NASA Hybrid Gas-Electric Propulsion (HGEP) Subproject
Advanced Air Transport Technologies (AATT)

Progress update for
One Boeing NASA Electric Aircraft Workshop

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Arlington VA

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Presentation Outline

- Notional Schedule for HEP Technologies Flight Demonstrators
- Component Technology Investment Method
- Summary of Contracts resulting from HGEP NASA Research Announcements
- Enabling Materials R&D
- Testbed Status
- Project Summary
## Hybrid Electric Technologies Flight Demonstrator

### System Design & Integration

*Definition of 150 PAX Hybrid Electric Concept and Flight Experiment*

<table>
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<tr>
<th>FY16</th>
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<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
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- **2016 HEP Configuration Decision Point**
- **2017 Evaluation of SCEPTOR & CAS Technologies**
  - **2025 Flight Test RDR**
  - **TRL2 HEGP Concept**
- **2025 Flight Test FDR**
  - **Flight Test PDR**
  - **Flight Test CDR**
  - **2021 Flight Test Configuration Finalized**

### Fuselage BLI

*Tailcone fan system to capture fuselage BLI benefit*

- **BLI2DTF Test**: Integ. BLI Inlet/Distortion Tolerant Fan at cruise
- **Integ. BLI System**
  - **2020 Fuselage BLI CFD Sims**
  - **BLI Test PDR**
  - **2020 Fuselage BLI Wind tunnel Test**

### HE Powertrain

*Generator, Power distribution system, and Motor for Tail Cone Fan*

- **1MW non-SC Inverter TRL4 NRA (GE)**
- **1MW non-SC Motor TRL 4 NRA (OSU)**
- **2MW Integrated Power System Test**
- **TRL4 3-5 MW Electric Machines, Inverters**
- **3-5 MW Electric Machines and Power Systems**
  - **MV Power and Electrical Machine TRL6 Demo**

### Turbofan-Generator Integration

*Small Core, Integrated Multi-Megawatt Generator*

- **Turbofan-Gen Integration Trade Study TRL 3 N+3 Low Emission Combustor**
- **TRL4 Core Integrated Adv Concepts**
- **Integrated Adv Gen Grd Design N+3 Comb Engine Demo**
- **Turbofan-Gen Grd Based Demo Integrated Turbofan-Gen TRL5 Demo**

- **Funded**
- **Partially Funded**
- **Unfunded**

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Notional, For Planning Purposes Only

Advanced Air Transport Technology Project
Advanced Air Vehicle Program
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.

Investments informed by concepts plus systems-level testbeds

With successively higher fidelity

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

Validate the vehicle architecture as well as component performance
Component Technology Focus: Electric Machines & Power Electronics

**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%

Fully Superconducting Electrical Machines
- 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%

**System-driven Powertrain Trades**

**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>
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<tr>
<th>Key Performance Metrics</th>
<th>Specific Power (kW/kg)</th>
<th>Specific Power (HP/lb)</th>
<th>Efficiency (%)</th>
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<tr>
<td>Minimum</td>
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<tr>
<td>Goal</td>
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<tr>
<td>Stretch Target</td>
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<td>15.2</td>
<td>66.5</td>
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**Cryogenic Inverter Requirements**

<table>
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<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>19.4</td>
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<tr>
<td>Goal</td>
<td>20</td>
<td>15.0</td>
<td>99.3</td>
</tr>
<tr>
<td>Stretch Target</td>
<td>25</td>
<td>21.0</td>
<td>99.4</td>
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</table>

**NASA In-House Inverter Research**
- Designing 14 kW Inverter based on HEIST motor and nacelle cooling and packaging requirements
  - 90% efficiency driven by cooling requirements
Ongoing Contracts resulting from HGEP NASA Research Announcements

Concepts:
- “Hybrid Electric Geared Turbofan Propulsion System Conceptual Design,” United Technologies Research Center
- “Hybrid Gas-Electric Propulsion System,” Rolls-Royce LibertyWorks
- TBD awards from recent announcement: “Single Aisle Electrified Aircraft Design Concept”

