X.9 PEM Fuel Cell Systems for Commercial Airplane Systems Power

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Fiscal Year (FY) 2011 Objectives

- Determine feasibility of implementing a proton exchange membrane (PEM) fuel cell on-board a commercial airplane.
- Quantify the performance benefit (or penalty) of such a fuel cell system.
- Understand the impact of the fuel cell on the existing electrical distribution system.

Technical Barriers

This project addresses the following technical barriers:

(A) System Weight and Volume
(B) Cost
(C) Efficiency

Technical Targets

Our project determines the PEM fuel cell applications and configurations that have the lowest volume and mass, and the configurations that lead to the highest energy efficiencies for aircraft use. Cost is addressed indirectly: the results of this project may make it easier for airplane companies to incorporate fuel cells into their designs, thus increasing the quantities of fuel cells manufactured and leading to lower per-unit costs.

FY 2011 Accomplishments

- Feasibility: Found that it is technically feasible to install and operate a PEM fuel cell system on-board a commercial airplane.
- Performance Impact: Found that, in some scenarios, using an on-board PEM fuel cell system could decrease the amount of jet fuel needed to generate electricity by over 30%. The amount of CO_2 that could be avoided by a fleet of PEM fuel cell-equipped airplanes could be over 20,000 metric tons per year (assuming renewable hydrogen is used to power the fuel cell). However, this benefit is not reachable using current fuel cell and hydrogen storage technology but rather requires DOE-target (2015) technology for both hydrogen storage and PEM fuel cells.
- Electrical System: Discovered that the addition of a fuel cell system does not adversely affect the existing electrical system, and in fact can provide a faster transient response that current aircraft generators that operate off of engine shaft power.

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Introduction

Fuel cells have become increasingly important as alternative sources of power, offering the potential for drastic reduction in emissions in particulate matter (PM), nitrogen oxides (NO_x), and CO_2. In addition, they offer exceptionally quiet operation, highly efficient use of the fuel energy, and a high energy storage density compared to batteries. For a number of years, the manufacturers of commercial aircraft, most notably Boeing and Airbus, have realized that fuel cells may offer advantages for commercial aircraft operation. Apart from the emissions reductions and thermal efficiency referenced above, they can constitute distributed power systems, enabling locating the power near the point of use and also reducing the power draw from the engines.

The real question is if fuel cells offer operational advantages over traditional power in systems that are used routinely in flight, for example galley power, in-flight entertainment, and to provide additional power to the aircraft electrical grid when "peaker" power is needed. This interest in the use of fuel cells is timely, as the electrical needs on-board aircraft are going up considerably. Systems that were formerly hydraulic in operation are now being converted to electric operation [1]. For the new Boeing 787, the aircraft-wide electrical generation capacity is 1.5 MW – almost an order of magnitude larger than previous designs. This study, then, is an initial investigation of the use of PEM fuel cells on-board commercial aircraft. We seek to understand how to physically deploy a fuel cell on an aircraft, the impact of system volume and weight on the airplane, and the impact on jet fuel consumption, both in relation to fuel currently devoted to electricity generation, and the overall fuel needed by the airplane to fly a given mission.

Approach

To accomplish this analysis, two basic airplane designs were considered: one airplane without a fuel cell (the base airplane), and one airplane designed to perform the same mission as the first airplane, only carrying a fuel cell and associated hardware to fulfill a specific electrical need. The difference in the performance of these two airplanes is made quantitative by calculating the fuel required to fly the mission in the two cases, which requires understanding the influence of weight, volume, and thermal issues on the airplane drag. Calculating the required fuel also allows us to assess fuel use as it directly relates to power generation on the airplane. The key point here is that we assess not only the benefit of the fuel cell on generating electricity, but also the penalty the fuel cell system places on the airplane's performance due to its added weight and possibly drag issues that arise from handling fuel cell thermal issues. Combining these two is necessary to determine the overall effect of the fuel cell system.

We performed the analysis by designing and examining several system options using realistic assumptions about performance and size of the various components. After assessment of the available state of the art in commercially available PEM fuel cells, the Hydrogenics HyPM 12 PEM fuel cell was chosen as a unit representative of the industry. For hydrogen storage, several options were considered: 350 bar compressed gas, 700 bar compressed gas, metal hydrides, and liquid hydrogen storage, in both conventional cryogenic storage and "cryo-compressed" storage. For storing hydrogen for the PEM aviation fuel cell, we selected 350 bar compressed gas tank technology due to its combination of high specific energy and current availability. Other equipment such as heat exchangers, blowers, and pumps were all selected based on commercially available units with the specifications appropriate for the system. For the electrical components, a ±270 volt direct current distribution system provided the lowest system weight, although the increase in weight due to a 230 volt alternating current system was less than 50 kg (110 lb). Both of these options provide the advantage of direct interface with the existing electrical system on the 787.

Results

After consideration of factors such as safety, available space, maintenance, and wiring and tubing/piping lengths, we chose to locate the fuel cell system in the airplane's fairing area (where the wings join the fuselage), although locating the system in the tail cone would not change the results by much. Locating the fuel cell system next to the load it serves could save up to 150 kg (331 lb) of mass and provide some redundancy benefits, but this was avoided because of the concern with occupying space that is currently used for other purposes.

