicable to most any type of energy storage device, independent of technology. The regulation would replace the existing 14 CFR § 25.1353(b) / EASA CS 25.1353(c). This regulation currently contains requirements for storage batteries, but does not contain adequate requirements for lithium based batteries or other types of ESDs, such as fuel cells or supercapacitors. Therefore, in the case of lithium batteries, the FAA, EASA, and other authorities must issue special conditions that are in lieu of the requirements contained in § 25.1353(b) / 25.1353(c). The recommended regulation is more performance based with the aim of avoiding the need to issue special conditions or change it every time new ESD technologies are introduced in the aircraft.

Although the Committee did not develop advisory material in the form of an advisory circular. The committee recommends that the data contained in Appendices A through G be used as the basis for advisory circular should the FAA/EASA adopt the recommendations to develop a part 25 fuel cell system safety baseline regulation. It should also use this report's data to update advisory circulars and policy associated with the existing regulations that have been identified as needing revisions to accommodate fuel cell systems.

In summary, the Committee is recommending the development of new and revised 14 CFR part 25 and EASA CS 25 airworthiness standards:

- One new regulation dedicated to fuel cell system safety is proposed.
    - 1 new regulation proposed: § 25.XXXX Fuel Cell System Safety
- One performance based regulation is proposed to help cover ESDs, known and new-to-come unknown ones.
    - Complete overhaul of the existing 14 CFR § 25.1353(b) / EASA CS 25.1353(c)
- 20 proposed changes to existing Part 25 / CS 25 regulations to address fuel cell systems
- 67 identified Part 25 / CS 25 regulations to be applicable to FCSs in their current wording
- 71 identified Parts 43, 91, 121, 125, and 129 regulations applicable to FCSs in their current wording

Energy Supply Device Aviation Rulemaking Committee Membership*

Co-Chairpersons

Joe	Breit	Boeing Commercial Airplanes
Stephen	Slotte	Federal Aviation Administration (FAA)

Industry Members

Emmanuel	Bensadoun	Air Liquide
Patricia	Chong	Ballard Power Systems
Wolfgang	Engel	Airbus Operations GmbH
Pedro	Figueiredo	Embraer
Charles	Foncin	Zodiac Aerospace
Colin	Halsey	GE Aviation
Andreas	Lauer	Airbus
Franck	Masset	Zodiac Aerospace
Charles	Lo	Honeywell Aerospace
Marianne	Mata	Boeing Defense, Space and Security
Olivier	Savin	Dassault-Aviation
Robert	Sievers	Teledyne Energy System
William	Smith	Infinity Fuel Cell
Claude	Vallee	SAFRAN Group

Government Members

Koorosh	Araghi	NASA Johnson Space Center
Linda	Brussaard	European Aviation Safety Agency (EASA)
John	Flores	FAA - Seattle Aircraft Evaluation Group
Tim	Hayward	FAA - Seattle Aircraft Evaluation Group
Mark	Hesselton	FAA - Aircraft Maintenance Division
Adalton	Martuscelli	Brazilian Agência Nacional de Aviação Civil (ANAC)
Kamwana	Mwara	NASA Johnson Space Center
Michael	Rottmayer	United States Air Force
Steve	Summer	FAA - William J. Hughes Technical Center
Mike	Walz	FAA - William J. Hughes Technical Center

* All members of the ESD ARC concur with the contents of this report with three exceptions.

1) Adalton Martuscelli, (ANAC), abstained from voting.
2) Franck Masset, (Zodiac Aerospace), was a contributing member of the ARC in its early stage. However, he changed positions within Zodiac Aerospace and was unable to continue his participation in the ARC. Therefore, he did not review and comment on the final report.
3) Michael Rottmayer, (United State Air Force), was a contributing member of the ARC in its early stage. Mr. Rottmayer also contributed content to the final report, however he did not review the completed report.

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1 OVERVIEW

Hydrogen fuel cells[2] are a maturing technology that may have valuable application to transport and other type of aircraft. Fuel cells (FCs) may provide benefits and savings as compared to traditional battery and combustion energy systems as it relates to weight, safety, maintenance, cost, reliability, volume, noise signature, thermal signature, efficiency, CO_2 reduction, air pollution, and others. However, any one or combination of these benefits must be evaluated with respect to a specific application or combinations of applications to realize their potential in a safe, reliable, and cost-effective manner. Appendix A of this report presents a comparison of FCs with other technologies such as batteries, capacitors, and combustion engines.

This report is about the technology and safety issues of various types of FCs. It is also about the identification of the need to develop new and revised regulatory standards to ensure their safe design, installation, and operation. The report also identifies existing regulatory standards that are applicable to FCs without the need for revision.

Six different FC types are discussed, and their characteristics, such as typical power capacity, electric efficiency, potential application use, and the advantages and challenges are compared. This discussion is located in in Appendix B. The six types of FCs discussed in appendix B are:

- Direct-Methanol Fuel Cell (DMFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

Two of these types have the most potential for use in modern transport airplanes and other types of aircraft. These two types; proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), are examined in detail in Appendix C. Therefore, the recommendations for regulatory standards are based on these two types. Although the standards could easily be adopted to address the other fuel cell technologies discussed in Appendix B.

Fuel cells need a source of hydrogen (H_2) in order to function. The source of H_2 is, to a large extent, application dependent. Sources of H_2 can include H_2 stored as a liquid, as a gas, or in a solid. Other sources of H_2 include light hydrocarbons, solid fuels, fuel reforming, and electrolysis. Appendix D provides a detailed narrative about sources and storage of H_2. Appendix D also discusses sources of oxygen (O_2) that is used by the FC as an oxidant. An

[2] "Hydrogen fuel cells" in this report are herein afterwards referred to as "fuel cells."

oxidant is necessary to recombine with the negative and positive H_2 ions to form one of the by-products of a FC: water. Together, H2 and O_2 are known as reactants.

Fuel cells have the potential to be used in multiple airborne applications. These applications can range from a source of emergency electrical energy that replaces the traditional ram air turbine (RAT), providing galley power, and act as a replacement for today's auxiliary power unit (APU). Several applications for using FCs on transport airplanes and unmanned aircraft systems (UAS) are discussed in detailed in Appendix E.

Fuel cells have the potential to introduce multiple hazards once installed aboard an aircraft. Some of these are the same as other systems already in use today, and some are unique due to the technology behind FCs. These hazards are summarized in Section 4 and are discussed in detail in Appendix F.

Recommendations for new and revised 14 CFR part 25 regulatory standards that can be applied to the design and installation of fuel cell systems are presented in Appendix G. The report also identifies existing part 25 regulatory standards that can be applied to fuel cell system certification without needing revision. Material that may be used to develop advisory material is also presented. Section 5 contains a summary of these recommendations, and they are discussed in detail in Appendix G. The Energy Supply Device Aviation Rulemaking Committee's (ESD ARC) charter, (Appendix J), specifies that: "FAA airworthiness standards should be written to be performance-based and should address all foreseeable energy supply device types to the greatest extent possible." Therefore, the development of a performance based regulation that is applicable to all ESDs is recommended to replace the current 14 CFR § 25.1353(b) or EASA CS 25.1353(c). This is in addition to fuel cell system specific regulatory recommendations given in this report.

2 WHAT IS A FUEL CELL?

Fuel cells are electrochemical devices that convert chemical energy of a fuel and oxidant (usually hydrogen and oxygen) directly into electrical energy. This electrical energy can then be conditioned and used for multiple purposes. A simplified diagram of a single cell in a fuel cell stack is shown in Figure 3.

Figure 3. Simplified Fuel Cell Diagram (Typical)

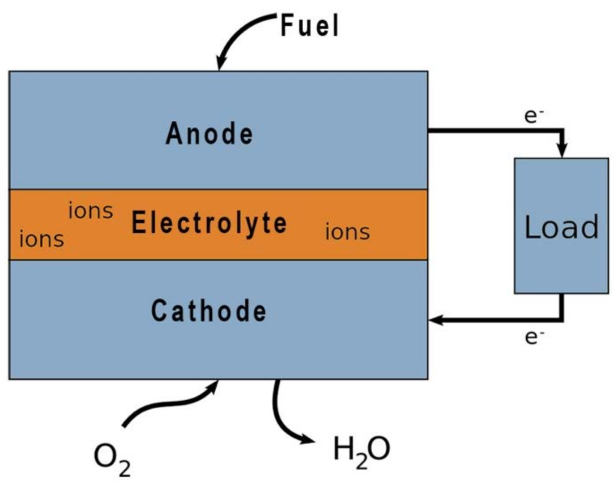
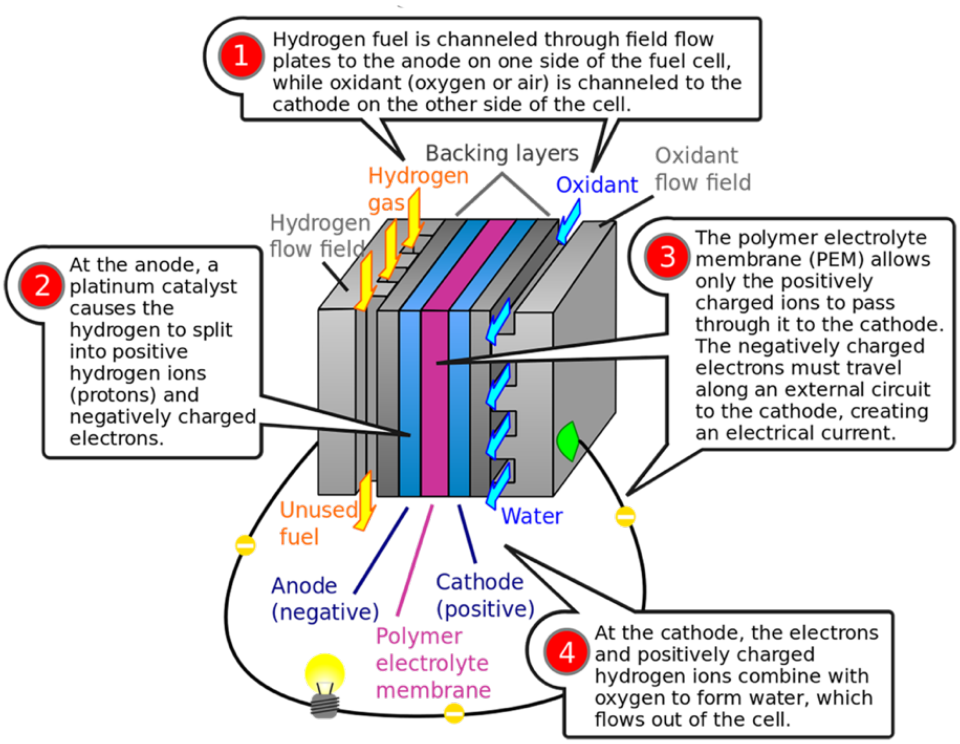


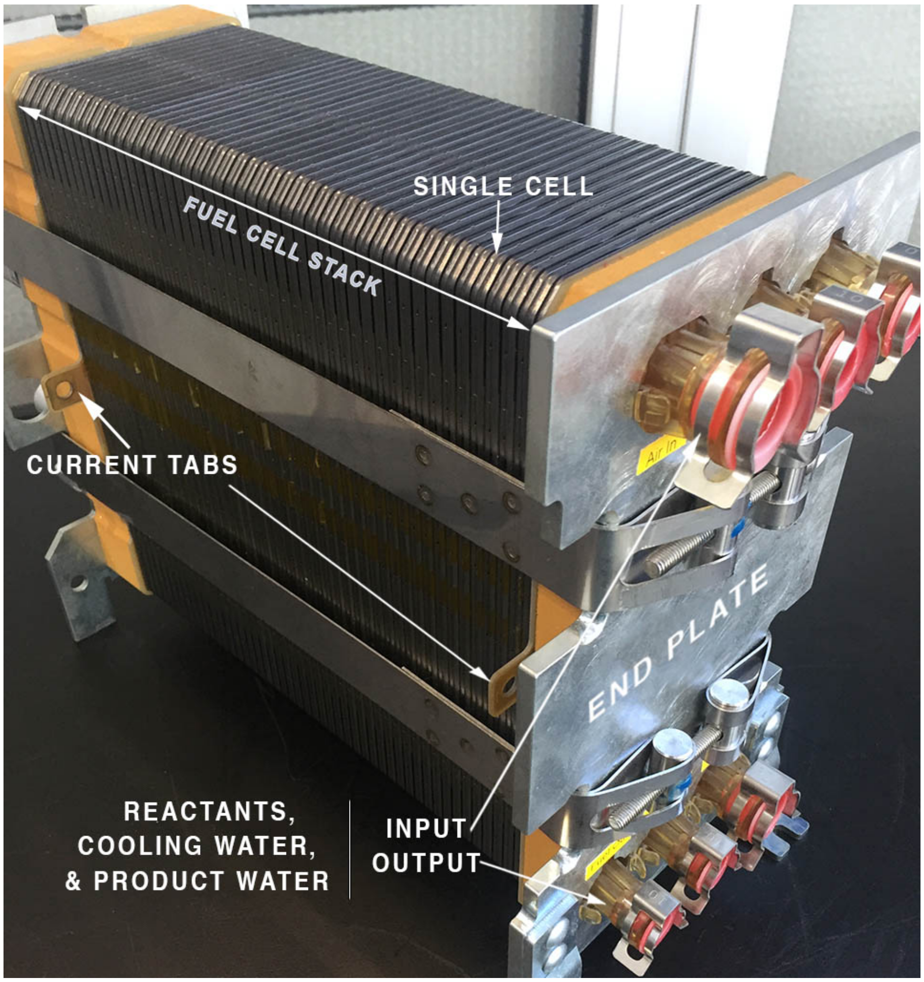
Figure 4 shows a more detailed cell description of one type of fuel cell: proton exchange membrane. It depicts how the fuel and oxidizer is delivered to a cell and where the electrochemical reaction at the catalyst takes place to produce electrical energy.

Figure 4. A Proton Exchange Membrane Fuel Cell Block Diagram



Each fuel cell produces approximately 0.6 volts of direct current. Placing each individual fuel cell with other individual fuel cells makes a fuel cell stack and this increases the amount of voltage produced. The more fuel cells in a stack, the higher the voltage output. The surface area of each individual cell controls the amount of current (i.e., amperage) available. Larger surface area equal higher current levels. A mock-up of a 46-cell fuel cell stack is shown in Figure 5. The reactants, product water and cooling water are fed though the manifold fittings on the end plate. Current is tapped off the two tabs just under the end plates.

Figure 5. Mock-Up of a Fuel Cell Stack Composed of 46 Individual Fuel Cells



2.1 FUEL CELL SYSTEM

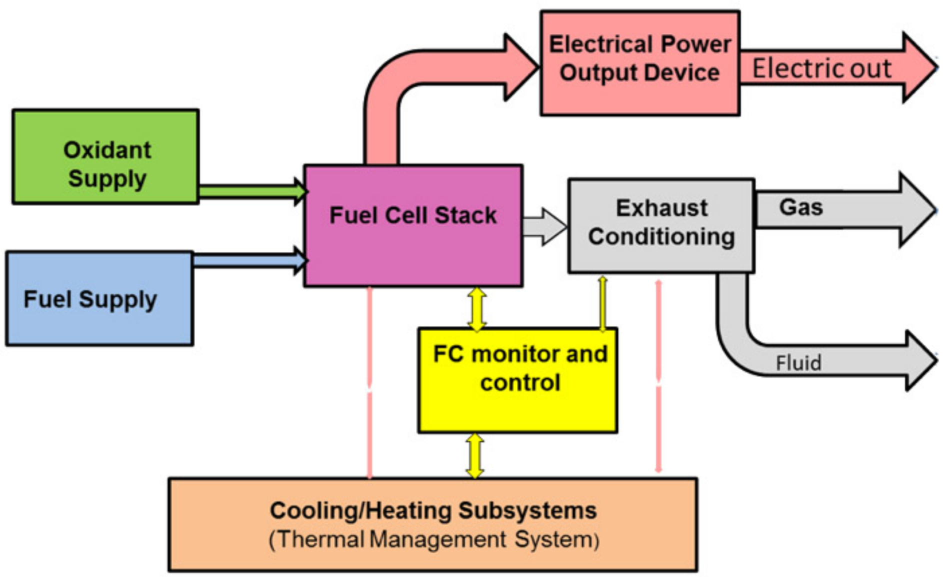
While it is the fuel cell assembled into a fuel cell stack itself that produces electricity, to do so requires other components. Fuel and oxidant must be supplied to the FC stack, it must be monitored and controlled, and it must be thermally managed. A fuel cell stack also produces by-products such as water and heat that must be dealt with. Its electrical power output may require conditioning so that it supplies the type of power its load requires.

A fuel cell system (FCS) is defined as follows:

> Those units and components using an electrochemical conversion process to produce electricity from a fuel and an oxidant. This includes reactants and reaction products, steam reformers, supply and exhaust devices, enclosures, fuel cell stacks, electric power output devices, cooling and heating devices and a centralized control and monitoring subsystem.

Figure 6 is a block diagram that depicts the various components of a FCS. A detailed description of each component of a FCS is given in Appendix C, section C.2.

Figure 6. Fuel Cell System



3 AIRBORNE APPLICATIONS FOR FUEL CELL SYSTEMS

Fuel cells have the potential to be used in many different applications on aircraft. These can range from non-integrated applications such as medical equipment/systems, through integrated non-power applications to non-essential and essential systems, galleys, and navigation. The FC technologies for these applications are at various stages of technical maturity, but in general most systems are still in development and not yet a true commercially ready product for use in aviation. Nonetheless, there is growing interest in looking at how FCs can enable new benefits and functionality relative to state of the art systems on the aircraft.

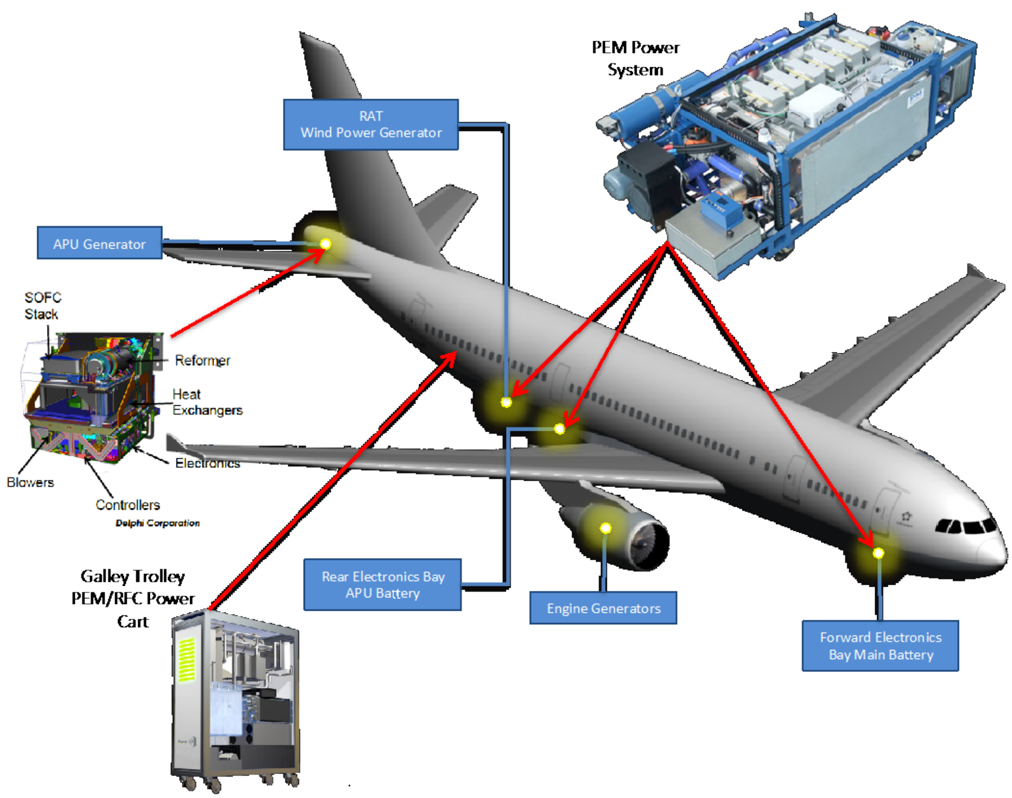
3.1 POSSIBLE AIRBORNE APPLICATIONS

To better understand how a FCS could be used on an aircraft the following uses for a FCS are discussed in detail in Appendix E:

- Galley power
- Stand-alone power / Medevac
- Auxiliary power
- Emergency power
- Unmanned aerial system propulsion

Several of these applications are illustrated in Figure 7.

Figure 7. Potential Fuel Cell Application on Aircraft



3.2 FUEL CELL INTEGRATION WITH AIRCRAFT SYSTEMS

This range of applications involves some level of integration with aircraft systems. On one end of the spectrum of applications, a FCS may, for instance, generate a small amount of supplemental electrical power to a dedicated payload onboard the aircraft independent of the aircraft electrical power sources. Thus, requiring small modifications to the aircrafts electrical architecture. On the other end of the spectrum, a FCS may be used to provide primary electrical power, supply water, or inerting gas to the aircraft while operating in a highly integrated manner with other aircraft systems. This would require major modifications to the aircraft. The lower levels of integration may be the easiest point of entry for introducing FCs in an aircraft, requiring less modification to the aircraft design or operation and fewer safety implications.

This report does not attempt to describe all the possible applications that FCs could be used for onboard an aircraft. Rather, the purpose of the applications that are discussed is to describe and classify them in such a way that any application may be filled by potentially a range of FCS technologies. In Appendix E, the applications are described as they appear from the aircraft view point and the type of functions that they are required to provide. This includes the expected benefits that they bring to the aircraft and how they integrate into the platform. Therefore, the key metrics differentiating the applications must be defined from the point of view of the aircraft, and not in terms of technology variants.

4 FUEL CELL HAZARDS

While fuel cells offer many benefits, they also can introduce hazards that must be addressed. The committee has identified the types of hazards commonly associated with the design, installation, and operation of fuel cells. This section summarizes those hazards. A detailed discussion of the hazards is contained in Appendix F.

4.1 INTRODUCTION

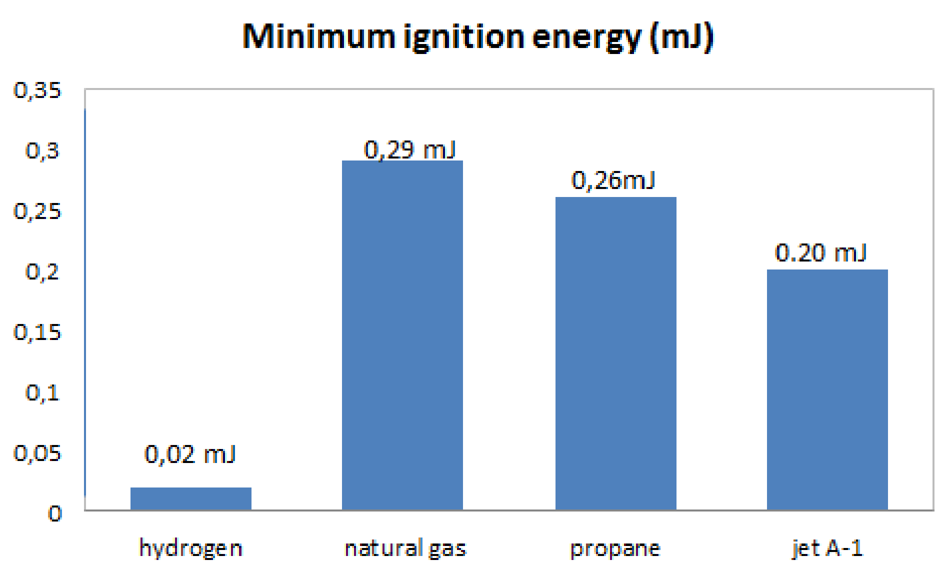
Hazards consideration should be made in accordance with SAE ARP 4754, *Guidelines for Development of Civil Aircraft and Systems*, and ARP 4761/ED 79, *Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment*. This identifies design hazards as well as interface requirements to other systems as installation risks. Based on the criticality of the system/sub-system, the related design assurance level should be determined according to ARP 4754, and the hazards need to be analyzed in accordance with ARP 4761. As oxygen and H_2 have specific hazards, design consideration should be extended by a dedicated oxygen-hazard and H_2-hazard analysis. These analyses should consider specific design hazards for all sub-systems (i.e., oxygen, H_2, fuel cell stack, pressure vessels, etc.) including system integration into the aircraft environment.

The location the FCS installation in the aircraft can greatly affect the hazard mitigation approaches. Hydrogen currently is not used as a fuel in civil aviation. The predominant and most feared hazard that can be created by H_2 is fire or explosion. As discussed in Appendix D, H_2 can be stored as a pressurized gas. The aviation community has significant experience with compressed gas in the form of oxygen, which is well covered in today's regulations. Similar hazard mitigation principles can therefore be applied with specific care to ensure that the fire/explosion risk of H_2 is properly managed.

The minimum ignition energy (MIE) for a wide range of H_2 concentrations in air or oxygen is very low. The MIE varies over the flammable range of hydrogen-air mixtures; for the most ignitable mixture, the MIE is 0.017 mJ. Therefore, in contrast to traditional fuel-air mixtures, the avoidance of a dedicated ignition source will not be sufficient to mitigate the fire risk. The only feasible method to extinguish a H_2 fire is to stop the supply of H_2. Traditional extinguishing methods will not suffice. Figure 8 depicts the MIE at stoichiometric conditions. This figure shows that the MIE of H_2 is 10 times less than jet fuel.

However, unlike traditional aircraft fuel tanks, a pressurized gaseous H_2 tank will not contain a fuel air mixture, but rather pure H_2. The lack of air, or oxygen, ensures that the compressed gas within the hydrogen tank is not flammable provided it is properly filled. As a result, the primary design methods to prevent H_2 fire hazards are the separation of H_2 and any oxidizer, preventing the accumulation of flammable mixtures and ensuring effective H_2 detection and shut-off means as last line of defense.

Figure 8. Minimum Ignition Energy at Stoichiometric Conditions



4.2 SUMMARY OF HAZARDS

The following is a summary of the hazards that are discussed in detail in Appendix F. The appendix discussion expands on each of these hazards, what causes them, and the means to mitigate the hazard.

4.2.1 Hazards

- Hydrogen fire and explosion hazards
    - H_2 ignition
    - H_2 combustion
    - Types of H_2 fires
        - Microflames
        - H_2 deflagration
        - H_2 detonation
- Mechanical/Materials Hazards
    - Material compatibility hazards
        - Embrittlement
        - Effect on mechanical properties
        - Diffusion and permeation
    - Failure of high-pressure gaseous storage systems
    - Failure of pressure relief devices
- Crashworthiness
- Installation Hazards
- Fueling and handling hazards
- Physiological hazards
- Cryogenic hazards
    - Cryogenic H_2 (liquid or cryo-compressed)
- Non-hydrogen fuel and oxygen hazards
    - Hydrocarbon fuel hazards
    - Oxygen hazards
- Electrical hazards
- Flammable mixture ignition
    - Ignition due to electrical sources
        - Static discharge
        - Electrical arc
        - Charge accumulation
        - Ignition by static electricity

        - Stray electrical current
        - Lightning
        - Corona discharges
        - Radiofrequency electromagnetic waves up to 10^{11} Hz
        - Electromagnetic waves from 3 x 10^{11} Hz to 3 x 10^{15} Hz
    - Ignition due to mechanical sources
        - Mechanical impact
        - Friction sparks
        - Friction and galling
        - Frictional Heating
        - Metal fracture
        - Tensile rupture
        - Mechanical vibration
        - Safety burst disk
    - Ignition due to thermal sources
        - Auto-ignition temperature
        - Compression heating
        - High temperature ignition
    - Resonance ignition
    - Flammability limits

5 REGULATORY STANDARDS AND ADVISORY MATERIAL

This section summarizes the recommended regulatory approach for new, revised, and existing regulatory standards applicable to the certification of a FCS on transport category airplanes. It also contains a discussion on the material that needs to be developed for advisory material. The recommendations for new, revised, and applicable existing regulations are discussed in detail in Appendix G.

5.1 DEVELOPMENT OF A FUEL CELL SYSTEM SAFETY BASELINE REGULATION

After developing the information on various types of fuel cell technologies, their possible aircraft applications, their potential hazards, and the review of existing part 25 regulatory requirements, it was decided that a new regulation, known as the baseline regulation, should be developed. The baseline regulation recommendation contains the elements necessary to address the unique safety issues associated with the design and installation of a hydrogen FCS on board a transport airplane. While the baseline rule is presented as a regulation, the Committee understands that it will most likely need revision to accommodate the FAA's and other airworthiness authority's regulatory language requirements.

Following the discussion of the baseline regulation in Appendix G, section G.4.2 provides a link between the hazards discussed in Appendix F and each subsection of the FCS baseline regulation.

Here is the recommended baseline regulation (located here in Appendix G):

25.XXX Fuel Cell System Safety

a) For the purposes of this chapter, a fuel cell system is defined as: Those units and components using an electrochemical conversion process to produce electricity from a fuel and an oxidant. This includes reactants and reaction products, steam reformers, supply and exhaust devices, enclosures, fuel cell stacks, electric power output devices, cooling and heating devices, and control and monitoring subsystem.

   For the purposes of this chapter, a reactant is any fuel or oxidizer supplied to the fuel cell system for the purposes of producing electrical energy.

b) The design and installation of a fuel cell system must prevent catastrophic or hazardous explosion due to ignition of fuel or vapors.

c) To comply with paragraph (b), catastrophic explosion due to ignition of fuel or vapors must be extremely improbable and not result from a single failure, a hazardous explosion due to ignition of fuel or vapors extremely remote, taking into account all factors, including;

   1) Emission of explosive or toxic gases
   2) Minimum ignition energy
   3) Static electricity
   4) Electrical faults
   5) Over pressurization of hydrogen fuel storage vessels
   6) Mechanical ignition sources
   7) Electromagnetic waves
   8) Lightning strikes
   9) Fire
   10) Heat emission

d) To comply with paragraph (c)(8) the following must be taken into account

   1) Direct lightning strikes to areas having a high probability of stroke attachment;
   2) Swept lightning strokes to areas where swept strokes are highly probable; and

3) Lightning-induced or conducted electrical transients

e) Hydrogen leakage detection must be installed in any area of the airplane where hydrogen may accumulate and create a hazardous condition.

f) Fuel cell system installation must not damage surrounding structure of adjacent systems, equipment, or electrical wiring from corrosive fluids or gases that may escape in such a way as to cause a hazardous condition

g) The fuel cell system must have a failure sensing and warning system to alert the flightcrew if its failure affects safe operation of the airplane

h) The design and installation of the reactant supply must prevent hazardous conditions due to improper handling by crewmembers, passengers, and maintenance and servicing personnel.

i) The fuel cell system must be designed to prevent hazardous hydrogen permeation and embrittlement of aircraft materials and structure, or otherwise to not have an adverse effect on the strength of materials or the flammability properties of materials.

j) Means must be available for controlling or extinguishing a fire, such as stopping flow of fluids, gasses, or vapors, shutting down equipment, fire containment, or use of extinguishing agents.

k) To protect fuel cell system design features that prevent catastrophic failures caused by all probable causes, the type design must include critical design configuration control limitations (CDCCLs) identifying those features and providing information to protect them. To ensure the continued effectiveness of those design features, the type design must also include inspection and test procedures, intervals between repetitive inspections and tests, and mandatory replacement times for those design features used in demonstrating compliance to paragraph (b) of this section. The applicant must include the information required by this paragraph in the Airworthiness Limitations section of the Instructions for Continued Airworthiness required by § 25.1529.

l) The effect of fuel cell system operation on the cabin air must be assessed in normal operation and failure cases in order to show compliance to CS/CFR § 25.831 (a)(b)(c).

m) Storage or disposal of by-products, such as water and oxygen depleted air, must not introduce hazardous conditions.

n) Hydrogen pressure tanks, and lines between tanks and the shutoff means must be:

   1) Protected from unsafe temperatures; and

   2) Located where the probability and hazards of rupture in a crash landing are minimized

o) Each fuel cell system fuel line within the fuselage must be designed and installed to allow a reasonable degree of deformation and stretching without leakage where its leakage could introduce a hazard.

5.2 EXISTING REGULATIONS REQUIRING REVISION, CFR/CS PART 25

The Committee also identified current CFR/CS 25 regulations that should be revised in order to support the certification of FCSs. They are located here in Appendix G.

Many of the regulations that the committee recommends be revised are located in CFR / CS part 25, subpart F, Powerplant. Adoption of these recommendations will require a paradigm shift in how the airworthiness authorities and industry approach these regulations. This is because these existing regulations are based on traditional combustion engines and APUs, and the use and storage of jet fuel. While no changes are proposed that would alter the applicability of these regulations as they are applied today to existing powerplants and fuel systems, they would expand their applicability to include reactants used by a fuel cell system. As an example, in Table 19 of Appendix G it is recommended that § 25.957, *Fuel flow between interconnected tanks*, be modified by replacing the word fuel with the words fuel/reactant. As revised, it would read as follows:

> If fuel **or reactants** can be pumped from one tank to another in flight, the fuel or **reactant** tank vents and the fuel **or reactant** transfer system must be designed so that no structural damage to the tanks can occur because of overfilling.

Another example if § 25.967(a), *Fuel tank installations*. The committee recommends that the word "fuel" be replaced by the words "fuel / reactant." As revised it would read

> "(a) Each fuel **or reactant** tank must be supported so that tank loads (resulting from the weight of the fuel in the tanks) are not concentrated on unsupported tank surfaces. In addition—…"

The committee also recommends revisions to current regulations located in CFR / CS part 25, subpart D, *Design and Construction*; subpart F, *Equipment;* subpart G, *Operating Limitations and Information*, and subpart H, *Electrical Wiring Interconnection Systems (EWIS)*.

In all, 26 existing regulations are identified as needing revision to accommodate the installation of fuel cell systems in transport category airplanes.

5.3 EXISTING REGULATIONS NOT REQUIRING REVISION, CFR/CS PART 25

Furthermore, the Committee also collected those regulations currently in CFR / CS 25 that are seen as applicable, but do not require revision. These are included in this report because they are applicable to addressing some FCS hazards. A total of 69 current regulations have been identified as applicable to fuel cell systems. They are located here in Appendix G.

5.4 PERFORMANCE BASED REGULATION

Electrical energy supply devices are continually changing to meet the needs of the More Electric Aircraft. Aircraft have used Lead Acid and Ni Cd batteries for years. These battery chemistries have been very reliable with known safety issues and mitigation techniques. Currently, the regulatory requirements for batteries are covered under 14 CFR § 25.1353(b)/ EASA CS 25.1353(c). While the aerospace industry has a long history of using both primary and secondary batteries, it, like many industries, is moving to batteries with more energy dense electrolytes to reduce the size and weight of the battery system. There has been a great deal of work in standard organizations (e.g., RTCA, SAE, IEEE) to provide guidelines for the safe design, installation and operation of Lithium batteries. However, the current regulatory requirements contained in CFR § 25.1353(b)/CS 25.1353(c) do not adequately address the unique safety issues associated with lithium based batteries. Therefore, the FAA and other aviation airworthiness authorities have issued Special Conditions to address the unique hazards of these batteries. The special conditions have been issued for both secondary or primary batteries; rechargeable and non-rechargeable.

Batteries and capacitors provide short term power storage on the aircraft and it is well understood on how to integrate them into a transport aircraft. There are many well established aerospace committees working to further refine the technical requirements for batteries and capacitors. The Committee felt hydrogen fuel cells would present the biggest challenge for integration and certification in an aircraft. Therefore, the Committee did not investigate these types of energy storage devices and instead concentrated on the design, installation, operation and safety issues associated with hydrogen fuel cells.

However, the Committee did develop a performance based requirement that is applicable to energy storage devices in general. If adopted, it could be applied to fuels cells, super capacitors, storage batteries of differing chemistries including those that are lithium based, and other types of energy supply devices. Adopting this recommendation would negate the need to continually develop and issue special conditions and also the need to revise it every time new ESD technologies are introduced in the aircraft. The performance based regulation follows and is located here in Appendix G.

14 CFR § 25.1353(b) / EASA CS 25.1353(c) (in lieu of the existing standard)

a) An energy supply/storage device, ESD, means any system installed on the airplane for the purposes of energy supply as required by systems or functions on the aircraft. The ESD includes functions of energy storage, energy generation or discharging energy, refilling or recharging, and or jettisoning.

b) For the purposes of this rule, 'energy' means any type of energy for the functioning of, or coming from the ESD, including, for example, fuels of any kind or electric current.

c) The characteristics of the ESD, including failure modes, must be identified.

d) Failure of the ESD must not contribute to, or cause, a catastrophic effect on the airplane unless shown extremely improbably, or a hazardous effect on the airplane unless shown extremely remote.

e) In normal operation or foreseeable malfunction of the ESD, no explosive, toxic, or corrosive gases or fluids:

    1) May accumulate in hazardous quantities

    2) May damage structures or adjacent essential equipment or systems

    3) May endanger passengers or crew

f) Hazardous effects on structures or essential equipment or systems caused by the maximum amount of heat that can be generated during normal operation or probable malfunctions must be prevented.

g) The ESD as described in a), b) and c) must:

    1) Maintain safe operating temperatures, pressures, or any other identified parameter, during normal operation (including storage, generation/discharging, refilling/recharging and / or jettisoning)

    2) Provide, as necessary, means of protection, or controlling the ESD to prevent hazardous conditions during normal operation or probable malfunction. The flightcrew should be able to monitor, receive warnings, and control as appropriate.

h) Each energy-storage-refilling or -recharging system must be designed to:

    1) prevent improper refilling or recharging

    2) prevent contamination of the stored energy during likely operating conditions; and

    3) prevent the occurrence of any hazard to the airplane or to persons during refilling or recharging

i) Likely errors during ground handling of the airplane, the ESD, or its components, must not lead to a hazardous event, like hazardous loss of energy or misfit of ESD components.

j) Suitability and reliability of ESDs must be proved based on experience, test, or analyses and be acceptable to the FAA.

k) Instructions for continued airworthiness as required by §§ 25.1529 and 25.1729, must contain proper procedures including safe storage and exchange procedures of the ESD or its components if such a function / possibility is provided.

5.5 OTHER CFR PARTS

Although the Committee did not thoroughly go through the CFR / CS parts 23, 27, and 29 airworthiness standards, the same concerns would apply with the typical differences between the different product types. The Committee therefore recommends when a rulemaking committee is created, this group amend the different airworthiness standards based on the conclusions presented in this report.

5.6 OPERATIONAL REGULATIONS

Operational requirements that are applicable to FCs contained in CFR parts 43, 91, 121, 125, and 129 are also identified in Appendix G, Table 21. The Committee did not identify any revisions to these operational requirements that are necessary to accommodate the operation of a FCS, because they are of general applicability and apply to many different airplane systems and their maintenance.

5.7 ADVISORY MATERIAL

Because the Committee did not develop and recommend actual regulatory language (with a few exceptions), specific advisory material was not developed. However, any advisory material later developed should be based on the data contained in Appendices A through H. Further explanation is contained in the following paragraphs and in Appendix G, SectionG.7.

For example, section F.7 in Appendix F, discusses hydrogen fire extinguishing. It states that a hydrogen fire should not be extinguished with water or chemicals. Static electricity generated across the leak orifice, or an adjacent hot surface, could explosively reignite the leaking hydrogen. The best way to deal with a hydrogen fire is to shut off the flow of hydrogen gas by closing supply valves, which will extinguish the flame. Essentially the shut-off of hydrogen is the only meaningful way to stop a hydrogen fire in flight because if the supply of hydrogen cannot be stopped the fire will always reignite on hot surfaces.

Another section in Appendix F, section F.3.3 discusses the failure of pressure relief devices (PRDs). It states, in part, that PRDs play a critical role in the implementation of most high-pressure gas storage systems. In the event of an over-pressure situation induced by, for example, overfilling, exposure to excessive heat, or a liquid to gas phase change, the PRD will activate and allow the gas to escape to a safe location. The PRD should be set such that that it prevents catastrophic failure of the pressure vessel, irreversible damage, or degradation of the pressure vessel life cycle.

A third example is the discussion of safety as it relates to a self-contained fuel cell powered Medevac unit. Section E.4.2.2 of Appendix E, discusses some important safety considerations of the unit. In part, it states that he FCS must be monitored and controlled real-time with a dedicated set of sensors, monitoring and control units. These controllers should be designed to render this system independent from any operator’s intervention. The FCS will then be able to control itself autonomously and shut itself off in any abnormal conditions encountered. However, the flight crew must have access to key data regarding the FCS state of health during operation (e.g., battery status, hydrogen content, temperature) and be in a position to shut it off if deemed necessary, via a dedicated interface (emergency button).

The preceding examples illustrate the type of information that is available in the appendices and the type of information that should be included in an advisory circular.

6 CONCLUSION

The fuel cell technologies discussed in this report are at various levels of maturity. For example, PEMFCs are in use today to power passenger cars, city busses, and warehouse forklifts. Solid Oxide Fuel Cells are used in stationary applications to provide power for buildings. The National Aeronautics and Space Administration (NASA) has used PEM fuel cells on the Gemini program and alkaline fuel cells on the Apollo and Space Shuttle programs. Although fuel cells have been demonstrated and are being developed for use in unmanned aircraft applications, fuel cells are currently not widely used in manned aircraft applications. Only recently have applications been made to certify fuel cells in commercial aviation. As certain technological, logistical, and regulatory hurdles are overcome, the use of fuel cells in both manned and unmanned aviation will become more prevalent.

The following paragraphs list, in bullet form, some salient points regarding the readiness of fuel cell systems to be deployed in an airborne environment for several applications (discussed in Appendix E) and what the FAA and other authorities can do to facilitate the certification of fuel cell systems.

6.1 WHAT ARE THE PRIMARY ROADBLOCKS TO DESIGNING AND INSTALLING A FUEL CELL SYSTEM IN AN AIRPLANE TODAY?

- Weight/Volume
- Technology maturity
- Cost benefit
    - Clean sheet design necessary for major FCS installation (e.g., APU)
- Lack of comprehensive airworthiness standards
- Lack of long term reliability data
- Hydrogen storage and refilling infrastructure

6.2 WHAT IS THE TIMELINE FOR VARIOUS FUEL CELL TECHNOLOGIES AND APPLICATIONS?

Galley

- Ready for early market
- A FCS is not a galley's plug substitute but offer extra services such as usable water and heat
- Venting line integration is a topic to prioritize
- Hydrogen storage and refilling is a topic to prioritize
- NOTE: Galley power profile can vary by a factor of three from one airliner to another

Medevac

- As much of a "Plug and play" system as possible
- Operation in cabin can be envisioned with no major show-stoppers
- Safety and proper operation can be appropriately controlled and monitored
- Needs a dedicated venting line to purge H_2 overboard
  - Safe H_2-Air mixture management via use of dedicated enclosures and H_2 monitoring
  - Mounting and installation of system on-board to take into account presence of H_2 venting line
  - Mounting and installation of system on-board to take into account concept of replaceable/swappable H_2 tanks

Auxiliary Power

- Fuel cells cannot compete with gas turbine APU in foreseeable future as a form fit function replacement
- Automotive PEM FCPS technology is mature for airplane, PROVIDED:
  - Hydrogen refilling infrastructure is available at airports,
  - Airplane modification to improve efficiency from pneumatic systems such as environmental control systems and main engine start (~2030) is necessary,
  - Operators modification of operating procedures to minimize duration of APU operation (minimize hydrogen fuel required)
    - Between gate power and main engine start
    - During flight idle descent
- Regenerative (Unitized) PEM/SO Fuel Cell is far less mature than PEM FC, however, it's independent of hydrogen infrastructure, and provide higher power density and specific power (+15 years)
- SOFC needs onboard fuel reformation, sulfur content in aviation fuel presents a major challenge
  - Stationary de-sulfurization station/equipment at airports
  - Clean sheet aircraft power system design with emphasis on:
    - More electric architecture
    - Energy & power optimization
    - Highly integrated mechanical/thermal/electric power system
    - Hybridized & distributed power supply systems

Emergency Power

- Technology is capable of supporting an emergency power system application, but is likely to take approximately 10 years before it is ready for large transport airworthiness certification.
- The packaging of this system requires a relatively small amount of fuel for infrequent operation of low power for short duration.
    - o No refueling, other than a possible service cart to top-off the system due to small usage in pre-flight checks. It is unlikely to require an H_2 infrastructure to support.
- Technology offers some advantages to the current RAT.

Regenerative Fuel Cell Energy Storage

- Technology is capable of supporting this application, but is likely to take approximately 10-15 years before it is ready for Part 25 air worthiness certification.
    - o Some UAS implementations are already in process
- Regenerative fuel cell systems are usually targeted for specialized applications.
    - o These include solar powered aircraft energy storage where H_2/O_2 storage is significantly lighter than currently available batteries
- Regenerative fuel cell technology has been demonstrated in flight, however most regenerative fuel cell systems for large transport aircraft are still in development.

Unmanned Aerial System (UAS)

- Fuel cell technology is capable of supporting a wide range of UAS applications within the next few years.
    - o Some early products currently available at power levels under 1kWfuel cell technology is being actively developed and utilized in UAS because of current market demand for the endurance and operational benefits they provide compared to batteries and combustion engines.
- UAS powered by hybrid fuel cell / battery systems are leading candidates for use in many UAS commercial and military applications to provide both propulsion and payload power.
- Developmental and operational experience with UAS fuel cells will provide data to the FAA to assist in later application to Part 25 transport

6.3 WHAT IS THE HIGHEST PRIORITY FOR THE AIRWORTHINESS AUTHORITIES SO THEY CAN FACILITATE CERTIFICATION OF FUEL CELL SYSTEMS?

- Development of new and revised airworthiness standards and associated advisory material that is based on the recommendations contained in this report.
  - The main new risks identified have to do with the introduction of Hydrogen. Other possible introduced fuel cell system hazards are known, or are similar to them.

Certification Regulations:

- One new regulation dedicated to fuel cell system safety is proposed, with clear links to the identified risks discussed in this report.
  - 1 new regulation proposed: § 25.XXXX Fuel Cell System Safety
- One performance based regulation is proposed to help cover ESDs, known and new-to-come unknown ones.
  - Complete overhaul of the existing 14 CFR § 25.1353(b) / EASA CS 25.1353(c)
- 20 proposed changes to existing regulations to address fuel cell systems
- 67 identified regulations to be applicable to FCSs in their current wording

Operational Regulations:

- 71 identified regulations to be applicable to FCSs in their current wording

APPENDIX A. COMPARISON OF FUEL CELLS WITH OTHER TECHNOLOGIES

A.1 FUEL CELL BENEFITS

Fuel cells are under consideration for use on aircraft because of their unique properties that may provide substantial benefits as compared to batteries and combustion engines currently in use today.

Each fuel cell and the system embodiment for each application can have differences as varied as heat engines. One could say aircraft propulsion is provided by the combustion of fuel and oxidizer to provide forward thrust. This can range from a piston engine propelling a general aviation type aircraft, a turboprop on a military transport airplane, a geared turbofan on a commercial airplane, a scramjet on a hypersonic aircraft, and H_2-O_2 main engines. Similarly, fuel cells range widely in characteristics. Weight, life, safety, maintenance, cost, reliability, volume, noise signature, thermal signature, type of oxidant, type of primary fuel, power profile, efficiency, CO2 reduction, air pollution, and more are all typical factors. Optimization of any one or combination of these can dramatically alter the fuel cell and fuel storage design and determine if benefits are sufficient to merit inclusion on an aircraft type.

With that in mind, there are broad fundamental differences between fuel cells and batteries and heat engines. The following provides a brief overview of these factors.

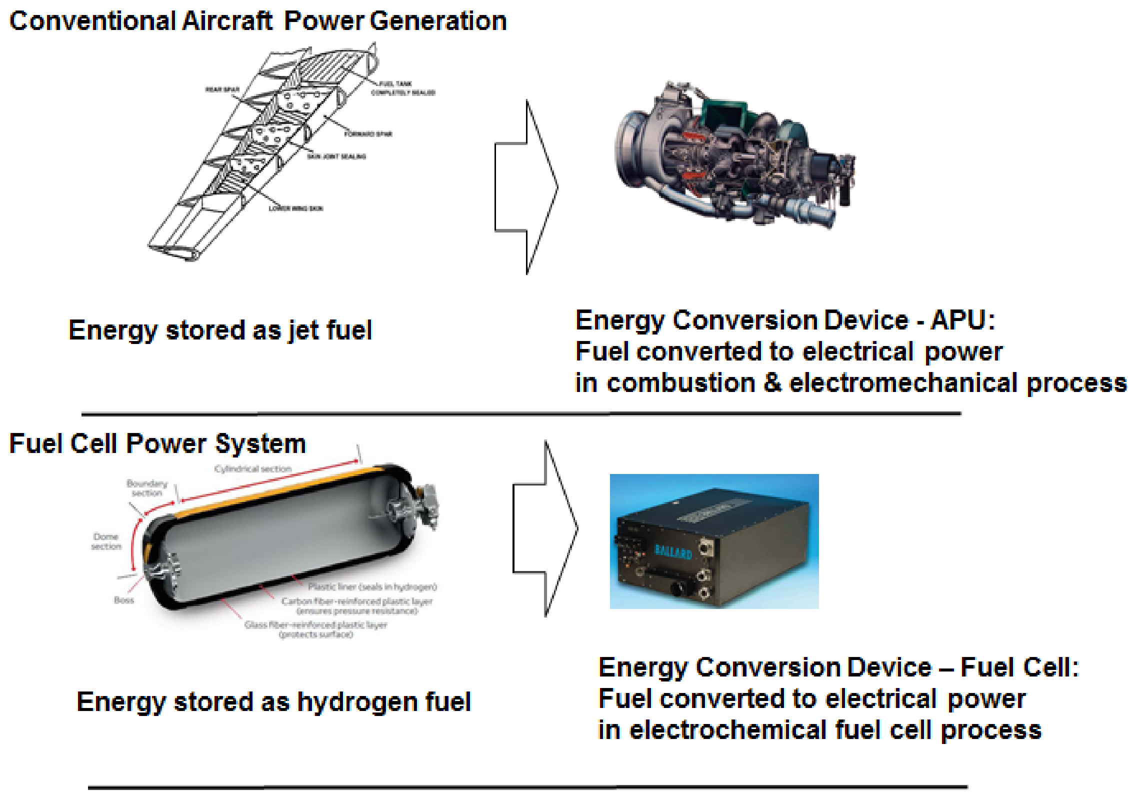
A.2 TECHNOLOGY COMPARISONS

This section discusses the comparisons of fuel cells to batteries and fuel cells to combustion systems by comparing factors such as size, cost, and energy density. It also compares specific power versus power density for various energy conversion methods as shown in Figure 9.

A.2.1 Fuel Cells Compared to Batteries

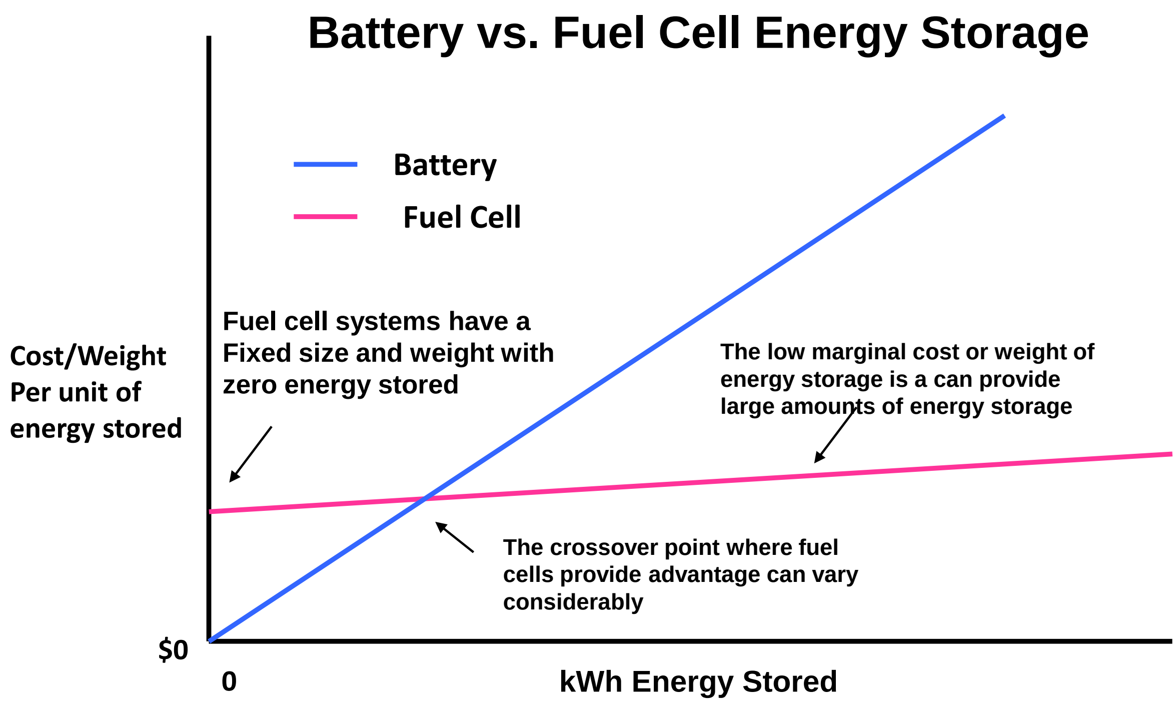
A fuel cell is similar to conventional combustion based power generation; it converts separately stored chemical energy into electrical power. This is also shown in Figure 9. The fuel in a fuel cell is converted electrochemically instead of by burning the fuel and converting the generated heat to mechanical energy as is done in an airplane engine or auxiliary power unit. By comparison, a battery combines both the storage function and the power conversion function. The chemical energy of the reactants inside the battery is converted electrochemically to electrical power. By separating the fuel (chemical reactants) and the electrochemical conversion cells, a fuel cell system can optimize both fuel storage and power generation.

Figure 9. Fuel Cells Convert Stored Fuel into Electrical Power Similar to Conventional Combustion Based Systems



An illustration comparing size and cost of fuel cells to batteries is shown in Figure 10. As shown, both batteries and fuel cells increase in cost and weight as the amount of energy stored increases. An advantage for batteries is that when small amounts of energy storage are required, only a small number of batteries are required. However, to increase storage, more batteries must be added. For example, if twice the amount of storage is needed for the battery, twice as many complete batteries are added.

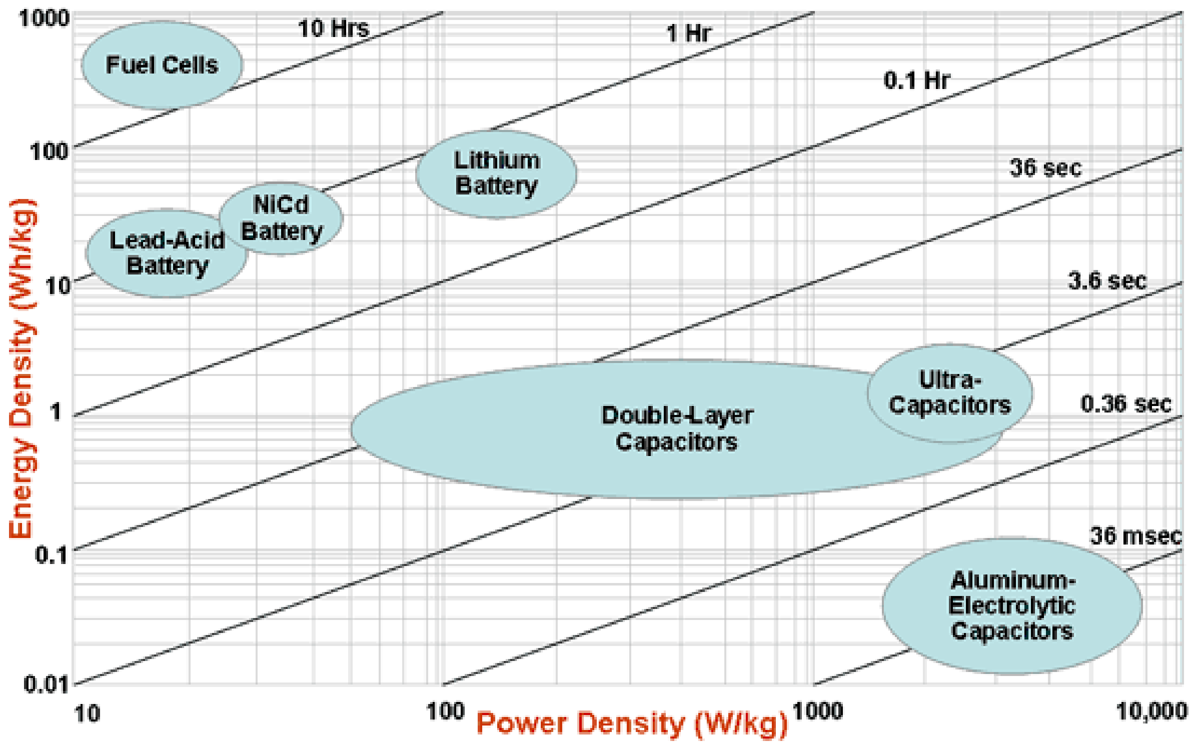
Figure 10. Comparison of Size and Cost of Fuel Cells to Batteries



For fuel cells, the scenario is different. Just like in an automobile, the fuel cell separates power production (equivalent to an automobile engine) from energy storage (equivalent to a gasoline tank). If little or no energy needs to be stored the cost and weight of the fuel cell and near empty tank must be accounted for. In these cases, the battery has an advantage. However, if more storage is needed, the tank only needs to be filled and if even more storage is needed a larger tank can be provided. Typically, with current technology, the cost/weight of simply expanding the fuel tank and adding fuel is far less than adding the same amount of energy stored in batteries. As a packaged storage device, the United States Department of Energy (U.S. DOE) has a target of a value for net kWh/kg of a hydrogen storage system of 2500 Wh/kg. The overall energy density of a complete fuel cell system will be lower than this value since it includes the fuel cell stack itself and the tank end caps, fittings and related packaging but the marginal value is very high. This means if the fuel cell has been justified for a given application and the fuel cell system weight is already budgeted, the marginal energy density of 2500Wh/kg exceeds almost all known batteries. That is why, in Figure 10, the slope of the batteries is far steeper than the slope of the added fuel. The fuel cell system weight will, of course, depend on the fuel cell type and other system requirements (power level, fuel type, etc.).

A representation of this is shown in Figure 11 that maps fuel cells and batteries in regard to specific energy or energy density, kWh/kg vs. specific power or power density, kW/kg. This chart from the U.S. Defense Logistics Agency, known as a Ragone chart, illustrates the very high energy density able to be achieved via fuel cells. This energy density makes the choice of a fuel cell very attractive. However, the applications where a fuel cell makes sense, will depend on the level of energy required and the chosen type of fuel cell system technology. Appendix E covers applications and how fuel cells can work in these applications.

Figure 11. Ragone Chart Comparing Batteries and Fuel Cells



Source US Defence Logistics Agency

A.2.2 Fuel Cells Compared to Combustion Systems

While a fuel cell shares the heat engine characteristic of separating power production and energy storage as shown in Figure 11, a fuel cell can typically achieve higher operating efficiencies than combustion processes. The potential savings, from a U.S. Department of Energy study[3], are illustrated in Figure 12 and Figure 13 where the efficiency for the conventional main engine generators feeding the 230 VAC buss of a modern commercial aircraft is shown at 53% (Figure 12) while the projected solid oxide fuel cell (SOFC) is shown at 65% (Figure 13), if the DOE programs hit their development targets. It should be recognized that there is still a substantial challenge reaching those targets.

[3] U.S. DOT, Electrical Generation for More-Electric Aircraft using Solid Oxide Fuel Cells; GA Whyatt, LA Chick; April 2012

Figure 12. Existing Electrical System Loads at Cruise Condition in Modern Commercial Aircraft

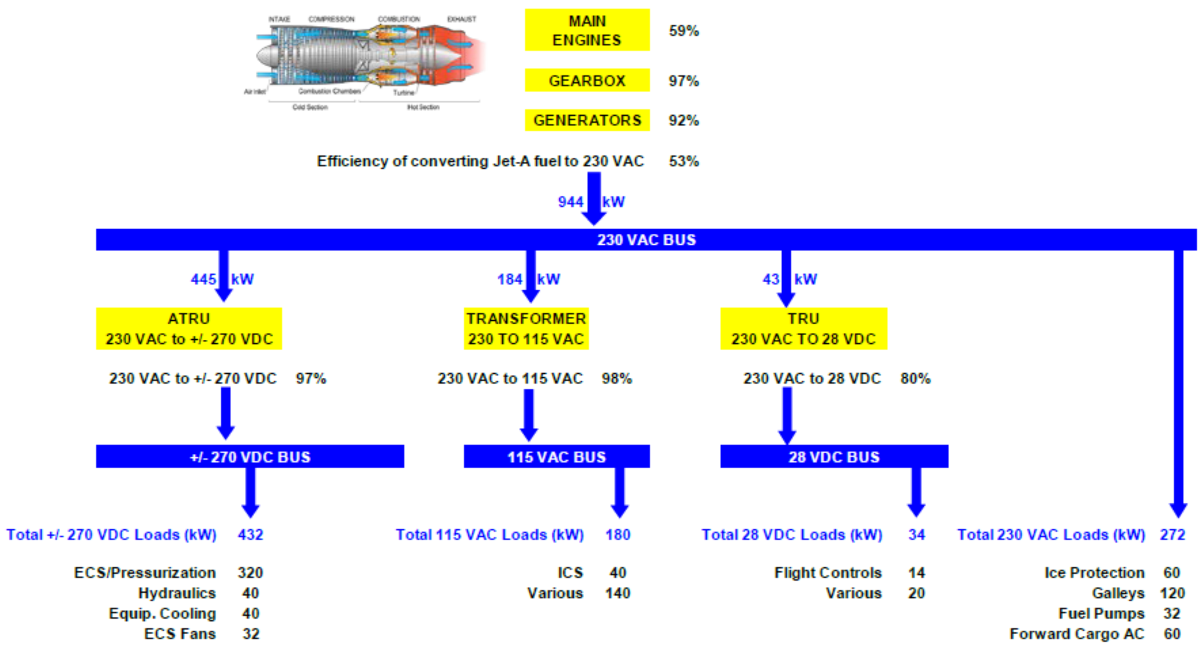
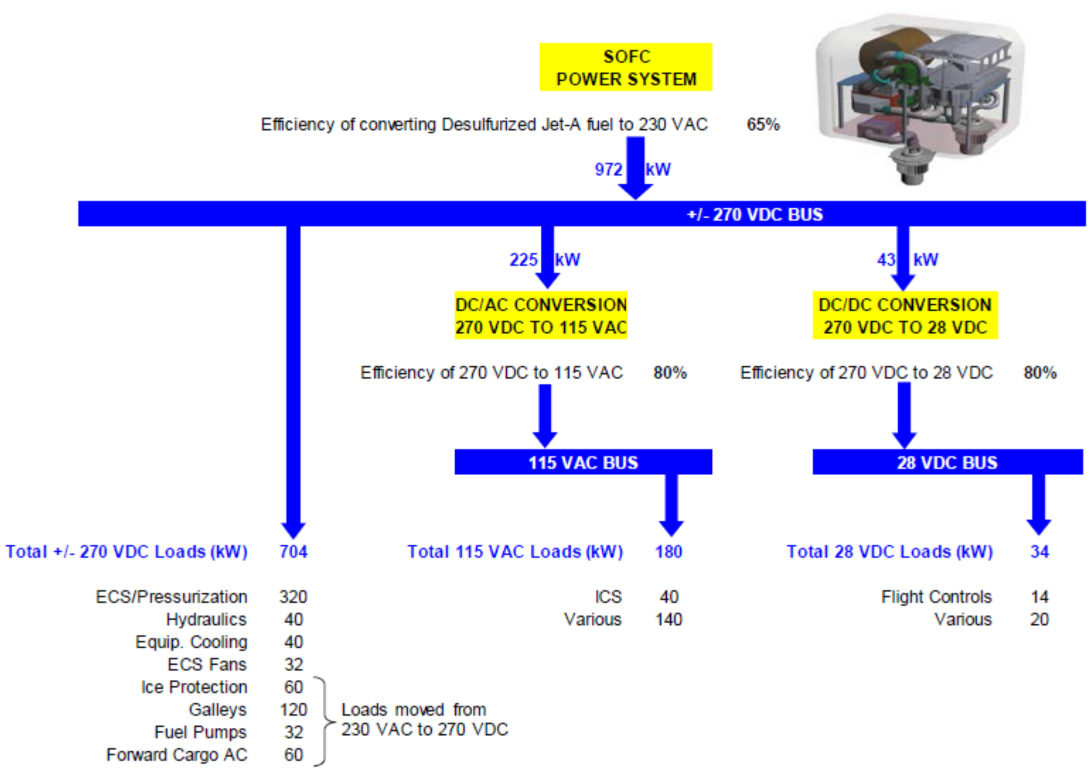


Figure 13. A Modern Commercial Aircraft Electrical System and Loads at Cruise Reconfigured for SOFC Direct Current Generation



A simplified representation is shown in Figure 14 illustrating how higher efficiency achievable by a fuel cell may lead to overall savings. In this figure, the higher efficiency of the fuel cell as compared to the combustion process can lead to overall savings even for higher initial weights. However, as also noted in the DOE study the projected weight of current SOFC technology makes practical application, at this time, challenging on a weight basis alone.