Electric Machines:
- “High Speed, High Frequency Air-Core Machine and Drive,” University of Illinois
- “10 MW Ring Motor,” Ohio State University

Power Electronics: Inverters and Rectifiers:
- “Silicon-Carbide Lightweight Inverter for Megawatt-Power,” GE Global Research
- “Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter for Future All-Electric Aircraft Applications,” Boeing Inc.
- “Modular and Scalable High Efficiency Power Inverter for Extreme Power Density Applications,” University of Illinois
Component Technology Focus: Electric Machines & Power Electronics

Fully Superconducting Electrical Machines
- SOA Superconductors unable to deliver req’d high current density, compactness, and low losses when exposed to stator’s high alternating currents, fields (AC) and frequencies
- HGEP focusing on manufacturability of stator coils and coil test beds

System-driven Powertrain Trades
- HGEP focusing on manufacturability of stator coils and coil test beds
- Coil-testing at 20K in motor rig to establish good current carrying capability in stator coils
- LN2 coil-testing and motor rigs as a cost-effective way to establish measurement processes and to systematically study the AC loss issue
- Establish design, control, and methodology testing for fully superconducting designs, which utilize both AC & DC fields
Component Technology: Status

Boeing Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter

- Power Semiconductors
- Topology
- Control and PWM
- Gate Drive

- NPC topology
- EMI Filter
- Cryogenic Cooling System

Cryogenic Cooling System

System Architecture

Component Technology: Status

University of Illinois Motor and Inverter

- Technology is promising – 13kW/kg at >96% efficiency achievable
- Design validated with computer modeling and component tests
- Key risk mitigation steps in 2017
- Opportunities/Challenges remain in system integration


**“Air Core” Machine**

**key parameters** | **Values**
--- | ---
rated power | 1MW (Spec = 1MW)
rated efficiency | 97.4% (Spec = 96%)
specific power | 15kW/kg (spec = 13kW/kg)
total machine weight | 144.2 lbs
machine active weight | 75.7 lbs
sync. reactance | 0.06 p.u.
insulation class | H
nominal speed | 15,000 RPM
line to line voltage | 650 V_{RMS}
DC bus voltage | ±500 V
Cooling | Forced air, 20m/s

• Modular converter structure *Redundancy, interleaving, scalability*
• 13-level flying capacitor demonstrated
• High speed, high frequency motor drive

Flying capacitor, multi-level inverter
Component Technology: Status

Ohio State University 10 MW Ring Motor

- Completed 300kW Wet coil technology demonstrator motor
- Completed 1MW Motor Preliminary Design
- 500 kW demonstrator buildup underway (pushing for 1 MW)
- Investigated primary motor/turbine
- 4000 kVA inverter design (COTS-based)

Variable Cross Section Wet Coils (VCSWC) Demonstrator

- Ring VCSWC or Variable Cross-Section Wet Coils Distributed Power Electronic
- External rotor

After design optimization, showing possible 11.2 hp/lb, but some issues need to be resolved

Codrin-Gruie (CG) CANTEMIR, 10 MW Ring Motor, October 2016 NRA Review
Codrin-Gruie (CG) CANTEMIR, 10 MW Ring Motor, EnergyTech16
Component Technology: Status

GE SiC Light-weight Inverter for MW-Power (SLIM)

Objectives:
- Develop & demonstrate advanced inverter
- Design power conversion concepts
- Demonstrate scalable inverter system
- Implement silicon carbide power technologies
- Execute TRL 4 demonstrator of 1MW, 2.4kV inverter

99.4% power stage efficiency can be achieved

- GE 1.7kV 500A SiC Dual module is used as the basic building block for SLIM.
- Classic Three level ANPC is selected as the topology of SLIM.
- Efficiency performance is verified by double pulse test results.
- Mechanical conceptual design is developed to meet the specific power density target.
- 1st 1MW demo unit will be built and tested in 2017.

