Material Challenges and Opportunities for Commercial Electric Aircraft

Dr. Ajay Misra
NASA Glenn Research Center
Cleveland, OH

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# NASA Goals for Fixed Wing Aircraft

<table>
<thead>
<tr>
<th>TECHNOLOGY BENEFITS*</th>
<th>TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)</th>
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</thead>
<tbody>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
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<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)</td>
<td>-33%</td>
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* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines.

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015.

‡ CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used.
Benefits of Electric Propulsion

- Significantly reduced emission (near zero for certain concepts) – green system

- Significant reduction in fuel burn due to higher efficiency of electrical systems

- Reduction in noise

- Advanced concepts (such as distributed propulsion and boundary layer ingestion) might be enabled by certain electric propulsion concepts
Both Concepts can use either non-cryogenic motors or cryogenic superconducting motors.
All Electric Propulsion

EADS – VoltAirs concept
- Li-Air battery
- High temperature superconducting motor
Progression of Adoption of Electric Propulsion in Aircraft

Power Level for Electrical Propulsion System

- kW class
  - All electric and hybrid electric GA

- 1-2 MW class
  - Turboelectric 50 PAX regional
  - Turboelectric distributed propulsion 100 PAX regional

- 2-5 MW class
  - Turboelectric 100 PAX regional
  - Turboelectric distributed propulsion 150 PAX

- 5-10 MW
  - Hybrid electric 737-150 PAX
  - Turboelectric 737-150 PAX

- > 10 MW
  - Turboelectric and hybrid electric distributed propulsion 300 PAX

Today           10 Yr          20 Yr            30 Yr              40 Yr

- Hybrid electric and all electric GA
Key Challenges for Large Commercial Electric Aircraft

- High power density superconducting motor (cryogenic)
- High power density non-cryogenic motor
- Lightweight thermal management system
- High power density power electronics
- Lightweight power transmission cable
- Energy storage system with high specific energy
Power Density of Gas Turbine Engines Compared to Projected Power Density of Electric Motors

- **Power Density, hp/lb**
- **Years From Today**

- **Superconducting (Cryogenic) Motor**
- **Non-Cryogenic Motor**
- **Gas Turbine Engine**
MgB$_2$ easy to fabricate in coil form – needs liquid hydrogen for cooling

The challenge for fully superconducting motor is to develop low ac-loss stator coils

- The state-of-the-art superconducting motor is limited to application of superconducting materials in rotor coils only
- Application of superconducting material in stator coils is limited by high ac losses due to the effect of varying magnetic field
Key Materials Challenge for Fully Superconducting Motor

Reduction of ac-loss in superconducting coil requires:

- Reducing filament size (state-of-the-art filament size on the order of 70-100 microns, experimental filaments of 30 micron diameter, need to reduce diameter to 10 microns or lower)
- Twisting wire with reduction in twist pitch
- Increasing resistivity of sheath material and reaction barrier

Significant manufacturing challenge to develop 10 micron or less diameter MgB$_2$ filament with superconducting properties and required mechanical properties for stator coil application
Material Advancements Needed for High Power Density Non-Cryogenic Electric Motor

- Higher electrical conductivity coil
- Stator coil insulation material with high thermal conductivity and higher temperature capability
- Magnets with higher energy product
- Higher temperature magnets

- Rotor
- Windings
- Permanent Magnets
- Stator
- Rotor Coils
- Commutator
- Shaft
- Brushes
- Stator Magnets
Coils With High Electrical Conductivity

Iodine-doped CNT from Rice University (2011)

2013- carbon nanotube fiber with high specific electrical conductivity by Rice Univ.

Challenge:
- CNT fiber with electrical conductivity greater than Cu
- Fabrication of coils with CNT fiber
- Motor design with CNT fiber
Development of Advanced Magnets

Breakthrough needed to significantly increase maximum energy product of magnets
High Temperature Magnets

No major improvement in increasing temperature capability of magnets over the last decade.

