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.

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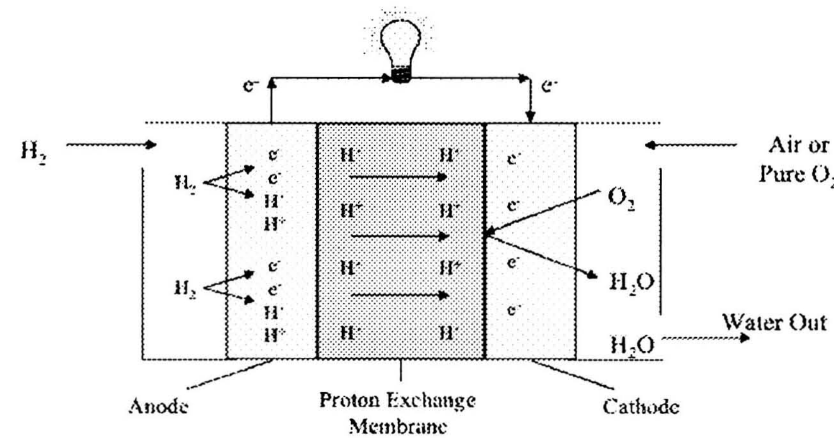
Introduction

- Growing interest in the use of fuel cells as a power source to enable more-electric or all-electric aircraft
  - Reduce or eliminate CO_2, NOx, and noise emissions
- NASA currently evaluating concepts for fuel cell power and propulsion systems for aircraft applications
- Presenting results of first-order feasibility study for an all-electric personal air vehicle utilizing a fuel-cell powered propulsion system
  - Focus on long-term, revolutionary concepts
  - Identify promising areas for technology development
- Wish to acknowledge Paul Schmitz of PCS, Inc. for his significant contribution to this work

How Fuel Cells Work

- A fuel cell is a device that:
  - Strips electrons from one chemical species, leaving that species in a charged state
  - Makes the electrons perform electrical work
  - Makes the charged species cross a barrier (to get the electrons back)
  - Returns the electrons, along with another chemical component, to the charged species to form an entirely different chemical species.



Anode Reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode Reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall Reaction: $2H_2 + O_2 \rightarrow 2H_2O$ + Electricity + Heat

