The Electrifying Future of Air Transportation

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NASA Vision for the Future of Commercial Aviation
The Era of Aviation Electrification

- This era is unfolding now!

- Completely transform aviation and air travel

- Open up the skies to new ways of moving people and cargo
  - Drones, personal air vehicles, on-demand urban air mobility

- Lead to radically new and better designs for commercial subsonic transport aircraft

Images courtesy of: Amazon, Airbus, Vision, Joby, NASA
Reduce carbon footprint by 50% by 2050, while…

• meeting increasing demand
• meeting landing and takeoff noise regulations
• meeting emissions regulations
• reducing aircraft development, manufacturing, and operational costs

Why Focus on Commercial Transport Aircraft?

2012 Fuel Consumption

- 100+ passenger aircraft consumed 87% of fuel!
Targeting Large Transports will Benefit Range of Aircraft Sizes

Left side of power range bar denotes is smallest motor that yields net benefit for a partially electrified airplane. Right side is the size of a generator for a twin turboelectric system for a fully electrified airplane.

1 MW electric machines identified as a key initial focus with impact on multiple seat classes.
Making Electrification Work: Offsetting Electrical System Penalties

- Improve aerodynamic and propulsive efficiency
  - Distributed propulsion, Boundary layer ingestion, Wing-tip propulsion
- Target weight reductions in other systems
- Use stored energy judiciously
- Leverage flexibility offered by decoupling of power and propulsion functions
- Think exciting configuration options beyond “tube-and-wing”
Electrification: Key Technical Challenges

• Electrical system weight and efficiency
• Energy storage capabilities
• High voltage
• Thermal management
• Flight controls
• Safety
• Certification
Electrified Aircraft Propulsion Architectures

**Parallel Hybrid**
- Electric Bus
- Turbofan
- Battery
- Motor
- Fan
- Fuel

**Turboelectric**
- Turboshaft
- Generator
- Electric Bus
- Distributed Fans
- Motor
- Motor
- Fuel

**Series Hybrid**
- Turboshaft
- Generator
- Electric Bus
- Distributed Fans
- Battery
- Motor
- Fuel

**All Electric**
- Battery
- Electric Bus
- Motor(s)
- I to Many Fans
Future Electrified Aircraft Concepts

Near-Term Concepts
- Parallel hybrids with judicious use of stored energy during mission
- Ongoing work with RR and UTRC
- Ambient temperature partially turboelectric
- High efficiency and high specific power electrical systems operating at much higher voltages than current aviation standard

Far-Term Concepts
- Superconducting turboelectric systems augmented with some stored energy use
- Multi-kV power architectures with very high efficiency and specific power electrical systems
Starc-ABL Powertrain Architecture

7-12% fuel (and energy) savings relative to baseline advanced aircraft with no improvements in energy storage technology
N3-X Superconducting Powertrain Architecture

Detailed Architecture Analysis conducted by GE & Rolls-Royce NA

2 30 MW Generators and 14 4.3 MW Motors

Electrical Efficiency of Cryogenic Components is Crucial

DC Bus Voltages in 4-8 kV Range
Technology development targeted toward large commercial aircraft

- Propulsion System Conceptual Design
- High Efficiency/Specific Power Electric Machines
- Flight-weight Power Systems and Electronics
- Integrated Flight Simulations and Testing
- Turbine-Generator Integration and Control
- Enabling Materials for Machines and Electronics
Ambient Temperature Electric Machines

Scalable high efficiency and specific power (96%, 13 kW/kg) MW-class non-cryogenic motors

**U of Illinois Permanent Magnet Motor**
- U of Illinois, UTRC, Automated Dynamics
- High pole-count, ironless motor with composite rotor
- Modular, air-core armature
- Modular, passively-cooled drive with wide-bandgap devices integrated with motor

**Ohio State University Ring Motor**
- Motor integrated on LPT spool of CFM56 engine
- Reversed (ring) concept with integrated, direct cooling based on Variable Cross-Section Wet Coils (VCSW) coil design
- Extensive testing of concept at three power levels
Partially Superconducting Machines

U of Illinois High Field Partially SC Motor
- U of Ill, Ohio State, MagSoft, AFRL collaboration on NASA award
- Conduction-cooled, “air-core” SC machine leveraging available MRI-magnet technology
- Active magnetic shield eliminates field outside motor while maximizing “air gap” flux density
- Specific power estimates up to 56 kW/kg for 20 MW, 6000 rpm machine with HTS windings

