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Investigation of Potential Fuel Cell Use in Aircraft

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Executive Summary

Fuel cells are a promising alternative power source for military and commercial aircraft subsystems and sensors. Two of the most promising types of fuel cells for use in aviation are proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFCs). This document presents the current state of PEM and SOFC technology and the technical challenges associated with the use of these fuel cells as onboard power sources of non-propulsion power for aircraft. We discuss current uses of fuel cells aboard aircraft, specifically on small unmanned aerial vehicles (UAVs) as the sole power source and on commercial aircraft to replace traditional auxiliary power units (APUs) or batteries. Technical challenges associated with modifying traditional aircraft architecture to incorporate more electric infrastructure are explored. Finally, we use the unmanned air vehicle Global Hawk as a case study for determining the breakeven point between fuel saved from reduced power demands on the aircraft engine due to the use of fuel cells as a power source and the weight added to the aircraft by the fuel cell system.

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There is increasing interest, in both military and commercial environments, in "more-electric" airplanes. Fuel cells are a promising alternative power source to provide the electric power for the more electric aircraft, both manned and unmanned. Currently, electrical power on military and commercial aircraft is generated through the use of auxiliary power units (APUs) or by a generator attached to the high-speed turbine shaft of an aircraft engine. However, there are disadvantages to each of these methods. APUs are not very efficient and are large sources of heat and carbon emissions. Use of a generator attached to the aircraft engine reduces the power available for flight and can warrant the use of an engine larger than would otherwise be required.

Proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFCs), are currently being used as energy sources for vehicles and power stations, but fuel cell use in aircraft is relatively limited. Most work to date has focused on using fuel cells as battery replacements on small Unmanned Aerial Vehicles (UAVs). Less work has been done on examining tradeoffs between traditional APUs or generators and fuel cells as replacements.

The objective of this Central Research Project (CRP) is to understand the current state of PEM and SOFC technology and the potential technical benefits and challenges associated with the use of these fuel cells as onboard power sources to either augment or replace traditional APUs, generators, or batteries. This study investigates the feasibility and potential limitations of the use of fuel cells as direct electric power sources in aircraft. We use Global Hawk as a case study to investigate the breakeven point of fuel cell use onboard the aircraft.

A. Introduction to Fuel Cells

While internal combustion engines change chemical energy of fuel to thermal energy to generate mechanical and/or electrical energy, fuel cells convert chemical energy from fuel directly into electrical energy. This direct conversion promises power generation with high efficiency and low environmental impact [1]. Fuel cells are not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. Low environmental impact is possible by avoiding combustion and the accompanying generation of CO_2. If provided a constant source of fuel and oxygen to sustain the chemical reactions, fuel cells can produce electricity indefinitely.

Fuel cell systems are composed of a number of components. Unit cells are where the electrochemical reactions occur. These are the fuel cells in the purest sense.

Typically, unit cells are electrically connected and combined into stacks. The number of unit cells and their arrangement determines the electrical output of the stack. Balance of plant refers to everything else required to operate the fuel cell and provide useful electrical energy. Components of balance of plant include fuel processor if needed, thermal management, humidification management, electric power conditioning, and interface functions.

Fuel cells, or technically unit cells, are typically categorized by the type of electrolyte substance used. Proton exchange membrane, also called polymer electrolyte membrane, fuel cells and solid oxide fuel cells are two of the most developed types of fuel cells. Most fuel cell research and development for aircraft applications has been focused on these types of fuel cells [2]. All unit cells consist of three basic components: an anode, a cathode, and an electrolyte. The electrolyte separates the anode and the cathode and is designed such that ions other than electrons can pass through it. Electrons are forced to migrate out of the electrolyte through a wire, producing an electric current that can power a load. The specific reactions that occur at the anode and at the cathode and the ions present in the fuel cell depend upon the type of fuel cell.

