Hybrid Gas-Electric Subproject Overview

Amy Jankovksy

NASA Interchange with Meggitt Aircraft
Braking systems
Aug 31, 2016
Outline

• Overview of Strategic Thrust 4b Roadmap
  – What is the meaning of hybrid electric propulsion in this context?
  – Aeronautics Research Mission Directorate (ARMD) Overview – Thrusts
  – ARMD Strategic Thrust 4b – Electric/Hybrid Electric

• Overview of Hybrid Gas-Electric Subproject

• Hybrid electric propulsion research in Convergent Aeronautical Solutions Project
Electrified Aircraft Propulsion Terminology

• Electrified Propulsion refers to the use of electric power for aircraft propulsion
  – Could be all or partially electric propulsion
  – Extension of the technology required for “More electric” or “All electric” use of electric power for secondary systems on aircraft

• Hybrid Electric has two meanings in aircraft context
  – One meaning is the use of two power sources, such as turbine engine and electric energy storage, to drive the same fan or propeller shaft—hybrid electric powertrain
  – Another meaning is the combination of more than one propulsive sources such as traditional turbofan engines augmented with a non traditional propulsive power source—hybrid electric propulsion

• Turboelectric Propulsion refers to on-air generated electric power for aircraft propulsion
  – Turboelectric generation already provides electric power for secondary systems on aircraft
  – Options exist for either all or partially turboelectric propulsion
NASA Aeronautics
NASA Aeronautics Vision for Aviation in the 21st Century

Global
Sustainable
Transformative

3 Mega-Drivers

Safe, Efficient Growth in Global Operations
Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Transition to Low-Carbon Propulsion
Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Innovation in Commercial Supersonic Aircraft
Achieve a low-boom standard

Real-Time System-Wide Safety Assurance
Develop an integrated prototype of a real-time safety monitoring and assurance system

Ultra-Efficient Commercial Vehicles
Pioneer technologies for big leaps in efficiency and environmental performance

Assured Autonomy for Aviation Transformation
Develop high impact aviation autonomy applications

U.S. leadership for a new era of flight
ARMD Roadmaps

**Strategic Thrust 1**
Safe, Efficient Growth in Global Operations

**Strategic Thrust 2**
Innovation in Commercial Supersonic Aircraft

**Strategic Thrust 3**
Ultra-Efficient Commercial Vehicles

**Strategic Thrust 4**
Transition to Low-Carbon Propulsion

**Strategic Thrust 5**
Real-Time System-Wide Safety Assurance

**Strategic Thrust 6**
Assured Autonomy for Aviation Transformation

**Community Outcomes and Vision & Strategy**
Near Term: 2015-2025
Mid Term: 2025-2035
Far Term: Beyond 2035

**Benefits, Capabilities (Expanded Outcomes)**

**Research Themes**
Long-Term Research Areas that will enable the outcomes (most outcomes encompass multiple research themes)

**Roadmap and Overarching Technical Challenges**
Specific measurable research commitments within the research themes (most research themes encompasses several technical challenges (TC); each ARMD program project list the TC’s for which they are responsible.)
The Low Carbon Propulsion challenge is to enable carbon-neutral growth in aircraft operations.

The proposed answer is a combination of alternative fuels and alternative propulsion.
Example aircraft concepts

**STARC-ABL concept**
- 150 passenger plane with two turbines and 2.6MW electric motor driven tail cone thruster
- 7-12% fuel burn reduction
- Uses jet fuel, standard runways & terminals

**IMPACT:** Reduce fuel use and emissions of biggest aircraft segment

**Thin Haul concept**
- 9 passenger plane, battery powered with turbine range extender
- Much more efficiency, cost effective and quiet than comparable aircraft

**IMPACT:** Drastically increase use of small and medium airports and cut emissions

• Key Technologies
  - Aircraft System Analysis – modeling, analysis compared to key metrics
  - Engine technologies – >1 MW power extraction from turbofan
  - Propulsion/Airframe Integration – benefit of tail cone thruster (takeoff to 0.8 Mach)
  - Power – >1 MW efficient, high specific power
  - Materials – turbine, magnetic materials, cable materials, insulation

• Key Technologies
  - Aircraft System Analysis – modeling, analysis compared to key metrics
  - Propulsion/Airframe Integration – Blown wing and/or possible fuselage boundary layer ingestion (BLI) (0-200 knots)
  - Energy Sources – advanced batteries, structural batteries, fuel cells
  - Flight Controls – possible opportunities to reduce control surfaces
Hybrid Electric Propulsion
Prove Out Transformational Potential

