
Sean Clarke, P.E.
Senior Systems Development Engineer, CEPT Principal Investigator
Aeronautics Research Mission Directorate, Armstrong Flight Research Center
2015 IEEE Transportation Electrification Conference and Expo, Dearborn, Michigan, June 17, 2015

Graphic: NASA/Maria Werries
Who is NASA Aeronautics?

Engineers, pilots, managers, programmers -- we are proud of our legacy of technology contributions to aviation.
Why is aviation so important?
The air transportation system is critical to U.S. economic vitality.

$1.5 \text{ TRILLION}
TOTAL U.S. ECONOMIC ACTIVITY
(civil aviation-related goods and services, 2012)

$75.1 \text{ BILLION}
POSITIVE TRADE BALANCE
(aerospace industry, 2013)

11.8 \text{ MILLION}
DIRECT AND INDIRECT JOBS
(civil and general aviation, 2012)

5.4% ($847.1 \text{ BILLION})
OF TOTAL U.S. GROSS DOMESTIC PRODUCT (GDP)
(civil and general aviation, 2012)
Why should I care?
Take the system view. You may not have flown today but something you needed did.

17.7 BILLION
TONS OF FREIGHT TRANSPORTED BY AIR
(all U.S. carriers, 2013)

$670.8 BILLION
SPENT BY AIR TRAVELERS IN U.S. ECONOMY
(domestic and foreign travelers, 2012)

741 MILLION
PASSENGERS ON U.S. CARRIERS
(domestic and foreign, 2013)
What are the challenges?

Challenges are driven by emerging global trends.

16 BILLION
GALLONS OF JET FUEL BURNED IN 2013
(U.S. airlines)

$8.1 BILLION
COST OF DELAYS TO U.S. AIRLINES IN 2013

$9.3 BILLION
SPENT BY AIRPORTS ON NOISE ABATEMENT SINCE 1982

3% AND 5%
OF GLOBAL CO₂ WARMING EFFECTS PROJECTED FROM AVIATION BY 2050

360 MILLION
PASSENGERS BEING ADDED IN ASIA PACIFIC FROM 2009 TO 2014
(market is growing and moving East)
Has NASA Aeronautics made a difference?

NASA-developed technology is on board every U.S. commercial aircraft and control tower.
Where do we see NASA’s benefits today?

NASA’s research has positive impacts on the aviation industry, government and the flying public.

**NASA technologies**

- Advanced composite structures
- Chevrons
- Laminar flow aerodynamics
- Advanced CFD and numeric simulation tools
- Advanced ice protection system

**NASA technologies**

- Low NOx combustors
- Low pressure turbine blade materials
- Fan aerodynamic and acoustic measurements
- Low noise, high efficiency fan design
- Ultra High Bypass technology
- High pressure turbine shroud materials
- Acoustics modeling and simulation tools

**NASA technologies**

- Massive datasets
- High-end computing
- Data mining algorithms
- Knowledge discovery of anomalies
- Human-in-the-loop simulations
- Automated decision support tools
- Trajectory and arrival modeling

---

16% to 20% more fuel efficient & reduced CO₂ emissions

28% to 30% reduction in NOₓ emissions

30% to 60% smaller noise footprint

Source: Boeing

15% to 16% reduction in fuel burn/reduced CO₂ emissions

50% reduction in NOₓ emissions

15 dB to 20dB noise reduction

Sources: CFM and Pratt & Whitney

---

Potential for $300M jet fuel savings per year

Reduced delays, noise and emissions

Increased identification of safety-related incidents

Sharing of safety-related trends across airlines

Reduced rate of incidents system wide

Sources: FAA and Southwest Airlines
What does NASA Aeronautics do?

NASA is with you when you fly.

NASA Aeronautics is committed to transforming aviation by dramatically reducing its environmental impact, improving efficiency while maintaining safety in more crowded skies, and paving the way to revolutionary aircraft shapes and propulsion.
What vision has NASA set for aviation?

A revolution in sustainable global air mobility.
What is NASA Aeronautics working on?

Our research continues to show how we’re with you when you fly.

Air traffic management tools that reduce delays and save fuel

A lower sonic boom to possibly enable supersonic flight over land

Ultra-efficient commercial aircraft

Transition to low-carbon propulsion

Technologies to keep aviation safe (sensors, networking, data mining)

Safe integration of more autonomy/autonomous functions in the airspace system
What is special about 2015?
March 3, 2015, represents 100 years since the founding of NACA, which became NASA in 1958.
Where can I get NASA Aeronautics news?

The web and Twitter: articles, news releases, images and videos.

www.nasa.gov/aero

@NASAAero
How is NASA improving aviation today?

We are meeting global aviation challenges by using six research thrust areas to organize our research.

- **Safe, Efficient Growth in Global Operations**
  - Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

- **Innovation in Commercial Supersonic Aircraft**
  - Achieve a low-boom standard

- **Ultra-Efficient Commercial Vehicles**
  - Pioneer technologies for big leaps in efficiency and environmental performance

- **Transition to Low-Carbon Propulsion**
  - Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

- **Real-Time System-Wide Safety Assurance**
  - Develop an integrated prototype of a real-time safety monitoring and assurance system

- **Assured Autonomy for Aviation Transformation**
  - Develop high-impact aviation autonomy applications
Where does NASA aeronautics research happen?

