

# Fuel Cell Propulsion Systems for an All-Electric Personal Air Vehicle

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# FUEL CELL PROPULSION SYSTEMS FOR AN ALL-ELECTRIC PERSONAL AIR VEHICLE

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## Abstract

There is a growing interest in the use of fuel cells as a power source for all-electric aircraft propulsion as a means to substantially reduce or eliminate environmentally harmful emissions. Among the technologies under consideration for these concepts are advanced proton exchange membrane and solid oxide fuel cells, alternative fuels and fuel processing, and fuel storage. This paper summarizes the results of a first-order feasibility study for an all-electric personal air vehicle utilizing a fuel cell-powered propulsion system. A representative aircraft with an internal combustion engine was chosen as a baseline to provide key parameters to the study, including engine power and subsystem mass, fuel storage volume and mass, and aircraft range. The engine, fuel tank, and associated ancillaries were then replaced with a fuel cell subsystem. Various configurations were considered including: a proton exchange membrane (PEM) fuel cell with liquid hydrogen storage; a direct methanol PEM fuel cell; and a direct internal reforming solid oxide fuel cell (SOFC)/turbine hybrid system using liquid methane fuel. Each configuration was compared to the baseline case on a mass and range basis.

## Introduction

A multidisciplinary effort is underway at the NASA Glenn Research Center to develop and evaluate concepts for revolutionary, non-traditional fuel cell power and propulsion systems for aircraft applications. There is a growing interest in the use of fuel cells as a power source for electric propulsion as a means to substantially reduce or eliminate environmentally harmful emissions. Among the technologies under consideration for these concepts are advanced proton exchange membrane and solid oxide fuel cells,

alternative fuels and fuel processing, and fuel storage. As part of this effort, system studies are being conducted to identify concepts with high payoff potential and associated technology areas for further development. Since the focus of the effort is on long-term, revolutionary concepts, the studies are being conducted to look at the ultimate potential of the fuel cell technology as opposed to the state-of-the-art performance. This paper summarizes the results of a first-order feasibility study that was performed for an all-electric personal air vehicle utilizing a fuel-cell powered propulsion system.

## Considerations for Electric Propulsion Systems

Fuel cells are an energy conversion device that transforms the chemical energy of a fuel and oxidant directly into usable electrical energy. Practically, a fuel cell is a device that: 1) strips electrons from one chemical species, leaving that species in a charged state; 2) makes electrons perform electrical work; 3) makes the charged species cross a barrier; and 4) returns the electrons, along with another chemical component to the charged species to form an entirely different chemical species. This process is shown schematically in Figure 1 for a PEM fuel cell. Electrons are stripped from the fuel, in this case hydrogen, at the anode to form a proton. The electrons are sent through a circuit to an external load while the proton passes through a membrane. At the cathode, the electrons recombine with the protons and oxygen from the air or another oxygen source to form water and heat. Single cells are coupled electrically to form stacks. The stacks along with the supporting ancillary equipment, such as pumps, compressors, and heat exchangers, form the fuel cell system.

Fuel cells offer many advantages over other power generating devices. Unlike batteries,

fuel cells provide continuous power as long as fuel and oxidant are supplied. When operated on hydrogen, the byproducts of the fuel cell reaction are heat and water. Although large quantities of heat can be generated during operation, in many instances the heat can be recaptured and supplied to other processes, such as heating of reactants or fuel processing, or the hot exit streams can be expanded in a turbine to produce power.

For aeronautics applications, fuel cell system power density, defined as the power output per unit weight, is a critical parameter. Figure 2 shows a graph of the expected required increases in system power density to enable electric propulsion for various size aircraft. As can be seen from this chart, fuel cell development for the Gemini, Apollo, and Space Shuttle missions resulted in a 10-fold increase in power density over 18 years. Beginning in the early 1990's, significant investments from the automotive industry resulted in a 7-fold increase over a span of 5 years. Current state-of-the-art technology performance is approximately 0.5 kW/kg at the system level. Based on a one-to-one replacement of the current propulsion system with a fuel cell system, it is estimated that nearly a 20-times increase in power density is required to enable all-electric flight of a large commercial aircraft.

