NASA’s Motivation for Exploring Electrified Propulsion

Explore use of alternative propulsion to reduce carbon use, noise and emissions in US airspace
- Promise of cleaner energy
- Potential for vehicle system efficiency gains (use less energy)
- Seek to leverage advances in other transportation and energy sectors
- Address aviation-unique challenges (e.g. weight, altitude)
- Recognize potential for early learning and impact on smaller or shorter range aircraft

Significant Challenges Remain
- Added weight and loss of Electrical Systems
- Can 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
Different Use Cases Lead to Different Vehicles

On Demand Mobility
Small Plane Focus

- All Electric, Hybrid Electric, Distributed Propulsion
- Enable New Aero Efficiencies
- Power Sharing
- Distributed Thrust Control
- Certification Trailblazing

Energy & Cost Efficient, Short Range Aviation

Low Carbon Propulsion
Transport-Class Focus

- Turbo Electric, Distributed Propulsion
- Enable New Aero Efficiencies
- High Efficiency Power Distribution
- Power Rich Optimization
- Non-flight Critical First Application

Energy & Cost Efficient, Transport Aviation
Concepts for Distributed Electric Propulsion, Commuters

Small Commuter Concept
- 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

Ground-based testing and Flight Demo for Distributed Electric
- Validate energy use reductions (up to 5X)
- Support projections for reduced operating costs, emissions, noise
- Demonstrate flight controls, power management and distribution, mission profiling, etc.
- Establish certification basis

This talk focuses on Transport Class
Single-Aisle Electrified Aircraft Design Space

Electrified Propulsion Vehicle Configurations

Variations almost unlimited

- Number of passengers,
- Transport range
- Assumed performance for new technologies
- Degrees and form of electrification
- **Currently focusing on three variations**

**N3-X**
Fully Turboelectric, Distributed, Superconducting, 300 PAX

**STARC-ABL**
Partially Turboelectric, Aft Boundary Layer Ingestion, 150 PAX
Component Technology Investment Method

Baseline Future Vehicle
Predicted Available Technologies

Concept that closes w/ Net Benefit

Derive Key Powertrain Performance Parameters

Dissect Contributors to Weight and Loss in SOA

Derive Key Subcomponents Performance Parameters

Vehicle Systems Studies including missions profile, propulsion system, CFD

Calculated power and efficiency curves, etc.

Materials and electromagnetic properties, EMI, fault tolerance, etc.

Build, test, fly, learn at successively higher power and voltage levels

- Validate the vehicle architecture as well as component performance

Investments informed by concepts plus systems-level testbeds

With successively higher fidelity
Large, 300 PAX Requires Superconducting

N3-X Aircraft Concept was Used to Focus Component Performance Parameters

- Lower Fan Pressure + Boundary Layer Ingestion
- Superconducting (including transmission)
- ~4 MW Fan Motors at 4500 RPM
- ~30 MW Generators at 6500 RPM
- ~5-10 kV DC Bus Voltages
- End-to-end efficiency of Powertrain = 98%

Turboelectric Propulsion contributes 9% fuel burn savings (total vehicle net is 70% compared to 2005 baseline)

Component Losses Including cryocoolers

<table>
<thead>
<tr>
<th>Component</th>
<th>Loss</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>0.45%</td>
<td>50 kW/kg</td>
</tr>
<tr>
<td>Rectifier</td>
<td>0.50%</td>
<td>25 kW/kg</td>
</tr>
<tr>
<td>Transmission</td>
<td>0.1%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Inverters</td>
<td>0.50%</td>
<td>25 kW/kg</td>
</tr>
<tr>
<td>Motors</td>
<td>0.48%</td>
<td>21 kW/kg</td>
</tr>
<tr>
<td>Cum. Loss</td>
<td>2.1%</td>
<td></td>
</tr>
</tbody>
</table>

Brown, Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System
GE Aviation, Architecture, Voltage and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)
300 PAX Size Class Technology Development Goals

Key Performance Goals for Superconducting Systems
*Derived from N3-X and related studies*