Proton Exchange Membrane (PEM) Fuel Cell

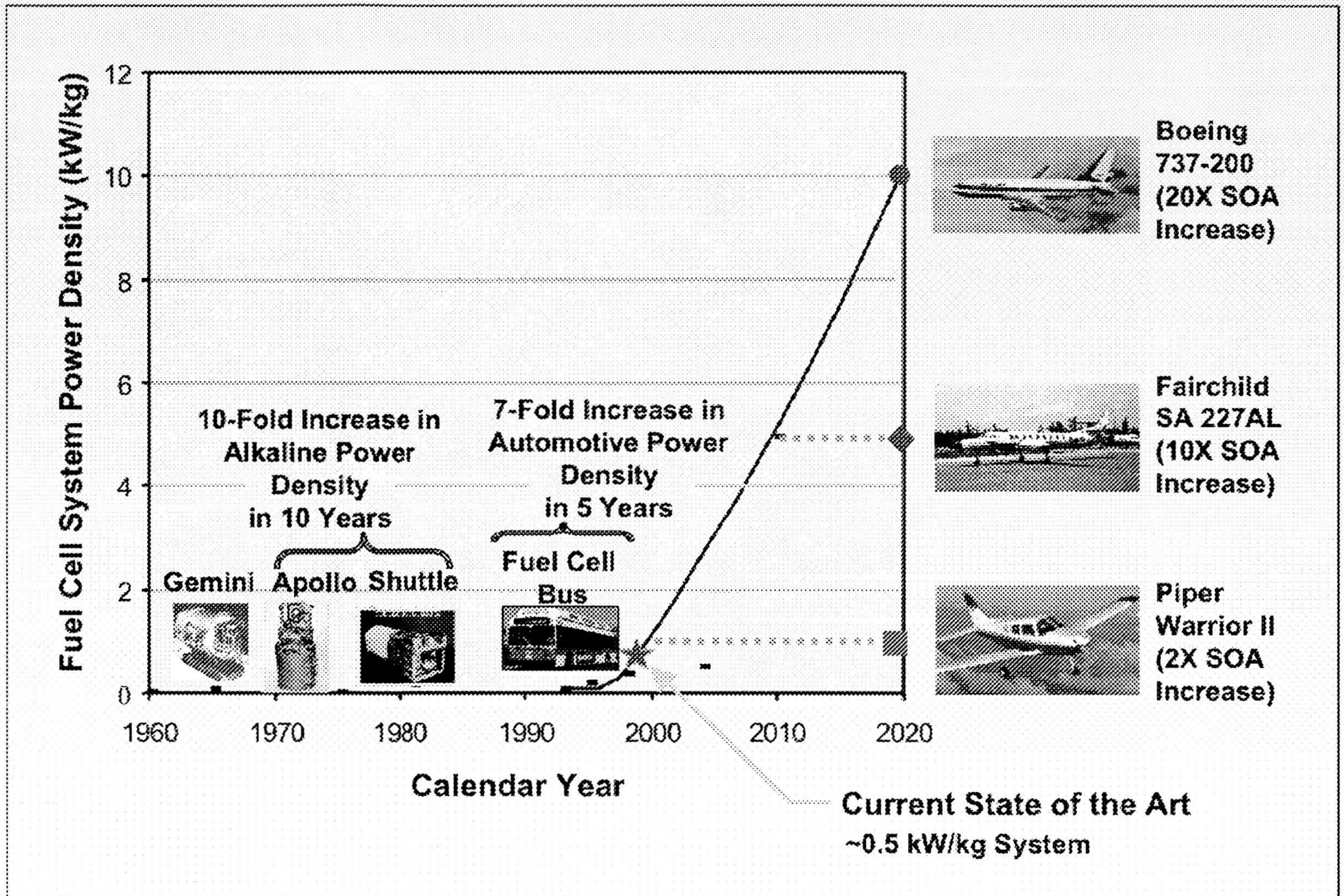
Advantages of Fuel Cells

- Provide continuous power as long as fuel and oxidant is supplied
- Minimal or even zero emissions to environment
  - Heat and water are only by-products with hydrogen fuel
- Fuel cell systems are inherently quiet
  - Stack has no moving parts
- Recapture and reuse of heat generated during operation
- Fuel cells can be part of hybrid power system
- Fuel cells are modular

Important Considerations for Aircraft Applications

- System power density
  - Power produced per unit mass
- Fuel type
  - Hydrogen, alcohols, hydrocarbons
- Fuel cell type
  - Proton exchange membrane
  - Solid oxide