B. PEM Technology

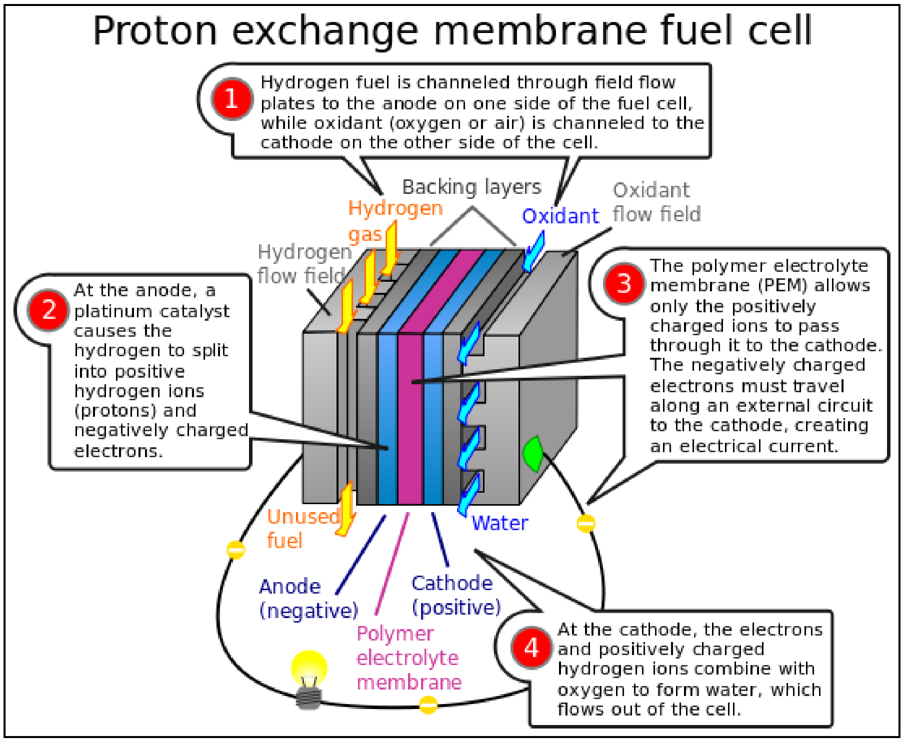
Because of major investments by the automotive industry over the past decade, PEM fuel cell technology is at a relatively high state of development [2]. Typically, PEM fuel cells use pure H_2 as fuel. H_2 is oxidized at the anode, producing positively charged H^+ ions and electrons. The positively charged ions pass through the electrolyte from the anode to the cathode. The electrons migrate out of the electrolyte and through a wire that connects the anode to the cathode, producing an electric current. At the cathode, the H^+ ions are recombined with the electrons and react with oxygen, producing H_2O. The half reactions are shown in Equation 1 and 2. A cartoon of a PEM fuel cell is shown in Figure 1.

Oxidation half reaction (occurs at the anode):

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

Reduction half reaction (occurs at the cathode):

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2}$$



Source: www.wikipedia.org

Figure 1. Construction of a PEM Fuel Cell

Relatively low operating temperatures make PEM fuel cells an attractive option. Lower temperatures result in short startup times and do not require additional balance of plant equipment to maintain high temperatures. However, several challenges are associated with typical PEM fuel-cell operating temperatures of ~80 °C. PEM fuel-cell performance is determined in part by the rate of hydrogen oxidation and oxygen reduction. Platinum is used as a catalyst to increase the rate of reaction at both the anode and the cathode. However, the rate of the reduction of oxygen at the cathode is quite low [3]. The performance of PEM fuel cells is limited primarily by the slow rate of the O_2 half reaction, which is more than 100 times slower than the H_2 oxidation half reaction.

Increasing PEM fuel-cell operating temperatures is a method of increasing reaction rates and is an option up to a point. Proton exchange membrane fuel cells are made possible by polymer electrolyte membranes. These membranes are composed of a solid, organic polymer that must be hydrated in order for the H^+ ions to be mobile. Therefore, PEM fuel cells must be operated under conditions that maintain liquid water.

In addition to the constraint of the presence of liquid water, water concentration in a PEM fuel cell is a delicate balance. Ion movement occurs by H_3O^+ ions moving from polymer site to polymer site within the membrane. Too little water prevents the membrane from conducting H^+ ions well; too much water prevents O_2 molecules from penetrating the excess liquid water and reaching the catalyst sites. Current PEM technology calls for humidity in a PEM fuel cell above 80 percent to prevent excess drying and proton conductivity inhibition and below 100 percent to prevent liquid water from collecting in the electrodes [4]. At operating temperatures greater than 60 °C, humidification of reactant gases is necessary to avoid excess drying of the fuel cell. This need for humidification results in additional balance of plant equipment.

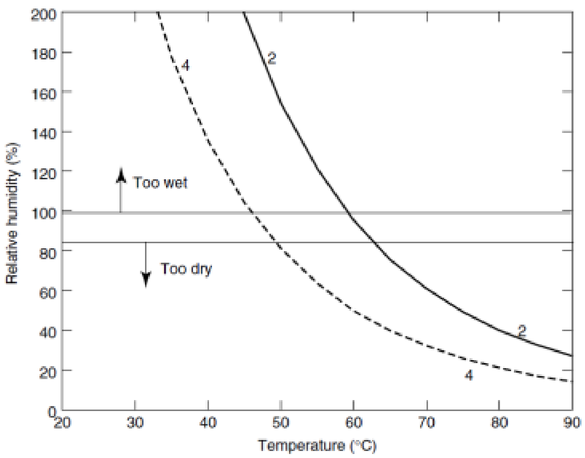


Figure 2. Relative Humidity versus Temperature for the Exit Air of a PEM Fuel Cell with Air Stoichiometry of 2 and 4

The entry air is assumed to be dry, and the total pressure is 1 bar [4].

Operating PEM fuel cells at temperatures greater than 100 °C is possible under pressurized conditions; however, this shortens the lifetime of the cell. PEM fuel cells smaller than 1 kW are usually operated at atmospheric pressure, and PEM fuel cells greater than 5 kW are typically operated at higher pressures. Higher pressures can increase fuel-cell performance but require compression equipment. This equipment has associated cost, weight, and space requirements.