- Near-term challenge is to design a MW-class, fully superconducting electric machine with:
  - 4 MW >16.4 kW/kg
  - 4,000 RPM >99% efficient
- Address issues with stator coil
  - Understand and reduce AC losses in wire
  - Medium temperature (20°K) superconducting coils
  - Manufacturability
- Advanced cryocoolers
- Cryogenic Power Converters
  - 17-35 kW/kg >99.0 % efficient

Fully Superconducting Machine Details

<table>
<thead>
<tr>
<th>Required Power</th>
<th>1 to 30 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Speed</td>
<td>2,000 to 12,000 rpm</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3 or more</td>
</tr>
<tr>
<td>SC(^*) type and properties range</td>
<td></td>
</tr>
<tr>
<td>BSCCO, YBCO, MgB(_2)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>20 to 77 K</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.2 to 2.5 T</td>
</tr>
<tr>
<td>SC wire parameters</td>
<td></td>
</tr>
<tr>
<td>SC filament diameter</td>
<td>5 to 100 (\mu)m</td>
</tr>
<tr>
<td>Twist pitch</td>
<td>0.5 to 10 cm</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>0.2 to 2.0 mm</td>
</tr>
<tr>
<td>Material properties</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>Al, Ti, Inconel, 304 S.S.</td>
</tr>
<tr>
<td>Composites</td>
<td>G10CR, various</td>
</tr>
</tbody>
</table>

_SC*: superconductor
BSCCO: barium strontium calcium copper oxide
YBCO: yttrium barium copper oxide
MgB\(_2\): magnesium diboride

Model and Design of a Fully Superconducting Electric Generator for Novel Aircraft Propulsion Applications G. Brown, J. Trudell (GRC) P. Masson (AML)
150 PAX Narrow Body Offers Nearer-term Options

Boeing SUGAR Volt
- Parallel hybrid, ~150 PAX
- 750 kW/kg batteries charged from green grid
- 1-5 MW, 3-5 kW/kg, 93% efficient electric machines
- 60% efficiency improvement over 2005 baseline aircraft if a renewable grid is assumed (i.e. wind) to charge batteries

Detailed Parallel Hybrid Analyses
- Looked further into mission optimization
- Rolls Royce
- United Technologies Research Center

STARC-ABL
- Single aisle, turboelectric (partially), 150 PAX
- Aft boundary ingesting electric motor (lightly distributed)
- 2.6 MW motor, ~2500 RPM
- 1.4 MW generator, ~7000 RPM
- 13.6 kW/kg, 96% efficient electric machines
- 7-12% fuel burn savings for 1300 nm mission
**Parallel Hybrid and STARC-ABL common themes**

### Concepts and Other Studies Expose Universal Needs

<table>
<thead>
<tr>
<th>Energy Storage</th>
<th>Electrical Distribution</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, stowing &amp; swapping batteries</td>
</tr>
<tr>
<td>Battery System Cooling</td>
<td>Thermal Mgt. of low quality heat</td>
<td>Small Core development and control</td>
<td>Aft propulsor design &amp; integration</td>
</tr>
<tr>
<td>Power/Fault Management</td>
<td>Mech. Integration</td>
<td></td>
<td>Integrated Controls</td>
</tr>
<tr>
<td>Machine Efficiency &amp; Power</td>
<td>Hi Power Extraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robust Power Electronics</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Component Technology Investment Strategy**

- Targeting common themes for powertrain
- Invest first in flightweight motors, generators and power electronics
- Successively include more interfaces (motor plus controller, filter, thermal control, etc.)
- Enabling materials to achieve required power, voltage, energy densities and efficiencies

**Targeted Higher Risk Work**

- Multifunctional structures (structure integrated with battery/supercapacitor)
- Electrolyte engineering for lithium-air batteries
- Variable frequency AC, high voltage (kV) transmission with double fed induction machines
- Additive manufacturing for electric machines
Power Requirements for Electric Machines

Electric machines required for selected electrified aircraft shown

- Total electric power used for propulsion
- Range of motor and generator sizes used in each configuration
- Up to 150 passengers can get away with MW range, traditional cooling
- Largest of the concepts require cryogens to get superconducting performance
- 1 MW class of machines common to majority of concepts NASA is looking at
- Benefit smaller transport class as well as single aisle