Challenge is to develop high temperature magnets with high maximum energy product (BH) and temperature capability greater than 400°C required.
Advanced Stator Coil Insulation Material

Challenge:
- Polymer composite stator coil insulation materials with order of magnitude increase in thermal conductivity
- Temperature capability of 400°C or higher
Power Electronics Semiconductor

Increase in power density by increasing temperature capability of semiconductor

SiC theoretical ~ 600°C

SOA SiC ~ 250°C

Si ~ 150°C

Need temperature capability beyond the current state-of-the-art (SOAA)

Defect-free SiC for large wafers is a technical challenge

High temperature packaging is a major barrier
Capacitors with higher energy density and higher temperature capability are required for increasing power density of power electronics.
Advanced Capacitors for High Power Density Power Electronics

Challenge:
- Polymer-nanoceramic composite with energy storage capability greater than 20 J/cm³
- High temperature ceramic capacitors with high breakdown strength

Ceramic capacitors with temperature capability beyond 200°C, but have low breakdown strength
Material Advances Critical for Increasing Power Density of Power Electronics

Projected power density improvements for power electronics

Higher temperature and compact power electronics will enable placement of power electronics on motor

Materials advances (higher temperature SiC semiconductor, high temperature packaging, and higher temperature capacitor with high energy density) are critical for 10-fold increase in power density of power electronics
Lightweight Power Transmission

- Electrical cables contribute to significant weight in commercial aircraft
  - 140 miles of Cu electrical wiring in Boeing 747 contributing to 3500 lb of wiring
- Transfer of MW of power in turboelectric and hybrid electric aircraft will require significantly large diameter of Cu cables, adding significant weight
- Lightweight power transmission system required

Superconducting transmission lines between generators and motors

High electrical conductivity carbon nanotube (CNT)
- Iodine-doped CNT from Rice University (2011)

Higher temperature electrical insulation with high thermal conductivity (enables more current to pass through wire, allowing for use of fewer wire)
Material Challenges with Higher Voltage Power Transmission

- Insulation thicknesses must more than double to prevent PD when voltage is doubled.

Corona discharge problem at high voltage

Require materials with high relative permittivity and high breakdown voltage.
High Energy Density Batteries Require Significant Advances in Materials

Requirements for hybrid electric aircraft

Energy Density, watt-hr/kg

- **Li-ion**
  - 15 yr
  - 30 yr

- **Li-S**
  - 15 yr
  - 30 yr

- **Li-Air**
  - 15 yr
  - 30 yr

Dendrite growth on Li anode

Engineered porous cathode structure

IBM
Thermal Management Challenge

- 10 MW power system with 1% loss = 100 kW of heat to be rejected; 3% loss = 300 kW of heat to be rejected
- Thermal management of each component – motors, power electronics, power transmission
- Integrated thermal management strategy required
- Lightweight thermal management system required

Material advances critical for lightweight thermal management system

- Graphite foam heat exchanger
- Lightweight recuperator materials for cryocooler
- Aligned nanotube as thermal interface material
- Flexible and mechanically strong aerogel insulation
Multifunctional Structures Enabling for Reducing Weight of Commercial Electric Aircraft

Multifunctional structure with load-bearing and thermal management capability

Conformal thin film battery

Batteries incorporated inside structure

Multifunctional battery with load-bearing capability

- **Cathode** → Structural Polymer (e.g. LiCoO₂) → Carbon Fibers → Anode Active Material (e.g. graphite)
- **Separator** → Insulating Fibers (e.g. glass)
- **Anode** → Chemically attached (EO)₃ to carbon fibers provide ion conduction
Material advances critical for future large commercial electric aircraft:

- Materials with electrical conductivity higher than that of Cu
- High temperature electrical insulation materials with high relative permittivity and high breakdown voltage strength
- Magnets with high maximum energy product \((BH)_{\text{max}}\)
- Higher temperature magnets
- Higher temperature power electronics semiconductor and packaging technology
- Materials to enable orders of magnitude increase in energy density and power density of energy storage system
- Lightweight thermal management materials
- Multifunctional materials

- 5X increase in power density of electrical motors
- 10X increase in power density of power electronics
- 10X reduction in weight of power transmission
- 10X reduction in weight of thermal management system