An additional technical challenge associated with PEM fuel cells is the use of pure H_2 as fuel. Impurities often present in H_2 fuel, such as sulfur and CO, bind to the surface of platinum catalysts. This decreases the number of available platinum catalyst sites available for H_2 oxidation. CO adsorption to platinum catalysts is temperature dependent (shown in Figure 3). At 80 °C, CO concentrations of 10 to 20 parts per million (ppm) cause significant loss in cell performance. At 130 °C, platinum-based catalysts can tolerate up to 1,000 ppm CO. The tolerance of the platinum catalyst must be balanced with the operating parameters of the electrolyte.

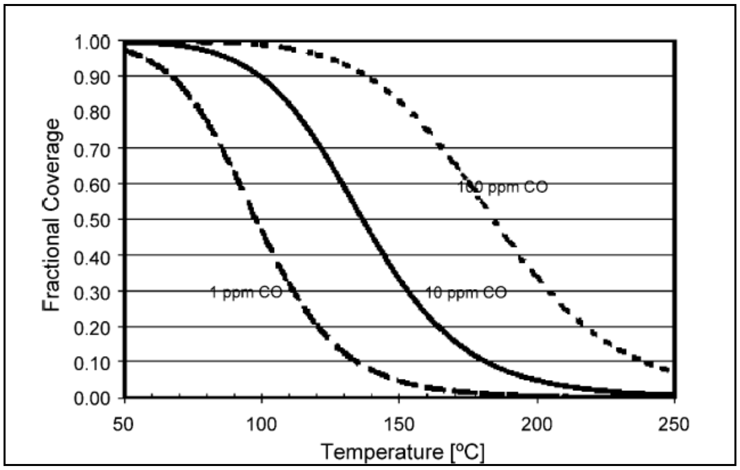


Figure 3. CO Coverage on a Platinum Catalyst as a Function of Temperature and CO Concentration

The partial pressure of H_2 is 0.5 bar [5].

Generation of H_2 fuel has its own technical challenges. Most of the H_2 produced today comes from hydrocarbon resources, typically methane (CH_4). Converting hydrocarbon fuels to hydrogen gas is technically challenging, requires processing temperatures of 700 °C to 1000 °C, and produces CO_2. Conventional technology focuses on steam reforming of methanol to H_2. The final gas mixture contains about 70 percent H_2, 24 percent CO_2, 6 percent N_2, and traces of CO [6]. Also, infrastructure has not been build to support mass transport of H_2 fuel.

A fuel cell generates heat in the process of converting chemical energy into electrical energy. The amount of heat generated and the necessary removal method affect the balance of plant requirements for the fuel-cell system. PEM fuel cell stacks smaller than 100 watts can be cooled with reactant air flow. PEM fuel cell stacks between 100 watts and 1 kW require the use of a separate air-cooling system with air blowers or pumps. PEM fuel cell stacks greater than 1 kW require water-cooling systems. The addition of a separate cooling system, either air or water cooling, greatly increases the balance of plant associated with the fuel cell.

In order to be a viable option for energy generation, PEM fuel cells must compete with current technologies. Today's PEM fuel cell systems achieve efficiencies between 40 and 60 percent [7]. The maximum theoretical efficiency, based on Gibbs free energy, of a PEM fuel cell using H_2 as the fuel, is 83 percent [4]. A current PEM unit cell produces a ~0.7 volt. An ideal H_2/air unit cell should provide 1.16 volts at 80 °C and 1 atmosphere.

C. SOFC Technology

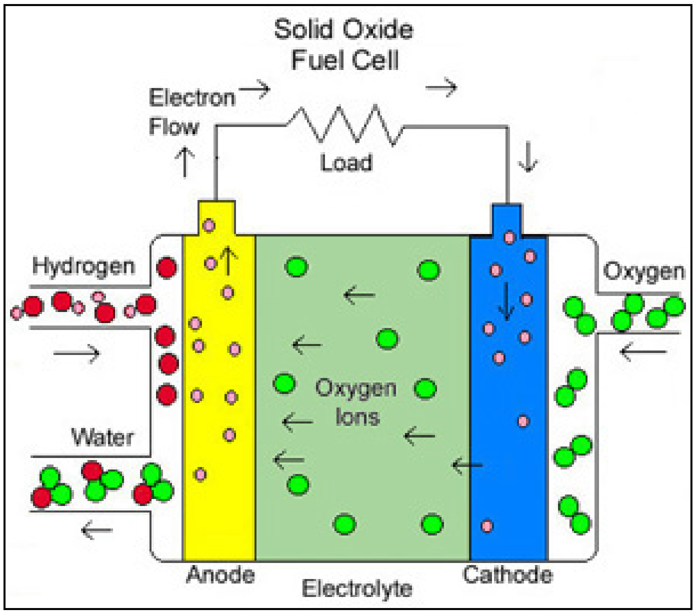
Like PEM fuel cells, SOFCs consist of an anode and a cathode separated by an electrolyte. In SOFCs, the electrolyte is a solid oxide or ceramic. A solid oxide electrolyte transports oxygen ions (O^{2-}) rather than H^+ ions. At the cathode, O_2 from air is reduced to O^{2-} and the O^{2-} ions are transported through the electrolyte to the anode. At the anode, O^{2-} ions react with gaseous fuel to produce water and heat and release electrons to the external circuit. If hydrocarbon fuel is used rather than pure H_2, CO_2 will be produced as well. The half reactions of a SOFC with pure H_2 fuel are shown in Equation 3 and 4. A cartoon of a solid oxide fuel cell is shown in Figure 4.