Figure 14. The Higher Conversion Efficiency of Fuel Cells Can Potentially Provide Cost and Weight Saving as Compared to Combustion Processes

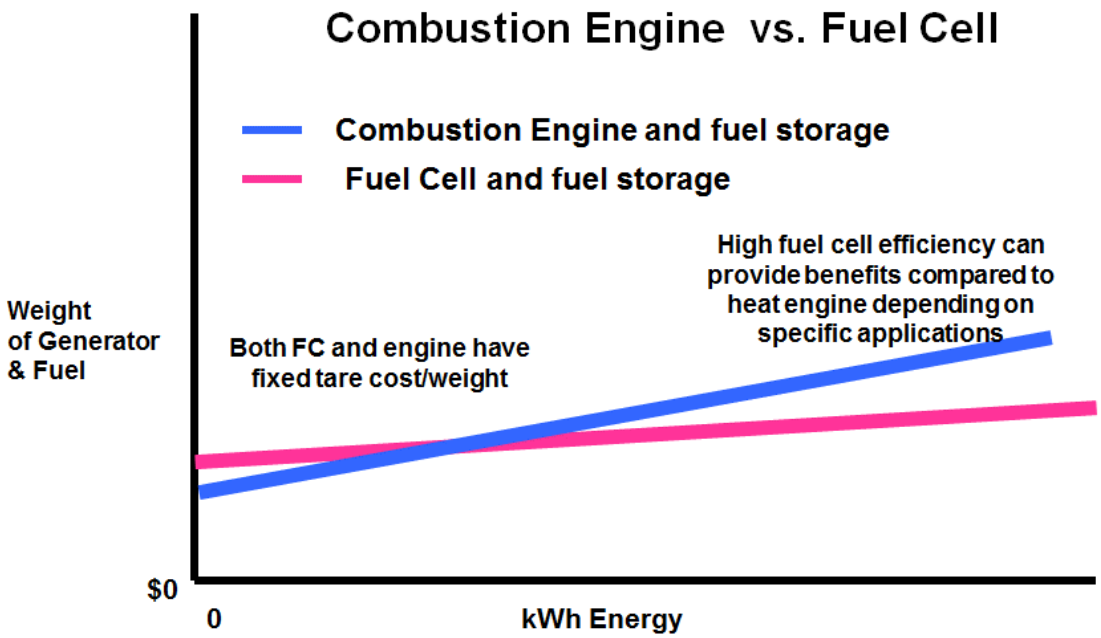
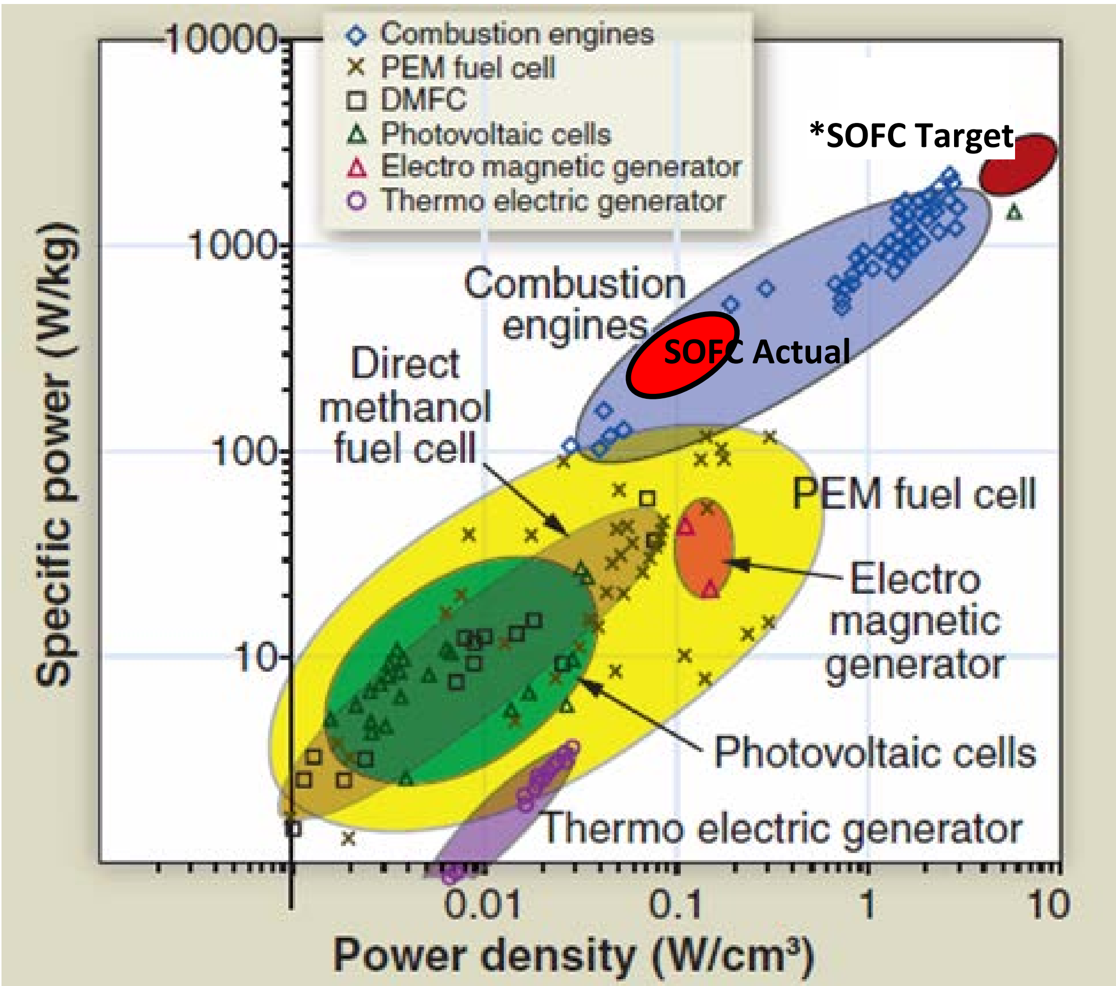


Figure 15 compares the specific power and power density of fuel cells and combustion engines. The figure shows that a SOFC could potentially be lighter than a combustion system, however, these power densities have not yet been demonstrated in working commercial prototypes. There is still development that will be needed and perhaps a change in power system usage model on the aircraft to make a fuel cell attractive in some of the potential aircraft applications.

Figure 15. Comparison of Specific Power versus Power Density for Various Energy Conversion Methods



(* Note the SOFC target values are for a laboratory-demonstrated power density of ~2 W/cm2. Commercially available SOFC units deliver power densities of ~ 0.2 W/cm2)

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APPENDIX B. FUEL CELL TECHNOLOGIES

A fuel cell is an electrochemical device that converts the energy of the chemical reaction between a fuel, such as hydrogen or hydrogen rich gases, alcohols, or hydrocarbons, and an oxidant, such as air or oxygen (O_2), to direct current (DC) power, heat, and other reaction products.

This appendix provides a basic technical background on multiple fuel cell options and their fundamental characteristics. Two technologies; proton exchange membrane (PEM) in both low and high temperature versions and solid oxide fuel cell (SOFC) will be explored further in Appendix C to understand how they work, how they might be used for aircraft applications, and where the issues might be that will need to be addressed. Background on hazards posed by these technologies is also provided.

Section B.1 looks at the fuel cell technology options and their basic capability. In section B.2, two technologies, proton exchange membrane and solid oxide fuel cells are examined in detail. The details of these systems are provided; key integration issues and failure modes are identified. The types of fuel are also described as well as their characteristics and integration issues.

Appendix D looks at the applications and how the fuel cell could be used and integrated into the aircraft. Additional discussions of key issues associated with the fuel cells in those applications are also identified.

B.1 FUEL CELL TECHNOLOGY OPTIONS

B.1.1 Overview

There is a range of fuel cell technologies now used in various applications. These use a variety of membrane and fuel types, and produce various byproducts as shown in Figure 16. Fuel Cell Chemistry of Various Fuel Cell Types. Fuel Cells are electrochemical devices that convert chemical energy of a fuel and oxidant directly into electrical energy. Fuel cells produce electricity through an electrochemical reaction and not through a combustion process; they are much more efficient and environmentally benign than conventional electric power generation processes. Their inherent characteristics make them uniquely suitable to address the environmental, climate change, and water concerns associated with fossil fuel based electric power generation.

Fuel sources for the fuel cell are to a large extent application dependent and can include liquid hydrogen, gaseous hydrogen, light hydrocarbons (when used with an SOFC), solid fuels (hydrides etc. where the hydrogen is either product of a reaction or decomposition), fuel reforming, or electrolysis.

Figure 16. Fuel Cell Chemistry of Various Fuel Cell Types

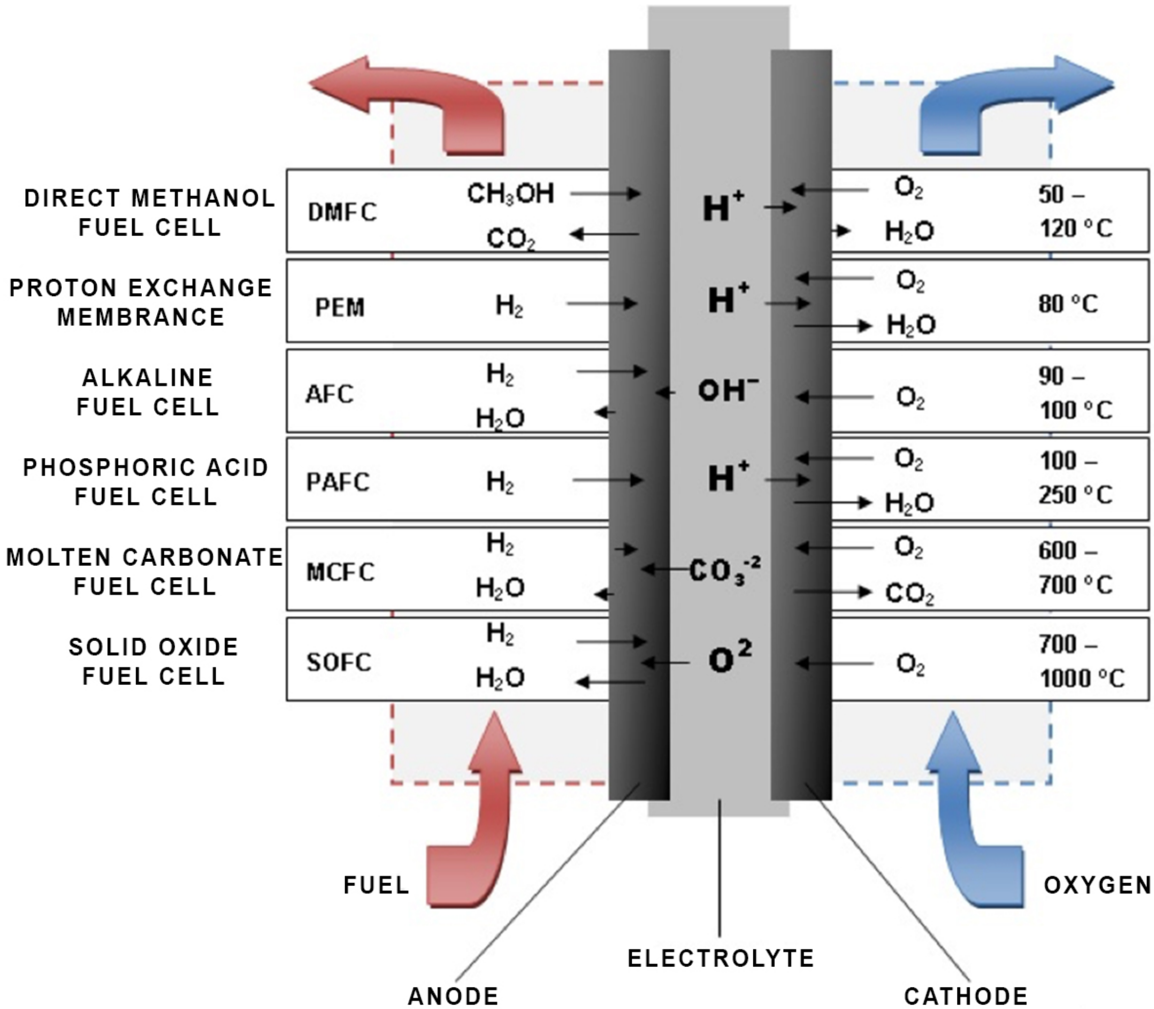


Table 1. Comparison of Fuel Cell Types

Fuel Cell Type	DMFC	Low-Temp PEM	High-Temp PEM	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Common Electrolytes	Perfluorosulfonic acid	Perfluorosulfonic acid	Phosphoric acid doped polybenzimidazole (PBI) membrane	Aqueous potassium hydroxide soaked in a porous matrix or alkaline polymer membrane	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	Yttria-stabilized zirconia
Operating Temperature	20°C to 130°C	80°C to 100°C	120°C to 180°C	<100°C	150°C to 200°C	600°C to 700°C	500°C to 1000°C
Typical Stack Size	50 W to 500 W	1 kW to 100 kW	1 kW to 100 kW	1 kw to 100 kW	5 kW to 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	300 kW to 3 MW, 300 kW module	1 kW to 2 MW
Electrical Efficiency (LHV)	20% to 30%	60% direct H240% reformed fuel	40% to 60%	60%	40%	50%	60%
Applications (Including Potential Aircraft Applications)	Backup power Specialty	Backup power Portable power Distributed generation Transportation Specialty vehicles Aircraft	Backup power Specialty	Military Space Backup power Transportation	Distributed generation	Electric utility Distributed generation	Auxiliary power Electric utility Distributed generation Aircraft

Fuel Cell Type	DMFC	Low-Temp PEM	High-Temp PEM	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Advantages	Low temperature Quick start-up and load following	Solid electrolyte reduces corrosion and electrolyte management problems Low temperature Quick start-up and load following	High carbon monoxide tolerance, No need for humidified gases	Wider range of stable materials allow lower cost components Lower temperature Quick start-up	Suitable for CHP Increased tolerance to fuel impurities	High efficiency Fuel flexibility Suitable for CHP Hybrid/gas turbine cycle	High efficiency Fuel flexibility Solid electrolyte Suitable for CHP Hybrid/gas turbine cycle
Challenges	Methanol crossover through the polymer membrane, Slow oxidation kinetics of methanol and methanol crossover, Short life	Expensive catalysts Sensitive to fuel impurities	R&D level activities, Lower power and efficiency	Sensitivity to CO_2 in fuel and air Electrolyte management (aqueous) Electrolyte conductivity (polymer)	Expensive catalyst Long start-up time Sulfur sensitivity	High temperature corrosion and breakdown of cell components Low start-up time Low power density	High temperature corrosion and breakdown of cell components Low start-up time Limited number of shutdowns Lower technology readiness level for airborne applications

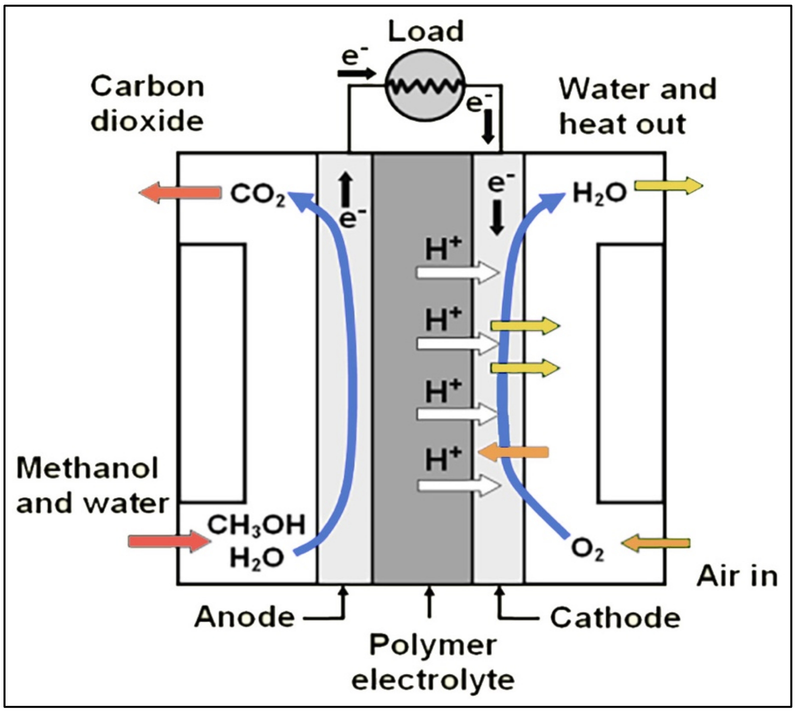
Table 2. Comparison of Fuel Cell Types and Chemistry

Chemistry	Direct Methanol Fuel Cell (DMFC)	Low-Temperature PPE	High-Temperature PEM	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
Fuel Capability	Methanol (CH_3OH)	Clean H_2	Clean H_2	Ultrapure H_2	Dirty H_2 from hydrocarbon reformate	Dirty H_2 from hydrocarbon reformate	Dirty H_2 from hydrocarbon reformate
Byproduct/ Exhaust	Carbon dioxide (CO_2) & water (H_20)	Water (H_20)	Water (H_20)	Water (H_20)	Water (H_20)	Carbon dioxide (CO_2) & steam/water (H_20)	Carbon dioxide (CO_2) & steam/water (H_20)
Self-Starting	Yes	Yes	No	Yes	No	No	No
Operating Life Limiter	CH_3OH crossover /diffusion	Humidity control	Membrane High temp	Potassium hydroxide (KOH) corrosion	Corrosion and oxidation	High-temperature corrosion	Thermal cycles
Electrolyte Type	Solid	Solid	Solid	Liquid + Solid	Solid	Liquid + Solid	Solid

B.1.2 Direct-Methanol Fuel Cells (DMFCs)

This is a subcategory of proton-exchange fuel cells (discussed in section B.1.3) in which methanol is used as the fuel. Their main advantage is the ease of transport of methanol, an energy-dense yet reasonably stable liquid at all environmental conditions. The general cell concept is shown in Figure 17.

Figure 17. Direct-Methanol Fuel Cell



Efficiency is quite low for these cells, so they are targeted especially to portable applications, where energy and power density are more important than efficiency.

DMFCs use a methanol solution (usually around 1M, i.e. about 3% in mass) to carry the reactant into the cell; common operating temperatures are in the range 20°C to 150°C, where high temperatures are usually pressurized. DMFCs themselves are more efficient at high temperatures and pressures, but these conditions end up causing so many losses in the complete system that the advantage is lost; therefore, atmospheric-pressure configurations are currently preferred.

Because of the methanol cross-over, a phenomenon by which methanol diffuses through the membrane without reacting, methanol is fed as a weak solution: this decreases efficiency significantly, since crossed-over methanol, after reaching the air side (the cathode), immediately reacts with air; though the exact kinetics are debated, the end result is a reduction of the cell voltage and efficiencies.

B.1.3 Proton Exchange Membrane Fuel Cell (PEMFC)

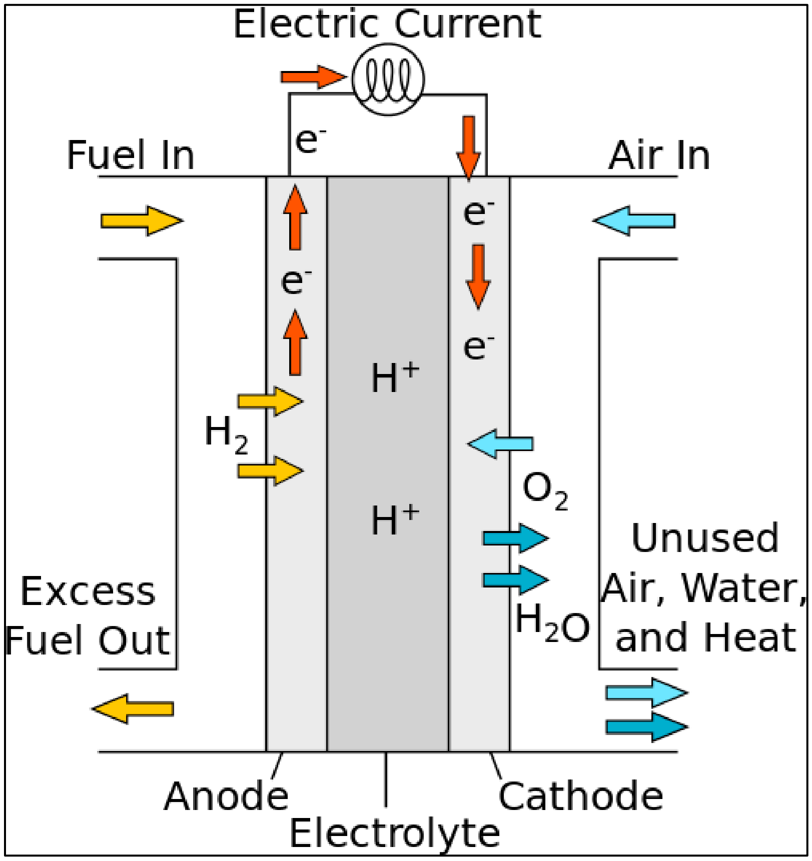
The proton exchange membrane, also known as PEM, uses a polymer electrolyte. PEM is one of the furthest developed (along with alkaline fuel cells) and most commonly used fuel cell systems. It was original developed and used by NASA in-Gemini missions in early 1960's. PEM FCs currently:

- Power automobiles, city busses, and forklifts,
- Serve as portable power sources, and
- Provide backup power in lieu of stationary batteries in offices.

The PEM system allows compact design and achieves a high energy-to-weight ratio. Another advantage is a relatively quick start-up when applying hydrogen. The low temperature version of the technology runs at a moderate temperature of below 80°C, with a maximum operating temperature of 80°C to 100°C and is 50 percent efficient. (The Internal Combustion Engine (ICE) is 25–30 percent efficient.) The high temperature versions run between 100°C to 200°C and is approximately 30% efficient.

The PEM fuel cell concept, shown in Figure 18, generally requires a platinum catalyst on the membrane and needs to manage the water at the membrane. The stack requires pure hydrogen; lower fuel grades can degrade the catalyst performance.

Figure 18. Proton Exchange Membrane Fuel Cell

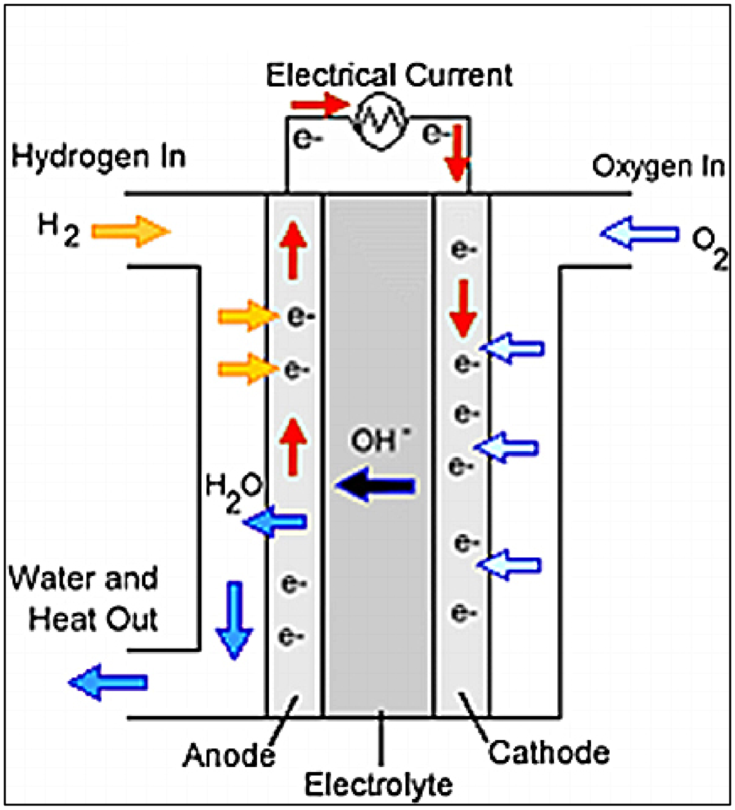


B.1.4 Alkaline Fuel Cell (AFC)

The alkaline fuel cell concept is shown in Figure 19. Also known as the Bacon fuel cell after its British inventor, Francis Thomas Bacon, it is one of the most developed fuel cell technologies. NASA has used alkaline fuel cells since the mid-1960s. They were used in Apollo-series missions and on the Space Shuttle. Alkaline fuel cells consume hydrogen and pure oxygen producing potable water, heat, and electricity. They are among the most efficient fuel cells, having the potential to reach 70%. They operate at temperatures less than 100°C.

There are two main variants of AFCs that exist: static electrolyte and flowing electrolyte. Static, or immobilized, electrolyte cells of the type used in the Apollo space craft and the Space Shuttle typically use an asbestos separator saturated in potassium hydroxide. Water production is managed by evaporation out the anode, as shown in Figure 19, which produces pure water that may be reclaimed for other uses. These fuel cells typically use platinum catalysts to achieve maximum volumetric and specific efficiencies. Flowing electrolyte designs, tend to use a more open matrix, which allows the electrolyte to flow either between the electrodes (parallel to the electrodes) or through the electrodes in a transverse direction (the ASK-type or EloFlux fuel cell).

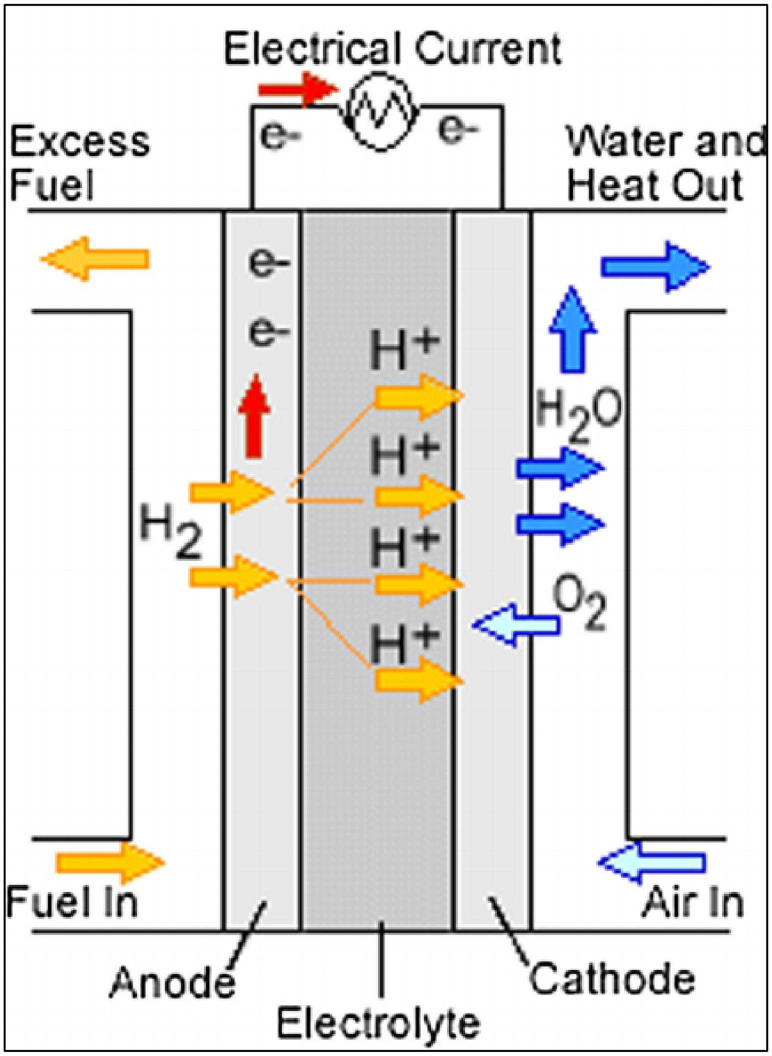
Figure 19. Alkaline Fuel Cell



B.1.5 Phosphoric Acid Fuel Cell (PCFC)

The PCFC concept is shown in Figure 20. Phosphoric acid is used as a non-conductive electrolyte to pass positive hydrogen ions from the anode to the cathode. These cells commonly work in temperatures of 150°C to 200°C. This high temperature will cause heat and energy loss if the heat is not removed and used properly. This heat can be used to produce steam for air conditioning systems or any other thermal energy consuming system. Using this heat in cogeneration can enhance the efficiency of phosphoric acid fuel cells from 40–50% to about 80%. Phosphoric acid, the electrolyte used in PAFCs, is a non-conductive liquid acid which forces electrons to travel from anode to cathode through an external electrical circuit. Since the hydrogen ion production rate on the anode is small, platinum is used as catalyst to increase this ionization rate. A key disadvantage of these cells is the use of an acidic electrolyte. This increases the corrosion or oxidation of components exposed to phosphoric acid.

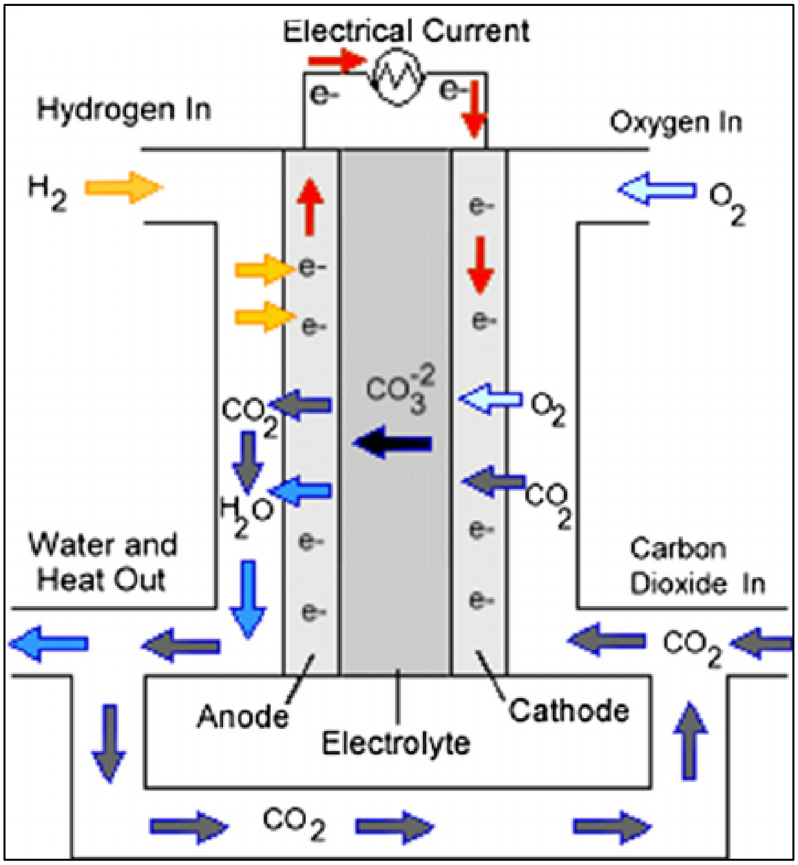
Figure 20. Phosphoric Acid Fuel Cell



B.1.6 Molten Carbonate Fuel Cells (MCFCs)

The MCFC concept is shown in Figure 21. Require a high operating temperature of 600°C to 700°C, similar to SOFCs (refer to section B.1.7). MCFCs use lithium potassium carbonate salt as an electrolyte, and this salt liquefies at high temperatures, allowing for the movement of charge within the cell – in this case, negative carbonate ions.

Figure 21. Molten Carbonate Fuel Cell



Like SOFCs, MCFCs are capable of converting fossil fuel to a hydrogen-rich gas in the anode, eliminating the need to produce hydrogen externally. The reforming process creates CO_2 emissions. MCFC-compatible fuels include natural gas, biogas, and gas produced from coal. The hydrogen in the gas reacts with carbonate ions from the electrolyte to produce water, carbon dioxide, electrons, and small amounts of other chemicals. The electrons travel through an external circuit creating electricity and return to the cathode. There, oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte, completing the circuit.

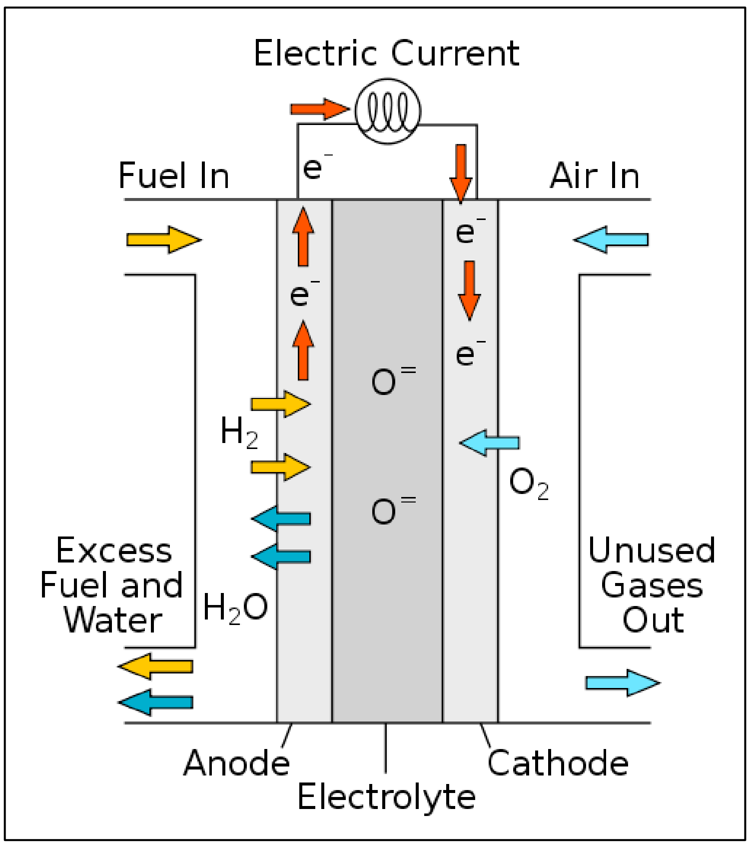
As with SOFCs, MCFC disadvantages include slow start-up times because of their high operating temperature. This makes MCFC systems less suitable for mobile applications, and this technology will most likely be used for stationary fuel cell purposes. The main challenge of MCFC technology is the cells' short life span. The high-temperature and carbonate electrolyte lead to corrosion of the anode and cathode. These factors accelerate the degradation of MCFC components, decreasing the durability and cell life.

Molten carbonate fuel cells hold several advantages over other fuel cell technologies, including their resistance to impurities. They are not prone to "carbon coking", which refers to carbon build-up on the anode that results in reduced performance by slowing down the internal fuel reforming process. Therefore, carbon-rich fuels like gases made from coal are compatible with the system.

B.1.7 Solid Oxide Fuel Cells (SOFCs)

Solid oxide fuel cells, shown in Figure 22, use a solid material, most commonly a ceramic material called yttria-stabilized zirconia (YSZ), as the electrolyte. Because SOFCs are made entirely of solid materials, they are not limited to the flat plane configuration of other types of fuel cells and are often designed as rolled tubes. They require high operating temperatures (500°C to 1000°C) and can be run on a variety of fuels including natural gas.

Figure 22 Solid Oxide Fuel Cell



SOFCs are unique since in those, negatively charged oxygen ions travel from the cathode (positive side of the fuel cell) to the anode (negative side of the fuel cell) instead of positively charged hydrogen ions travelling from the anode to the cathode, as is the case in all other types of fuel cells. Oxygen gas is fed through the cathode, where it absorbs electrons to create oxygen ions. The oxygen ions then travel through the electrolyte to react with hydrogen gas at the anode. The reaction at the anode produces electricity and water as by-products. Carbon dioxide may also be a by-product depending on the fuel, but the carbon emissions from an SOFC system are less than those from a fossil fuel combustion plant.

SOFC systems can run on fuels other than pure hydrogen gas. However, since hydrogen is necessary for the reactions listed above, the fuel selected must contain hydrogen atoms. For the fuel cell to operate, the fuel must be converted into pure hydrogen gas. SOFCs are capable of internally reforming light hydrocarbons such as methane (natural gas), propane and butane.

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APPENDIX C. FUEL CELL SELECTION FOR USE IN AN AVIATION ENVIRONMENT

C.1 INTRODUCTION

This appendix discusses two types of fuel cells; PEM and SOFC. These two technologies are the most feasible types for installation on board an aircraft. While a DMFC might also be selected for low power applications, it is not covered in this section. Some applications where a DMFC could be used would be for self-contained portable low power systems (i.e. laptop computer power modules) and smaller unmanned aerial vehicles. The following sections will describe the PEM and SOFC technology in more depth than the overview provided in Appendix B. The information on how the technology is configured into a system with all the components and subsystems is also discussed. Important features that might have an impact on the aircraft safety are discussed. System failure modes will also be identified for consideration in Sections C.4, C.5 and C.7.

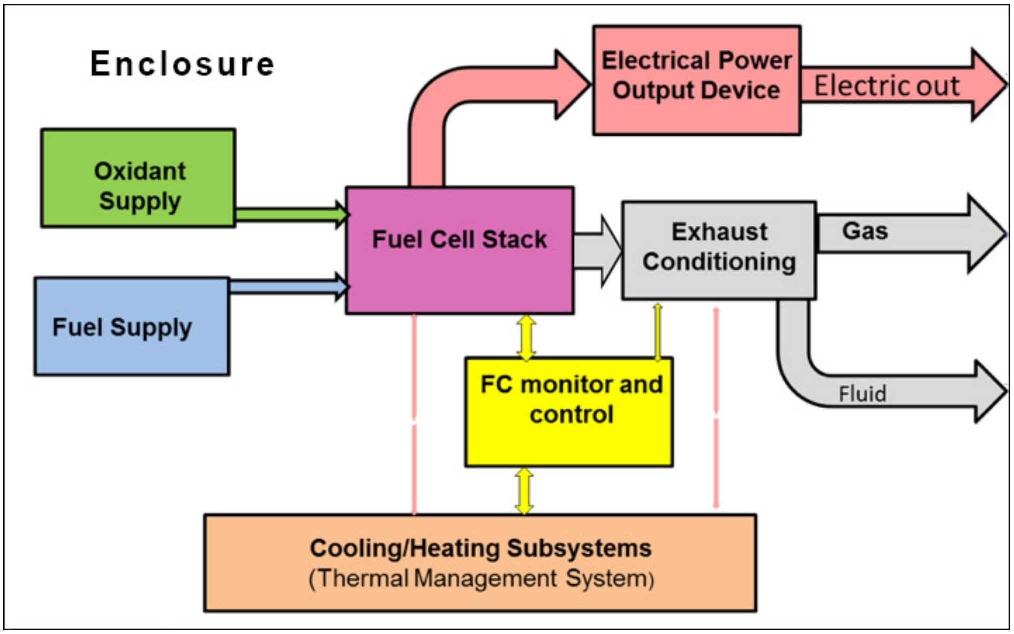
Two variations of the PEM technology are discussed; low and high temperature. PEM fuel cells are generally more mature than SOFC for transportation applications. PEM fuel cells, for example, are being used in commercial automotive application, while SOFCs are used commercially primarily in the stationary power market, with other SOFC mobile applications still in development stages. This will tend to favor PEM FCS for early introduction into the aircraft. However, the projected SOFC capability and technology maturation over the next few years may allow for greater opportunity for SOFC's in aircraft applications.

Proton exchange membrane and SOFC technology could also be used for regenerative systems described in Appendix D, section D.10, *Regenerative FC Energy Storage*. This technology could be used to generate fuel on the aircraft for fuel cell operation as needed by the fuel cell. This has the potential to store more energy than a battery of the same weight (if the energy storage is above 10 kWh) or store energy that might otherwise be wasted as heat.

C.2 THE FUEL CELL SYSTEM

The fuel cell system, shown in conceptual blocks in the Figure 23, is made up of the fuel cell stack and subsystems. The fuel cell stack is that portion of the fuel cell system that performs the electrochemical conversion of fuel and oxidant into electric energy, thermal energy, and exhaust products. The systems also includes an enclosure, fitting, wiring, and all devices allowing the connection to other fuel cell subsystems.

Figure 23. Fuel Cell System Block Diagram



The following descriptions provide a general overview of each of the subsystems shown in Figure 23. These sytems, and some that are specific to either PEMFC and SOFC system designs are discussed in greater detail in the following sections of this appendix. The applications sections also provides detail for the specific concepts offered as examples of a system for the specific application.

C.2.1 Oxidant Supply

The oxidant supply subsystem is generally composed of the oxygen or air needed for the fuel cell stack and the equipment needed to deliver it to the stack. It may include the tank to contain the oxidant and the valves, regulators, and piping to prepare oxidant for the fuel cell stack. Additional detail on the oxidant supply design options and consideration is provided in Appendix D, section D.9, *Oxygen Sources and Environmental Control Impacts*.

C.2.2 Fuel Supply

This subsystem is generally composed of the fuel needed for the fuel cell stack, the tank to contain it and the valves, regulators and piping to prepare the fuel for the fuel cell stack. This can include any special fuel (H_2, reformate, enriched H_2, or other not common to aircraft) and tank (not from kerosene tank), even if separately located, is part of FCS. It also includes a reformer to process, for example, fuel from the aircraft tank to make it suitable for the fuel cell stack. Additional detail on the fuel supply design options and consideration is provided in oxygen sources Appendix D, section D.9, *Oxygen Sources and Environmental Control Impacts*.. Discussion of the reformer options is provided in section D.8 of Appendix D, *Reformer.*

C.2.3 Fuel Cell Stack

This subsystem is composed of the cells that combine the reactants electrochemically and produce power. The stack also produces water, waste heat, and in the case of an SOFC, CO_2. PEM stacks generally include water cooling to the cells to remove heat to the cooling heating system. In cases where humidification of the reactants is required and water must be removed, like the PEMFC stack, the fuel cell stack subsystem also includes components needed for water removal.

C.2.4 Exhaust Conditioning

This subsystem includes any components needed to transport or manage the water or CO_2 products. Exhaust lines are considered part of FC system if they are connected to the exhaust conditioning components of the FC. It does not include any exhaust lines that would be included in the basic aircraft type design (i.e., those not installed specifically to accommodate the fuel cell system. It can also include inert gases that are a part of the fuel and oxidant supply. It may also include oxygen depleted air.

C.2.5 Cooling/Heating

This subsystem includes the means to remove heat from the stack and other components in the FC system. It may include the component to regulate the temperatures within the system. This also includes, and is not limited to, fans, blowers, vents, liquid loops and heat exchangers controlled by the FC system. The function can be shared by FC system and aircraft. The FC supplier must provide heat load and rejection information to aircraft manufacturer.

C.2.6 Electric Power Output

This system conditions the power from the FC stack and matches it to the aircraft's electrical bus requirements. A battery may be included in this section if needed for peak power or start up if the bus cannot provide the power for starting. Wiring and other electrical wiring interconnection system (EWIS) components necessary for the installation and proper functioning of the FC are part of the FC system. EWIS components basic to the aircraft's type design are not part of the FC system.

C.2.7 FC Monitoring and Control

This subsystem controls all the FC functions and provide communication and command data lines to the aircraft. A battery may be included in this section if needed for controls backup power or startup power. Wiring installed with the FC and connectors are part of the FC system. Wiring that is part of the aircraft is not part of the FC system. The flight deck indicators and controls for the FC are not part of the FC system

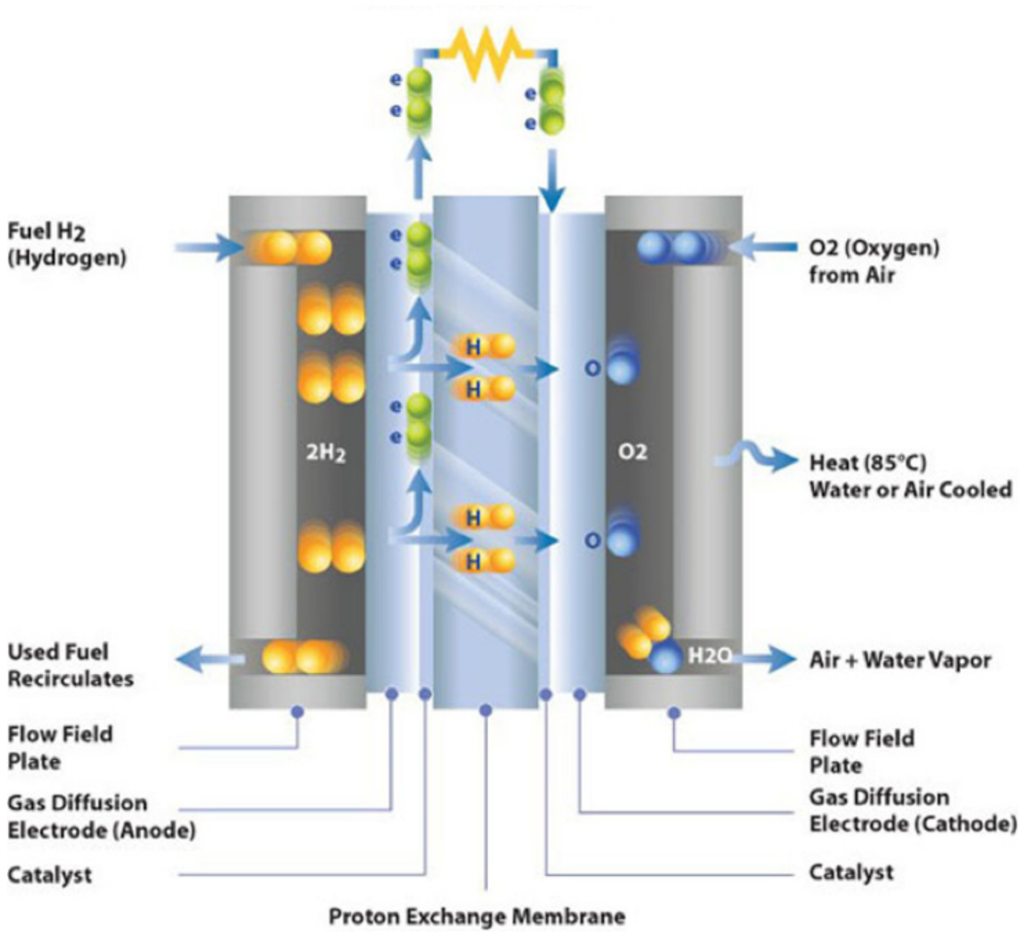
C.2.8 Enclosure

This subsystem may be an open or sealed structure around part or all the FC system. This structure may be required for the proper operation, safety, or mechanical attachment of the fuel cell system and is part of the FC installation. Mounting features that provide mechanical attachment of the enclosure or system components to the aircraft are part of the FC system.

C.3 PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL: LOW & HIGH TEMPERATURE

The core of the PEM fuel cell consists of a membrane electrode assembly (MEA), which is placed between two flow-field plates. The MEA consists of two electrodes, the anode and the cathode, which are each coated on one side with a thin catalyst layer (usually platinum) and separated by a solid membrane electrolyte. The flow-field plates direct hydrogen to the anode and oxygen (from the air) to the cathode. Refer to Figure 24.

Figure 24. Example of a Single Cell PEM Fuel Cell



On the anode, hydrogen flows through channels in flow field plates and reaches the anode catalyst layer. The platinum catalyst promotes the separation of hydrogen into protons (hydrogen ions) and electrons. The free electrons, produced at the anode, are conducted in the form of a usable electric current through the external circuit. Hydrogen can be supplied to a fuel cell directly or may be reformed from natural gas, methanol, or petroleum using a fuel processor, which converts the hydrocarbons into hydrogen and carbon dioxide through a catalytic chemical reaction. This is known as fuel reforming.

On the cathode, oxygen from the air flows through the channels in flow field plates. The hydrogen protons that migrate through the proton exchange membrane combine with oxygen in air and electrons returning from the external circuit to form pure water and heat. The air stream also removes the water created as a by-product of the electrochemical process.

The reactions occurring in the fuel cell is as follows:

Anode reaction: $H_2 \rightarrow 2H \rightarrow 2e$

Cathode Reaction: $\frac{1}{2} O_2 + 2e + 2H \rightarrow H_2O$

Overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ + Electricity + Heat

As heat is also produced in the overall reaction, it must be removed to maintain the target operating temperature. Heat removal may be done directly through the air stream or via a cooling fluid flowing through coolant channels that are typically integrated in the flow field plates.

A single cell consists of the membrane electrode assembly and two flow-field plates. To obtain the desired power output, cells may be repeated in series to form a fuel cell stack. Increasing the number of cells in a fuel cell stack increases the output stack voltage, while increasing the surface area of the cells increases the output current. The fuel cell stack can have elastomeric seals between cells and cell components and/or encapsulated externally to prevent coolant or reactant leaks. The stack also contains the manifolds that provide even distribution of reactants and coolant to each cell.

There are two version of the PEM FCS; the low temperature (LT) and the high temperature (HT), based on different cell membrane technology. There are detailed discussions on each technology in the following sections, but the primary trade-offs are:

- LT is more mature
- LT has higher efficiency
- HT is less sensitive to contaminant in the air that could cause performance degradation
- HT has a smaller heat rejection system

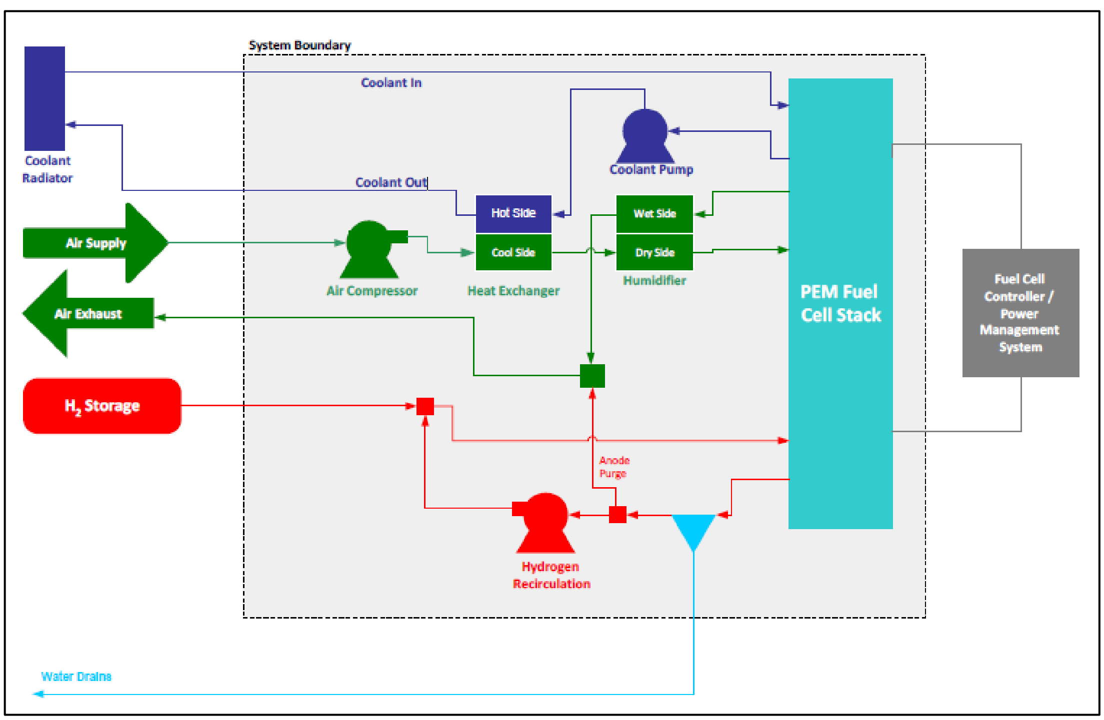
C.4 LOW-TEMPERATURE PEM FUEL CELLS

Low Temperature PEM (LT-PEM) Fuel Cells are typically limited to less than 120°C due to stability of the membrane and evaporation of water. More practically it is limited to 85°C to 90°C in high or peak temperature application. Because of the thin membrane, and low resistance losses, LT-PEM fuel cells tend to deliver high power density and offer the advantages of low weight and volume, compared to other fuel cell types. The low temperature operation also allows them to start quickly (less warm-up time) and to start from freeze condition (0°C), which makes them particularly well suited for transportation applications such as automobiles and fleet vehicles. However, water must be managed to keep the membrane wet for ion conduction, but not flooded, and carbon monoxide (CO) easily contaminates catalysts at low temperature, complicating use of reformed fuels

Figure 25 is a typical schematic of a LT-PEM Fuel Cell System. Within the boundary diagram, it can be generalized that the following subsystems (in addition to the PEM Fuel Cell Stack) are typical of a PEM Fuel Cell System:

- Air Subsystem;
- Fuel Delivery Subsystem;
- Coolant Subsystem;
- Power Management System.

Figure 25. Typical Low-Temperature Proton Exchange Membrane Operational Diagram



C.4.1 LT-PEM Oxidant Supply—Air Subsystem

As O_2 is required in the cathode reaction, every PEM system must have an air or O_2 delivery subsystem. The Air subsystem has two main roles: to deliver the air at the required flow, pressure, temperature, and humidity; and to exhaust the depleted air, anode purge gas and liquid water out of the fuel cell system. A typical air subsystem consists of the following components to perform the following functions:

- Air compressor or blower—delivers the air to correct pressure and flow
- Heat exchanger—takes the incoming air supply, and heats it up with the coolant outlet stream, in preparation for air humidification. This heat exchanger is coupled with the coolant subsystem.
- Humidifier—takes the heated air, and humidifies it with the air exhaust, exiting the fuel cells stack.

Some systems are designed to operate on pure O_2. For these systems, an air compressor or blower is not required. Furthermore, because there is no nitrogen gas (N_2), the O_2exhaust exiting the fuel cell stack can be recirculated with the incoming O_2 (like what is shown in Figure 25 for the H_2 side) to provide the correct temperature and humidity, thus reducing or eliminating the need for the heat exchanger and humidifier.

C.4.2 LT-PEM Fuel Supply—Fuel Delivery Subsystem

As H_2 is required in the Anode reaction, every PEM system must have a fuel delivery subsystem. The fuel delivery subsystem has three main roles: supply the fuel cell stack with the correct pressure, flow; recirculate the H_2 exiting the fuel stack with the incoming H_2; and separate liquid water from the H_2 exhaust and direct it the oxidant exhaust stream. A typical fuel delivery system has the following components:

- Pressure regulators—to regulate to the correct pressure and flow
- H_2 recirculation system—to recirculate the anode exhaust with the incoming H_2
- Water separator—to separate out liquid water

C.4.3 LT-PEM Fuel Cell Stack

The fuel cell stack is composed of a series of electrochemical cells. As illustrated in Figure 24, these cells have a membrane and a means to conduct electrical current. The stack contains flow passages and manifolds for the oxidant and fuel, as well as coolant that must be circulated to remove excess heat (to cooling system) and keep the stack at the target operating temperatures. The stack can have elastomeric seals between cells and cell components and/or encapsulated externally to prevent coolant or reactant leaks.

C.4.4 LT-PEM Exhaust Conditioning

Conditioning of the exhaust in a typical low temperature PEM system may include: transfer of heat and humidity from the exhaust to the incoming oxidant supply; removal of liquid water; and extra dilution of H_2. Extra dilution of H_2 in the exhaust is further discussed as follows.

The exhaust from a typical low temperature PEM system design may combine both the anode and cathode exhaust refers to the may contain hydrogen gas combine the anode exhaust before venting to atmosphere. Therefore, hydrogen gas may be present in the exhaust from the anode purging or from transfer leaks through the fuel cell membrane. During normal operation, the hydrogen concentration in the exhaust will be well below flammable limits, but to minimize the risk of ignition event extra dilution of the exhaust such as dilution by cooling fan air flow should be considered.

C.4.5 LT-PEM Cooling/Heating

As heat will be generated by the PEM electrochemical reaction, every PEM system must have a coolant subsystem to extract the heat that is generated. A secondary purpose is to provide heating to the incoming air supply. A typical coolant subsystem has the following main components:

- Coolant Pump and thermostatic valve system—to provide the correct flow, temperature and pressure within the coolant loop.
- Heat Exchanger and bypass valve system—the bypass valve system directs a portion of the coolant from the main coolant loop to the heat exchanger. The heat exchanger is coupled with the air delivery system, and provides heating to incoming air supply. Since the operating temperature is generally around 80 °C, the heat exchangers are much larger than high temperature PEM and SOFC.

C.4.6 LT-PEM Electrical Power Output: Power Management Subsystem

The main purpose of the power management subsystem is to collect the current/voltage that the fuel cell stack outputs to: provide power main load and to power the balance of plant components within the fuel cell system.

C.4.7 LT-PEM FC Monitoring and Control

The fuel monitoring and control system should provide two main functions: provide control interlocks to ensure safe operation and prevent damage to the system on shutdown; and provide operating state control to enable start-up and shut-down sequence and fault responses.

C.4.8 LT-PEM Enclosure

The LT- PEM Fuel Cell stack and certain of the sub-systems may be packaged in an enclosure. The enclosure must provide: maintenance access; ventilation inlet; ventilation outlet; and/or ingress protection against environmental elements such as dust, dirt or water. Hydrogen gas leak detection is also needed and system and fuel supply shut-down should occur if a detection occurs.

C.4.9 LT-PEM Startup and Shutdown

The time for a LT-PEM Fuel Cell stack to produce power can be quick and the power can be generated as soon as reactants gases are supplied to stack. If the PEM fuel cell stack is started below freezing conditions, there will be additional time that is required to warm up and prepare the stack to have access to the reactant gases.

Exact details of start-up and shut-down sequence are considered proprietary. However, in general, start-up and shutdown strategies are designed to enable the safe start and shutdown of a fuel cell, and to mitigate against conditions that lead to failure modes within the PEM fuel cell stack. Nitrogen gas may be needed to inert the fuel cell stack at shutdown. Water must also be managed if the system will drop below freezing.

C.4.10 LT-PEM Airframe Integration Considerations

Low temperature PEM fuel cells have inherent operational characteristics that should be considered for airframe integration:

- LT-PEM Fuel Cells operate at temperatures of 60 °C to 80°C. The heat discharge could be usable in the in other aircraft systems.
- LT-PEM Fuel Fell stacks generate water as a byproduct. The water could be used for other aircraft system needs in the pressurized volume and the passenger cabin. Also, in an environment where temperatures get below freezing (while the fuel cell is not running) designs must clear the system of water or be water freeze tolerant to avoid events that lead to failure of the fuel cell stacks.
- Some LT-PEM Fuel Cell system designs need N_2 to use during shutdown. As such, the addition of N_2 pressurized gas bottle would be needed for this type of system design.
- LT-PEM Fuel Cell system designs need to purge the anode exhaust. As such, a safe venting path for the exhaust is required.
- LT-PEM Fuel Cells need to reject about 1 kW of heat for every 1 kW in electrical power. Therefore, a low temperature (60-80°C) coolant subsystem and radiator to reject the heat is necessary. The installation needs to provide an adequate area for a radiator and in a suitable location that will allow heat to be rejected.

C.4.11 LT-PEM Fuel Cell Failure Modes

Examples of common LT-PEM Fuel Cell failure modes include hazardous fluid leakage that may develop over time or in response to cell reversal. This includes fuel-to-coolant transfer, which may result in the presence of hydrogen within (and possibly emitted from) the cooling system, and fuel-to-air transfer, which may result in potentially flammable mixtures being emitted during operation.

Cell reversal is typically caused by overheating or fuel starvation. Cell reversal failures are typically uncommon (and may be mitigated through cell voltage monitoring), but are most frequently caused by a lack of protons (i.e., fuel starvation) or failure to conduct protons (i.e., overheat or dehydration causing loss of membrane conductivity) in one or more cells, where the remaining cells then drive these starved cells into voltage reversal, causing an electrical shorting failure across the affected cell's membrane. These membrane-shorting failures then permit fuel-to-air transfer and the possible formation of flammable emissions in the cathode exhaust, and/or if plates are cracked or damaged, can lead to ignited external fuel leaks, and/or fuel-to-coolant transfer leaks putting potentially flammable concentrations of hydrogen in the system exhaust or ventilation flows, or in the radiator or storage tank head-space within cooling systems.