Power Density Trends for Aircraft Applications



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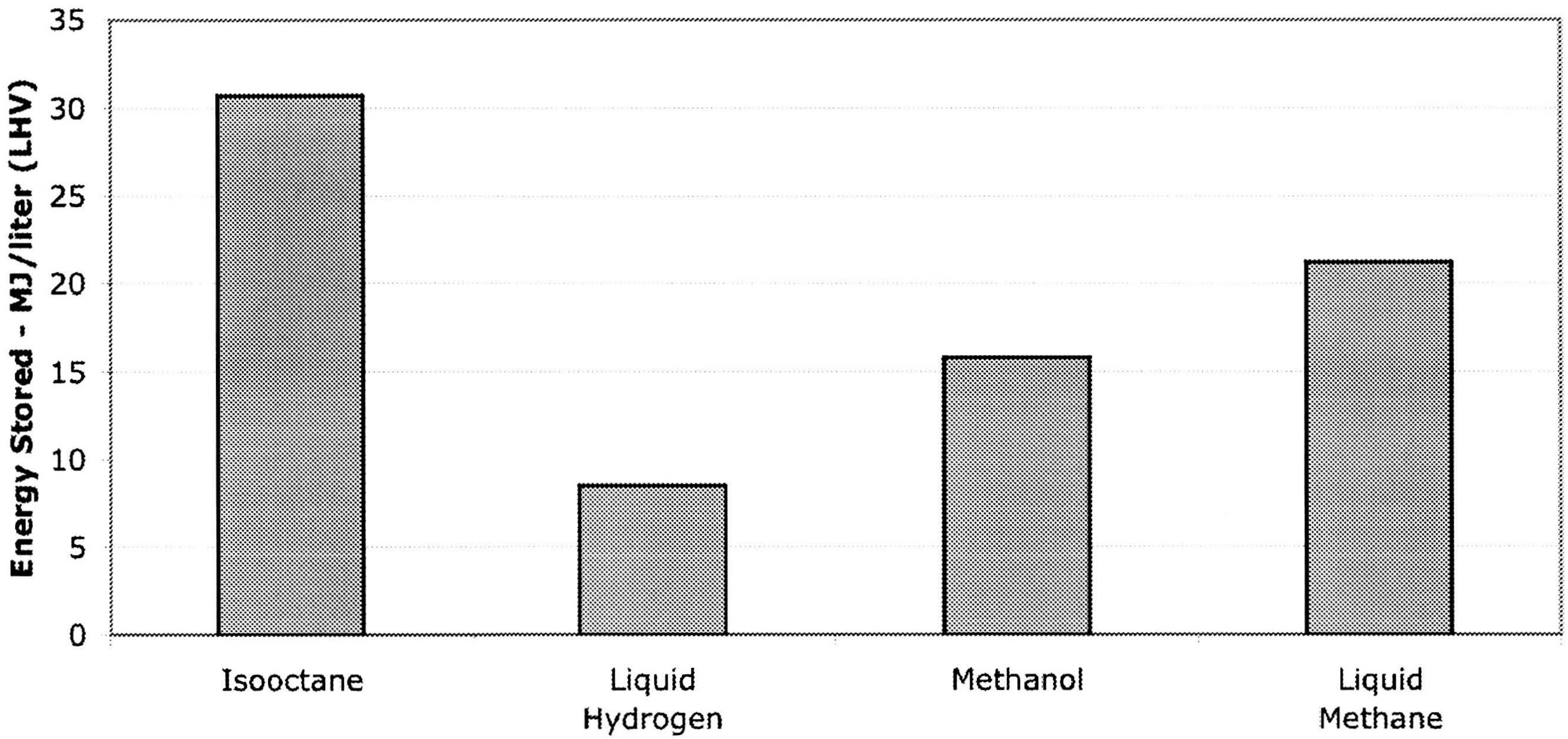
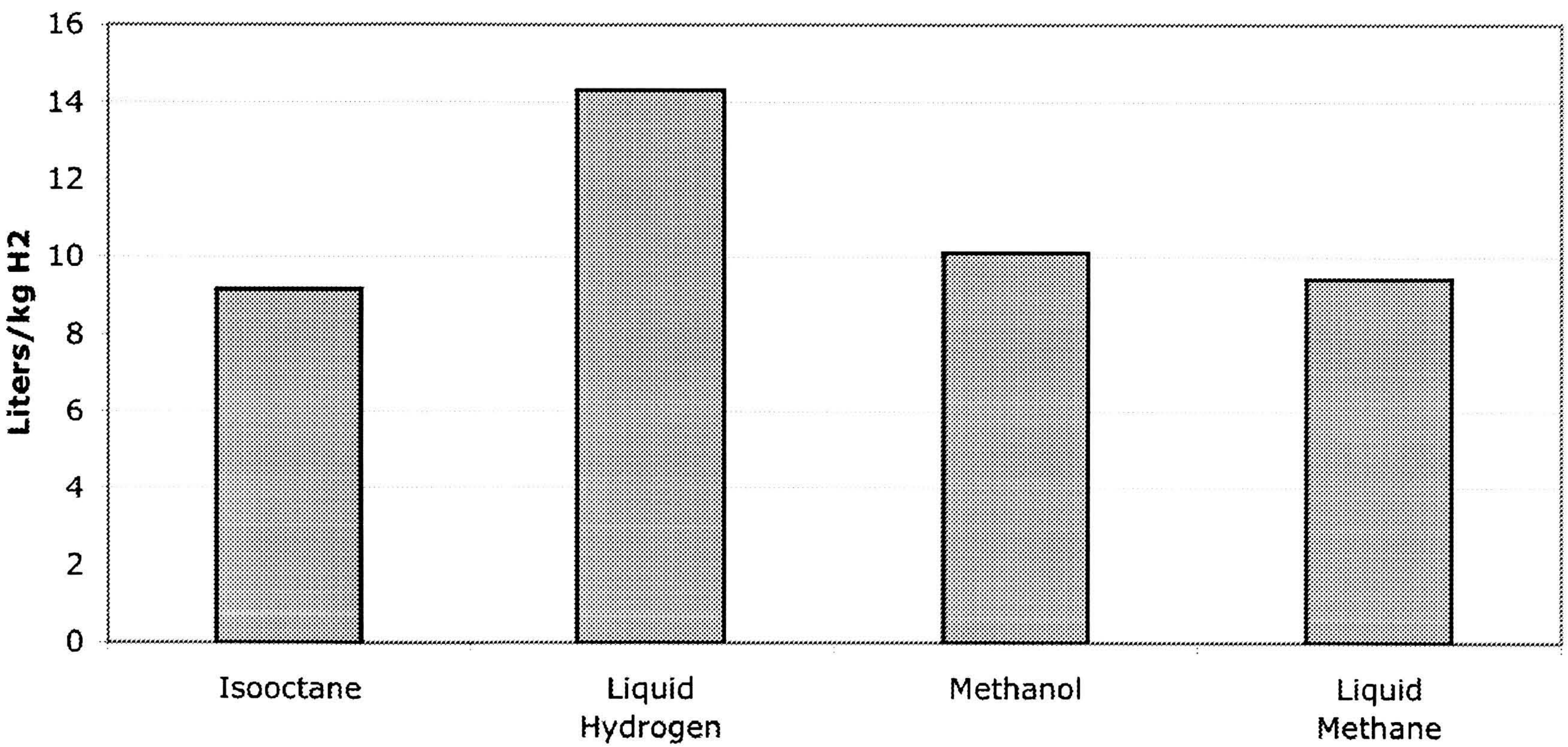
Selection of Fuel

