Promising Electric Aircraft Drive Systems

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Outline

• Background
• Critical Technologies for Electric Aircraft
• Power-system configuration options
• Comparing Electric Aircraft Power-systems
• Analytical approach
• Typical component subsystem performance
  – Energy Storage
  – Energy Conversion
• Power-system weight comparisons
• Electric power systems performance targets
• Summary
Background

• The idea to power aircraft with electric motors has been around a long time
  – Patents filed in 1943 for both battery and piston-engine hybrid electric airplanes
  – Progress limited by key technology barriers
    > A source of electricity with power and energy densities suitable for aircraft
    > Electric motors with high power/weight ratios

• What has changed
  – Environmental concerns are accelerating development of electric power-system technologies that have the potential to overcome the historical barriers
Worldwide Interest in Piloted Electric Aircraft

Pipistrel Taurus – 2007
Li-Polymer battery
65 mph 1.0 hr

Boeing Dimona – 2008
PEM fuel cell + Li-ion battery
62 mph for 20 min

Antares DLR-H2 – 2008
PEM fuel cell + battery
106 mph, 10 min flight, 465 mi range

DigiSky SkySpark – 2009
Li-Polymer battery
155 mph, 8 minute flight

Yuneec E430 – 2009
Li-ion battery
~1.5-2 hr with 60 mph cruise

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Why Now

• Increasing public awareness of environmental and climate concerns

• Maturation and accelerated development of key enabling technologies

• Possible near term market opportunities with reasonable paths for growth
Critical Technologies for Electric Aircraft

Electric Motor

Battery/Energy Storage

Fuel-cell

Hydrogen Storage
Non-Cryogenic Electric Motors

- Power density of non-cryogenic motor will continuously increase with the growth in electric car market (> 6 kW/kg motors can be expected in future).

- > 20 kW/kg power density can be achieved for cryogenic motors
Battery Energy Storage

Battery technologies in development have the potential for 10X increase in storage capacity over currently available Li-ion batteries.

Fuel-cell power-systems will require some battery storage to balance power demands.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Specific Energy (kW•h/kg)</th>
<th>Specific Density (kW•h/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-H₂</td>
<td>~50,000 cycles</td>
<td>200</td>
</tr>
<tr>
<td>Li-ion</td>
<td>~100-15,000 cycles</td>
<td>400</td>
</tr>
<tr>
<td>Li-S</td>
<td>~300 cycles</td>
<td>800</td>
</tr>
<tr>
<td>Li-Polymer</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Advanced Li-S</td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td>Li-ion nano-Si</td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Li-ion ~100-15,000 cycles</td>
<td></td>
<td>400</td>
</tr>
<tr>
<td>Li-S ~300 - ? cycles</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>Li-Polymer</td>
<td></td>
<td>1000</td>
</tr>
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<td>Li-ion nano-Si</td>
<td></td>
<td>1500</td>
</tr>
</tbody>
</table>
Fuel Cell Systems - Advantages / Disadvantages

- **Proton Exchange Membrane (PEM) Fuel-cell:**
  - More mature, operational in cars, high power density demonstrated
  - Need pure H₂, availability and storage challenge
  - Lower operating temperature (low quality heat released) needs larger heavier heat exchanger

- **Solid Oxide Fuel-Cell (SOFC):**
  - Less mature, currently low power density systems
  - 30-45 minute startup warm-up
    > Battery startup operations could reduce impact
  - Can use hydrocarbon fuels
  - Efficiencies greater than 60 % for hybrid system
    > Fuel-cell with gas turbine bottoming cycle
  - **Higher power density needed for mobile systems**
    > Pathway exists to achieve higher power density but will require significant technology development
State of Fuel-cell Technology

- Significant opportunity exists to reduce weight of balance of plant through use of lightweight materials and composite materials (~50% weight reduction possible) – 1 kW/kg stack would correspond to 0.66 kW/kg at system level
- Effective system integration may yield further weight reductions

**Technology Readiness Level (TRL)**

- Stack Power Density (kW/kg)

<table>
<thead>
<tr>
<th>TRL</th>
<th>Proton Exchange Membrane (PEM) Fuel Cell</th>
<th>Solid Oxide Fuel Cell (SOFC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>0.5 kW/kg at system level</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