Explore and demonstrate vehicle integration synergies enabled by hybrid electric propulsion

Work toward full PAI and HEP

Environmental Benefit

Increasingly electric aircraft propulsion with minimal change to aircraft outer mold lines

Modeling
Explore Architectures
Test Beds
Component Improvements

Build, learn, demonstrate

Certify, Operate

Knowledge through Integration & Demonstration

Gain experience through integration and demonstration on progressively larger platforms

Advanced Air Transport Technology Project
Advanced Air Vehicle Program
Electrified Propulsion Flight Opportunities

- Hybrid Electric Propulsion Demonstrators
  - Transport Scale
    - Ground Test Risk Reduction
    - Design & Build
    - Flight Test
    - Preliminary Design
    - Design & Build
    - Flight Test
    - Design & Build
    - Flight Test

- “Purpose-Built” UEST Demonstrators
  - Ground Test Risk Reduction
  - Preliminary Design
  - Design & Build
  - Flight Test
  - Potential Candidates

- Fully integrated UEST Demonstrator
  - Preliminary Design
  - Design & Build
  - Flight Test

- Notional – For Planning purposes only

Advanced Air Transport Technology Project
Advanced Air Vehicle Program
Outline

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Electrified Aircraft offer compelling Environmental Advantages

- Energy sector convergent technology
- Promise of cleaner energy
- Potential for vehicle system efficiency gains (use less energy)
- Leverage advances in other transportation sectors
- Address aviation-unique challenges (e.g. weight, altitude)
- Recognize potential for early learning and impact on small aircraft

Significant Challenges Remain

- Added weight and Electrical Systems losses
- Some concepts require Energy Storage advances
- How to integrate?
- How to control? How to fly?
- How to certify and maintain safety?

The solutions will be SYSTEMS-level
Hybrid Gas Electric Propulsion SubProject (HGEP)

Technical Areas:
- Propulsion System Conceptual Design
  - Superconducting (cryo)
  - 1 MW Superconducting Motor Test
  - Non-superconducting
  - Superconducting Wire
- High Efficiency/Power Density Electric Machines
  - Power System Architecture & Modeling
  - Intelligent Motor Drive
  - NASA Electric Aircraft Testbed (NEAT)
- Flightweight Power
  - Insulation
  - Advanced Magnetic Materials
  - Wide Bandgap Semiconductors
  - Conductors
- Enabling Materials for Machines and Electronics
  - Hybrid Electric Integrated Systems Testbed (HEIST)
  - Piloted Sims
- Integrated Flight Simulation & Testing
  - Hardware-in-the-Loop Testing
  - Electromagnetic Components & Materials

Approach:
- Detailed assessment of reference design concept through modeling and analysis
- 200 kW Subscale System Demo’s on hardware-in-the-loop testbed
- Select Component Demo’s at 1-2 MW Level
- Component maturations for key enabling materials and subcomponents
Hybrid Gas Electric Propulsion SubProject (HGEP)

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Technical Areas:
- Propulsion System Conceptual Design
- High Efficiency/Power Density Electric Machines
- Flightweight Power
- Enabling Materials for Machines and Electronics
- Integrated Flight Simulation & Testing

Two New Technical Areas in FY17
- Aft Boundary Layer Ingestion BLI2
- Turbine/Generator Integration & Controls

Electromagnetic Components & Materials
Hardware-in-the-Loop Testing
Machine TRL Advancement
Propulsion Power Grid Architectures
Machine Power with Application to Aircraft Class

<table>
<thead>
<tr>
<th>Non-cryogenic</th>
<th>100 kW</th>
<th>Largest Electrical Machine on</th>
<th>Aircraft</th>
<th>30 MW</th>
<th>Superconducting</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Seat</td>
<td>0.5 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>19 Seat</td>
<td>2 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
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<tr>
<td>50 Seat Turboprop</td>
<td>3 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>50 Seat Jet</td>
<td>12 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>150 Seat</td>
<td>22 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>300 Seat</td>
<td>60 MW Total Propulsive Power</td>
<td>1 MW</td>
<td>10 MW</td>
<td>3 MW</td>
<td>30 MW</td>
</tr>
</tbody>
</table>