Mechanical Layout - Concept
Enabling Materials for Electrified Propulsion

Power System Weight Drivers

Improved Power Density
- OGA investment
- CAS investment

Distribution Cables
- AATT conductors
- CAS transmission cables

Battery or Equivalent
Fuel
Turbine Engine
Generator
Motor
Fan

Power Condition
- AATT Design
- AATT Conductors
- AATT Insulation
- AATT Filtering

Magnetic Materials

High Efficiency Component Development
- Inductor Filters – for 20 kHz ripple suppression in motor controllers
- DOE sponsored PV-to-grid integration transformer

High Conductivity Materials

- Theoretically CNT or graphene has high conductivity
- Limited evidence of specific conductivity improvements
- Looking at separated “metallic” CNT

Insulation Materials

- Survey organic/inorganic composite solutions
- Quantify thermal bottlenecks
- Enable novel materials/engineering solutions
Enabling Materials for Electrified Propulsion

Complete cycle of alloy to component development for nanocrystalline soft magnetic materials

Define Product Requirements

Alloy Development → Characterization → Strain Annealing → Cast Thin, Amorphous Ribbon → Optimized Alloy

Component fabrication using tailored nanocomposite soft magnetic material

Wind Core → Coat or infiltrate if needed → Apply Windings
Testbeds - Status

**TESTBED (HEIST)**

Flight Controls and Simulation Integrated with Electrified Aircraft Hardware-in-the-Loop

**System Description**

**Performance**
- Hybrid-electric propulsion
- Hardware-in-the-loop and SIM
- 265 kilowatt system
  - 200 kilowatt batteries
  - 65 kilowatt Capstone turbogenerator
- Aerodynamic feedback using dynamometers

**Safety and Reliability**
- Emergency-Stop (E-Stop) network
  - Capable of removing power from all sources (batteries or turbogenerator) and sinks (motors or dynamometers)
- Contactor relay network
  - Capable of removing power from any (one or more) source and/or sink
  - Emulate failures, degraded performance, and off-nominal conditions

**Functionality**
- Four trailers (mobile test setup)
- Testing from SIM and cockpit
- Test support station for added situational awareness

- Completed Design Review for 1st Phase (100V battery-powered)
- Control dev’t underway
- Currently testing the heat sink motor for a passively cooled motor controller (in-house design, GIMC/HEIST)
Testbeds - Status

NASA Electric Aircraft Testbed (NEAT)
- Completed single-string testing of a motor pair and validated emulation concept in summer 2016
- Supported SCEPTOR EMI testing
- Being configured for 500 kW STARC-ABL layout in 2018
- Full-scale STARC-ABL will follow
- Facility capabilities being brought online as budget allows (cooling, altitude, cryo, etc)
Concepts: Status

STARC-ABL
- Ongoing efforts for more in-depth analyses for vehicle concept
- High fidelity CFD being used to improve aerodynamics

Battery Parallel Hybrid
- Rolls Royce, “NASA Hybrid Gas-Electric Propulsion System”
- UTRC, “Parallel hybrid Geared Turbofan™ (GTF™) engine propulsion system”

ESAero ECO-150 Distributed Concept
- Phase II SBIR: Continued Development of Environmentally Conscious "ECO" Transport Aircraft Concepts as Hybrid Electric Distributed Propulsion Research Platforms

New Contracts resulting from NASA Research Announcement
- 12 month studies, objective vehicles for 2013 EIS
- Intended to help inform component technology investments, future flight demonstrator plans, gain industry perspective

HGEP Project

Focused on:
• Proving feasibility of concept(s) that close(s) w/ net benefit
• Technology maturation
  • High energy density, high efficiency electric machines
  • Flightweight Power Systems
  • Enabling Materials
  • Integrated Systems & Testing
• Enabling and advocating for required flight demonstrations
• Boundary Layer Ingestion studies and tests (AATT’s IBLI)
• Beginning to plan work in Turbine/Generator Integration & Controls