Risks that may lead to cell reversal result from non-intentional operational conditions include:

- Loss of, or inadequate, coolant flow
- Loss of, or inadequate, humidity
- Loss of, or inadequate, fuel supply

Hazardous fluid leakage due to cell reversal damage may (or may not), depending on stack and system design and levels of oxidant O_2-enrichment above atmospheric, lead to immediate or delayed ignition of flammable emissions or leakage; causing further potential hazards (e.g., toxic smoke and possible hydrogen fluoride emissions from the cells), with possible secondary involvement of stack or enclosure insulating materials, and the possibility for high pressures within the packaging or system cathode exhaust due to hydrogen combustion or detonation.

Hazardous fluid leakage may also result if the fuel cell stack is operated above its maximum allowable working pressure and/or maximum allowable cross pressure, causing membrane failure and internal transfer and/or external leakage.

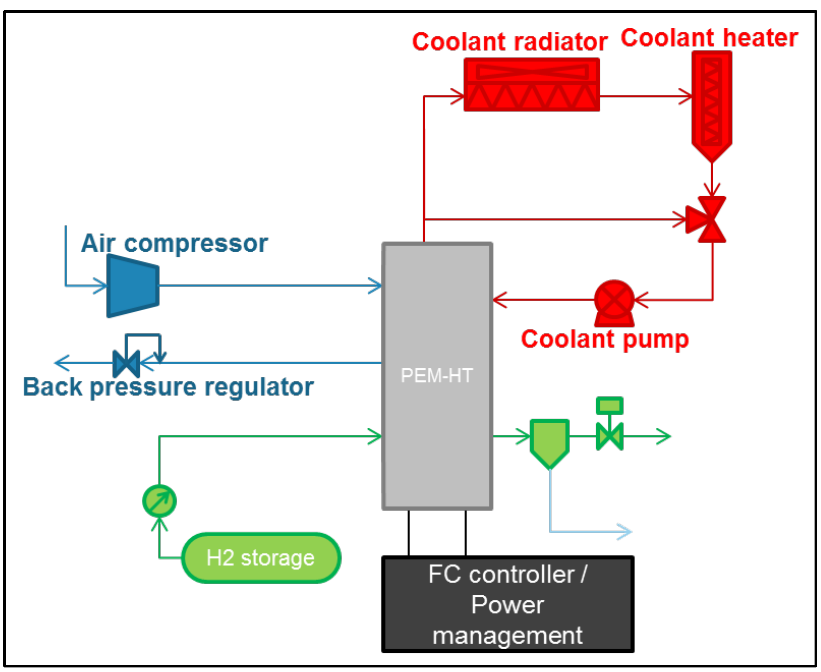
C.5 HIGH-TEMPERATURE PEM FUEL CELLS

A high temperature PEM could be the same technology as a low temperature PEM operating at a higher pressure or a PEM with a different electrolyte, as in the case of a Phosphoric Acid Fuel cell. High Temperature PEM (HT-PEM) Fuel Cells maybe based on a phosphoric acid doped Polybenzimidazole (PBI) membrane. Phosphoric acid acts as the proton carrier through the membrane, instead of liquid water in the case of LT-PEM Fuel Cells. Therefore, no water management is needed, and removal of produced water vapor is considerably eased-up compared to liquid water in the case of LT-PEM Fuel Cells. Also, membrane performance is not subjected to a hydration requirement for proton conduction, or to flooding conditions in case of inefficient water removal.

High Temperature PEM Fuel Cells operate typically between 120°C and 180°C to ensure that water is produced as vapor and to ensure stability of the membrane. Operating HT-PEM below 100°C is possible but may result in reduced performance and durability due to liquid water production washing the phosphoric acid. Operating HT-PEM Fuel Cells above 180 °C is possible, up to 200°C or even 220°C, but may result in accelerated aging and reduced lifetime. Due to thicker membrane and higher activation losses compared to LT-PEM Fuel Cells, HT-PEM Fuel Cells offer lower power and efficiency. Nevertheless, the development of HT-PEM Fuel Cell has started more recently, hence yielding a less mature technology than the LT-PEM Fuel Cell. But it is expected that nominal performances will soon increase to viable levels as the technology matures. The high temperature operation requires more warm-up time, but presents the advantage of enhanced heat exchange due to a higher temperature difference between the fuel cell and the cold source where the heat is dissipated. Consequently, the size of heat exchangers for fuel cell cooling, or for heat recovery, can be reduced in size. The high temperature functioning allows a higher tolerance to pollutants (such as CO, CO_2, NOx), notably in fuel, offering more opportunities to operate with a fuel processor (e.g., reformers).

Figure 26 is a typical schematic of a HT-PEM Fuel Cell System. It is comprised of an air subsystem, fuel delivery subsystem, thermal management subsystem, and power management subsystem. These subsystems are described in the following paragraphs.

Figure 26. Simplified Example Schematic of High Temperature PEM FC System



C.5.1 HT-PEM Air Subsystem

The air subsystem of a HT-PEM Fuel Cell is simpler than that of a LT-PEM Fuel Cell. It mainly consists in delivering air at the required flow rate and pressure (no humidification required), and to exhaust the depleted air containing water steam. A typical air subsystem is comprised of the following components:

- Air compressor or blower that delivers the air to correct pressure and flow;
- A back-pressure regulator to maintain sufficient pressure inside the stack;
- As for the LT-PEM, air independent systems are possible and would be similar to those described previously in section C.4.1.

Pressurized, pure O_2 could also be used.

C.5.2 HT-PEM Fuel Delivery Subsystem

As for the LT-PEM, H_2 is required at the anode. In a HT-PEM Fuel Cell system, the fuel delivery subsystem usually comprises the followings:

- Pressure regulator to deliver fuel at the desired pressure
- Water separator to condense and separate out liquid water (optional)
- Purge valve to close and open the anode circuit in order to evacuate the water steam from the reaction

C.5.3 HT-PEM Thermal Management Subsystem

As for the LT-PEM, an HT-PEM requires the generated heat to be removed. The thermal management subsystem is also used to heat-up the fuel cell stack during start-up phase. The main components are:

- Coolant pump and thermostatic valve system to provide the required coolant flow rate within the fuel cell stack and within the heat exchanger
- Coolant radiator to exchange the heat to be evacuated with a cold sink such as air from the exterior or any other fluid in order to recover and valorize the rejected heat from the fuel cell stack
- Coolant heater to heat-up the coolant and the fuel cell stack during start-up phase of the fuel cell stack; the coolant heater can also be a heat exchanger to recover heat from another system of the aircraft

As the heat generated by the HT-PEM Fuel Cell Stack is comprised between 120°C and 180°C, the temperature difference with the cold source is greater than in the case of a Low Temperature PEM Fuel Cell Stack which temperature is below 100°C. The result is that the coolant radiator is of a smaller size as the required exchange surface is less. The cold source flow rate required (air as an example) is also less which results in reduced parasitic losses.

C.5.4 HT-PEM Electrical Power Outlet: Power Management Subsystem

As with LT-PEM Fuel Cells, the main purpose of the power management subsystem is to collect the current/voltage that the fuel cell stack outputs to: provide power main load and to power the balance of plant components within the fuel cell system.

C.5.5 HT-PEM FC Monitor and Control

As with LT-PEM Fuel Cells, the fuel monitoring and control system should provide two main functions: provide control interlocks to ensure safe operation and prevent damage to the system on shutdown; and provide operating state control to enable start-up and shut-down sequence and fault responses.

C.5.6 HT-PEM Exhaust Conditioning

- HT-PEM fuel cell stacks generate water in the form of steam. In an environment where temperatures get below freezing, especially while the fuel cell is not running, designs must clear the system of water or be water freeze tolerant to avoid events that lead to failure of the fuel cell stacks. The removal of water in the form of steam is eased-up compared to the case of liquid water as in the case of LT-PEM fuel cell.
- Water is produced in the form of steam. This could be usable in in other aircraft systems.
- Some HT-PEM system designs need to purge the anode exhaust that contains H_2. As such, a safe venting path for the exhaust is required.
- Due to Phosphoric acid doping, exhaust acidity, and therefore, corrosivity should be taken into consideration for material selection.

C.5.7 HT-PEM Enclosure

The HT-PEM fuel cell stack and some of the sub-systems may be packaged in an enclosure. The enclosure must provide: maintenance access; ventilation inlet; ventilation outlet; and/or ingress protection against environmental elements such as dust, dirt or water. Hydrogen gas leak detection is also needed and system and fuel supply shut-down should occur if a detection occurs.

C.5.8 HT-PEM Startup and Shutdown

As for LT-PEM FC systems, exact details of start-up and shut-down sequence are considered proprietary. However, in general, start-up and shutdown strategies are designed to enable the safe start and shutdown of a fuel cell, and to mitigate against conditions that lead to failure modes within the PEM fuel cell stack. Dependent on the PEMFC design, purging events during startup and shutdown may be required to clear the stack of inert gases. This could require some additional system interface or design features, especially if the system is in the pressurized hull/passenger compartment (to make sure there are no issues with those gases in the passenger compartment).

C.5.9 HT-PEM Airframe Integration Considerations for High Temperature PEM Fuel Cells

High Temperature PEM Fuel Cells have slightly different inherent operational characteristics compared to LT-PEM Fuel Cell, which should be considered for airframe integration:

- HT-PEM FC's operate at temperature of 120°C to 180°C. This could be usable in other aircraft systems.
- Water is produced in the form of steam. This could be usable in other aircraft systems.
- Some HT-PEM system designs need N_2 to use during shutdown. As such, the addition of N_2 pressurized gas bottle would be needed for this type of system design.
- Some HT-PEM system designs need to purge the anode exhaust. As such, a safe venting path for the exhaust is required.
- HT-PEM FC's need to reject about 1 kW of heat for every kW in electric. Need to provide a coolant subsystem at temperature comprised between 120°C and 180°C and radiator to reject the heat. Designs need to provide adequate area for a radiator or a heat exchanger and a location to allow the heat to be rejected or recovered for valorization.
- The time for a HT-PEM fuel cell stack to produce power depends of its initial temperature and varies from few seconds (if initially above 100°C) to few minutes (if initially below 100°C) and the power can be generated as soon as reactants gases are supplied to the stack. If the HT-PEM fuel cell stack is started below freezing conditions, additional time is required to warm up and prepare the stack to have access to the reactant gases.
- HT-PEM fuel cell stacks generate water in the form of steam. In an environment where temperatures get below freezing (while the fuel cell is not running) designs must clear the system of water or be water freeze tolerant to avoid events that lead to failure of the PEM fuel cell stacks. The removal of water in the form of steam is eased-up compared to the case of liquid water as in the case of LT-PEM fuel cell.

C.5.10 HT-PEM Failure Modes

Most failure modes of HT-PEM fuel cells are common to those of LT-PEM fuel cells. One of the major differences between HT and LT–PEM fuel cells is that HT-PEM fuel cells do not require hydration of the membrane to ensure proton conductivity as the proton carrier in the membrane is the phosphoric acid. As a consequence, the proton conductivity is not dependent on hydration of the membrane neither on an overheat situation triggering a drying of the membrane. The membrane material, PBI for Polybenzimidazole, has a very good thermal stability, allowing it to withstand high temperature peaks without breaking or cracking, although functioning at temperature above 180°C will generally accelerate aging. In the case of a fuel-to-air transfer due to pinhole formation, the leaked fuel meets air in the cathodic catalytic region which enhances a catalytic combustion. The catalytic combustion forms water directly without producing electrons usable in the electrical circuit and generates heat. If the phenomenon is not stopped, it can bolt as the generated heat would increase the temperature locally and cause membrane material degradation and increasing leakage.

In the case of high temperature PEM fuel cells, the coolant liquid is generally not water as the temperature is above 100°C. Different fluids being liquid in the range of 120°C to 180°C and more can be used as coolant. As an example, synthetic oils can be used. In case of leak of hot oil, it is necessary to collect the leaked product to prevent from ignition.

C.6 SOLID OXIDE FUEL CELLS

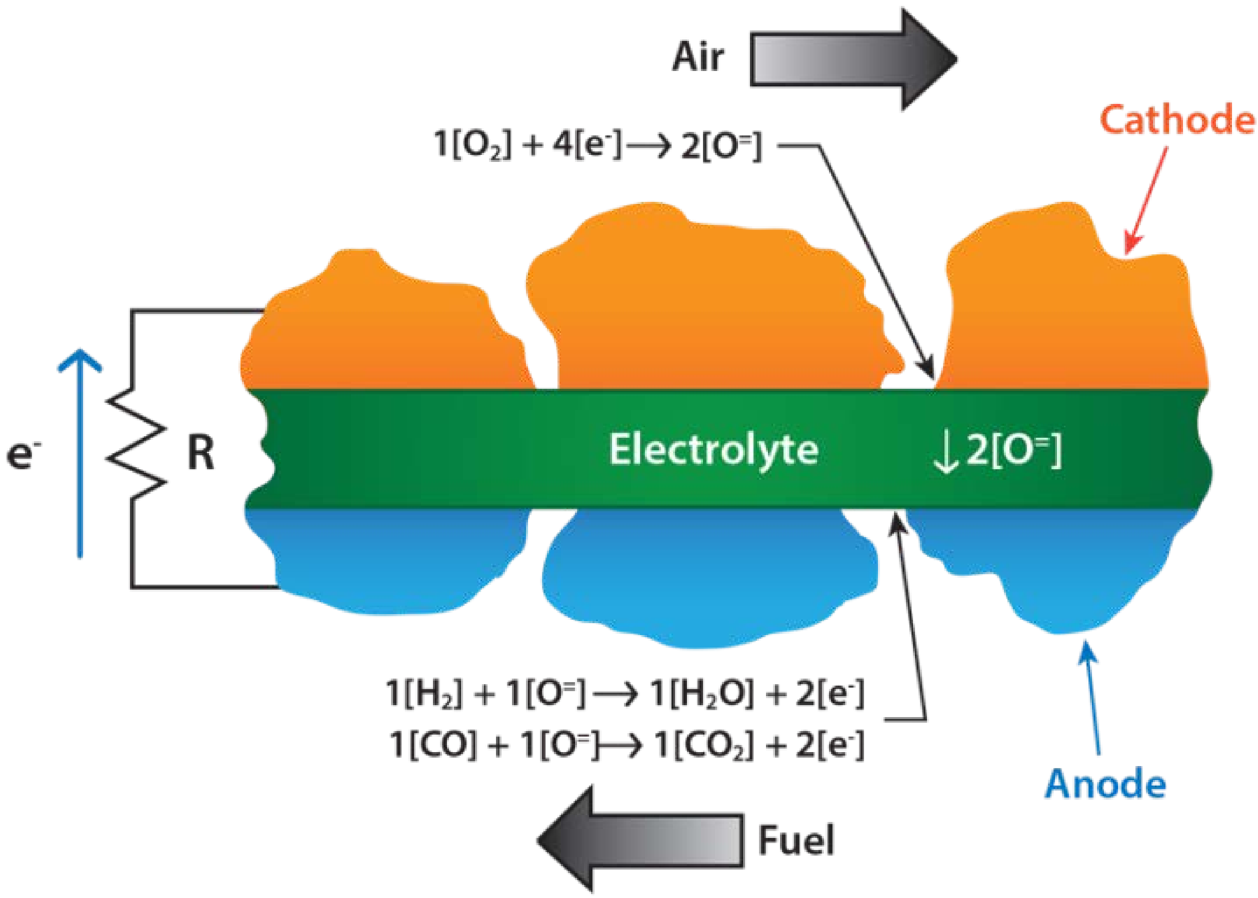
Fuel cells are often characterized by their electrolyte material; the SOFC has a solid oxide or ceramic electrolyte capable of very high temperature operation (600°C to 800°C). Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, and low emissions. A SOFC cell consists of three bonded layers: a cathode, an anode, and a ceramic electrolyte separating the electrodes. Each electrode is a thin, porous, electronic (e-) conductor. Electrode porosity is required for gaseous diffusion between the electrode's outer surface and the electrode/electrolyte interface. The electrolyte is a thin, fully dense oxygen ion (O=) conductor, but not an electronic conductor. The electrolyte needs to be fully dense to prevent gaseous fuel from contacting air and burning. The cells in an SOFC can be either of a tubular configuration or a flat planar configuration.

SOFCs can operate on hydrogen, CO, or reformed / processed hydrocarbon fuels. In contrast to the low temperature fuel cells for which CO is a contaminant, SOFC can utilize both H_2 and CO in the electrochemical reaction. (H_2 and CO are produced by the coal gasification process and by reformation of hydrocarbon fuels, such as CH_4, as discussed in more detail later in this section.) Figure 27 illustrates the electrochemical physics of a SOFC operation. As shown, gaseous fuel flows across the outer surface of the porous anode, and H_2 and/or CO molecules reach the anode/electrolyte interface by pore diffusion. The fuel-side electrochemical reactions occur at triple points, located at this interface. At a fuel-side triple point the electrolyte (oxygen ion donor), the anode (electronic conductor), and the pore (source of the H_2 or CO molecule) meet. Oxygen ions (O=) are extracted from the electrolyte, and the following exothermic reactions occur:

$$1[H_2] + 1[O=] \longrightarrow 1[H_2O] + 2[e-]$$

$$1[CO] + 1[O=] \longrightarrow 1[CO_2] + 2[e-]$$

Figure 27. Electrochemical (Cell) Physics of Solid Oxide Fuel Cell



In the process, two electrons are transferred to the anode (negative electrode) for each H_2 or CO molecule reacted, and the reaction products, H_2O and CO_2, diffuse back toward the outer surface of the porous anode, where they enter the fuel stream.

A competing reaction to the CO electrochemical reaction is the so-called water-gas shift reaction, where CO reacts with H_2O to form additional H_2 and CO_2. Both the shift reaction and the electrochemical reaction do occur but the shift reaction is a strong function of temperature with the tendency to shift towards the reaction products (H_2 and CO_2) as the temperature is decreased. (Water-gas shift reactors for PEM and PAFC operate in the 200 °C to 350 °C range in order to completely react the CO.)

As also indicated in Figure 27, air flows across the outer surface of the cathode, and O_2 reaches the cathode/electrolyte interface by pore diffusion. The air-side electrochemical reactions also occur at triple points, located at the cathode/electrolyte interface. (For the purpose of explanation, the assumption here is that the cathode is a pure electronic conductor. Cathodes with mixed conductivity–both electronic and ionic–are discussed later.) An air-side triple point is where the electrolyte (oxygen ion acceptor), the cathode (electronic conductor), and the pore (source of O_2) meet. At these sites, electrons are extracted from the cathode and the following O_2 reduction reaction occurs:

$$1[O_2] + 4[e^-] \longrightarrow 2[O^=]$$

These oxygen ions enter and are transported through the electrolyte by solid state diffusion from the high oxygen-pressure side (i.e., the cathode/electrolyte interface) to the low oxygen-pressure side (i.e., the anode/electrolyte interface). For each O_2 molecule reacted at the cathode/electrolyte interface, four electrons are extracted from the cathode (positive electrode). At the low end of the SOFC operating temperature range (650 °C to 700 °C), the ability to electrochemically reduce O_2 is poor for pure electronic-conducting cathodes, which contributes to poor cell performance. So, cathodes having mixed conductivity (oxygen ion and electronic) have been under development for a number of years. Such cathodes improve the electro-catalytic activity of the O_2 reduction reaction, particularly at low temperatures, by increasing the number of sites for the reaction to occur

Because of the reactions at both interfaces and the oxygen ion conductivity of the electrolyte, electrons are transported from the cathode to the anode and a potential difference (voltage) is generated. When the anode is connected to the cathode through an external circuit, as shown in Figure 27, current will continue to flow as long as air flow, fuel flow, and cell temperature are maintained. If the cell temperature drops too low (e.g., below ~650 °C), the electrolyte oxygen ion conductivity as well as the air side electro-catalytic activity will become very small, resulting in unacceptably poor cell performance. In addition to being the source of oxygen for the electrochemical reaction, air flow on the cathode side is used to control cell temperatures by removing the thermal energy released during the fuel electrochemical reactions.

As discussed previously, SOFC can utilize both H_2 and CO in its electrochemical reaction. However, hydrocarbons (CH_4, C_2H_6, etc.) in fuels such as natural gas and coal-derived fuel gas (referred to as syngas) must first be reformed (i.e., reacted with steam) to produce H_2 and CO prior to the fuel side electrochemical reaction. Because of its high operating temperature, the SOFC is particularly well suited for hydrocarbon reformation. The reformation temperature for methane (CH_4) at 1 atm. pressure must be greater than ~700 °C for the endothermic (i.e., cooling) reformation reaction to go to completion according to:

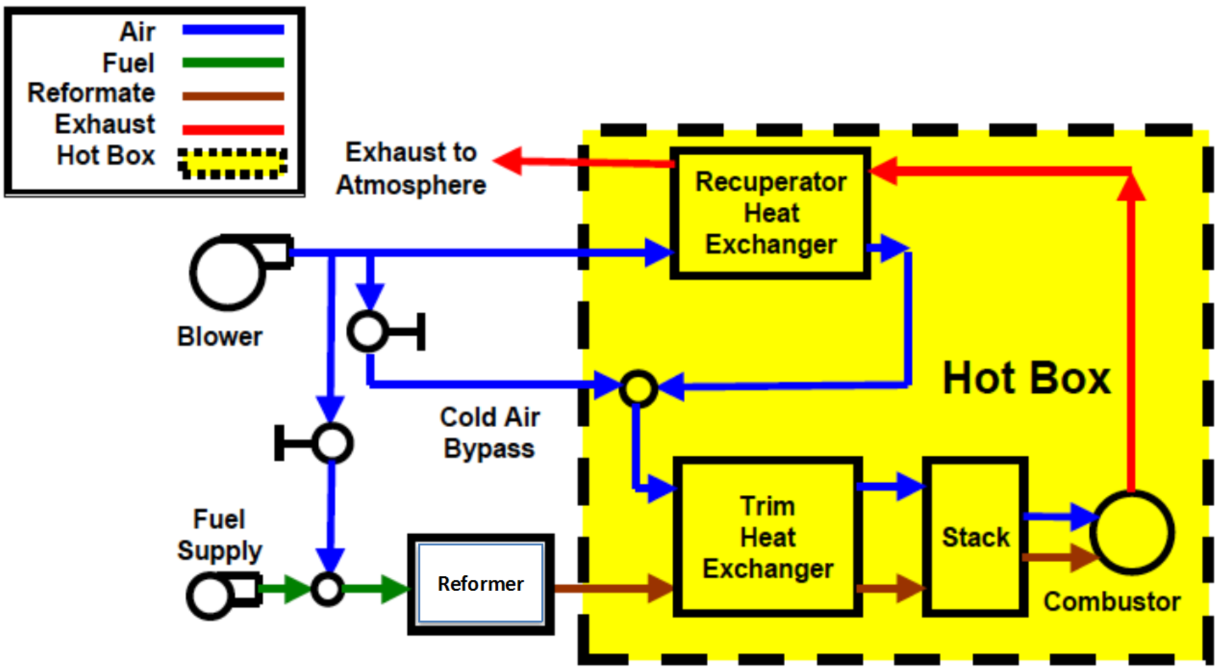
$$1[CH_4] + 1[H_2O] \longrightarrow 3[H_2] + 1[CO]$$

Nickel is an excellent catalyst for this reaction. Therefore, the cell's anode, which contains nickel, can be used as the catalyst as long as the resultant cell temperature gradients due to this endothermic reaction can be kept in the acceptable range. This is called on-cell reformation or direct internal reformation. Being endothermic, the direct internal reformation process can have the beneficial effect of reducing the air flow requirement for cell cooling, thereby reducing system cost (smaller heat exchanger, main air blower, ducting, etc.), and improving system electrical efficiency (reduced air pumping power).

C.7 **SOLID OXIDE FUEL CELL SYSTEM DESCRIPTIONS**

Figure 28 illustrates a simple piping and instrumentation system configuration based on hydrocarbon fuel as the fuel source.

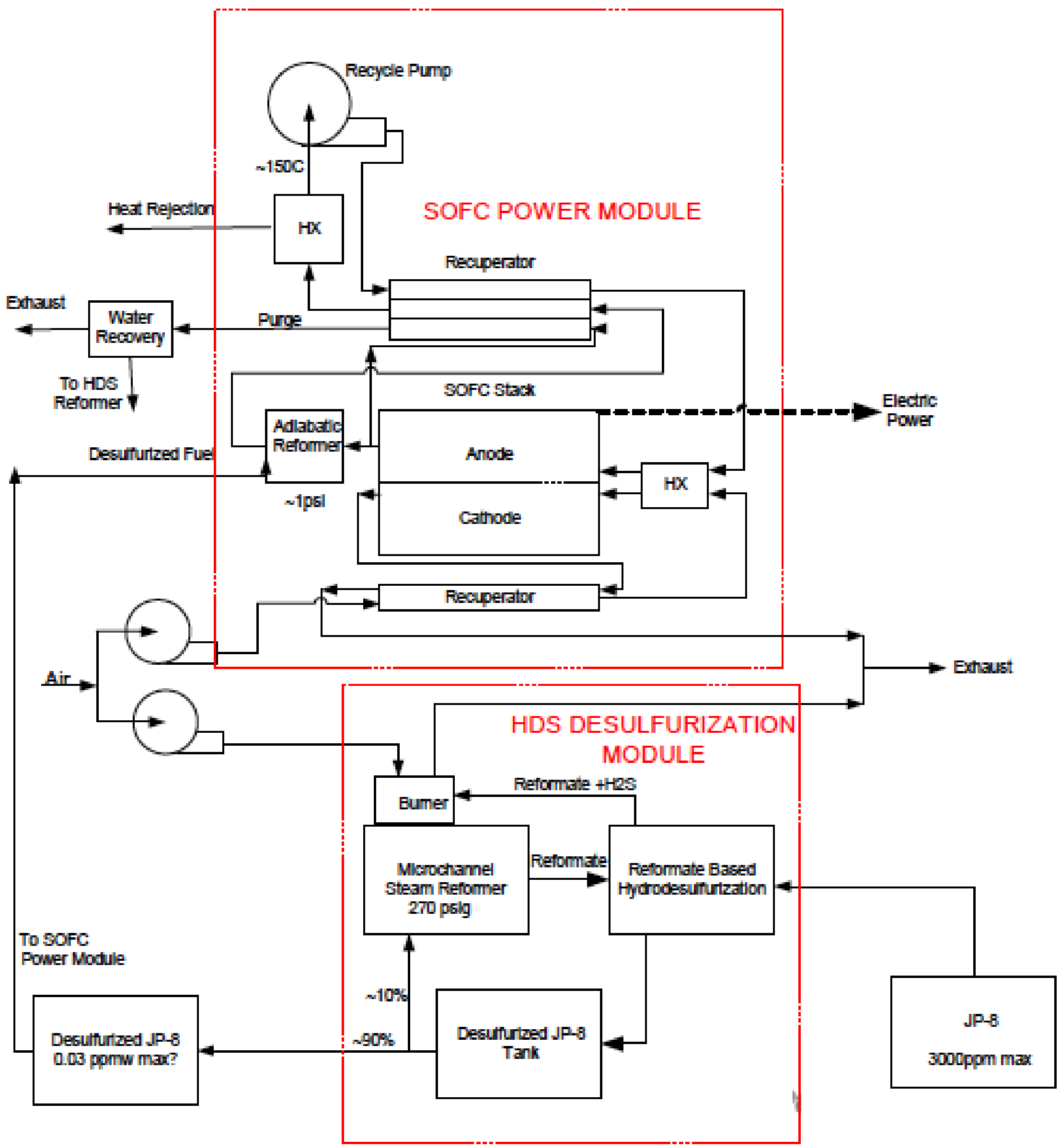
Figure 28. General Solid Oxide Fuel Cell System Piping and Instrumentation Diagram



Due to the higher temperatures, a SOFC usually is staged with lower temperature components grouped external, and higher temperature components grouped internal, to a thermally insulated area. The SOFC has many of the same functions as other fuel cell technologies. The system above shows the SOFC operating with a reformer, as would be the case if using a higher hydrocarbon based fuel (e.g., on an aircraft). If the SOFC is operating directly on hydrogen or CO, then no reformer is needed. A detailed discussion of fuel reformation is provided in Appendix D, section D.8, *Reformer*.

A more detailed example of an SOFC system with reformer is shown in Figure 29.

Figure 29. Example SOFC with Desulfurizer and Reformer



This system that can operate on a standard liquid fuel, which is one of the advantages of SOFC technology. The fuel is first processed in the "HDS Desulfurization Module" to reduce the sulfur down to a level acceptable to SOFC technology. Then, the resultant fuel is fed into the SOFC power module, which has similar functions to Figure 28.

C.7.1 SOFC Air Subsystem

Like PEMFCs, every SOFC must have an air delivery subsystem. The air subsystem must deliver the air at the required, flow, pressure, and temperature to the SOFC stack and exhaust the unutilized air. Since SOFC operates at a very high temperature there is no membrane humidification. An SOFC air subsystem has similar components such as blowers or compressors, but the thermal aspect of air handling becomes more important. SOFC systems must include heat exchangers or heaters to bring the incoming flow up to SOFC operating conditions. Most SOFCs use the waste heat from the electrochemical reaction to heat up incoming reactant flows.

C.7.2 SOFC Fuel Delivery Subsystem

The fuel delivery system running on pure hydrogen must supply the fuel cell stack with the correct pressure, flow; and temperature for operation. Again, for SOFC technology the use of regenerative heat exchangers is critical. Waste heat is generally used on the fuel side to heat up incoming flows.

The fuel delivery system running on liquid fuel is more complex as shown in Figure 29. It requires a number of processing steps to change the chemical form of the fuel from a complex hydrocarbon to the H_2 and CO that is generally required for the stack. A part of this system will need insulation around it to keep it at the appropriate operating temperature without loss of efficiency.

C.7.3 SOFC Stack

The stack is composed of several electrochemical cells. The basic cell was described in Figure 27. The cells have a passage for the fuel and oxidant and a means to conduct current. The cells either contain manifolds to route reactants and products to and from each cell or use external manifolds generally bonded to the stack. The stack should be insulated, or headed, to assist keeping it at operating temperature.

C.7.4 SOFC Exhaust Subsystem

High temperature SOFC stacks produce water as the main exhaust product, in steam form. Other exhaust products include unutilized air coming from the cathode; unutilized H_2/fuel coming from the anode; and other hot gas products like CO and CO_2 (if utilizing other types fuel, like natural gas). See Appendix D for the utilization of other types of fuel reactants.

Normally, output exhaust temperatures are at least 200°C to 300°C. The exhaust (such as unutilized H_2, air, steam, or fuel reformation products) can be also be recirculated, for usage, back into the SOFC/reformer. As mentioned before, the heated product can be used to heat up incoming reactants through the usage of regenerative heat exchangers.

If no recirculation or exhaust burner is being utilized, either a fan or a vent stack should be used to help dissipate the H_2/fuel reactant (to help ensure it stays below the flammability limit). If a reformed fuel is being used, provisions to deal with the potential leakage of CO & CO_2, which can create a toxic atmosphere, need to be addressed in the subsystem design. If CO_2 is contained in the exhaust, it should either be vented, or some sort of high temp CO_2 scrubber should be used. Any hazardous gasses that might be contained within the exhaust should be vented out of the aircraft.

C.7.5 SOFC Coolant Subsystem

In most SOFC systems the incoming air and fuels absorb heat from the stack and the streams are used to reject the heat to ambient. A cooling system like the one used in the PEM FC is usually not needed for an SOFC stack, but some cooling may be needed for supporting system components (i.e. control electronics, power converters). Because of the high temperature of the system, it is possible to use the rejected heat from an SOFC system for other applications. The heat exchangers can be smaller than those required for PEM fuel cells.

C.7.6 SOFC Power Management Subsystem

The power management subsystem of an SOFC is similar to other fuel cell technologies.

C.7.7 SOFC Startup and Shutdown

SOFC's require a longer startup time due to high temperature operation and use of a ceramic based electrolyte. There is no "cold start" capability as the electrolytes do not become electrochemically active until higher temperatures. A heat source, such as electrical heating or combustive heating, is required to bring the SOFC up to operating temperature. Also, most planar SOFC systems require a controlled temperature ramp up and down as to not thermally shock the stack. Larger SOFC systems could take hours to start-up and cooldown. SOFCs need to be shut down in a manner that will maintain a desired cool-down rate of the system. This may often include ensuring any purge gases flowed to a SOFC stack during startup and shutdown are kept at low flow rates to maintain a slower rate of heat-up/cool-down.

C.7.8 SOFC Airframe Integration Considerations

- SOFC operation at 600°C to 800°C. This is likely only usable outside the cabin pressurized volume. Designs need to account for adequate heating of reactants to SOFC operating temperature. SOFC systems operate above the auto-ignition temperature of hydrogen, meaning that leakages internal to the stack would instantly react and produce heat instead of building up to an explosive mixture.
- SOFC's need to reject about 1 kW of heat for every 1 kW of electrical power produced. Most of this heat may be directly exhausted but also may be used for other purposes. Designs need to provide adequate area in a location that allows heat to be rejected.

- If the SOFC is operating on a reformed fuel, then gas handling/ventilation requirements would have to be in place for CO and CO_2.
- Thermal cycling (heat up and cooldown from ambient temperature to operational temperature) currently impacts the operational life of SOFCs more than PEMFCs.
- Shock and vibration could be a concern for the ceramic membranes without adequate vibration protection.

C.7.9 SOFC Failure Modes

Solid Oxide Fuel Cells have many advantages embedded in their usage; however; they also include disadvantages or failure modes in their operation. For SOFCs one key aspect is the structural integrity of the cell and hence its thermo-mechanical long-term behavior.

Failure modes generally are categorized as:

- SOFCs should not be thermally ramped and cooled more than necessary, since multiple thermal cycles can limit the operating life of SOFCs. A typical limit may be no more than 25 cycles, although manufacturers are working to develop SOFC stacks capable of a higher number of thermal cycles. There must be careful thermal management (Ramp-up, Ramp-down, thermal cycle & system thermal equilibriums) during those cycles; this included delta inlet temperatures (cathode vs. anode), delta outlet temperatures (cathode vs. anode), maximum inlet temperatures (anode & cathode), and maximum outlet temperatures (anode & cathode).
- System Pressure: failure modes included reactant delta pressure (maximum) and reactant supply absolute pressure (maximum). Generally, SOFCs cannot withstand large pressure differences across the cell as some other FC technologies (i.e. PEMFC)
- Flow rates: this involves reactant inlet flow rates (a limited range of rates). SOFC cell materials can be degraded if they are not provided adequate reactants during operation.
- Reactants impurities: since a SOFC is capable of operating utilizing hydrocarbon fuels as a fuel source, impurities are another major failure mode. They can be harmful to the performance of SOFCs. Some of these impurities include Hydrogen sulfide (H_2S), hydrogen chloride (HCl), and ammonia (NH_3)[4]. Some SOFC material sets are less sensitive to sulfur impurities than PEMFCs.
- Brittle fracture of Ceramic Electrolyte: Among all existing fuel cell technologies, the planar SOFC is the most promising one for high power density applications. A planar SOFC consists of two porous ceramic layers (the anode and cathode) through which flows the fuel and oxidant. These ceramic layers are bonded to a solid electrolyte layer to form a tri-layer structure consists of positive-electrolyte-negative across, which the electrochemical reactions take place to generate electricity. Because SOFCs operate at high temperatures,

[4] Fuel Cell Systems Explained (2nd Edition) – James Larminie, Andrew Dicks

the cell components (e.g., tri-layer and seals) are subjected to harsh environments and severe thermomechanical residual stresses. Under combined thermomechanical, electrical and chemical driving forces, stack failure can occur suddenly due to material fracture or loss of adhesion at the material interfaces.

- Oxidation: oxidation is based on what catalyst materials are used in SOFC cell construction.
- SOFCs also contain other material-related failure modes, such as when using certain interconnects (the connections between neighboring fuel cells). For example, some metal interconnects can tend to form oxide coatings, which can limit their electrical conductivity and act as a barrier to mass transport[5]. SOFC seals can sometimes fail, especially glass seals. The failures can involve the migration of silica from glass seals, sometimes onto the anodes and cathodes, causing a degradation in cell performance.

As SOFC stacks reach the end of their lives, there are a few indicators that can help identify this point. One indicator is the level of cell voltages being measured from the fuel cell stack, especially during use. When cell voltages begin to drop below the expected range when a power load is demanded from the fuel cell, this serves as a sign of performance loss. Another signal of an approaching end of life for a SOFC, are irregular temperature readings. For example, temperature readings are significantly above the expected range, this may indicate uneven reactant distribution (or in the case of internal steam reformation – uneven reformation distribution) within the SOFC stack. Another indication of an approaching end of fuel cell life, are lower than expected reactant usage readings. This may indicate leaks that have started to develop in an SOFC system.

C.8 ADDITIONAL CONSIDERATIONS FOR PEM AND SOFCs

The following is provided to provide some of the important aspects of PEM and SOFC electrochemistries that must be addressed in order to move the technology forward so that it could be considered for use in aviation. This information is based on data provided by NASA.

- Terrestrial and aerospace fuel cells have demonstrated ${}_{g}H_2/{}_{g}O_2$ operation in many short-term demonstrations since the 1970's using a wide range of electrochemistries.
    - The electrochemistries demonstrated include alkaline, phosphoric acid, polymer electrolyte membranes (PEM), and ceramic solid oxide chemistries.
    - Documented handling issues associated with liquid electrolytes eliminated alkaline and phosphoric acid chemistries from a NASA fuel cell technology trade study leaving only the PEM and solid oxide chemistries as viable candidates for use in aviation.

[5] Fuel Cell Systems Explained (2nd Edition) – James Larminie, Andrew Dicks

- There is a critical lack of PEM life/durability data to extrapolate system performance over projected mission duration. However, PEMFCs are the electrochemistry of choice for FC powered automobiles.

  Operating a PEM fuel cell in a vehicle, the PEMFC stack has an estimated service life of 2,000–4,000 hours. Wetting and drying caused by short distance driving contributes to membrane stress. Running continuously, the stationary stack is good for about 40,000 hours. The stack does not die suddenly but fades similar to a battery. Stack replacement is a major expense[6].

  - Life/durability is application and operation dependent
  - For some space applications PEM fuel cell stack has been rated and tested up to 30,000 hours of operation

- There is a critical lack of Solid Oxide life/durability data to extrapolate system performance over projected mission duration

  Electric utilities use three types of fuel cells, which are molten carbonate, phosphoric acid and solid oxide fuel cells. Among these choices, the solid oxide (SOFC) is the least developed, but it has received renewed attention because of breakthroughs in cell material and stack design. Rather than operating at the very high operating temperature of 800–1,000°C (1,472–1,832°F), a new generation of ceramic material has brought the core down to a more manageable 500–600°C (932–1,112°F). This allows the use of conventional stainless steel rather than expensive ceramics for auxiliary parts.

  High temperature allows direct extraction of hydrogen from natural gas through a catalytic reforming process. Carbon monoxide, a contaminant for the PEM, is a fuel for the SOFC. Being able to accept carbon-based fuels without a designated reformer and delivering high efficiency poses significant advantages for this type of fuel cell. Cogeneration by running steam generators from the heat by-product raises the SOFC to 60 percent efficiency, one of the highest among fuel cells. As a negative, high stack temperature requires exotic materials for the core that adds to manufacturing costs and reduces longevity.[7]

  Bloom Energy’s Bloom Box SOFC stationery power systems are estimating the current units will have a 10-year life as long as the fuel-cell stacks are swapped out twice. However, there are currently no operational solid oxide fuel cell systems that have approached this age[8].

  - Life/durability is application and operation dependent

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[6] Source: http://batteryuniversity.com/learn/article/fuel_cell_technology

[7] Source: ibid

[8] Source: https://www.seattle.gov/light/IRP/docs/dbg_538_app_i_5.pdf

- Typical multi Kilo-Watt stationery solid oxide fuel cell systems are rated for 10,000 hours of operation before removal and replacement of the fuel cell stack

- Fuel cell system-level development and demonstration required
  - Concept of Operations
  - Inter-system (ancillary components, materials, etc.) dependence
  - Automated monitoring, diagnostics, and recovery
- Supporting component development required
  - Actuators: pumps, valves, mass flow controllers, etc.
  - Reformations : flexible fuel options, hydrocarbon fuel, etc.
  - Electronics: cell voltage monitoring
  - Power Management and Distribution System, (PMADS): high voltage connectors and convertors that operate in the aircrafts
- Solid Oxide Seal Improvements
  - Enabling seal technology improvement required to consider solid oxide fuel cell
  - Improved thermal cycling adds recovery capability
  - Improved coking mitigation techniques required for flexible fuel options
  - Improved recovery capability should reactant be lost

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APPENDIX D. FUELS AND OXYGEN

D.1 INTRODUCTION

The fuel and oxygen options play an important factor in the integration of a fuel cell system into an aircraft. A PEMFC requires pure hydrogen to be supplied as a gas. Impurities in the fuel stream can lead to rapid degradation. Whereas SOFCs can be supplied with a lower purity fuel containing a mix of H_2, CO_2, CO and other trace gases without performance issues. This reactant stream can come from a reformer that uses hydrocarbon/aircraft fuels, converting it into a reactant stream usable by the SOFC. The latter system allows for operations that are not much different than what is currently done for an aircraft. On the other hand, as described in Appendices B and C, the SOFC system is more complex than that PEMFC system.

This appendix will look at the fuel and oxygen sources for the SOFC and PEMFC, and will include reformer technology descriptions. Fuel storage and oxygen sources are discussed. Each section includes a summary of failure modes.

Hydrogen fuel storage introduces some unique concerns. The considerations and means to mitigate H_2 storage risks are also discussed in the following sections.

D.2 FUEL SOURCES

D.2.1 Pressurized Hydrogen Gas

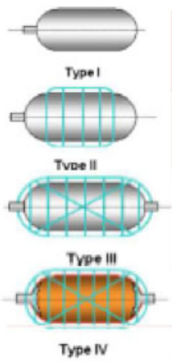
Hydrogen gas can be stored in a compressed-gas tank at high pressures to improve energy density. Pressure is typically 35 MPa (5000 psi) for mobile applications. Although storage of pressure of 70 MPa (10,000 psi) is also used. Higher pressures require material and design improvements to ensure tank integrity.

The cost of H_2 storage vessels is essentially dictated by cost of the carbon fiber that must be used for lightweight structural reinforcement. Compressed hydrogen tanks of 35 MPa and 70 MPa have been demonstrated in several prototype FC vehicles and are commercially available, although these are vehicle and not aircraft applications.

Four types of high pressure storage vessels are discussed in this appendix based on their sufficient level of maturity and their current use in other industrial areas such as chemical industries or hydrogen mobility’s applications (e.g., cars, forklift).

Gas pressure vessels can be divided into Types I, II, III and IV and each are discussed in the following paragraphs. Refer to Figure 30.

Figure 30. Hydrogen Storages Vessel Types



Type I	Pressure vessel made of **metal** (mainly for stationary application (SA))
Type II	Thick **metallic** liner hoop wrapped with **a fiber-resin composite** (SA)
Type III	**Load-sharing** liner fully-wrapped with a **fiber-resin composite** (portable applications (PA))
Type IV	**Non load-sharing** liner fully-wrapped with a **fiber-resin composite**.

D.2.2 Type I Pressure Vessels

Type I Pressure vessels are metal cylinders typically constructed of steel or aluminum. This kind of technology is heavy and commonly used for industrial and stationary applications at relative low pressure (<20 MPa or 2900 psi).

D.2.3 Type II Pressure Vessels

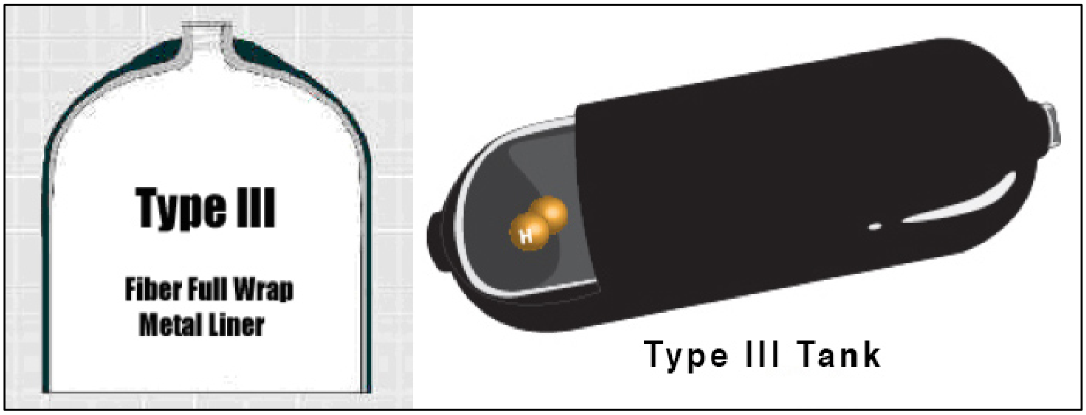
Type II Pressure vessels are metal cylinders with filament windings such as glass fiber or carbon fiber around the cylindrical portion (hoop wrapped). This kind of technology is also heavy and commonly used for industrial and stationary applications at low to high pressure (< 100 MPa or 14,500 psi).

Type I and II Pressure vessels have volumetric and gravimetric capacities that are too limited for aeronautical application.

D.2.4 Type III Pressure Vessels

The most advanced lightweight storage system for the case of compressed gas consists of a vessel, which is an advanced composite tank using a metallic (Type III), shown in Figure 31, or plastic (Type IV) liner and fully wrapped with resin impregnated continuous filaments.

Figure 31. Type III Pressure Vessel



The structure of these two types is based on two fundamental components: the liner, essentially a barrier for hydrogen permeation, and the composite structure that ensures the mechanical integrity of the tank.

Below is a description of a Type III vessel:

The liner of a Type III vessel is generally built with aluminum and is part of its mechanical integrity. The fiber full wrap is generally built with resin and carbon fiber. Type III Pressure vessels are composite cylinders with fiberglass or carbon fiber full wrap with a metallic liner.

A Type III pressure vessel exhibits:

- Good gravimetric capacity (35 MPa or 5000 psi) or lower gravimetric capacity (70 MPa or 10000 psi)
- Low volumetric capacity (35 MPa or 5000 psi) or high volumetric capacity (70 MPa or 10000 psi)
- No (very low) hydrogen permeation rate thank to the metallic liner
- Limited pressure cycling capability
- Possible liner corrosion due to the liner material being metallic

Pressure vessels must be adequately qualified for the environment they are installed in, and equipped with protective devices to prevent excessive pressure and consequent risk of rupture. The protective devices are required to prevent excessive pressure in the system and adequate countermeasures must be available to keep the pressure at a level which does not lead to unacceptable leakage.

Protective devices, depending on the installation, could be pressure relief devices (PRD), rupture disc, or a thermally activated pressure relief device (TRD).

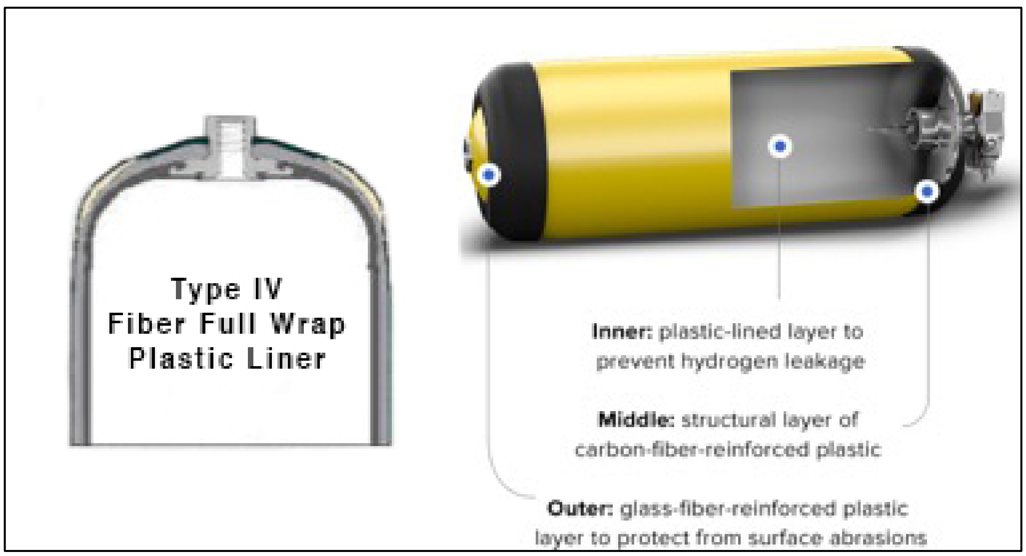
Pressure vessels installed inside the equipment must be adequately certified. The type III vessel certification could be defined using the standards listed below:

- EC 79-2009 EU H_2 Regulation
- ISO 15869 Gaseous Hydrogen and Hydrogen Blends
- SAE J 2579 Compressed Hydrogen Vehicle Fuel Containers
- ISO11119 Gas cylinders—Refillable composite gas cylinders and tubes
- ISO 11114 Gas cylinders
- DOT CFFC until 5000psi (344 bar) (For information, the oxygen cylinders currently used in aircraft are DOT certified).
- European Union (EU) Transportable Pressure Equipment Directive (TPED) Directive 2010/35/EU
- EU Pressure Equipment Directive (PED) 2014/68/EU

D.2.5 Type IV Pressure Vessels

A Type IV pressure vessel is shown in Figure 32.

Figure 32. Type IV Pressure Vessel



The liner of a Type IV vessel is generally built with high density polymer. This liner represents a hydrogen diffusion barrier and is not significantly part of the vessel's mechanical integrity.

The fiber full wrap is generally built with carbon fiber composite shell and induces the mechanical strength. Type IV Pressure vessels are composite cylinders with fiberglass or carbon fiber full wrap with a polymer liner.

Type IV 700 bar (70 MPa or 10000 psi) exhibits:

- Good gravimetric and volumetric capacities
- Significant pressure cycling capability
- Possible hydrogen permeation due to polymer liner material
- Possible liner clogging because of permeation and hydrogen trapped between the liner and the composite wrap
- Limited operating temperature range

Pressure vessels must be adequately qualified for the environment they are installed in and equipped with protective devices to prevent excessive pressure and consequent risk of rupture. The protective devices are required to prevent excessive pressure in the system and adequate countermeasures must be available in order to keep the pressure at a level which does not lead to an unacceptable leakage.

Protective devices, depending on the installation, could be pressure relief devices (PRD) or thermally activated pressure relief device (TRD).

The pressure vessels which will be installed inside the equipment have to be adequately certified.

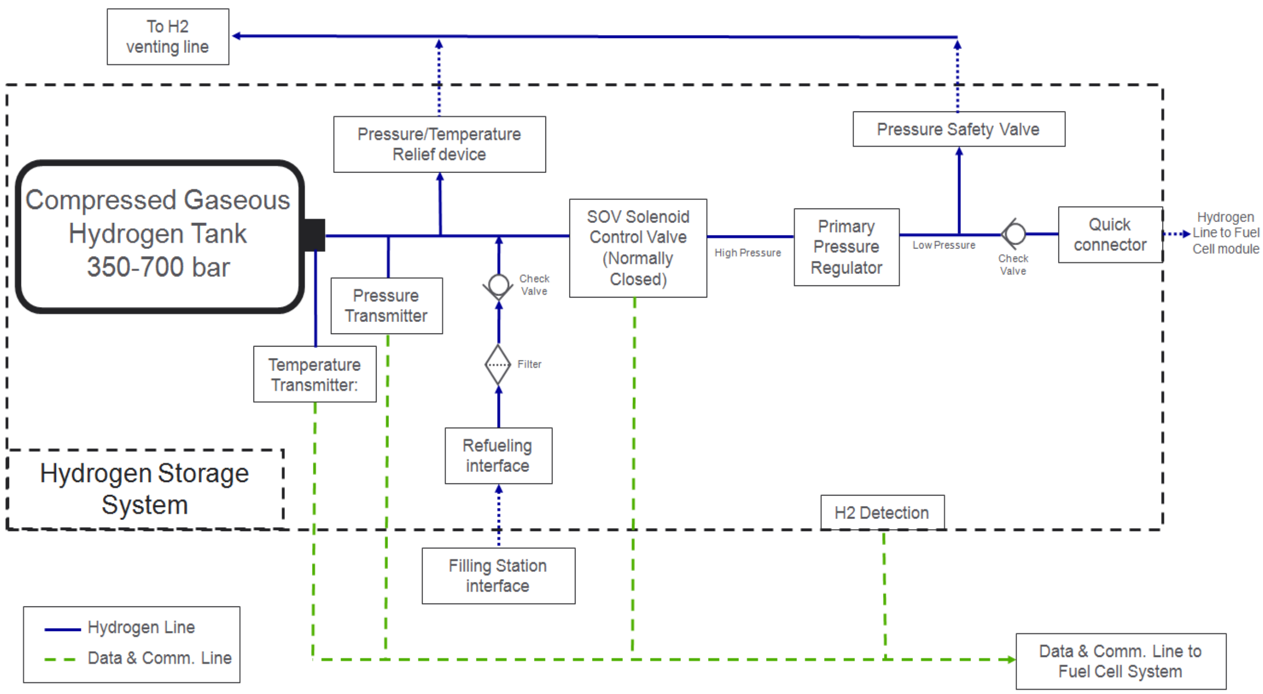
The Type IV vessel certification could be defined using actual standards listed below:

- EC 79-2009 EU H_2 Regulation
- ISO 15869 Gaseous Hydrogen and Hydrogen Blends
- SAE J 2579 COMPRESSED HYDROGEN VEHICLE FUEL CONTAINERS
- ISO11119 Gas cylinders—Refillable composite gas cylinders and tubes
- ISO 11114 Gas cylinders
- DOT not applicable for Type 4 cylinders (For information, the oxygen cylinders currently used in aircrafts are DOT certified).
- EU Transportable Pressure Equipment Directive (TPED) Directive 2010/35/EU
- EU Pressure Equipment Directive (PED) 2014/68/EU

D.3 **COMPRESSED HYDROGEN STORAGE SYSTEM (CHSS)**

The Compressed Hydrogen Storage System (CHSS) is a system which is used to store H_2 at high pressure and to supply it, in safe and reliable conditions to the Fuel Cell Module (FCM) at low pressure. This system contains components which ensure dedicated functions to fill, store, and supply the hydrogen for a fuel cell application. A picture of an onboard CHSS is shown in Figure 33:

Figure 33. Onboard Compressed Hydrogen Storage System (CHSS) Schematic



A Compressed Hydrogen Storage System consists of:

- Pressure vessel (Type III or IV depending of the application);
- Relief devices components:
  - Pressure Relief Device (or eventually rupture discs) activated by an overpressure
  - Temperature Relief Device activated by an over-temperature
- Solenoid Control Valve (SOV) (Normally Closed) to close the H_2 supply if a problem has been detected (H_2 leak or other)
- Primary Pressure Regulator (1st stage) to transform high pressure to low pressure so as to avoid high pressure in the FCM, (in this configuration, a second pressure regulator (2nd stage for pressure adjustment), is requested in the FCM)
- Pressure Safety Valve to avoid high pressure in the FCM
- Regulation valves (check valves)
- Refueling interface

- H_2 Low Pressure Quick Connector to FC system
- Filters to protect components from impurities
- Piping, Fittings
- Sensors (Pressure Transmitter, Temperature Transmitter)
- H_2 Detection to detect potential leaks and to close the SOV if required
- Electrical equipment and electric wiring

D.3.1 CHSS Components: Standards and Certifications

The components which will be installed inside the CHSS must be adequately qualified for the environment they are installed in and compliant with H_2 operation.

SAE J2579 H_2 Storage Systems for Vehicles could be used as a guide.

The components which will be installed inside the CHSS must be compliant with an explosive atmosphere to prevent fire ignition with consequent risk of explosion. The explosive atmosphere compliance section of this report will cover the ignition risk in case of Medium leakage (refer to section D.3.3).

IEC 60079 Explosive atmospheres could be used as a guide.

D.3.2 Refueling Protocol Compressed Hydrogen

A specific refueling interface and fueling protocol will have to be done depending the application considered (Galley, APU, or other) and depending on the fuel considered (High Pressure 350 or 700 bar).

The documents listed below could be used as a guide.

- ISO 23273:2013 Fuel cell road vehicles -- Safety specifications -- Protection against hydrogen hazards for vehicles fueled with compressed hydrogen
- ISO 17268, Gaseous hydrogen land vehicle refueling connection devices
- ISO 20100 - Gaseous hydrogen — Fueling stations
- SAE J-2601 - Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles (also includes 70 MPa possibility)
- SAE J-2799 – (for 70 MPa) – requires also special fueling protocols (reference SAE J-2601)

D.3.3 CHSS Failure Modes

CHSS failure modes can include:

- Hydrogen Fire

- Hydrogen Supply interruption
- Monitoring failure

These failures will be addressed in Appendix F, Hazards, in terms of impact to aircraft, and what design considerations are necessary to mitigate the consequences of CHSS failures.

Leakage rates, per ANSI/AIAA G-095-2004, are defined in relation to the Lower Flammability Limit (LFL) of H_2 as follows:

- **Low Leakage:** Low leakage is an amount of leaking fuel which leads to a fuel concentration in a fuel/air mixture below 25% of the LFL (1% volumetric H_2 concentration). No safety issues.
- **Medium Leakage:** Medium leakage is as an amount of leaking fuel which leads to a fuel concentration in a fuel/air mixture between 25% and 50% of the LFL (1% to 2% volumetric H_2 concentration).
- Probability of occurrence of a medium external leakage and failure of the corresponding active protection means must remain below 10^{-9} per flight hour. The medium H_2 leakage may lead to a very localized H_2 concentration between LFL and Higher Flammability Limit (HFL).
- Indeed, due to the concentration gradient between 100% directly at the leak and 1% to 2% in the surrounding area, any H_2 leakage leads to local H_2 concentration between LFL and HFL in the immediate vicinity of the leak.
- In the corresponding (relatively small) volume must be demonstrated that the probability of ignition of such a mixture is below 10^{-9} per flight hour, unless it can be demonstrated that the ignition of the highest expected flammable mixture's volume does not lead to any safety issue.
- **High Leakage:** High leakage is as an amount of leaking fuel which leads to a fuel concentration above 50% of the LFL (>2% volumetric H_2 concentration). Probability of occurrence of a high external leakage shall remain below 10^{-9} per flight hour.

D.3.4 CHSS Intrinsic and External Risks

There are several intrinsic risks that include:

- Vessel Burst (overpressure induced or not by over temperature)
- H_2 Leakage leading to potentially explosive atmosphere
- H_2 embrittlement (refer to Material compatibility chapter (ISO11114))
- Static Electricity creating ignition in potentially explosive atmosphere

There are several external risks that include:

- Fire

- Electrical ignition sources:
- Electrical short circuits, sparks, and arcs.
- Lightning.
- HIRF
- EMI
- Electro Static Discharge
- Thermal Sources:
  - Hot Surfaces
  - Frictions/contacts
- Vibrations
- Shocks
- Contamination: e.g. fluid leakages
- Accidental damage/Foreign Object Damage (FOD)

CHSS intrinsic and external risks will be addressed in Appendix F, Hazards, in terms of impact to aircraft, and system designs to be considered in the future will need to address means for mitigation.

D.4 **LIQUID HYDROGEN**

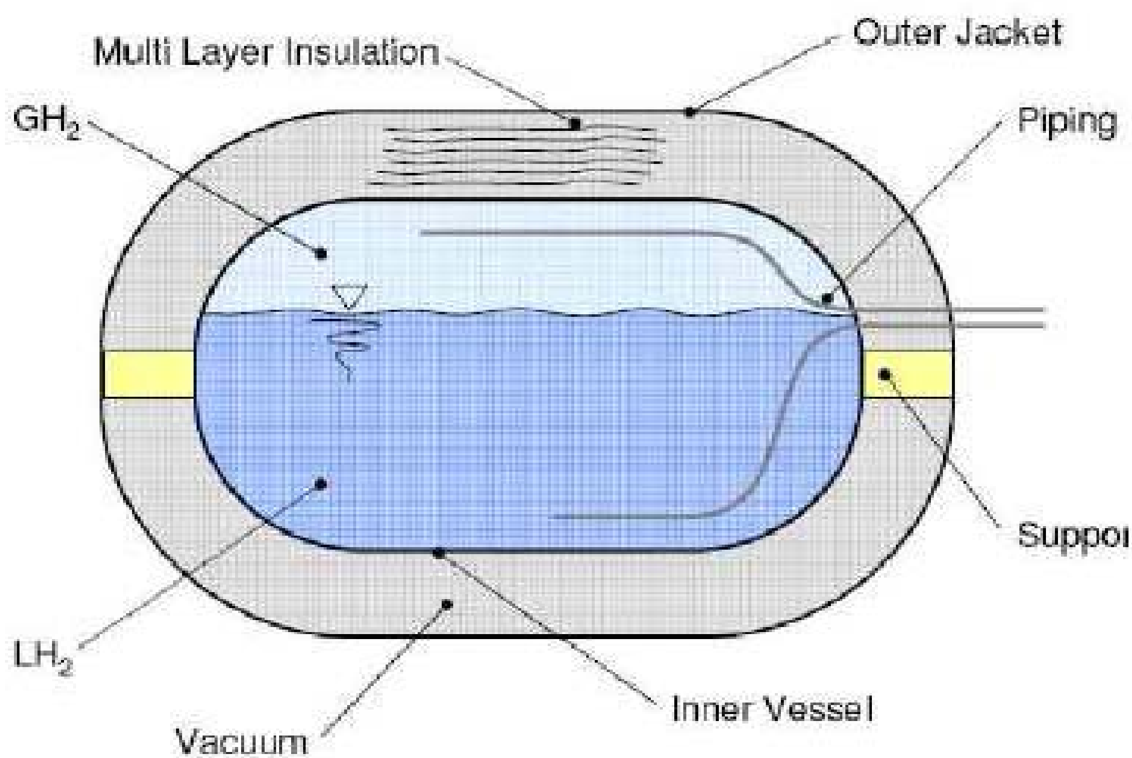
Hydrogen can be stored in a liquid form at low temperature and relatively low pressures to improve energy density compared to compressed hydrogen. The hydrogen temperature in its liquid form is below 20°K (-253°C) and is considered as a cryogenic temperature.

Liquid Hydrogen is stored in its liquid state at a very low temperature of around 20K, so the tank must be designed with a specific cryogenic insulation to minimize heat leaks. Generally, liquid tanks are designed with an efficient Multi-Layer Insulation. Both the Inner Vessel and Outer jacket are usually made with metal (stainless steel or aluminum) and the space in between is filled with a multilayer insulation and then let under vacuum to enhance thermal insulation.