- 50-250 kW Electric Machines
- 0.3-1.5 MW Electric Machines
- 0.3-6 MW Electric Machines
- 1-11 MW Electric Machines
- 3 -30 MW Electric Machines
Propulsion Systems & Conceptual Design

- Parallel Hybrid options studied in detail because podded configurations may allow fleet retro-fit or earlier entry into service
- Single Propulsor Distribution studied to explore minimal airframe modification

<table>
<thead>
<tr>
<th>Study Fidelity / TRL</th>
<th>Boeing SUGAR VOLT Cruise Hybrid</th>
<th>UTRC TO / Climb Hybrid</th>
<th>R-R NA Fleet Opt Hybrid</th>
<th>NASA Turboelectric Aft BLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Flight Fuel Saving for 900nm</td>
<td>14%</td>
<td>6%</td>
<td>24%</td>
<td>7%</td>
</tr>
<tr>
<td>In-Flight Energy Saving for 900nm</td>
<td>0%</td>
<td>2.5%</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>In-Flight Emission Reduction</td>
<td>~ 14%</td>
<td>~ 6%</td>
<td>&gt;24%</td>
<td>~ 7%</td>
</tr>
<tr>
<td>Noise Reduction Potential</td>
<td>Low, fan stays the same, but ground op. noise reduced with core size</td>
<td>Low, fan stays the same, but ground op. noise reduced with core size</td>
<td>Moderate, noise decrease with reduced fan &amp; core size</td>
<td>Moderate, noise decrease with reduced fan &amp; core size</td>
</tr>
</tbody>
</table>

These studies were performed with independent assumptions. Result comparisons are provided for reference only.
Propulsion Systems & Conceptual Design

Technology development needs determined from configuration studies
- Elucidate challenges associated with electrified propulsion development
- Inform research investments

<table>
<thead>
<tr>
<th>Energy Storage</th>
<th>Electrical Dist.</th>
<th>Turbine Integration</th>
<th>Aircraft Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Energy Density</td>
<td>High Voltage Distribution</td>
<td>Fan Operability with different shaft control</td>
<td>Stowing fuel &amp; batteries; swapping batteries</td>
</tr>
<tr>
<td>Battery System Cooling</td>
<td>Thermal Mang’t of low quality heat</td>
<td>Small Core dev’t and control</td>
<td>Aft propulsor design &amp; integration</td>
</tr>
<tr>
<td></td>
<td>Power/Fault Mang’t</td>
<td>Mech. Integration</td>
<td>Integrated Controls</td>
</tr>
<tr>
<td>Machine Efficiency &amp; Power</td>
<td></td>
<td>Hi Power Extraction</td>
<td></td>
</tr>
<tr>
<td>Robust Power Elec.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend
- Parallel Hybrid Specific
- Common to both
- Turboelectric Specific
Electric Machine Component Development

NASA Sponsored Motor Research

- 1MW
- Specific Power > 8HP/lb (13.2kW/kg)
- Efficiency > 96%
- Awards
  - University of Illinois
  - Ohio State University
- Phase 3 to be completed in 2018

NASA In-House Motor Research

- Analytical Studies and Prototype Testing focused on ultra-high efficiency 99%
NASA Sponsored Inverter Research

- 1MW, 3 Phase AC output
- 1000V or greater input DC BUS
- Ambient Temperature Awards
  - 3 Years (Phase 1, 2, 3)
  - GE – Silicon Carbide
  - Univ. of Illinois – Gallium Nitride
- Cryogenic Temperature Award
  - 4 years (Phase 1, 2, 3)
  - Boeing – Silicon CoolMOS, SiGe

### Ambient Inverter Requirements

<table>
<thead>
<tr>
<th>Key Performance Metrics</th>
<th>Specific Power (kW/kg)</th>
<th>Specific Power (HP/lb)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>12</td>
<td>7.3</td>
<td>98.0</td>
</tr>
<tr>
<td>Goal</td>
<td>19</td>
<td>11.6</td>
<td>99.0</td>
</tr>
<tr>
<td>Stretch Target</td>
<td>25</td>
<td>15.2</td>
<td>99.5</td>
</tr>
</tbody>
</table>

### Cryogenic Inverter Requirements

<table>
<thead>
<tr>
<th>Key Performance Metrics</th>
<th>Specific Power (kW/kg)</th>
<th>Specific Power (HP/lb)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>17</td>
<td>10.4</td>
<td>99.1</td>
</tr>
<tr>
<td>Goal</td>
<td>26</td>
<td>15.8</td>
<td>99.3</td>
</tr>
<tr>
<td>Stretch Target</td>
<td>35</td>
<td>21.3</td>
<td>99.4</td>
</tr>
</tbody>
</table>