Oxidation half reaction (occurs at the anode):

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \tag{3}$$

Reduction half reaction (occurs at the cathode):

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{4}$$



Source: www.iit.edu

Figure 4. Cartoon of a Solid Oxide Fuel Cell

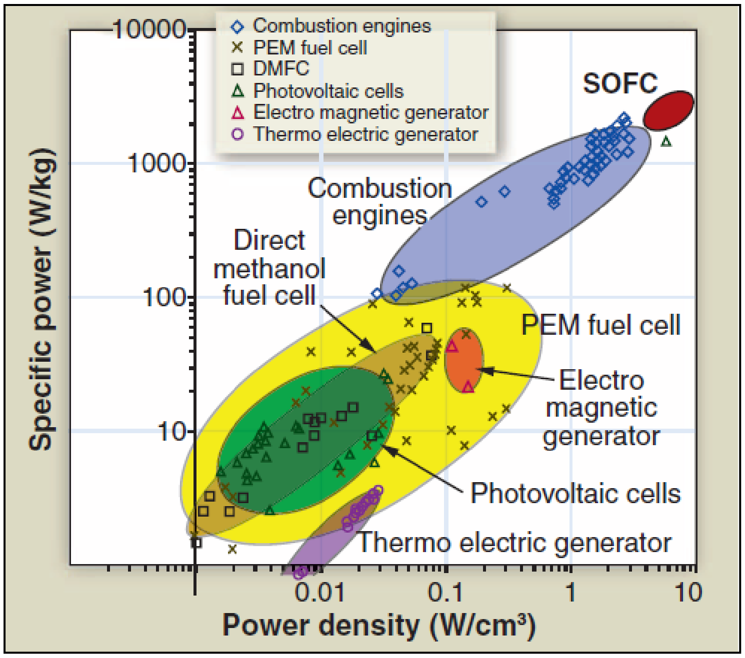
SOFCs differ from PEM fuel cells in several ways. Three main differences are fuel requirements, operating temperatures and therefore catalyst needs, and additional efficiencies in combined heat and power applications. Because the electrolyte transports oxygen ions rather than hydrogen ions, SOFCs can oxidize hydrocarbons and do not require pure H_2 as fuel. This opens the possibility of using existing fuel and infrastructure to power SOFCs, particularly in ground and air vehicles, rather than developing infrastructure for H_2 fuel.

Typical operating temperatures of SOFCs range from 650 to 1000 °C. These high temperatures are driven in part by the choice of electrolyte. For large-scale manufacturing, conventional multilayer thick-film ceramic processing (e.g., tape casting) is the current method of electrolyte production. Because of its properties as a good oxygen ion conductor and a stable electrolyte, yttria-stabilized zirconia (YSZ) is a popular electrolyte. However, the use of YSZ in this manufacturing process results in a minimum electrolyte thickness of ~10 µm [8]. For YSZ-based SOFCs, this thickness requires operating temperatures greater than 700 °C. These temperatures remove the need for catalysts in many cases because electrochemical reactions proceed more quickly at higher temperatures. However, most of the technical challenges associated with SOFCs are the result of high operating temperatures.

Operating temperatures greater than ~800 °C drive higher system component costs, higher performance degradation rates, and slower startup and shutdown cycles compared to fuel cells that operate at lower temperatures. The development of lower temperature SOFCs depends on higher conductivity electrolytes. Work has been done on alternative electrolytes such as aliovalent-doped ceria and isovalent-cation-stabilized bismuth oxides. These compounds have superior ionic conductivity at lower temperatures; however, development is at the laboratory level [9].

SOFCs have the potential to achieve high efficiencies when fuel-cell energy generation is combined with heat and power applications. Typical operating temperatures of SOFCs yield high-temperature exit gases that carry large amounts of heat energy that can be converted into electrical energy via turbines. Heat from exit gases can also be used to preheat fuel-cell reactants. Efficiency of SOFCs ranges from 40 to 65 percent [1]. Overall efficiency has the potential to be greater than 85 percent in combined heat and power applications [10].

Currently, commercial stationary-application zirconia-based SOFC units deliver power densities of ~0.2 W/cm^2 at 900 °C. A comparison of specific power versus power density for various energy conversion methods is shown in Figure 5. Note the SOFC values are for a laboratory-demonstrated power density of ~2 W/cm^2. Commercially available SOFC units deliver power densities of ~0.2 W/cm^2, which are consistent with power densities demonstrated by PEM fuel cells.



Note the SOFC values are for a laboratory-demonstrated power density of ~2 W/cm^2. Commercially available SOFC units deliver power densities of ~ 0.2 W/cm^2[9].