The Inner Vessel containing the H_2 mass is supported inside the Outer Jacket by means of Supports designed to reduce heat leaks and to withstand the requested mechanical loads.

Based on the design shown in Figure 34, the Liquid Hydrogen tank design for mobile applications have similarities, but depend mostly of the application considered. The Liquid Hydrogen tank for trailers used on public roads for gas delivery for industrial applications do not have the same design than the Liquid Hydrogen tank used for spaceship propulsion. Therefore, each mobile application has its own specific design and is a mature technology.

Figure 34. Schematic View of a Typical Liquid Hydrogen Tank



Mobile Liquid hydrogen tanks have already been demonstrated and validated in several prototypes of fuel cell vehicles but are not considered as commercially available.

Liquid Hydrogen tanks exhibits:

- Good gravimetric capacity and high volumetric capacity
- Low pressure technology
- Mature technology for Mobile application

D.4.1 Liquid Hydrogen Tank: Protective/Safety Devices

The Liquid Hydrogen tank pressure is relatively low (generally < 12 bar) but the Liquid hydrogen tank is considered as a pressure vessel.

Pressure vessels must be adequately qualified for the environment they are installed in and equipped with protective devices to prevent excessive pressure with consequent risk of rupture. The protective devices are required to prevent excessive pressure in the system and shall be such that adequate countermeasures are available to keep the pressure at a level which does not lead to a high leakage of the system.

Protective devices, depending on the installation, could be pressure relief devices (PRD) or rupture discs.

Protective devices shall be used to provide over-pressure protection from burst if hydrogen is vaporized due to suddenly significant heat transfer as for example the loss of vacuum between the Inner vessel and the Outer Jacket.

If necessary, redundant protective devices shall be used to ensure that boil-off can be vented and does not cause any over-pressure.

D.4.2 Liquid Hydrogen Tank: Standard and Certifications

The Liquid hydrogen tank which will be installed inside the equipment must be adequately certified. Tank certification could be defined using the standards listed below:

- Regulation (EC) No 79/2009 of the European Parliament and of the Council Of 14 January 2009 On Type-Approval Of Hydrogen-Powered Motor Vehicles
- SAE J2579 Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
- ISO 13985:2006 Liquid Hydrogen–Land vehicle fueling system interface
- ISO 21010 Cryogenic vessels–Gas/materials compatibility
- ISO 21029 Cryogenic vessels–Transportable vacuum insulated vessels of not more than 1000 liters volume
- EU Transportable Pressure Equipment Directive (TPED) Directive 2010/35/EU
- EU Pressure Equipment Directive (PED) 2014/68/EU
- DOT / U stamp certification

D.5 LIQUID HYDROGEN STORAGE SYSTEM (LHSS)

A Liquid Hydrogen Storage System (LHSS) is a system which is used to store H_2 in liquid form and to supply it to the Fuel Cell Module (FCM) at low pressure and in safe and reliable conditions. This system contains components which ensure dedicated functions to refuel, store, and supply the hydrogen for the fuel cell application.

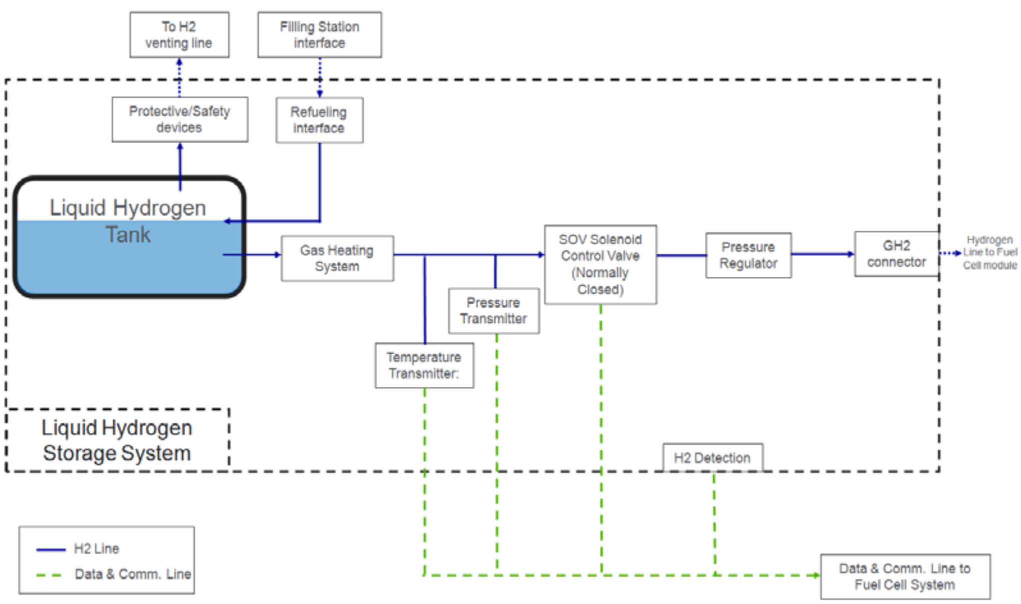
The Liquid Hydrogen Storage System consists of:

- Liquid hydrogen tank (refer description above)
- Protective/Safety devices components to protect the tank form a potential over-pressure
- Gas Heating System to vaporize and heat the gaseous hydrogen to obtain acceptable gaseous temperature for downstream components

- SOV Solenoid Control Valve (Normally Closed) to close the H_2 supply if a problem has been detected (H_2 leak or other)
- Pressure Regulator to transform the H_2 Gas tank pressure to the Fuel Cell Module pressure (in this configuration, a second pressure regulator is not definitely requested for pressure adjustment in the Fuel Cell Module)
- Refueling interface (cryogenic connector)
- Sensors (Pressure Transmitter, Temperature Transmitter)
- H_2 Detection to detect potential leaks and to close the SOV if required
- Regulation valves (check valves)
- Filters to protect components from impurities
- Piping, Fitting
- Electrical equipment and electric wiring

A picture of onboard Liquid Hydrogen Storage System (LHSS) is shown in Figure 35:

Figure 35. Onboard Liquid Hydrogen Storage System Schematic (LHSS)



D.5.1 LHSS Components: Standards and Certifications

The components installed inside the LHSS must be qualified for the cryogenic environment they are installed in and must be compliant with H_2 operation.

The following standards could be used as a guide.

- ISO 21013 Cryogenic vessels - Pressure-relief accessories for cryogenic service
- EN 13648 Cryogenic vessels - Safety devices for protection against excessive pressure
- ISO 21011 Cryogenic vessels - Valves for cryogenic service
- ISO 21013-1,2 Cryogenic vessels - Valves for cryogenic service
- ISO 26142 (2010) Hydrogen detection apparatus
- SAE J2579 Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

The components installed inside the LHSS must be qualified for use in an explosive atmosphere to prevent fire ignition with consequent risk of explosion. The explosive atmosphere compliance will cover the ignition risk in case of Medium leakage (refer to section D.3).

International Electro-Technical Commission (IEC) standard, IEC 60079, *Explosive Atmospheres*, could be used as a guide.

D.5.2 Refueling Protocol Liquid Hydrogen

Depending on the application (e.g., SOFC as an APU) and the type of fuel to be used (e.g., liquid $H_{2)}$, a specific fueling protocol will have to be considered

The following standards could be used as a guide.

- ISO 13984:1999 Liquid Hydrogen – Land vehicle fueling system interface
- ISO 13985:2006 Liquid Hydrogen – Land vehicle fueling system interface
- SAE J2783 Liquid Hydrogen Surface Vehicle Refueling connection

D.5.3 LHSS Failure Modes

A LHSS has multiple failure modes including:

- Hydrogen Fire
- Hydrogen Supply interruption
- Monitoring failure
- Hydrogen Liquid or Gas Leakage
- Leakage rates are defined in section D.3
- Unvented boil off

The risks associated to the LHSS will be listed below.

The ISO standard "ISO TR 15916 2005 Safety of Hydrogen Systems provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety.

The hazards associated with these failure modes are addressed in Appendix F, Hazards.

D.5.4 LHSS Intrinsic and External Risks

There are several intrinsic risks that include**:**

- Vessel Burst (overpressure induced or not by over temperature due to heat leak)
- H_2 Leakage leading to potentially explosive atmosphere
- H_2 embrittlement (refer to Material compatibility chapter (ISO11114))
- Static Electricity creating ignition in potentially explosive atmosphere
- Cryogenic burns

There are several external risks that include:

- Fire
- Electrical ignition sources
- Electrical short circuits, sparks, and arcs.
- Lightning.
- HIRF
- EMI
- Electro Static Discharge
- Thermal Sources
    - Hot Surfaces
    - Fiction/contacts
- Vibrations
- Shocks
- Contamination: e.g. fluid leakages
- Accidental damage/FOD

D.6 **SOLID HYDROGEN STORAGE**

Solid hydrogen storage usually provides hydrogen on demand at a low pressure and stored in a stable state. This mitigates many of the issues related to the containment and delivery of hydrogen at high pressure or liquid form.

The storage volume of both gaseous and liquid hydrogen is limited by the physical density of hydrogen (700 bar gas 63g/l @0°C, Liquid 70g/l @20°K), however the density of hydrogen in a solid hydrogen storage material is not bounded by the properties of hydrogen but by properties of the storage material (a solid). For example, the density of hydrogen in Lithium Borohydride (LiBH) is 123g/l, twice as dense as gaseous hydrogen at 700 bar pressure.

Solid hydrogen storage refers to a number of techniques to store hydrogen within a host material. These fall into two broad categories; absorption as a chemical compound or absorption on materials (usually carbon-based materials). In terms of safety, these techniques leverage an advantage over either high pressure gaseous hydrogen storage or liquid storage as the hydrogen requires a conversion or energy input to release it from the storage material.

The hydrogen is bonded by either physical forces (usually referred to as physisorption) or chemical forces (usually referred to as chemisorption), although the boundary between the two is sometimes blurred as some hydrogen storage techniques may fall into both categorizations. Physisorption tends to have faster adsorption / desorption and greater energy efficiency whereas chemisorption results in the absorption of larger volumes of gas although sometimes it is not reversible or may require high temperatures to release the absorbed gas.

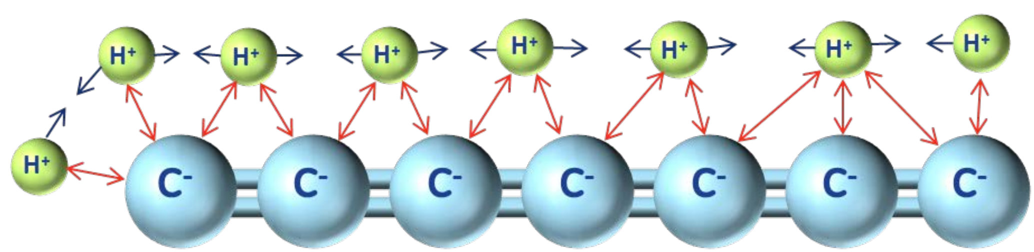
Examples are physisorption of hydrogen on materials with a high specific surface area are Activated Carbon (AC), Graphite Nanofiber (CNF), Carbon Nanotubes (CNTs), Metal Organic Frameworks (MOFs), and doped polymers.

Examples of chemisorption are hydrogen intercalation within host metals and metallic hydrides, desorption of hydrogen from complex compounds, and chemical oxidization of metals with water.

D.6.1 Physisorption

In order to store large quantities of hydrogen, viable materials need to be relatively light and have a large specific surface area. Physisorption, as depicted in Figure 36, is the phenomenon where gas molecules interact with several atoms at the surface of a solid and consist of an attractive interaction (Van der Waals) and a repulsive interaction between the hydrogen gas molecule and host molecule. Many materials are being studied at present with experimental results indicating the around 4% wt can be achieved.

Figure 36. Physisorption Molecular Level Illustration



D.6.2 Chemisorption

A much greater level of understanding exists of the processes involved in chemical reactions than that of physisorption, this has led to technologies at higher Technology Readiness Level[9] (TRL) being developed. The main types of Chemisorption processes are desorption/decomposition of hydrogen from complex compounds, chemical oxidization of metals with water, and hydrogen intercalation within host metals and metallic hydrides.

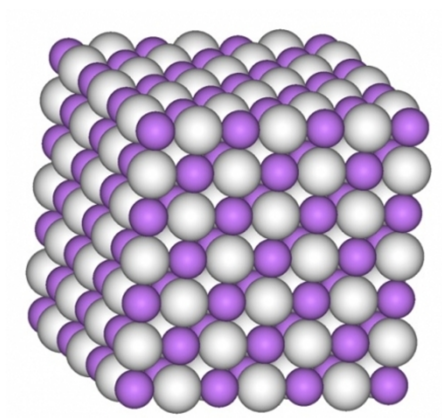
The aim of the technology employed is to achieve a system weight and volume like that of 700 bar gaseous hydrogen.

Releasing hydrogen from hydrides either by decomposition or by a chemical reaction are the most promising solid storage technologies and are discussed in the following paragraphs. There are other materials which can be used for solid hydrogen storage. However, they are not discussed because of the infancy of those technology/techniques.

D.6.3 Metal Hydrides

Binary Hydrides contain a metallic element from the alkali metal or alkaline earth metal groups and hydrogen, these hydrides are what are commonly termed metal hydrides and is depicted in Figure 37.

Figure 37. Metal Molecular Hydride Structure

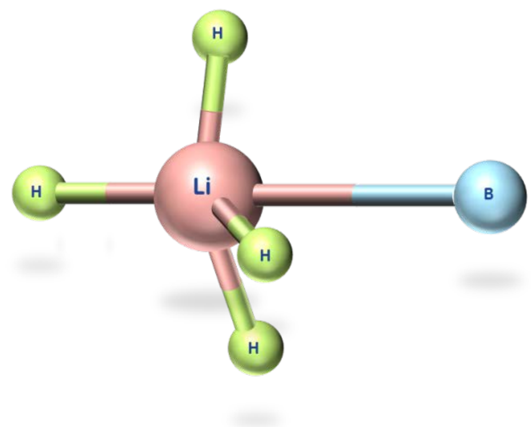


The structure is that of a typical metal, crystalline, with hydrogen in the interstitial sites, hence metal hydrides are also referred to as interstitial hydrides. They are ionic compounds, that is, the atoms are bound together by ionic attraction.

[9] Technology readiness levels (TRL) are a method of estimating technology maturity of Critical Technology Elements (CTE) of a program during the acquisition process.

Complex metal hydrides contain more than one type of metal or metalloid, an example is Lithium Borohydride $LiBH_4$. As is shown in Figure 38, the hydrogen is covalently bonded to the host material.

Figure 38. Covalently Bonded LiBH4 Molecular Structure



The hydrogen can be release from the hydride by either a chemical reaction and/or decomposition.

Hydrides tend to form stable hydrides and therefore usually require quite a lot of energy to decompose, however, metal hydrides also readily react with water or acids.

Releasing hydrogen by a chemical reaction involves adding one or more reactants. In the simplest form, a binary hydride will react with water to produce a hydroxide and hydrogen. Most reactions of this type are highly exothermic, consequently resulting in fast kinetics with high hydrogen production rates; however, they do suffer from controllability and/or containment and usually require excess heat to be managed.

Appling energy heat to a hydride will break the bonds between the molecules thus releasing the hydrogen gas. This is commonly referred to as chemical decomposition, or simply decomposition. Clearly there is a relationship between the energy required to break the bonds and the stability of the hydride. Although the amount of energy is relatively high there are materials that decompose at temperatures close to, or below, ambient, or can be destabilized to reduce the energy requirements. The energy can be derived from several sources, for example waste heat, direct combustion of aviation fuel, or a parasitic load on the fuel cell.

Other factors that influence the design of a solid hydrogen system include the storage chemical(s), recharging of the system or replacement of the spent fuel, disposal of the by-products, control under the influence of an exceptional situation (for example an aircraft fire could decompose the material leading to hydrogen release). Reactant containment in these off normal conditions would need to be evaluated.

D.7 **JET FUEL**

Jet fuel, or other hydrocarbon fuel options similar to jet fuel, as a source for fuel cells is still low in maturity. Reformer technologies are still in development, and coupling the reformer to the fuel cell results in a complex system needing multiple steps to start up, and adds additional time and complexity to that startup. The SOFC is the most likely early user of the reformer technology. It can accept a wider spectrum of reformer product chemistries. As discussed in Appendix B, section B.1.3, PEMFC need very pure H_2 and is less likely to be able to use a reformer product.

D.8 **REFORMER**

In general, hydrocarbon fuel is reformed to syngas (synthesis gas) before being fed to the fuel cell. Unless there is a reliable option for internal reforming within a SOFC stack (not available at the time of this report's release), the fuel cell will need some form of external reformation. Steam reforming, auto thermal reforming, and partial oxidation are the most commonly used reaction technologies for producing syngas from hydrocarbon fuels. Each of these reforming technologies has received much attention in the research and patent literature. Table 3 provides a listing of the various reforming technologies discussed in Sections D.8.1 to D.8.4.

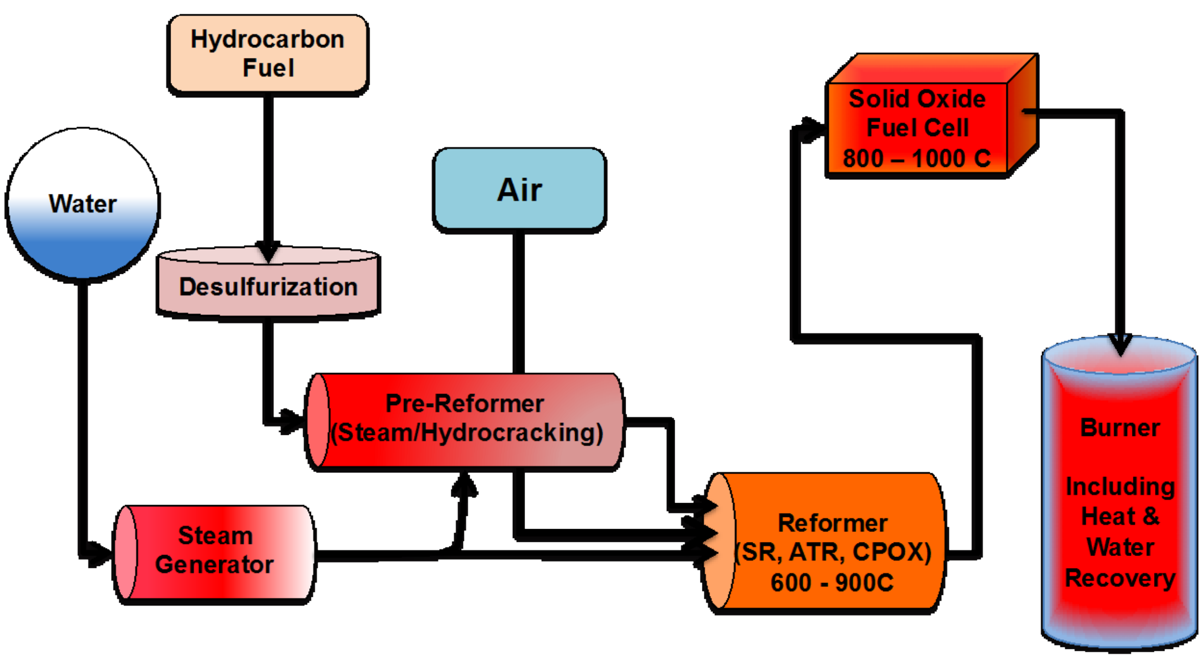
Table 3. Reforming Technologies

Reforming Technology	Potential for Use in Aviation?	Maturity Level of Technology
Steam	Fuel processing for fuel cell systems, such Solid Oxide Fuel Cells; Can potentially enable usage of hydrocarbon fuel options, such as jet fuel	Mature technology, for large-scale industrial applications; Lower technology readiness level for airborne applications
Autothermal	Fuel processing for fuel cell systems, such Solid Oxide Fuel Cells; Can potentially enable usage of hydrocarbon fuel options, such as jet fuel Requires less steam for reformation	Lower technology readiness level for airborne applications

Reforming Technology	Potential for Use in Aviation?	Maturity Level of Technology
Catalytic Partial Oxidation	Fuel processing for fuel cell systems, such Solid Oxide Fuel Cells; Can potentially enable usage of hydrocarbon fuel options, such as jet fuel Requires no steam for reformation	Mature technology, for large-scale industrial applications; Lower technology readiness level for airborne applications
Hydrodesulphurization	Removes sulfur from natural gas and other refined petroleum products; Can potentially be used with various reformers, to assist with fuel processing;	Mature technology, for industrial and commercial applications;

Figure 39 illustrates a simple hydrocarbon reformation system.

Figure 39. Hydrocarbon Reformation System



D.8.1 Steam Reforming

Catalytic steam reforming (SR) of natural gas is one of the most energy efficient ways to produce hydrogen and carbon monoxide. Steam reforming does not require the mixing of air in the reaction mixture and therefore produces higher H_2 concentration in the reformed product. The elimination of oxygen from the initial fuel mixture improves the overall system efficiency by minimizing energy losses from catalytic combustion. Steam reforming does, however, require an external heat source due to the endothermic reactions that occur. This method for producing reformate can therefore only realize its advantage when effective heat utilization from the SOFC stack can be achieved. The cost of the conventional steam reforming catalysts is relatively low although they tend to be vulnerable to sulfur-based catalyst poisons. Steam reforming technology is widely used in industrial syngas production at very large scale.

Table 4. Advantages and Disadvantages of Stream Reforming

Characteristic	Advantage	Disadvantage
Hydrogen Yield	Generally higher than 50% at $T > 600^{O}C$	Potential high level of carbonaceous material formation
Heat Requirement	Heat generated from SOFC can be used to drive SR reaction with overall higher system efficiency	External heat transfer device is required, therefore, results in system complexity and potential higher cost
Startup/Transients	Relative stable during transition operation.	Still needs external igniter to start up, although the catalyst bed can be used for catalyst combustion tentatively. Heat transfer efficiency and higher volume makes the start-up slow.

Potential hazards regarding Steam Reforming, include an insufficient steam-to-methane molar ratio, which can be a major contributing factor to carbon formation. An insufficient ratio, can also impact the fuel conversion efficiency as well. Additional hazards, include potential Carbon Monoxide and Carbon Dioxide gas leakage, which are produced because of the steam reformation reactions. This could result in a toxic atmosphere environment. And along with the aforementioned hazards, other related hazards which are included in the usage with a SOFC, are H_2/fuel gas leakage (which could result in fire and oxygen deficiency hazards).

D.8.2 Autothermal Reforming

Autothermal reforming (ATR) presents a flexible choice, providing reasonable hydrogen and carbon monoxide yields. The process is catalytic and involves input streams of both air and water that will react with the fuel stream to produce syngas. Effectively, an ATR combines the exothermic nature of a partial oxidation reaction (hydrocarbon fuel reacting with air) with the endothermic steam reforming reaction to balance the heat requirements. Reactions can occur on the same catalyst or on a steam reforming catalyst located in close proximity to the partial oxidation catalysts. The quality of the ATR reformate, defined in terms of hydrogen mole fraction, is superior to the catalytic partial oxidation (CPOX) reformate but not as good as the SR reformate. The advantage, though, is that we would have a thermally neutral system component, more responsive than a SR reformer, moderate in cost, size and weight requirements. On the downside, a more extensive control system is needed for ATRs to ensure robust operation of the fuel processing system.

Table 5. Advantages and Disadvantages of Autothermal Reforming

Characteristic	Advantage	Disadvantage
Hydrogen Yield	About 50% concentration	Lower hydrogen yield than SR
Heat Requirement	None	May need startup heat, and control systems to switch between lean burning and ATR regimes
Startup/Transients	Moderate. Can be set up to fast response times by switching between CPOX and ATR (relying in CPOX portion for the faster response time)	Transient fluctuations for load matching may be as much as 1-10 per second…Such deviations will reflect on efficiency levels if we are switching between CPOX/ATR for responding to transients

D.8.3 Catalytic Partial Oxidation Reforming

Catalytic partial oxidation uses reaction technology where the hydrocarbon fuel is mixed with just enough oxygen to convert the carbon in the fuel to carbon monoxide. Fuel is reacted with air over a catalyst and the combustion is prevented from going to completion by controlling the amount of oxygen and residence time. Due to the fast reaction rates the CPOX reformer has short response times; these reactors are very compact and contact times are typically milliseconds. The CPOX system is comparatively more fuel flexible than SR or ATR and can tolerate higher levels of sulfur contaminants in the hydrocarbon fuels. Two disadvantages of this technology are the low hydrogen content and the high operating temperatures could lead to catalyst degradation.

Table 6. Advantages and Disadvantages of Catalytic Partial Oxidation

Characteristic	Advantage	Disadvantage
Hydrogen Yield		Relatively low yield can be turned by improving catalyst and convert some CO back to H_2.
Heat Requirement	No external heat required. The system is exothermic	The heat generated from the reaction needs to be removed or utilized in the system.
Startup/Transients	Startup is fast. Transient test is relatively easy to control.	High temperature startup/shutdowns may cause catalyst degradation.
Additional	Startup is fast. Transient test is relatively easy to control.	High temperature startup/shutdowns may cause catalyst degradation.

D.8.4 Hydrodesulfurization

Hydrodesulphurization (HDS) is used to remove Sulfur, from natural gas and other refined petroleum products. This since sulfur can deactivate catalysts for various reformers, as well as the electrodes of SOFCs. Natural gas and petroleum liquids tend to contain organic sulfur compounds, which need to be removed. HDS requires a hydrogen rich stream to feed into the reactor, so it would not be ideally suited for internally reformed SOFCs, which don't require a hydrogen-rich reactant stream. But for SOFC systems that utilize external reformers, and thus produce hydrogen-rich input streams, a HDS reactor would be suitable. From the hydrogen-rich gas produced by the external reformer, a small portion can be recycled back into a HDS reactor, as it is working to remove sulfur from the system.

Often the reaction works by having the sulfur-containing compounds, flowed over a supported nickel-molybdenum oxide or cobalt-molybdenum oxide catalyst, and converted into hydrogen sulfide via hydrogenolysis reactions of the type:

$$(C_2H_5)_2S + 2H_2 \rightarrow 2C_2H_6 + H_2S$$

Though generally, the operating conditions and feed gas composition help determine the choice between using nickel or cobalt, as a catalyst. And usually, this process is operated at 300°C to 400°C, to optimize the rate of reaction. And the H_2S that is formed, is then normally absorbed into a bed of zinc oxide, creating zinc sulfide:

$$H_2S + ZnO \rightarrow ZnS + H_2O$$

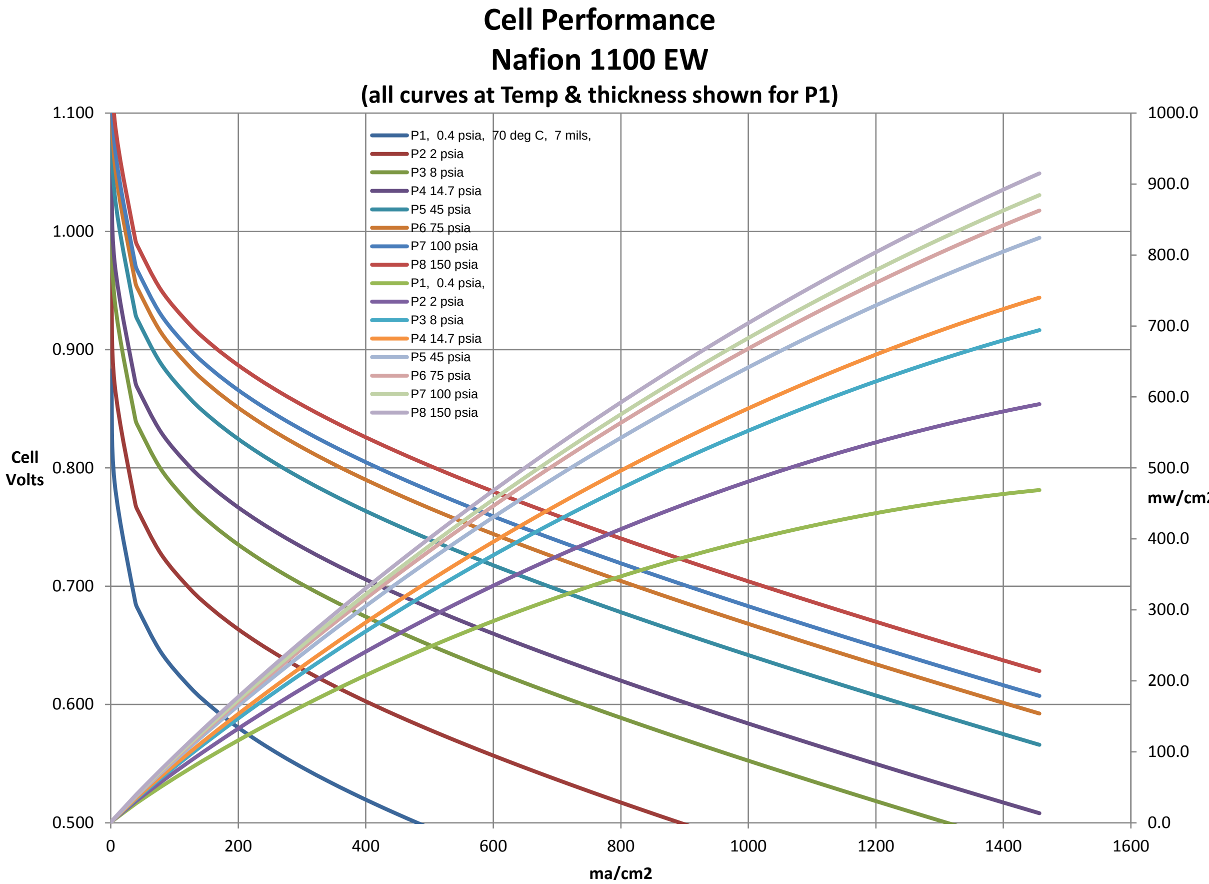
D.9 OXYGEN SOURCES AND ENVIRONMENTAL CONTROL IMPACTS

D.9.1 Role of Oxygen in the Fuel Cell Reaction and Aircraft Fuel Cell and Impacts on Environmental Control System, ECS, Design

A fuel cell stack is an energy conversion device that converts potential energy stored in an external fuel into electrical energy, waste heat and reaction by-products. This is done via an electrochemical reaction that combines the fuel with an oxidizer. While other oxidizers such as chlorine or bromine can be used, for the purposes of this report it is assumed that the oxidizer for the fuel cell technology of interest is oxygen that is derived from stored sources or from ambient air.

Oxygen is fundamental to the fuel cell operation. Both PEM and SOFC systems utilize O_2 supplied either directly as a pure gas or from air sources. The characteristics of varying sources can impact fuel cell operation. For example, in PEM fuel cells the oxygen electrode is highly affected by oxygen partial pressure (PP). Figure 40 illustrates this relationship (note this chart assumes both gases at the same PP but still illustrates the relationship). This is relevant since the O_2 electrode is more sensitive to pressure than the H_2 electrode for PEM fuel cells. In Figure 40, P1 of 0.4 roughly relates to a PO_2 of ambient air in depressurization, P2 of 2.0 psia is roughly ambient PO_2 at 10.9 psia and P3 represents bleed air PO_2 assuming 40 psia bleed air.

Figure 40. PEM Fuel Cell Performance is Directly Affected by Reactant Partial Pressure



Also in most but not all PEM fuel cells, oxygen flow or air flow is often used to remove water, which is a reaction product. Further, since fuel cell waste heat will most likely be rejected to the external environment, the air supply may be required to remove waste heat as well as provide oxygen.

The following reviews likely sources of fuel cell oxygen, discusses consideration of the supply of oxygen from differing sources, and reviews thermal implications for various potential applications. These applications can include:

- Distributed Power, (e.g., galley fuel cell)
- Ram Air Turbine Replacement (RAT)
- Auxiliary Power Unit (APU) Replacement
- Isolated Systems (e.g., Palletized Medevac)

Table 7 summarizes these relationships and the likely sources of oxygen.

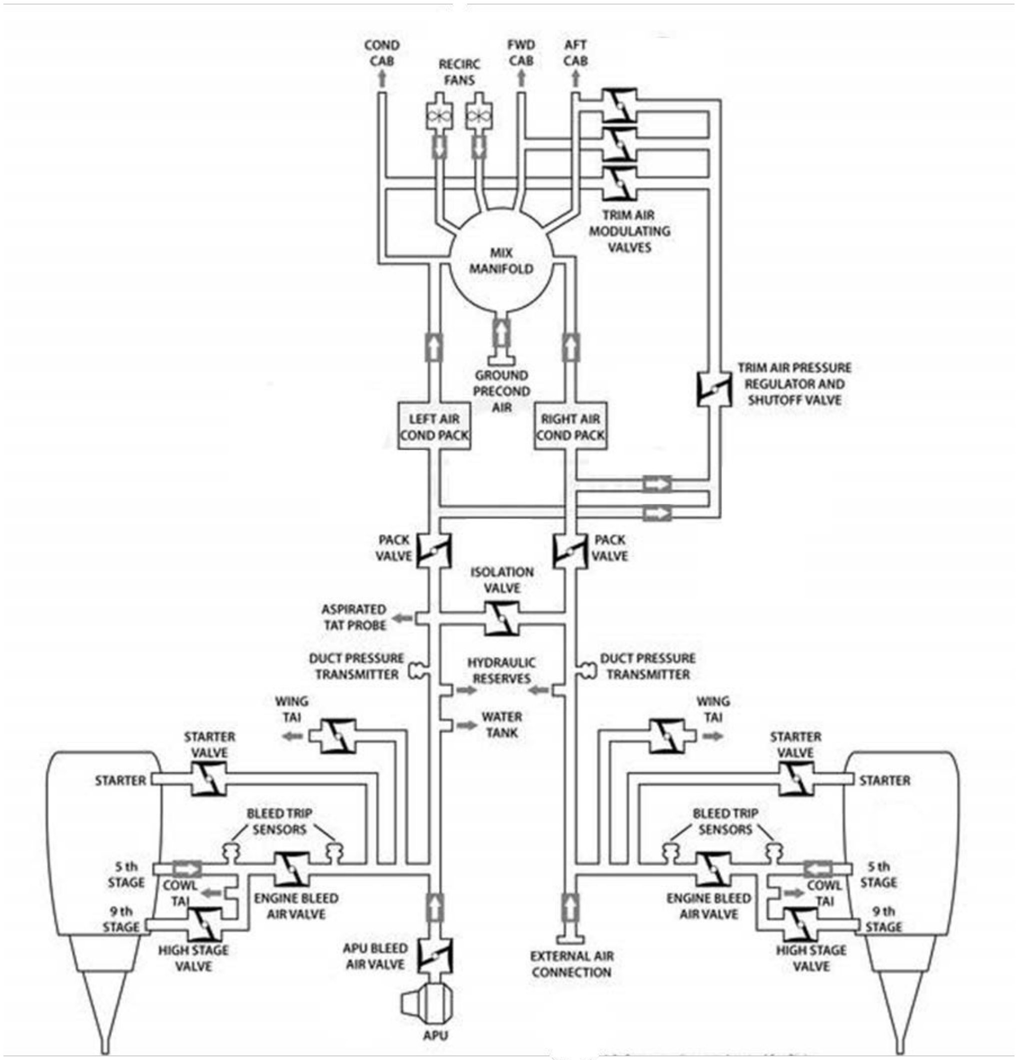
Table 7. Different Applications have Various Likely Oxidizer-Fuel Combinations

Application	Distributed Power	RAT Replacement	APU Replacement	Isolated System
H_2-air (bleed air or ambient)	X		X	X
H_2-O_2		X		
Reformate-air (bleed air or ambient)	X		X	X
Reformate-O_2	X			X

D.9.2 Current Sources of Oxygen in Aircraft

Supply of oxygen for life support in pressurized transport aircraft is basic to their design. These aircraft typically operate at altitudes up to 45,000 feet and some have operated at over 60,000 ft. Human life is not sustainable at these altitudes and an artificial atmosphere is vital. Normal breathing air oxygen is provided from the ambient air typically through systems that provide this through engine bleed air or in bleedless systems via environmental control system (ECS) compressors. Refer to Figure 41.

Figure 41. Typical Aircraft Engine Bleed Air System



It should be noted that bleedless systems that provide pressurized air are increasingly utilized due to improvements in overall fuel consumption and simplification of engine buildup due to the elimination of the pneumatic system and associated pre-coolers, control valves, and required pneumatic ducting.

All pressurized transport aircraft also provide pure oxygen for emergency or medical use. This is typically stored either as gaseous oxygen or in the form of chemicals that release oxygen when a reaction is initiated. Pilot oxygen systems typically utilize separate gaseous stored oxygen that can be supplied within seconds of a depressurization event. These systems are regulated under various FAA/SAE criteria.

Table 8. Potential Sources of Fuel Cell Oxygen have Different Characteristics

Source	Temperature	Source Pressure	Cabin Pressure	Delivered or Available O_2 Partial Pressure psi.	O_2 Partial Pressure During Emergency Depress. (with function engines)
Engine Bleed (approx.)	200-250°C	275 kPa (40 PSI)	NA	Approx. 8	8
Electrical compressed air (bleedless systems)	30 – 250°C	90 – 275 kPa (13 – 40 PSI)	NA	2.7 – 8.4	0.42
Cabin air	Cabin	NA	10.9	Approx. 2	0.42
Ram air	External ambient	Variable with altitude	Variable with altitude	Variable with altitude	0.42
Stored gaseous	Cabin	Nominal 1,850 psia	NA	Per FC design	Per FC design
Stored chemical	Cabin (at package outlet)	0-2000 psia	NA	Per FC design	Per FC design

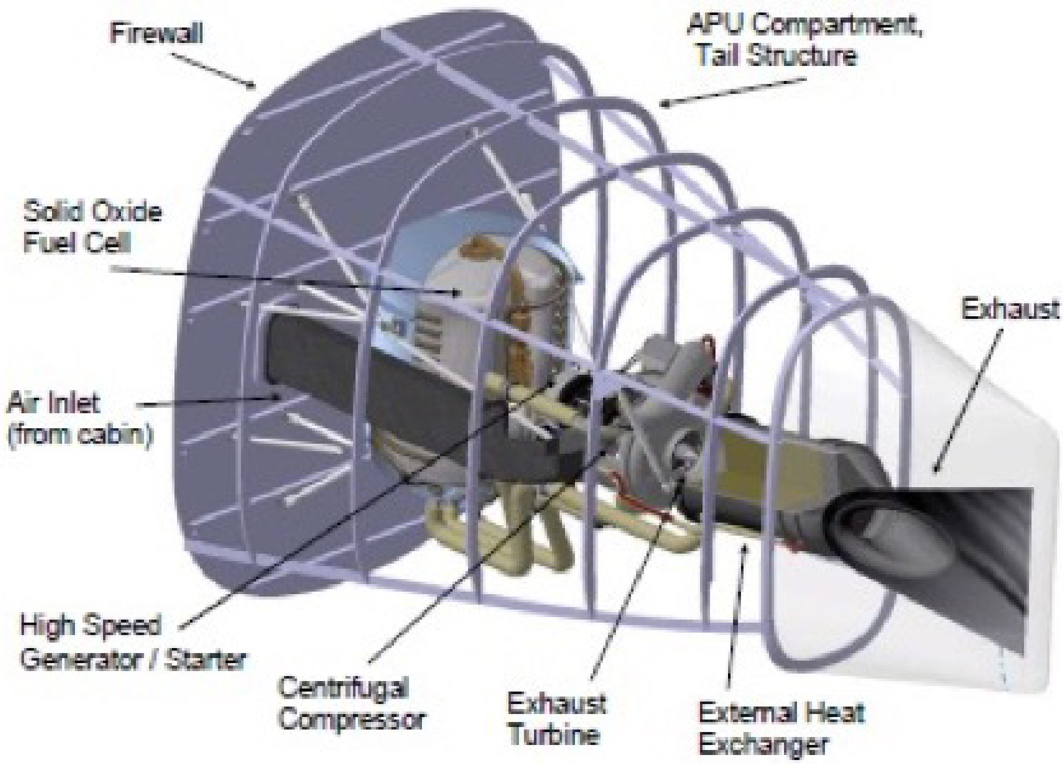
D.9.3 Common Fuel Cell System Location Issues

A primary consideration in system implementation is system location and its impact on O_2 supply and heat rejection. The following briefly discusses these issues.

D.9.4 Fuel Cell Systems External to Pressurized Area

While some of the fuel cell systems being considered are assumed to be within the pressurized aircraft volume this is not the only suitable location. For example, a SOFC, designed as a drop-in APU replacement would likely be sited outside the pressurized area (Figure 42). Due to the highly efficient O_2 electrode it would not suffer unacceptable performance loss due to low O_2 PP and a location outside the pressurized area would be more suitable when considering operation of an extremely high temperature device.

Figure 42. Conceptual Fuel Cell Design for APU Applications



(external to the pressurized area)

The emergency power system will also likely be external to the pressurized area. It is unlikely that this system could be an SOFC due to start up transient limitations. The PEMFC could be used in this application, and start up would be near instantaneous with pressurized H_2 and O_2. Some forms of chemical O_2 could be used, but the system design would have to take the chemical generation start up in account.

D.9.5 Thermal Issues Related to Fuel Cell Systems Fully Contained within Pressurized Volume

If 100% of the heat from the fuel cell is rejected within the pressurized volume the impact can be considerable when compared to the thermal load from the passengers.

The average heat generation by a comfortable, sedentary person, excluding heat loss due to evaporation of moisture, is about 70 W (ASHRAE 1997b). The total heat load in an aircraft cabin will include heat loads from electronics and heat gain through the aircraft skin. Including these heat sources, the total heat load can reasonably be taken as twice the occupant-generated amount, or 140 W/person. If the cabin temperature is kept in the middle of the ASHRAE "comfort envelope" (ASHRAE 1992) at 23 °C and the air is supplied to the cabin at 10 °C, the equation below can be used to determine the required rate of flow of conditioned air to the cabin:

$$23°C=10°C+(140/m)(1/1{,}000) \Rightarrow m = 0.0108\ kg/s \cdot person = 0.646\ kg/min \cdot person$$

That is, adequate temperature control in the cabin requires that conditioned air be supplied to the cabin at about 0.65 kg/min (1.4 lb/min) per person to maintain a comfortable temperature. This requirement is more than twice the CFR part 25 requirement of 0.25 kg/min per person for outside air and provides one rationale for recirculating cabin air (see section on recirculation).

By comparison, a 10kW fuel cell or set of fuel cells will generate approximately 10,000 watts of heat or the equivalent of 143 passengers. This may impose a considerable demand on the ECS design or require separate heat rejection not coupled to the ECS.

In addition to thermal considerations, decisions related to various combinations of fuel and oxidizer sources also may impact ECS design and are discussed below.

D.9.6 Fuel Cell Oxygen Reactant Overview

The fuel cell interacts with the oxygen supply in varying ways according to the nature of the fuel cell. For example, a H_2-O_2 system operating with gases supplied from stored reactants may interact minimally with the oxygen/ECS system as it does not consume oxygen from the air but may require air flow for cooling. However, a reformate-air fuel cell may consume oxygen from the cabin air supply for the fuel cell reaction, vent the products of the reaction to the cabin air and require cabin air for cooling.

Table 9. Each Oxygen/Reactant Combination has Different Aircraft Design Implications identifies reactant/oxidizer combinations which are discussed in more detail in the following sections.

Table 9. Each Oxygen/Reactant Combination has Different Aircraft Design Implications

O_2 Source	**Reactant**
Stored O_2	Hydrogen
Stored O_2	Reformate
Bleed air	Hydrogen
Cabin air	Hydrogen
Bleed air	Reformate
Cabin air	Reformate

D.9.6.1 Stored Oxygen—Hydrogen

This assumes pressurized O_2 and H_2.

- Effect on fuel cell performance: From a fuel cell performance standpoint, this combination is optimal. The fuel cell reaction benefits from higher O_2 PP and the PP of stored O_2 pressure can far exceed any possible with ambient or bleed air.
- Effect on O_2 depletion: With oxygen supplied from storage there is no O_2 depletion. However, care must be taken to consider failure modes that could cause high local concentrations of O_2.
- Reaction by-products: In this case the only reaction by-products are heat and water in the form of liquid or vapor. Some hydrogen may also be vented but this can be much less than for air systems. As noted above the design should provide for proper venting of these by-products. In the case of water vapor this may be a beneficial factor to air quality but consideration must be given to any design that introduces this water vapor to the cabin to ensure that there is no negative impact such as ensuring no local condensation that can lead to metal corrosion over time.
- Effect on Engine: Since the system is independent of the engine no effects are expected.
- Unique Bleed Air Effects on Cabin Interior Design: Factors such as heat rejection, O_2 depletion, water vapor and proper venting are common to all designs.
- Depressurization Considerations: Since the O_2 supply is independent of cabin or bleed air the fuel cell reaction is not affected unless heat removal is via ambient air. Consideration should be given to of heat removal during a depressurization event.

D.9.6.2 Stored Oxygen—Reformate

This assumes oxygen is stored in a pressurized tank, but the fuel is supplied by a reformer.

- **Effect on Fuel Cell Performance:** Generally, these comments are the same as for H_2-O_2.
- **Effect on O_2 depletion:** Same comments as for H_2-O_2
- **Reaction by Products:** Same comments as for H_2-O_2 except additional by-products of the reformation reaction must be addressed
- **Effect on Engine:** Same comments as for H_2-O_2
- **Unique Bleed Air Effects on Cabin Interior Design:** Same as for H_2-O_2.
- **Depressurization Considerations:** Same as for H_2-O_2

D.9.6.3 Oxygen from Bleed Air—H_2 Fuel from Storage Tank

This assumes the oxygen is derived from bleed air and the fuel cell system uses pressurized H_2 gas as the reactant fuel.

- **Effect on Fuel cell performance:** From a fuel cell performance standpoint, this combination is highly attractive. The fuel cell reaction benefits from higher O_2 PP and with bleed air pressures as high as 40 psia O_2 PP is approximately 8 psi. This combination does however require interaction with the engine bleed system. The tradeoffs of this must be assessed by each aircraft designer.

- **Effect on O_2 depletion:** With oxygen supplied from bleed air no cabin oxygen is consumed so this approach has minimal general or local oxygen depletion due to the reaction however some amount of O_2 depleted air would be vented. It is expected this amount of depletion would be inconsequential but any design should perform the analysis required to ensure safe and proper venting of the O_2 depleted bleed air.
- **Reaction by-products:** In this case the only reaction by-products are heat and water in the form of liquid or vapor and O_2 depleted bleed air. Some hydrogen will also be vented with nitrogen diffusing from the air. As noted above the design should provide for proper venting of these by products. In the case of water vapor this may be a beneficial factor to air quality but consideration must be given to any design that introduces this water vapor to the cabin to ensure that there are no negative impacts such as ensuring no local condensation that can lead to metal corrosion over time.
- **Effect on Engine:** While the majority of large transport aircraft utilize engine bleed air for ECS, modern aircraft design is trending away from this to improve fuel economy. The amount of air required for a fuel cell seems to be below levels that would impact engine performance or efficiency however the aircraft designers must decide, using their own criteria, if this type of oxygen supply is beneficial.
- **Unique Bleed Air Effects on Cabin Interior Design:** Factors such as heat rejection, O_2 depletion, water vapor and proper venting are common to all designs however when engine bleed air is utilized consideration must be given to introduction of this to the fuel cell location including routing of lines and failure modes.
- **Depressurization Considerations:** Use of engine bleed air is beneficial in a depressurization scenario. The fuel cell reaction, especially for a PEM fuel cell, is highly sensitive to the oxygen PP of the reaction. As long as the engines are operational, bleed air at design pressure will continue to flow to the fuel cell and fuel cell operation will not be adversely impacted by a depressurization due to reduction of O_2 pressure. If the engines cease operation the fuel cell will also cease operation. In this scenario provision should be made for a separate O_2 supply.

D.9.6.4 Oxygen from Cabin Air—H_2 Fuel from Storage Tank

This assumes air is consumed from the cabin and the fuel is pressurized H_2.

- **Effect on Fuel cell performance**: From a fuel cell performance standpoint, this combination is less attractive than use of bleed air but is viable. The typical cabin pressure at altitude is 10.9 psia resulting in a PP of approximately 2.2 psi vs. 8 psi when bleed air is utilized. However, cabin air is widely available providing a designer with freedom to site the fuel cell in many locations and blowers/compressors that elevate air pressure are commonly used in many fuel cell systems to increase O_2 PP. The tradeoffs of this vs. bleed air must be assessed by each aircraft designer.

- **Effect on O_2 depletion:** With oxygen supplied from cabin air the oxygen available for life support is reduced by the amount consumed by the fuel cell. The amount depends on the particular fuel cell but this needs to be considered in system design and location. A human consumes approximately 0.44 g/min of O_2 while a fuel cell will consume approximately 9 g O_2/min/kw. For a 200-passenger aircraft, a 10kW fuel cell would consume O_2 at rate of approximately 90g O_2/min while 200 passengers would consume O_2 at a total rate of 200 x 0.44g/min = 88 g/min total. So, for a 10kW fuel cell this would equate to approximately the O_2 consumption of 200 passengers. Due to the design of the typical ECS under CFR part 25 this would only reduce O_2 PPs by a very small amount (by about an additional 0.8%) and this expected amount of depletion would be inconsequential but any design should perform the analysis required to confirm this. (from the publication cited above)

  The rate of flow of outside air has a substantial and direct impact on the concentration of contaminants in the cabin air. The flow rate has a negligible effect on the PO_2, in that only a tiny portion of the oxygen in this air is consumed by the aircraft occupants. A typical sedentary adult consumes oxygen at about 0.44 g/min (0.001 lb/min) (Nishi 1981). With the CFR part 25 minimal design outside-air flow rate of 0.25 kg/min (0.55 lb/min) per cabin occupant, oxygen is brought into the cabin at 0.058 kg/min (0.127 lb/min) per person. Oxygen consumption by the occupants reduces the PO_2 levels by about 0.8% in this case, compared with a PO_2 reduction of up to 25% due to the reduced cabin pressure, as explained earlier. Thus, adequate oxygen concentrations in the cabin are maintained, even at ventilation rates far below those specified in CFR part 25, as long as the cabin is adequately pressurized.

- **Reaction by products:** As with the H_2-Bleed air case, in this case the only reaction by-products are heat and water in the form of liquid or vapor and O_2 depleted air. Some hydrogen will also be vented as nitrogen diffusing from the air impacts hydrogen-side fuel cell performance and must be vented. As noted above, the design should provide for proper venting of these by-products. In the case of water vapor this may be a beneficial factor to air quality but consideration must be given to any design that introduces this water vapor to the cabin to ensure that there are no negative impacts such as ensuring no local condensation that can lead to metal corrosion over time.

- **Effect on Engine:** Since there is no direct interface with the engine there is no direct effect on the engine.

- **Use of Cabin Air on Cabin Interior Design:** While the overall effects related to humidity, oxygen depletion, and heat generation appear to be reasonable, attention must be paid to proper design. For example, if an area containing a fuel cell were improperly ventilated there could be a risk of oxygen depletion to dangerous levels.

- **Depressurization Considerations:** The fuel cell reaction, especially for a PEM fuel cell, is highly sensitive to the oxygen PP of the reaction. In a depressurization, cabin pressure may rapidly decrease from 10.9 psia (O_2 PP of 2.1 psi) to about 0.4 psi impacting fuel cell performance. Fuel cell design must consider operation under these conditions.

D.9.6.5 Oxygen from Bleed Air—H_2 Fuel from Reformate

This assumes oxygen is derived from bleed air and the fuel is from a reformer.

- **Effect on Fuel cell performance**: From a fuel cell performance standpoint, this combination is highly attractive. The fuel cell reaction benefits from higher O_2 PP and the air supply can be at pressures as high as 40 psia resulting in a PP of approximately 8 psi. This combination does however require interaction with the engine bleed system. The tradeoffs of this must be assessed by each aircraft designer.
- **Effect on O_2 depletion:** With oxygen supplied from bleed air no cabin oxygen is consumed so this approach has minimal general or local oxygen depletion due to the reaction however some amount of O_2 depleted air would be vented. It is expected this amount of depletion would be inconsequential but any design should perform the analysis required to ensure safe and proper venting of the O_2 depleted bleed air.
- **Reaction by products:** Comments from H_2-O_2 must be considered. The designer must also consider management of reformate waste products including CO_2 and possibly CO and added heat from reformation reaction.
- **Effect on Engine:** While most large transport aircraft utilize engine bleed air for ECS, modern aircraft design is trending away from this to improve fuel economy. The amount of air required for a fuel cell seems to be below levels that would impact engine performance or efficiency however the aircraft designers must decide, using their own criteria, if this type of oxygen supply is beneficial.
- **Unique Bleed Air Effects on Cabin Interior Design:** Factors such as heat rejection, O_2 depletion, water vapor and proper venting are common to all designs however when engine bleed air is utilized consideration must be given to introduction of this to the fuel cell location including routing of lines and failure modes.
- **Depressurization Considerations:** Use of engine bleed air is beneficial in a depressurization scenario. The fuel cell reaction, especially for a PEM fuel cell, is highly sensitive to the oxygen PP of the reaction. As long as the engines are operational, bleed air at design pressure will continue to flow to the fuel cell and fuel cell operation will not be adversely impacted by a depressurization due to reduction of O_2 pressure. If the engines cease operation the fuel cell will also cease operation. In this scenario provision should be made for a separate O_2 supply.

D.9.6.6 Oxygen from Cabin Air—H_2 Fuel from Reformate

This assumes air is consumed from the cabin and the fuel is from a reformer.

- **Effect on Fuel cell performance**: From a fuel cell performance standpoint, this combination is less attractive than use of bleed air but is viable. The typical cabin pressure at altitude is 10.9 psia resulting in a PP of approximately 2.2 psi vs. 8 psi when bleed air is utilized. However, cabin air is widely available providing a designer with freedom to site the fuel cell in many locations. The tradeoffs of this vs. bleed air must be assessed by each aircraft designer.

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- **Reaction by products:** Comments from H_2-O_2 must be considered. The designer must also consider management of reformate waste products including CO_2 and possibly CO and added heat from reformation reaction.

- **Effect on Engine:** Since there is no direct interface with the engine there is no direct effect on the engine.

- **Effects on Cabin Interior Design:** While the overall effects related to humidity, oxygen depletion, and heat generation appear to be reasonable, attention must be paid to proper design. For example, if an area containing a fuel cell were improperly ventilated there could be a risk of oxygen depletion to dangerous levels.

- **Depressurization Considerations:** The fuel cell reaction, especially for a PEM fuel cell, is highly sensitive to the oxygen PP of the reaction. In a depressurization, cabin pressure may rapidly decrease from 10.9 psia (O_2 PP of 2.1 psi) to about 0.4 psi impacting fuel cell performance. Fuel cell design must consider operation under these conditions.

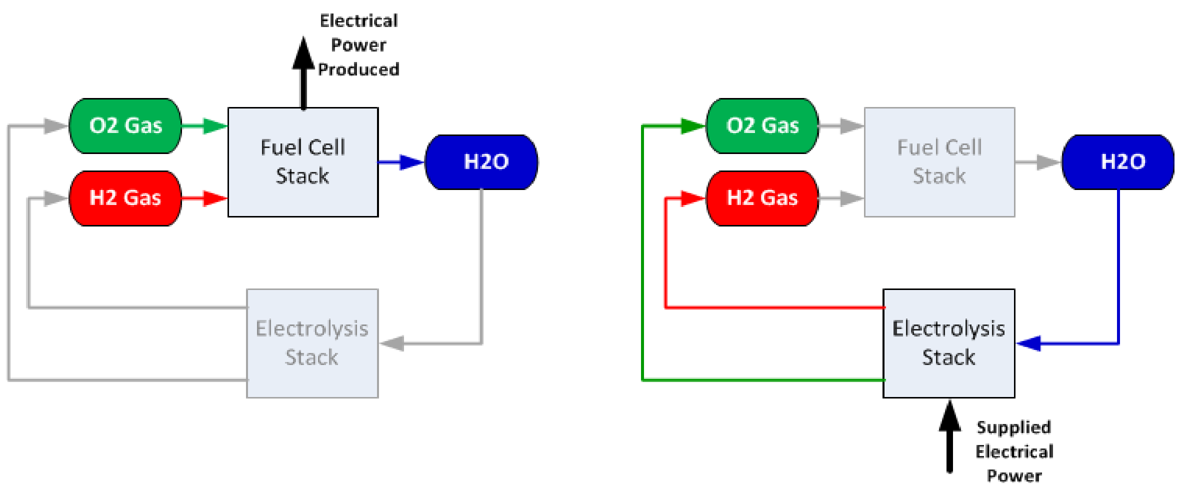
D.10 REGENERATIVE FUEL CELL ENERGY STORAGE

Regenerative fuel cell energy storage (RFCES) systems encompass systems where there is electrochemical cell technology providing electrical power by operating in fuel cell mode and also electrochemical cell technology providing reactant generation by operating in electrolysis mode. In the electrolysis operation mode, incoming water is electrochemically separated into its hydrogen and oxygen components by the reverse chemical reaction of the fuel cell. Specific cell operating characteristics determine if the reaction is endothermic or exothermic. The overall electrolysis reaction for a water reactant is:

$$\text{Electrolysis Reaction: } H_2O + \text{Electricity} \rightarrow H_2 + \tfrac{1}{2}\, O_2$$

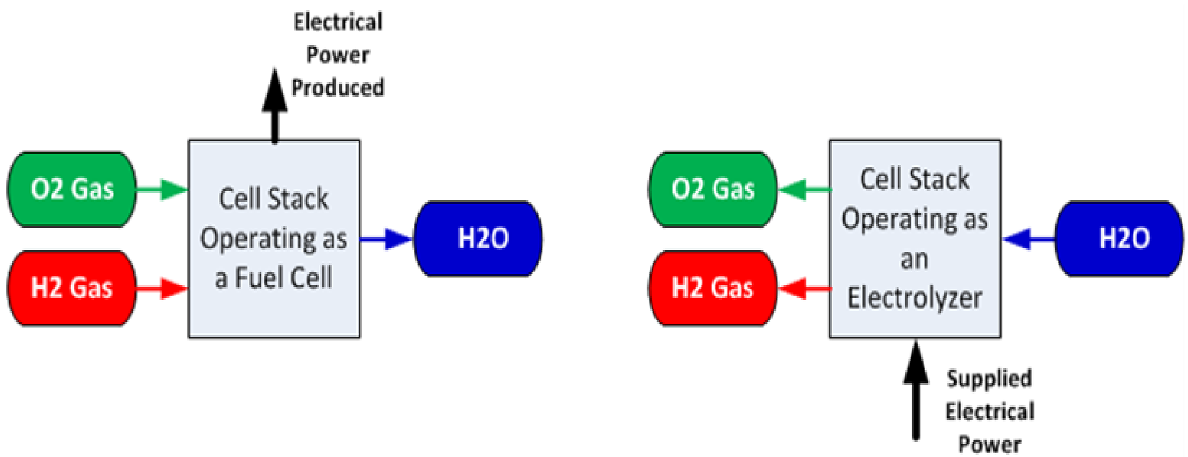
The fuel cell and electrolyzer functions can be split into discrete functions, where one or more set of stacks operate in fuel cell (FC) mode and then one or more different stacks operate in electrolysis (EL) mode (see Figure 43), or as a unitized function where the same stack operates in both fuel cell and electrolysis modes (see Figure 44).

Figure 43. Discrete Stacks in a Simplified Regenerative FC Energy Storage (RFCES) System



[Operation shown in fuel cell mode (left) and electrolysis mode (right) for discrete stacks]

Figure 44. Unitized Stacks Operating in a Simplified RFCES System



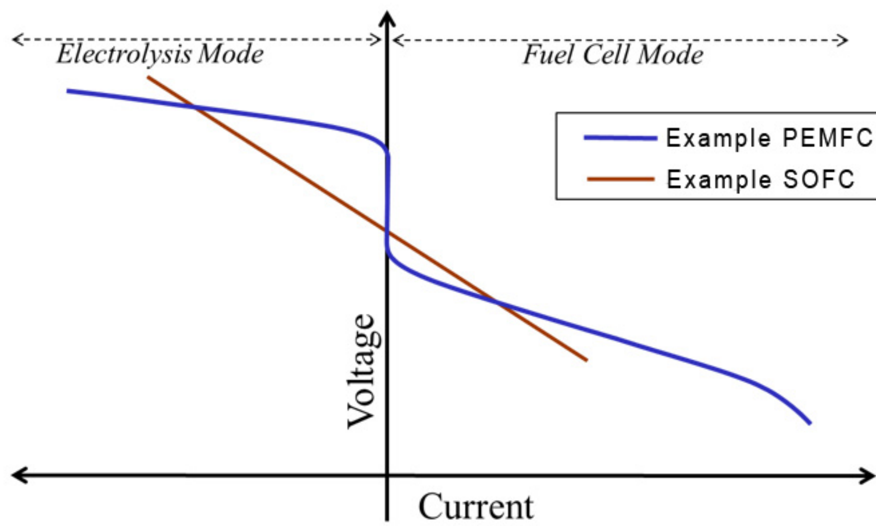
[Operation shown in fuel cell mode (left) and electrolysis mode (right)]

An RFCES system can operate as a fuel cell using hydrogen and oxygen reactants to generate power and water when external power is not available. When external power is supplied, the system it can use the external power to electrochemically convert the stored water back to hydrogen and oxygen gas. The electrolyzer stack may supply the gas pressurization for storage or a separate compressor may supply the pressurization. RFCES systems primarily operate as a closed system with the water generated being used to supply all reactants needed. An example application for an airborne RFCES system would be in an unmanned aerial vehicle operating over a day/night cycle, where electrical power is supplied by solar cells during the day to provide vehicle power and also support electrolysis operation to generate reactants. Then in the evening when solar power is not available, the system would produce power from the stored reactants. A RFCES system would also have an advantage if there is power available that would normally be wasted which could instead be used in the RFCES to increase to total efficiency of the system.

Depending on the type of fuel cell, multiple reactants may be used to power non-regenerative, or open-loop, fuel cells when the fuel cell is being used only for power production. However, when used for regenerative energy storage, the fuel cell has to operate using hydrogen and oxygen gas that can be generated from water electrolysis. Primarily PEMFC and SOFC cell technology has been investigated for RFCES systems, with more demonstrator systems using PEMFC technology as it is considered to be at a higher readiness level than SOFC. Demonstrators for PEMFC regenerative systems have used both unitized and discrete stacks. Proton Exchange Membrane Fuel Cells have a shift in their voltage performance when the same stack operates between fuel cell and electrolysis modes, as shown in Figure 45. Because of this, many PEMFC regenerative system demonstrators have focused on using discrete stacks where each stack can be tailored for either fuel cell or electrolysis operation, allowing for a more efficient total system than would be possible in a unitized stack. Solid Oxide Fuel Cell technology operates at a significantly higher temperature than PEMFC, and has a more linear voltage relationship when operated across fuel cell and electrolysis modes as shown in

Figure 45 but has had more limited development for use in regenerative systems. It should be noted that the data shown in Figure 45 is shown as an example for curve characteristics only and is not meant to portray representative performance across all cells. Performance of cells in a stack will vary based on operating conditions, manufacturer, and stack technology.