Another important consideration is the type of fuel to be used. The byproducts of the hydrogen reaction in a fuel cell are heat and water. While hydrogen is the fuel of choice from an environmental standpoint (zero emissions), there are some issues associated with its use for aircraft applications. Figure 3 compares the energy stored per unit volume for a variety of fuels. As can be seen from this chart, liquid hydrogen contains significantly less energy per unit volume than other liquid fuels. In addition, when comparing the volume required to store 1 kg of hydrogen (Figure 4), it can be seen that liquid hydrogen is much less volumetrically efficient, requiring up to 40% additional volume than the other fuels. However, while hydrocarbons and alcohols are more efficient in storing hydrogen, a fuel processing or reforming activity must take place, either internal or external to the fuel cell, to convert the hydrocarbon to usable hydrogen fuel. Since a byproduct of the reformation process is  $\text{CO}_2$ , emissionless

operation is compromised unless the  $\text{CO}_2$  is scrubbed from the exit stream.

The two main fuel cell types under consideration for aircraft applications are the PEM and the SOFC. Each of these systems offers distinct advantages as well as issues associated with their use in aircraft propulsion applications. PEM fuel cell technology is at a relatively high state of development due to major investments in recent years by the auto industry. PEM fuel cells operate at relatively low temperatures (20 to 90 °C) and use a proton-conducting polymer membrane as an electrolyte. The anode and cathode are catalyzed porous electrodes bonded directly onto the membrane to form a single cell called a membrane electrode assemble (MEA). Cells are connected electrically in series with bipolar plates, which also serve to deliver and distribute the fuel and oxidant to the anode and cathode. For the most part, PEM fuel cells use hydrogen as the fuel, although some small direct methanol systems have been developed in which the methanol is reformed into hydrogen within the fuel cell.<sup>1</sup> Being low temperature systems, PEM fuel cells cannot directly reform hydrocarbon fuels. Thus, if a PEM system were to be used with a hydrocarbon fuel, a separate fuel processing plant would be required. In addition, PEM systems require low sulfur and CO concentrations in the hydrogen stream to avoid contamination of the catalysts, adding to the complexity of the fuel processing.

The solid oxide fuel cell is an all-ceramic, high-temperature (600 to 1000 °C), solid-state device that uses an oxide ion conducting ceramic material as the electrolyte. The ceramic anode, electrolyte, and cathode materials are deposited in layers to form the solid oxide equivalent of the PEM MEA. There are two primary design types, tubular and planar. The tubular design was pioneered by the US Westinghouse Electric Corporation (now Siemens-Westinghouse) in the late 1970s and has been used primarily for stationary terrestrial powerplant applications. The more recent planar design resembles the PEM configuration in that the ceramic cells are stacked together in a bipolar configuration using metal or ceramic interconnects between the cells to provide a series connection, much like the PEM bipolar plate. The main

advantage of the planar design over the tubular is that higher power densities can be achieved due to the lower losses inherent in the bipolar configuration. This is significant for mobile applications where mass and volume are typically limited. The planar design is, however, still at a low level of technology development as compared to either PEM or the tubular SOFC. Among the technology challenges that are currently being addressed in the industry are the thermal robustness of the ceramics, cell sealing at high temperatures, and cell scale-up.<sup>1</sup>

Although less technically mature, SOFCs offer some potential advantages over PEM fuel cells for aircraft applications. Due to its high operating temperature, the waste heat from the SOFC product stream can be extracted and used for other processes in the system such as fuel heating and reformation. The hot product stream can also be expanded through a turbine to extract power to run the fuel cell system ancillary equipment, such as pumps and air compressors. Unlike the PEM, SOFCs have the option to use CO as a fuel as well as hydrogen. Because of this CO tolerance, hydrocarbon fuels can be more readily used with less processing than in the PEM system. Also, with the high operating temperatures, SOFCs have the potential for direct internal reforming of light hydrocarbons. Direct natural gas reformation has been demonstrated in the tubular design and some work has been done in designing planar stacks with internal processing of natural gas.<sup>2-4</sup> Additionally, SOFCs are more sulfur tolerant than PEM fuel cells, requiring less fuel processing to reduce sulfur levels.