Aeronautics research takes place at four of NASA’s centers.
Hybrid Electric Propulsion (HEP) Vehicles

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

- 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

- Creative ideas and technology advances needed to exploit full potential

- NASA can help accelerate key technologies in collaboration with OGAs, industry, and academia
 Technologies benefit more electric and all-electric aircraft architectures:

- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

**Power Level for Electrical Propulsion**

- **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 Timeline to Tech. Readiness Level 6**

- **Today**
- **10 Year**
- **20 Year**
- **30 Year**
- **40 Year**

Hybrid Electric Propulsion Vehicles

NASA’s Current Investments

• Advanced Air Transport Technology
  – Targets single aisle passenger aircraft
  – Goal of current work is to develop enabling technologies and to validate vehicle concepts

• Convergent Electric Propulsion Technology
  – Targets distributed propulsion vehicle architectures
  – Flight validation of transformational electric propulsion integration capabilities

• Vertical Lift Hybrid Autonomy
  – Targets long range, high endurance rotocraft missions
  – Goal of current work is to demonstrate cryogenic HEP power system to inform propulsion system models
Both concepts can use either non-superconducting motors or cryogenic superconducting motors.

Hybrid Electric

Turboelectric
Estimated Benefits From Systems Studies

**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

**N3–X** (baseline Boeing 777–200)
- ~63% energy use reduction
- ~90% NOx reduction
- 32-64 EPNdB cum noise reduction

**CEPT** (baseline Tecnam P2006T)
- 5x lower energy use
- 30% DOC Reduction
- 15 dB lower community noise
- Propulsion redundancy, improved ride quality, and control robustness
Investment in Hybrid and Turbo-Electric Aircraft Technologies

- Highly Efficient, High Power Density Electric Machines
- Efficient, Low Noise Propulsors
- Boundary-Layer Ingestion Systems
- Integrated Vehicles & Concepts Evaluation
- Highly Efficient Gas Generator
- Flightweight Power Mgt. & Electronics
Flightweight Power Management and Electronics

- Multi-megawatt aircraft propulsion power system architecture
- 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

- Distributed propulsion control and power systems architectures
- Superconducting transmission line
- Lightweight power electronics
- Integrated motor w/ high power density power electronics
- Lightweight Cryocooler
- Lightweight power transmission

Distributed propulsion control and power systems architectures

Superconducting transmission line

Integrated motor w/ high power density power electronics

Lightweight power electronics

Lightweight Cryocooler

SiC Power Module

Standard Power Module
High Efficiency, High Power Density Electric Machines

- Develop High efficiency, high specific power electric machines
  - Cryogenic, superconducting motors for farther term
  - Non-superconducting motors for near and intermediate term
- Advance Materials and manufacturing technologies
- Design and test 1 MW non-superconducting electric motors starting in FY2015

Normal conductor 1-MW rim-driven motor/fan

Fully superconducting motor

Low A/C loss superconducting filament

High thermal conductivity stator coil insulation

Superconducting electromagnetic model

Flux density for rim-driven motor
Enabling System Testing & Validation

- Develop Megawatt Power System Testbed and Modeling Capability
- Key Performance Parameter-driven requirements definition and portfolio management
- Technology demonstration at multiple scales
- Identification of system-level issues *early*
- 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
Projected Timeline to Tech. Readiness Level 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

**Power Level for Electrical Propulsion**
- Today
- 10 Year
- 20 Year
- 30 Year
- 40 Year
Armstrong Electric Propulsion Roadmap

**Performance and Control of Integrated Systems Testing in Preparation for 1-2MW flight demonstrator**

- **FY13**
- **FY14**
- **FY15**
- **FY16**
- **FY17**
- **FY18**
- **FY19**
- **FY20**

**Adv Air Transport Technology**
AFRC/GRC

**Convergent Aeronautics Solutions**
AFRC/LARC/GRC
ESAero/Joby Aviation

**Team Seedling**
AFRC/LARC
ESAero/Joby

**Risk Reduction Testing for Airplane**

**Capturing Complexities of Hybrid Architectures**

**Spiral Development for MW scale**

**Risk Reduction for kW airplane**

**1-2 MW Flight Project**
Primary Objective
• Goal: 5x Lower Energy Use

Derivative Objectives
• 30% Lower Total Operating Cost
• Zero In-flight Carbon Emissions

Secondary Objectives
• 15 dB Lower community noise.
• Flight control redundancy, reliability
• Certification basis for DEP technologies.
• Scaling study for commuter and regional turbo-prop research investments.
First High Speed LEAPTech Test
Convergent Aeronautics Solutions DEP Airplane

PHASE I
- Requirements Definition, Systems Analysis, Wing System Design, Design Reviews
- Ground validation of DEP highlift system
- Flight testing of baseline Tecnam P2006T

