Technical Challenges and Barriers Affecting Turbo-electric and Hybrid Electric Aircraft Propulsion

Dr. Ajay Misra
Deputy Director, Research and Engineering
NASA Glenn Research Center

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Why Electric

- Improve fuel efficiency
- Lower emissions
- Reduced noise
- Low operating cost
- Efficiency of electrical components significantly higher than IC engines or gas turbine engines
All Electric Aircraft

Battery → Electric Bus → Motor(s) → 1 to Many Fans

Power Converter
Battery Capability Required for All Electric Urban Mobility Aircraft

Current commercial battery state-of-the-art: 170 Wh/kg
Studies by Happerle (German Aerospace Center)
Dornier 328 turboprop
28 passengers
Baseline range – 750 miles
Speed for electric – 140 – 200 mph

Considering 30 min of reserve
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Series Hybrid Electric Aircraft

- Gas turbine/IC engine used either to charge batteries or provide auxiliary power to drive the motor
- Battery used during takeoff and part or all of cruise
- Gas turbine/IC engine used primarily during part of cruise
- Gas turbine/IC engine can continuously run at the most efficient point
- Gas turbine is sized much smaller

Challenge:
- Efficiency of small engines relatively low (on the order of 30%) compared to large gas turbine engines
Degree of hybridization can be adjusted depending on the mission. One option is for gas turbine to always operate at its peak efficiency point and to use battery when power required is larger than power delivered by the gas turbine (e.g., during takeoff).

Challenge:
- Increased complexity of the mechanical coupling
- Increase in control complexity as power flow has to be regulated and blended from two power sources
Battery Requirement for Commuter and Regional Hybrid Electric Aircraft

48 passenger turboprop

- For 600 nm, battery pack with specific energy greater than 500 Wh/kg for total energy to be less than conventional propulsion
- Battery specific energy must be at least 600 Wh/kg for operating fuel/energy cost parity with advanced conventional propulsion

RUAG Dornier – DO228NG (Juretzko)

- 20 passenger hybrid electric aircraft
- 335 – 350 miles range with battery specific energy of 150 Wh/kg

Hybrid electric, 70 Passengers (Based on Isikveren et.al., ISABE 2015 Paper)

Range, Nautical Miles

Battery Pack Specific Energy (Wh/kg)

Range for 15% block fuel reduction

Assuming pack specific energy = 60% of cell specific energy

200 400 500 600 700 800 900

300 400 500 600 700 800 900

Graph showing the relationship between range and specific energy for hybrid electric aircraft.
Single Isle 737-Class Aircraft

Boeing SUGAR Volt
- Parallel hybrid, ~150 PAX
- 1-5 MW, 3-5 kW/kg, 93% efficient electric machines
- 60% efficiency improvement over 2005 baseline aircraft if a renewable grid is assumed

Lent (UTRC):
- Single aisle 737 class, geared turbofan
- Electric motor used during takeoff along with gas turbine engine
- Addition of turbogenerator during takeoff more effective
- Batteries greater than 1000 Wh/kg required to be competitive with turbogenerator

Pompet et.al. (Germany):
- Single aisle 180 passengers, 3300 n miles base line
- 13 % block fuel reduction for 1500 Wh/kg battery pack
- 6% block fuel reduction for 1000 Wh/kg battery pack
- May not be any benefit for battery pack with less than 1000 Wh/kg specific energy

Battery requirement: 750 Wh/kg

Single-aisle 737 class hybrid electric aircraft will require 1000 Wh/kg or higher battery specific energy
Hybrid Electric Helicopters

- **Light Utility**: Sikorsky S-300 C
- **Multi Mission**: Bell 206 L4
- **Medium Utility**: Airbus EC 175

<table>
<thead>
<tr>
<th>Range, Miles</th>
<th>Light Utility (S-300 C)</th>
<th>Multi-Mission (Bell 206 L4)</th>
<th>Medium Utility (Airbus EC 175)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no electric)</td>
<td>290 Wh/kg</td>
<td>523 Wh/kg</td>
<td>Baseline (no electric)</td>
</tr>
<tr>
<td>Hybrid – 290 Wh/kg</td>
<td>130</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Hybrid – 523 Wh/kg</td>
<td>150</td>
<td>120</td>
<td>90</td>
</tr>
</tbody>
</table>
Battery Chemistry Possibilities