NASA In-House Inverter Research

- Designing 14 kW Inverter based on HEIST motor and nacelle cooling and packaging requirements
  - 99% efficiency driven by cooling requirements
Enabling Materials

• Use composite materials systems and advanced manufacturing techniques
• Concurrently tailor component materials for hybrid/turbo electric applications and design power components that utilize advanced materials

Dielectrics and Insulation
Improve electrical insulation systems
• Study interface functionalization to enable new composite formulations
• Increase both the thermal conductivity and high voltage stability

Nano-crystalline Magnetic Materials
Enable high frequency operation with low electrical losses
• Collaborate with industry and academia to produce nano-crystalline magnetic material
• Perform alloy development and microstructural stability of soft magnetic alloys
• Support power electronic component development using new alloys

High Conductivity Copper
High risk, high pay-off investment in carbon nano-tube (CNT)/copper composites
• Chemical engineered CNT interfaces
• Sorted CNTs to isolate the metallic conducting from semi-conducting
• SBIR investment in new manufacturing techniques
**Power System Architectures**

**HEIST**: Hybrid Electric Integrated Systems Testbed  
Flight controls integrated with Electrified Aircraft Hardware in the Loop

- **Battery Powered**  
- **Turbine Powered**  
- **Hybrid Power Sharing**

**NEAT**: NASA Electric Aircraft Testbed  
High power ambient and cryogenic flight-weight power system testing

- Designed for modularity
- **Propulsor**
- **Load**
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Convergent Aeronautics Solutions Project
Aircraft Hybrid Electric Propulsion Activities

• M-SHELLS – Multifunctional Structures for High Energy Lightweight Load-bearing Storage
  • Integrates hybrid battery/supercaps into aircraft structure to increase effective specific power & specific energy
  • Converges advanced electrochemistries, microstructures, manufacturing, and nano-technologies
• LION – Integrated Computational-Experimental Development of Li-Air Batteries for Electric Aircraft
  • Investigates “electrolyte engineering” concepts to enables Li-Air batteries with high practical energy densities, rechargeability and safety
  • Converges advances in predictive computation, material science, and fundamental chemistry
• HVHEP – High Voltage Hybrid Electric Propulsion
  • Variable-frequency AC, kV, power distribution with DFIM machines for multi-MWe DEP applications
  • Minimizes constituent weights of power electronics, TMS, and fault protection
• Compact High Power Density Machine Enabled by Additive Manufacturing
  • 2 to 3x increase in specific power of electric machines for DEP enabled by additive manufacturing
  • Compact, lightweight motor designs/topologies, integrated cooling, and multi-material systems/components.
• DELIVER – Design Environment for Novel Vertical Lift Vehicles – cryo-cooling HEP task
  • Maximizing efficiency and power density of electronic components by cryogenic LNG-fuel cooling
  • Longer-range hybrid/electric UAS with reduced fuel-burn and emissions (CO2, sulfur, particulates)
• FUELEAP – Fostering Ultra-Efficient, Low-Emitting Aviation Power
  • GA aircraft / early-adopter application of JP-fueled SOFC power plant for clean, hybrid/electric architecture
  • Zero NOx electric power production at ~2x typical combustion efficiencies
• SCEPTOR – Scalable Convergent Electric Propulsion Technology and Operations Research
  • Seeks 5x reduction in cruise-energy-use by aerodynamic benefits of DEP & batteries in place of engines
  • DEP enables high efficiency wing & high performance wingtip motors for cruise
NASA SCEPTOR Primary Objective

- Goal: 5x Lower Energy Use
  (Comparative to Retrofit GA Baseline @ 150 knots)
  - Motor/controller/battery conversion efficiency from 28% to 92% (3.3x)
  - Integration benefits of ~1.5x (2.0x likely achievable with non-retrofit)

NASA SCEPTOR Derivative Objectives

- ~30% Lower Total Operating Cost (Comparative to Retrofit GA Baseline)
- Zero In-flight Carbon Emissions

NASA SCEPTOR Secondary Objectives

- 15 dB Lower community noise (with even lower true community annoyance).
- Flight control redundancy, robustness, reliability, with improved ride quality.
- Certification basis for DEP technologies.