Figure 5. Comparison of Specific Power versus Power Density for Various Energy Conversion Methods

D. More Electric Aircraft

The concept behind More Electric Aircraft (MEA) is to replace the pneumatic and hydraulic systems onboard aircraft with one that is fully based on electricity. The motivation for this stems from the desire to simplify power distribution, reduce maintenance, and improve reliability and system adaptability. Figure 6 illustrates typical commercial aircraft subsystems and delineates the pneumatic, electric, mechanical, and hydraulic subsystems. Figure 7 shows a proposed re-architecture that would remove the central hydraulic and pneumatic systems.

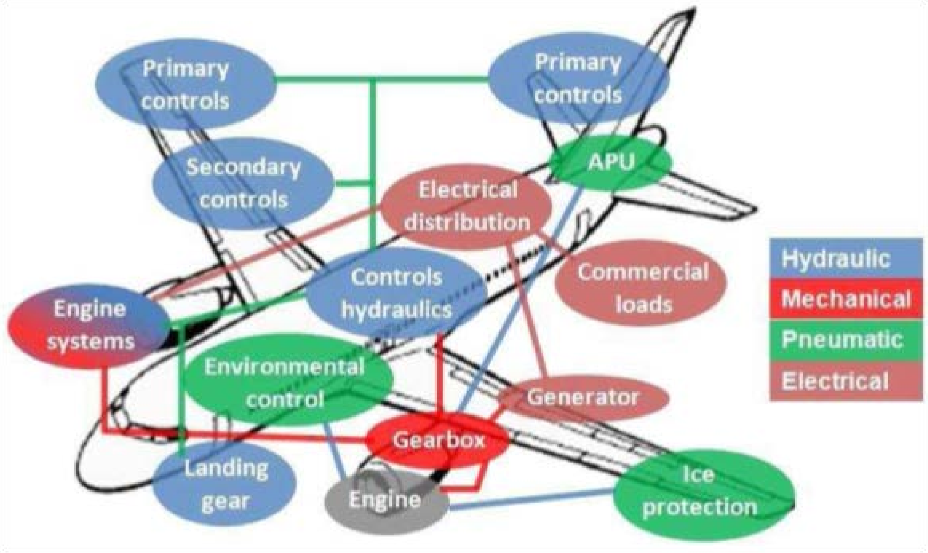


Figure 6. Typical Current Subsystem Architecture

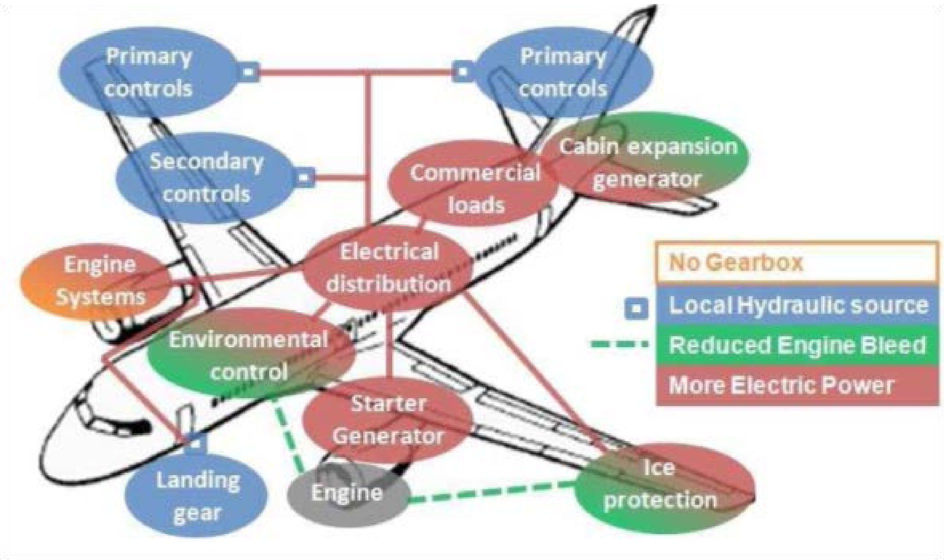


Figure 7. Alternative Subsystem Architecture with More Electric Systems

As the figures show, the central hydraulic system and a significant portion of the engine bleed air are removed, and these functions are transitioned to electric systems. For a military aircraft, the subsystems are the same as for commercial aircraft, just with differing levels of power draws. Table 1 provides the range of powers needed for major subsystems in an all-electric architecture [11].

Table 1. Subsystem Power Exemplar Requirements

Subsystem	Commercial	Military (ISR)
Flight Controls	80 kW	80 kW
Fuel Pumps	10 kW	10 kW
Environmental Control System	400 kW	10 kW
Avionics	10 kW	*25 kW**
Payloads/Passenger Needs	40 kW	*50 kW**
Misc. Subsystems	310 kW	5 kW – 30 kW
Total	**850 kW**	**175 kW – 200 kW**

*This value represents aspects that are uniquely military. This value represents current systems and is likely to grow in magnitude in the future.