- 1.25 kW/kg at system level
- 0.5 kW/kg at system level

**Commercial PEM Fuel Cell**

**Developmental SOFC**

Balance of Plant Contributes Significant Weight (~50%)
Hydrogen Storage

Extensive Research Underway on Solid State Hydrogen Storage

- Complex hydrides
- Microspheres
- Nanotubes

H₂ content of Reformed kerosene
- Volumetric Density: 320 kg/m³
- Gravimetric Density: 33%

Gravimetric Density (% weight Hydrogen)

Volumetric Density (kg/m³)

- DOE 2010 Goal
  - 2 kW•h/kg
- DOE 2015 Goal
  - 3 kW•h/kg
- Low Temp Hydrides
- Compressed H₂ (with container)
- Liquid/Cryogenic H₂ (with container)

- Current available: 3-6 wt%
- Potential for > 15 wt % based on theoretical limits
Power-system configuration options

Energy Storage (Chemical)

- Hydrocarbon
- Hydrogen
- Electrochemical

Energy Conversion (Mechanical Final Output)

- Baseline
- IC Engine
  - Chem - Mech
- Fuel-cell (SOFC)
  - Chem - Elect
  - C_{n-1}H_{2(n+1)} - H_2
- Fuel-cell (PEM)
  - Chem - Elect
- Reform
- PM/D
  - Elect - Elect
  - PM/D
  - Elect - Elect
- Electric Motor
  - Elect - Mech
- Electric Motor
  - Elect - Mech

IC: Internal (Intermittent) Combustion
PEM: Proton Exchange Membrane
SOFC: Solid Oxide Fuel-Cell
PM/D: Power Management/Distribution
Comparing Electric Aircraft Power-systems

- Power-systems are normalized by maximum power and total available energy
- System weight is used as a figure of merit
- Two reference mission used as a basis for comparison
  - Light Utility General Aviation (GA)
    - 3525 lb GTOW
    - 170 Knts
    - 300 HP
    - 4.75 hr endurance
  - Light Primary Trainer
    - 1100 lb GTOW
    - 85 Knts
    - 67 HP
    - 1.5 hr endurance
- Electric aircraft synergistic advantages not considered
Analytical Approach

• Vehicle Power-systems are decomposed into energy storage and energy conversion subsystem components
  
  – **Energy storage components**
    > Fuel: Hydrocarbons, H$_2$, electrochemical…
    > Containers: tanks, pressure vessels, batteries…
  
  – **Energy conversions components**
    > Chemical to mechanical: Combustion Engines
    > Chemical to electric: Fuel-cells, Batteries
    > Electric to electric: Power Management
    > Electric to mechanical: Electric Motors

• Storage component weights scale to *energy* requirement

• Conversion component weights scale to *power* requirement

• Weight of Power-systems providing equivalent mechanical energy (Power delivered over time) is the primary figure of merit
Power-system Energy Model

- **$E_R$: Energy Requirement**
  
  \[ E_R = \sum_{n}^{m} (P_n)(t_n) \]
  
  Where:
  - $P_n$ is power level for interval $n$
  - $t_n$ is time at interval $n$

- **$E_S$: Total stored energy**
  
  \[ E_S = \frac{E_R}{(\eta_1)(\eta_2)(\eta_3)(\eta_4)} \]
  
  Where:
  - $\eta_n$ is efficiency of energy conversion component $n$

**Reference Missions:**

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>$E_R$ (kW*hr)</th>
<th>$P_{\text{max}}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Utility GA</td>
<td>800</td>
<td>225</td>
</tr>
<tr>
<td>Light Trainer</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>
Power-system Weight Model

- $W_S$: Total system weight
  
  $W_S = W_{ES} + W_{EC}$

- $W_{ES}$: Sum of energy storage component weights
  
  $W_{ES} = \sum_n (E_S)(\gamma_n)$

- $W_{EC}$: Sum of energy conversion component weights
  
  $W_{EC} = \sum_n^m (P_{max})(\theta_n)$

Where:

- $P_{max}$ is Maximum power
- $\gamma_n$ is the weight scaling factor for energy storage component $n$
- $\theta_n$ is weight scaling factor for energy conversion component $n$
Energy Storage
Typical and Projected Performance Parameters

