Hybrid Gas-Electric Subproject Overview

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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 Vision for Aviation in the 21st Century

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

Global Sustainable Transformative

6 Strategic Thrusts
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

**Benefits, Capabilities (Expanded Outcomes)**

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

**Community Outcomes and Vision & Strategy**

Near Term: 2015-2025
Mid Term: 2025-2035
Far Term: Beyond 2035

**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 systems.

- Introduction of Low-Carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems
- Initial Introduction of Alternative Propulsion Systems
- Introduction of Alternative Propulsion Systems to Aircraft of All Sizes

Forecasted Carbon Emissions Growth (Without improvements)
Technology Development—Ongoing Fleet Renewal Operational Improvements—ATC/NextGen/Additional Technology Advancement and Low Carbon Fuels
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
- Increasingly electric aircraft propulsion with minimal change to aircraft outer mold lines
- Modeling
  - Explore Architectures
  - Test Beds
  - Component Improvements

Knowledge through Integration & Demonstration

2020
- Small Aircraft

2030
- Build, learn, demonstrate

2040
- Certify, Operate
- Single Aisle Transport

Environmental Benefit

Gain experience through integration and demonstration on progressively larger platforms
Electrified Propulsion Flight Opportunities

Hybrid Electric Propulsion Demonstrators
- Transport Scale
  - Ground Test Risk Reduction
    - Design & Build
    - Flight Test
  - Small Scale “Build, Fly, Learn”
    - 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

- Preliminary Design
  - Design & Build
  - Flight Test

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

FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26

Notional – For Planning purposes only

Advanced Air Transport Technology Project
Advanced Air Vehicle Program
Outline

• Overview of Strategic Thrust 4b Roadmap
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• Overview of Hybrid Gas-Electric Subproject

• Hybrid electric propulsion research in Convergent Aeronautical Solutions Project
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

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)**

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

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**Two New Technical Areas in FY17**
- Aft Boundary Layer Ingestion BLI2
- Turbine/Generator Integration & Controls HGEP
<table>
<thead>
<tr>
<th>Non-cryogenic</th>
<th>Largest Electrical Machine on Aircraft</th>
<th>Superconducting</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kW</td>
<td>1 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td></td>
<td>3 MW</td>
<td></td>
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<tr>
<td></td>
<td>10 MW</td>
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<td></td>
<td>30 MW</td>
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</table>

**Machine Power with Application to Aircraft Class**

- **9 Seat**
  - 0.5 MW Total Propulsive Power
  - 50-250 kW Electric Machines

- **19 Seat**
  - 2 MW Total Propulsive Power
  - 0.1-1 MW Electric Machines

- **50 Seat Turboprop**
  - 3 MW Total Propulsive Power
  - 0.3-1.5 MW Electric Machines

- **50 Seat Jet**
  - 12 MW Total Propulsive Power
  - 0.3-6 MW Electric Machines

- **150 Seat**
  - 22 MW Total Propulsive Power
  - 1-11 MW Electric Machines

- **300 Seat**
  - 60 MW Total Propulsive Power
  - 3-30 MW Electric Machines

**Advanced Air Transport Technology Project**
**Advanced Air Vehicle Program**
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>
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<tbody>
<tr>
<td></td>
<td>Detailed analysis down to subsystem</td>
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<td>Detailed analysis down to subsystem</td>
<td>High level; airframe and prop. system</td>
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<tr>
<td>In-Flight Fuel Saving for 900nm</td>
<td>14%</td>
<td>6%</td>
<td>24%</td>
<td>7%</td>
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<tr>
<td>In-Flight Energy Saving for 900nm</td>
<td>0%</td>
<td>2.5%</td>
<td>7%</td>
<td>7%</td>
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<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>
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</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>
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</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>
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<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>
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<tr>
<td>Power/Fault Mang’t</td>
<td>Mech. Integration</td>
<td></td>
<td>Integrated Controls</td>
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<tr>
<td>Machine Efficiency &amp; Power</td>
<td>Hi Power Extraction</td>
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<tr>
<td>Robust Power Elec.</td>
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</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%
Electric Machine Component Development

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

<table>
<thead>
<tr>
<th>Key Performance Metrics</th>
<th>Ambient Inverter Requirements</th>
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<tbody>
<tr>
<td></td>
<td>Specific Power (kW/kg)</td>
<td>Specific Power (HP/lb)</td>
<td>Efficiency (%)</td>
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</tr>
<tr>
<td>Minimum</td>
<td>12</td>
<td>7.3</td>
<td>98.0</td>
<td></td>
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<tr>
<td>Goal</td>
<td>19</td>
<td>11.6</td>
<td>99.0</td>
<td></td>
</tr>
<tr>
<td>Stretch Target</td>
<td>25</td>
<td>15.2</td>
<td>99.5</td>
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<table>
<thead>
<tr>
<th>Key Performance Metrics</th>
<th>Cryogenic Inverter Requirements</th>
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<tr>
<td></td>
<td>Specific Power (kW/kg)</td>
<td>Specific Power (HP/lb)</td>
<td>Efficiency (%)</td>
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</tr>
<tr>
<td>Minimum</td>
<td>17</td>
<td>10.4</td>
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<tr>
<td>Goal</td>
<td>26</td>
<td>15.8</td>
<td>99.3</td>
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<tr>
<td>Stretch Target</td>
<td>35</td>
<td>21.3</td>
<td>99.4</td>
<td></td>
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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 advance 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

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

**Designed for modularity**

Propulsor

Load

1MW
10MW
4 x 250kW
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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
SCEPTOR X-57 Research Objectives

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.