Currently, this move toward MEA has been directed using larger, more extensive power generation through generators connected to the turbine shaft of the aircraft's engine. This requires larger engines to provide not just propulsive thrust but also significant electrical power (15 to 25 percent of total power generated by engine).

An alternative means to generate power for this newly suggested system architecture is fuel cells. Figure 8 shows a possible architecture where a fuel cell power unit is used to replace the aircraft's APU. Much of the research and development done to date has been geared toward replacing the APU on commercial aircraft. The APU provides much of the power for subsystems in flight and on the ground but is generally inefficient and consumes significant amounts of fuel. The commercial application looks to replace the APU with a fuel cell stack to power aircraft subsystems.

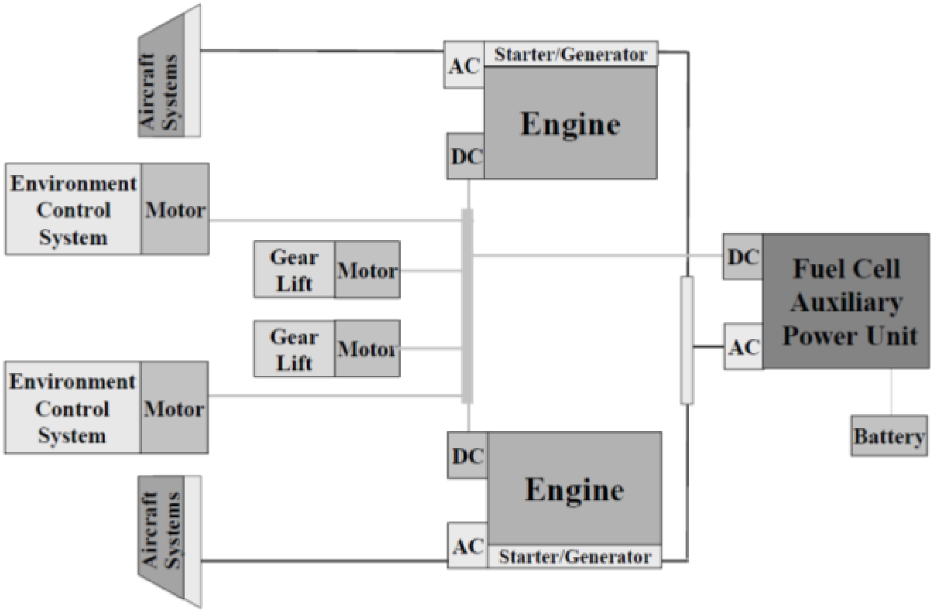


Figure 8. Aircraft Power Subsystem Architecture with Fuel Cell Replacing Standard Auxiliary Power Unit [12]

A similar architecture of replacing the APU would be applicable to manned military cargo aircraft. The use of a fuel cell for onboard power has direct linkages to high-altitude long-endurance (HALE) unmanned intelligence, surveillance, and reconnaissance (ISR) aircraft, as well. For HALE aircraft, as operating altitudes increase, the excess power required for power generation compared to thrust required for flight becomes a stressing condition and can limit operational altitudes (which is in fact the case for the RQ-4B Global Hawk). Depending on fuel choices, integration specific challenges, and overall power needs, either SOFC or PEM-based fuel cells can be used to off-load from the engine the requirement to generate power for the subsystems and payload.

E. Use of Fuel Cells in Aircraft

The use of fuel cells in aircraft has moved in two primary directions: as the sole source of power aboard small UAVs and as replacement for APUs on larger aircraft. AeroVironment, Inc., in Monrovia, CA, built and flew the first fuel-cell-powered aircraft in 2003 [13]. Since that time, an ever-increasing number of researchers have developed fuel-cell-powered UAVs of increasing size and endurance. To date, fuel-cell-powered UAVs have been relatively small, less than 50 pounds, with demonstrated endurance of less than 24 hours. The majority of developed UAVs have used PEM fuel cells rather than SOFC as the power source. This is most likely due to the lower operating temperatures of PEM fuel cells and the corresponding smaller balance of plant requirements. Table 2 presents a list of published fuel-cell-powered UAV demonstrations up to 2009.

Table 2. Published Fuel-Cell-Powered UAV Demonstrations[13]

Organization (date)	Fuel Cell Type	Reactant Storage Type	Endurance (est.)
AeroVironment (2003)	PEM	H_2 Sodium Borohydride	0.2 hr
AeroVironment (2005)	PEM	H_2 Cryogenic	24 hr
FH Wiesbaden (2005)	PEM	H_2 Gaseous	90 s
Naval Research Lab (2006)	PEM	H_2 Gaseous	3.3 hr
Adaptive Materials Inc. (2006)	SOFC	Propane	4 hr
Georgia Inst. of Tech. (2006)	PEM	H_2 Gaseous	0.75 hr
CSU Los Angeles (2006)	PEM	H_2 Gaseous	0.75 hr
DLR/HyFish (2006)	PEM	H_2 Gaseous	0.25 hr
CSULA/OSU (2007)	PEM	H_2 Gaseous	12 hr
KAIST (2007)	PEM	H_2 Sodium Borohydride	10 hr
AeroVironment (2007)	PEM	H_2 Sodium Borohydride	9 hr

Two of the most successful fuel-cell-powered UAV demonstrations to date are AeroVironment's Puma UAV and Naval Research Laboratory's Ion Tiger UAV. In 2008, a fuel cell hybrid Puma demonstrated an endurance of 9 hours. The Puma is a hand-launched, 12.5-pound aircraft with a wingspan of 8.5 feet capable of speeds up to 30 mph. Typical operating altitudes are between 100 and 500 feet and line-of-sight (LOS) range is up to 10 km. The UAV fuel-cell system recharges the lithium ion battery, which provides peak power during takeoff and dash.