NASA High Efficiency Megawatt Motor (HEMM)
- 1.4MW wound-field synchronous motor with a stretch performance goal of 16 kW/kg specific power and 99% efficiency
- Conductively self-cooled, SC rotor windings combined with slotless stator
- Exceptional specific power and efficiency without external cooling weight penalty commonly attributed to SC machines
- Direct drive at optimal turbomachinery speeds (no gearbox)
Fully Superconducting Machines

**Fully Superconducting Machine Conceptual Design**
- Detailed concept design completed of 12MW fully superconducting machine achieving 25 hp/lb (41 kW/kg) (collaboration with Navy, Air Force, Creare, HyperTech, Advanced Magnet Lab, U of FL)
- Plans to build and test fully superconducting electric machine test at 0.5 MW level

**Testing Capability to Verify AC Loss in Coils at 20°K**
- Measure MgB2 superconductor losses at 20K to 30K
- Accommodate relevant coil size and current, magnetic field and frequency
- Complements AFRL LN2 test rig by extending to LH2 temperature
- Facility planning complete, rotating core under construction
Fully Superconducting Machines …contd.

Supercond. AC Loss Model Development
- Superconductor AC loss models (NRA with Applied Magnetics Lab/U of Houston), including new treatment for elliptical fields
- Construction of an AC loss facility with elliptical field capability through NRA at FSU Center for Advanced Power Systems

Lightweight Cryocooler Technology Development
- Creare turbo-Brayton cryocooler development under NASA SBIR
- Goal is 3 kg/kW-input at 30% of Carnot (6x better than current SOA)

MgB₂ Wire Development by Hyper Tech Research
- Demonstrated capability to fabricate 10 micron diameter wire filaments
- Reducing losses in AC stator requires Litz-like wire with fine, tightly twisted filaments
Flight-Weight Power Converters

NASA Sponsored Inverter Research Specifications: 1 MW, 3 Phase AC output, > 1 kV DC bus, 19 kW/Kg and 99% specific power and efficiency (26 kW/Kg, 99.3% for cryo)

GE SLIM (SiC Lightweight Inverter for MW Power)
- 1.7/2.5 kV SiC MOSFET modules
- 3 level topology
- FPGA based controller
- Advanced filter design

U of Illinois GaN-based Inverter
- Flying capacitor multi-level (9-level) topology to minimize current and torque ripple and AC losses
- Capacitor-based inverters with potential to offer much higher power density than inductor-based designs
- Higher equivalent switching frequency
- 200 kW prototype demonstration in 2018
Cryogenic Power Converters

GaN Devices Offer Increased Performance
- GaN devices operate at low temps
- Results indicate potential efficiency gains
- ON resistance decreases for GaN and Si
- GaN has lower Gate to Source threshold voltage
- U of Illinois NRA 200kW inverter incl. cryo operation characterization

MTECH Cryogenic Inverter
- 2009 start SBIR program
- Demonstrated potential for > 25 kW/kg specific power, > 99% efficiency

Boeing/UTK Cryogenic Inverter
- 1 MW operation with 26 kW/kg, >99% efficiency
- LNG or LH2 operation
- 1 kV input, 200-3000 Hz output
- 3-level Active Neutral Point Clamped Configuration
- Si CoolMOS technology (TRL 4 by 2019)
Turbine High Power Extraction

GE Power Extraction Test on F110 Engine

- Collaboration between GE, AFRL, and NASA
- Upto 1 MW power offtake, 250 kW from turbine low spool and 750 kW from high spool at altitude conditions
- Engine continued to generate conventional thrust
- Understand impact of high power extraction on engine operability

Image courtesy of: Aviation Week
NASA Electric Aircraft Testbed (NEAT) Facility

- Reconfigurable testbed to support full-scale large aircraft powertrain testing
- 24 MW input power, cryogenic handling, multi-MW cooling, and 120K ft. altitude flight environment capability
- Plans to demonstrate high fidelity turbo-generation and ducted fan transient emulation, test MW-class research motors, inverters, and single- and multi-string powertrains
Electrification: The Promise

- **Energy usage**: reduced by more than 60%
- **Harmful emissions**: reduced by more than 90%
- **Objectionable noise**: reduced by more than 65%

**2020**
- Gain experience through integration and demonstration on progressively larger platforms

**2030**
- Increasingly electric aircraft propulsion with minimal change to aircraft outer mold lines

**2040**
- Advanced configuration with fully integrated hybrid electric propulsion and airframe
The Path Forward…

- Work both ambient temperature and superconducting solutions
- Scale up from regional jets to large single-aisle and beyond
- Advance core technologies including turbine-coupled generators, motors, power system architectures, power electronics, thermal management, flight controls
- Demonstrate technologies at component, subsystem, and system level
- Focus on viable concepts offering net reductions in energy use, noise, and emissions

Exciting times ahead! Need your help!