Evolution of Fundamental Technologies for Future Electrified Aircraft

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Electrical Component Technologies for Electrified Aircraft

Key Technologies:
- Battery with 3-5X increase in specific energy
- Electric motor with 3-5X increase in power density
- Power converter with 3-5X increase in power density
Battery Requirement for Electrified Aircraft (Notional)

Today

<table>
<thead>
<tr>
<th>Pack Level Wh/kg</th>
<th>Battery Requirement for Electrified Aircraft (Notional)</th>
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<tbody>
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More system analysis required to identify requirements

Hybrid Electric
Battery Chemistry Possibilities

The graph compares the specific energy of various battery technologies. The y-axis lists different battery chemistries, including Pb-acid, Ni-Cd, Ni-metal hydride, Li-ion, Li-S, Zn-air, Li-air, and Gasoline. The x-axis represents energy density in watt-hours per kilogram (Wh/kg), ranging from 0 to 14,000.

- **Battery Pack**
  - Practical: Low energy density
  - Theoretical: Moderate to high energy density

- **Cell**
  - Practical: High energy density
  - Theoretical: Very high energy density

The chart highlights that Li-air and Li-ion batteries offer the highest specific energy both theoretically and practically, making them promising candidates for future applications.
Limits on Useable Specific Energy

Based on current packaging and integration technologies

Useable Energy Density (Wh/L)

Useable Specific Energy (Wh/kg)

Tesla Model S

Nissan Leaf

Gr-NMC622

Li-NMC622

Li-S

Li-O₂

Mg-ion

Notional Progression of Battery Capability at Cell Level

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

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

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

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

- **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
Interdisciplinary Approach for Li – Air Battery Development

NASA Team
- **ARC Team**
  - Atomic Simulations, Computational Chemistry, Multiphysics Modeling

GRC Team
- Development of materials for cathode and electrolyte, Experimental Characterization, Battery Pack Design

AFRC
- Electric Aircraft Requirements, Electric UAV Demo

External Partners
- **CMU** Computational Screening
- **IBM Almaden**
  - Fundamental Chemistry
  - Synthetic Chemistry
- **UC Berkeley/LBNL**
  - Characterization Methods
- **Stanford/S LAC**
  - Adv. Characterization
- **ARL** Atomistic Simulations

- Lithium disc (5/8" dia.)
- Can (positive)
- Separator (0.8" dia.)
- Cover (negative)
- Lithium disc (5/8" dia.)
Multifunctional Structures With Energy Storage Capability

Batteries with some load bearing capability or structure with energy storage capability ????
Technology Options for Increasing Power Density of Non-Cryogenic Electric Motors

- High conductivity materials (better than Cu)
- Insulation materials with higher thermal conductivity
- Better magnetic core materials (high permeability and high magnetic strength)
- Higher slot fill at windings
- Advanced thermal management
- Lightweight structures
- Higher speed
- New topologies based on advanced materials
Amorphous and Nanocomposite Magnets

Challenge: Manufacturing

- Co alloys
- Amorphous nanocomposite
- Si steel

Amorphous and Nanocomposite Magnets:
- Reduction in core losses – higher frequency operation
- Higher rotational speeds
- Smaller and lighter motors for the same amount of power

Increasing Efficiency
Permeability

Magnetic Flux Density
Magnet Strength

Silicon Steel Laminations
Rotor Windings
Commutator
Fabrication Process Development at NASA GRC for Amorphous Magnetic Materials

Spin Caster

Casting Co alloy

(b) A 25-mm by 1.6-km spin cast ribbon

25 mm by 1.6 km Spin Cast Ribbon
Advanced Permanent Magnets

Breakthrough needed to significantly increase maximum energy product of magnets and increase temperature capability.

Need computational design of new materials and development of advanced fabrication techniques for nanocomposites.
Advanced Insulation System

- Combination of low thermal conductivity of insulation and temperature constraints current that can be drawn through conductors

- Thin film insulation with higher thermal conductivity and temperature capability would increase fill factor in slot – more conductor in same space

- High voltage capability for insulation system

Polymer – boron nitride nanotube (BNNT) composite development

BNNT – Electrically insulating, high thermal conductivity
Potential for Carbon Nanotube Conductors

Theoretical electrical conductivity of Carbon nanotube (CNT) higher than Cu, but significant processing challenges remain to separate non-metallic from metallic.
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.

Small diameter superconducting filament development to reduce ac losses.
Notional Timeline for Increase in Motor Power Density

- **Today**
  - Current industrial
  - Current electric vehicles

- **5 Years**
  - Siemens (200 kW)
  - System level, 95% efficiency

- **10 Years**
  - Various claims (100–200 kW)

- **15+ Years**
  - Future non-superconducting (MWs), Advanced magnets
  - Current NASA research (power density at electromagnetic level), 3 MW, >96% efficiency
  - Fully Superconducting, CNT conductor, MWs

- **Power Density, kW/kg**
  - Non-superconducting
  - Superconducting/High conductivity
  - Partial superconducting

The diagram illustrates the expected increase in motor power density over time, with different technologies and performance levels projected for various timeframes.
Wide bandgap semiconductor (SiC and GaN) devices enable:
• Higher frequency operation (on the order of MHz) that reduces energy storage requirements for passives (inductors and capacitors)
• Smaller passives – reduced volume and weight
• Higher temperature operation – better thermal management
<table>
<thead>
<tr>
<th>Company</th>
<th>Continuous power rating, MW</th>
<th>Specific power goal, kW/kg</th>
<th>Efficiency goal, %</th>
<th>Topology</th>
<th>Switch material</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Electric</td>
<td>1</td>
<td>19</td>
<td>99</td>
<td>3 level</td>
<td>SiC/Si</td>
<td>Liquid</td>
</tr>
<tr>
<td>University of Illinois</td>
<td>0.2</td>
<td>19</td>
<td>99</td>
<td>7 level</td>
<td>GaN</td>
<td>Liquid</td>
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<td>Boeing</td>
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<td>26</td>
<td>99.3</td>
<td></td>
<td>Si</td>
<td>Cryogenic</td>
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GE – 1 MW Inverter

University of Illinois – 200 kW Inverter
Development of Amorphous Magnetic Materials for High Frequency Inductors and Transformers

- Cast ribbon
- Strain annealing
- Coated transformer core
Enablers for Increasing Power Density of Power Converters Based on Wide Bandgap Devices

- High temperature packaging technology for SiC-based devices – durability at high temperature is key

- Higher switching frequency enabled by wide bandgap semiconductor devices (SiC and GaN) - reducing the size of passives (inductors, transformers, and capacitors)

- Advanced magnetic materials with capability for high frequency operation

- Full use of high frequency feature of SiC devices require thin film capacitor with high current carrying capability at high temperature

- Passives and EMI will be enabler for increasing power density

- Innovative topology enabled by advances passives and high switching frequency
Progression of All Electric and Hybrid Electric Aircraft Limited by Advances in Battery Technology

Notional timeline based on optimistic projections

### All Electric

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Timeline

Pack Level Wh/kg

- 10 - 20 passenger, 300 miles
- 20 – 30 passenger, > 400 miles
- 50-70 passenger, 800 miles
- 50-70 passenger, 1000 miles
- Single aisle 737 class

2-3 passenger, 400 + miles

NASA GRC • RESEARCH AND ENGINEERING DIRECTORATE
Enabling Technologies for All Electric and Hybrid Electric Aircraft

- High specific energy battery technologies for cell and battery pack
- Advanced magnets
- High-conductivity electrical conductors
- Advanced capacitors
- Advanced insulation system