Energy Storage weight factors: $\gamma$ (energy density)

- **Fuels**
  - Hydrogen ($\text{H}_2$) 33.5 kW*hr/kg
  - Kerosene ($\text{C}_{12}\text{H}_{26}$) 14.3 kW*hr/kg

- **Batteries ($\eta = .98$)**
  - Li-S (2010) 0.25 kW*hr/kg
  - Li-ion/Li-S (2015) 0.65 kW*hr/kg

- **Tanks**
  - Liquid HC 10.0
  - $\text{H}_2(\text{gas})$ (2010) 0.06
  - $\text{H}_2(\text{gas})$ (2015) 0.10
Energy Conversion weight factors; $\theta$ (power density)

- **Fuel-cells ($\eta = 50\%$)**
  - Proton Exchange Membrane (PEM)
    - 2010: Automotive systems 0.9 kW/kg
    - 2015 1.5 kW/kg
  - Solid Oxide Fuel-Cell (SOFC)
    - 2010 0.25 kW/kg
    - 2015 0.50 kW/kg

- **Power management/distribution ($\eta = 97\%$)**
  - 2010: Automotive systems 5.0 kW/kg
  - 2015 8.0 kW/kg
Mechanical Energy Conversion
Typical Performance Parameters

Energy Conversion weight factors; $\theta$ (power density)

- **Internal Combustion Engine ($\eta = 30\%$)**
  - **Continental IO-550 (300 HP)**
    - Power = 224 kW
    - Weight = 227 kg
    - $\theta = 1.0 \text{ kW/kg}$
    - Weight = 0.984 kW/kg
  - **Rotax 912S (100HP)**
    - Power = 74.6 kW
    - Weight = 68 kg
    - $\theta = 1.10 \text{ kW/kg}$

- **Electric Motors ($\eta = 95\%$)**
  - **Tesla Automobile (244 HP)**
    - Power = 182 kW
    - Weight = 52.2 kg
    - $\theta = 3.4 \text{ kW/kg}$
    - Weight = 3.49 kW/kg
  - **Honda FCX (134 HP)**
    - Power = 100 kW
    - Weight = 33.8 kg
    - $\theta = 2.96 \text{ kW/kg}$

- **Gas Turbine ($\eta = 34\%$)**
  - **P&W PT6A (1500 HP)**
    - Power = 1125 kW
    - Weight = 220 kg
    - $\theta = 5.1 \text{ kW/kg}$
Light Utility Aircraft
Power-systems weight comparison

GTOW
3564 kg

1600 kg ~ 3525 lb
315 km/hr ~ 170 kns
225 kW ~ 300 HP
4.75 hr

Electrical Power Systems Weight (kg)

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel

Light Primary Trainer
Power-systems weight comparison

500 kg ~ 1100 lb GTOW
160 km/hr ~ 85 knts
50 kW ~ 67 HP
1.5 hr

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel

Electrical Power Systems Weight (kg)

Piston Engine
Gas Turbine
PEM 2010
PEM 2015
SOFC 2010
SOFC 2015
Battery 2010
Battery 2015
Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Piston Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>• PEM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; η</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td>Power density; θ</td>
<td>0.9 kW/kg</td>
<td>2.5 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; γ</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td>Fuel/Tank weight ratio; ρ</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>• SOFC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; η</td>
<td>50%</td>
<td>65%</td>
</tr>
<tr>
<td>Power density; θ</td>
<td>0.25 kW/kg</td>
<td>0.90 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; γ</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td><strong>• Pure Battery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery energy density; γ</td>
<td>0.25 kW*hr/kg</td>
<td>2.35 kW*hr/kg</td>
</tr>
</tbody>
</table>
Summary

• Available electric motor and power-management systems are adequate, however significant technology challenges remain in the development of batteries, fuel-cells, and light weight H₂ tanks

• Battery powered aircraft will require a 10X energy density increase to match Light Utility GA piston performance, but looks like a viable option for Light Primary Trainer aircraft in the near future

• Several potentially viable approaches exist for electric propulsion-systems and targets for component performance have been identified, but significant development work remains before the best solution is known

• The rate Electric Aircraft Propulsion technologies are advancing is encouraging and holds the promise of new more capable aircraft in the near future.