- Hydrogen
  - Clean - no emissions
  - Lower energy per unit volume and lower volumetric efficiency than other fuels
- Hydrocarbons and alcohols
  - Store energy more efficiently than hydrogen
  - Require reforming activity, either internal or external to fuel cell
  - Byproduct of reformation is CO_2 - requires additional processing step to scrub gas
  - Contain sulfur which poisons fuel cells

Energy Stored Per Unit Volume for Various Fuels



Volume Required to Store 1 kg Hydrogen



Proton Exchange Membrane (PEM) Fuel Cells

- Relatively high state of technology development
- Most advanced technology for mobile applications
- Low temperature operation (20-90 ^{o}C)
- Low operating temperature not amenable for internal reforming of hydrocarbon fuel
  - Some small direct methanol systems have been demonstrated
  - Requires external fuel processor for other types of fuel
- Low operating temperature not amenable for use in hybrid configuration
- Sulfur and CO intolerant

Solid Oxide Fuel Cells (SOFC)

- All ceramic solid state device
- Two types of configurations - tubular and planar
  - Planar can achieve higher power densities due to lower losses
- Less technically mature than PEM
- High operating temperature (600 - 1000 °C)
  - High grade waste heat can be extracted and used for other processes
  - Hot product stream can be expanded through turbine to extract additional energy
  - Potential for internal reforming of hydrocarbon fuels
- CO can be used as fuel as well as hydrogen
- More sulfur tolerant than PEM

Study Methodology

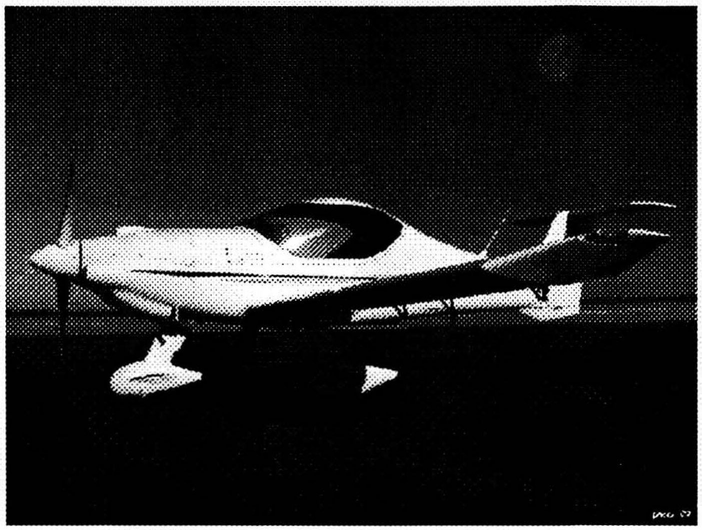
Objective :

- Assess the impact of direct reforming PEM and SOFC-Hybrid power system architectures on aircraft take-off weight and range of a fuel cell-powered aircraft

Approach:

- BanBi with Rotax engine selected as baseline aircraft
- Replace Rotax engine with fuel cell subsystem
- Assume 88 liter BanBi fuel tank capacity as available overall tank volume as a constraint
- Retain functionality of BanBi in terms of payload capacity, take-off weight, and range
- Consider PEM (LH_2 and direct methanol) and SOFC/turbine hybrid (liquid methane) systems
- Calculate weight of fuel cell subsystem, fuel, and tank for each option based on 88 liter constraint
- Determine range for each architecture using the Breguet range equation