- Pb-acid
- Ni-Cd
- Ni-metal hydride
- Li-ion
- Li-S
- Zn-air
- Li-air
- Gasoline

Energy density, watt-hours/kg

- Practical
- Theoretical
Reduction in Cell-to-Pack Battery Specific Energy

Specific Energy (Wh/kg)

Typically 40 – 50% decrease

Reduction in Specific Energy From Cell to Pack:
- Thermal management
- Battery management system
- Safety features
- Packing
Limits on Useable Specific Energy

Based on current packaging and integration technologies

- Tesla Model S
- Nissan Leaf
- Gr-NMC622
- Li-NMC622
- Li-S
- Mg-ion
- Li-O₂

Notional Progression of Battery Capability

- **5 Years:**
  - 300 – 350 Wh/kg
  - Si anode, advanced cathode

- **10 Years:**
  - 300 – 400 Wh/kg
  - Li metal anode, advanced cathode

- **15 Years:**
  - 400 – 500 Wh/kg
  - Li metal anode, sulfur cathode

- **> 500 Wh/kg,**
  - Li – oxygen, Beyond Li chemistries

**SOA – 250 Wh/kg at cell level**
Projected Advances in Battery Technology

Rate of increase in specific energy is typically on the order of 5 – 8% per year
Specific energy loss from cell to pack is typically 50 to 60%

Assuming 8% increase per year at cell level

Innovation required in:
- New chemistries and materials for cells
- Pack design and integration
Dependency of Evolution of Electrified Aircraft on Battery Advances

Notional timeline based on optimistic projections

More system analysis required to identify requirements

**All Electric**

<table>
<thead>
<tr>
<th>Year</th>
<th>Battery Wh/kg</th>
<th>Passengers</th>
<th>Range (miles)</th>
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</thead>
<tbody>
<tr>
<td>Today</td>
<td>150-170</td>
<td>2-3</td>
<td>200</td>
</tr>
<tr>
<td>2021</td>
<td>300</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>2025</td>
<td>400</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>2028</td>
<td>500</td>
<td>2-3</td>
<td>100-120</td>
</tr>
<tr>
<td>2030</td>
<td>600</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>???</td>
<td>700</td>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>???</td>
<td>800</td>
<td>300</td>
<td>&gt;400</td>
</tr>
<tr>
<td>???</td>
<td>1000</td>
<td>70</td>
<td>800</td>
</tr>
</tbody>
</table>

**Hybrid Electric**

- 20 passenger, 300 miles
- 20 – 30 passenger > 400 miles
- Light utility helicopter (15% block fuel reduction)
- 70 passenger, 1000 miles
- Single aisle 737 class (15% block fuel reduction)

Timeline

Notional timeline based on optimistic projections

More system analysis required to identify requirements
Batteries with some load bearing capability or structure with energy storage capability ????
Application of Fuel Cells

X-57 FUELEAP System
Using Solid Oxide Fuel Cell:
Power output: 120kW (161hp) max continuous,
158kW (209hp) peak
  • Specific power: 314 W/kg (0.19 hp/lb)
  • Efficiency: 62% (10k ft, std day)

Solid oxide fuel cells
• High efficiency
• Low power density at system level
• Potential range extender for small hybrid electric aircraft
• Durability, thermal cycling

PEM fuel cell:
• Needs hydrogen
Benefits of Turboelectric Propulsion:

- Enables new aircraft configurations
- Decoupling of speeds of turbine and fan
- Multiple fans can be driven by one gas turbine, providing high propulsive efficiency due to higher bypass ratio (BPR)
- Can enable boundary layer ingestion capability

Challenge:

- Development of distortion tolerant fan

Boundary Layer Ingestion Testing at NASA GRC
Single-aisle Turboelectric Aircraft with Aft Boundary Layer Ingestion (STARC – ABL)
- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted turbine engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor
- Projected 7 – 12 % fuel burn savings for 1300 nm mission
• Dozen, small electric motors that accelerate airflow over the wing – provides more lift at low speed – enables takeoff in normal runway