Figure 45. Example Cell Voltage Characteristics Between Fuel Cell and Electrolysis Operation



RFCES systems have many of the same fuel cell performance characteristics as non-regenerative or open loop fuel cells. However, since any fluid that is exhausted or vented from the system can result in less fuel available for use later on, regenerative fuel cell systems are typically operated as a closed loop system. Thus, fluid handling in RFCES systems is more critical. Typically, reactants loaded into regenerative systems initially are of higher purity, and additional hardware is included in the system in order to maintain reactant purity. This limits the need to purge (i.e. remove inerts) and helps protect the cells from degradation. Due to the fact that RFCES systems are usually operating on pure, pressurized reactants, the efficiencies of the fuel cell mode operation in RFCES are generally higher than lower pressure air-based fuel cell systems. The total roundtrip efficiency of a RFCES system can have a wide range, dependent on specific designs (type of cell, unitized or discrete stacks) and operation (power levels, pressures, duration, etc.). Various efficiencies for RFCES systems have been published. Initial discrete PEM stack based breadboard systems have shown roundtrip efficiencies of over 42%[10], and studies have cited roundtrip efficiencies as high as greater than 80%[11] for discrete stacks in ground based, high temperature RFCES systems. It is desirable in both unitized and

[10] "Improved Round Trip Efficiency for Air Independent Regenerative Fuel Cell Systems", Proton Energy Systems, Final Technical Report for Office of Naval Research Contract No. N00014-10-C-0369, 5/11/2012

[11] "LOW COST, HIGH EFFICIENCY REVERSIBLE FUEL CELL (AND ELECTROLYZER) SYSTEMS", Technology Management Inc., Proceedings of the 2001 DOE Hydrogen Program Review, NREL/CP-570-30535

discrete regenerative fuel cell systems to limit the amount of reactant crossover in the stack as internal leakage in a RFCES system has a direct negative impact on efficiency. While RFCES systems generally have lower roundtrip efficiencies than battery based systems, RFCES systems have the advantage of being able to size the reactant storage portion of the system independently from the power and reactant generation portion of the system.

As in non-regenerative systems, RFCES balance of plant components are needed to ensure that fluids are supplied and removed from the electrochemical stacks at the correct pressures, flow ranges, humidity, and temperature. In many cases, RFCES systems require more complexity in the balance of plant components as fluids are processed rather than exhausted out of the system. For example, electrolysis operation necessitates more extensive water handling components than in a fuel cell only operation, such as water pumps to supply flow to the cell stack. Electrolysis products of hydrogen and oxygen destined for gas storage in tanks must be dried or water extraction components added to the tanks to limit condensed water build up in the gas tanks. Gas processing and storage components need to maintain separation of hydrogen and oxygen gas to preclude unintended gas mixtures from forming. Heat exchangers or heaters are needed for most incoming reactants to the stacks. As most RFCES systems are closed loop, most waste heat from the systems need to be rejected via heat exchangers rather than directly through exhaust. Solid oxide technology operating as an electrolyzer requires higher temperature heat exchangers and a means of generating steam to feed the electrolysis operation.

Regenerative fuel cell systems usually require additional power management from an external source (i.e. from solar cells, excess engine power) to support electrolysis operation with appropriate currents/voltages. Discrete stack RFCES have the advantage of being able to tailor the fuel cell and electrolysis stack design to support different power and voltage ranges for each operational mode. Unitized stacks have the same group of cells functioning in both fuel cell and electrolysis modes, and therefore are limited to the operational voltages dictated by the stack's IV curve. Because of this, unitized stacks normally operate at a higher voltage in electrolysis mode than in fuel cell mode which can lead to a more complex electrical power system design.

Multiple non-regenerative fuel cell demonstrators have flown on aircraft, but limited testing or demonstrations have been performed on RFCES systems for aircraft. A PEM RFCES system was built and tested at NASA Glenn Research Center in 2005. The system operated for 5 days on day/night cycles. An OEM in collaboration with its partners, flew a regenerative fuel cell demonstrator in 2012 (see Figure 46).

Figure 46. Regenerative FC Energy Storage System Demonstrator

(Installed and Flown in 2012)

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APPENDIX E. APPLICATIONS FOR FUEL CELL SYSTEMS

E.1 OVERVIEW

This appendix discusses several potential applications for fuel cells. These are illustrated in Figure 47 through Figure 50. The applications described are only examples and do not provide the details necessary to be considered complete enough for an actual certification program. The appendix also discusses FCS integration with other airplane systems (section E.2.)

One potential application is a using a solid oxide fuel cell as an auxiliary power unit (APU). Auxiliary power units are typically located in the tapered tail cone section of the rear fuselage in commercial jet aircraft, as shown in Figure 48. The current technology is shown along with an insert of an SOFC system that has been developed to an early prototype level for the trucking industry. In that application, the fuel cell uses truck fuel to provide overnight cab power instead of running the diesel engine. The APU application is discussed in section E.4.

The use of fuel cells could also be used in galley carts, as shown in Figure 49. Emergency power, as well as distributed power, and energy storage, applications areas shown in Figure 50, where fuel cell systems can be integrated and operated throughout the aircraft.

Sections E.3 through E.7 discuss various applications for fuel cells in aviation.

Figure 47. Potential Fuel Cell Applications on Aircraft

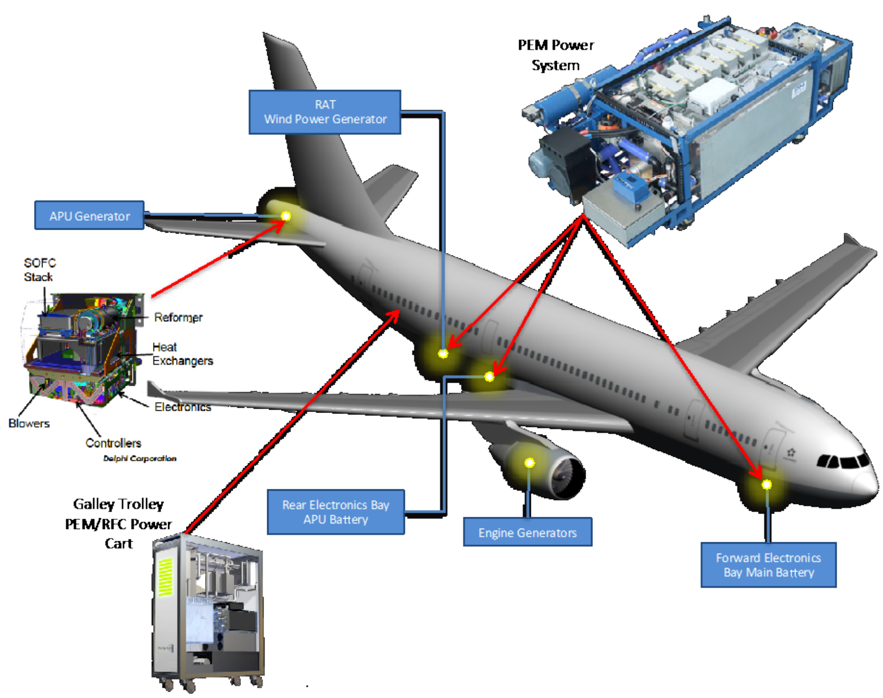
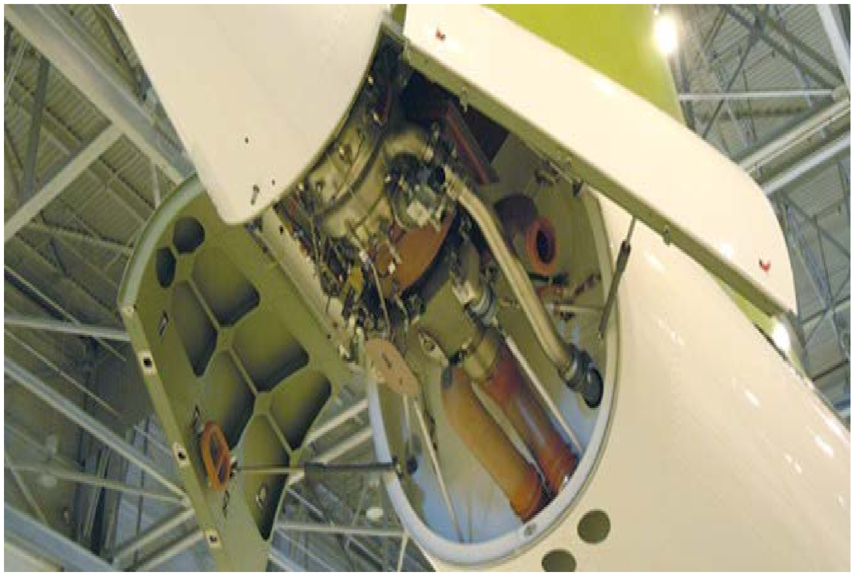


Figure 48. Aircraft Auxiliary Power System



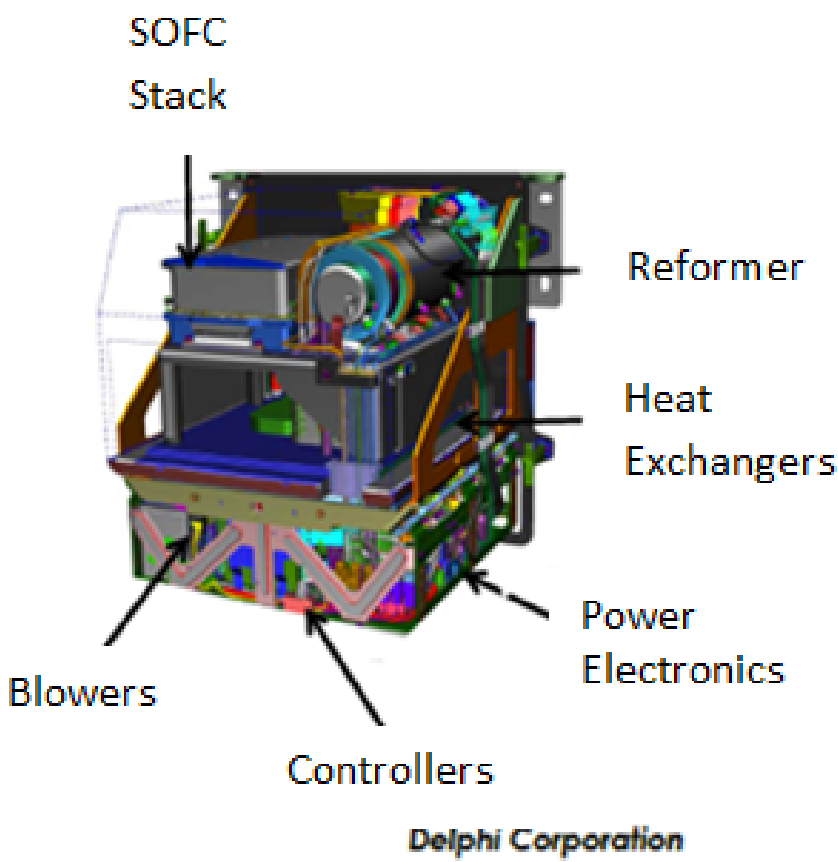


Figure 49. Aircraft Galley Power Trolley Cart

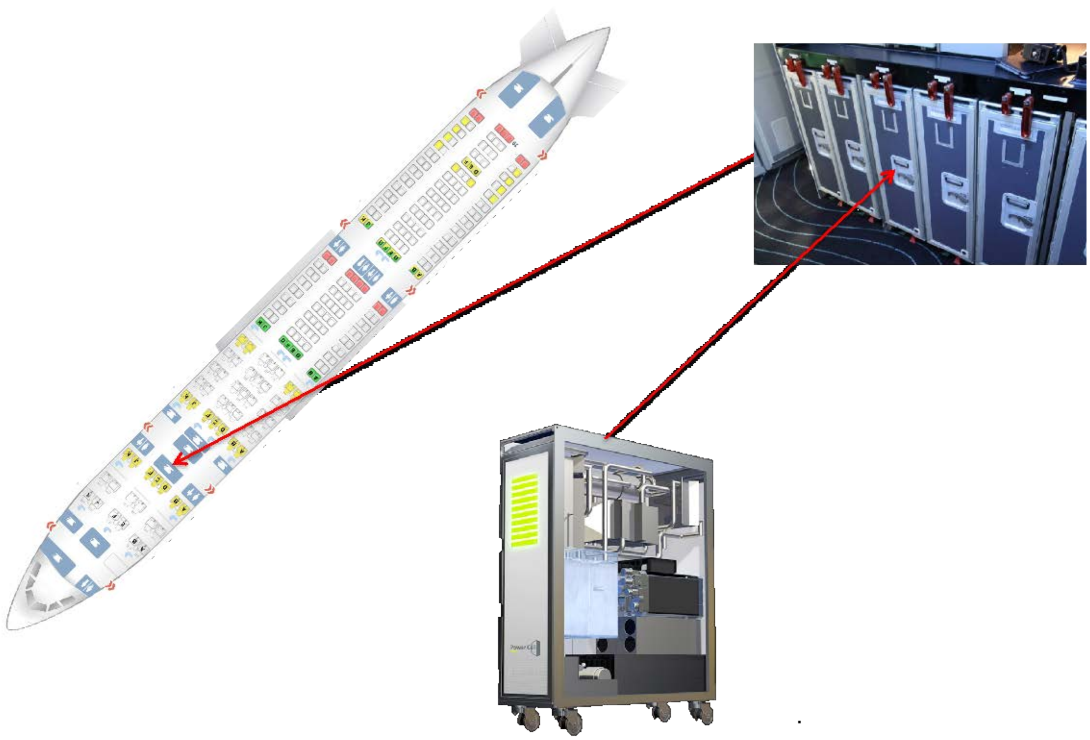
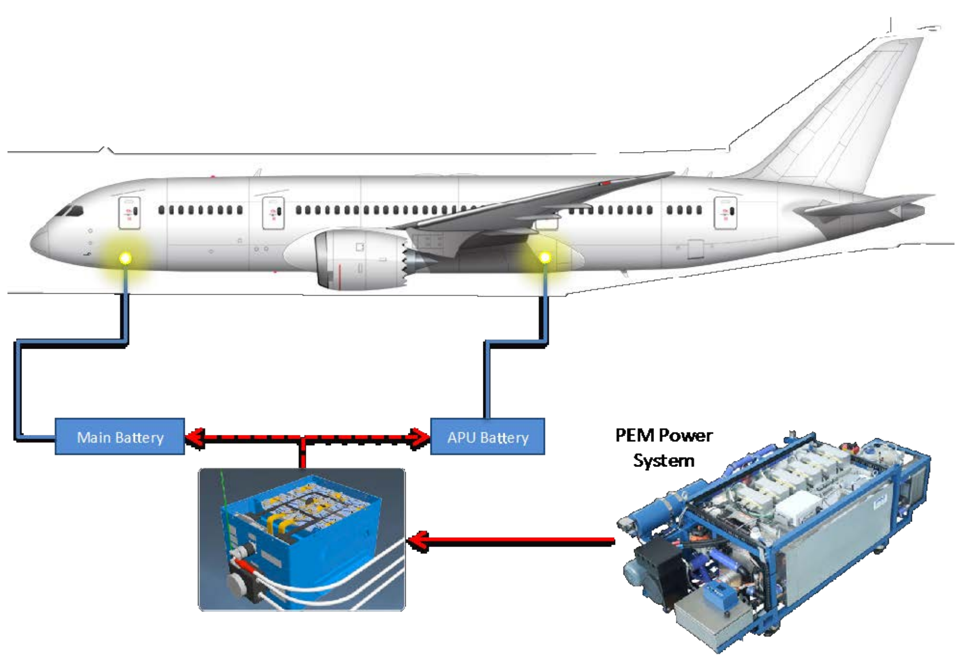


Figure 50. Aircraft Fuel Cell System



E.2 FUEL CELL INTEGRATION WITH AIRCRAFT SYSTEMS

Installing a fuel cell system on an aircraft involve some level of integration with other aircraft systems. On one end of the spectrum of applications, a FCS may, for example, generate a small amount of supplemental electrical power to a dedicated payload onboard the aircraft that is independent of the aircraft electrical power sources. Thus, requiring only minor modifications to the aircraft in order to accommodate the FCS. On the other end of the spectrum, a FCS may be used to provide primary electrical power, supply water, or supply inerting gas to the aircraft. This would require it to operate in tight connection with other aircraft systems, thus, imposing major modifications to the aircraft. The lower levels of integration may be the easiest point of entry, requiring less modification to the aircraft design or operation and fewer safety implications.

The intent here is not to describe all the possible applications that a FCS may address onboard an aircraft. Rather, the purpose of this section is to describe and classify them in such a way that any application may be filled by potentially a range of fuel cell system technologies. The applications are described as they appear from the aircraft view point and the type of functions that they are required to provide. Including the expected benefits that they bring to the aircraft and how they integrate into the platform. Therefore, the key metrics differentiating the applications must be defined from the point of view of the aircraft, and not in terms of technology variants.

The applications of a FCS onboard an aircraft may therefore be differentiated according to the following characteristics:

- The intended functions to be provided by the FCS, in particular the role it plays in ensuring aircraft safety and systems' reliability. This can be captured under the existing criticality classifications.
- The level of integration of the FCS within the aircraft platform

These two characteristics should yield an assessment of the complexity of the installation, integration, operation, and maintenance of FCS for a given application.

The criticality for passenger aircraft can be broken down into the following three categories:

(1) NON-ESSENTIAL—Functions whose failures would not contribute to or cause a failure condition which would significantly impact the safety of the airplane or the ability of the flight crew to cope with adverse operating conditions. Airplane conditions which result from improper accomplishment or loss of non-essential functions may be probable.

(2) ESSENTIAL—Functions whose failures would contribute to or cause a failure condition which would significantly impact the safety of the airplane or the ability of the flight crew to cope with adverse operating conditions. Failure conditions which result from improper accomplishment or loss of essential functions must be improbable.

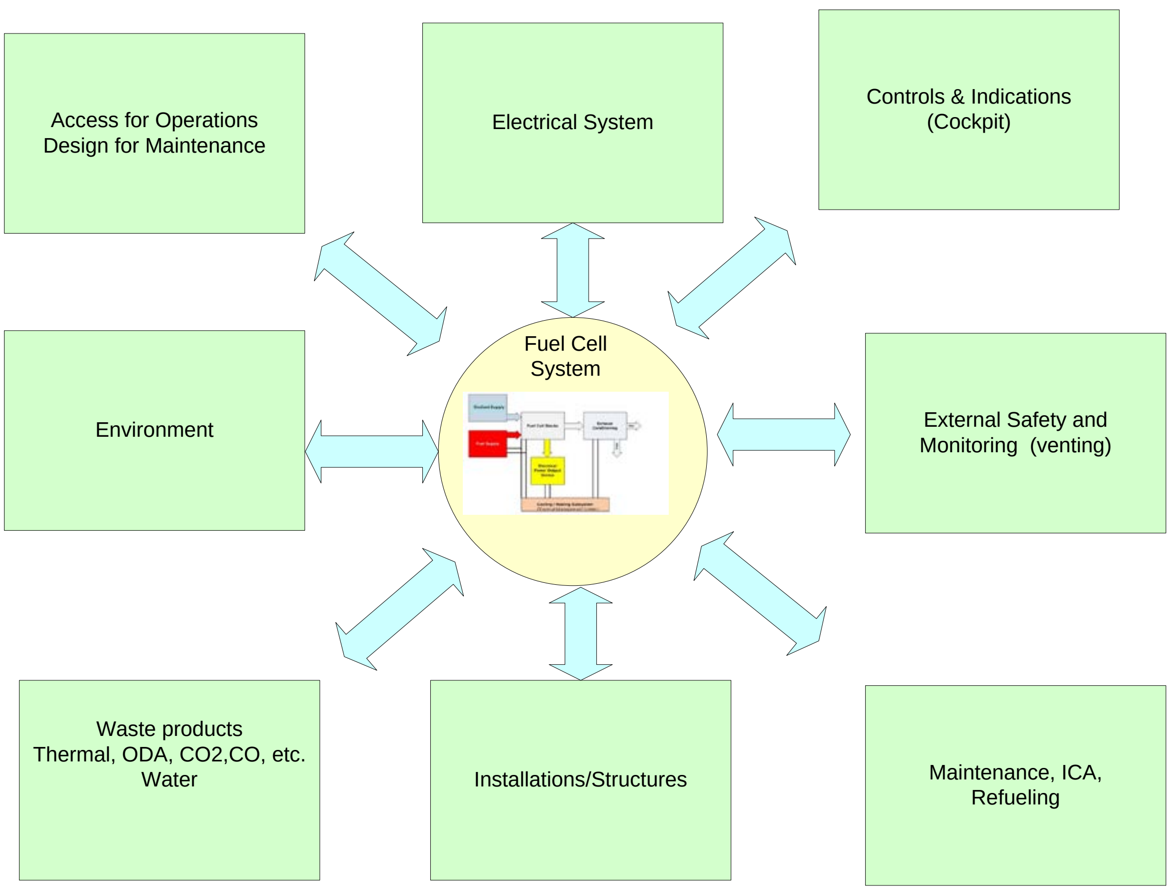
(3) CRITICAL—Functions whose failure would contribute to or cause a failure condition which would prevent the continued safe flight and landing of the airplane. Failure

conditions which result from improper accomplishment or loss of critical functions must be extremely improbable.

The level of criticality will have an impact on the introduction of new technology into a specific application. The criticality can also depend on the concept of operation. This report will provide one or two concepts of operation, but does not cover all the ways to design the power system and aircraft, and the possible operational scenarios.

The level of integration is related to the number and complexity of the interfaces between the fuel cell system defined in the main body of the report section 2.1 and the aircraft hardware, processes and operations as defined in Figure 51. These interface types help structure and classify the interfaces and provide a measure of the level of integration. The highly integrative nature of fuel cell technologies will require review of multiple regulatory areas.

Figure 51. Illustration of Interface Types



Each interface type illustrated in the Figure 51 is further defined below. These interfaces may contain, but not necessarily limited to, the elements and aspects shown.

Electrical system

- Power connection to the FC
- Power from FC to electrical distribution
- Isolation relays and circuit protection

Controls Indicators

- ON and OFF controls
- Monitor indicators
- Maintenance controls

External Safety

- Isolation Box
- External venting
- External monitoring

Maintenance/Instructions for Continued Airworthiness

- Refueling
- Inspection
- Life limited parts
- Warning Labels

Installation Structure

- Attachment to aircraft
- Routing and pluming of remote fuel source

Waste Products

- Waste Heat dissipation
- Storage or venting of oxygen depleted air (ODA)
- Storage or draining of waste water

Access for operation

- Assess to operation and maintenance controls
- Access for inspection and part replacement

Environment

- Pressurized / unpressurized
- Maximum Altitude
- Operational temperature range
- Maximum storage temperature

The systems and specific applications described in this section will address these interface types and their number and complexity.

There are a number of applications addressed in this section. Table 9 provides typical examples of key parameters for these applications. There are two applications in the table (and applications not even included in the table) that are not covered in the detailed sections to follow, but those that are included provide examples of the strategies and approaches for integrating fuel cells into an aircraft. The fuel cell type and fuels identified in the table and the sections below are one possible approach. These examples were picked because they have the best definition of the systems and the interfaces at this time.

Table 9: Performance Parameters of Key Applications

System Parameters	Applications					
	Galley Power	**Independent Power Medevac**	**Ground Power Cart***	**APU**	**RAT**	**Main Battery***
Ave Power (kW)	10–15	3–5	40–500	40–1350***	7–40	0-12****
Operating Duration	1–17 hr	5 hr	NA	5 hr	3–5 hr	60 min
Voltage	115/230 AC	28 VDC	115/230 AC	115/230 VAC 25 VDC	115/230	28 VDC
Electrical Bus	Non-essential	Non-essential	AC/DC	Main AC	Emergency AC	Emergency DC
Comm Bus**	Status	Status	Control	Control	Control	
Location on Aircraft	Cabin	Cabin	External	Tail section unpressurized	Non-pressurized	E&E Bay/APU compartment
Other Requirements	Cabin air	Cabin Air		Pneumatic and hydraulics power	High Altitude Air/ Cold Start	

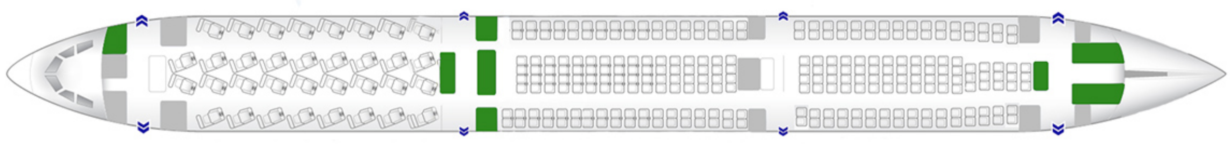
System Parameters	Applications					
	Galley Power	Independent Power Medevac	Ground Power Cart*	APU	RAT	Main Battery*
Level of Integration	See Applications discussed in Sections E.3 through E.7					
Criticality Classification	Non-essential	Non-essential	Non-essential	Essential/ Critical	Critical	Critical
Fuel Cell System	PEM	PEM	PEM or SOFC	SOFC	PEM	RFC
Fuel Type	Compressed H_2	Compressed H_2	H_2 or hydrocarbon /Reformate	H_2 or hydrocarbon/ Reformate	Compressed H2 or Chemical H_2	H_2
Oxidizer	Cabin Air	Compressed O_2	Air	Air	Compressed O_2	O_2
Thermal Heat Rejection	Handle by cabin's ECS	Handled by cabin's ECS	Ambient Air	Ambient Air	Ambient Air	Ambient air
Start-up time from Ambient	Depends on the airline. Typically, <10 minutes	< 10 mins	PEM < 10 min SOFC > 1 hr	> 1 hr	< 10 min	PEM < 10 min SOFC > 1 hr

* Not included in the examples below
** Comm bus can be used for status reporting only or include control
*** Equivalent shaft power
**** Transient peak power

E.2.1 General Description of Typical Aircraft Galley

A transport category airplane typically has several galleys installed at various positions in the aircraft Figure 52 shows an installation example).

Figure 52. Schematic of Typical Cabin Layout Illustrating Galley Installation at Various Locations in the A/C



A galley includes several types of galley inserts that are divided in two main categories: non-electrical inserts and electrical inserts (GAINS) that are used to store and prepare beverages and food for passengers. Typical galley requirements are shown in Table 10.

Table 10. Typical Standard Galley High-Level Requirements

	Short Range	**Long Range**
Galley power need (peak)	Up to 25 kW	Up to 50
Flight duration	0.75–5 hours	5–15 hours
Energy requirement	No constraint (unlimited)	No constraint (unlimited)
GAINs input voltage	115 VAC	115 VAC
Lighting input voltage	28 VDC	28 VDC

A galley unit is typically composed of:

- A galley structure/monument (housing the various galley inserts)
- A set of Electrical Galley Inserts (GAINs) for
  - Beverage makers
  - Coffee makers
  - Ovens (steam oven, convection oven)
  - Water Boiler
  - Bun Warmer / Toaster
- A set of non-electrical inserts (Standards Units, Trolleys) mostly used for stowage purpose.

- Work lights required / necessary in the galley monument vicinity.

Optionally, galleys can also include air chillers (used to maintain food cold before it is served to passengers) and trash compactors. The exact definition of the Galley equipment list is defined by each customer depending on the targeted route and service level.

The main galley / aircraft interfaces are as follows:

- Mechanical interfaces (interfaces between the galley structure/monument and the aircraft)
- Water system interfaces (interfaces between galley and both potable and waste water aircraft systems)
- Air / ventilation system interfaces (interfaces between galley and fresh air supply and interfaces between "used air" (from the ovens and air chiller units) from the galley and the cabin air extraction system)
- Electrical power supply
    - Electric power is supplied as 115 VAC 400Hz 3 phases to the GAINS and 28 VDC to work lights (generally generated from the 115 VAC supply through Transformer Rectifier Unit installed in the galley).
    - Electric power is supplied to the galleys through dedicated power feeders. Each galley position in the aircraft is allocated and number of power feeders.
- Human-Machine Interface (to power on/off and to report about the system status)

E.2.2 Functional Description/Operation

In this fuel cell powered galley concept, a fuel cell system is provided that is dedicated to generating and providing power and energy to galley loads such as:

- Galley inserts (e.g., ovens, water boilers, beverage makers, bun warmers)
- Air chillers,
- Trash compactors,
- Lights

The general capabilities of the fuel cell system are shown in Table 11. The FCS is specifically designed to power the dedicated set of galley loads and the complete FCS is <u>not</u> connected to the aircraft electrical power network. It is therefore operated completely <u>autonomously</u> and remotely with regards to this aircraft electrical power network.

Table 11. Typical Fuel Cell Powered Galley High-Level Requirements

	Short Range	Long Range
Galley power (peak)	10–30 kW	10–50
Galley power (mean)	5–15 kW	5–20 kW
Flight duration	0.75–5 hours	5–15 hours
Energy requirement*	~ 10–50 kWh	~10–100 kWh
GAINs input voltage	115 VAC or DC	115 VAC or DC
Lighting input voltage	28 VDC	28 VDC
Generated heat power	10–30 kW	10–50 kW
* Energy Requirement need to be defined on a case by case basis as it depends on the aircraft operator target route and service level.		

As further options (then impacting the system design and rated power), the system might also:

1. Provide electric power/energy to other equipment located remotely from the galley position,
2. Be connected to the aircraft electrical power network so as to complement or backup "conventional" power supply to some equipment.

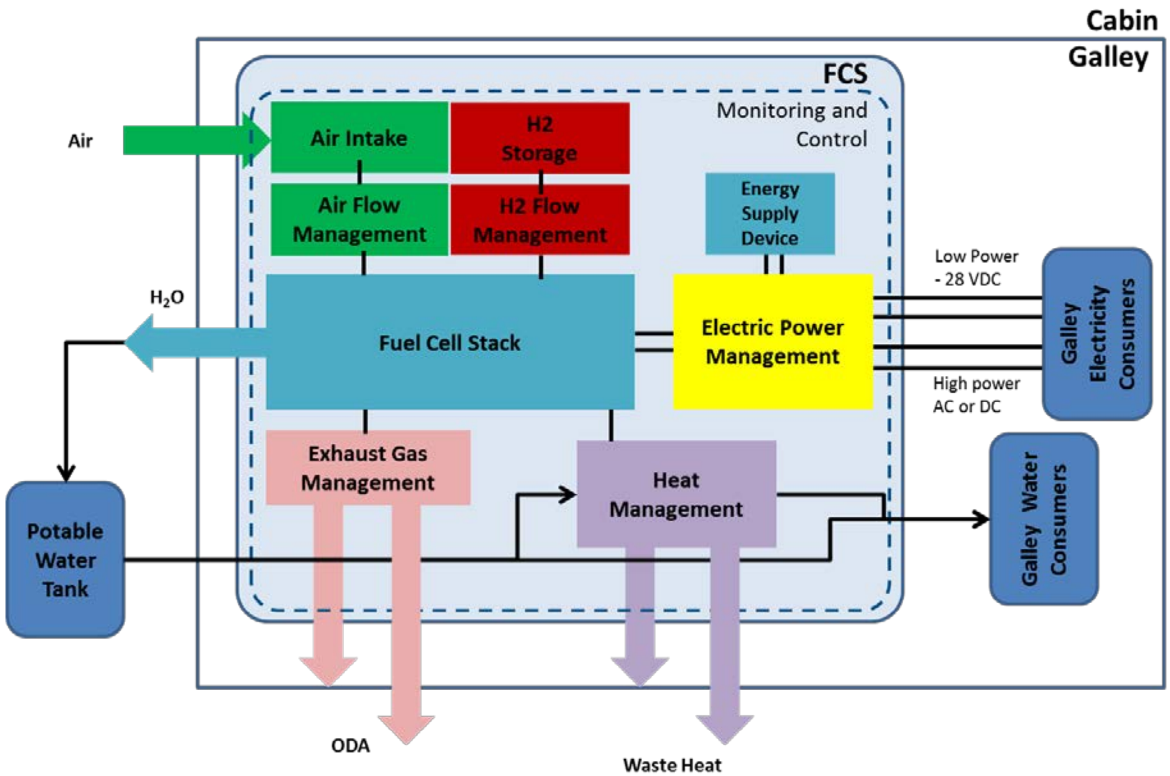
Moreover, FCS by-products (water, heat and Oxygen Depleted Air) might be used to fulfill or contribute to some of the required galley functions:

- Use heat generated by the FCS to provide heat to some of the heat consumers (e.g., galley inserts, beverage makers, water boilers).
- Use water generated by the FCS either as potable water or for non-potable water needs (toilet for instance).
- Use Oxygen Depleted Air generated by FCS for fuel tank inerting.

E.2.3 Architecture Principles

A schematic of a fuel cell powered galley is presented in Figure 53. It illustrates the system architecture and main interfaces between the system and the aircraft cabin. These interfaces are described in more detail below.

Figure 53. Fuel cell galley functional architecture (example)



For a fuel cell powered galley, oxygen is drawn from the cabin air and supplied to the fuel cell stack after appropriate conditioning (pressure, temperature and humidity). Hydrogen can be supplied either from a high pressure compressed gas source (typically 350 bars H_2 gas vessels) or from alternatives storage means described in 0. Before being supplied to the fuel cell, hydrogen is also conditioned (pressure, temperature and humidity) so that the fuel cell is operated in the most favorable conditions.

Fuel cell generates electric power under certain voltage characteristics. This needs to be controlled and adapted to the galleys consumer's electrical characteristics requirements (28 VDC, 115 VAC or DC high voltage). This is achieved through dedicated power conversion and control equipment. In order to fulfill the requested mission profile and to optimize the system sizing and weight, the fuel cell is associated with a secondary energy supply device (i.e., a battery) that allows for an optimal hybridization strategy.

Furthermore, to provide a completely autonomous solution, the secondary energy device is sized such as it can supply the required energy to ensure startups and shutdowns of the system. This is because the FCS cannot start by itself as it needs pre-start safety checks (such as hydrogen detection) and need also power to bring oxidant to the stack.

Heat generated by the fuel cell is collected by a liquid heat carrier and then further transferred to a dedicated radiator equipped with a fan. The heat not used within the system is then released in the cabin air. Before being transferred to the radiator, this heat carrier is also circulated to equipment in the system requiring significant cooling capacity (power conversion and compressor for instance).

The heat generated by the fuel cell system is used in the galley to replace some of the electrical consumers. This has multiple advantages: it reduces the electrical requirements (thereby reducing the amount of hydrogen required for the mission) and it also reduces the amount of heat to be released to the cabin air.

Water generated by the fuel cell is used within the system to fulfill the fuel cell reactant gas humidification requirements. Remaining water is then expelled out of the system to the aircraft water and waste system.

Installation of the system can be performed in either in one single location, or in a modular approach, with modules installed in different locations.

E.2.4 Aircraft Interfaces

According to the above-mentioned description and architecture principles, aircraft interfaces are listed below. New interfaces required due to the presence of the FCS are flagged "NEW". Table 12 provides a summary of each interface type, interface description, and applicable regulatory standards.

Table 12. Galley Cart Interface Descriptions and Applicable Standards

Interface Type	Interface Description	Applicable Standards* § 25.XXX
Electrical System	Electrical wire dedicated to GAINs power supply. Remains inside the galley monument. Battery for startup and hybridization.	1351,1353, 1357, 1431, 1301, 1309, 17xx, 1360, 1365, , TSO-C175, TSO-C184, ETSO-C175, ETSO-C184
Controls Indicators	Start/stop button for galley crew, enabled from flight desk (kill switch) Indicators have to be sent to the aircraft to give a status about failure, need of maintenance, etc.	1302, 1322, 1357(f),
External Safety	H_2 and inert venting line to inside or outside of aircraft, fuel connection is external (between tank and FC), Need H_2 leak detector (location TBD), replace filter, water connections, heat dissipation to cabin (some heat will reduce coffee heating), forced air, external lock on cart, pressure vessel in cabin	1301, 1309, 899, 1316, 1317, 851, 831, 869 modified, 1183, 1185, 1187, 863 modified, 17xx, fire detection and suppression regs, looking at new regs for H_2 leak detection on aircraft, H_2 explosion reg, 795

Interface Type	Interface Description	Applicable Standards* § 25.XXX
Maintenance/ICA	System health monitoring with a maintenance plug to have access to the monitoring and control subsystem H_2 storage in a trolley for easy refilling, replace filter	1529, 1729, 21.50,
Installation Structure	The AC structure has to sustain the overweight of the galley. Galley cart lock. Fixation device on the monument to lock the trolley	302, 561, 581, 789, TSO-C175, TSO-C184, ETSO-C175, ETSO-C184
Waste Products	Water to toilette or waste water circuit ODA in cabin Heat in cabin, H_2 from fuel cell vented to outside of aircraft	Icing, heating elements, 1309, 831, CS302, 603, 601
Access for operation	Back of trolley access for maintenance. Operator panel in galley for status, controls and diagnostics.	611, 1719, 1529, 1360, 1541, 1555, 1561, TSO-C175, TSO-C184, ETSO-C175, ETSO-C184
Environment	Will be pressurized area in cabin. Operating temp -5 to 45 ^{o}C. Operating cabin pressure < 10,000 ft.	1301, 1309
* The standards are only based on the general descriptions of the applications. In an actual certification program, the Aviation Authority will decide which standards are applicable. A detailed examination of applicable regulatory standards for FCS in general is discussed in Appendix G.		

- Mechanical (fixing features of the galley to the aircraft – mostly should not be impacted by the addition of fuel cell system))
- ***NEW*** - No more electrical interfaces to the aircraft electrical power network
- ***NEW*** - Air supply to the fuel cell system (added) and to the Galley inserts (as for conventional system). Air is taken from the cabin, and therefore there is an indirect link to the Environmental Control System (ECS).
- ***NEW*** - Oxygen Depleted Air Exhaust (ODA). Fuel cell operation consumes part of the oxygen fed to the fuel cell. The exhaust gas from the cathode side of the fuel cell has therefore a low level of oxygen (compared to air). Two options can then be considered for expelling this ODA gas out of the system.
    - Exhaust ODA directly in the cabin environment. In this configuration, this creates a new interface with cabin air (and therefore ECS) and cabin equipment (ODA gas composition and flowrate will have to be taken into consideration to assess this impact)

- Exhaust ODA outside cabin or aircraft. In this configuration, this creates new mechanical interfaces with the aircraft as the ODA has to be ducted to the appropriate disposal location.

- ***NEW*** - Heat generated by the fuel is collected through a dedicated coolant loop. For each kW of electricity generated, about 1 kW of heat is also generated. Part of this heat is used for ensuring galley functions, but the remaining heat is disposed of to the cabin air. This creates an additional new interface between the galley and the aircraft cabin (and the ECS).
- Water and Waste System interfaces.
  - Potable Water inlet to the galley or use in water boilers, beverages makers and/or ovens.
  - Waste water exhausts
    - From Galley inserts. These are required for expelling "used" water out of the galley.
    - ***NEW*** From fuel Cell system. Water generated by the fuel cell can be used in the galley environment, but most probably some water will not be used and needs to be expelled out of the galley. This waste water from the fuel cell system could also be mixed with the waste water from the galley to save unnecessary interfaces.
- ***NEW*** – Hydrogen Supply and vent lines. These interfaces are specifically required because of the presence of the fuel cell system in the galley environment. Several interfaces may have to be considered depending on the system configuration and installation.
  - Hydrogen supply:
    - Case 1: hydrogen storage system is "self-contained" and located in a galley cart/trolley. This configuration does not create any additional interfaces with the aircraft (interfaces between the storage and the fuel cell system are provided inside the galley).
    - Case 2: hydrogen storage system is installed in a remote location from the galley position. In this configuration, additional new interfaces (hydrogen containing piping) are created between the galley and the hydrogen storage location.
    - For both cases, abnormal operation or failure from the system itself, but also from other equipment in the system surrounding has to be taken into account (need for venting out hydrogen contained in the storage in case of fire for instance).
    - Case 1 has many advantages and is for now preferred.
      Hydrogen refilling is done during normal trolley refurbishing. It should not increase the maintenance duration of AC between 2 flights.
      The trolley is refilled outside the aircraft which is safer.
      Hydrogen trolley is installed in the galley and fixed by a dedicated tooling. The trolley can only be removed and installed by trained operator with a special tool

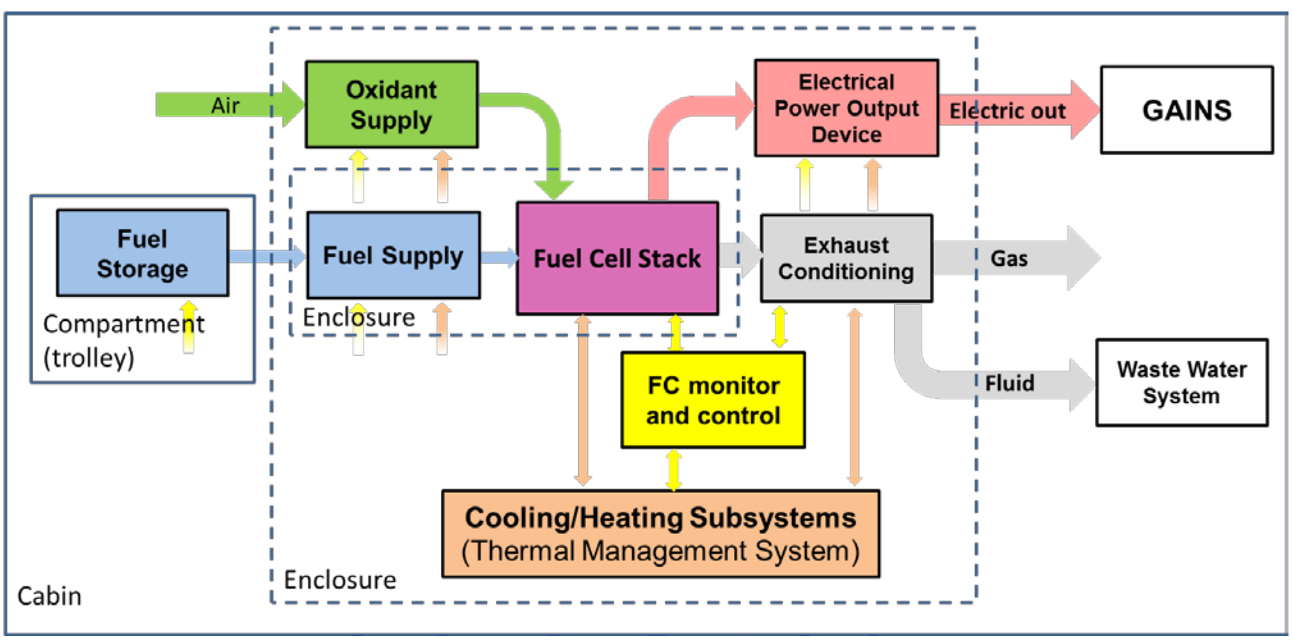
to avoid wrong trolley manipulation.
The hydrogen is delivered through a quick connector at the rear of the trolley. Leak tightness is ensured by automatic test.

- Hydrogen functional normal hydrogen releases. During normal operation, the fuel cell system may release hydrogen (due to permeation through the fuel cell stack sealing or to functional purges for instance). These "normal" hydrogen release will then be released into the galley surroundings directly to the cabin air (after adequate dilution and/or mitigation) or vented outside the aircraft. This creates interface with the ECS which has to be taken into consideration.
- Hydrogen leakage management. In case of abnormal operation or failure, abnormal hydrogen release from the system could occur. As for "functional" hydrogen releases during normal operation, abnormal releases would be released in the galley surroundings after appropriate dilution and/or mitigation. This creates interface with the ECS which has to be taken into consideration.

- Human- Machine Interface. The fuel cell powered galley will be completely autonomous from aircraft electrical network, but will still have to allow crew members to power it on and off, to report about its status to the crew. An enable button is also foreseen in the flight deck, allowing pilots to authorize the fuel cell startup but also switch off the system.

This application is non-essential and has only a few interfaces (level of integration) to the aircraft.

Figure 54. Fuel Cell Galley, Compartment and Enclosure Illustrations (example)



E.3 APPLICATION: STAND ALONE POWER

This type of system is self-contained and can be installed and removed from the aircraft. Examples of such applications include the powering of payload in “special aircraft”. A “special aircraft” is defined as an aircraft which has been modified to accommodate specific missions, which are not passenger or cargo transport, such as:

- Medical evacuation (“Medevac”)
- Electronic warfare
- Maritime surveillance

The associated payload may therefore be:

- Medical kits including beds and monitoring devices, freezers, heaters
- Weapon guidance systems,
- Radars, observation devices,

A dedicated FCS may be used to supply the power to such payload, independently from the native aircraft’s electrical network.

The following sections detail the case of a Medevac application on a business jet, as illustrated in Figure 55 and Figure 56.

Figure 55. Dedicated Medevac Aircraft

Figure 56. Dedicated Medevac Aircraft—On-Board Installation

E.3.1 General Description of Medevac on Special Aircraft

Getting an airline aircraft modified to accommodate someone with a straight leg means removing seats, increasing the time it takes to board, and having specific personnel to accompany, so it can be expensive and cumbersome to organize.

Moreover, airliners operate from main airports, so liaison to them is a concern, while business jets can operate from smaller airports, meaning a faster and easier access. Business aircraft fly higher than commercial airliners, thus are less subject to air turbulences and this can be critical for injured passengers. For all these reasons, Medevac missions are best accommodated with business jets. A medevac medical module is shown in Figure 57.

Power generation capability for medical equipment and redundancy in case of failure is key to the success of the Medevac mission. The Medevac payload typically consists of:

- A medical module which carries a stretcher, with dedicated lighting, oxygen bottles, several pieces of monitoring and analysis equipment, etc.
- A blood bank with power supply for conditioning, storage of medical equipment (blood gas analyzer, etc.)
- A loading system (lift device).

Figure 57. Medevac Medical Module

Today the power required to operate the medical equipment is supplied by the native aircraft generators. A malfunction of the aircraft electrical generation or distribution system could jeopardize the medical mission. There have been instances when lives were lost in this kind of situation.

E.3.2 Fuel Cell Powered Medevac Payload on a Special Aircraft

The application described here consists in using a dedicated FCS to supply electrical power to Medevac modules on-board a Special Aircraft.

It is expected that the use of a dedicated FCS will improve the reliability of vital power supply to the Medevac modules.

Such a system would consist of a fuel cell (a stack and its ancillaries), a H_2 storage sub-system and possibly an O_2 storage sub-system.

As most of the Medevac aircraft operators also use their aircraft for more conventional missions (passenger transport), it is important that the aircraft be easily rearranged from one configuration to another.

The FCS would then be a plug and play box which should be easily mounted and dismounted into and from the aircraft. On a business jet the most convenient option is probably to install such a box in the luggage compartment, in the rear section of the cabin.

The amount of power required for the medical kits ranges from 3 to 5 kW and should be fairly constant throughout the flight. The operating time may reach 10 hours for certain missions. The energy needs to accomplish the mission may therefore be in the order of 40 kWh.

The H_2 storage sub-system and the rest of the FCS should therefore be sized against this requirement.

The FCS will be sized in such a way that the heat generated by its operation remains within the limits of what the ECS is capable of handling in the cabin. Due to the location of the FCS in the rear of the pressurized area (luggage compartment) and because cabin air flows from front to rear, the temperature rise due to this additional heat rejection in the cabin will be spatially limited to the FCS vicinity. However, the cabin temperature in a Medevac aircraft is usually set at higher levels than common aircraft, for the sake of the patient's comfort.

E.3.2.1 Functional Description

Several different architectures may be laid out to address the needs of such an application. Below is a list of the main features that characterize these candidate architectures. It describes how these features can rely on different technical options (reference Figure 54). An interface summary, Table 13, is found at the end of the section.

- In order to manage transient loads, hybridization with a battery could be used. The fuel cell would then be responsible for recharging this battery on a regular basis throughout the course of the flight.
- The electrical power generated by the fuel cell would be supplied to the equipment via a dedicated bus, independent from the native aircraft network. For an application on a business jet, a 28 VDC bus could be used.
- The cooling of the FCS would be performed using heat exchange with the cabin environment via a dedicated radiator.
- The heat rejected by the FCS could also be used to heat up the medical beds, thus replacing the electrical heaters used in today's equipment. A dedicated liquid loop would be used for this purpose. This principle would yield a smaller electrical demand from the equipment and thus a smaller, more optimized, FCS.
- The hydrogen would be stored in pressurized gas form in a dedicated tank.
- The oxidant required to accommodate the electrochemical reaction within the fuel cell may either come from cabin air or from a dedicated oxygen storage sub-system. On certain business jets, it may be preferable not to consume cabin air and instead obtain the O_2 using compressed O_2 in a dedicated tank. This source of compressed oxygen may very well be of the same kind as the one used in the medical equipment, and for which certification specifications already exist.
- Whether the oxidant source is compressed oxygen or cabin air, unconsumed oxygen (compressed O_2 source) or Oxygen Depleted Air (cabin air as the O_2 source) coming from

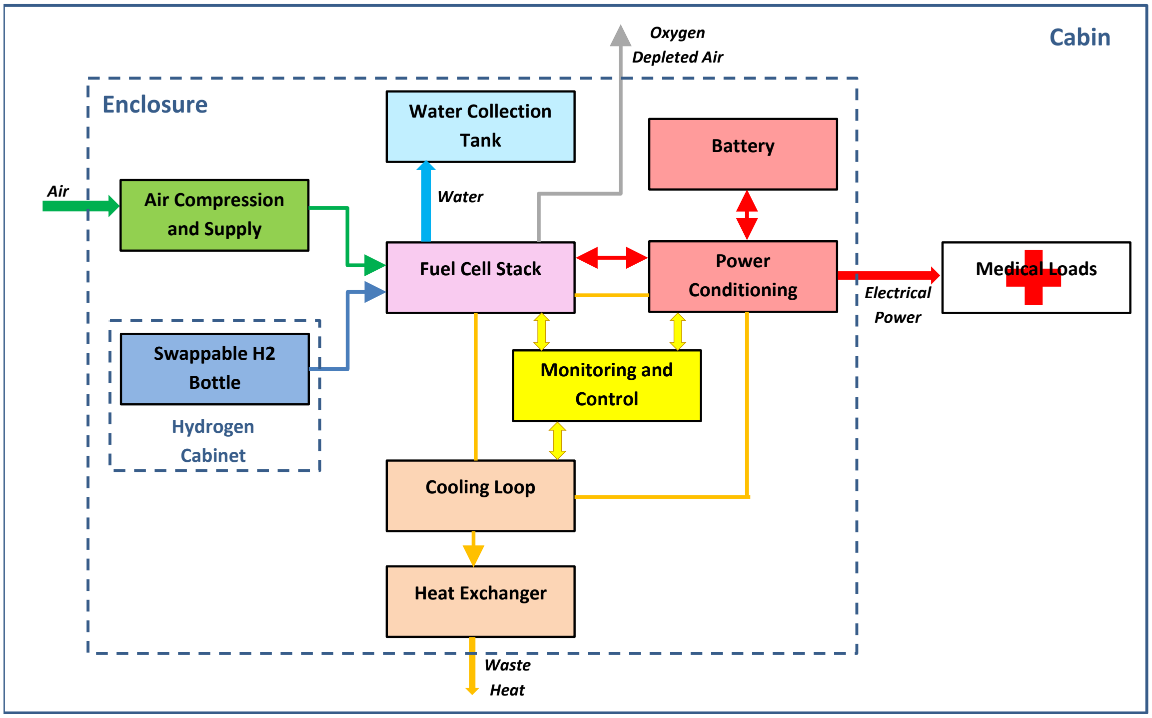
the FCS could then be released into the cabin atmosphere. Although it is expected that the amount of additional O_2 or ODA is negligible, it will be necessary to verify that this flow does not alter the composition of the overall cabin air to a point where it may impact the passengers or crew well-being.

- The water by-product could be collected and used for various purposes on-board.
- The FCS will be started and shut down according to a well-defined protocol which allows for a safe operation in any condition. This protocol will include the purge phases which may be required for proper stack operation. The purge gas injected into the cabin should be handled in such a way that it does not introduce any safety concern. There must be appropriate venting inside or to the outside for acceptable air-hydrogen mixture inside or outside the cabin.
- Similarly, any traces of H_2 coming from permeation through stack seals or else must be handled in such a way that it does not introduce safety concern (i.e., an acceptable air-hydrogen mixture is maintained inside the cabin). H_2 detectors may also be needed.
- Apart from the controlled hydrogen and O_2 or ODA, no other gas release into the cabin is expected from the FCS.
- It should be noted that H_2 venting lines from the system may be needed to purge excess H_2 (Low, Medium or High Pressure) outside of the aircraft to prevent any undesired accumulation inside the cabin. These lines will need accommodation to outside of the aircraft. Because of the very nature of the Medevac missions, the aircraft is not susceptible to remain on ground in harsh weather conditions for too long: The Medevac aircraft lands on an airfield to pick up the patients and departs back as fast as possible. In addition, the cabin atmosphere has to remain within the appropriate temperature condition, which implies that the FCS will most likely never have to endure freezing or even a cold start scenario.

There are several important recommendations for designing a system for this application

- Safe H_2-Air mixture management via use of dedicated enclosures and H_2 monitoring
- Mounting and installation of system on-board to take into account presence of H_2 venting line
- Mounting and installation of system on-board to take into account concept of replaceable/swappable H_2 tanks

Figure 58. Medevac Fuel Cell Functional Architecture (example)



E.3.2.2 Safety

The FCS must be monitored and controlled real-time with a dedicated set of sensors, monitoring and control units.

These controllers should be designed to render this system independent from any operator's intervention. The FCS will then be able to control itself autonomously and shut itself off in any abnormal conditions encountered.

In addition to this, the flight crew will have access to key data regarding the FCS state of health during operation (e.g., battery status, hydrogen content, temperature) and will be in a position to shut it off if needed, via a dedicated interface (emergency button).

The H_2 storage sub-system should be equipped with dedicated sensors to allow for a real-time measurement of the hydrogen content in the vicinity air.

In order to avoid any accumulation of hydrogen resulting from leaks, the H_2 storage sub-system (vessel, distribution components, sensors, etc.) should be installed in a dedicated closed compartment which will be continuously ventilated. The composition of the air-hydrogen mixture exiting this compartment will be monitored so that the appropriate control actions may be triggered.

Excess hydrogen susceptible to yield too rich of a hydrogen-air mixture in the cabin will be purged outside of the aircraft, via dedicated venting lines (low, medium, or high Pressure).

An additional fire extinguisher may be used by the flight or medical crew in the luggage compartment to handle an aircraft fire scenario in the vicinity of the FCS.

As such, a FCS performs functions whose failures would not lead to safety concerns for the airplane or would impair the ability of the flight crew, it may be considered as a non-essential system.

Yet, the failure of this system may very well have a critical impact on the well-being, even the life, of the patients being transported and taken care of. As such, a FCS should be considered at the same level of criticality for the patients as are the medical equipment themselves.

E.3.2.3 Medevac Aircraft Interfaces

Table 13. Medevac Interface Description Summary (example of stand-alone power)

Interface Type	Interface Description Summary	Applicable Standards* § 25.XXXX
Electrical System	Dedicated wire harness, routed through the aircraft. Subject to applicable CFR/CS part 25 EWIS regulations, with no other connection to any other electrical system on the aircraft. Internal battery for self-starting and monitoring.	1301, 1309, 1351, 1353, 1357, 1360, 1365, 17XX
Controls Indicators	System health indicator and emergency shutoff needed on flight deck. Medical crew will operate the fuel cell system from a control panel located on the fuel cell in the cabin.	1322
External Safety	System is contained within an enclosure. H_2 leakage monitoring in enclosure. H_2 venting line from system needs accommodation to outside of aircraft.	1309, 1316, 581 or 954 (for the venting outside), 899, 17XX, 851, 831, 1183, 1185, 863, 865
Maintenance/ICA	High pressure H_2 tank in system box is replaced as needed. System status and maintenance indicators on system. Maintenance instruction provided. Vent line to will need to be installed as needed (see above). System must be installed and removed without fuel and connected to aircraft harness. Empty water tank.	1529, 1729, 21.50
Installation Structure	Enclosure is used to physically install the system into cabin. Install vent line. Mounting structure	301, 302, 581, 561, 601

Interface Type	Interface Description Summary	Applicable Standards* § 25.XXXX
Waste Products	Water collected in a dedicated tank within enclosure. Waste heat is 5 kW or less, rejected directly to the cabin, so that it can be handled by aircraft ECS. Venting unconsumed oxygen or ODA into cabin at low levels (see above)	1309, 831, CS302, 603, 601
Access for operation	Access door for refueling. Control panel located on the system. Vent line connections can be accessed for inspection.	611, 1719, 1529, 1360, 1541, 1555, 1561
Environment	Installed in the pressurized area in the cabin. Operating temp 10-45 °C. Operating cabin pressure < 10,000 ft.	1301, 1309
* The standards are only based on the general descriptions of the applications. In an actual certification program, the Aviation Authority will decide which standards are applicable. A detailed examination of applicable regulatory standards for FCS in general is discussed in Appendix G		

E.4 APPLICATION: AUXILIARY POWER

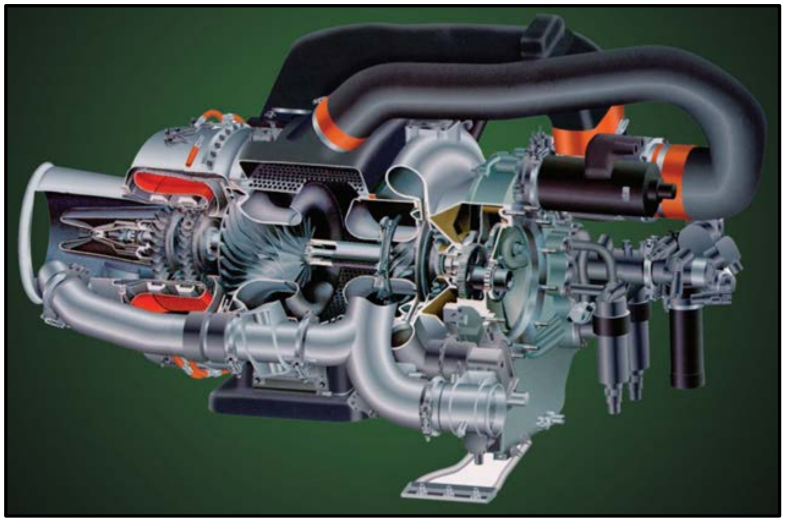
An APU is defined by TSO-C77b as "Any gas turbine-powered unit delivering rotating shaft power or compressor air, or both, that is not intended for direct propulsion of an aircraft."

The APU main functions are:

- Provide bleed air or electrical power for main engine start (MES)
- Provide bleed air for the ECS when the main engines are off
- Provide electric power for the airplane when the main engines are off
- Provide hydraulic power for ground operations

APUs vary based on the size and power architecture of the aircraft. A 90 KVA APU is shown in Figure 59. The electrical power requirement for an APU varies from about 40KW for a small regional airplane to 90kW for narrow body transport category airplane to 240kW for large wide body airplane to 450KW for large More Electric Aircraft (MEA). Note that the traditional APU also provides pneumatic (bleed air) power for the ECS and MES whereas the MEA only demands electric power. The bleed air system of the APU demand much more shaft power than that of the electric generator on the same APU. The combined power can reach 1.35 MW.

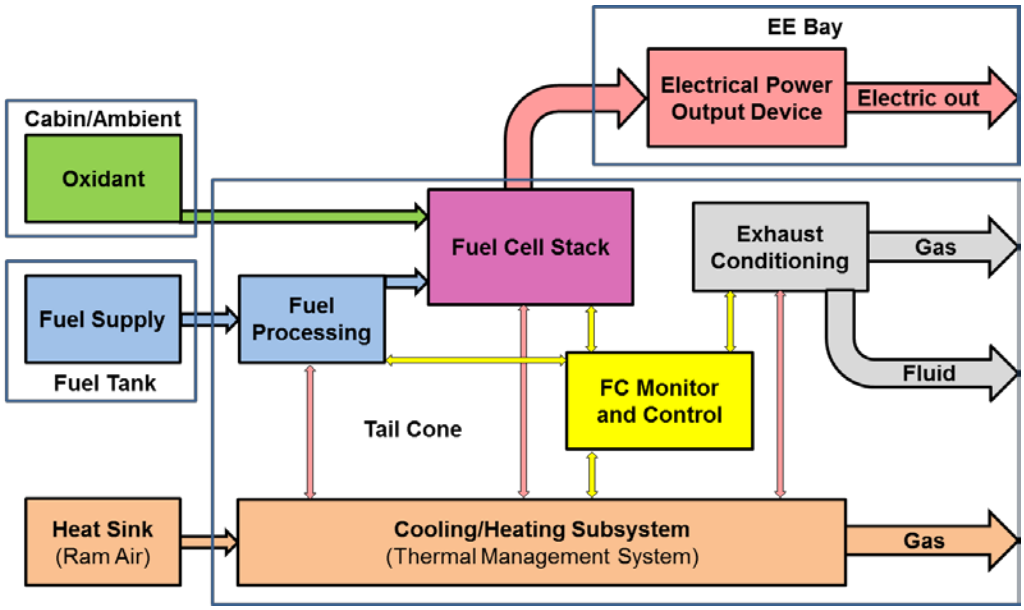
Figure 59. Narrow Body Transport Aircraft APU, 90 KVA 361 lbs (164KG)



The performance and reliability criteria for any aircraft system are determined by the use of that system to maintain controls of the aircraft during normal and abnormal conditions. The criticality of an APU relative to flight safety in any particular aircraft installation will determine if the APU system should be considered essential, or non-essential. Airplanes that rely on APUs for provision of back-up electrical power in flight in the event of a failure of the primary power sources are usually considered essential installations.

Although it is unlikely that a fuel cell APU (FCAPU) would replace a traditional APU in form, fit, and function due to the size, weight, and other technical challenges; it is assumed as such for the purposes of discussion in this report. This notional FCAPU application is described below. The general architecture is shown in Figure 60.