BanBi Aircraft

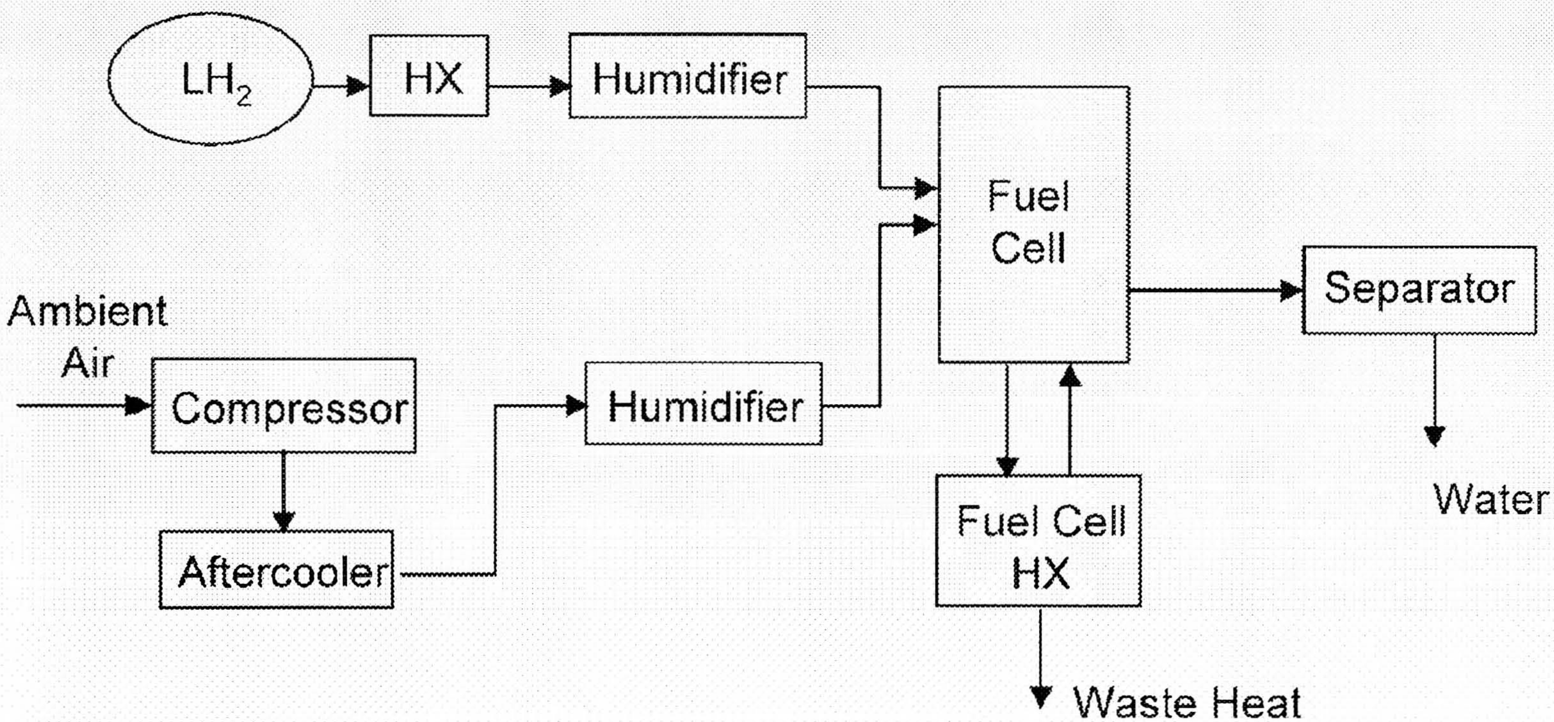


- *Two-seat light kit plane*
- *Single engine/prop*
- *Rotax 912 engine (60 kW net)*
- *Isooctane fuel*

Weight Statement

- Empty Weight: 524 lb
- "Standard" Pilot: 170 lb
- Standard Fuel Weight: 139 lb
- Additional Payload: 159 lb
- Max Takeoff Gross Weight: 992 lb

Liquid Hydrogen PEM Fuel Cell Block Diagram



- PEM mass and performance based on automotive technology
- Fuel cell provides 60 kW to aircraft + parasitic power
- PEM operating at 80 °C, 3 atm