Ion Tiger is a 25-pound fuel-cell UAV with a demonstrated endurance of greater than 24 hours. It is powered by a PEM fuel-cell system, which includes balance of plant equipment such as a humidifier, air blower, fuel delivery/conservation system, cooling pumps, and electronics to control the system components and regulate the power and voltage produced by the fuel cell. In addition to providing power for flight, the fuel cell powers an onboard 5-pound payload.

The other focus of much research and development, and the interest of this CRP, has been the prospect of using fuel cells to replace APUs aboard larger aircraft. Much of the published work has focused on commercial, rather than military, use. Contrary to small fuel-cell-powered UAVs, commercial research and development has included both SOFCs and PEM fuel cells.

The Boeing Company and Airbus SAS are both working to develop fuel-cell solutions and incorporate them into future aircraft. In a 2003 presentation at the Solid State Energy Conversion Alliance (SECA) Annual Meeting, Boeing discussed fuel-cell APUs as a way to reduce emissions and fuel use. Because the use of jet fuel is strongly preferred, Boeing discussed SOFCs as an option. Expected power requirements for fuel cells were estimated to be 440 kW. Drawbacks of SOFCs as APU replacements include the weight of the fuel cell system, specifically the balance of plant, and the startup time required to reach typical SOFC operating temperatures [12]. A 2012 article in *Aviation Week & Space Technology* describes Boeing's work to develop a liquefied natural-gas fuel and hydrid-electric propulsion passenger aircraft for the 2045 timeframe [14]. Airbus is also working on alternative energy source for its aircraft. In its 2011 document, *The Future by Airbus*, Airbus presents fuel cells as a possible power source for cabin and aircraft systems [15].

In addition to information provided in published material, direct insight into fuel-cell development for commercial aircraft was obtained through a teleconference with Mr. Jeff Rolf, Vice President of Commercial Airframe Programs, Business Development and Global Support at Parker Hannifin Corporation. Mr. Rolf discussed Parker's effort to integrate fuel cells into commercial aircraft. According to Mr. Rolf, the technical viability of fuel cells as APU replacements is not in question. Rather the integration of the fuel cell balance of plant into the aircraft is problematic. The power generated vice weight of the fuel cell system is an active area of research. Also, as discussed above, remaining technical issues include thermal management of the fuel cell, poisoning of the catalyst, and the life cycle of the fuel cell system. Interestingly, from Parker's perspective, the commercial industry is far more interested in fuel cell use in aircraft than is the U.S. military. Mr. Rolf was not able to state why this is so.

F. Global Hawk Case Study

Global Hawk is a high-altitude, long-endurance UAV used by the U.S. Air Force. It provides ISR with a sensor suite that includes an electro-optical/infrared (EO/IR) sensor and synthetic aperture radar (SAR). Because of its mission and the combination of time-on-station requirements and payload, Global Hawk was selected as a case study to determine the breakeven point of including a fuel-cell system aboard the aircraft. In addition to providing thrust for aircraft movement, power drawn from the aircraft engine is used for the EO/IR sensors, SAR, aircraft hydraulic system, environmental control system, and avionics.

Aircraft engines are sized for the amount of thrust and power required at altitude. It is this demand, rather than the thrust required at takeoff, that drives engine size. Historically, the power demands of the systems aboard the aircraft have been met by the use of APUs or by attaching a generator to the high-speed turbine shaft of the aircraft engine. Both methods result in higher fuel burn because engines that are larger than necessary to provide only aircraft propulsion are needed to provide power to the non-propulsion aircraft systems. Fuel cells as a means of providing non-propulsion power aboard aircraft would result in a reduction in the amount of power required from the aircraft engine and, therefore, a reduction in engine size. However, the reduction in installed power and the corresponding fuel savings are offset by the weight added to the aircraft by the fuel cell system. One goal of this CRP was to determine the breakeven point for Global Hawk.

A U.S. Block 30 Global Hawk has a gross takeoff weight of 32,011 pounds and a wingspan of 130.9 feet. The maximum lift-to-drag ratio $(L/D)_{max}$ is approximately 22. The lift-to-drag ratio of a turbojet aircraft during cruise is $0.866(L/D)_{max}$. This yields a lift-to-drag ratio during cruise of 19. Assuming level flight and using Equation 5, the thrust required at altitude during cruise is 1684 pounds. This thrust includes aircraft propulsion and electric power to the onboard systems such as the sensor payload, communication equipment, and hydraulics.

$$\frac{T}{W} = \frac{D}{L} \tag{5}$$

where T = thrust (lb), W = weight (lb), L/D = lift-to-drag ratio.