#### Study Methodology

A top-level study was performed to assess the impact of liquid hydrogen-fueled PEM, direct methanol PEM, and direct reforming SOFC-hybrid fuel cell architectures on aircraft take-off weight and range for a fuel cell-powered aircraft. The study expanded on the results of previous work by Freeh in which the Rotax 912 engine of a BanBi aircraft was replaced with an electric propulsion system consisting of a PEM fuel cell system with compressed hydrogen storage, an electric motor, and associated power management and distribution. The BanBi is a two-seat, single engine/prop light kit plane produced by American Ghiles Aircraft. Freeh concluded

that, even with the elimination of additional payload capability, aircraft range was significantly less due to the tank volume and weight issues associated with compressed hydrogen storage. The weight statement for the reference BanBi aircraft with the Rotax 912 engine is given in Table 1. The range with the 60 kW (81 hp) Rotax was approximately 800 nm.<sup>5</sup>

The approach taken for the current study was to choose the BanBi with Rotax 912 engine as the baseline reference system. Based on the weight breakout in Table 1, the line items impacted by the conversion of the BanBi to electric propulsion were the engine and accessories, fuel tank, and fuel weight. The Rotax engine and accessories were replaced with a 60 kW (net) fuel cell propulsion system, which included the fuel cell stack, ancillaries, electric motor, and power conditioning. Fuel and tank weights were calculated based on a constraint of 88 liter total available volume, which corresponds to the BanBi tank volume. It was also assumed that full payload capacity would be retained. Finally, the take-off gross weight was calculated and the aircraft range determined using the Breguet range equation.

Block diagrams of the systems considered in this study are shown in Figures 5 to 7. In the liquid hydrogen-fueled PEM system (Figure 5), liquid hydrogen is stored in an insulated cryogenic tank. The hydrogen is first passed through a heat exchanger to vaporize the fuel and then through a humidifier to humidify the gas before entering the fuel cell. On the air side, ambient air is compressed in a single stage compressor before passing through an aftercooler to remove the heat of compression. The air then passes through a humidifier before entering the fuel cell. A heat exchanger removes the waste heat from the fuel cell. This waste heat may be used to preheat the hydrogen in an optimized system. Finally, a separator removes the water from the fuel cell air exit stream. The fuel cell stack is sized to provide the 60 kW to the electric motor as well as the additional power required by the compressor, which is the most power-intensive ancillary. This system takes advantage of the PEM technology, which is the most advanced, lightest weight fuel cell technology for mobile applications.

Figure 6 shows the direct methanol PEM system. The system is similar to the previous system, except that the methanol is fed directly to the fuel cell stack and is internally reformed into hydrogen. This feature eliminates the need for a separate fuel processing unit, which would add weight to the system. Again, the fuel cell is sized to provide 60 kW to the motor as well as the power required by the compressor. In addition to benefiting from the advancements in PEM technology, methanol provides an increase in stored hydrogen per unit volume as compared to liquid hydrogen. Methanol is also a liquid at room temperature, which allows for easier ground handling.

The final system, a direct internal reforming SOFC/turbine hybrid with liquid methane fuel, is shown in Figure 7. Since direct reforming of natural gas has been demonstrated in tubular solid oxide systems and designs have been proposed for similar planar stacks, liquid methane was chosen as the fuel for this system. Like methanol, liquid methane also provides a more efficient means of storing hydrogen. As in the direct methanol system, the ability to reform the fuel in the fuel cell stack eliminates the weight associated with an external fuel processing unit.

