Hybrid-Electric and Distributed Propulsion Technologies for Large Commercial Air Transports: A NASA Perspective

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Advanced Air Transport Technology Project

Explore and Develop Technologies and Concepts for Improved Energy Efficiency and Environmental Compatibility for Fixed Wing Subsonic Transports

- Early stage exploration and initial development of game-changing technologies and concepts for fixed wing vehicles and propulsion systems
- One of two NASA Aeronautics projects (along with Environmentally Responsible Aviation (ERA) project) focused on subsonic commercial transport vehicles
- Commercial focus, but dual use with military
- Gen N+3 time horizon; ERA project horizon is Gen N+2
- Research vision guided by vehicle performance metrics developed for reducing noise, emissions, and fuel burn

Evolution of Subsonic Transports

- 1903
- 1930s
- 1950s
- 2000s

DC-3
B-707
B-787
The Case for Hybrid Electric Propulsion

• Why electric?
  – Fewer emissions (cleaner skies)
  – Less atmospheric heat release (less global warming)
  – Quieter flight (community and passenger comfort)
  – Better energy conservation (less dependence on fossil fuels)
  – More reliable systems (more efficiency and fewer delays)

• Considerable success in development of “all-electric” light GA aircraft and UAVs

• Advanced concept studies commissioned by NASA for the N+3/N+4 generation have identified promising aircraft and propulsion systems

• Industry roadmaps acknowledge need to shift in direction toward electric technologies

• Creative ideas and technology advances needed to exploit full potential

• NASA can help accelerate key technologies in collaboration with OGAs, industry, and academia
Estimated Benefits From Systems Studies

**Boeing/GE SUGAR** (baseline Boeing 737–800)
- ~60% fuel burn reduction
- ~53% energy use reduction
- 77 to 87% reduction in NOx
- 24-31 EPNdB cum noise reduction

**NASA N3X** (baseline Boeing 777–200)
- ~63% energy use reduction
- ~90% NOx reduction
- 32-64 EPNdB cum noise reduction

**NASA CEPT for GA** (baseline Tecnam P2006T)
- 5x lower energy use/cost and emission
- 15 dB lower community noise
- Propulsion redundancy, improved ride quality, and control robustness
The NASA Perspective

• Develop and demonstrate technologies that will revolutionize commercial transport aircraft propulsion and accelerate development of all-electric aircraft architectures

• Enable radically different propulsion systems that can meet national environmental and fuel burn reduction goals for subsonic commercial aircraft

• Focus on future large regional jets and single-aisle twin (Boeing 737-class) aircraft for greatest impact on fuel burn, noise and emissions

• Research horizon is long-term but with periodic spinoff of technologies for introduction in aircraft with more- and all-electric architectures

• Research aligned with new NASA Aeronautics strategic R&T thrusts in areas of transition to low-carbon propulsion and ultra-efficient commercial transports
85% of fuel use is in small single-aisle (100-150 pax) and larger classes; regional jets and turboprops account for only 15% of fuel use.
## Progression of Electric Technology for Commercial Transport Aircraft

<table>
<thead>
<tr>
<th>Conventional Aircraft</th>
<th>More Electric Aircraft</th>
<th>All Electric Aircraft</th>
<th>Electric Propulsion Aircraft</th>
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<tbody>
<tr>
<td>i.e. B737, A320, etc.</td>
<td>(B787, A380, etc.)</td>
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<tr>
<td><strong>Engine</strong></td>
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<tr>
<td>- Gas turbine</td>
<td>- Gas turbine</td>
<td>- Gas turbine</td>
<td>- Electric propulsion</td>
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<tr>
<td></td>
<td>- Less hydraulic &amp; pneumatic extraction</td>
<td>- NO hydraulic &amp; pneumatic extraction</td>
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<tr>
<td><strong>Hydraulic System</strong></td>
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<tr>
<td>- Flight control</td>
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<tr>
<td>- Landing gear</td>
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<td></td>
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<tr>
<td>- Utility actuation</td>
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<tr>
<td><strong>Pneumatic System</strong></td>
<td>- De-ice</td>
<td>- 787</td>
<td>- Electric</td>
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<td>- ECS</td>
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<tr>
<td><strong>Electrical Power System</strong></td>
<td>- Motors</td>
<td>- Electric</td>
<td></td>
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<tr>
<td>- Lighting &amp; Heating</td>
<td>- Avionics</td>
<td>- Electric</td>
<td></td>
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<tr>
<td>- Avionics</td>
<td>- System controllers</td>
<td>- Electric</td>
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</table>
Both concepts can use either non-cryogenic motors or cryogenic superconducting motors.
Hybrid Electric Propulsion Technology Projections