PHASE II
- DEP wing development and fabrication
- Ground and flight test validation of electric motors, battery, and instrumentation
- Goals:
  - Establish Electric Power System Flight Safety
  - Establish Electric Tecnam Retrofit Baseline

PHASE III
- Flight test electric motors relocated to wing-tips, with DEP wing including nacelles (but no DEP motors, controllers, or folding props).
- Achieves Primary Objective of High Speed Cruise Efficiency

PHASE IV
- Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).
- Achieves Secondary Objectives
  - DEP Acoustics Testing
  - Low Speed Control Robustness
  - Certification Basis of DEP Technologies
**kW System Understanding**

- Lessons learned on Packaging distributed electric propulsion wiring, instrumentation and non-propulsion electrical systems in a high aspect ratio wing
- Aero and Acoustic Tool Validation
- Verification and Validation of Flight Motors and Motor Controller
- Establish Standards for Air Worthiness Propulsion Motors
- Battery weight/capacity for various flight profiles
- Weight/Volume Restrictions
- Thermal Management, Cooling for Motor/Motor Controller and DEP
- Dynamic Aero/Propulsive Loading
- DEP Crossflow Characterization and Aero/Propulsion interaction Thrust/Stall Margins and Cruise
- EMI Concerns
- Pilot Input to Basic Fly-By-Wire Propulsion Control, not autonomous
- Emergency Recover from DEP Motors and Wing-Tip Cruise Motors failures
Hybrid Electric Integrated Systems Testbed (HEIST)
Integration and Performance Challenges are Studied so Larger, More Advanced System Testbeds Can Be Designed

- Autonomous Flight Controller
- Study system complexities of 2 power sources
- COTS and low TRL components
- Laid out in the actual configuration of the aircraft, using real line lengths
- Verify vital aircraft system
- Effects of failure and subsequent treatment
- Electric switch w/variable interruptions, times are studied to assess their impact on the computers and components
- EMI/EMC effects
- Ironbird is controlled from a flight simulator
- Provides configurable test configurations and conditions
Two redundant power sources to balance power regeneration and load shedding

Verify any failure in one path will not cause an overload on the alternate path

Each path capable of handling entire power load

Using distributed electric propulsion for flight control by nature are dynamic, with lots of moves, adds and changes going on all the time
Collect high-fidelity data of motor, motor controller, battery system efficiencies, thermal dynamics and acoustics

V&V of components and system interfaces

Evaluation of low TRL components

Model single system before transitioning to multiple motors

Gain knowledge in test methodologies, processes, and lessons learned

Measurements

300 lbf thrust, 500 ft*lbs torque, 0-40,000 RPM, 500V, 500 Amps
**kW System Integration**

- EMI Concerns
- Pilot Input to autonomous Fly-By-Wire Propulsion Control
  - Flight control development for propulsion coupled pitch, yaw and roll
  - Emergency Recover
- Understand cooling systems for motors and batteries
- System controllers for bus architectures with multiple power sources
- Verification and validation of Hybrid Electric turbine/motors, DEP and controllers for air airworthiness
Small Business Initiative Research

- **SBIR/METIS/Phase II**
  Lightweight turbine generator (40 kW)

- **SBIR/ESAero/GA/Phase II**
  Fault tree and failure mode, effects and criticality analysis

- **SBIR/ESAero/Phase III**
  IronBird instrumentation and data acquisition

- **LEARN/RHRC/Phase II**
  Characterize propulsion airframe interaction using closely spaced ducted electric motors

- **STTR/RHRC/Phase II**
  Modular flight testbed for studying various hybrid architectures
Technologies that can enable or accelerate hybrid, turbo- and all electric Aircraft

• Electric Machine Topologies:
  – Higher efficiency designs: reduce the losses in the motor through better topologies without sacrificing power density
  – Ironless or low magnetic loss
  – Concepts which allow motor to be integrated into the existing rotating machinery (shared structure)
  – Concepts which 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 w/ a pressurized LH2 source
  – Flight qualification of new components

• Cryocoolers
  – Flight weight systems for superconducting and cryogenic machines, converters and transmission lines

Vehicle and thermal management concepts need to be defined alongside propulsion systems to assure that the full system is lightweight and thermally balanced.
Technologies that can enable or accelerate hybrid, turbo- and all electric Aircraft

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

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

• 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 swapable

• Thermal Management
  
  Transport class HE aircraft will need to reject 50 to 800 kW of heat in flight
  – Cooling for electric machines with integrated power electronics
  – Advanced lightweight cold plates for power electronics cooling
  – High performance light-weight heat exchangers
  – Lightweight, low aerodynamic loss, low drag heat rejection systems
  – Materials for improved thermal performance

• System-level enablers
  – Flight-weight, air cooled, direct shaft coupled turbo-electric generation in the above 500kW range
  – Regenerative power absorbing propeller and ducted fan designs (efficient wind-milling)
NASA is with you when you fly

AERONAUTICS
WITH YOU WHEN YOU FLY