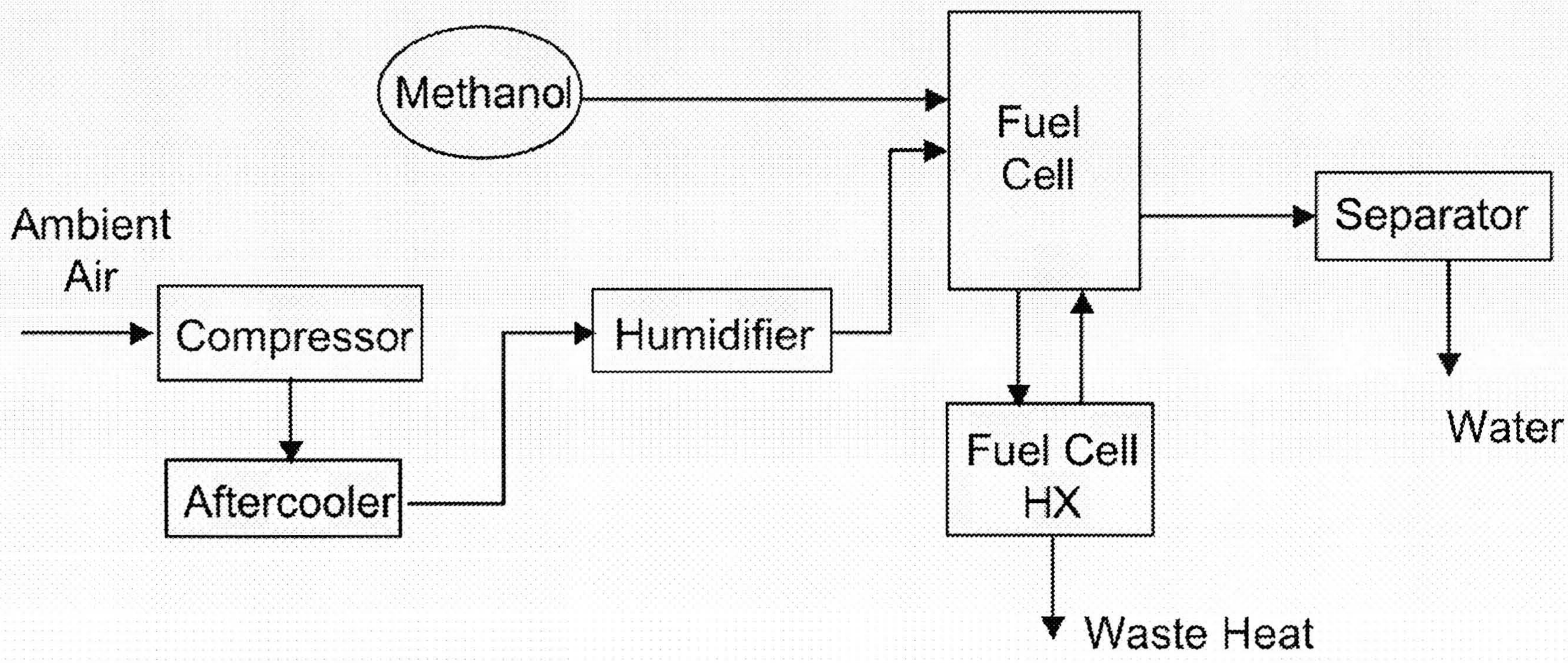
Why Consider Reformation?

- Liquid hydrogen has significantly lower density than other fuels
  - < 1/4 density of methane; < 1/8 density of methanol
- Energy stored per unit volume of liquid hydrogen is also lower than other fuels, such as methane, methanol, and isooctane