The amount and method of recovering the heat rejected from the fuel cell (waste heat recovery) was found to be a critical factor in determining the performance benefit of the fuel cell system. To this end, eleven different waste heat recovery options were examined thermodynamically. We found that a system that uses the heat from the fuel cell to pre-heat the jet fuel carried by the airplane will provide the largest overall performance benefit. This method of heat recovery is already used in commercial airplanes within the engine compartment, where the lubrication oil is cooled by jet fuel, and it is more ubiquitous in military aircraft where the fuel is used to cool many of the military airplane's systems.

We considered the integration of the fuel cell system with the airplane's electrical system, for it is necessary to ensure that the addition of the fuel cell system does not disrupt the electrical system or cause instabilities. Through dynamic simulation we found that the fuel cell system performed satisfactorily whether connected to the airplane's system or as a stand-alone system. In fact, our results indicate that the integration of the fuel cell system with the existing electrical system may provide a faster response to load changes than the current configuration.

Conclusions and Future Directions

In the end, we found that while adding a fuel cell system using today's technology for the PEM fuel cell and hydrogen storage is technically feasible, it will not give the airplane a performance benefit no matter which configuration was chosen (although there may be other benefits that make it worthwhile from the airplane manufacturer's or airline's point of view). However, when we repeated the analysis using DOE-target technology for the PEM fuel cell and hydrogen storage, we found that the fuel cell system would provide a performance benefit to the airplane (i.e., it can save the airplane some fuel), depending on the way it is configured. This analysis also showed that the DOE-target technology fuel cell system could generate electricity using over 30% less fuel than the current airplane, even considering the penalties due to the fuel cell system's weight and drag (Figure 1). If a fleet of 1,000 airplanes were equipped with such systems, it could save over 20,000 metric tons of CO_2 annually (Figure 2).

This project is complete. It is recommended that subsequent work on this topic focus on detailed design and testing of an actual aviation PEM fuel cell system, including both mechanical and electrical aspects.

FY 2011 Publications/Presentations

1. J.W. Pratt, L.E. Klebanoff, K. Munoz-Ramos, A.A. Akhil, D.B. Curgus, and B.L. Schenkman, "Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes," Sandia Report SAND2011-3119, May 2011.

2. Lennie Klebanoff, Joe Pratt, Karina Munoz-Ramos, Abbas Akhil, Dita Curgus, and Ben Schenkman, "PEM Fuel Cell Systems for Commercial Airplane Systems Power," presented

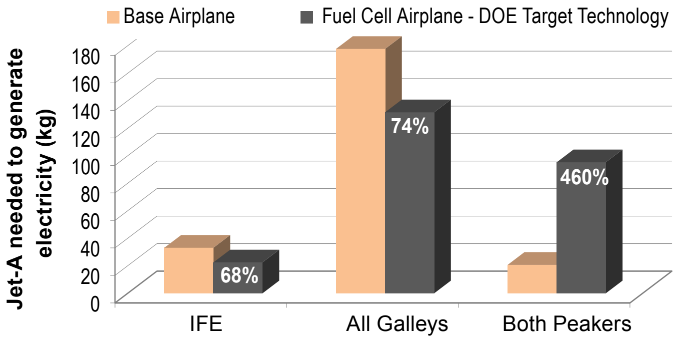

FIGURE 1. The amount of fuel required by the Base Airplane and the Fuel Cell Airplane to generate electricity and heat for each of three different loads: the in-flight entertainment (IFE), all galleys, and both peakers. IFE is a 20 kW load; All Galleys refers to a fuel cell providing power for three on-board galleys with a total power consumption of 120 kW, and Both Peakers refers to providing power for a short duration in times of peak power demand at 150 kW. The Base Airplane uses the main engine generator with a fuel-to-electricity efficiency of 34%, while the Fuel Cell Airplane assumes a PEM fuel cell system cooled by the airplane's jet fuel, and consists of DOE target technology for the PEM fuel cell and hydrogen storage.

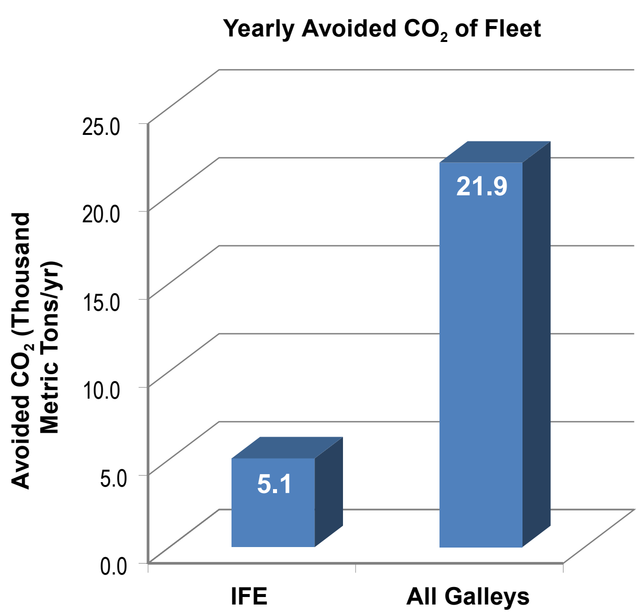

FIGURE 2. Yearly avoided CO_2 emissions for a fleet of 1,000 fuel cell-carrying airplanes operating 750 hrs/yr for each of two different loads: the IFE and All Galleys. The fuel cell system is fuel cooled and assumes renewable hydrogen, as compared to the Base Airplane generating electricity via the main engines at 34% efficiency.

at 2011 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting May 9-13, 2011, Arlington, Virginia.

References

1. Sinnett, M. (2007). "787 No-Bleed Systems: Saving Fuel and Enhancing Operational Efficiencies." Aero Quarterly, 6-11.