In this concept, liquid methane is pumped to a heat exchanger where the methane is vaporized and heated to the fuel cell operating temperature. Ambient air is compressed and also sent through a heat exchanger to heat the stream to the fuel cell temperature. The methane is converted to hydrogen and CO in the fuel cell stack, both of which are used as fuel. Excess methane and air exiting from the fuel cell stack are burned and expanded in a turbine. The turbine exhaust stream is split and passed through the air and methane heat exchangers to provide heat to the incoming fuel cell streams. The turbine is connected via a shaft to the air compressor and a generator. In this arrangement, the turbine provides power to the compressor. The fuel cell and turbine/generator combine to provide the 60 kW required by the motor. Because of the amount of heat produced and consumed within this system, thermal integration of the components is an important consideration in the optimization of the system.

Since the SOFC planar technology is currently at a low level of development, performance predictions for the direct reforming stack were based on extrapolations from current state-of-the-art to a timeframe of twenty to thirty years into the future in order to assess the ultimate potential of the technology.<sup>6</sup> It was assumed that the cell weight for the direct reforming technology was equivalent to the weight of the lightest state-of-the-art hydrogen-air cells available today. It was also assumed that the performance with direct reformation was comparable to the best performance currently available for hydrogen-air technology.

#### Discussion of Results

Figure 8 summarizes the results of the analysis. The bars on the graph represent the total aircraft weight while the diamond symbols indicate the calculated range for that particular system. The BanBi baseline is shown at a gross take-off weight of 992 lbs with a range of approximately 840 nm using 88 liters of iso-octane.

The gross take-off weight is met with the PEM fuel cell system fueled by liquid hydrogen. However, the constraint of the 88 liter fuel tank volume results in a range that is approximately 1/4 that of the baseline case, illustrating the challenges associated with hydrogen as a fuel. The volume available in the aircraft for hydrogen storage is a critical parameter. In order for a hydrogen-fueled aircraft to be practical, novel hydrogen storage techniques must be investigated and employed.

The direct methanol case shows an improvement in range over the baseline case but exceeds the gross take-off weight. Although the empty weight of the aircraft is essentially the same for both PEM systems, the methanol fuel weight is much heavier than that of liquid hydrogen due to its higher density, resulting in a heavier gross take-off weight.

The most promising system is the direct internal reforming SOFC/turbine hybrid system. This system has the potential to achieve the baseline gross take-off weight while exceeding the range. This is the most advanced system considered with the most aggressive fuel cell performance projections.

However, it is possible to trade fuel weight for fuel cell weight and/or system performance to relax the constraints on the fuel cell technology and still achieve comparable range to the BanBi baseline aircraft.

#### Summary

A top-level study was performed to assess the impact of PEM/liquid hydrogen, direct methanol PEM, and SOFC-hybrid fuel cell architectures on aircraft take-off weight and range for a small fuel cell-powered aircraft. Based on the study methodology, the SOFC-hybrid system appears to offer the most potential in terms of achieving an acceptable take-off weight and range. This is due to a number of factors, including: the use of a hydrocarbon fuel, which is more volumetrically efficient than liquid hydrogen storage; direct internal reforming of the fuel, thus eliminating an external fuel processor; and the ability to extract energy from the hot fuel cell exhaust streams by expanding the gas in a turbine.