- In order to achieve maximum range, this would dictate the use of fuels other than hydrogen

Why Consider Direct Reformation?

- Previous study performed by Kohout and Schmitz shows that reformer can be significant weight penalty
- Two options for direct reforming
  - Direct methanol PEM
  - SOFC

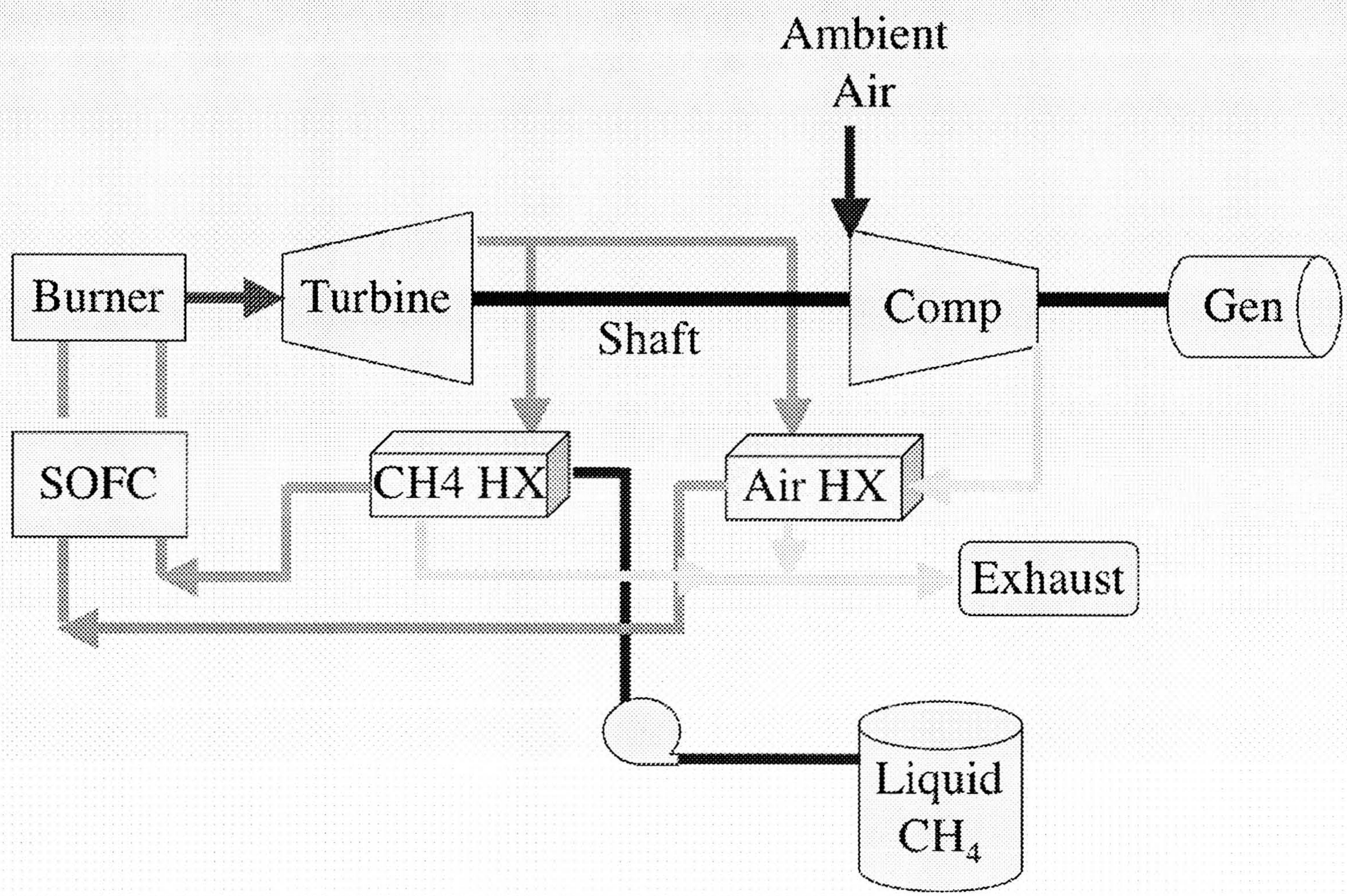
Direct Methanol PEM Fuel Cell Block Diagram