Figure 60. Notional Fuel Cell APU Functional Architecture



The integration and installation aspects of the FCAPU includes at least the following:

1. The main FCAPU is housed in the FCAPU compartment of the aircraft, which is an unpressurized zone with a firewall separating it from the pressurized cabin.
2. The FCAPU includes the fuel processing system, fuel cell stack, fuel cell monitor and control, exhaust stream conditioning, and integrated power/thermal management system which may include turbo-machinery such as gas compressor and turbine, and burner/combustor.
3. There are physical penetrations in the FCAPU compartment which include the fuel interface, oxidant (air) interface, heat sink (cooling air) interface, electric power input/output interface, signal and control interface, exhaust stream interface, maintenance access panel, installation access panel.
4. There are external monitoring sensors inside the compartment for gas concentration, temperature, fire. There is external fire suppression system inside the compartment.
5. The FCAPU is support by the compartment structure through mounting brackets and struts, which serves the functions of linear and rotational acceleration stability, shock absorption, vibration isolation.
6. The fuel is common jet fuel, stored in aircraft fuel tank. It is supplied to the fuel processing equipment that includes desulfurizer and reformer before delivered to the fuel cell stack as hydrogen enriched fuel. The major constituents of the hydrogen enriched fuel are CH_4, CO, CO_2, H_2O, and H_2 during normal operation. Alternatively, the fuel can be of ultra-low sulfur or bio-fuel stored in a dedicated fuel tank which can also

be used by the main engine as a reserve fuel blend. In this case, the desulfurizer will not be necessary.

7. FCAPU uses air as oxidant, from cabin or from ambient free stream air, conditioned to the proper purity, pressure, and temperature before entering the fuel cell stack. The operating pressure of the fuel and oxidant are between 1 to 3 bars.
8. The FCAPU is highly thermally integrated, and requires ambient air as heat sink to maintain operational conditions. The spent waste ODA stream can be reused as icing protection before discharged overboard.
9. The fuel cell stack generates 270 VDC electric power that will be delivered to power conditioning equipment where it will be inverted and conditioned to 28VDC, 115VAC and 230 VAC @ 400Hz circuits before connected to the primary and secondary distribution systems.
10. To ensure continuous airworthiness of the FCAPU, Build-In-Test (BIT) is constantly performed and monitored; periodical inspections and maintenance are required, such as a sulfur trap (if any), fuel, and air filters replacement, liquid replacement, and cleaning of equipment.
11. The FCAPU is likely to run continuously for as long as practical to reduce thermal cycle. Also, the highly thermally integrated system responds slowly to varying load demand. To maintain optimal efficiency and power density, the FCAPU is designed to operate in either full load or standby condition. Other energy supply devices such as regenerative fuel cells or batteries should be included in the overall aircraft power system architecture to manage the transient power demand. However, these ESDs are not considered part of the FCAPU.

E.4.1 APU Aircraft Interfaces

The interface types are described the Table 14. This system is highly integrated (level of integration) and will require extensive design and development. Given this high level of integration, when implemented, this system will be "Essential" or even "Critical", and unlikely to be operated on the ground only.

Table 14. APU Interface Descriptions and Applicable Standards

Interface Type	Interface Description	Applicable Standards*, § 25.XXXX
Electrical System	Connect to primary and secondary distribution systems. 28VDC, 115VAC, 230VAC, 270VDC	1351, 1353, 1357, 1431, 1301, 1309, 17XX, 1355
Controls Indicators	Connecting to cockpit, maintenance computer, and local display for controls and indicators. On/Off/Standby. Monitoring health,	1302, 1322, 1357(f), 777,

Interface Type	Interface Description	Applicable Standards*, § 25.XXXX
	temperatures, Pressures, speed (rpm), and mass flow. BIT.	
External Safety	Fuel/H_2 leak detection, fire detection and suppression, using aircraft fuel (could also use H_2 as fuel – depends to system design)	1301, 1309, 899, 1316, 1317, 954, 851, 831, 869, 1183, 1185, 1187, 981, 863, 865, 9xx, 17xx, fire detection and suppression regs, looking at new regs for H_2 leak detection on aircraft
Maintenance/ICA	Replace sulfur traps, air filters, fuel filters, batteries, health monitoring, and water reservoir check.	1529, 1729, 21.50, 1360, 1541, 1555, 1561, 1557
Installation Structure	Mounted to airframe in non-pressurized zone, DO-160 Equipment Cat. D3, air intake and exhaust	302, 561, 581
Waste Products	Water and heat recycled through fuel reforming system, ODA and cooling air vented through exhaust	Icing, heating elements, 1309, 831, CS302, 603,
Access for operation	Access for inspection, replace traps/filters, check water reservoir	611, 1719, 1529, 611, 1719, 1529, 1360, 1541, 1555,
Environment	Unpressurised	1301, 1309
* The standards are only based on the general descriptions of the applications. In an actual certification program, the Aviation Authority will decide which standards are applicable. A detailed examination of applicable regulatory standards for FCS in general is discussed in Appendix G.		

The current APU requirements make using a fuel cell as an APU in a transport aircraft very challenging. Many technical teams have for over a decade studied the possibility of using a fuel cell as an APU. Some of those challenges were articulated in a NASA report: NASA/CR—2006-214458/VOL1. *Solid Oxide Fuel Cell APU Feasibility Study for a Long Range Commercial Aircraft Using UTC ITAPS Approach. Volume 1; Aircraft Propulsion and Subsystems Integration Evaluation*.

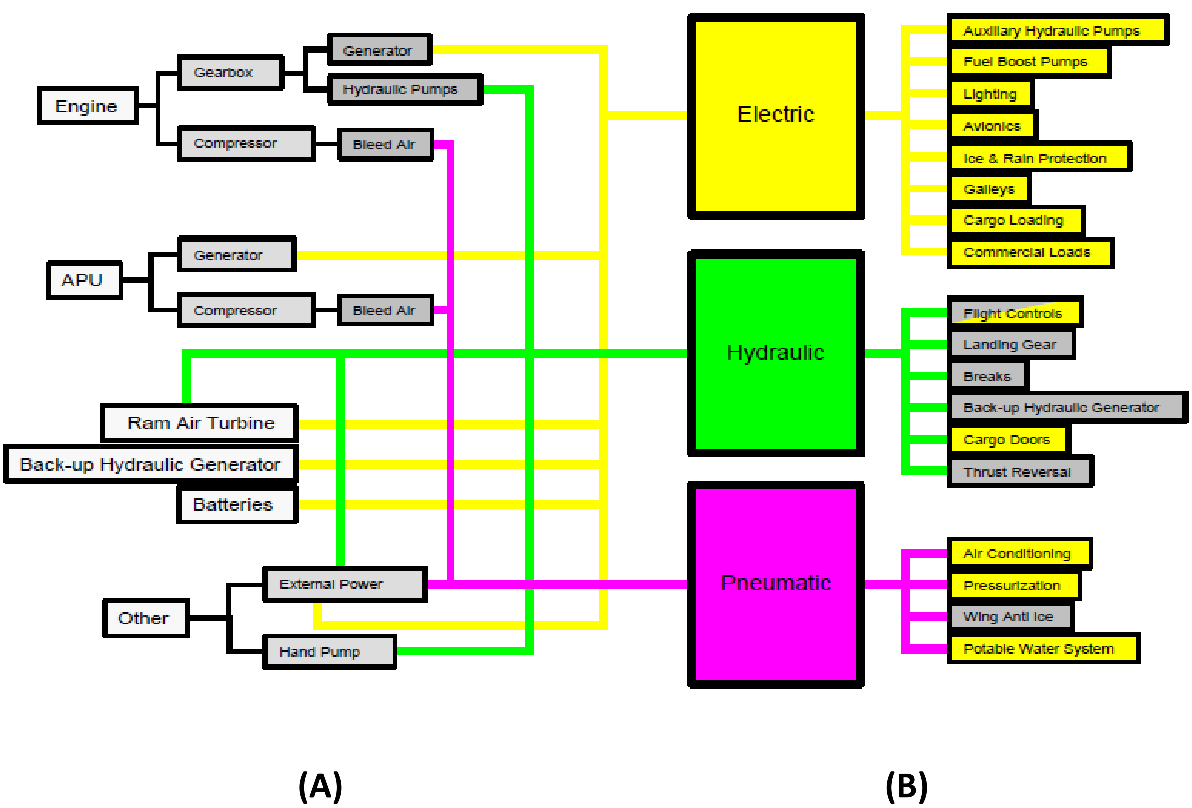
- The SOFC system specific power (kW/kg) is about three times lower than that of a conventional gas turbine APU. The corresponding weight penalty increases the amount of fuel burned by the aircraft (equivalent of 0.4 percent aircraft mission fuel burn).
- The SOFC system operation during cruise condition requires input air stream and providing that air from the ambient (ram air) introduces ram-drag penalty. This ram-drag penalty increases the amount of fuel burned by the aircraft (equivalent of 0.3 percent aircraft mission fuel burn).
- The SOFC system (which is a hybrid system with the SOFC stack and the turbo-machinery) generates both ac and dc power. The dc power is from the stack and the ac power is from

the turbine generator. The distribution of the power (ac and dc) generated by the SOFC system in the aircraft requires additional power electronics (power converters etc), which, in turn, increase the amount of fuel burned by the aircraft.

- The current technology of the SOFC system requires a longer time (more than 30 min) to startup the SOFC system. Therefore, frequent starting and stopping cycles for the SOFC system may not be a good option for the aircraft application.
- The processing of the Jet-A fuel with sulfur levels between 300 to 1000ppm requires a bulkier desulfurizer, which restricts the de-sulfurization options for the aircraft.
- The exhaust gas coming out of the SOFC system is at rather high temperature (> 600 °C) and utilization of this hot stream is a challenge. To realize any potential benefit from the SOFC system for aircraft application, the system integration concepts for the SOFC system should provide substantial benefits to overcome penalties imposed by the technical challenges listed above.

With the continued move to the more electric aircraft, using electric start, and replacing many the hydraulic and pneumatic loads. Many of the challenges still exist but things have moved forward.

Figure 61. Energy supply (A) and Consumers (B) with Future Electric Systems (yellow) According to Scenario



Realizing the benefit of using fuel cells as an APU requires a few paradigm shifts to offset its disadvantages:

- The aircraft power system architecture moves towards More Electric Architecture (MEA).
- Power and energy supply/demand must be optimized and integrated at aircraft level.
- FCAPU taking on more functionalities over the traditional one to become a primary, non-propulsive power system.

E.4.2 Future FCAPU Outlook

For the fuel cell to be used as an APU requires a great deal of changes. The projected new system will likely expand beyond providing traditional functions. It will combine or contribute to functionalities to become a Fuel Cell Power System (FCPS) that provides functions such as:

- Electrical power for flight deck, flight control, lighting, galley, in-flight entertainment
- ECS power/thermal management provide electric power to the higher coefficient of performance (COP) vapor cycle system (VCS)
- MES with starter/generator
- Cabin pressurization with electrically driven cabin air compressor
- Full time power to unload burden from the main engine for improved propulsive efficiency and operability
- Lavatory water replenishment from FCPS waste stream
- Cargo compartment fire suppression from FCPS waste ODA
- Distributed power for redundancy,
- Emergency power
- Emergency oxygen supply
- Fuel tank inerting
- Icing protection
- Electric-Taxi

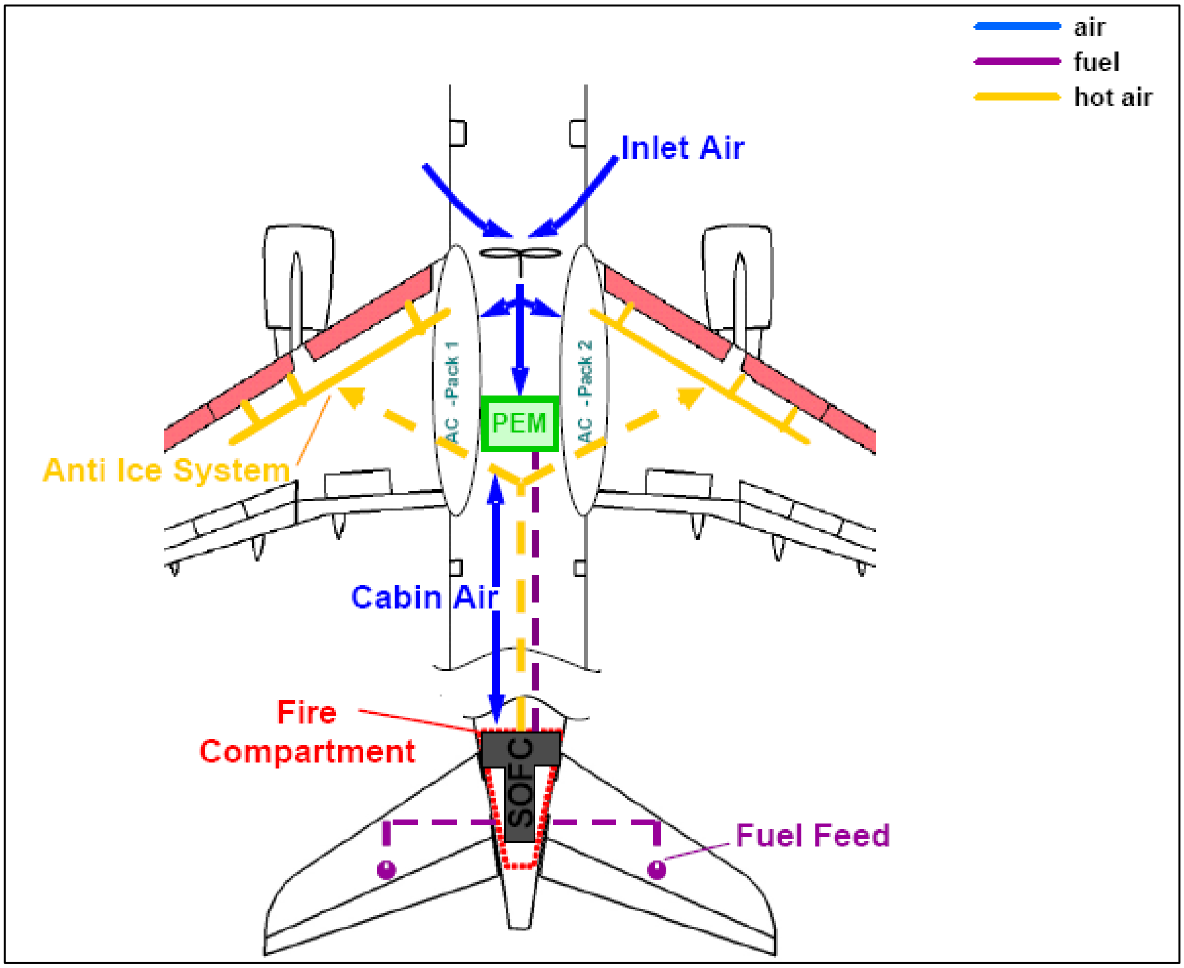
When aircraft level energy and power demands are optimized, functions and equipment that can be potentially replace by the FCPS are:

1. Auxiliary Power Unit
2. Electric generators
3. Ram Air Turbine
4. Oxygen bottles

5. Fire suppressant

Major transport category airplane manufacturers have done a great deal of preliminary work on assessing the challenges of using a fuel cell as an APU. It is clear from their efforts that current technology will not provide a form fit and function replacement for the APU. Most of the scenarios that have been explored use both SOFC and PEMFC and/or a combination of both with electrical energy storage (mostly batteries). Figure 62 is one example of potential system configuration.

Figure 62. Potential Aircraft Power System configuration



Though the future FCPS will be highly integrated with other systems and replacing some existing systems, the combination of the possible system architecture is unlimited, it can be broken down and analyzed in these basic energy supply device groups:

1. SOFC with gas turbine hybrid for baseload, and will be analyzed as “form fit function” drop-in APU replacement

2. Regenerative for load shaping, store energy during low power segment of the mission and augment the power supply during high power demand segment of the mission. This may be analyzed the similar way as fuel cell emergency power supply.
3. Batteries for peak and transient shaving.

Each of the above ESD groups can be analyzed independently and the interconnectivity will be part of the aircraft.

Some of the main problem areas are in supplying the fuel for the fuel cell. For stored hydrogen FC systems, the size and weight maybe prohibitive if it provides all power during the flight and ground operation, while it may be logistically challenging to compete with ground (gate or ground cart) power if it's only used for ground operation at gate.

While it would be best to use the same fuel as the engines, however the sulfur continent in the fuel requires additional processing stage to provide a usable fuel for the fuel cell, which adds weight, volume, and maintenance frequency. Other solutions would be to partition fuel tank for ultra-low sulfur fuel or bio-fuel storage dedicated for the fuel cell operation, this fuel can be blended with kerosene fuel for gas turbine engines when reserve fuel is needed.

E.4.3 PEM Fuel Cell Power System

As stated at the beginning of this section, the FC APU in this section is assumed to be a form fit function drop-in replacement that uses the same fuel as the main engines. Since there is no gaseous hydrogen refilling infrastructure in all airports, SOFC systems with onboard fuel reformation involve more interfaces with the aircraft, becomes the technology of choice for the purpose of discussion.

However, with the advancement of fuel cell power system technology in passenger automobiles the PEM fuel cell power system has matured and the specific power has improved to a point where it starts to make sense for airplane implementation consideration, only if certain conditions are met:

1. Hydrogen refilling infrastructure exist in all air commercial transport airports wherever the FCAPU equipped airplanes fly, worldwide.
2. Air transport airplanes made substantial modifications to minimize power demand on FCAPU to reduce the system size, e.g., the pneumatically powered systems such as main engine start (MES) and air cycle system (ACS) within the ECS.
3. These airplanes do not need ETOPS certification.
4. Operators of these airplanes will modify their operating procedures to minimize FCAPU run time between refilling to reduce the hydrogen fuel tank size and weight.

E.5 APPLICATION: FUEL CELL EMERGENCY POWER SYSTEM

The emergency power system provides power for the essential loads when both the normal sources of electrical power fail (e.g., main engine generators and APU generators).

On modern transport category airplanes emergency power is supplied by the Ram Air Turbine (RAT). This system consists of a wind powered turbine that drops out of the aircraft under in an emergency situation and may provide power at 28V DC or 115V AC 3 phase, in addition some designs include a hydraulic output. These systems provide sufficient power for the essential loads such as minimal instrumentation and control of the flight surfaces.

Some RAT's cannot be deployed at altitude due to the mechanical load on the aircraft and so the aircraft reduces its altitude to around 25,000 feet before deploying. This shortens the glide time if thrust has also been lost. At low air speeds the RAT usually become ineffective so the function is taken over by batteries (e.g., on landing approach).

To make comparisons the example FCS will be a 15 kVA 115V AC 3 Phase system supplying only electrical power. The PEM fuel cell system to support this function may need to operate for 3 hours to meet ETOPS requirements.

This example FCS will require around 2.7 kg of hydrogen. A tank pressurized to 700 bar or solid hydrogen fuel source will weigh around 42 kg. This is close to the weight of the entire equivalent RAT system. A fuel cell replacement system in today's technologies would weigh 2 to 3 times that of the RAT. However, there are still advantages in using a PEM FCS.

The fuel cell system would consist of fuel cell, a fuel supply, an oxidant, a cooling system and electrical conditioning. Although the volume of the system would be greater than the equivalent RAT, the elements could be distributed around the aircraft rather than contained as a single entity.

The hydrogen supplied can be derived from either a 700-bar pressurized type 3 tank or a solid hydrogen solid fuel store which operates at or below 12 bar. Although more expensive, the solid hydrogen fuel store has the advantage of containing the hydrogen in an inert state over an extended period of time and only requires a low pressure supporting system.

The oxidant can be provided by a high-pressure tank, similar to those already installed on an aircraft or by an air scoop/ram air input, or even generated on board in a similar way to the solid fuel store. The system will require around 900 liters of air per minute or around 36,000 liters of oxygen (50-liter tank at 700 bar) delivered between 4 °C and 60 °C.

Approximately for each kW of electrical energy generated a kW of heat will need to be dissipated by the cooling system. Ram air is a convenient method if it is a chosen method for the oxidant as the outside temperature is low. It should be noted that up to 6x the volume of the oxidant is required for the cooling air

The electrical conditioning system converts the varying DC output of the fuel cell to a conditioned 3 phase AC output. In order to provide stable energy an element of energy storage will be required either in the form of super-caps/batteries or magnetics (iron).

All by-products (e.g., water, heat, O_2) would be exhausted.

The startup time (usually about 10 minutes) could be an issue for emergency power, so it is likely that the system will be kept at hot standby in flight. Once in standby, the time to operational state is on the order of a few seconds, less than of the deployment of the RAT and can either be executed under pilot control or automatically.

Compared to the RAT, the fuel cell system will be able to operate at much higher altitudes and provides power continuously at any altitude leading to a longer glide time. However, at very low air speeds, the cooling capability may be affected dependent on its design.

A further advantage is that the fuel cell system can be turned off (and restarted if required), the RAT however, cannot be retracted once deployed so it will continue to disrupt the aerodynamics of the aircraft.

The fuel cell system can be exercised periodically, both in flight using a small quantity of the stored hydrogen, or on the ground using an auxiliary supply, whereas the RAT requires downtime to test/maintain the system which, to some operators, may be a significant inconvenience.

In terms of safety, the lack of external rotational components is a benefit of the fuel cell system but clearly the careful handling of the fuel, oxidant and potentially high pressures need to be considered.

E.5.1 Emergency Power System Aircraft Interfaces

All the interfaces to the aircraft are summarized in Table 15. This system is classified as Critical to the aircraft, but the overall level of integration is probably less than an APU, depending on the oxygen supply and the heat rejection.

Table 15. Emergency Power Interface Descriptions and Applicable Standards

Interface Type	Interface Description	Applicable Standards*, 25.XXXX
Electrical System	Emergency bus 115V AC, 28V DC Batteries on emergency power bus used for starting and recharged when operational	1351, 1353, 1357, 1431, 1301, 1309, 17xx, 1355, 1362
Controls Indicators	Cockpit interface control and monitoring to include power On/Off/Standby and Warnings of H_2 leaks, fuel capacity (calculated and reported by system)	1302, 1322, 1357(f),

Interface Type	Interface Description	Applicable Standards*, 25.XXXX
	Maintenance computers, bit, health monitoring	
External Safety	External low pressure H_2 vent, external drain (ODA with water vapor), Box surround system Venting may occur after use on ground Hydrogen leak detection/monitoring Fire detection and suppression	1301, 1309, 899, 1316, 1317, 851, 831, 869 modified, 1183, 1185, 1187, 863 modified, 865, 17xx, fire detection and suppression regs, looking at new regs for H_2 leak detection on aircraft, H_2 explosion reg,
Maintenance	Periodic coolant checks and replacement, air filter, maintenance log for bit Refueling total 100lb approx., may need tooling or split to smaller canisters External H_2 input for system test	1529, 1729, 21.50,
Installation Structure	Air scoop, Installation in non-pressurized area mounted on structure, Door surrounds air input to external physical interfaces (i.e. air scoop, exhaust)	302, 561, 581, 789
Waste Products	Thermal, Water in ODA all exhausted outside	Icing, heating elements, 1309, 831, CS302, 603, 601
Access for operation	Access for inspection for coolant levels, replace filters, refueling all via door	611, 1719, 1529, 1360, 1541, 1555, 1561
Environmental	Unpressurized	1301, 1309
* The standards are only based on the general descriptions of the applications. In an actual certification program, the Aviation Authority will decide which standards are applicable. A detailed examination of applicable regulatory standards for FCS in general is discussed in Appendix G.		

E.6 UNMANNED AERIAL SYSTEM (UAS) PROPULSION

There is a growing interest in UASs in the both the military and commercial sectors. This increase in interest has resulted in UAS capable of a wide range of uses, both for personal and commercial applications. This has driven a strong demand for access within the National Airspace System (NAS). Figure 63 shows some UAS's which are in use today. Figure 64 shows an example UAV with a PEMFC power system. Fuel cells have been under consideration for UAS applications as a high energy prime electric power and propulsion system source to extend UAS flight durations.

E.6.1 UAS Class Designation by U.S. Military

We will first define the different classes of UASs to outline the applicable fuel cell types and fueling solutions. Following are the definition used by the US military, these size classes can be defined as follows:

- Group 1
    - 0-20lb gross take-off weight (GTOW) for the vehicle
    - Flight ceiling limited to <1200ft AGL (above ground level)
    - Flight speed <100knots
- Group 2
    - 21-55lbs GTOW
    - Flight ceiling limited to <3500ft AGL
    - Flight speed <250knots
- Group 3
    - <1320lbs GTOW
    - Flight ceiling limited to <FL180 AGL (or 18,000ft)
    - Flight speed <250knots
- Group 4
    - >1320lbs GTOW
    - Flight ceiling limited to <FL180 AGL
- Group 5
    - >1320lbs GTOW
    - Flight ceiling >FL180 AGL

E.6.2 Fuel Cell Types Based on UAS Class Designation

Groups 1 and 2 UAS are common in the hobby, commercial and military markets and are typically hand or rail-launched systems. Traditionally, these vehicles are powered by a battery or small commercial internal combustion engine fueled by gasoline or other specialty fuel. Power levels typically range from <100W to up to 5kW for required flight, operating voltage commonly range from 12 to 48V. Within this size class of vehicle, both proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) have been considered. Due to the difference in fuel cell type, operating start-up procedures may vary but typically include the following: fuel cell start/warm-up, perform flight check procedures for UAS, and then launch once the fuel cell is in a ready state. The fuel cell start/warm-up procedures and times will vary based on the type, size, and design of the fuel cell. Generally, low temperature PEMFCs can provide power more immediately (e.g. 0 to 2-minute start times) than a higher temperature SOFC (e.g. > 10 minutes for an SOFC). Landing/shut-down procedures are much the same: The FCS can be placed in stand-by mode upon landing (if re-launch/re-fueling required) or proceed to the shut-down state where fuel flow will be stopped and fuel lines purged upon cooldown for safe storage and future restart. Note: the fuel cell can be designed to allow for "hot swap" fuel cartridges while the fuel cell is in standby mode to avoid complete system cooldown if re-launch required.

For the smaller Group 1 UASs, the fuel cell power system would be a replacement for the battery that is more commonly used, and the fueling solution considered disposable. Due to the weight and volume constraints in Group 1 UAS, man developmental efforts have used H_2 fueled PEMFCs since they traditionally have exhibited higher system power density (in terms of W/kg). A discussion on the H_2 fuel sources solution are discussed in other sections. If logistically feasible, compressed H_2 can be used but is typically limited by storage capacity, i.e. ~2 wt% H_2 storage.

Metal hydride or liquid H_2 systems have additional complexities and weight challenges for this size class of vehicle. Chemical hydrides (chemical H_2 storage, e.g. sodium borohydride) have been used to extend flight durations due to their higher H_2 storage capacity, (i.e. 5-10 wt% H_2).

There are various safety considerations with any of these fuel types. Appendices D and F provide a more detailed discussion on this topic. Maintaining proper safety protocols and considerations of the flight environment should be forefront when integrating and operating fuel cell UASs. Current Group 1 and 2 UASs operate within line of sight to avoid any safety incidents such as loss of aircraft or communications. More automated UASs are typically designed with warning and cautions to alert the operator of any operational issues. An example of this could be low fuel warnings and limits where the vehicle would be automatically directed into a landing condition to avoid a safety event leading to loss of aircraft before any critical flight power is disrupted. Since this class of vehicles typically belly land in a cleared space (without landing gear), proper safety protection should be in place to avoid any damage to the fuel cell or fuel tank upon landing.

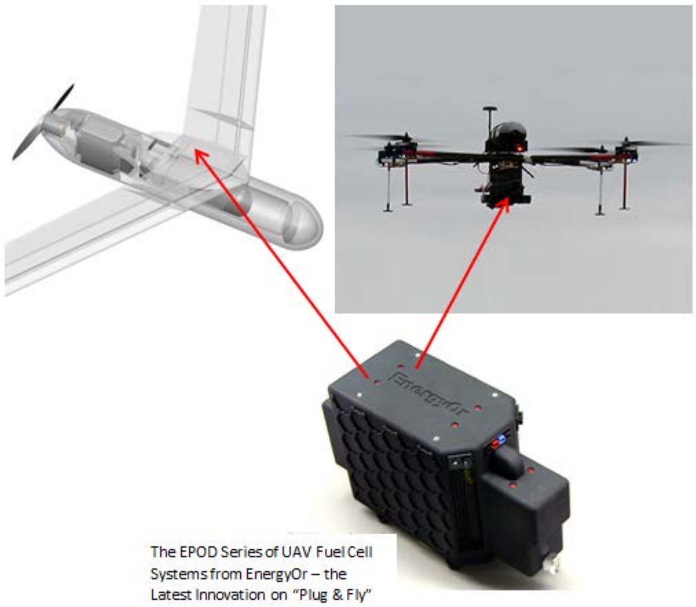
For the larger Group 2 UASs, where generally greater than 1kW power is required for flight power, solid oxide fuel cells have more commonly been considered due to their high operating efficiencies and fuel flexibility. The traditional propulsion system on this size of UAS is an internal combustion engine operating on liquid hydrocarbon or specialty fuel. PEMFC-powered UAS with compressed or liquid H_2 fueling solutions have been flight demonstrated. SOFC-based power systems operating on liquid hydrocarbon fuel are under development for extended flight operations. A discussion on the unique safety considerations for these systems is included in Appendices D and F. Since these UASs are typically rail- or bungee-launched (and either belly land or air-captured), proper safety considerations must be accounted for in the design and integration of the fuel cell to be able handle the required shock and accelerations loads. Due to the size of these vehicles, and to maintain a safe flight environment, proper flight and power controls/monitoring should be in place to maintain control in the case of an emergency to avoid any safety events.

Larger Group 3 SOFC-based UAS power systems are currently under development and have been flight tested for long endurance operations. Due to the amount of energy required for flight, liquid hydrocarbon fueled systems are typically considered for this application. To minimize size/weight of the power system, the fuel cell systems are typically hybridized with a battery in most cases. In this situation, the fuel cell is sized to provide cruise power and onboard power as required (e.g., avionics, payload, battery charging), while a battery is electrically connected in parallel to support peak power requirements (e.g., take-off, dash). As discussed in the preceding paragraphs, similar hybrid approaches have been developed for Group1 and 2 UASs.

The propulsion systems for Group 4 and 5 UASs are typically engine-based. However, as the demand for more electric power continues to grow, these systems are quickly becoming power-limited. Fuel cells have been considered as a high efficiency power source to provide more electric onboard power as an APU, providing non-flight critical power. To avoid a secondary fuel onboard and further safety requirements, these fuel cell systems are being designed to operate on the same fuel source as the main engine.

Figure 63. Unmanned Aerial Systems (UAS)

Figure 64. Active UAS Advance Fuel Cell Energy Storage



Technical Specifications[1]		H_2Quad 400
System Performance	Payload Capacity	400 g
	Flight Time	2 hours
	Max. Continuous Net Output Power	450 W [2]
	Peak Net Output Power	1000 W
	DC Output Voltage Range	32 – 45V
	Net Energy Available	900 Wh
Environment	Ambient Temperature (Max.)	35°C [3]
	Flight Altitude	1000 m [4]
Physical	Maximum Take-off Weight (MTOW)	6.3 kg
	Airframe Diagonal Wheelbase	1200 mm

(1) Specifications are subject to change without notice
(2) At STP (20°C, 1 atm)
(3) System configurations for higher ambient temperatures available
(4) Higher altitudes available on request

E.6.3 U.S. Navy Ion Tiger Program

The U.S. Navy Ion Tiger program is one of several DoD initiatives to demonstrate a practical, lightweight fuel cell system for unmanned air vehicles (UAVs) to significantly improve battlefield surveillance and communications capabilities. Figure 65 and Figure 66 provide an overview of the program.

Figure 65. Ion Tiger Fuel Cell-Powered UAV

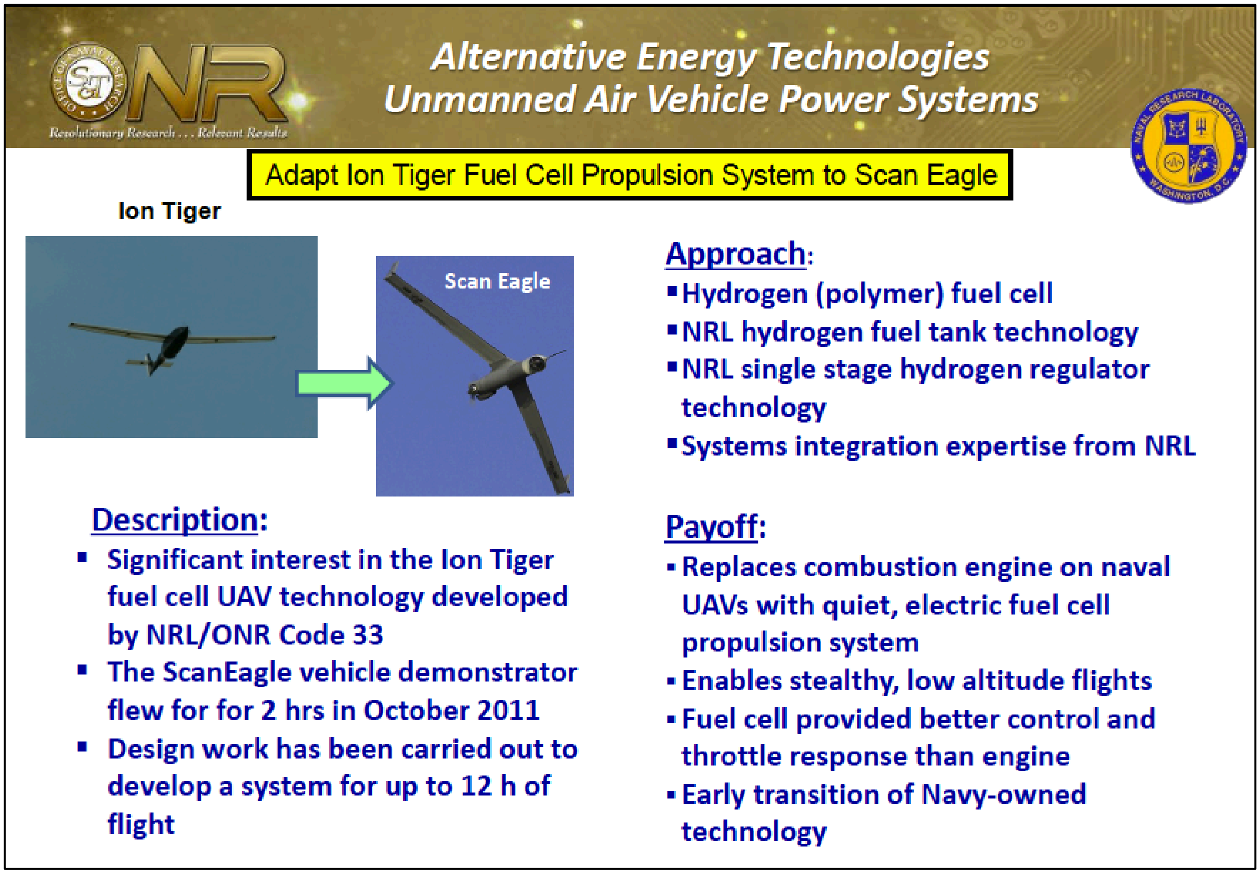


Figure 66. Ion Tiger Fuel Cell-Powered UAV

Ion Tiger's electric fuel cell power system has the low noise and thermal signature of a battery-powered UAV, while taking advantage of the fuel cell's high operating efficiency on high energy hydrogen fuel. The 550-W (0.75-horsepower) fuel cell has about four times the efficiency of a comparable internal combustion engine. The Ion Tiger flew for 26 hours in November 2009 while carrying a 5-pound payload using hydrogen compressed to 5000-psi in a carbon/aluminum pressure vessel. In May 2013, the same researchers at the U.S. Naval Research Laboratory flew their fuel cell powered Ion Tiger UAV for 48-hours and 1 minute on April 16-18 by using liquid hydrogen fuel in a new, NRL-developed, cryogenic fuel storage tank and delivery system. These 1-day and 2-day demonstrations prove that hydrogen fuel cells provides a clear path to long endurance electric flight. In comparison, the Ion Tiger would be able to fly for only 4 hours on the comparable weight of lithium batteries.

E.6.4 UAS Aircraft Interfaces

A fuel cell must be designed for the intended operational environment and requires a high degree of integration with the UAS vehicle in order to obtain its benefits of high operational efficiency. Classification of Failure Condition shows an overview of expected interfaces.

Table 16. UAS Interface Descriptions

Electrical System	For smaller UASs (Groups 1-3), fuel cells would be the main power source the aircraft. For larger UASs (Groups 4-5), the fuel cell may ideally provide auxiliary power. A battery may be used as part of the fuel cell system for start-up, peak power, or emergency power.	For smaller UAS's, fuel cells would be the main power source the aircraft. For larger UAS's the fuel cell could provide auxiliary power. A battery could be used as part of the fuel cell system for start-up, peak power, or emergency power.
Controls Indicators	UASs are typically controlled by a ground operator, with warnings, cautions, and alerts to notify the ground operator of an issue in flight, such as a low fuel / power warning or loss of communication link. More automated UASs may automatically be directed into a landing condition to avoid a safety event leading to loss of aircraft before any critical flight power is disrupted	UAS's are typically controlled by a ground operator. More automated UASs typically are designed with warning and cautions to the ground operator, such as for low fuel warnings. An example of this could be low fuel warnings and limits where the vehicle will automatically be directed into a landing condition to avoid a safety event leading to loss of aircraft before any critical flight power is disrupted.
External Safety	Unmanned flight reduces safety issues. There are many factors that may determine the level of UAS safety requirements, such as fuel source (e.g. hydrogen) and type of storage, operating and exhaust temperatures, etc.	Unmanned flight reduces safety issues. Changes in UAV safety requirements would be determined by fuel type (i.e. hydrogen) and operating temperatures for insulation and exhaust design.
Maintenance/ICA	Fuel cells are typically designed as a highly integrated power source with limited maintenance for the lifetime of the vehicle. Some smaller systems are disposable. Refueling or fuel tank swap is a primary maintenance consideration.	UAS fuel cells highly integrated with limited maintenance. Some smaller systems are disposable. Refueling or fuel tank swap to be primary maintenance.
Installation Structure	Structure designed to support shock/vibe levels and thermal requirements. Field installation usually not applicable unless the fuel cell is designed to be modular	Structure designed to support shock/vibe levels and thermal requirements. Field installation usually not applicable.
Waste Products	Waste products (i.e. H_2O, CO, CO_2) exhausted	Waste products exhausted
Access for operation	Field access expected to be limited to possible fuel cartridge swap or refueling	Field access expected to be limited to possible fuel cartridge swap or refueling.

Environment	Shock and vibe dependent on launch and landing method. Operation under temperature, altitude, and humidity operations are based upon design considerations	Shock and vibe dependent on launch and landing method. Exposed to ambient environment based on altitude

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APPENDIX F. FUEL CELL SYSTEM HAZARDS

F.1 INTRODUCTION

The main airworthiness standard to be satisfied regarding fuel cell system design hazards is CFR/CS 25.1309. The hazard consideration should be made in accordance with SAE ARP 4754 (Guidelines for Development of Civil Aircraft and Systems) and ARP 4761 (Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment). This identifies design hazards as well as interface requirements to other systems as installation risks.

Based on the criticality of the system/sub-system the related design assurance level has to be determined according to ARP 4754 and the hazards need to be analyzed in accordance with ARP 4761. As oxygen and hydrogen do have specific hazards, design consideration should be extended by a dedicated oxygen hazard and hydrogen hazard analysis. These analyses should consider specific design hazards for all sub-systems (i.e., oxygen, hydrogen, fuel cell stack, pressure vessels, etc.) including system integration into the aircraft environment.

The location the fuel cell system installation in the aircraft can greatly affect the hazard mitigation approaches.

Hydrogen currently is not used as a fuel in civil aviation. The predominant and most feared hazard that can be created by hydrogen is fire or explosion. However, the aviation community has significant experience with compressed gas in the form of oxygen, which is well covered in today's regulations. Similar hazard mitigation principles can therefore be applied with specific care to ensure that the fire/explosion risk of hydrogen is properly managed.

The minimum ignition energy for a wide range of hydrogen concentrations in air or oxygen is very low. Therefore, in contrast to traditional fuel air mixtures, the avoidance of a dedicated ignition source will not be sufficient to mitigate the fire risk. The only feasible method to extinguish a hydrogen fire is to stop the supply of hydrogen. Traditional extinguishing methods will not suffice.

However, unlike traditional aircraft fuel tanks, a hydrogen tank will not contain a fuel air mixture but rather pure hydrogen. The lack of air, or oxygen ensures that the compressed gas within the hydrogen tank is not flammable.

As a result, the primary design methods to prevent hydrogen fire hazards are the separation of hydrogen and any oxidizer, preventing the accumulation of flammable mixtures and ensuring effective hydrogen detection and shut-off means as last line of defense.

F.2 HYDROGEN FIRE AND EXPLOSION HAZARDS

This section introduces the hazards related to the fire, ignition, combustion, explosion, and unique H_2 properties.

Experience shows that escaped hydrogen is very easily ignited (NASA, 1997). Ignition sources include mechanical sparks from rapidly closing valves, electrostatic discharges in ungrounded particulate filters, sparks from electrical equipment, catalyst particles, heating equipment, lightning strikes near the vent stack, etc. Ignition sources must be eliminated or isolated in appropriate way and operations should be conducted as if unforeseen ignition sources could occur.

The ignition energy of hydrogen-air mixture varies with its composition, and becomes infinite at the flammability limits. Less energy is needed to ignite a mixture that is closer to its stoichiometric composition. Over the flammable range of hydrogen-air mixtures, the ignition energy varies by almost three orders of magnitude. The minimum ignition energy (MIE) is 0.017 mJ for the most ignitable mixture. In addition, to the mixture composition, the ignition energy depends on other factors such as the initial pressure and temperature of the environment. Ignition sources capable of forming shocks, for example high-energy spark discharges and high explosives, can directly initiate detonation.

Hydrogen has very wide flammability limits, which range from approximately 4% to 75% at sea level. At altitude, while the rich limit collapses somewhat, the lean limit remains at approximately 4%. This combined with the low MIE necessary for ignition, provides for the challenge of safely designing a hydrogen system and adequately mitigating its risks. The following chapters will explain in detail the flammability hazards associated with hydrogen as well as typical mitigation strategies.

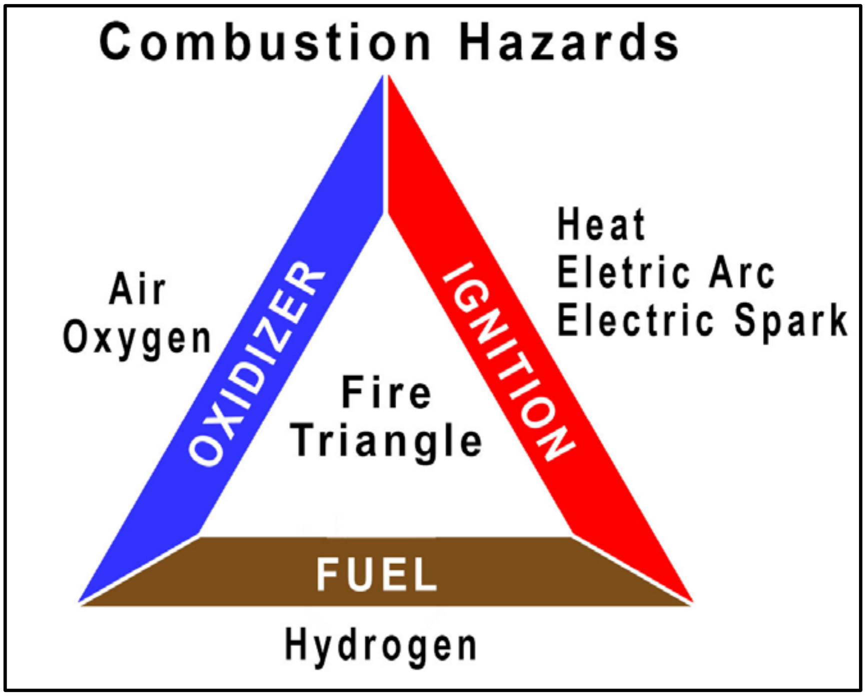
F.2.1 Hydrogen Combustion

Hydrogen combustion hazards are characterized by mixture flammability, the presence and type of ignition sources, and the type of combustion process possible for the conditions. As with any fuel, for a fire to be possible the following elements must occur simultaneously, as shown in Figure 67:

- A flammable chemical, with a concentration within its flammability limits;
- An oxidant, at a concentration putting the combustible in its flammable range; and
- A thermal or electrical ignition source having some minimum energy.

Note: Ignition is the starting of a fire while burning represents the continuous process of the fire.

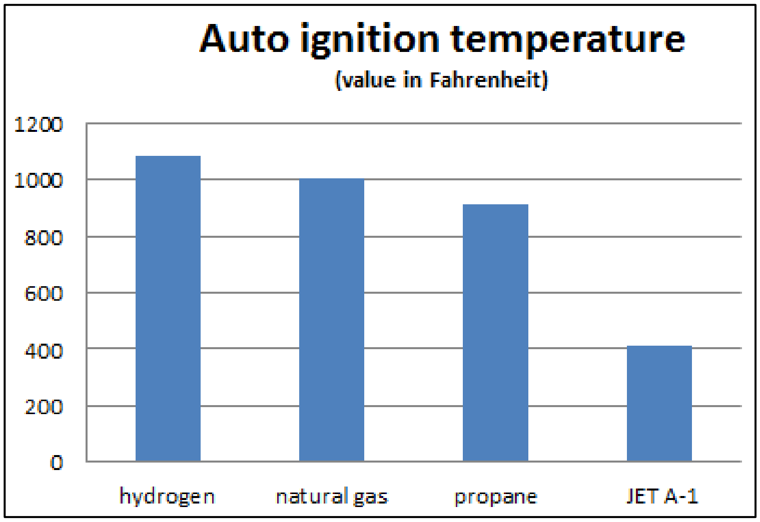
Figure 67. Fire Triangle



There are a number of hydrogen hazard scenarios in which the ignition energy is inherent in the mixing process and therefore the resulting combustion is described as spontaneous.

The auto-ignition temperature of a substance is the lowest temperature at which it will spontaneously ignite without the presence of a flame or spark. The auto-ignition temperatures of hydrogen and natural gas are very similar. Both have auto-ignition temperatures over 538 °C (1,000 °F), much higher than the auto-ignition temperature of gasoline vapor, as shown in Figure 68.

Figure 68. Auto Ignition Temperature (Value in Fahrenheit)



Hydrogen's flammability range (between 4% and 75% in standard atmosphere) is very wide compared to other fuels, as shown in Figure 69. Under the optimal combustion condition (a 29% hydrogen-to-air volume ratio), the ignition energy required to initiate hydrogen combustion is much lower than that required for other common fuels (e.g., a small spark will ignite it), as shown in Figure 70. However, at low concentrations of hydrogen in air, the ignition energy required to initiate combustion is similar to that of other fuels.

Figure 69. Flammability Range and Ignition Energy Versus Concentration

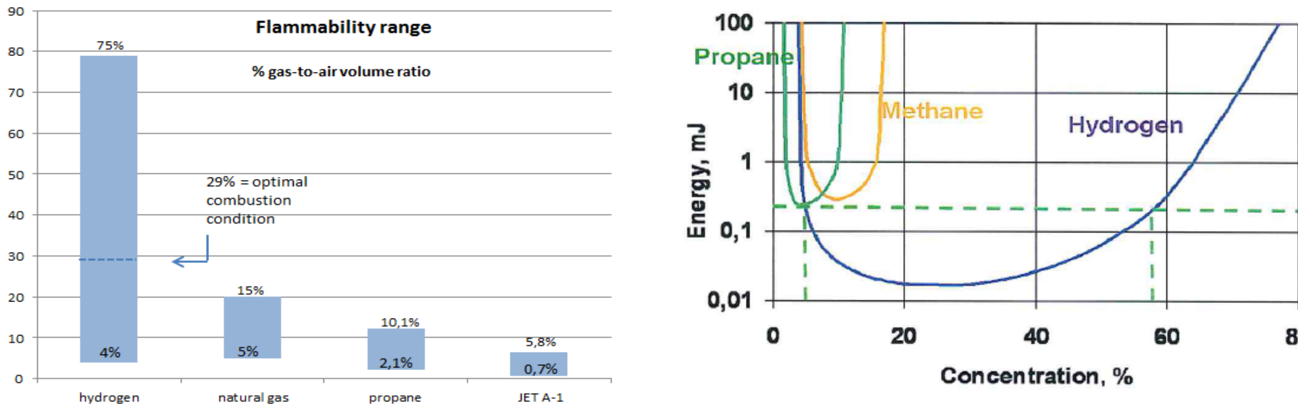
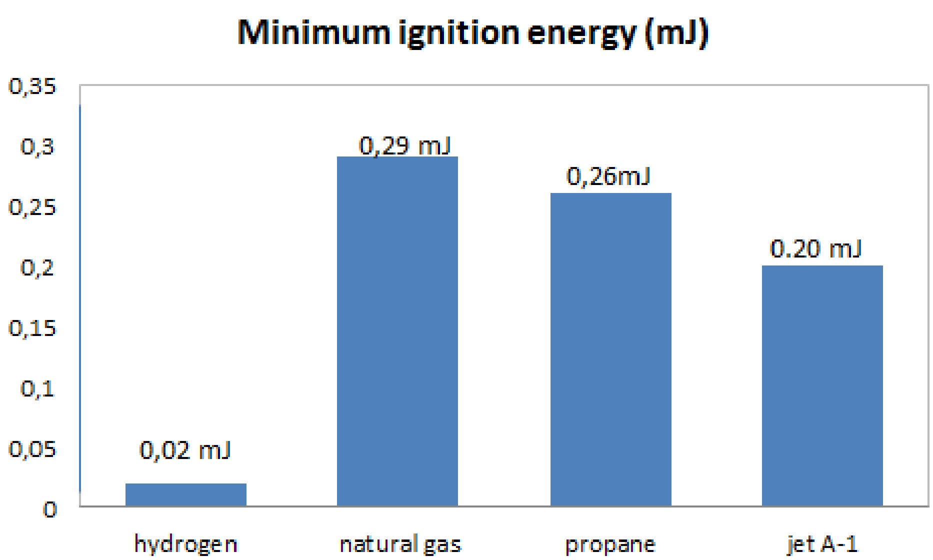


Figure 70. Minimum Ignition Energy at Stoichiometric Conditions



Hydrogen burns with a pale blue flame that is nearly invisible in daylight, so it is almost impossible to detect by the human senses. Impurities such as other burning materials and dust will introduce color to the hydrogen flame. At night, hydrogen flames are visible. The adiabatic flame temperature of a hydrogen/air mixture can reach 2045°C (3712°F) while the adiabatic flame temperature of a hydrogen/oxygen mixture can reach ≈ 3200°C (5792 °F). Therefore, hydrogen/air mixture is very similar to Jet A-1 which has its max adiabatic flame temperature of approximately 2200 °C, while a hydrogen/oxygen mixture results in a significantly higher adiabatic flame temperature. *(Proceedings of ASME GT2009-60333)*

Additionally, hydrogen flames radiate little infrared (IR) heat, but substantial ultraviolet (UV) radiation. This means that when someone is very close to a hydrogen flame, there is little sensation of heat, making inadvertent contact with the flame a significant concern. The heat transmission of a H_2 jet fire will occur at 93% by convection and at 7% by radiation.

This is to be compared to a hydrocarbon jet fire where 70% of the heat transfer to an impinged object occurs by convection and also to a hydrocarbon pool fire where approximately 70% of the heat transfer to an impinged object occurs by thermal radiation and 30% by convection.

Hydrogen's low emissivity reduces the heat transferred by radiation to objects near the flame, thus reducing the risks of secondary ignitions although the flame temperatures of hydrogen and the other common fuels are comparable.

If a large hydrogen cloud comes into contact with an ignition source, ignition will result in the flame flashing back to the source of the hydrogen. In open spaces with no confinement, flames will propagate through a flammable hydrogen-air cloud at several meters per second. The result is a rapid release of heat, with little overpressure and a combustion product of steam. However, if hydrogen gas mixtures enter confined regions flammable limits are reached more easily due to the loss of dilution effects, ignition is very likely and can result in flame acceleration and generation of high pressures. Flammable mixtures of hydrogen intrinsic to the fuel cell system in confinements (e.g. inside pipes or ducts), if ignited, will readily result in accelerated flames and conditions that can transition to detonation.

A stoichiometric mixture is a mixture in which both fuel and oxidizer are fully consumed (complete combustion) to form combustion product(s). For example, the two diatomic gases, hydrogen (H_2) and oxygen (O_2), can combine to form water as the only product of an exothermic reaction between them, as described by the equation

$$2H_2 + O_2 = 2H_2O$$

Thus, the stoichiometric hydrogen-oxygen mixture is composed of 66.66% by volume of hydrogen and 33.33% of oxygen. Therefore, the stoichiometric concentration of hydrogen in air (assuming 21% of oxygen and 79% of nitrogen) is 29.59% by volume (2 / (2+1+3.76) = 0.2959) with air content of 70.41%.

Hydrogen's main safety asset is its buoyancy which confers hydrogen the ability to rapidly flow out and mix with the ambient air to a safe level below the LFL. Hydrogen has a density of 0.0838 kg/m3 which is far below than air density of 1.205 kg/m^3 (NTP). The unwanted consequences of a hydrogen release into the open atmosphere, and in partially confined geometries, are drastically reduced by buoyancy.

However, the cold, dense hydrogen gases produced by LH_2 spills will not rise. The higher density of saturated vapor may cause a hydrogen cloud to flow horizontally or downward immediately upon release if an LH_2 spill or leak occurs,

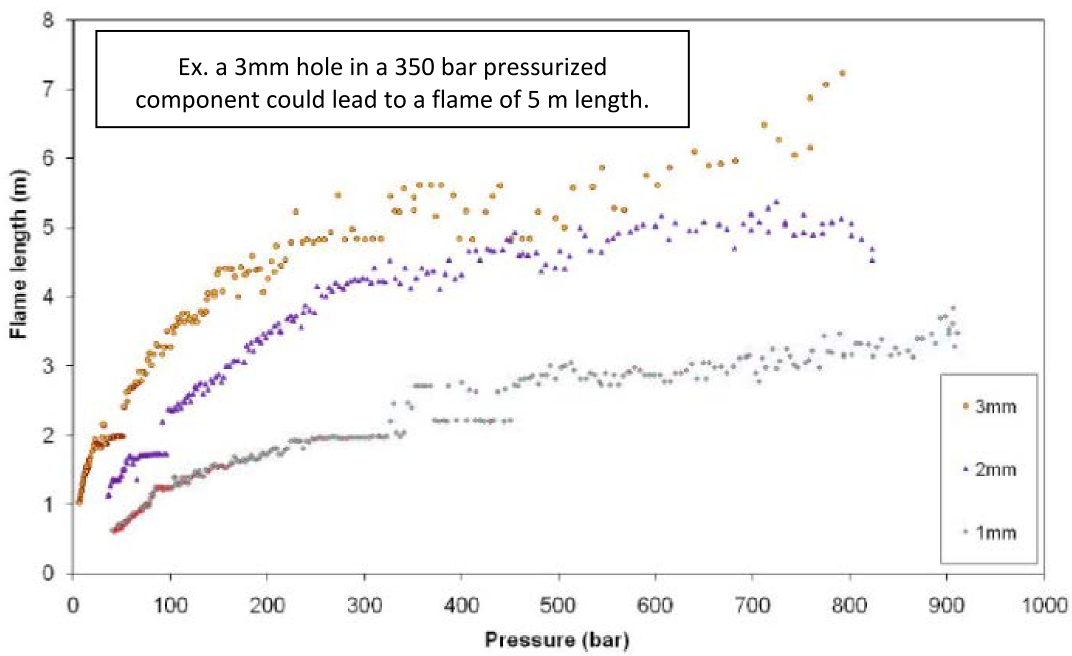
The rapid release of a volume of hydrogen creates a "bubble" that under ambient conditions and release into an unconfined region will rise at rates varying from 1.2 to 9 m/s *(McCarty et al.1981)* depending on hydrogen gas and atmospheric conditions.

F.2.2 Type of Hydrogen Fires

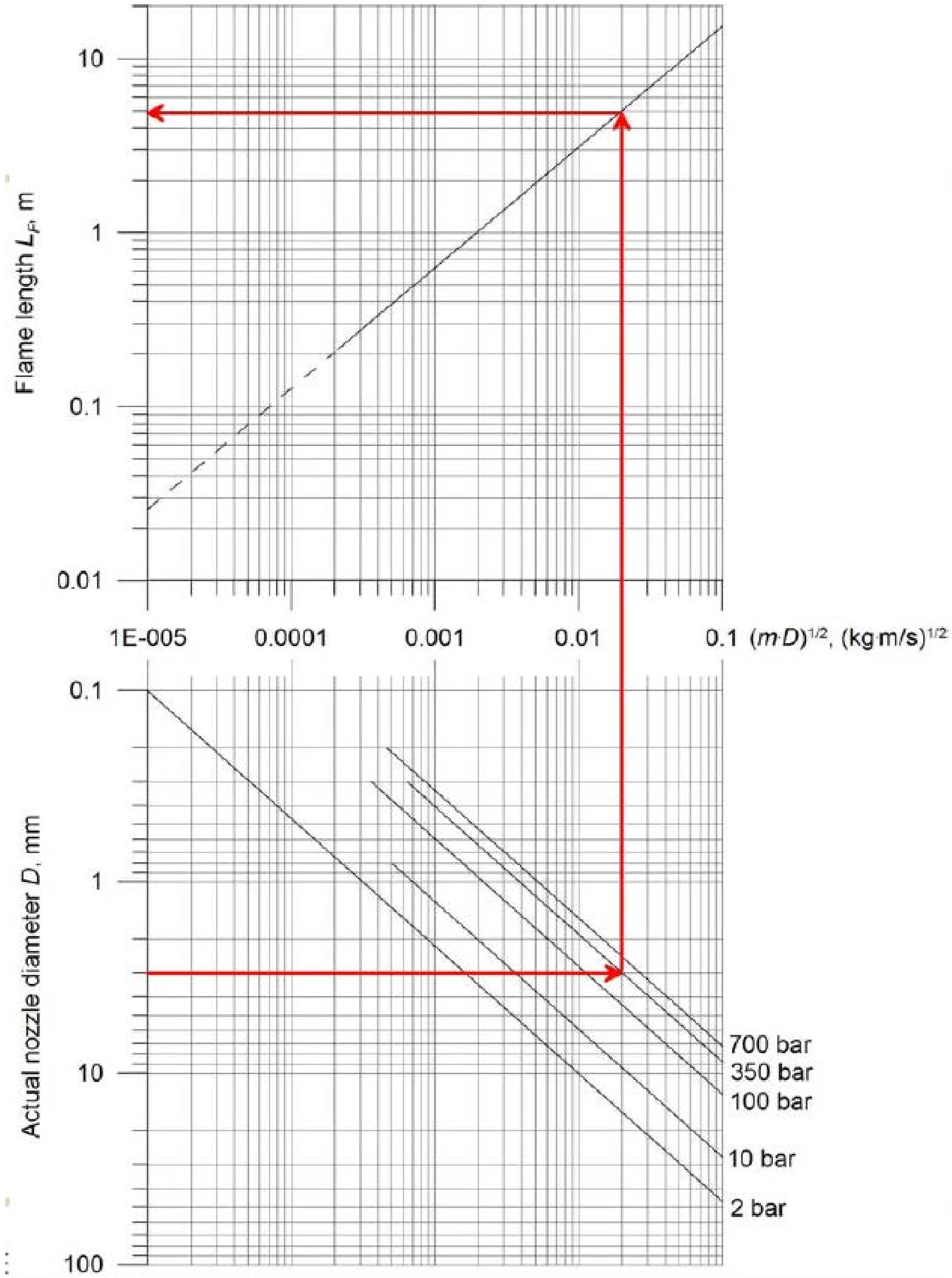
F.2.2.1 Hydrogen Jet Fire

Hydrogen jets resulting from high pressure storage tanks and equipment of between 350-700 bar will be mainly in a form of under-expanded jets, defined as a jet with pressure at the nozzle exit which is above the atmospheric pressure. The jet will have air at its edges and can combust in a jet flame, which is similar to a Bunsen burner flame. To limit the hazard associated to a jet fire, the feed line pressure and diameter of a pipe and restrictor orifice should, by design, limit the mass flow rate of hydrogen to a technological level that is required for the FC to function. (i.e. restrictor or feed line diameter as small as possible, high pressure component as limited as possible). Figure 71 provides a tool to evaluate the potential flame length resulting from hydrogen stored at a given pressure and a leaking diameter. (*Molkov - University of Ulster*)

Figure 71 Flame Length Determination: Diagram and Experimental Values



flame lengths as function of the pressure and size of the orifice



In the context of hydrogen high pressure component, due consideration shall be given to the high momentum jet release that could hit surrounding objects. Such jet releases can lead to ablation of any passive fire protection material and cascading effects resulting from the burning of that material.

F.2.2.2 Microflames

A small leak in a hydrogen system could ignite, burn undetected for a long time, and potentially degrade surrounding materials or ignite any hydrogen release that may occur nearby *(Butler et al., 2009)*. Hydrogen leaks can support combustion at flow rates much lower than leaks of other gaseous fuels.

Report SAE J2579*, (2009)* states that a localized hydrogen leak from a typical compression fitting cannot sustain a flame (that can subsequently weaken material and cause a loss of containment), when the mass flow rate is below 28 µg/s. The report indicates that if a leak is below 28 µg/s, a sustained (micro) flame at the leak area will not occur and the released H_2 will have to be addressed through ventilation and proper design to avoid accumulation.

F.2.2.3 Hydrogen Deflagration

Deflagration is a flame moving through a flammable mixture as a subsonic wave, with respect to the unburned mixture. Without confinement, laminar burning occurs with the flame front moving 2 to 3 m/s. Under these conditions pressure buildup can reach a factor of 8 times the initial pressure. Sensitive H_2/air mixtures are characterized by hydrogen concentrations that exceed 12 percent by volume. (WST-IR-117-001-08 NASA). A deflagration explosion is the more likely event in an open gas cloud since the minimum volume concentration mixture to allow a deflagration is low, 4% in air for burning, and the minimum ignition energy is small, about 1 mJ at 4% concentration.

Confined volumes in which the volume to surface area ratio is large, or volumes for which length ≈ width ≈ height do not promote significant flame acceleration.