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Table 1: BanBi Weight Statement with Rotax 912 Engine

Component	Weight, lbs
Total Structure	196
Systems + Equipment	96
Engine + Accessories	128
Gearbox	37
Propeller	35
Cowl + Mounts	14
Fuel Tank(s)	19
<b>Empty Weight (lbs)</b>	<b>524</b>
Pilot	170
Additional Payload	159
Fuel Weight	139
<b>Takeoff Gross Weight (lbs)</b>	<b>992</b>

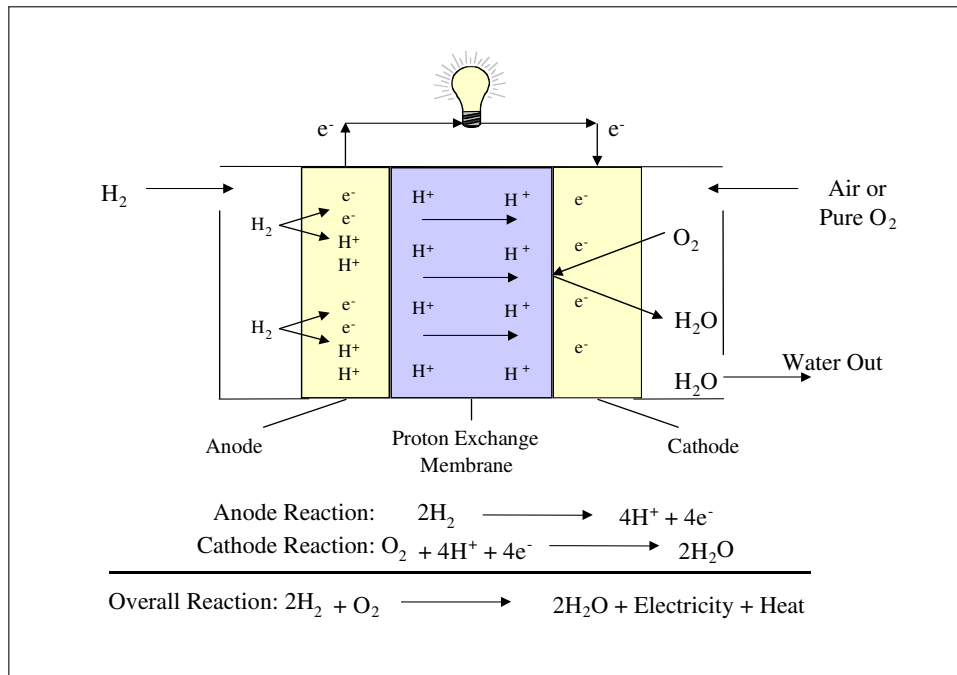


Figure 1: Proton Exchange Membrane Fuel Cell Diagram

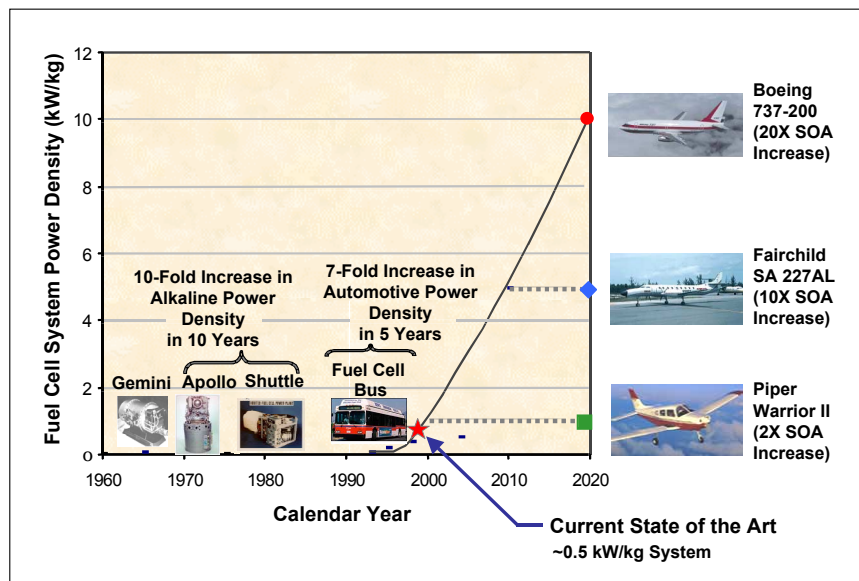


Figure 2: Advances in Fuel Cell Power Density Required to Enable Electric Propulsion