Direct Methanol PEM Fuel Cell Assumptions

- Methanol is only fuel that can be directly reformed at PEM fuel cell operating temperatures
- Direct methanol fuel cells currently nearing commercialization for small portable electronics applications
- Larger systems under development for automotive applications
  - Current direct methanol technology has methanol crossover problems which leads to performance penalty
  - Membrane development required to overcome crossover
- Assume comparable mass and performance to SOA H_2-air automotive technology
- PEM sized to provide 60 kW output to aircraft and parasitic (compressor) power

SOFC-Turbine Hybrid System Block Diagram



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SOFC-Turbine Hybrid Design

- SOFC system power output is a combination of Turbine/Generator output (minus compressor work) + fuel cell power output
- Balance between fuel cell output and turbine output varies as a function of fuel cell and turbine/compressor efficiencies
- Maximum stack temperature rise sets minimum airflow
- Minimum stack entrance temperature from ambient air + Liquid storage tank sets minimum turbine exit temperature (to preheat air/CH_4 to minimum SOFC entrance temperature)
- Burner burns all excess CH_4 if excess air is available

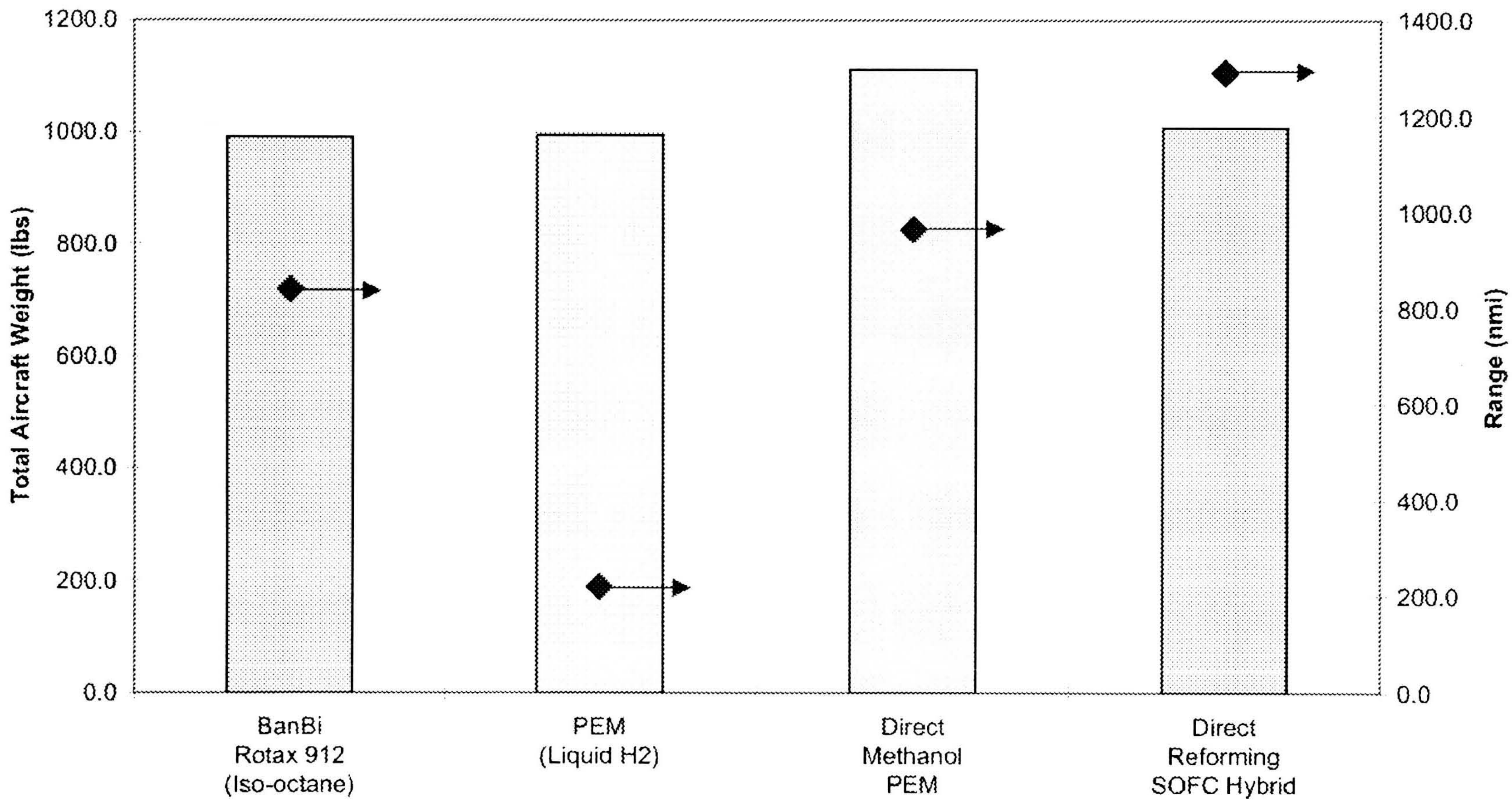
Direct Internal Reforming SOFC Assumptions

- Assume planar SOFC stacks capable of direct internal reforming of methane fuel
- Planar stack technology operating on hydrogen is at low level of technology development
  - Small developmental stacks (<15 cells) have been demonstrated with short lifetimes
  - Performance and weight varies dramatically across industry
- Direct internal reforming of methane has been demonstrated in tubular solid oxide stacks
- Direct internal reforming has been demonstrated in molten carbonate fuel cells in a planar stack configuration
  - Major issue is generation of high thermal gradients across cell leading to thermal stresses in the ceramic materials
  - Stack design includes extra cells to pre-reform fuel before passing fuel to active cells in order to moderate thermal gradients

Direct Internal Reforming SOFC Assumptions (cont'd)

- Assume cell weight for direct reforming system equivalent to weight of lightest state-of-the-art H_2-air cells available today
- Assume performance with direct reformation comparable to best performance currently available for H_2-air technology
- Fuel cell operating parameters:
  - 800 deg.C average operating temperature
  - 3 atm pressure
  - Minimum 15% excess fuel flow rate (determined by turbine output and system heat balance requirements)
  - Complete internal reformation of CH_4

Comparison of PEM and SOFC/Hybrid Systems



Discussion of Results

- Gross take-off weight is met with liquid H_2-PEM fuel cell but 88 l fuel tank constraint results in 1/4 range of baseline case
- Direct methanol PEM shows improvement in range, but exceeds gross take-off weight
  - Empty aircraft weight is essentially the same, but fuel weight is higher for methanol
- Most promising system is direct internal reforming SOFC/hybrid
  - Use of hydrocarbon fuel provides more volumetrically efficient storage of hydrogen
  - Internal reforming eliminates need for external fuel processor
  - Ability to extract additional energy from hot fuel cell exhaust stream

Discussion of Results (cont'd)

- SOFC hybrid has potential to achieve gross take-off weight while exceeding range
  - Most advanced system with most aggressive fuel cell performance projections
  - May be possible to trade fuel weight for fuel cell weight and/or system performance

Conclusions

- For a hydrogen fueled aircraft, available storage volume is a critical parameter
- Other fuels (hydrocarbons, alcohols) offer more efficient storage, but require some level of processing
  - Internal reforming eliminates need for external processor
- Internal reforming SOFC/hybrid appears most promising
  - Least mature of all systems considered
  - Considerable technology development required to meet performance predictions
- Continuing to evaluate and up-date analysis as technology develops