F.2.2.4 Hydrogen Deflagration Mitigation

In confinements where the length/width ratio is less than 8 there is little acceleration of the flame speed so the design shall consider this recommendation.

Ventilation is the main mitigation to avoid the H_2 ignition leading to deflagration.

F.2.2.5 Hydrogen Detonation

The detonation process is initiated directly with a shock wave, or when conditions are right, a deflagration can transition to detonation in a process called deflagration-to-detonation transition. Detonations are characterized by high velocities and large overpressures. (WST-IR-117-001-08 NASA). The detonation range mentioned in ISO/TR 15916 (2004) is 18-59% by volume of hydrogen in air.

It is much more difficult to initiate a hydrogen detonation than a hydrogen fire, looking at the concentration and ignition energy levels. Today the probability of a fire on board an A/C is higher than 10E-7 while the probability of a detonation (e.g. fuel tank explosion prevention) needs to be better than 10E-9.

Causing a detonation in a gas cloud is difficult (compared to deflagration), since the minimum volume concentration for hydrogen is 18% in air and the ignition energy is in the 10 kJ range. Therefore, initiating a detonation in a hydrogen cloud is not as likely as initiating a deflagration.

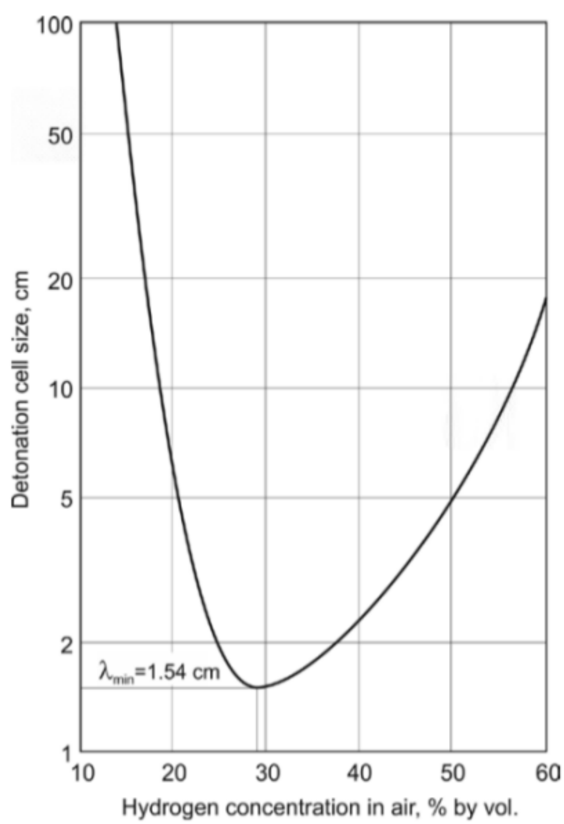
Detonations are characterized by high velocities (1500 m/s (4922 ft/s) or greater) and large overpressures, as great as 15 to 120 times the initial pressure. (WSTF-IR-1117-001-08)

F.2.2.6 Hydrogen Detonation Mitigation

The detonation cell width, often denoted as lambda (λ), is a fundamental parameter of the detonation process found to be proportional to the chemical reaction zone length (length of the area where the chemical reaction is occurring). Indeed, a diameter of the tube, where detonation can propagate, should be of the order of a detonation cell size. The length, a, of a detonation cell is one to two times its width, b. The aspect ratio, a/b, increases with decreasing initial pressure. Detonation cell lengths for stoichiometric GH_2-air/GOX at 101.3 kPa (14.7 psia) are 15.9 mm (0.626 in.) and 0.6 mm (0.024 in.), respectively *(Bull, Ellsworth, and Shiff 1982)*.

The detonation cell size is a function of a mixture composition. Figure 72 shows results of the classical work by Lee on dependence of detonation cell size on concentration of hydrogen in air (*Lee, 1982*).

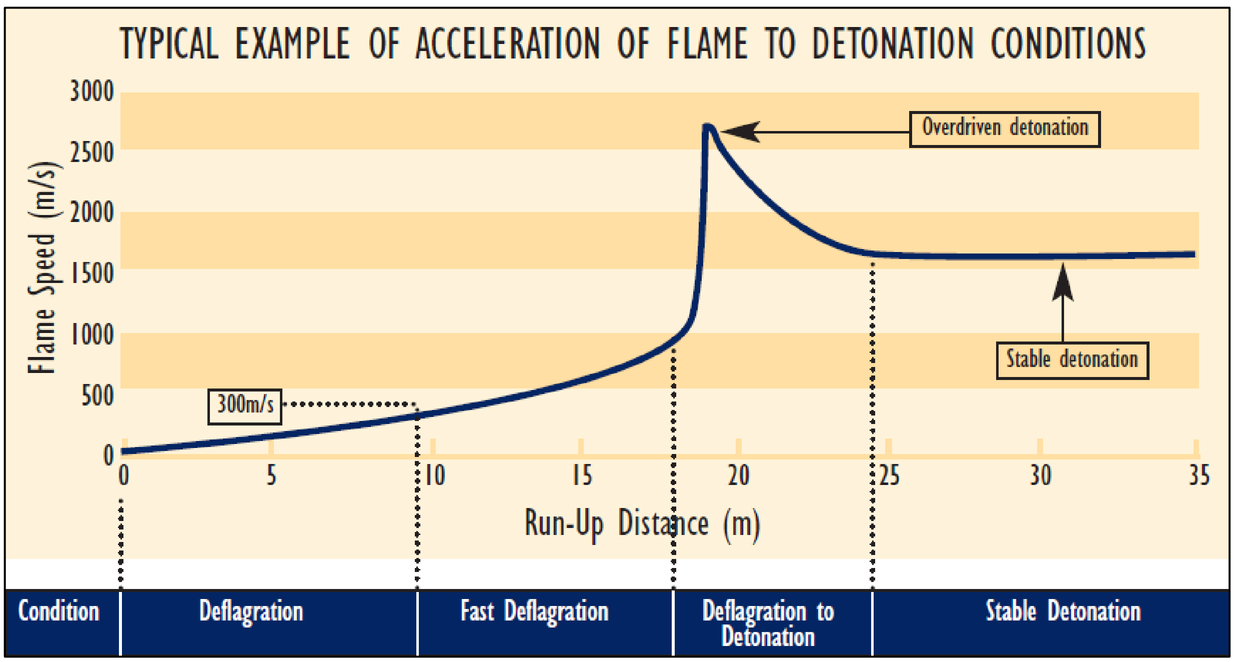
Figure 72. Detonation Cell Size as A Function of Hydrogen Concentration in Air



The cell size is a parameter that can limit detonations. For smooth tubes, the smallest tube diameter that will propagate a detonation is = (cell size/π). Larger diameters will propagate a detonation shock wave, but smaller diameters cannot because the reflected shock waves will break up the primary wave front. For a stoichiometric hydrogen-air mixture, the minimum tube diameter is about 0.5 cm *(Guirao, 1989).* At the upper and lower explosion limits, the minimum tube diameter is about 0.3 meter. Propagation of a detonation in a channel requires that the channel width be at least as wide as the cell size. A similar phenomenon with flame quenching is seen for hydrogen flames. If two plates are closer than 0.5 mm, a hydrogen flame cannot propagate because too much heat is lost to the walls for the flame to sustain itself.

It is possible to ignite a deflagration that can "run up" or transition to a detonation. This is referred to a deflagration-to-detonation transition, or DDT.

Figure 73. Typical Example of Acceleration of Flame to Detonation Conditions



The experimentally observed run-up distance for DDT in stoichiometric hydrogen-air mixture in a tube has typical length to diameter ratio of approximately 100. The presence of obstacles in a tube can essentially reduce run-up distance for DDT. Run up distances for DDT in sensitive mixtures could be ≈ ½ meter

The following are strategies that could be implemented to minimize the potential for flame acceleration or detonation within a fuel cell:

- Avoiding confinement and congestion where flammable hydrogen-air mixtures might form;

- Using flame arrestors, small orifices, or channels to prevent deflagration and detonation from propagating within a system;

Limit the amount of hydrogen that can escape through a leak by limiting the high-pressure portion of the hydrogen supply system to the minimum. The feed line pressure and diameter of a pipe and restrictor orifice should, by design, limit the mass flow rate of hydrogen to a technological level that is required for the FC to function. As a good practice, the high-pressure line should be minimized. The release duration, due to the time required to detect the leak and operate the valve should be reduced as much as possible. The leak detection time and time of shutting down hydrogen supply line is therefore a critical parameter for safety.

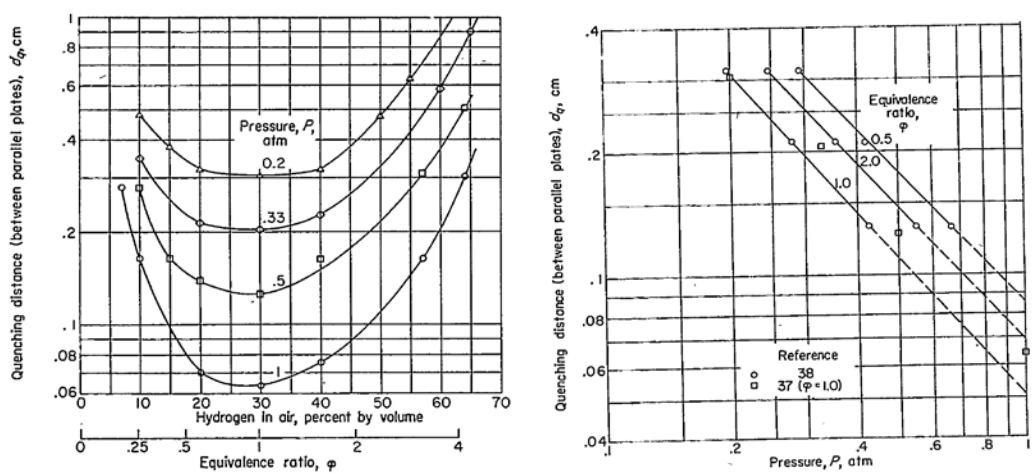
F.2.2.7 Mitigation of Fire Hazard—Quenching Gap for Isolating Fire

The quenching gap is defined as the spark gap between two flat parallel-plate electrodes at which ignition of combustible fuel air mixtures is suppressed; smaller gaps totally suppress spark ignition. The quenching gap is the passage gap dimension requirement to prevent propagation of an open flame through a flammable fuel air mixture that fills the passage. *(WST-IR-117-001-08 NASA).* Quenching of any flame occurs when heat losses from flame are comparable with heat generation due to combustion, and then the chemical reactions cannot be sustained.

The quenching distance decreases with increase of pressure and temperature, and is highly dependent on the mixture composition. This is probably the main reason of the published data scattering.

ISO TR 15916 provides a quenching gap value of 0.064 cm (for 20°C, 15 K and 101,325 kPa).

Figure 74. Effect of Pressure Concentration and Pressure on Quenching Distance



(NACA report 1383)

The quenching gap is one of the key parameter that is used to design a flame arrestor which might be used to prevent a hydrogen fire propagating from one A/C zone to another or outside the aircraft.

F.2.2.8 Mitigation of Fire Ignition—Explosion Proofness

Components located in flammable fluid leakage or fire zones should be qualified to show that they are not nominal ignition sources. Electrical components may be qualified for use within flammable fluid leakage zones by showing the components meets the appropriate criteria such as the explosion proof requirements defined in section 9 of RTCA Document DO-160/ED14. Other components must be shown to be free of potential arcing or friction ignition sources and have maximum surface temperatures with margin below the autogenous ignition temperature of the flammable fluid that could exist within the zone. Components located in flammable fluid leakage should be qualified to show that they are not being ignition sources or that they are intrinsically safe.

> **Note**: Explosion proof test sequence requirements as defined in section 9 of RTCA Document DO-160/ED14 might need to be adapted to the hydrogen environment. Other standard, used in industry, could be acceptable pending comparison analysis.

F.2.2.9 Mitigation of Fire Ignition—Gas Leakage Detection

Hydrogen Sensor response time, resolution and accuracy needs to be adequate for the measurement intent. Impacting factors include pressure levels, humidity, temperature, vibration, etc. need to be considered in the design and qualification of the sensor. *(AIR6464, AS/ARP for fuel cell).* In event of a failure, shut off action shall be initiated for any non-essential application.

Hydrogen sensors when ensuring FC safety should have periodic maintenance & calibration to maintain in-service performance.

F.2.2.10 Mitigation of Fire Ignition—Ventilation

Ventilation is one mitigation means to reduce the risk associated to a hydrogen fire. In general leaking hydrogen must be vented overboard unless it can be shown that no hazard exists by its discharge within the compartment in which it is installed. Hazard associated with the loss of ventilation are to be considered in the design and safety analysis.

Ventilation is as well one mitigation means to face the risk of permeation due to hydrogen storage. During fuel cell operation, ventilation will probably be used to manage possible leaks however, for non-operating condition where ventilation is reduced or stopped, it is important to define maximum allowable permeation rate for hydrogen fuel cell vehicles with compressed hydrogen tanks onboard to define when LFL of hydrogen in air (4% by volume) is reached.

Permeation in the context of compressed gaseous hydrogen (CGH) 2 systems is diffusion through the walls or interstices of a container vessel, piping or interface material. Permeation may be categorized as a long term slow hydrogen release from a CGH 2 system. For metallic containers or containers with metallic liners, i.e. Types 1, 2 or 3, the permeation rate is considered to be negligible. However, hydrogen permeation is an issue for containers with non-metallic (polymer) liners, i.e. Type 4 containers.

All these vessel types are suitable for aviation use, while for weight reasons type 3 or 4 will most probably be selected. In any case the permeation rate will need to be verified by analysis or test

F.2.2.11 Mitigation of Fire Hazard—Flammability of Materials in Potential Leakage Areas of Hydrogen

The material flammability shall be such that a sustained fire will not be supported after electrical power and the fuel and oxidant supply have been terminated.

The slow leak rates that result from diffusion or permeation through a material do not pose a flammability hazard if the hydrogen is allowed to dissipate in the open. *(NASA WSTF-IR-1117-001-08)*

In case of higher leak or concentration due to permeation, Hydrogen concentration below LFL can have a significant impact on material fires. As hydrogen increases from zero (0) to four percent (4%), materials:

- can no longer self-extinguish,
- burn at a faster rate
- are consumed at a faster rate

This behavior is similar to what occurs in potential leakage areas of oxygen, although the severity of its impact may be increased.

F.2.2.12 Mitigation of Fire Hazard—Separation of Leakage from Ignition Sources (Nominal and Potential)

Separation of leakage and ignition sources is a fundamental tool in minimizing the probability for ignition, particularly with respect to preventing a single failure from causing both leakage and ignition. An arc fault between an electrical wire and a metallic flammable fluid line may puncture the line and result in a serious fire. The same applies to electrical equipment. When wiring is run parallel to or crossing flammable fluid lines, maintain as much physical separation as possible.

F.2.2.13 Mitigation of Fire Hazard—Isolation of Leakage from Ignition Sources (Nominal and Potential)

As far as practical Isolation of flammable reactants leakage (such as H_2) and ignition sources should be separated with a barrier. If this cannot be achieved, other precautions should be taken such as double walled hydrogen lines, vapor barriers, ventilation, etc.

F.2.3 Potential Ignition Sources

This section discusses the potential of H_2 ignition from electrical, mechanical, and thermal sources.

F.2.3.1 Ignition Due to Electrical Sources

F.2.3.1.1 Static Discharge

The energy stored as static electricity on an object varies depending on the size of the object and its capacitance, the voltage to which it is charged, and the dielectric constant of the surrounding medium

Example: the accumulation of electrostatic charges created by the friction of dry hydrogen flowing over, or through, nonmetals. Two-phase flow or flow with solid particles can cause a static discharge.

Minimum Spark Energy for Ignition for H_2 in Air is 0.017 mJ at 101.3 kPa. The potential for static discharge should be eliminated by proper bonding and grounding.

The spark from a human electrostatic discharge can be up to 500 times that needed to ignite hydrogen. This energy is typically discharged in less than a microsecond and sufficient to ignite not only near stoichiometric mixtures yet mixtures close to the flammability limits.

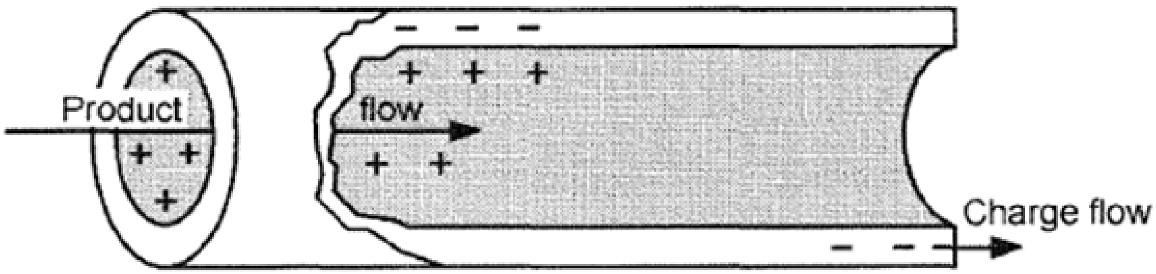
F.2.3.1.2 Electric Arc

Electric arcs can provide the energy to ignite a combustible mixture of hydrogen and air/oxygen. Some examples of sources of electric arcs include switching circuits, electric motors and short circuits, loose connections. Large electric arcs create shockwaves sufficient to directly initiate detonation. *(WST-IR-117-001-08 NASA)*

F.2.3.1.3 Charge Accumulation

Electric charge buildup (Figure 75) is a function of the relative rates of charge accumulation and charge dissipation within the flowing fluid.

Figure 75. Electric Charge Buildup



Electric charge buildup is very small for flowing hydrogen, but solid particles in the flow could greatly increase the buildup of an electric charge.

The buildup of an electric charge could cause a spark that could result in an ignition of a combustible mixture of hydrogen and air/oxygen. *(WST-IR-117-001-08 NASA)*. For this reason, all hydrogen conveying equipment must be thoroughly grounded.

F.2.3.1.4 Ignition Energy

The mere fact that a spark results from high voltage does not mean that ignition of a flammable mixture will occur. For combustion to be initiated, sufficient energy must be transferred from the spark to the surrounding flammable mixture. The energy that is stored and available from a capacitive discharge is related to voltage and capacitance by the following formula:

$$E = 0.5CV^2$$

Where,

E = energy (in joules)

C = capacitance (in farads)

V = potential (in volts)

The minimum spark ignition energy for hydrogen in air has been reported as 0.016 mJ. This would equate to a voltage of less than 2 kV for a human with a typical capacitance of 100 pF. Such voltages could readily be obtained by a person and the discharge itself would be barely noticeable.

F.2.3.1.5 Ignition by Static Electricity

For an electrostatic charge to be a source of ignition, the following four conditions must be met[12]

1. A means of generating an electrostatic charge must be present.
2. A means of accumulating an electrostatic charge capable of producing an incendive spark.
3. A means of discharging the accumulated electrostatic charge in the form of an incendive spark (that is, a spark gap) must be present.
4. An ignitable vapor-air mixture must be present in the spark gap.

F.2.3.1.6 Stray electrical current

Stray currents can flow in electrically conductive systems or parts of systems:

- As a result of short circuit or short circuit to earth owing to faults in electrical installations.
- As a result of magnetic induction (near electrical installations with high current or radio frequency).

F.2.3.1.7 Lightning

At the point of a lightning strike there is a powerful electric discharge. The electric potential can be transmitted on long distances if conveyed by metallic pipes such as pipes.

F.2.3.1.8 Corona Discharges

Corona discharges are not discrete spark discharges, like capacitive or brush discharges, but are a quasi-constant current emitted from a pointed object that is at a different potential to its surroundings. The corona current is initiated when the potential is high enough to cause the local electric field to exceed a threshold value which depends upon curvature of the point.

F.2.3.1.9 Radiofrequency Electromagnetic Waves up to 10^{11} Hz

Radiofrequency (RF) waves will induce electric currents and voltages in any conducting structure on which they impinge. The magnitude of the currents and voltages will depend upon the size and shape of the structure, and the wavelength and strength of the RF signal.

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[12] API Recommended Practice 2003, Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents; American Petroleum Institute, September 2015

F.2.3.1.10 Electromagnetic Waves from 3 x 10^{11} Hz to 3 x 10^{15} Hz[13]

Radiation in this spectral range can be a source of ignition, especially when focused, through absorption by explosive atmospheres or solid particles.

F.2.3.2 Ignition Due to Mechanical Sources

Some mechanical sources capable of igniting hydrogen combustion are:

- Mechanical impact
  - EN 13463-1 provides consideration on condition under which single impacts between metal parts need not to be considered as potential ignition sources (e.g., impact velocity, energy, couple of materials impacted)
- Friction sparks are caused by hard objects coming into shearing contact with each other, such as metal striking metal, metal striking stone, or stone striking stone. Friction sparks are particles of burning material that have been sheared off as a result of contact. The particle initially is heated by the mechanical energy of friction and impact.
- Friction and galling
  - Galling is a form of wear caused by adhesion between sliding surfaces. The combination of friction and galling generates heat
- Frictional Heating: Parts of a component or system can rub against each other with enough force and/or velocity to raise any one part to its ignition temperature at the given oxygen pressure and concentration.
- Metal fracture
- Tensile rupture
  - Metal fracture or tensile rupture can produce spark or a loss of function
- Mechanical vibration
  - Materials that are poor heat conductors such as plastics can reach their ignition temperatures when stressed or vibrated.
  - Vibration may reduce gasket material resilience and cause a leak.
- Safety burst disk
  - Sudden hydrogen releases into piping filled with air, after a safety burst disk ruptures, can be spontaneously ignited at pressures as low as about 2 MPa. The way in which the burst disk ruptures (non-instantaneous burst) is probably the most important factor for spontaneous ignition as it affects the hydrogen-air mixing. *(Dryer et al., 2007).*

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[13] Support to Safety Analysis of Hydrogen and Fuel Cell Technologies (SUSANA) Project *FCH-JU-325386* (Funded by European Commission)

F.2.3.3 Ignition Due to Thermal Sources

F.2.3.3.1 Auto-Ignition Temperature

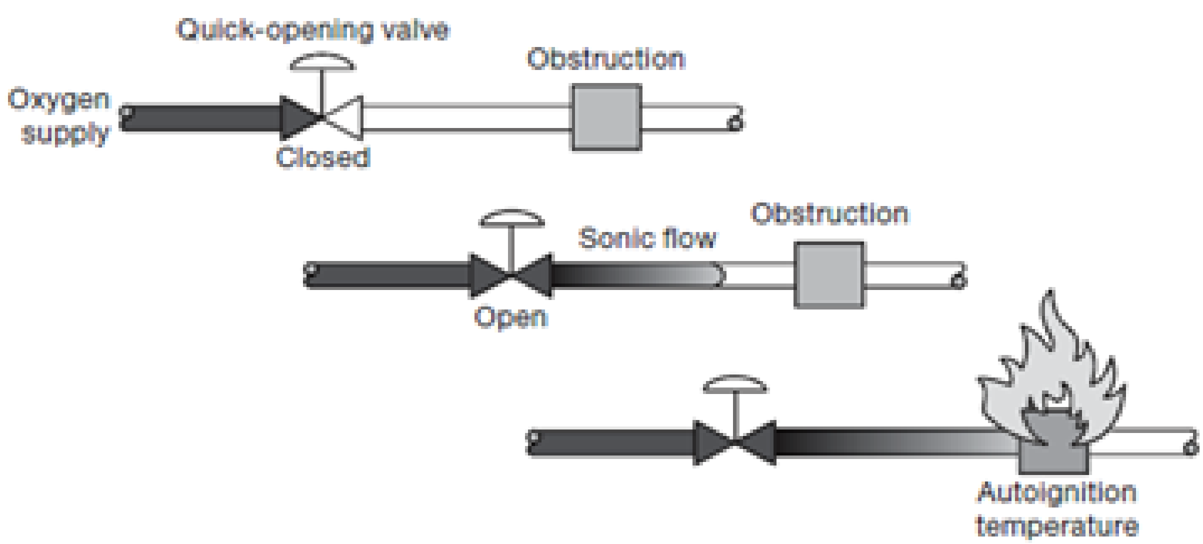
The standard auto-ignition temperature of hydrogen in air is above 510°C *(Baratov et al., 1990).* It is relatively high compared to hydrocarbons having long molecules. However, it can be lowered by catalytic surfaces. Objects at temperatures from 500°C (932°F) to 580°C (1076°F) can ignite hydrogen-air or hydrogen-oxygen mixtures at atmospheric pressure. Substantially cooler objects of about 320°C (608°F) can cause ignition under prolonged contact at less than atmospheric pressure *(NASA, 1997).* Hot air jet ignition temperature is 670°C (1238°F*) [BRHS, 2009].*

F.2.3.3.2 Compression Heating

To avoid the possible risk of fire or explosion, high-pressure shut-off valves should be designed to provide effective slow opening and closing. This requirement is applicable for oxygen systems –reference EASA AMC 25.869(c).

A common example of compression heating, shown in Figure 76 in an oxygen system occurs when a valve (especially a fast opening ball or plug valve) is opened quickly and the gas stream compresses the oxygen downstream against an obstruction. A closed valve or regulator is an obvious obstruction, but often the obstruction is not obvious because it exists within the valve itself. For example, the obstruction may exist at a valve seat as it is being opened, at the outlet of a partially open regulator, or at another small orifice. In addition, the gas stream can be obstructed at the angle in an elbow fitting. For hydrogen lines, an ignition could occur only in the presence of oxidizing contaminants.

Figure 76. Compression Heating Example



F.2.3.3.3 High Temperature Ignition

Material and gas exposure to high temperature components that are not adequately insulated can be a source of ignition.

F.2.3.3.4 Resonance Ignition (Repeated Shock Waves in a Flow System)

Resonance: Acoustic oscillations within resonant cavities can cause a rapid rise in gas temperature. For hydrogen a line, an ignition concern could occur only in the presence of oxidizing contaminants.

F.3 MECHANICAL/MATERIALS HAZARDS

A hydrogen system can consist of structural members and will involve a multitude of different materials. Awareness of the unique properties of hydrogen is essential for the safe use of hydrogen. This section will concentrate on the mechanical/materials related hazards.

F.3.1 Material Compatibility Hazards

The selection of a suitable material for hydrogen applications requires consideration of the following as appropriate:

F.3.1.1 Embrittlement

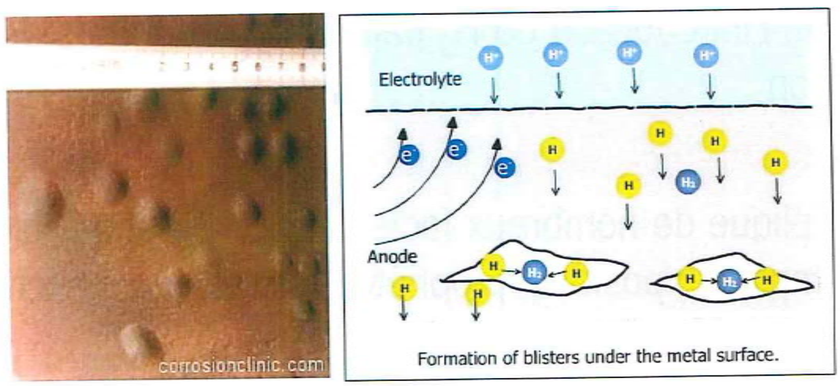
Hydrogen can cause a significant deterioration in the mechanical properties of metals. This effect is referred to as hydrogen embrittlement.

Hydrogen embrittlement involves a large number of variables such as the temperature and pressure of the environment; the purity, concentration, and exposure time of the hydrogen; and the stress state, physical and mechanical properties, microstructure, surface conditions, and nature of the crack front of the material. A crack consists of two surfaces within a solid body, between which atomic bonds do not exist, and where the surfaces are bounded by their intersections with the surface of the body or by a line along which atomic bonds exist. The surfaces are called fracture surfaces or crack faces, and the line is called the crack front.

Once absorbed, dissolved hydrogen may be present either as atomic or molecular hydrogen or in combined molecular form (e.g., methane). These individual hydrogen atoms within the metal gradually recombine to form hydrogen molecules, creating pressure from within the metal. The pressure causes cracks due to the intermolecular forces between two surfaces This pressure can increase to levels where the metal has reduced ductility and load-bearing capacity, cause cracking and catastrophic brittle failures at stresses below the yield stress of susceptible materials and the subsequent spills and leaks create hazards. There is a critical surface displacement at which the two surfaces no longer feel the force from each other, that is, a displacement between opposing surfaces that exceeds the effective range of the forces.

Figure 77. Hydrogen-Induced Cracks (HIC)

Figure 78. H_2 Blistering



Sources of hydrogen causing embrittlement have been encountered in the making of steel, in processing parts, in welding, in storage or containment of hydrogen gas, and related to hydrogen as a contaminant in the environment that is often a by-product of general corrosion.

F.3.1.1.1 Effect on Mechanical Properties

The mechanical properties of metals are reduced in the presence of hydrogen. As an example of severe hydrogen embrittlement, the elongation at failure of 17-4PH precipitation hardened stainless steel was measured to drop from 17% to only 1.7% when smooth specimens were exposed to high-pressure hydrogen.

The susceptibility of steel to hydrogen embrittlement increases as the pressure of the hydrogen environment increases. The susceptibility of an alloy to adverse hydrogen effects increases as the strength of the alloy increases. Embrittlement leading to an increased crack growth rate results in a decreased fatigue life.

If exposed to hydrogen and cyclic stresses, a metal or alloy is almost certain to have a lower resistance to fatigue than if hydrogen were not present.

F.3.1.1.2 Embrittlement mitigation

Proper material selection during fuel cell design will avoid the embrittlement phenomenon. In addition, effect of low leakages on surrounding aircraft systems and structure should be considered. As with any good design, the material selected must be adequate for the intended use. This is also applicable for material exposed to hydrogen. There has been a lot of evaluation, testing and analysis regarding material compatibility with hydrogen. Embrittlement on Aircraft systems and structures should not be a concern as long as there is no H_2 accumulation over an extended period of time.

Designers should, in the absence of data, assume a substantial (up to fivefold) decrease in resistance to fatigue. Aluminum is one of the few metals known to show only minimal susceptibility to hydrogen.

Most GH_2 equipment is made of medium strength steel. Hydrogen embrittlement concerns are addressed through increased thickness, surface finish, welding techniques, and materials selection.

Materials in contact with hydrogen gas shall comply with the metallic compatibility characteristics documented in ISO 11119.

Another valuable source of information comes from Sandia National Laboratories which gathers existing materials data for inclusion in the Technical Reference for Hydrogen Compatibility of Materials. SAND2012-7321 Individual sections of this report may be updated or added periodically at this website: http://www.sandia.gov/matlsTechRef.

One should therefore take into consideration that:

- At room temperature, most elastomers are inert with respect to $H_{2.}$
- At high pressure, steels (especially cold worked ferritic steels) can suffer from hydrogen embrittlement. Metals with a face-centered cubic structure, such as, austenitic stainless steels, aluminum alloys, copper, and copper alloys, generally are satisfactory for hydrogen service. Nickel, a face-centered cubic material, is an exception and generally should not use because it is subject to severe hydrogen embrittlement. Un-stabilized austenitic stainless steel (some of the 300 series) can revert to a martensitic structure when stressed above the yield stress at low temperature, reducing the ductility of the steel.
- At high temperatures, one should use austenitic steels (AISI 316 or 304) to avoid segregation of carbon at grain boundaries.
- At low temperatures materials should remain sufficiently ductile. Steels such as AISI 316L or 304L, as well as aluminum and aluminum alloys could be used.

Many types of elastomers are compatible with H_2 gas at ambient temperature. For high pressure service caution must be observed if elastomers will be subject to rapidly changing pressures

F.3.1.2 Diffusion and Permeation

Hydrogen is the smallest molecule and possesses a low viscosity as a fluid. It can penetrate and leak through materials and seals more readily that other gases including helium and nitrogen; consequently, the possibility of diffusion as a result of permeation or material porosity must be evaluated for a hydrogen system.

Permeation refers to the property of a substance, gas, vapor, or liquid, i.e. a “permeate”, to penetrate through a solid. Permeation is not as a leakage a failure but can be a normal behavior of the material in presence of H_2.

Permeation is a process, driven by concentration gradient that has several steps:

- Absorption at the material interface in which the permeate is adsorbed at the surface of the solid,
- Diffusion in which the permeate moves through pores or molecular gaps within the solid, and
- Desorption, whereby the adsorbate leaves the solid.

F.3.2 Failure of High-Pressure Gaseous Storage Systems

A compressed gas can have significant potential energy. Failure in high pressure gas storage systems can be the result of a passive component failure (i.e., tank, tubing, etc.) or an active component failure (i.e., valve, pressure relief device). Specific component hazard failures are discussed in the following sections. Hydrogen storage systems should be qualified to survive damage resulting from shipping and handling (such as dropping).

Critical failure of passive components, such as tanks and lines, would result in the leakage/rupture of the component. Side effects of leakage/rupture of a component could be debris/shrapnel to the immediate area, release of flammable gas, and/or system in operation. Most passive components are screened by design and testing requirements both prior to installation and post installation into a system.

Design, manufacture, integration and test of compressed gas systems must take safety into account; mitigation approaches are discussed in later sections

F.3.3 Failure of Pressure Relief Devices

Pressure relief devices (PRDs) play a critical role in the implementation of most high-pressure gas storage systems. In the event of an over-pressure situation induced by, for example, overfilling, exposure to excessive heat, or a liquid to gas phase change, the PRD will activate and allow the gas to escape to a safe location. The PRD should be set such that that it prevents catastrophic failure of the pressure vessel, irreversible damage, or degradation of the pressure vessel life cycle.

Two main failure modes of the PRD are feasible:

- Type 1 Failure: A PRD should activate but does not
- Type 2 Failure: A PRD activates when it should not

A Type 1 failure has far more hazardous potential than a Type 2 failure because it results in a situation where the internal pressure within a vessel can exceed its MAWP and consequent leakage/rupture.

The scenario leading to overpressure could be an external heat source (e.g. a fire, bleed lines, adjacent equipment, etc.)

Current thermally activated PRDs are local heat detectors only. Hence, they activate when their immediate surroundings are heated, but cannot detect localized heat sources elsewhere in the middle of the container. They protect containers from large, distributed fires, but not highly localized fires.

PRD´s are utilized on today´s civil aircraft, (e.g., for high pressure fire extinguisher containers), and the design and integration of such devices is a normal practice. In addition, the PRD´s are a failure mitigation means typically used where the probability of the failure itself and the probability of the loss of the mitigation means is extremely remote

Type 2 failures typically result from improperly maintained equipment, improper selection or sizing, or compromised structural properties possibly due to the hydrogen environment. *(NREL 2013)*

A type 2 failure is not detrimental to the fuel cell system but can be detrimental for an aircraft depending on the system integration.

Since the PRDs and associated connections and tubes can be damaged by the exposure to water or ice, PRD vent systems should be designed to prevent the ingress of foreign material or accumulation of moisture in the system. Additionally, moisture in the vent line could potentially freeze under cold service conditions.

Safety valves should be designed so the movable parts cannot stick or seize even with unequal heating or cooling.

A rupture disk or relief valve shall be installed in every section of a line where liquid or cold gas can be trapped.

Supplemental pressure-relief devices should be installed to protect against excessive pressures created by exposure to fire or other unexpected sources of external heat.

F.3.4 Crashworthiness

This requirement is that certain equipment will not detach from its mountings, or separate in a manner that presents a hazard during an emergency landing. It applies to equipment installed in compartments and other areas of the aircraft where equipment detached during emergency landing could present a hazard to occupants, fuel systems or emergency evacuation equipment.

The requirement for crashworthiness is applicable for a fuel cell system as for any other system and the specifics of the assessed system need to be considered along with the individual system architecture.

In addition to a crash, consideration should be made for an emergency landing made within the operating limits of the aircraft. This is in contrast to a crash, which is a maneuver that is out of control and typically results in the loss of the aircraft hull.

In addition to the equipment no detaching criteria; an additional pass/fail criterion linked to the FC system should be “no H_2 hazardous leak allowed”.

In addition, current pressure vessel standard ISO 11119 requests gun fire test to prove that the pressure vessel will remain structurally intact (without explosion) after an impact.

Regarding pressure vessels, it is recommended:

- To accept the ISO standard 11119 part 1 to 3 for the aviation qualification of high pressure vessels for oxygen and hydrogen.
- To consider the generation of ETSO requirements for high pressure vessels on board civil aircraft.
- To promote the application of the ISO standard in harmonization activities between ISO and DOT.

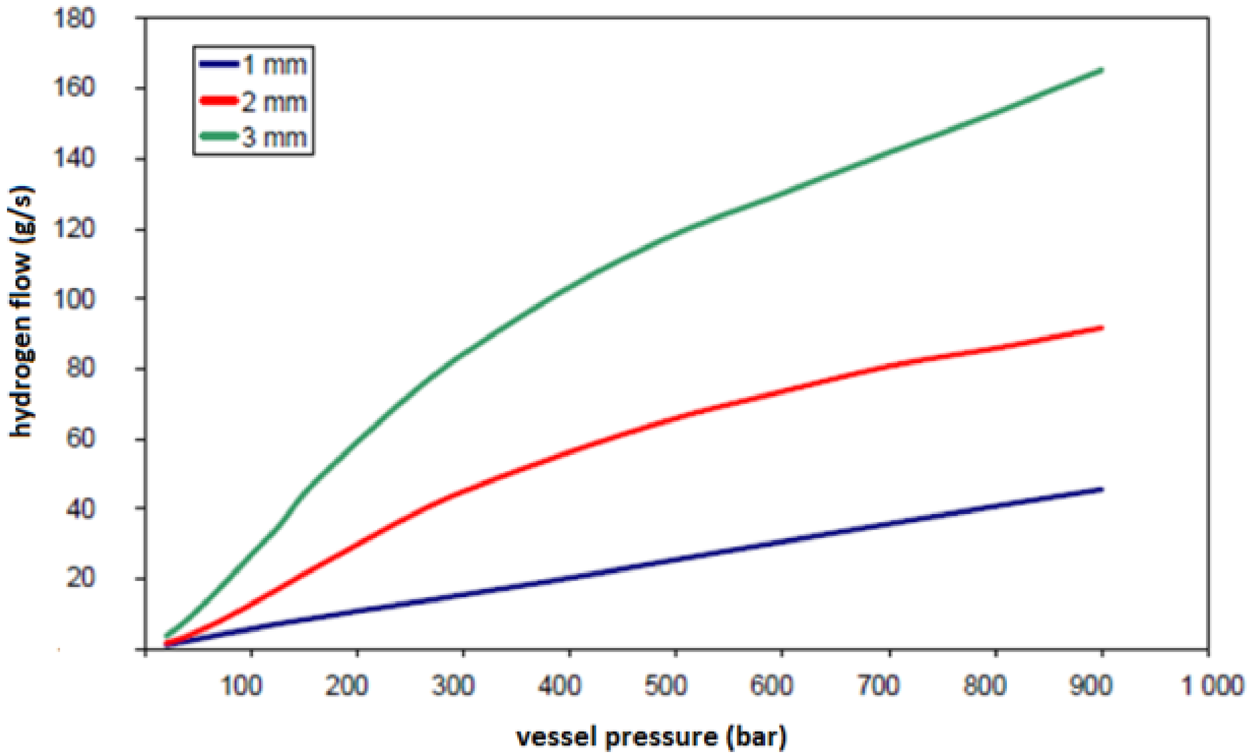
F.4 HAZARD DEPENDENT ON APPLICATION/IMPLEMENTATION

For fuel cells operating on hydrogen fuel, consideration for hydrogen hazards must be included in the design. Some example hydrogen mitigation hazards for systems of an aircraft are:

- Passenger and crew compartments and areas connected to them should be considered to contain nominal ignition sources.
- Single failures of hydrogen containing components shall not lead to uncontrolled leakages. If single failures result in hydrogen leakage, mitigation means shall be provided to prevent uncontrolled leakage (reference § 25.1309).
- Ventilation has to be provided where hydrogen leakage into any compartment is a possibility. In general leaking hydrogen must be vented overboard unless it can be shown that no hazard exists by its discharge within the compartment in which it is installed.

Figure 79 provides an order of magnitude of the hydrogen flow released from a pressure carrying component from a given diameter orifice.

Figure 79. Hydrogen Flow for A Given Diameter Orifice



One can easily conclude that a gaseous 350 bar H_2 pressure vessel or associated high pressure piping that leaks through a given diameter orifice will release within a few seconds a hazardous amount of H_2 into its installation area. An applicant will have to demonstrate the effectiveness of the mitigation means to address the effect of such hazard or to demonstrate that such hazard is extremely improbable.

Installation of high pressure components could be proposed into an occupied/pressurized area only if a mitigation mean is provided to cope with the above high leakage scenario. Fuel cell systems must be designed to safely dissipate heat and exhaust products. A system installed inside the pressurized volume can have the reaction products vented outside of the pressurized area. A hydrogen based fuel cell product released inside the pressurized area of an aircraft would affect the heat and water content of the air which the aircraft design and environmental control systems would have to accommodate. Fuel cell systems which have the potential to leak CO, CO_2 or other hazardous fuel by-products would have additional safety and ventilation requirements. One advantage of installing a fuel cell in an unpressured area is that it is easier to vent H_2 leakage overboard, however the environment is harsher.

F.5 PHYSIOLOGICAL HAZARDS

Personnel present during leaks, fires, or explosions of hydrogen systems can incur several types of injury.

- Asphyxiation is a hazard when someone enters a region where hydrogen or a purge gas has displaced the air, diluting the oxygen below 19.5% by volume.
- Burns can result from direct contact with a hydrogen fire, thermal radiation from a hydrogen fire, or contact with a surface that has been heated by a hydrogen fire. Reference FAR 25.1360.
- Frostbite (freezing, cryogenic burn) can result from contact with a cold fluid or a cold surface.
- Blast (overpressure) can result from a detonation, deflagration or from the unconfined expansion of a compressed gas.
- Fragments may be created when a hydrogen explosion acts on its container or other items in close proximity. These fragments can result in injury or death to personnel, and damage or destruction of equipment.
- Noxious gases generated in case of fire.

Toxicity is not an issue with hydrogen or its combustion product, water.

F.6 OPERATIONAL AND MAINTENANCE HAZARDS

Dedicated procedures must be developed to prevent against specific hydrogen hazards. As an example, unless the hydrogen storage tanks will be removed, always leave a small amount of pressure in the tanks so that the internal pressure is a few psi above atmospheric pressure. Any time tank pressure falls below atmospheric, it is possible for air to enter, and the tank must be to purge with nitrogen before refilling with hydrogen. In addition, a means needs to be provided to ground the Fill Station, during Refueling, prior to fill nozzle connection. Another alternative is to have a pressure vessel refueling procedure outside of the airplane.

Maintenance procedures should also be developed according to §§ 25.1529 and 25.1729 to ensure proper maintenance for safe continued operation of the FCS.

For instance, in these maintenance procedures could be included to periodically check all connections in the hydrogen fuel system for leaks. Leak checks should also be conducted after repair or replacement of any fuel system lines or valves.

Anyone who will operate or maintain hydrogen-fueled system should receive hydrogen safety training. At a minimum, this training should cover the characteristics of hydrogen, operation of onboard safety systems, hydrogen fueling operations, and actions to take in an emergency.

In addition to specific hydrogen hazards, fuel cells can induce well-known hazards such as:

- <u>Electric shock,</u>
    - When working -with voltage systems, always ensure that proper safety procedures are followed.

- Hot temperature,
    - Hot temperature of stack and balance of plant components might dictate to let the temperature cool down before maintenance actions.

Even though these hazards are well known, the Instructions for Continuing Airworthiness should be checked to address these.

Relevant marking, labelling and a set of maintenance instruction are needed to ensure safe maintenance.

F.7 HYDROGEN FIRE EXTINGUISHING

A hydrogen fire should not be extinguished with water or chemicals. Static electricity generated across the leak orifice, or an adjacent hot surface, could explosively reignite the leaking hydrogen. The best way to deal with a hydrogen fire is to shut off the flow of hydrogen gas by closing supply valves, which will extinguish the flame. Essentially the shut-off of hydrogen is the only meaningful way to stop a hydrogen fire in flight because if the supply of hydrogen cannot be stopped the fire will always reignite on hot surfaces.

For firefighting on ground:

If a small flame must be extinguished in order to gain access to a hydrogen supply valve, a dry-powder extinguisher is recommended. Normal procedures can be used to extinguish secondary fires, if any, ignited by the burning hydrogen.

The flow of hydrogen through a leaking PRD/TRD cannot be stopped. The best approach in this situation is to let the fire burn until all of the hydrogen has been consumed. (US department of Transportation)

F.8 CRYOGENIC HYDROGEN (LIQUID OR CRYO-COMPRESSED) HAZARDS

An essential safety concern of liquid hydrogen's low temperature is that, with the exception of 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. Leaks of air or other gases exposed with liquid hydrogen can plug pipes and orifices and jam valves. *(ISO/TR 15916:2004).*

Oxygen enrichment can increase the flammability and even lead to the formation of shock-sensitive compounds. Oxygen particulate in cryogenic hydrogen gas may even detonate.

The volume of liquid hydrogen expands significantly with the addition of heat. The coefficient of thermal expansion at NBP (normal boiling point at absolute pressure of 101.325kPa) is 23 times that of water at ambient conditions *(ISO/TR 15916:2004).* The significance for safety arises when cryogenic storage vessels have insufficient ullage space to accommodate expansion of the liquid. This can lead to an over-pressurization of the vessel or penetration of the liquid hydrogen into transfer and vent lines.

A considerable increase in volume is associated with the phase change of liquid to gaseous hydrogen, and yet another volume increase occurs for gaseous hydrogen that is allowed to warm from the NBP to NTP (Normal Temperature and Pressure). The ratio of the final volume to the initial volume for the phase change from liquid to gaseous hydrogen and expansion of heated gas is 847 *(ISO/TR 15916:2004).* This total volume increase can result in a final pressure of 177 MPa (starting with an initial pressure of 0.101 MPa) if the gaseous hydrogen is in a closed vessel. Pressure relief devices should be installed as a safety measure in any volume in which liquid hydrogen or cold gaseous hydrogen could be trapped, to prevent overpressure from expansion of the liquid hydrogen or cold gaseous hydrogen.

In addition,

- Hydrogen liquid-to-gas transition is cold and can generate burns.
- Material selection should be compatible to cryogenic temperature.
- Cryogenic component and lines need to have adequate insulation to prevent condensation of liquid air on lines and overheating of cryogenic liquid.

Refer to annex B of ANSI/AIAA G-095-2004 for insulation selection guidelines

F.9 NON-HYDROGEN FUEL AND OXYGEN HAZARDS

F.9.1 Hydrocarbon Fuel Hazards

F.9.2 Oxygen

Oxygen hazards are addressed already in the regulation and existing guidance materials do exist, so it is not the intent of this document to develop the oxygen risks. It should be noted however that currently installed oxygen systems provide a safety benefit to the aircraft in the form of providing oxygen in the event a smoke/fire event. This safety benefit is considered when evaluating the installation requirements for certification. Any installation of a pressurized oxygen system should consider a complete risk/benefit analysis to ensure adequate safety levels are maintained. Some fuel cell installations will dictate to have in the same vicinity oxygen, hydrogen, and electrical power and possibly a flammable coolant. This unique environment needs to be reevaluated

Fuel cell equipment includes the use of pressurized vessels, regulators, valves, tubing and fittings stack and electrical harnesses made of metals and nonmetals. All of these materials are combustible in a 100% pressurized oxygen atmosphere.

From a safety aspect, fuel cells using air instead of pressurized oxygen substantially reduce the risk associated with operation in an oxygen environment.

SAE document AIR825/13, *Guide for Evaluating Combustion Hazards in Aircraft Oxygen Systems*, may be used as a guideline for how to conduct an oxygen systems hazard analysis. Confer also to the FAA policy statement PS-ANM-25.1441-01, *Mitigating Fire Hazards in Gaseous Oxygen systems,* dated 12/9/14.

F.10 **ELECTRICAL HAZARDS**

A FCS should have protections against the following hazard conditions associated with an electrical power generating system to maintain equivalent level of safety with traditional methods of supplying electricity:

- Uncontrolled over voltage
- Uncontrolled under voltage
- Uncontrolled over frequency
- Uncontrolled under frequency
- Voltage instability
- High voltage DC
- Frequency instability
- Voltage distortion
- High ripple
- Electromagnetic interference
- Unprotected feeder faulty

This is usually addressed by qualification against RTCA DO160 standard and aircraft power quality requirements and by complying with CFR/CS §q 25.1431. Other applicable references are MIL-STD-704 and ISO 1540.

APPENDIX G. RECOMMENDATIONS FOR REGULATORY STANDARDS AND ADVISORY MATERIAL

G.1 INTRODUCTION

After developing the information on various types of fuel cell technologies, their possible aircraft applications and potential hazards, and the review of existing part 25 regulatory requirements, it was decided to develop one new part 25 regulation. The proposed regulation addresses the main concerns the Committee identified as necessary to cope with the installation of a fuel cell system (FCS) on board an aircraft. This proposed regulation is referred to as the fuel cell system safety baseline regulation and it is located in section G.4.1. Section G.4.2. discusses the background of this proposed regulation along with references to the hazards as described in Appendix F and current regulations that address similar issues.

The committee also identified regulations currently existing in the CFR / CS 25 that would need revising in order to support the certification of FCSs. These are located in Table 19 in section G.5. Furthermore, the Committee also collected those regulations currently in CFR / CS 25 that are seen as applicable, but do not need revising. These are included in this report, because some hazards were identified to be covered by those regulations. They are located in Table 20 in section G.6. The committee also identified operational requirements contained in CFR parts 43, 91, 121, 125, and 129 that are applicable to fuel cell systems. These are located in Table 21 in section G.8.

As discussed in the main body of this report, the committee did not develop recommendations for ESDs other than fuel cells. However, the committee did develop a more performance based regulation that could be used as the basis for replacing the exiting § 25.1353(b) (FAA) / 25.1353(c) (EASA). The current § 25.1353(b) / 25.1353(c) addresses storage batteries. However, its requirements are not sufficient to address all of the safety concerns attributed to Lithium-based batteries. This has led to the issuance of special conditions. The recommended replacement for § 25.1353(b) / 25.1353(c), if adopted, would negate the need to issue special conditions for lithium-based batteries as well as other types of ESDs, including fuel cells. The proposed regulation is located in section G.5.1.

Although the Committee did not thoroughly go through the CFR / CS parts 23, 27, and 29 airworthiness standards, the same concerns would apply with the typical differences between the different product types. The Committee therefore recommends if a rulemaking committee is created, this group will amend the different airworthiness standards based on the conclusions presented in this report.

Recommendations for material that should be included in an advisory circular(s) is included in section G.7 of this Appendix.

G.2 DISCUSSION

For the purposes of the regulation a fuel cell system is defined as: Those units and components using an electrochemical conversion process to produce electricity from a fuel and an oxidant. This includes reactants and reaction products, steam reformers, supply/exhaust devices, enclosures, fuel cell stacks, electric power output devices, cooling or/and heating devices, and a centralized control and monitoring subsystem.

The approach taken by the Committee was as follows. The Committee first needed to have the technical details of the FCS as expected to be installed in aircraft. The fuel cell types identified to have this potential are the PEM and SOFC.

The next step was to identify the hazards of such installations. After the identification of the hazards, the Committee compared the identified risks with the current CFR / CS 25 regulations. Appendix F, identifies which hazards in particular need attention, when installed in an aircraft. Those were identified as not yet properly addressed in the current airworthiness codes.

In order to help the discussions on the regulations, a few examples for the use of FCS are described in Appendix E. With the examples, applicable regulations were identified as a starting point. These examples are not intended to be complete, nor to be acceptable in an actual certification project.

Appendices B and C describes different types of fuel cells (FC), using different technologies. From the different types of FCs described, PEM and Solid Oxide fuel cells are the most feasible types for use in commercial aviation in the near future. Therefore, the regulatory standards and advisory material discussed are based on these two FC types. If another type of FC is introduced, the particular technical differences with the PEM and Solid Oxide FCs should be identified and considered again.

Solid Oxide and PEM FCs are part of the example applications presented in Appendix E. These example applications were used to find the applicable regulations and to identify whether the current regulations are applicable as they are, or need modification. This exercise also revealed design, installation, and safety concerns that are not addressed by the current 14 CFR Part 25 or CS25. The examples are “galley power”, “stand-alone power” (Medevac), “auxiliary power”, “emergency power”, and “UAS”. The considerations regarding the applicable airworthiness regulations are collected in Tables 12, 14, and 15 in Appendix E.

Appendix F identifies the different hazards of fuel cell installations. The main conclusion is that the hydrogen is giving some hazards that might not be new in itself, but are not currently well addressed in the airworthiness requirements. Hydrogen is more common in “On ground solutions”, which drove the developing of standards covering different aspects of hydrogen and fuel cells. One important consideration is the fire risks associated with the use of hydrogen. Oxygen is currently in use on board aircraft; hence dedicated requirement exists in case the fuel cell installation encompasses oxygen bottles, even though most systems will probably use cabin or external air to supply the needed oxygen to the fuel cell.

G.3 REGULATORY STANDARDS AND ADVISORY MATERIAL

G.3.1 Regulatory Standards

Sections G.4 and G.5 contain recommendations for new and revised CFR/CS 25 regulatory standards that are based on the identified hazards discussed in Appendix F.

Section G.6 identifies current CFR/CS part 25 regulations applicable to fuel cell systems that do not require revision.

Section G.8 Identifies maintenance and operational regulations contained in CFR parts 43, 91, 121, 125, and 129 that are applicable to fuel cells.

G.3.2 Advisory Material

Section G.7 discusses the development of Advisory Material regarding fuel cell systems. It discusses what should be included in an advisory circular to support compliance to any new and revised regulations

G.4 NEW CFR/CS 25 REGULATIONS

Fuel cell systems can introduce unique hazards that are not currently, or fully, addressed by the current set of CFR/CS 25 regulatory standards. Therefore, the ESD ARC recommends that a new fuel cell system safety baseline regulation be developed to address these hazards. Section G.4.1 identifies the requirements, or type of requirement, that should be included in the regulation. Rationale that aligns each subparagraph of the baseline regulation to specific fuel cell hazard categories is given in section G.4.2.

The classification of failure conditions used in the baseline regulation is given in Table 17. These failure conditions are identical to those proposed by the Aviation Rulemaking Advisory Committee for the draft (Arsenal) version of AC 25.1309-1B, dated June 10, 2002.

Table 17. Classification of Failure Condition

Term	Explanation
Hazardous	Failure conditions that would reduce the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions to the extent that there would be, for example: A large reduction in safety margins or functional capabilities; Physical distress or excessive workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or Serious or fatal injuries to a relatively small number of persons other than the flight crew.
Catastrophic	Failure conditions that would result in multiple fatalities, usually with the loss of the airplane. (NOTE: A catastrophic failure condition was defined differently in previous versions of § 25.1309 and in accompanying advisory material as "a failure condition that would prevent continued safe flight and landing.")

G.4.1 The Hydrogen Fuel Cell System Baseline Regulation

25.XXX Fuel Cell System Safety

a) For the purposes of this chapter, a fuel cell system is defined as: Those units and components using an electrochemical conversion process to produce electricity from a fuel and an oxidant. This includes reactants and reaction products, steam reformers, supply and exhaust devices, enclosures, fuel cell stacks, electric power output devices, cooling and heating devices, and control and monitoring subsystem.

   For the purposes of this chapter, a reactant is any fuel or oxidizer supplied to the fuel cell system for the purposes of producing electrical energy.

b) The design and installation of a fuel cell system must prevent catastrophic or hazardous explosion due to ignition of fuel or vapors.

c) To comply with paragraph (b), catastrophic explosion due to ignition of fuel or vapors must be extremely improbable and not result from a single failure, a hazardous explosion due to ignition of fuel or vapors must be extremely remote, taking into account all factors, including;

   1) Emission of explosive or toxic gases
   2) Minimum ignition energy
   3) Static electricity
   4) Electrical faults
   5) Over pressurization of reactant storage vessels
   6) Mechanical ignition sources

7) Electromagnetic waves
8) Lightning strikes
9) Fire
10) Heat emission

d) To comply with paragraph (c)(8) the following must be taken into account
   1) Direct lightning strikes to areas having a high probability of stroke attachment;
   2) Swept lightning strokes to areas where swept strokes are highly probable; and
   3) Lightning-induced or conducted electrical transients

e) Hydrogen leakage detection must be installed in any area of the airplane where hydrogen may accumulate and create a hazardous condition.

f) Fuel cell system installation must not damage surrounding structure of adjacent systems, equipment, or electrical wiring from corrosive fluids or gases that may escape in such a way as to cause a hazardous condition.

g) The fuel cell system must have a failure sensing and warning system to alert the flightcrew if its failure affects safe operation of the airplane

h) The design and installation of the reactant supply must prevent hazardous conditions due to improper handling by crewmembers, passengers, and maintenance and servicing personnel.

i) The fuel cell system must be designed to prevent hazardous hydrogen permeation and embrittlement of aircraft materials and structure, or otherwise to not have an adverse effect on the strength of materials or the flammability properties of materials.

j) Means must be available for controlling or extinguishing a fire, such as stopping flow of fluids, gasses, or vapors, shutting down equipment, fire containment, or use of extinguishing agents.

k) To protect fuel cell system design features that prevent catastrophic failures caused by all probable causes, the type design must include critical design configuration control limitations (CDCCLs) identifying those features and providing information to protect them. To ensure the continued effectiveness of those design features, the type design must also include inspection and test procedures, intervals between repetitive inspections and tests, and mandatory replacement times for those design features used in demonstrating compliance to paragraph (b) of this section. The applicant must include the information required by this paragraph in the Airworthiness Limitations section of the Instructions for Continued Airworthiness required by § 25.1529.

l) The effect of fuel cell system operation on the cabin air must be assessed in normal operation and failure cases in order to show compliance to CS/CFR § 25.831 (a)(b)(c).

m) Storage or disposal of by-products, such as water and oxygen depleted air, must not introduce hazardous conditions.

n) Hydrogen pressure tanks, and lines between tanks and the shutoff means must be—

   1) Protected from unsafe temperatures; and

   2) Located where the probability and hazards of rupture in a crash landing are minimized.

o) Each fuel cell system fuel line within the fuselage must be designed and installed to allow a reasonable degree of deformation and stretching without leakage where its leakage could introduce a hazard.

G.4.2 Background on the Proposal of the New Regulation 25.XXX Hydrogen Fuel Cell System Safety: Relation of Regulatory Standards to Safety Concerns

This section describes the relationship between the proposed baseline regulation paragraphs and the relevant safety issues discussion in Appendix F of this report.

(a) “Definition of Fuel Cell System”

The proposed definition of fuel cell system contained in (a) reflects, with some variation, the one used by the industry.

(b) “The design and installation of a Fuel Cell System must prevent catastrophic explosion due to ignition of fuel or vapors.”

A fuel cell system typically introduces hazards that are not yet commonly known in aviation, mostly to deal with the used reactants (e.g., hydrogen and oxygen). Hence the reference to ignition of fuel vapors. The wording chosen here is what we think is adequate according to current rulemaking practices.

The reason to introduce this specific paragraph is linked to the hazards as identified in sections F2.1, F2.2, F3.3, F3.4, F4, F5, F9.2, F2.3.1.1, F2.3.1.2, and F2.3.3 of Appendix F. Currently we know paragraphs in CFR/CS 25 that relate to this proposed paragraph. These are identified as §§ 25.863, 25.981, 25.1183, 25.1185, 25.1189(a).

(c) “To comply with paragraph (b), catastrophic explosion due to ignition of fuel or vapors must be extremely improbable and not result from a single failure, taking into account all factors that could cause a catastrophic explosion, including….”

Paragraph (c) provides a number of factors that must be considered when demonstrating that a catastrophic explosion due to ignition of fuel or vapors is extremely improbable. The list is not meant to be exhaustive and other factors may need to be addressed. This will depend on the specific design characteristics of the fuel cell system at hand.

1. <u>Emission of explosive or toxic gases</u>. The background can be found in the identified hazards per sections F2.2.9, F2.2.10, F2.2.11, F2.2.12, F2.2.13, F3.1.1, F3.2, F4 of

Appendix F. Failure modes of the FCS can lead to emission of explosive or toxic gases, see sections C.4.11, C.5.10, and C.7.9. The current CFR/CS 25 regulations §§ 25.1441, 25.1450, 25.863, 25.963, 25.965, 25.1183, 25.1185(c), 25.1453, 25.1707, 25.1723, 25.1723 are also related to this item.

2. Minimum ignition energy. The background per hazard sections F2, F9, F2.3.1 of Appendix F. The current CFR/CS 25 regulations §§ 25.981, 25.1183, 25.1185, and 25.1723 are also related to this item.
3. Static electricity. The background can be found per hazard sections F10, F4, F2.3.1of Appendix F The current CFR/CS 25 regulations §§ 25.899, 25.1715 are also related to this item.
4. Electrical faults. The background can be found per hazard sections F10, F4, F2.3.1of Appendix F. The current CFR/CS 25 regulations §§ 25.863(b)(3), CS 25.1353(e), 25.1723 are also related to this item.
5. Over pressurization of reactant storage vessels. The background can be found per hazard section F8.1 of Appendix F. The current CFR/CS 25 regulations §§ 25.601, 25.603 are also related to this item.
6. Mechanical ignition sources. The background can be found per hazard section F2.3.2 in Appendix F. Depending on the technology used, the FC Stack can be sensitive to mechanical damage and release flammable/explosive gases as a result, for instance SOFC, see section C.7.9. The current CFR/CS 25 regulations §§ 25.863, and 25. 981are also related to this item.
7. Electromagnetic waves. The background can be found per hazard section F2.3.1.9, F2.3.1.10 of Appendix F. The current CFR/CS 25 regulations §§ 25. 981 (a), 25.1435, 25.1703, and 25.1707 are also related to this item.
8. Lightning strikes. The background can be found per hazards sections F2, F2.3.1.7of Appendix F. The current CFR/CS 25 regulations §§ 25.581, 25.954, 25. 981, and 25.1316 are also related to this item.
9. Fire. The background can be found per hazards sections F2.2.1, F9.2, F4 of Appendix F. The current CFR/CS 25 regulations §§ 25.853, 25.863, 25.865, 25.867, and 25.869 are also related to this item.
10. Heat emission. The background can be found per hazards due to fire and high operating temperatures for specific types of FCS. The current CFR/CS §§ 25.855(g), 25.863, 25.867.

(d) "To comply with (c)(8) the following must be taken into account . . ."