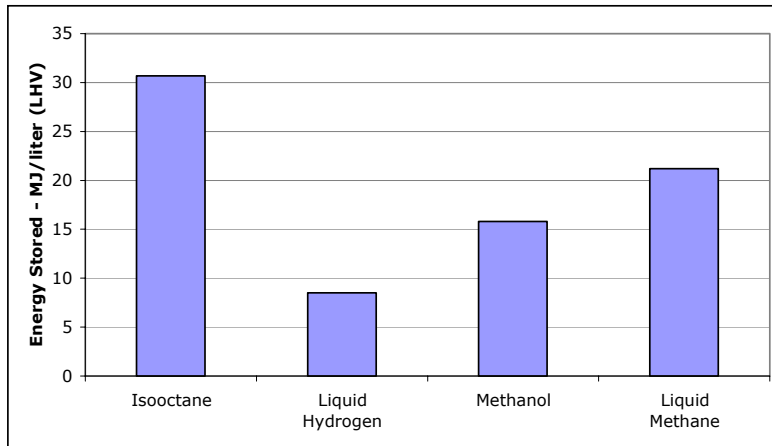


Figure 3: Energy Stored per Liter for Various Liquid Fuels <sup>7,8</sup>

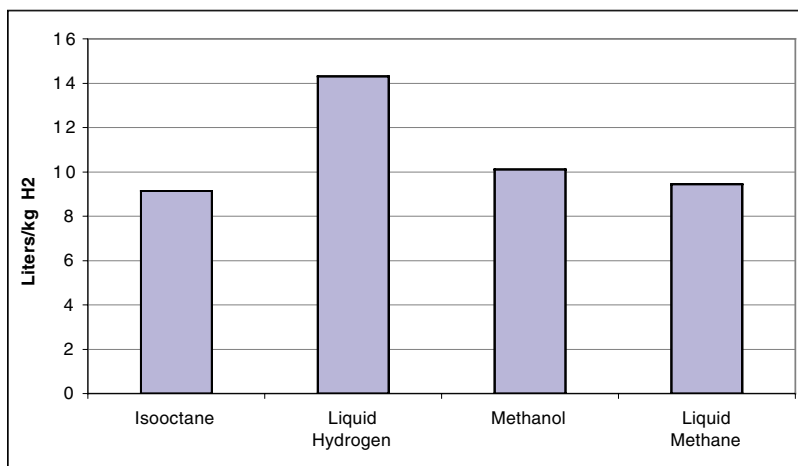


Figure 4: Volume Required to Store 1 kg of Hydrogen

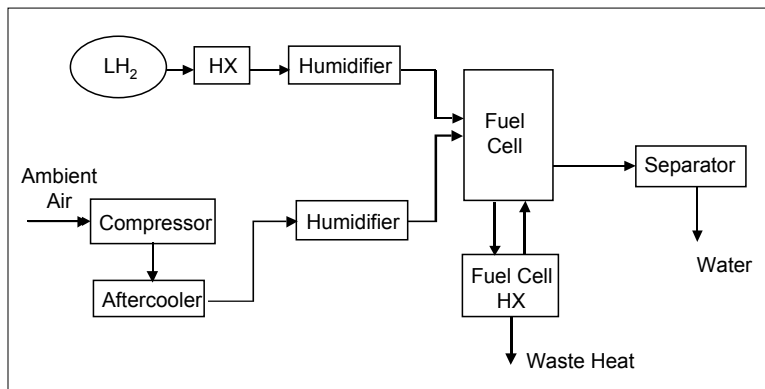


Figure 5: Block Diagram of Liquid Hydrogen PEM Fuel Cell

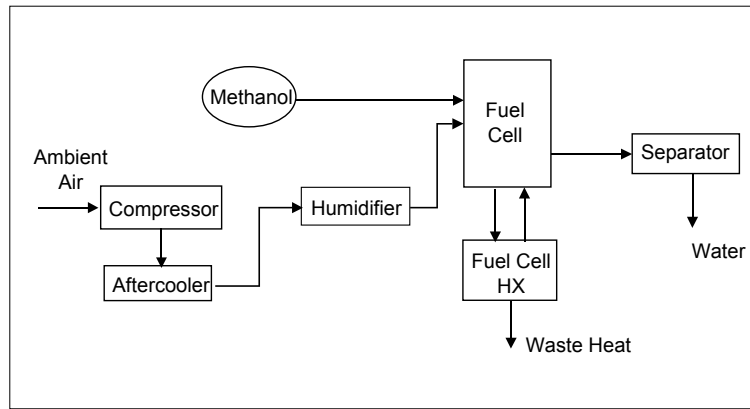