• Cruise – two electrically driven propellers mounted on tip of each wing

X – 57: Distributed Electric Propulsion Demonstrator

• 9 passenger plane, battery powered with turbine range extender
• Much more efficient, cost effective and quiet than comparable aircraft
• Increase use of small and medium US airports and decrease emissions
Need analytical tools to assess benefits of propulsion airframe integration on electrified propulsion aircraft configurations
High Power Density Electric Motors

Key Technologies for Increasing Power Density:
- Higher conductivity materials
- Insulation materials with high thermal conductivity
- Better magnetic materials
- Better packing density
- Advanced topology
- Thermal management
- Lightweight structures
- High speed operation

Current industrial

Current electric vehicles

Siemens (200 kW)
System level, 95% efficiency

Various claims (100 – 200 kW)

NASA research (power density at electromagnetic level), 1 – 3 MW, >96% efficiency

Large gas turbine engine
High power density power converters needed

Need 2-3X increase in power density of MW scale converters

Goal:
- 19 kW/kg plus 99 % efficiency with non-cryogenic cooling
- 26 kW/kg plus >99 % efficiency with cryogenic cooling

Approach – Wide bandgap semiconductors (SiC and GaN)

Advanced magnetic materials to handle the higher switching speeds afforded by new SiC and GaN semiconductors.
Large Aircraft with Superconducting Motor

Current research: Development of fully superconducting, MW scale motor

High ac losses major challenge for superconducting stator

Power densities greater than 20 kW/kg achievable
Thermal Management Challenges

- For a 5 -10 MW system, 100s of kW heat generated
- Heat from multiple sources – power electronics, motors, batteries
- Integration of heat rejection from multiple sources
- Low grade heat difficult to handle
- Increasing use of composites lowers the heat rejection capability of the system
- Lightweight and compact thermal management system required
- Integrated thermal management approach at the aircraft level required
Transmission of MWs of power will require large diameter Cu with severe weight penalty.

High voltages (on the order of 2000 V or more) will be required for the current generation of power cables (Cu, Al):
- Advanced insulation materials required
- Thermal management of the power cable system

New materials with higher electrical conductivity than Cu required:
- Carbon nanotubes show promise
- Superconducting materials possibility – will require cryogenic cooling of transmission cables
Development of Integrated System

- Integration of multiple components and optimization of performance of integrated system a challenge
  - Optimum power extraction from turbine
  - Coupling of generator, motor, and fan
  - Optimized energy management
- Control system with energy coming from multiple sources
- Integrated testing required to address system and sub-system level integration challenges

NASA Electric Aircraft Testbed (NEAT) for testing multi MW level power system
Notional Progression of Electrified Aircraft

- **Today**
  - 4-passenger all electric urban commuter
  - 9-10 passenger commuter all electric and hybrid electric range extender

- **5 Years**
  - 4-seater all electric urban commuting
  - 9-10 seater all electric and hybrid electric range extender
  - 20-30 passenger commuter hybrid electric aircraft
  - 50 passenger regional hybrid electric aircraft with limited range

- **10 Years**
  - 20-30 passenger commuter all electric aircraft
  - 50-100 passenger regional hybrid electric aircraft with full range

- **15 Years**
  - Large aircraft with superconducting motors and hydrogen fuel ??

- **20 Years +**
  - Turboelectric single aisle with innovative architecture
Concluding Thoughts

- Electrified Aircraft is a reality – NOT “IF”, IT IS “WHEN”

- Progression of all electric and hybrid electric aircraft is a strong function of advances in battery technology

- Turboelectric aircraft with innovative propulsion architecture and integrated airframe-propulsion system is an attractive option for large single aisle aircraft

- Advances in many component technologies required
  - 3 to 5 times increase in power density of electric motors
  - 3X increase in power density of power converters
  - 3 - 5X decrease in weight of power cables for MW level power transmission

- Integration of technologies and demonstration of integrated technologies at sub-system and system level are required