This proposed regulation is based on the current § 25.954 "Fuel System Lightning Protection". Like a fuel system for engines, the fuel cell system is vulnerable for the effects of a lightning strike. This can be due to direct effects, but also to indirect effects like induced or conducted transients. The current § 25.954 only addresses this for the fuel system for power plants (engines.)

The current 25.1316 “Electrical and electronic system lightning protection” and 25.1317 “HIRF protection” are generally valid, so also for the new fuel cell systems.

Background for inclusion can be found in the hazards sections F3.1.1, F4, F10.1, and F11 of Appendix F. Current CFR/CS 25 regulations related to this are §§ 25.581, 25.899, 25.954, 25. 981, 25.1316 and 25.1317.

(e) “Hydrogen leakage detection must be installed in any area of the airplane where hydrogen may accumulate and create a hazardous condition”

Hydrogen will not be detected by humans as it does not smell, nor does it have a color. In areas where hydrogen could accumulate and create a catastrophic explosion, means of detection are needed. For more information see section F2.2.4, F2.2.6, F2.2.9of Appendix F.

(f) Fuel cell system installation must not damage surrounding structure of adjacent systems, equipment, or electrical wiring from corrosive fluids or gases that may escape in such a way as to cause a hazardous condition. Like other ESD, the FCS uses different fluids and / or gases that, when escaping from the system, may cause damage and consequential failures of surrounding structural elements, equipment or EWIS components. The same type of regulation is currently used for specific types of batteries. For more information see section F3, F4 and F.6 of Appendix F. Current CFR/CS 25 regulations related to this new regulation are §§ 25.831, 25.1353, 25.1529, and 25.1541.

(g) “The fuel cell system must have a failure sensing and warning system to alert the flightcrew if its failure affects safe operation of the airplane.”

Some of the failure cases of the fuel cell system can have an adverse effect on the safe operation of the aircraft. These failure cases can be related to the function the fuel cell system contributes to, or failures related to the fuel cell system, own functioning. Next to this, failures of the fuel cell system can also affect other systems or structures in its environment influencing safe operation. All these cases should be analyzed to determine if the flight crew should be alerted. The warning should be in accordance with CFR/CS § 25.1322.

(h) “The design and installation of the reactant supply must prevent hazardous conditions due to improper handling by crew members, maintenance, passengers, or servicing personnel.”

This regulation is in line with the current practices in CFR/CS 25. It intends to address hazards like burns, freezes, etc. In the case of the fuel cell system, it not only addresses those parts of the system permanently installed in the aircraft, but also parts that are removable. For instance, when an empty reactant vessel is exchanged for a full one, or is brought on board in some kind of container that is attached to the piping of the fuel cell system. This regulation is in accordance with similar regulations regarding protection of crew members, maintenance, passengers, or servicing personnel for other identified hazards (i.e. electrical shock.) Reference CFR/CS § 25.1360.

(i) "The fuel cell system must be designed to prevent hazardous hydrogen permeation and embrittlement of aircraft materials and structure, or otherwise to not have an adverse effect on the strength of materials or the flammability properties of materials."

Hydrogen is highly diffuse and can penetrate many materials. This can lead to changes in the characteristics of the material it has entered. Examples are flammability characteristics and structural integrity of materials. The latter needs consideration in combination with the possible permeation in primary or secondary structural elements of the aircraft. See section F3.1.1 of Appendix F. Current regulations CFR/CS §§ 25.571, 25.601, and 25.603 support this issue.

(j) "Means must be available for controlling or extinguishing a fire, such as stopping flow of fluids, gasses, or vapors, shutting down equipment, fire containment, or use of extinguishing agents."

Next to the risks of explosion, the risk of fire needs to be addressed as well. Hydrogen fire is barely visible. A Hydrogen fire does not radiate a lot of heat. This makes a detection difficult, but necessary. The temperature is high; therefore, a Hydrogen fire can easily combust other materials in its reach. The means to detect and extinguish a Hydrogen fire can be different for several FCS, its function and location in the airframe.

Apart from the Hydrogen, the fuel cell system itself can cause a fire. I.e. if the fuel cell operates at high temperature. Other risks should be analyzed and measures taken accordingly. As example, such a risk could be the due to the use of a reformer to get Hydrogen from jet fuel. If the FCS uses a reformer, it is expected that the fuel used by the FCS will be the jet fuel already in use for the propulsion system and CFR/CS § 25.1181 should be considered.

However, most of the fuel cell system does not need to comply with CFR/CS § 25.1181 and therefore will need to be installed in a zone where means to protect the airplane from the hazardous effects of fire may be required. These means may differ from the fire protection means for designated fire zones as currently defined within the CS and FAR regulation.

See for instance F6, F5, F9, F2.3.2, F2.3.3, F2.3.3.1 of Appendix F.

(k) "To protect fuel cell system design features that prevent catastrophic failures caused by all probable causes, the type design must include critical design configuration control limitations (CDCCLs)…."

This requirement is similar § 25.981 for fuel tanks (reference). For a FCS, the need for CDCCL or other airworthiness limitations should be analyzed.

(l) "The effect of fuel cell system operation on the cabin air must be assessed in normal operation and failure cases in order to show compliance to CS/CFR § 25.831 (a)(b)(c)."

Oxygen is available in normal air. Therefore, it is not necessary for a fuel cell system to include dedicated O_2 storage when used as one of the reactants. In case the O_2 is taken from the air inside the aircraft, a thorough analysis should first be made that the required amounts by the FCS allow enough oxygen in the air for crew members and passengers.

Hydrogen will not be detected by humans as it does not smell, nor does it have a color. In certain amounts, it can be harmful to humans. The explosion risk should be considered when Hydrogen when the possibility exists to accumulate Hydrogen in certain areas.

The current CFR/CS 25 regulation that are supporting this is § 25.831.

(m) "Storage or disposal of by-products, such as water and oxygen depleted air, must not introduce hazardous conditions."

In addition to electrical energy, a FCS produces some other products as well. For instance, water, heat, and oxygen depleted air. If fossil fuels are used as the original source of hydrogen there will be more by-products, such as carbon dioxide. The disposal or storage of these by-products, must not create new hazards and they should be properly addressed.

Current applicable regulations include CFR/CS §§ 25.831 and 25.1455.

(n) "Hydrogen pressure tanks, and lines between tanks and the shutoff means must be—

> **1) Protected from unsafe temperatures; and**
>
> **2) Located where the probability and hazards of rupture in a crash landing are minimized."**

The current regulations address the protection of oxygen equipment. Similarly, the hydrogen equipment needs protection as well. This needs to be addressed by a new regulation similar to CFR/CS § 25.1453 or a changed CFR/CS §25.1453 that next to oxygen also addresses hydrogen (or in the ideal case, it is made more general, and design details are provided in the guidance material.) The guidance material can point out to existing standards for such equipment. References to such standards can be found in Appendix D, where type III and IV vessels are identified as suitable for use on aircraft. However, this list might not be complete.

The current regulation related to crash landing loads is CFR/CS §§ 25.561, 25.562, and 25.563.

(o) "Each fuel cell system fuel line within the fuselage must be designed and installed to allow a reasonable degree of deformation and stretching without leakage where its leakage could introduce a hazard."

This requirement mirrors the existing regulations for fuel and main power cables, CFR/CS §§ 25.993(f) and 25.1703(c). The idea is that the fuselage can be damaged with partial separation or other structural damage without the hydrogen lines breaking apart. Allowing for a certain amount of stretching will help to minimize the probability of a hydrogen-fed fire and subsequent explosion inside the fuselage. As it is used in this recommendation, a "reasonable degree of deformation and stretching" should be about 10% of the length of the hydrogen line.

G.5 REVISIONS TO EXISTING REGULATORY STANDARDS

With a few exceptions for most of the proposed regulations in this section the changes will be minor wording revisions. Most proposed changes consist of adding references or FCS related terminology or technical specificities. The exceptions are the recommendation for a performance based requirement (section G.5.1) to replace the existing CFR/CS § 25.1353(b) and a new paragraph to CFR/CS § 25.1707 (section G.5.2).

G.5.1 Performance Based Requirement Applicable to All Energy Storage Devices

Electrical energy supply devices are continually changing to meet the needs of the More Electric Aircraft. Aircraft have used Lead Acid and Ni Cd batteries for years. These battery chemistries have been very reliable with known safety issues and mitigation techniques. Currently, the regulatory requirements for batteries are covered under 14 CFR § 25.1353(b)/ EASA CS § 25.1353(c). While the aerospace industry has a long history of using both primary and secondary batteries, it, like many industries, is moving to batteries with more energy dense electrolytes to reduce the size and weight of the battery system. There has been a great deal of work in standard organizations (e.g., RTCA, SAE, IEEE) to provide guidelines for the safe design, installation and operation of Lithium batteries. However, the current regulatory requirements contained in CFR § 25.1353(b)/CS § 25.1353(c) do not adequately address the unique safety issues associated with lithium based batteries. Therefore, the FAA and other aviation airworthiness authorities have issued Special Conditions to address the unique hazards of these batteries. The special conditions have been issued for both secondary or primary batteries; rechargeable and non-rechargeable.

Batteries and capacitors provide short term power storage on the aircraft and it is well understood on how to integrate them into a transport aircraft. There are many well established aerospace committees working to further refine the technical requirements for batteries and capacitors. The Committee felt hydrogen fuel cells would present the biggest challenge for integration and certification in an aircraft. Therefore, the Committee did not investigate these types of energy storage devices and instead concentrated on the design, installation, operation and safety issues associated with hydrogen fuel cells.

However, the Committee did develop a performance based requirement that is applicable to energy storage devices in general. If adopted, it could be applied to fuels cells, super capacitors, storage batteries of differing chemistries including those that are lithium based, and other types of energy supply devices. Adopting this recommendation would negate the need to continually develop and issue special conditions and also the need to revise it every time new ESD technologies are introduced in the aircraft.

14 CFR § 25.1353(b) / EASA CS 25.1353(c) (in lieu of the existing standard)

a) An energy supply/storage device, ESD, means any system installed on the airplane for the purposes of energy supply as required by systems or functions on the aircraft.

The ESD includes functions of energy storage, energy generation or discharging energy, refilling or recharging, and or jettisoning.

b) For the purposes of this rule, ‘energy’ means any type of energy for the functioning of, or coming from the ESD, including, for example, fuels of any kind or electric current.

c) The characteristics of the ESD, including failure modes, must be identified.

d) Failure of the ESD must not contribute to, or cause, a catastrophic effect on the airplane unless shown to be extremely improbably and not resulting from a single failure, or a hazardous effect on the airplane unless shown extremely remote.

e) In normal operation or foreseeable malfunction of the ESD, no explosive, toxic, or corrosive gases or fluids:

  1) May accumulate in hazardous quantities

  2) May damage structures or adjacent essential equipment or systems

  3) May endanger passengers or crew

f) Hazardous effects on structures or essential equipment or systems caused by the maximum amount of heat that can be generated during normal operation or probable malfunctions must be prevented.

g) The ESD as described in a), b) and c) must:

  1) Maintain safe operating temperatures, pressures, or any other identified parameter, during normal operation (including storage, generation/discharging, refilling/recharging and / or jettisoning)

  2) Provide, as necessary, means of protection, or controlling the ESD to prevent hazardous conditions during normal operation or probable malfunction. The flightcrew should be able to monitor, receive warnings, and control as appropriate.

h) The design and installation of the ESD systems must minimize Likely errors during ground handling of the airplane, the ESD, or its components, to prevent a hazardous event.

i) Instructions for continued airworthiness as required by §§ 25.1529 and 25.1729, must contain proper procedures including instructions on preventing the occurrence of any hazard to the ESD system, airplane, or to persons during refilling or recharging, and safe storage and exchange procedures of the ESD or its components if such a function / possibility is provided.

G.5.2 Identification of Current Part 25 Regulations that Require Revision

Table 19 identifies the CFR/CS part 25 regulations that the committee proposes to change, with the indication of the change. For each regulation, it is indicated what hazard the intended to address. These are indicated with a number, as given in the Table 18. The hazard identification number indicates the Appendix F section in which the hazard is discussed.

Table 18. Safety Risks

Hazard ID #	Safety Risks
F2	H_2 Fire & Explosion Risk
F3	Mechanical and Material Hazards
F4	Hazard Dependent on Application / Implementation
F5	Physiological Hazards
F6	Operational and Maintenance Hazard
F7	Hydrogen Fire Extinguishing
F8	Cryogenic Hazards
F9	Non-Hydrogen Fuel and Oxygen Hazards
F10	Electrical Hazards

Table 19. Identification of Current Part 25 Regulations that Require Revision

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
831	Ventilation	Galley power, APU, RAT, Main Battery, Medivac,	Add a subparagraph (b)(3) to address the maximum H_2 concentration limit.	F5/F10/F7 Hazard of asphyxiation, harmful chemical generation. Noxious gases generated in case of fire. Leakages in system due to possible failures like cell reversal or brittle fracture of ceramic electrolyte. See also C.4.11, C.5.10, and C.7.9	• AMC 25.831 • AC 20-32B • AC 25-9A • AC 25-16 • AC 25-795-3 • PM ANM-03-112-06 • PS-ANM100-2000-00103
869	Fire protection: systems	Galley power, APU, RAT, Main Battery, Medivac,	Add a new subparagraph (d) for Hydrogen lines in equivalence with existing (c) for O_2 lines.	F2/F4/F9/F10/F7 (Auto-) ignition or combustion of Hydrogen, fire risk, different ways of Hydrogen fire and explosion risks. See also C.4.11, C.5.10.	• AMC 25.869 • AC 25-869-1A

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
901(c)(d)	Installation	APU, Medivac	The basic intent of the requirement is correct. “Fuel cell system” could be added behind Auxiliary power unit	F2/F3/F4/F9/F10/F7 Rapid release of pressure	• AC 20-144 • AC 20-128A • AC 25-16 • AC 25.981-1C
951(a)	General	All	Proposal to extend the wording in this regulation as needed to say Fuel / Reactant supply system	F6 High load and a starved fuel supply could lead to stack damage, with some follow consequences	
952(a)	Fuel system analysis and test	All	Proposal to extend the wording in this regulation as needed with "Fuel / Reactant Supply System"	F6 High load and a starved fuel supply could lead to stack damage, with some follow consequences	
952(b)	Fuel system analysis and test	All	Proposal to extend the wording in this regulation as needed with "Fuel / Reactant Supply System"	F2/F9/F7	

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
955(a)	Fuel flow	Galley Power, APU, RAT, Main Battery, Medivac	The relevant parts of this requirement should be reworded for the fuel cell system. Or the relevant parts included in the fuel cell system safety baseline regulation presented in section G.4 1 Change the wording to "Fuel / reactant supply system." The listing in "Compliance must be shown as follows" is very system dependant and need to be reviewed and changed or deleted.	High load and a starved fuel supply could lead to stack damage, with some follow-on consequences.	

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
955(b)	Fuel Flow	Galley Power, APU, RAT, Main Battery, Medivac	Proposed wording to cover fuel cell system: Add a new (b)(3): If a fuel cell stack can be supplied with reactants from more than one reactant tank, the reactant supply system. ”- For each fuel cell stack, in addition to having appropriate manual switching capability, be designed to prevent interruption of reactant flow to that stack, without attention by the flight crew, when any tank supplying reactants to that stack is depleted of usable reactants during normal operation, and any other tank, that normally supplies reactants to that stack alone, contains usable reactants.	High load and a starved fuel supply could lead to stack damage, with some follow consequences.	
957	Flow between interconnected tanks	All	Needs to be rewritten: Replace fuel by fuel / reactants	High load and a starved fuel supply could lead to stack damage, with some follow consequences	

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
959	Unusable fuel supply	All	Needs to be rewritten: Replace fuel by fuel / reactants and engine by engine & fuel cell system	F6 Fuel starvation during operation should be prevented to, as this can damage the stack, like cell reversal, or fast degradation.	
963(a)(d)	Fuel tanks: general	All	Revision needed: Replace the word “fuel’ with the phrase “fuel / reactant” Each fuel cell system supplying fuel/reactant tank must be able to withstand without failure, the vibration, inertia, fluid, and structural loads that it may be subjected to in operation	F3/F4/F6 While considering the crashworthiness aspects of the fuel cell system and its concerned parts, the applicable elements in 25.721 and 25.994 should be taken into consideration.	• AC 20-128A • AC 25-30 • AC 25-994-1
967(a)	Fuel tank installations	All	Revision is needed: Replace fuel by fuel / reactant	F3/F4/F6	
967(b)	Fuel tank installations	All	Revision is needed: replace drain holes by drain and ventilation holes	F2/F9/F7	
967(e)	Fuel tank installations	All	Revision is needed: replace fuel-proof by fuel/reactant-proof	F5/F7	

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
1187(e)	Drainage and ventilation of fire zones	Galley Power, APU, RAT	As for designated fire zone, needs to be addressed in fuel cell system safety baseline regulation (section G.4.1.) In drafting the new regulation, it must be noted that, there is little probability to extinguish a hydrogen fire with an agent.	F2/F5/F6	
1189(b)	Shutoff means	All	Propose to add following for fuel cells: The closing of any reactant shutoff valve for any fuel cell stack may not make reactants unavailable for the remaining stacks. Or leave it only in the new regulation: the new regulation includes wording on means to shut-off (see section G.4.1.)	F2/F7/F8/F6 Fuel starvation can lead to cell reversal.	• AC 20-135 • AC 20-128A • AC 25-994-1 • AC 25.1435-1
1189(e)	Shutoff means	All	This regulation is applicable for fuel cell systems. Replace the word “drain” with the phrase “drain or vent.”	F2/F7/F9 SOFC use coolants like oil due to high temperature operation	• AC 20-135 • AC 20-128A • AC 25.994-1 • AC 25.1435-1

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
1435(a), (b), (c)	Hydraulic Systems	All	A similar regulation for high pressure H_2 storage vessels needs to be developed.	F3/F6 If the FC stack operate under pressure, should be designed accordingly. See C.4.11, C.5.10, and C.7.9	• AC 25-16 • AC 25.1435-1
1436(a), (b), (c)	Pneumatic systems — high pressure	All	And the Appendix L of CS 25, which has no FAA equivalent. A similar regulation applicable for the high-pressure parts of a fuel cell system should be written.	F4/F6/F7 If the FC stack operates under pressure, should be designed accordingly. See C.4.11, C.5.10, and C.7.9	
1438	Pressurization and low pressure pneumatic systems	All	A similar regulation applicable for the high-pressure parts of a fuel cell system should be written.	F4/F6/F7	
1557(b)	Miscellaneous markings and placards	All	Revise to account for H_2 fuel refilling. This could be accomplished by replacing the word “fuel” with “fuel and reactants”	F6	
1705(b)	Systems and functions: EWIS	Galley Power, APU, RAT, Main Battery, Medevac	Add reference to § 25.XXX *Hydrogen Fuel Cell System Safety*.	F2-F10	• AC 25.1362-1

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
1707	System separation: EWIS	Galley Power, APU, RAT, Main Battery, Medevac	Proposal to add a new paragraph (m) based on existing para (g) for O_2 “Except to the extent necessary to provide electrical connection to hydrogen storage components and lines, EWIS must be designed and installed with adequate physical separation from hydrogen lines and other hydrogen system components, so that an EWIS component failure will not create a hazardous condition.” Or based on 25.1707(e) (fuel lines and fuel system components): Except to the extent necessary to provide electrical connection to the fuel systems components, the EWIS must be designed and installed with adequate physical separation from fuel lines and other fuel system components, so that: (1) An EWIS component failure will not create a hazardous condition. (2) Any fuel leakage onto EWIS components will not create a hazardous condition.	F4	• AC 25-795-7 • AC 25.1353-1A

CFR/CS § 25.XXX	Title of Regulation	Applications	Necessary Revisions & Comments	Address which Hazard?	AC / Policy Memorandum
1723	Flammable fluid fire protection: EWIS	Galley Power, APU, RAT, Main Battery, Medevac	Revise this regulation to add flammable gas (i.e., for the H_2 gas). So, it would say: "…in each area where flammable fluid, gas, or vapors might escape..."	F2/F9/F7	•
1727	Flammable fluid shutoff means: EWIS	Galley Power, APU, RAT, Main Battery, Medevac	Revise this regulation to add flammable gas shutoff means (i.e., for the H_2 gas)	F4	•

G.6 CURRENT CFR/CS 25 REGULATIONS APPLICABLE TO FUEL CELL SYSTEMS THAT DO NOT REQUIRE REVISION

Table 20. Current CFR/CS 25 Regulations Applicable to Fuel Cell Systems that Do Not Require Revision

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
23	Load distribution limits.	ALL	Specific Structural requirements for ESD need to be developed. No need to change, generically applicable on aircraft level. H_2, O_2 consumption, production of H_2O.	F3/F6	• Appendix K of CS 25

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
301	Loads	Galley power, APU, RAT, Main Battery, Medevac		F3	
302	Interaction of systems and structures	Galley power, APU, RAT, Main Battery, Medevac	No need to change, generically applicable on aircraft level.	F3/F4 Embrittlement. Structural Loads.	
561	General	Galley power, APU, RAT, Main Battery, Medevac	The hydrogen tank and fuel cell system installation shall be able to withstand the expecting loads in case of an emergency landing. No need to change, generically applicable on aircraft level.	F3/F4	• AC 25-30
581	Lightning protection	Galley power, APU, RAT, Medevac	Consideration is relevant in relation to hydrogen tank and tubing ignition prevention from direct and indirect effects of lightning strike. Direct lightning effects will have an influence on the elements which connect the tank. Pure hydrogen does not react to electrical currents. Regions where it is mixed with air are susceptible to ignition effects. The proper bonding and grounding should be implemented including vent lines, and exhaust. No need to change, generically applicable on aircraft level.	F10/F7	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
601	General	Galley power, APU, RAT, Medevac	Specific Structural requirements for ESD need to be developed. No need to change, generically applicable on aircraft level. Guidance material might be necessary for fuel cell systems.	F3/F4	• AC 25-16
603	Materials	Galley power, APU, RAT, Main Battery, Medivac,	No regulatory change is needed. AC revision will be necessary. This requirement is used for aircraft structures only. The fuel cell systems include vessels containing the Hydrogen which are often (partially) made of composite materials. The AMC 20-29 / AC 20-107 is applicable, but should be reviewed and changed to support these kinds of vessels.	F3/F8 The usage of composite materials in fuel cell systems that might pose an advert risk to the aircraft when failing. For instance, brittle fracture of ceramic electrolyte (section C.7.9), membranes failure modes (section C.5.10)	• AC 25-16 • AC 20-107 • See AMC 25.603: for • Composite Materials see AMC • 20-29
611	Accessibility provisions	Galley power, APU, RAT, Medivac	This requires the necessary inspections and maintenance tasks. No need to change, generally applicable on aircraft level.	F6	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
734	Protection against wheel and tyre failures NOTE: CS 25 only. There is no CFR part 25 equivalent regulation	All	No need to change, generally applicable on aircraft level.	F3/F4 (F5) Rapid Release of Pressure from hydrogen vessels Protection of pressure systems of the FCS in general	• AMC 25.734
777	Cockpit controls	Galley Power, APU, RAT, Main Battery, Medivac,	No change necessary.	F4/F6	• AC 20-175
789	Retention of items of mass in passenger and crew compartments and galleys	Galley power, Medivac,	No need to change, generally applicable on aircraft level.	F4	
795(c)(1) 795(c)(2)	Security considerations	Galley power, APU, RAT, Main Battery, Medivac,	No need to change, generally applicable on aircraft level. Discussed with the Cabin Safety expert, should be applicable. Guidance material is available regarding this requirement, to be checked if this applies and / or should be altered.	F4	• AC 25-795-3 • AC 25-795-7 • AC 25-795-9

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
851(a)(5) (a)(6) (a)(7) (a)(8) (b)	Fire extinguishers	Galley power, APU, RAT, Main Battery, Medivac		F2/F9	• AC 20-144 • AC 120-80A
853	Compartment interiors	Galley power, Medivac		F3	• AC 25-16
863	Flammable fluid fire protection	Galley power, APU, RAT, Medivac	No need to change, generally applicable on aircraft level.	F2/F9	• AC 20-135 • AC 25.981-1C • AC 25-994-1 • AC 25.1435-1
865	Fire protection of flight controls, engine mounts, and other flight structure	Galley power, APU, RAT	As stated in the document FCS maturity of the WG 80: Applicable if fuel cell systems are installed adjacent to designated fire zones.	F3	• AC 25-16
899	Electrical bonding and protection against static electricity	Galley power, APU, RAT	No need to change, generally applicable on aircraft level.	F10	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
903(b)(f)	Engines	APU	Should be explained what intent is for fuel cell system What about other sub requirements? (f) depending whether system support non-essential / essential APU	F3/F4	• AC 20-135 • AC 20-128A • AC 25-16 • AC 25.1435-1
943	Negative acceleration	APU	Applicable in case fuel cell is used as part of the power plant system or APU.	F3/F4/F6	• AC 25.1435-1
965	Fuel tank tests	All		F3	
1181	Designated fire zones; regions included	All;	A fuel cell is not combustion engine, but some work with high temperatures (e.g., SOFC)	-	• AC 20-135
1183(a), (b), (c)	Flammable fluid-carrying components	Galley power, APU, RAT, Medevac		F2/F4/ F7/F9 Some FCS use different coolants than water, for instance synthetic oils for SOFC.	• AC 25.1435-1
1185(a)	Flammable fluids	Galley power, APU, RAT, Medevac		F4	• AC 20-135 • AC 25.1435-1

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1187(a), (b), (c), (d)	Drainage and ventilation of fire zones	Galley power, APU, RAT, Medevac		F2/F7/F9 Some FCS use different coolants than water, for instance synthetic oils for SOFC.	
1189(a)	Shutoff means	All	The advisory material to the new fuel cell system safety baseline regulation should include wording on means to shut-off, as one of the possibilities regarding the new regulation j) (see section G.4.1.)	Some FCS use different coolants than water, for instance synthetic oils for SOFC.	
1191	Firewalls	All	Applicable for FCS, e.g. for reformer, SOFC	F4	• AC 20-135 • AC 20-128A • AC 25-994-1 • AC 25.1435-1
1301	Function and installation	ALL		F4 See also sections C.4.11, C.5.10, and C.7.9	• AC 20-144 • AC 25.795-9 • AC 25.981-1C • AC 25.1301-1A • AC 25.1435-1
1302	Installed systems and equipment for use by the flight crew	ALL		F4	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1309	Equipment, systems, and installations	ALL		F3/F4 See also sections C.4.11, C.5.10, and C.7.9	• AC 25-16 • AC 25-795-7 • AC 25.795-9 • AC 25.981-1C • AC 25.1435-1
1310	Power source capacity and distribution	APU, Main Battery, RAT, Medivac		F10	
1315	Negative acceleration	All	CS 25 only. No 14 CFR part 25 equivalent	Should not lead to failures of pressure vessels, starvation of fuel for FC stacks, or any other operational failure.	• ANM 25.1315
1316	Electrical and electronic system lightning protection	All		F10	• AC 25.981-1C • AC 20-136B • AC 20-155A.
1317	High-intensity Radiated Fields (HIRF) Protection	All		F10	• AC 20-158A
1322	Flightcrew alerting	ALL		F6	• AC 25.795-9 • AC 25.1435-1

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1351	General	All		F10	• AC 25.16
1355	Electrical equipment and installations	ALL		F10	
1357	Circuit protective devices	ALL		F10	• AC 25-16 • AC 25.1353-1A
1360	Precautions against injury	ALL		F4/F10	• AC 25.1360-1
1362	Electrical supplies for emergency conditions	APU, Rat, Main Battery		F10	• AC 25.1362-1
1363	Electrical system tests	APU, Rat, Main Battery		F10	• AC 25.16
1365	Electrical appliances, motors, and transformers	Galley Power, Medevac		F10	
1431	Electronic equipment	ALL		F10	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1436	Pneumatic systems – high pressure	ALL	CS 25 only. No 14 CFR part 25 equivalent.	F4/F6/F7 If the FC stack operate under pressure, should be designed accordingly. See C.4.11, C.5.10, and C.7.9	
1441(b)	Oxygen equipment and supply	ALL		F9	
1450	Chemical oxygen generators	ALL		F9	• AC 25.795-9
1453	Protection of oxygen equipment from rupture	ALL		F9	
1455	Draining of fluids subject to freezing	ALL		F4/F6	• AC 25.1455-1
1527	Ambient air temperature and operating altitude.	All		F5/F6 Depending FCS type, certain temperature delta’s during operation should be avoided to prevent degradation.	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1529	Instructions for Continued Airworthiness	ALL		F6	• Order 8110.54A • AC 25-16 • AC 25.981-1C • AC 25-27A
1535	ETOPS approval. CMP	APU, RAT, Main Battery	ETOPS approval. CMP	-	• AC 120-42B
1541	General	APU, RAT, Main Battery		F4	• 25.1435-1
1553	Fuel quantity indicator	APU		F6 High load and a starved fuel supply could lead to stack damage, with some follow consequences.	
1555	Control markings	APU, RAT, Main Battery		F6	
1581	General	ALL		F6	
1585	Operating procedures	ALL		F6 In coordination with hydrogen hazards and certain failure modes of the FCS (see sections C.4.11, C.5.10, and C.7.9)	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1701	Definition	Galley Power, APU, RAT, Main Battery, Medevac		F10	• AC 25-1701-1
1703	Function and installation: EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F4/F10	• AC 25.1353-1A
1709	System safety: EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F3/F4/F10	
1711	Component identification; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F4	• AC 25.1353-1A
1713	Fire Protection; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F2/F9/F10	
1715	Electrical bonding and protection against static electricity; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F10	
1717	Circuit protective devices; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F10	• AC 25.1353-1A
1719	Accessibility Provisions; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F6	
1721	Protection of EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F10	

CFR/CS § 25.XXX	TITLE of REGULATION	APPLICATION	COMMENTS	ADDRESS WHICH HAZARD?	AC / POLICY MEMORANDUM
1729	Instructions for Continued Airworthiness; EWIS	ALL		F6	• Order 8110.54A • AC 25-16 • AC 25.981-1C • AC 25-27A
1731	Powerplant and APU fire detector system; EWIS	Galley Power, APU, RAT, Main Battery, Medevac		F3	
1733	Fire detector systems, general: EWIS	Galley Power, APU, RAT, Main Battery, Medevac	CS 25 does not contain 25.1733, however, the technical equivalent of this requirement is CS 25.1705(2) & (3)	F10	

G.7 ADVISORY MATERIAL FOR FUEL CELL SYSTEMS AND OTHER ESD

The tables in sections G.5.2 and G.6 indicate the Advisory Material that is currently available in relation to the identified applicable regulations. In accordance with the decision on revising the regulation, the corresponding advisory material should be updated accordingly.

The proposed new regulation, § 25.XXX Fuel Cell System Safety, clearly needs accompanying guidance material. Section G.4.2 gives a short overview what could be discussed in an AC, as this indicates the background and hazards that are addressed by the proposed regulation. In addition, the tables in Sections G.5.2 and G.6 in the column addresses which hazard could be used in the development of advisory material.

The guidance material should also reference those standards that help towards a safe design of the FCS or its individual components. For instance, the standards for hydrogen vessels as listed in section D.5.1. The SAE and EUROCAE have dedicated working groups for FCS in aviation. The documents produced by these groups should be acceptable for compliance finding as well and as such be discussed in the developed advisory material.

The introduction of a performance based regulation to replace the existing prescriptive regulation on storage batteries, needs the development of advisory material. Parts of the current CFR § 25.1353(b)/CS 25.1353(c) that prescribe how the different battery types should be installed feed into such advisory material.

Currently most aviation authorities use special conditions for rechargeable and non-rechargeable Li battery and battery systems. These are prescriptive of nature, and the very Lithium battery specific elements in these special conditions should be incorporated in the advisory material. The means of compliance that is published with these special conditions should also feed in the to be developed advisory material.

The proposed revision to CFR § 25.1353(b)/CS 25.1353(c) is written to help streamline future certification of new ESD systems. As stated previously, the Committee has focused on hydrogen fuel cell systems. However, advisory material for other ESDs should be based on the works of the various standard's committee that are investigating these ESDs.

G.8 14 CFR OPERATIONAL REGULATIONS APPLICABLE TO FUEL CELL SYSTEMS

Table 21. 14 CFR Operational Regulations Applicable to Fuel Cell Systems

14 CFR	Description	Notes
PART 43 – MAINTENANCE, PREVENTIVE MAINTENANCE, REBUILDING, AND ALTERATION		
§ 43.3	Persons authorized to perform maintenance, preventive maintenance, rebuilding, and alterations.	
§ 43.5	Approval for return to service after maintenance, preventive maintenance, rebuilding, or alteration.	
§ 43.7	Persons authorized to approve aircraft, airframes, aircraft engines, propellers, appliances, or component parts for return to service after maintenance, preventive maintenance, rebuilding, or alteration.	
§ 43.9	Content, form, and disposition of maintenance, preventive maintenance, rebuilding, and alteration records (except inspections performed in accordance with part 91, part 125, §135.411(a)(1), and §135.419 of this chapter).	
§ 43.10	Disposition of life-limited aircraft parts.	
§ 43.11	Content, form, and disposition of records for inspections conducted under parts 91 and 125 and §§135.411(a)(1) and 135.419 of this chapter.	
§ 43.13	Performance rules (general).	
§43.16	Airworthiness limitations.	
PART 91 – GENERAL OPERATING AND FLIGHT RULES		
§91.205 (c) (5)	Powered civil aircraft with standard category U.S. airworthiness certificates: Instrument and equipment requirements.	
§91.503 (b)(7) & (c)1-4	Flying equipment and operating information.	
PART 121 – OPERATING REQUIREMENTS: DOMESTIC, FLAG, AND SUPPLEMENTAL OPERATIONS		
§121.105	Servicing and Maintenance Facilities.	
§121.133	Manual Requirements – Preparation.	
§121.135	Manual contents.	
§121.162	Aircraft Requirements, ETOPS Type Design Approval Basis.	
§121.219	Special Airworthiness Requirements - Ventilation	OEM to provide Specific requirements for ESD for operators to follow

14 CFR	Description	Notes
§121.221	Special Airworthiness Requirements - Fire Precautions	OEM to provide Specific requirements for ESD for operators to follow
§121.223	Special Airworthiness Requirements - Proof of Compliance with §121.221	OEM to provide Specific requirements for ESD for operators to follow
§121.227	Special Airworthiness Requirements - Pressure cross-feed arrangements	OEM to provide Specific requirements for ESD for operators to follow
§121.229	Special Airworthiness Requirements - Location of Fuel Tanks	OEM to provide Specific requirements for ESD for operators to follow
§121.231	Special Airworthiness Requirements - Fuel Line Systems and Fittings	OEM to provide Specific requirements for ESD for operators to follow
§121.233	Special Airworthiness Requirements - Fuel lines and fittings in designated fire zones	OEM to provide Specific requirements for ESD for operators to follow
§121.235	Special Airworthiness Requirements - Fuel valves	OEM to provide Specific requirements for ESD for operators to follow
§121.245	Special Airworthiness Requirements - Fire Walls	
§121.247	Special Airworthiness Requirements - Fire Wall Construction	
§121.253	Special Airworthiness Requirements - Powerplant fire protection	
§121.255	Special Airworthiness Requirements - Flammable liquids	Specific requirements for ESD need to be developed
§121.257	Special Airworthiness Requirements - Shutoff Means	Specific requirements for ESD need to be developed
§121.259	Special Airworthiness Requirements - Lines and Fittings	Specific requirements for ESD need to be developed
§121.261	Special Airworthiness Requirements - Vent and drain lines	Specific requirements for ESD need to be developed
§121.263	Special Airworthiness Requirements - Fire-extinguishing systems	Specific requirements for ESD need to be developed
§121.265	Special Airworthiness Requirements - Fire-extinguishing agents	Specific requirements for ESD need to be developed
§121.267	Special Airworthiness Requirements - Extinguishing agent container pressure relief	Specific requirements for ESD need to be developed

14 CFR	Description	Notes
§121.269	Special Airworthiness Requirements - Extinguishing agent container compartment temperature	Specific requirements for ESD need to be developed
§121.271	Special Airworthiness Requirements - Fire Extinguishing systems material	Specific requirements for ESD need to be developed
§121.273	Special Airworthiness Requirements - Fire-detector systems	Specific requirements for ESD need to be developed
§121.275	Special Airworthiness Requirements - Fire Detectors	Specific requirements for ESD need to be developed
§121.277	Special Airworthiness Requirements - Protection of other airplane components against fire	Specific requirements for ESD need to be developed
§121.313	Instrument and Equipment requirements - Miscellaneous equipment	Specific requirements for ESD need to be developed
§121.363	Maintenance, Preventative Maintenance and Alterations; Responsibility for Airworthiness	
§121.365	Maintenance, Preventative Maintenance and Alterations - Maintenance, preventive maintenance, and alteration organization.	
§121.367	Maintenance, Preventative Maintenance and Alterations; Maintenance, preventive maintenance, and alterations programs.	
§121.369	Maintenance, Preventative Maintenance and Alterations - Manual requirements	
§121.371	Maintenance, Preventative Maintenance and Alterations - Required inspection personnel	
§121.373	Maintenance, Preventative Maintenance and Alterations - Continuing analysis and surveillance	
§121.374	Maintenance, Preventative Maintenance and Alterations - Continuous airworthiness maintenance program (CAMP) for two-engine ETOPS	
§121.375	Maintenance, Preventative Maintenance and Alterations - Maintenance and preventive maintenance training program.	
§121.379	Maintenance, Preventative Maintenance and Alterations - Authority to perform and approve maintenance, preventive maintenance, and alterations.	
§121.380	Maintenance, Preventative Maintenance and Alterations - Maintenance recording requirements.	
§121.401	Training Program - General information	
§121.407	Training Program - Approval of airplane simulators and other training devices.	

14 CFR	Description	Notes
§121.1003	Hazardous Materials Training Program – General information	
§121.1005	Hazardous Materials Training Program - Hazardous materials training required.	
§121.1111	Continued Airworthiness and Safety Improvements - Electrical wiring interconnection systems (EWIS) maintenance program.	
§121.1113	Continued Airworthiness and Safety Improvements - Fuel Tank System Maintenance Program	Specific requirements for ESD need to be developed
PART 125 – CERTIFICATION AND OPERATIONS: AIRPLANES HAVING A SEATING CAPACITY OF 20 OR MORE PASSENGERS OR A MAXIMUM PAYLOAD CAPACITY OF 6,000 POUNDS OR MORE AND RULES GOVERNING PERSONS ON BOARD SUCH AIRCRAFT		
§125.121	Special Airworthiness Requirements - Proof of compliance with §125.119.	
§125.131	Special Airworthiness Requirements - Fuel lines and fittings in designated fire zones	
§125.133	Special Airworthiness Requirements - Fuel valves	
§125.143	Special Airworthiness Requirements - Firewalls	
§125.151	Special Airworthiness Requirements - Powerplant fire protection	
§125.153	Special Airworthiness Requirements - Flammable fluids	
§125.157	Special Airworthiness Requirements - Lines and Fittings	
§125.159	Special Airworthiness Requirements - Vent and drain lines	
§125.161	Special Airworthiness Requirements - Fire-extinguishing systems	
§125.163	Special Airworthiness Requirements - Fire Extinguishing Agents	
§125.213	Instrument and Equipment Requirements - Miscellaneous equipment	
§125.215	Instrument and Equipment Requirements - Operating information required	
§125.243	Maintenance Manual Requirements - Certificate holder’s responsibilities	
§125.245	Maintenance Manual Requirements - Organization required to perform maintenance, preventive maintenance, and alteration	
§125.247	Maintenance Manual Requirements - Inspection programs and maintenance	
§125.249	Maintenance Manual Requirements	
§125.251	Maintenance Manual Requirements; Required inspection personnel	

14 CFR	Description	Notes
PART 129 – CERTIFICATION AND OPERATION: FOREIGN AIR CARRIERS AND FOREIGN OPERATORS OF U.S. REGISTERED AIRCRAFT IN COMMON CARRIAGE		
§129.14	Maintenance program and minimum equipment list requirements for US registered aircraft	
§129.111	Electrical wiring interconnection systems (EWIS) maintenance program.	
§129.113	Fuel Tank system maintenance program	
§129.117	Flammability reduction means	

APPENDIX H. ACRONYMS AND DEFINITIONS

H.1 ACRONYMS

A/C	Aircraft
AC	Alternating Current
AC	Advisory Circular
AIAA	American Institute of Aeronautics and Astronautics
AIR	Aerospace Information Report
AFC	Alkaline Fuel Cell
ANAC	Brazilian Agência Nacional de Aviação Civil
ANSI	American National Standards Institute
AMC	Acceptable Means of Compliance
ASTM	American Society for Testing and Materials
APU	Auxiliary Power Unit
ARP	Aerospace Recommended Practice
ATA	Air Transport Association
ATR	Autothermal Reforming
BLEVE	Boiling Liquid Expanding Vapor Explosion
BPCU	Bus Power Control Unit
BOV	Boil Off Valve
CFFC	Carbon Fiber Full Composite
CGH	Compressed Gaseous Hydrogen
CHSS	Compressed Hydrogen Storage System
CPOX	Catalytic Partial Oxidation

CS	Certification Specification
DC	Direct Current
DDT	Deflagration-to-Detonation Transition
DMFC	Direct-Methanol Fuel Cell
DOD	Department of Defense
DOP	Design Operating Pressure
DOT	Department of Transportation (United States)
EASA	European Aviation Safety Agency
ECS	Environmental Control System
ESD ARC	Energy Supply Device Aviation Rulemaking Committee
ENMF	Electrical Network Management Function
ETOPS	Extended Operations
EU	European Union
EUROCAE	European Organization for Civil Aviation Equipment
EWIS	Electrical Wiring Interconnection System
FAA	Federal Aviation Administration
FCAPU	Fuel Cell Auxiliary Power Unit
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
FCA	Fuel Cell Aircraft
FCPS	Fuel Cell Power System
FCS	Fuel Cell Stack
FCS	Fuel Cell System

FCM	Fuel Cell Module
FHA	Functional Hazard Assessment
FMES	Failure Mode Effects Summary
FTA	Fault Tree Analysis
FOD	Foreign Object Damage
GH_2	Gaseous Hydrogen
GHe	Gaseous Helium
H_2O	Water
HAZOP	Hazard and Operability
HCFC	Hydro-Chlorofluorocarbons
HDC	Hydrodesulfurization synthesis gas
He	Helium
HPZ	High Pressure Zone
HT-PEM	High Temperature Proton Exchange Membrane
IEC	International Electro-Technical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Organization for Standardization
JAA	Joint Aviation Authority
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LH2	Liquid Hydrogen
LHSS	Liquid Hydrogen Storage System
LHV	Lower Heating Value
LN2	Liquid Nitrogen

LOX	Liquid Oxygen
LPZ	Low Pressure Zone
LRU	Line Replaceable Unit
LT-PEM	Low Temperature Proton Exchange Membrane
NFPA	National Fire Protection Association
MAWP	Maximum Allowable Working Pressure
MIE	Minimal Ignition Energy
MCFC	Molten Carbonate Fuel Cell
NASA	National Aeronautics and Space Administration
NOx	Nitrogen oxides (Nitric oxide, nitrogen dioxide)
N_2	Nitrogen Gas
RFCES	Regenerative Fuel Cell Energy Storage
RTCA	Radio Technical Commission for Aeronautics
PAO	Polyalphaolefin
PBI	Polybenzimidazole
PEM	Proton Exchange Membrane -OR- Polymer Electrolyte Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PCFC	Phosphoric Acid Fuel Cell
PMADS	Power Management and Distribution System
PO_2	Partial Pressure of Oxygen
PP	Partial Pressure
PRD	Pressure Relief Device
SAE	SAE International
SOFC	Solid Oxide Fuel Cell

SOV	Shut Off Valve
SRV	Safety Relief Valve
SSA	System Safety Assessment
TAO	Thermal Acoustic Oscillators
TMS	Thermal Management System
UAS	Unmanned Aerial System –OR- Unmanned Aircraft System
UFL	Upper Flammability Limit

H.2 STANDARD TERMINOLOGY

Auto-Ignition Temperature: The lowest temperature at which a substance will ignite without the presence of an addition ignition source such as a flame or spark.

Balance of Plant: The assembly of equipment used in the control of the reactants supporting the operation of the fuel cell stack. The equipment may consist of valves, sensors, pumps, compressors, humidification devices and water.

Combustion: A chemical reaction accompanied by the evolution of light and heat.

Common Mode Failure: The result of a failure event which, because of dependencies, causes multiple failures within a system, resulting in the system failing to perform its intended function.

Compartment: A space that is enclosed (by barriers) except for openings necessary for interconnection, controls, fuel supply and ventilation.

Control Failure: A failure in the controls in the fuel cell system so that it no longer operates correctly. Built-in-test and fail-safe measures need to be provided for this scenario.

Deflagration: A flame moving through a flammable mixture as a subsonic velocity, with respect to the unburned mixture.

Designated Fire Zone: A region in the aircraft which is designed to cope with a fire likely to occur (e.g., by means of fire resistant/proof materials and fire detection).

Detonation: An exothermic chemical reaction coupled to a shock wave that propagates through a detonable mixture. The velocity of the shock wave is supersonic with respect to the unburned gases. After initiation, the thermal energy of the reaction sustains the shock wave, and the shock wave compresses the unreacted material to sustain the reaction.

Double Barrier: A system of two independent barriers, each of which is capable of acting as the sole partition between energized and accessible parts in the event of failure of the other partition.

Electrical Wiring Interconnection System (EWIS): EWIS, as used in this report, is defined by CFR/CS § 25.1701.

Enclosure: Physical envelope that partially or completely surrounds and belongs to the fuel cell system or subsystem. It may be necessary for installation, interconnection, controls, safety, fuel supply and ventilation. It can be used as a barrier to isolate the fuel cell from the compartment.

Exhaust: Fluids and gases leaving the fuel cell system during normal operation through the exhaust.

Exhaust Conditioning: The conditioning of exhaust products, such as the collection of fluids or dehumidification of gases.

Explosion: The rapid equilibration of pressure between the system and the surroundings. The pressure of the gas may be dissipated as a shock wave. Explosions may occur through mechanical failure of vessels containing high-pressure fluids or through rapid chemical reactions producing large volumes of gases.

External Hydrogen Leakage: The following leakage levels are defined in relation to the Lower Flammability Limit (LFL) of hydrogen (H_2):

Low Leakage (0 to 25% LFL): Low leakage is defined as an amount of leaking fuel which leads to a fuel concentration in a fuel/air mixture below 25% of the LFL (1% volumetric H_2 concentration). Refer to ANSI/AIAA G-095-2004.

Medium Leakage (25 to 50% LFL): Medium leakage is defined as an amount of leaking fuel which leads to a fuel concentration in a fuel/air mixture between 25% and 50% of the LFL (1 to 2% volumetric H_2 concentration).

High Leakage (>50% LFL): High leakage is defined as an amount of leaking fuel which leads to a fuel concentration above 50% of the LFL (>2%) volumetric H_2 concentration).

Fire Zone: A potential flammable fluid leakage zone that contains a nominal ignition source. Note: This is not a Designated Fire Zone per § 25.1181. It is a zone where means to protect the airplane from the hazardous effects of fire may be required, but these means may differ from the fire protection means for designated fire zones per § 25.1181.

Flammable Fluid Leakage Zone: Any area where flammable liquids or vapors are not intended to be present, but where they might exist due to leakage from flammable fluid carrying components (e.g. leakage from tanks, lines, etc.).

Flammability Limits: The lower flammability limit (LFL) and upper flammability limit (UFL) vapor concentrations (usually reported as percent by volume) of fuel in a flammable mixture that will ignite and propagate a flame. These limits are functions of temperature, pressure, diluents, and ignition energy.

Fuel Cell Stack: That portion of the fuel cell system achieving electrochemical conversion of fuel and oxidant into electrical energy, thermal energy and exhaust gas. This includes the fuel cell housing, fittings, wiring and all devices allowing the connection to other subsystems.

Fuel Cell System: Those units and components using an electrochemical conversion process to produce electricity from a fuel (on the anode side) and an oxidant (on the cathode side). This includes reactants and reaction products, supply/exhaust devices, fuel cell stacks, electric power output devices, cooling or/and heating devices and a centralized control and monitoring subsystem.

Fuel Supply: Hydrogen gas or liquid and any other hydrocarbon fuel.

Hydrogen Cloud: A large volume of air-hydrogen mixture.

Hazardous Area: Defined as an area or space in which a hazardous condition, such as an explosive gas atmosphere, may be present in such quantities as to require precautions for the construction, installation and use of apparatus, in order to comply with the intended applications for civil aircraft. Refer to IEC 60079 Standards family.

Ignition: The initiation of combustion.

Ignition Sources: Any process or event that is capable of causing a fire or an explosion. Open flames, sparks, static electricity and hot surfaces are possible ignition sources.

Leak: Refers to a leak in the hydrogen system. The consequences of a high pressure leak are more hazardous than a low pressure leak.

Loss of Communication: Refers to a loss of communication between the airplane and the fuel cell system.

Loss of Power: Refers to a loss of output power from the fuel cell system for any reason (i.e. the fuel cell is not providing its intended function).

Lower Heating Value: The heating value or calorific value is the total energy released as heat when a substance undergoes complete combustion with oxygen under standard conditions. The lower heating value assumes that all the products of combustion remain gaseous. The higher heating value assumes that water is condensed and thus includes the heat of vaporization (condensation) of the water vapor formed from hydrogen during combustion.

Maximum Allowable Working Pressure (MAWP): A term commonly used dealing with high pressure containers. It describes the maximum pressure to be seen inside the system under worst case but allowed operating conditions. Hence it is a normal operating and not a failure case. Proof and burst pressure are to be calculated from MAWP and not from nominal pressure at ISA temperature.

Microflame: The minimum amount of hydrogen leakage that will support a flame

Minimum Ignition Energy (MIE): The minimum energy required for the ignition of a particular flammable mixture at a specified temperature and pressure.

Nominal Ignition Source: A flammable fluid ignition source, which is not associated with a failure condition.

Normal Discharges: Discharges expected during normal operation and not associated with failure conditions.

Normal Operation: All transient and steady state operating conditions according to the inflight envelope of the aircraft which occurs during start, intended operation and shut down which does not involve a component or system failure.

Overpressure: An overpressure in the high-pressure system which could lead to a tank or high pressure line exploding causing injury to personnel or damage to vehicle structure. Pressure relief devices are typically incorporated into tanks and high pressure lines to preclude this situation.

Oxidant Supply: The supply of an oxidizing agent; a substance that oxidizes another substance. This is generally air or pure oxygen.

Permeation: Diffusion through the walls or interstices of a container vessel, piping or interface material.

Point of Release: Interface where the ventilation exhaust or other discharges, potentially containing hazardous fluids, is expelled exterior to the aircraft.

Potential Ignition Source: A flammable fluid ignition source, which is associated with a failure condition.

Potentially Unsafe Condition: A condition that could lead to hazardous or catastrophic conditions according to CS25.1309, is defined as a potentially unsafe condition. Among these there are conditions caused by fluids and electrical voltages which have the potential to cause a hazard as follows:

Flammability and Explosiveness: Sufficient quantities of fuel/air mixtures at or above the Lower Flammability Limit (LFL) are flammable as well as sufficient quantities of fuel/air mixtures at or above the Lower Explosiveness Limit (LEL) are by explosive. Fuel/air mixtures below 25% of the LFL are considered nonhazardous. Note the LFL of H_2 in air is 4 vol%, where LFL = f(T,P), => 4 vol% (1 bar, 25 °C) for upper propagation (ANSI G-095-2004, Table A2.2).

High Pressure: High-pressure fluids in the fuel supply, fuel cell stacks, and/or thermal management subsystem can transfer kinetic energy causing personal injury and damage to critical systems and structure.

Purges: Normal discharges associated with the time limited removal of fluids or inert gases from fuel cell systems.

Proton Exchange Membrane (PEM) Fuel Cell: A fuel cell that employs proton exchange membrane as the electrolyte.

Quenching distance: The gap dimension required to prevent the propagation of an open flame through a flammable fuel-air mixture.

Rapid Release of Pressure: Refers to a rapid release of pressure from the hydrogen storage tank or lines. A high-pressure leak can propel a pressure vessel at high force and velocity potentially causing injury to personnel or damage to vehicle structure.

Reformed Fuel: The product of a fuel reformation process where hydrocarbon fuels are broken down into hydrogen rich gas which can be utilized directly or be further processed to be used as fuel for a fuel cell.

Secondary Fire Load: A secondary fire is the result of ignition of material by a primary fire. The secondary fire load is the amount of energy that is being released by the secondary fire after shut off of the primary fire. A secondary fire will extinguish either once all material is burned or the fire is self-extinguished due to the material selection or other adequate precautions.

Start-Up Time: Start-up refers to the processes and time required to turn-on a fuel cell until the time is it fully functioning and able to supply its rated power output.

Stoichiometric Mixture: A mixture in which both fuel and oxidizer are fully consumed (complete combustion) to form combustion product(s). The stoichiometric hydrogen-oxygen mixture is composed of 66.66% by volume of hydrogen and 33.33% of oxygen. The stoichiometric concentration of hydrogen in air (assuming 21% of oxygen and 79% of nitrogen) is 29.59% by volume with air content of 70.41%.

Thermal Management System: Active heating or cooling of the fuel cell stacks and supporting equipment to maintain optimum power generation while ensuring the FCS in within normal operating limits.

Uncontrolled Leak: An uncontrolled leak is defined as a leak that is either not detected or cannot be controlled (i.e., stopped or kept at a safe leakage level) by the fuel cell system.

Uncontrolled Fire: An uncontrolled fire is a situation where the fuel supply to the fire cannot be shut-off or the fire is not detected.

Ventilation: Means of using the flow of air to dilute and remove potential hazardous gases from a controlled volume. Ventilation may be active or passive.

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APPENDIX I. ESD ARC CHARTER

This appendix contains the original charter statement for the ESD ARC. The charter was revised by the FAA Administrator on June 29, 2017, to extend ESD ARC's duration until January 31, 2018. The revised charter instructed the committee to submit its report detailing recommendations no later than December 8, 2017. Other than the date extension, no other changes to the charter where made. Both charter statements can be found on the FAA Committee Database website at:

http://www.faa.gov/regulations_policies/rulemaking/committees/documents/.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Aviation Rulemaking Committee Charter

Effective Date: 4/9/2015

SUBJECT: Energy Supply Device Aviation Rulemaking Committee

1. **PURPOSE.** This charter establishes the energy Supply Device Aviation Rulemaking Committee (ARC) according to the Administrator's authority under Title 49 of the United States Code (49 U.S.C.) 106(p)(5). The sponsor of this ARC is the Director of the Aircraft Certification Service and this charter outlines the committee organization, responsibilities, and tasks.

2. **BACKGROUND.** The aviation industry has indicated significant interest in hydrogen fuel cells in airplanes. A hydrogen fuel cell produces electrical energy from hydrogen and oxygen reacting. Currently. the aviation industry is conducting research and pursuing efforts to install fuel cells on airplanes because fuel cells:

   a. Are efficient sources of electric energy and produce usable waster and heat as byproducts;
   b. Could significantly reduce airplane weight, emission of pollutant gases and· noise and
   c. Support Europe's Clean Sky initiative.

   The aviation industry has been studying, performing tests and developing prototypes to support several applications of fuel cells on airplanes. Some applications that have been discussed during industry meetings are as follows:

   a. Use the electrical energy to replace an airplane's main battery, ram air turbine and auxiliary power unit·

b. Power equipment such as galley cookers, chillers coffee makers inflight entertainment systems, cargo unit load devices and medical equipment; and
c. Use the water produced as a byproduct to reduce the need for water refilling trucks and ground support equipment.

Carrying hydrogen on-board an airplane creates safety issues that need to be understood and carefully addressed. For example, hydrogen is highly combustible and, due to its small molecular size, commonly leaks. The FAA is tasking the Energy Supply Device ARC to develop a thorough understanding of the safety issues and appropriate installation requirements to support the FAA's anticipated application for a fuel cell installation.

The FAA considers hydrogen fuel cells to be a main driver in determining appropriate airworthiness standards for energy supply device installations associated with this ARC. However, FAA airworthiness standards should be written to be performance-based and should address all foreseeable energy supply device t pesto the greatest extent possible.

3. **OBJECTIVES AND TASKS OF THE ARC.** The Energy Supply Device ARC will provide a forum for the aviation community to discuss and provide recommendations to the FAA and is tasked to specifically:

   a. Develop a plan for determining appropriate airworthiness standards and guidance for energy supply device installation, with a primary focus on transport airplanes but also considering other types of aircraft.
   b. Identify hazards associated with installations of hydrogen fuel cells, batteries, ultra-capacitors, and other energy supply devices on transport airplanes and other types of aircraft.
   c. Identify the designs and operational principles that may be used to safeguard against these hazards.
   d. Identify the current rules in Title 14, Code of Federal Aviation Regulations (14 CFR) part 25 that are applicable for addressing energy supply device installations.
   e. Determine proposed revisions of, and any additions to, the applicable part 25 rules needed to provide an appropriate and adequate level of safety for energy supply device installations and operation.
   f. Review the existing advisory circulars and FAA policy memorandums and statements that provide guidance relating to this subject and determine proposed revision s or additions to the guidance. As a part of this effort, determine proposed guidance on the assumptions and approach that should be used to perform a safety assessment of these energy supply device installations.
   g. Recommend appropriate airworthiness standards and guidance for energy supply device installations

Recommendation Report. The Energy Supply Device ARC shall provide recommendations that may be used by the FAA to develop appropriate airworthiness standards and guidance for energy supply device installations on transport airplanes and other types of aircraft. The report should include:

a. A list of the types of energy supply devices studied.
b. An explanation of all hazards associated with installing energy supply devices on airplanes.
c. Discussion on the designs and operational principles the ARC considers will be used to safeguard against these hazards.
d. An explanation of how the proposed airworthiness standards and guidance will sufficiently address all of the associated hazards.
e. Any additional information the ARC considers, in associated with the task, that would help the FAA further understand the recommendation.
f. Estimated costs associated with certification of each recommended energy supply device.

4. ARC PROCEDURES

a. The Energy Supply Device ARC acts solely in an advisory capacity by advising and providing written recommendations to the Director r of the Aircraft Certification Service and the Director of the Office of Rulemaking.
b. The Energy Supply Device ARC may propose additional tasks as necessary to the Director of the Aircraft Certification Service for approval.
c. **Status Reports.** The Energy Supply Device ARC will provide a status update to the Director of the Aircraft Certification Service every six months.
d. **Recommendation Report.** The Energy Supply Device ARC will submit a report detailing recommendations within 24 months from the effective date of the charter.
    i. The Indus try Co-Chair sends the recommendation report to both the Director of the Aircraft Certification Servicer and the Director of the Office of Rulemaking.
    ii. The Director of the Aircraft Certification Service determines when the recommendation report is release d to the public.
e. The Energy Supply Device ARC may reconvene following the submission of the recommendation report for the purposes of providing advice and assistance to the FAA. at the discretion of the Director of the Aircraft Certification Service, provided the charter is still in effect

5. ARC ORGANIZATION, MEMBERSHIP, AND ADMINISTRATION. The FAA will establish a committee of members of the aviation community. Members will be selected based on their familiarity with energy supply device design, operation, installation and regulatory compliance. Membership will be balanced in viewpoints. interests, and knowledge of the objectives and scope.

The provisions of the August 13, 2014. Office of Management and Budget guidance, “Revised Guidance on Appointment of Lobbyists to Federal Advisory Committees, Boards, and Commissions" (79 FR 47482), continues the ban on registered lobbyists participating on Agency Boards and Commissions if participating in their “individual capacity." The revised guidance now allows registered lobbyists to participate on Agency Boards and Commissions in a “representative capacity" for the "express purpose of providing a committee with the views of a nongovernmental entity. a recognizable group of persons or nongovernmental entities (an industry, sector, labor unions, or environmental groups, etc.) or state or local government". (For further infor1ation see the Lobbying Disclosure Act of 1995 (LOA) as amended, 2 U.S.C 1603, 1604, and 1605.)

a. The Director of the Aircraft Certification Service will:
   1) Select and appoint industry and the FAA participants as members to the Energy Supply Device ARC,
   2) Select an industry Co-Chair from the membership of the Energy Supply Device ARC,
   3) Select the FAA Co-Chair from the FAA line-of-business,
   4) Provide the FAA participation and support from all affected lines-of-business,
   5) Provide administrative support for the Energy Supply Device ARC, through the Transport Airplane Directorate, and
   6) Receive all status reports and the recommendation report.

b. Once appointed, the Industry Co-Chair will:
   1) Coordinate required ARC (and task group, if any) meetings in order to meet the objectives and timelines,
   2) Provide notification to the members of the time and place for each meeting,
   3) Establish and distribute meeting agendas in a timely manner,
   4) Keep meeting notes, if deemed necessary,
   5) Perform other responsibilities as required to ensure the objectives are met,
   6) Provide status reports in writing to the Director of the Aircraft Certification Service, and
   7) Submit the recommendation report to the Director of the Aircraft Certification Service.

6. **COST AND COMPENSATION.** The estimated cost to the Federal Government for the Energy Supply Device ARC is approximately $2,500. All travel costs for government employees are the responsibility of the government employee's organization. Non-government representatives, including the Industry Co-Chair, serve without government compensation and bear all costs related to their participation on the ARC.

7. **PUBLIC PARTICIPATION**. Meetings are not open to the public. Persons or organizations outside the ARC who wish to attend a meeting must get approval in advance of the meeting from either the Industry Co-Chair or the FAA Co-Chair.

8. **AVAILABILITY OF RECORDS**. Consistent with the freedom of Information Act, Title 5, U.S.C., section 552, records, reports, agendas, working papers, and other documents that are made available to or prepared for or by the ARC will be available for public inspection and copying at the FAA, Transport Airplane Directorate, 1601 Lind Avenue SW. Renton, WA 98057-3356. Fees will be charged for information furnished to the public according to the fee schedule published in Title 49 of the Code of Federal Regulations, part 7.

   You can find this charter on the FAA Committee Database website at:

http://www.faa.gov/regulations_policies/rulemaking/committees/documents/.

9. **DISTRIBUTION**. This charter is distributed to the Director of the Aircraft Certification Service, the Office of the Associate Administrator for Aviation Safety, the Office of the Chief Counsel, the Office of Aviation Policy and Plans, and the Office of Rulemaking.

10. **EFFECTIVE DATE AND DURATION**. The Energy Supply Device ARC is effective upon issuance of this charter and will remain in existence for 28 months, unless the charter is sooner suspended, terminated, or extended by the Administrator.

Issued in Washington, D.C. on April 9, 2015

Michael P. Huerta
Administrator

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