Projected Timeframe for Achieving Technology Readiness Level (TRL) 6

Technologies benefit more electric and all-electric aircraft architectures:
- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

- kW class
  - All-electric and hybrid-electric general aviation (limited range)

- 1 to 2 MW class
  - Hybrid electric 50 PAX regional
  - Turboelectric distributed propulsion 100 PAX regional
  - All-electric, full-range general aviation

- 2 to 5 MW class
  - Hybrid electric 100 PAX regional
  - Turboelectric distributed propulsion 150 PAX
  - All electric 50 PAX regional (500 mile range)

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

- >10 MW
  - Turbo/hybrid electric distributed propulsion 300 PAX

Projected Timeframe for Achieving Technology Readiness Level (TRL) 6:
- Today
- 10 Year
- 20 Year
- 30 Year
- 40 Year
Electric Drives Tied to Aircraft Classes

Electric Drive Technology Development Impacts Propulsion & Vehicle Suite

Electric Drives enable distributed propulsion, improve concentrated propulsion

1 MW electric machines are identified as a reasonable feasibility study point
# Transitioning to Electric Propulsion

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<tbody>
<tr>
<td>Gas Turbine</td>
<td>Gas Turbine</td>
<td>Gas Turbine</td>
<td>Gas Turbine</td>
<td>Gas Turbine + Electric</td>
<td>Electric</td>
</tr>
<tr>
<td>Non-Propulsive Power Source</td>
<td>Gas Turbine</td>
<td>Gas Turbine + Electric</td>
<td>Electric</td>
<td>Gas Turbine + Electric</td>
<td>Electric</td>
</tr>
<tr>
<td>Generation</td>
<td>&lt; N</td>
<td>N, N+1</td>
<td>N+2,N+3</td>
<td>N+3, N+4</td>
<td>&gt; N+4</td>
</tr>
</tbody>
</table>

**Recommended NASA Investment Target**

- "Turboelectric Distributed” Gas Turbine Power, Decoupled Distributed Electric Propulsors
- “Hybrid Electric” Gas Turbine and Electric Dual Power, Coupled Propulsor

**Ambient Temperature or Cryogenic and Superconducting**

**Seeking spin-off or demo opportunities**
Hybrid-electric configurations and concepts
Boeing-GE “SUGAR-Volt” Hybrid Electric Propulsion Configuration

### Lithium-Ion Batteries
- Lithium-Ion (today) [Supercapacitor]
- Lithium-Ion (Stanford, Yi Cui)
- Lithium-Ion (South Korea, Jaephil Cho)

### Lithium-Sulfur Batteries
- Lithium-Sulfur (Sion Power)
- Lithium-Sulfur (in 2014) Oxis, Sion

### Other Batteries
- Supercapacitor, X-CAP
- Zinc-Air (Evtech)
- Zinc-Air (mpower)
- Zinc-Air (Energizer)
- Lithium-Thionyl Chloride (Tadiran)
- Lithium-Air (Poly Plus)
- Lithium-Air, Carbon Nanotube, MIT
- Lithium Carbon Phosphate
- Electrostatic nanocapacitors (SuperCapacitor)

### Performance Metrics
- **SUGAR 2030 Assumption**
- **Engine**
  - SLS Thrust (lbf): 27300, 18800, 18800
  - TOC Thrust (lbf): 5962, 3145, 4364
  - Cruise SFC (%): Base, -29.7%, -49.0%
  - Bypass Ratio: 5.1, 13, 13
  - Fan Diameter (in): 61, 86, 80
  - Propulsion Sys Wt (lbs): 5257, 7096, 10475
  - Fuel Burn (%/seat): Base, -38.9%, -63.4%