Assuming a standard specific fuel consumption for turbojets of 0.5 pound of fuel per hour per pound thrust, an as-configured Global Hawk burns 842 pounds of fuel per hour.

Aircraft propulsion is a large component of the thrust requirements. However, providing electric power is not an insignificant drain on the engine. Recalling Table 1, if we assume the total onboard electric power requirement due to the SAR (~50 kW), the EO/IR sensor (~1 kW), flight controls (~80 kW), avionics (~25 kW) and other subsystems (~5 kW to 40 kW) is 200 kW and a typical Global Hawk cruise speed of 575 km per hour, 281 pounds of thrust (1250 N) are needed to power the onboard systems.

Assuming an engine efficiency of 45 percent, the aircraft engine must generate 625 pounds of thrust to provide electric power to the subsystems. Using an alternative power source such as fuel cells for non-propulsion activities and assuming an engine that can be scaled as needed, the installed power of the Global Hawk engine could be reduced by 37 percent (625 pounds/1684 pounds). This 37-percent reduction in engine size yields an engine that burns only 539 pounds of fuel per hour.

While reducing cruise fuel burn, a fuel-cell system will contribute additional weight to the Global Hawk aircraft. A detailed analysis by Pacific Northwest National Laboratory (PNNL) of the feasibility and potential benefits of using a SOFC system to provide electric power onboard a Boeing 787 aircraft determined the ratio of power generated to additional weight due to the fuel cell balance of plant equipment required is 344 watts to 1 kg. Using this ratio, the needed 200 kW corresponds to an addition of a 1,279-pound fuel cell system to the aircraft.

If we assume that the aircraft size is fixed and the weight of the aircraft is constant, fuel that is not used to generate electric power from the aircraft engine can be used to increase aircraft endurance or provide additional thrust for propulsion at higher altitudes. In the above case study, with the additional weight of the fuel-cell system of 1,279 pounds, it will take 4.2 hours for the fuel-cell-equipped Global Hawk to breakeven (303 pounds of fuel per hour/1,279-pound weight). After 4.2 hours, the weight of the fuel cell system will have paid for itself in terms of jet fuel saved. A fuel-cell-equipped Global Hawk Block 30 aircraft, burning 539 pounds of fuel per hour versus the standard 842 pounds, would have an operational endurance of 30 hours, an increase of 54 percent.

G. Summary

Advantages of using fuel cells as an electrical energy source include potential reduction in aircraft engine size, efficient energy conversion, and low carbon emissions. Two of the most promising types of fuel cells for aviation systems are the PEM fuel cell and the SOFC. There are advantages and disadvantages to each such as type of fuel required as input, operating temperature of the fuel cell, and the weight of the balance of plant required. Several technical challenges remain prior to incorporating fuel cells as power sources in commercial and military aircraft. Challenges beyond fuel cell development include continued development of electrical actuators, high power electronics, and efficient power control systems. Each of these is needed to enable the MEA architecture necessary to fully utilize fuel-cell-generated electricity. For the Global Hawk case study, the time required to reach the breakeven point between reduction in fuel consumption due to a smaller engine and the additional weight due to the fuel-cell balance of plant is on the order of 4 hours. It is clear there is potential benefit in transitioning to more electric aircraft. As fuel-cell technology continues to improve, the benefits are expected to become increasingly easier to realize.

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Appendix A
Acronyms and Abbreviations

APU	auxiliary power unit
CRP	Central Research Project
DMFC	direct-methanol fuel cell
EO	electro-optical
HALE	high-altitude long-endurance
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
LOS	line-of-sight
MEA	More Electric Aircraft
PEM	proton exchange membrane
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
SAR	synthetic aperture radar
SECA	Solid State Energy Conversion Alliance
SOFC	solid oxide fuel cell
UAV	unmanned aerial vehicle
YSZ	yttria-stabilized zirconia

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Kathleen M. Spencer, Project Leader

14. ABSTRACT

Fuel cells are a promising alternative power source for military and commercial aircraft subsystems and sensors. Two of the most promising types of fuel cells for use in aviation are proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFCs). This document presents the current state of PEM and SOFC technology and the technical challenges associated with the use of these fuel cells as onboard power sources of non-propulsion power for aircraft. We discuss current uses of fuel cells aboard aircraft, specifically on small unmanned aerial vehicles (UAVs) as the sole power source and on commercial aircraft to replace traditional auxiliary power units (APUs), generators, or batteries. Technical challenges associated with modifying traditional aircraft architecture to incorporate more electric infrastructure are explored. Finally, we use the unmanned air vehicle Global Hawk as a case study for determining the breakeven point between fuel saved from reduced power demands on the aircraft engine due to the use of fuel cells as a power source and the weight added to the aircraft by the fuel cell system.

15. SUBJECT TERMS

Fuel cells, More Electric Aircraft, Unmanned Air Vehicle, Proton Exchange Membrane (PEM), Solid Oxide Fuel Cell

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