Near-term Challenge is to focus on 1-3 MW powertrains with MW-class components

- Electric Motors and Generators
  - 1-3 MW >13 kW/kg
  - >96% efficient ~2500-7000 RPM
- Power Converters (rectifiers, inverters)
  - >1 kV DC bus 3φ AC
  - >12-25 kW/kg >98% efficient
Impact of Materials on Electrical Machine Performance

Electromagnetic Finite Element Analysis Conducted

- Identified sensitivity of Power Density and Efficiency to differing material property improvements
- Four machine types for two drive conditions, common dimensions)

Materials Technologies Studied

- Improved dielectrics and insulation
- Carbon nanotube/Copper composites to increase conductivity
- Nanocrystalline magnetic materials to enable high frequency circuit devices
  - 50% reduction in loss at high frequency

<table>
<thead>
<tr>
<th>Drive</th>
<th>Motor Type</th>
<th>Baseline Materials</th>
<th>Improved Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Power Density kW/kg (HP/lb)</td>
<td>Efficiency</td>
</tr>
<tr>
<td>Standard</td>
<td>SPM</td>
<td>10.6 (6.4)</td>
<td>95.1%</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>10.4 (6.3)</td>
<td>96.6%</td>
</tr>
<tr>
<td></td>
<td>SRM</td>
<td>4.6 (2.8)</td>
<td>93.5%</td>
</tr>
<tr>
<td></td>
<td>IM</td>
<td>3.5 (2.1)</td>
<td>94.8%</td>
</tr>
<tr>
<td>Tip Drive</td>
<td>SPM</td>
<td>9.6 (5.8)</td>
<td>90.9%</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>9.8 (6.0)</td>
<td>96.5%</td>
</tr>
<tr>
<td></td>
<td>SRM</td>
<td>8.7 (5.3)</td>
<td>96.4%</td>
</tr>
</tbody>
</table>

K. Duffy, Electric Motors for Non-Cryogenic Hybrid Electric Propulsion (AIAA 2015-3891)

1. Surface-mounted permanent magnet (SPM)
2. Interior permanent magnet (IPM)
3. Synchronous reluctance motors (SRM)
4. Induction Motors (IM)
High Fidelity CFD using rapid techniques

- Critical for designs where propulsion and airframe are highly coupled
- Refine and optimize concepts (shape tail, nacelle, attachment points, etc.)
- Viscous simulation to study boundary layer
- Adaptive mesh provides for rapid iterations between airplane shape and predicted propulsive benefits

Dynamic Modeling

- Electrified aircraft have increased steady-state and peak (transient) cooling and power requirements, nonlinear transient loads
- Developing virtual testbed using Distributed Heterogeneous Simulation\(^1\) (computationally efficient, integrated system simulations with protection of proprietary data)
- Using Air Force Research Lab (AFRL)’s INVENT Modeling Requirement and Implementation Plan (MRIP) platform

Piloted Simulations and Controls Research

- Performance and control research and testing in preparation for flight demonstrators
- Validate ideas such as hybrid power sharing, windmilling, battery start
- Lessons and scalability for larger MW-scale architectures

Jensen, Housman, Denison, Barad, Kiris, STARC-ABL CFD Studies,

Papathakis et. al., Design and Development of a 200-kW Turbo-electric Distributed Propulsion Testbed

AFRL INVENT MRIP, Cleared for public release, 88ABW-2011-4647, 26Aug11

1. PC Krause and Associates, Inc.
Risk Reduction Enabled by Integrated Systems Testbed

Full aircraft and mission ground simulation at 200 kW scale in HEIST
- Distributed propulsion along wing
- Turbogenerator or batteries (or both)
- Integrated with flight simulator and cockpit
- Can emulate failure scenarios
- Aerodynamic feedback via dynamometers

Full-scale Powertrain Testing at NEAT
- 1-10’s MW, reconfigurable testbed
- Validate that powertrain is still flightweight and efficient with all systems interacting
- Include thermal, electromagnetic and fault controls
- Study bus stability with different power source, varying loads, and mixing of cryogenic systems with ambient

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

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NEAT: NASA Electric Aircraft Testbed
High power ambient and cryogenic flight-weight power system testing
We are looking forward to developing technologies, studying airplane architectures and controls, and helping to pave a way forward for electrified planes in the US airspace.