### Advanced Composite Fan
- 1.35 PR, 89.4" fan
- Advanced 3-D aero design
- Sculpted features, low noise
- Thin, durable edges

### 4-Stage Booster
- HPT 2-Stage
- CMC nozzles + blades
- Next-gen ceramic
- Active purge control
- Next-gen disk material

### Advanced Motor & Gearbox
- 5500 HP power output
- Advanced gear box

### LPT
- 8-Stage
- Highly Loaded Stages
- CMC blades/vanes (weight)
### ESAero ECO-150 and Dual-Use Split-Wing Ambient Temperature Turboelectric Configuration

<table>
<thead>
<tr>
<th></th>
<th>ECO-150 (3-3)</th>
<th>DU-Civil (2-3-2)</th>
<th>737-700 (3-3)</th>
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<tbody>
<tr>
<td>TOGW</td>
<td>139,700</td>
<td>142,400</td>
<td>154,500</td>
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<tr>
<td>Propulsion Wt (“dry”)</td>
<td>28,350</td>
<td>27,820</td>
<td>10,430</td>
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<tr>
<td>Payload*</td>
<td>30,000</td>
<td>30,000</td>
<td>24,000</td>
</tr>
<tr>
<td>Fuel*</td>
<td>28,900</td>
<td>28,900</td>
<td>46,612</td>
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<tr>
<td>Seat-Mile/ Gal</td>
<td>121</td>
<td>118</td>
<td>65</td>
</tr>
<tr>
<td>Motor hp/lb</td>
<td>2.46</td>
<td></td>
<td>4.30</td>
</tr>
<tr>
<td>Gen hp/lb</td>
<td></td>
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* At 3440 nm range
Power is distributed electrically from turbine-driven generators to motors that drive the propulsive fans.

Wing-tip mounted superconducting turbogenerators

Superconducting motor driven fans in a continuous nacelle
Concept Flight Validation of Transformational Electric Propulsion Integration Capabilities through a Low Cost On-Demand Aviation Demonstrator as a Pathway to Ultra-Low Emission Commercial Aviation
EADS VoltAir Concept

- EADS VoltAir all-electric 50 pax concept for 2035 EIS
- Displayed at the 2011 Paris airshow
- Next-gen Li-air batteries, two HTS electric motors driving two coaxial, counter-rotating shrouded propellers
- Easy battery swap for quick airport turnaround
- EADS predicts technology improvements will lead to HTS motors with power-to-weight ratios eventually exceeding gas turbines of today
Bauhaus Luftfahrt Ce-Liner Concept

- All-electric concept for 2035 EIS
- 200 Pax capacity
- C-Wing design based on Kroo and McMasters (Stanford/Boeing/UWA)
- Twin HTS electric motors supplied by advanced Li-ion batteries
- Cargo containers for batteries will quick allow airport turnaround with no recharging time
- Predict battery technology will allow 700 nm range by 2030, 1000 nm by 2035, 1600 nm by 2040
- Company also has the Claire Liner concept vehicle – box-wing, extreme STOL aircraft with laminar flow and integrated wing fans
EADS/Rolls-Royce eConcept

- EADS/RR distributed hybrid-electric propulsion concept for 2050 EIS
- Single large turbine engine embedded in tail generates electricity to six ducted fans (20+ effective BPR)
- Turbine engine drives hub-mounted bidirectional superconducting motor
- Structural stator vanes used to extract power and circulate cryo coolant
- Advanced Li-air batteries for storage; anticipate 1000 Wh/kg energy densities achievable in 20 years
- Turbine+battery power for takeoff and climb; batteries recharged during cruise and during gliding descent with windmilling fans; turbine power during landing
- Cranfield and Cambridge U partners
Hybrid-electric propulsion research portfolio
Practical values for Li-Air, Li-S and Zn-Air are optimistic projections. Significant technical challenges must be overcome to achieve these values.
**NASA Technology Investment Strategy**

