Promising Electric Aircraft Drive Systems

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Michael Dudley: NASA Ames Research Center

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

Specific Energy (kW•h/kg)

- **Ni-H₂**: 50,000 cycles
- **Li-ion**: ~100-15,000 cycles
- **Li-S**: ~300 - ? cycles
- **Li-Polymer**
  - Advanced Li-S
  - Li-ion nano-Si

Specific Density (kW•h/m³)

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

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

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)
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
- Fuel-cell (PEM)
  - Chem - Elect
- Reform
  - \( C_nH_{2(n+1)} \rightarrow H_2 \)
- Battery
  - Chem - Elect
- PM/D
  - Elect - Elect
- 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, H₂, 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>Mission</th>
<th>$E_R$</th>
<th>$P_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Utility GA</td>
<td>800 kW*hr</td>
<td>225 kW</td>
</tr>
<tr>
<td>Light Trainer</td>
<td>60 kW*hr</td>
<td>50 kW</td>
</tr>
</tbody>
</table>
Power-system Weight Model

- $W_S$: Total system weight
- $W_{ES}$: Sum of energy storage component weights
- $W_{EC}$: Sum of energy conversion component weights

\[
W_S = W_{ES} + W_{EC}
\]

\[
W_{ES} = \sum_n \left( E_S \right) (\gamma_n)
\]

\[
W_{EC} = \sum_n^{m} \left( P_{\text{max}} \right) (\theta_n)
\]

Where:
- $P_{\text{max}}$ 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 ($H_2$) 33.5 kW*hr/kg
  - Kerosene ($C_{12}H_{26}$) 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
  - $H_2$ (2010) 0.06
  - $H_2$ (2015) 0.10
Chemical and Electrical Energy Conversion

Typical and Projected Performance Parameters

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

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

- **Power management/distribution ($\eta = 97\%$)**
  - 2010: Automotive systems $5.0 \text{ kW/kg}$
  - 2015 $8.0 \text{ kW/kg}$
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
    - \( \theta = 1.0 \text{ kW/kg} \)
  - *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
    - \( \theta = 3.49 \text{ kW/kg} \)
  - *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

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

GTOW 3564 kg

Electrical Power Systems Weight (kg)

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel

Piston Engine
Gas Turbine
PEM 2010
PEM 2015
SOFC 2010
SOFC 2015
Battery 2010
Battery 2015
Light Primary Trainer
Power-systems weight comparison

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

Electrical Power Systems Weight (kg)

- Motor
- Power Mgmt
- Fuel-cell
- Battery
- Tank
- Fuel

GTOW
Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

<table>
<thead>
<tr>
<th>System Type</th>
<th>Efficiency; $\eta$</th>
<th>Power density; $\theta$</th>
<th>Battery energy density; $\gamma$</th>
<th>Fuel/Tank weight ratio; $\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEM</strong></td>
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</tr>
<tr>
<td></td>
<td>50%</td>
<td>0.9 kW/kg</td>
<td>0.25 kW*hr/kg</td>
<td>0.06</td>
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<tr>
<td></td>
<td>60%</td>
<td>2.5 kW/kg</td>
<td>0.75 kW*hr/kg</td>
<td>0.20</td>
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<tr>
<td><strong>SOFC</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>0.25 kW/kg</td>
<td>0.25 kW*hr/kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65%</td>
<td>0.90 kW/kg</td>
<td>0.75 kW*hr/kg</td>
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<tr>
<td><strong>Pure Battery</strong></td>
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<tr>
<td></td>
<td>0.25 kW*hr/kg</td>
<td>2.35 kW*hr/kg</td>
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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.