Figure 6: Block Diagram of Direct Methanol PEM Fuel Cell

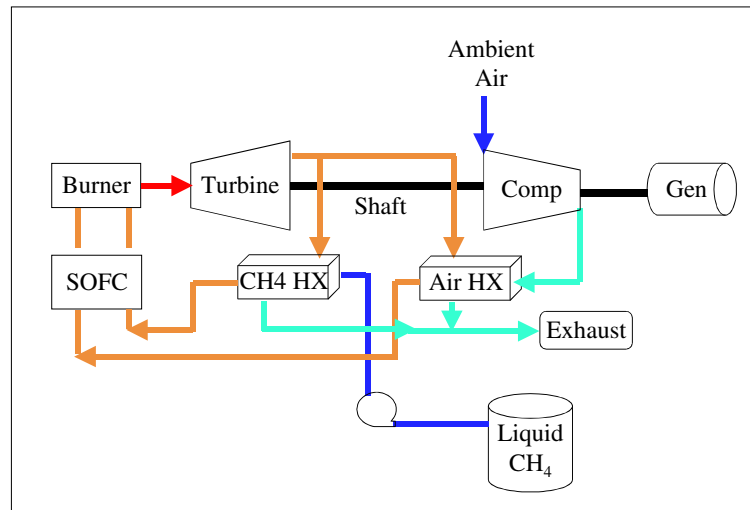


Figure 7: Block Diagram of SOFC/Turbine Hybrid System

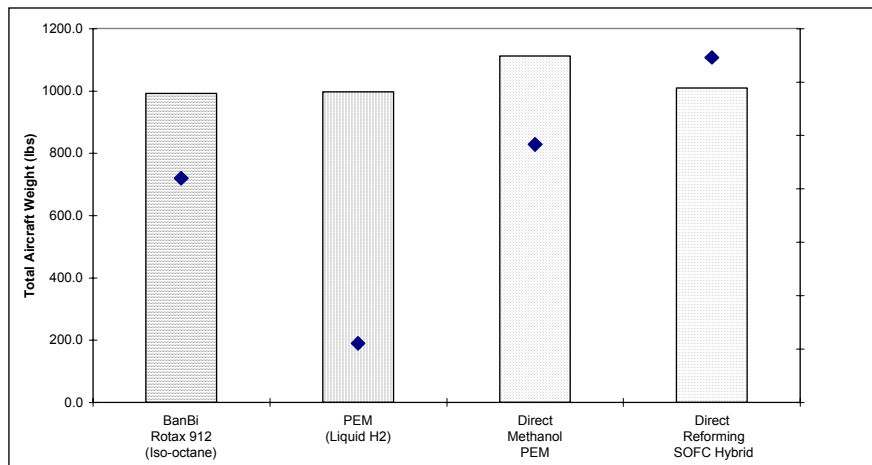


Figure 8: Total Aircraft Weight and Range for Various System Configurations



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