### MW Size Motors

- **Today**: 4 hp/lb (6.6 kW/kg)
- **2020**: 8 hp/lb (13.2 kW/kg)
- **2025**: 10 hp/lb (16.5 kW/kg)
- **2030**: 12 hp/lb (19.7 kW/kg)
- **2035**: 20 hp/lb (33.0 kW/kg)
- **Non-Cryogenic**: 25 hp/lb (41.1 kW/kg)

### Cryogenic, Superconducting

- **2020**: 8 hp/lb (13.2 kW/kg)
- **2025**: 10 hp/lb (16.5 kW/kg)
- **2030**: 12 hp/lb (19.7 kW/kg)
- **2035**: 20 hp/lb (33.0 kW/kg)

#### Increase in power density and reduction of weight of other electrical components

- **Power Electronics**:
  - 2X increase in power density
  - 5X increase in power density
  - 10X increase in power density

- **Power Transmission System**:
  - 2X decrease in weight
  - 5X decrease in weight
  - 10X decrease in weight

- **Electric Propulsion-Aircraft Integration**:
  - Perf. and control system verification in KW scale
  - Perf. and control system verification in MW scale
  - Subscale flight test

- **Distributed electric propulsion performance and control**
In addition to advances in individual technologies, integration of functions can offer further increase in power density.
Enabling Technologies for Hybrid-Electric Propulsion

• Electric Machine Architectures
  – Alternate topologies for higher efficiency and power density
  – Ironless or low magnetic loss
  – Concepts that allow motor to be integrated into the existing rotating machinery (shared structure)
  – Concepts that decouple motor speed and compressor speed

• Electric Machine Components and Materials
  – Flux diverters or shielding to reduce AC loss or increase performance
  – Composite support structures
  – Improvements in superconducting wire, especially wire systems designed for lower AC losses
  – Rotating cryogenic seals
  – Bearings: cold ball bearings, active & passive magnetic bearings; hydrostatic or hydrodynamic or foil for systems with a pressurized LH2 source
  – Flight qualification of new components

• Cryocoolers
  – Flightweight systems for superconducting and cryogenic machines, converters, and transmission lines
Enabling Technologies for Hybrid-Electric Propulsion

- Power electronics
  - More efficient topologies
  - Compact, highly integrated controller electronics
  - Flight certifiable, high voltage devices
  - Cryogenic compatible devices

- Thermal management
  - Cooling for electric machines with integrated power electronics
  - Advanced lightweight cold plates for power electronics cooling
  - High performance lightweight heat exchangers
  - Lightweight, low aerodynamic loss, low drag heat rejection systems
  - Materials for improved thermal performance

- Power transmission
  - Light weight, low-loss power transmission
  - Light-weight, low-loss protection and switching components

- System-level enablers
  - Flight-weight, air cooled, direct shaft-coupled turbo-electric generation in 500kW and above range
  - Regenerative power-absorbing propeller and ducted-fan designs for efficient wind-milling

- Better conductors
  - Carbon nano-tube or graphene augmented wires
  - Robust, high temperature superconducting wires

- Energy storage
  - Increased battery energy density
  - Multifunctional energy storage
  - Rapidly charging and/or rapidly swappable
High Efficiency, High Power Density Electric Machines

- Cryogenic, superconducting motors for long term
- Normal conductor motors for near and intermediate term
- High power to weight ratio is enabling
- Materials and manufacturing technologies advances required
- Design and test 1-MW noncryogenic electric motor starting in FY2015; fully superconducting motor in FY2017

Normal conductor 1-MW rim-driven motor/fan

Nanoscale ultra-high strength low percent rare-earth composite magnets

High thermal conductivity stator coil insulation

Low A/C loss superconducting filament

Superconducting electromagnetic model

Fully superconducting motor

Flux density for rim-driven motor
High Power Density MW Class Non-Cryogenic Motor

- Design and test scalable high efficiency and power density (96%, 8 hp/lb) MW-class non-cryogenic motor for aircraft propulsion

- U of Illinois, UTRC, Automated Dynamics
  - Migrate from traditional “metal-intense” to composite and silicon-intense design
  - High fundamental frequency (10X conventional)
  - High pole-count, ironless motor with composite rotor
  - Modular, air-core armature
  - Modular, passively cooled drive with wide-band-gap devices integrated with motor

- Ohio State University
  - Design a motor for integration on LPT spool of CFM56 class engine
  - Reversed (ring) concept with cooling based on Variable Cross-Section Wet Coils (VCSW) coil design with integrated, direct cooling
  - Extensive design trade-space analysis and testing of motor concept at three power levels
High Efficiency, High Power Density Superconducting Machines

- Advance SOA for crucial components to minimize power loss and enable thermal management
- Detailed concept design completed of 12MW fully superconducting machine achieving 25 hp/lb
- In collaboration with Navy, Air Force, Creare, HyperTech, Advanced Magnet Lab, U of FL
- Fabricating and testing superconducting machine components at laboratory scale
- Developing system for FY17 fully superconducting electric machine test at 1 MW design level
Enabling System Testing and Validation

- Develop Megawatt Power System Testing and Modeling Capability
- Key Performance Parameter-driven requirements definition and portfolio management
- Technology demonstration at multiple scales
- Early identification of system-level issues
- Develop validated tools and data that industry and future government projects can use for further development

Eventual flight simulation testing at NASA Armstrong Flight Research Center
Flight-weight Power Management and Electronics

- Multi-KV, Multi-MW power system architecture for aircraft applications
- Power management, distribution and control at MW and subscale (kW) levels
- Integrated thermal management and motor control schemes
- Flightweight conductors, advanced magnetic materials and insulators

![Superconducting transmission line](image)

![Lightweight power transmission](image)

![Integrated motor with high power density power electronics](image)

![Lightweight Cryocooler](image)

![Lightweight power electronics](image)

![Distributed propulsion control and power systems architectures](image)
System Testing and Validation

- Use system-level simulation capability to emerge requirements.
- Demonstrate technology at appropriate scale for best research value.
- Integrate power, controls, and thermal management into system testing.
- Validated tools and data that industry and future government projects can use for further development.

Propulsion Electric Grid Simulator—hardware-in-the-loop electrical grid

Fully cryogenic motor testing Glenn/SMIRF

Eventual flight simulation testing at NASA Armstrong Flight Research Center
Integrated Vehicles and Concept Evaluations

- Determine design requirements and trade space for hybrid electric propulsion vehicles
- Identify near-term technologies that can benefit aircraft non-propulsive electric power
- Enhance analysis capabilities to model non-traditional vehicle configurations with hybrid electric systems
- Establish vehicle conceptual designs that span power requirements from general aviation (<1 MW) to regional jets (1-2 MW) to single-aisle transports (5-10 MW)
Hybrid Electric Propulsion System Conceptual Design

- Hybrid-electric geared turbofan conceptual design
  - UTRC, Pratt and Whitney, UTC Aerospace Systems
  - High Efficiency Drive Gear integrating high speed motor and low pressure turbine
  - Bi-directional flow of power
  - Hybrid battery/fuel cell for high density energy storage
  - Combined fuel/fan thermal management system

- Hybrid-electric geared turbofan conceptual design
  - Rolls Royce, Boeing, GA Tech
  - Identify best performing architecture based on engine cycles, motor, power conversion, energy storage, and thermal management
  - Innovative integration of novel gas turbine cycles and electrical drives
  - Potential side effects of system design considerations
  - Provide roadmap and technology maturation plan
Looking to the Future…

- Exciting challenges for an industry that was deemed “mature”
- Conceptual designs and trade studies for electric-based concepts
- Tech development and demonstration for N+3 MW class aircraft
- Development of core technologies - turbine coupled motors, propulsion systems modeling, power architecture, power electronics, thermal management, and flight controls
- Multiplatform technology testbeds demonstrating
  - Fully superconducting motor
  - 8 hp/lb (2x SOA) non-cryogenic electric motors
  - 2x power density increase for power electronics
  - Performance and control system verification for distributed electric propulsion at kW scale
- Development of multi-scale modeling and simulations tools
- Focus on future large regional jets and single aisle twin-engine aircraft for greatest impact
What is special about 2015?

March 3, 2015, represents 100 years since the founding of NACA, which became NASA in 1958.