NASA Green Propulsion Technologies
Pushing Aviation to New Heights

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• Nearly a century of aeronautics research; more than 70 years at NASA Glenn Research Center

• Global economic importance of aviation

• NASA Aeronautics Mission and subsonic research

• Why hybrid-electric propulsion?

• A NASA perspective on enabling hybrid-electric propulsion for commercial transport aircraft

• NASA technologies for hybrid-electric propulsion

• Looking to the future
We’ve come so far, yet we have so far to go.
Who is NASA Glenn?

Lewis Field (Cleveland)
- 350 acres
- 1626 civil servants and 1511 contractors
- 66% of workforce are scientists and engineers

Plum Brook Station (Sandusky)
- 6500 acres
- 11 civil servants and 102 contractors
NASA Glenn Awards and Recognition

**R&D 100 Awards (1966 to 2014)—Glenn has 118, highest in the Agency in these disciplines**
- Aeropropulsion systems
- In-space propulsion systems
- Aerospace communications
- Power and energy conversion

**Colliers**
- Contributions to airline accident reduction (2008)
- Advance turboprop technology (1987)
- Thermal ice prevention systems (1946)

**Emmy**
- Contributions to the Communications Technology Satellite (1987)

**Patents**
- 43 to Glenn
- 38 to Glenn partners (fiscal years 2010 to 2013) as of July 25, 2013

**NASA Software of the Year**
- 5 Glenn awards in the past 15 years

**FLCs**
- Federal Laboratory Consortium (FLC) Excellence in Technology Transfer (2009 and 2011)

**Presidential Rank (2005 to 2011)**
- 17 Meritorious
- 4 Distinguished
Glenn: More than 70 years of Aeropropulsion history/accomplishments

1940s: Engine research begins

- Turbocharging of reciprocating engines enabled high altitude flight of B-29 Superfortress.
- America’s first turbojet tested at Glenn’s Lewis Field. Hands-on experience with early jet engines begins.
- Icing Research Tunnel built at Lewis Field—significantly enhanced aviation safety advancing icing technology…the longest operating and second largest refrigerated wind tunnel in the world.

1950s: Advanced air-breathing propulsion SOA

- Pioneered transonic compressors, cooled turbines, and stable afterburning.

1960s: Developed technologies for noise and emissions reductions

- 10 dB quieter and 60% cleaner—developed unique expertise in wind turbine design for power generation.
Glenn: More than 70 years of Aeropropulsion history/accomplishments

1970s: Technologies for high-efficiency turbofan engines

- Energy Efficient Engine (EEE) Program enabled current highly efficient designs of GE90 and PW4000 powering Boeing 777 aircraft.

1980s: Technologies for ultra-efficient high-speed turboprops

- Potential to achieve 35% reduction in fuel consumption – Advanced Turbo Prop (ATP) program

1990s: Chevron nozzles—from idea to deployment

- Basic studies on jet mixing suggest that tabs can enhance jet mixing, with the potential to reduce noise
- Computational and experimental research to develop understanding of the governing fluid mechanics
- Team effort involving industry, universities, and NASA
Glenn: More than 70 years of Aeropropulsion history/accomplishments

2000s: Green aviation—from idea to deployment
- Ground-test evaluation in engine test stands
- Flight evaluation in relevant environments
- Twin Annular Premixing Swirler (TAPS) Combustor
  ~50% reduction in nitrogen oxide emissions

2010s: Low boom, biofuels, and icing
- Commercial N+2 supersonic aircraft wind tunnel research proves viable low-boom design.
- NASA Glenn Propulsion Systems Laboratory achieves first engine ice crystal icing rollback at simulated cruise altitude.
- NASA Glenn-led biofuels research flight campaigns further green aviation research.
- European Airbus-led High Altitude Ice Crystals/High Ice Water Content field campaign in Darwin, Australia.
NASA Aero Centers: Conducting research to
Ultra-High Bypass (UHB) Ratio Turbofan Engines
Lower noise and lower fuel burn compared to current engines

Seedling Idea: Late 1980s
- Basic computational and experimental research to establish the benefits of low-pressure ratio fans

Fundamental Research: 1989 to 2006
Proof-of-concept fan/nacelle model tests assessing noise, performance, and aeromechanics
- Fan noise prediction and acoustic liners
- Experimental methods (rotating microphone)
- Low-pressure ratio fans for lower noise and higher propulsive efficiency

Systems Assessment: 2007 to 2010
- Geared turbofan demo 2008 (partnership)
- Flight tests on B747 and A340 (industry funded)
Twin Annular Premixing Swirler (TAPS) Combustor

~50% reduction in nitrogen oxide emissions

Seedling Idea: 1995
- Basic computational and experimental research to develop fundamental understanding of Lean Burning Technology

Fundamental Research: 1998 to 2003
- Development of Lean Burning TAPS Proof of Concept Sector test at NASA and GE and CFM56 full annular rig and engine demonstration

Systems Assessment: 2005 to 2009
- GEnx Engine Certification in ground engine test stands

Engine Test
In service in 2011
What do emerging global trends reveal?

China and India are growing economically at unprecedented rates.

Asia-Pacific will have the largest middle class.

Source: National Intelligence Council
What do emerging global trends reveal?

The world will be predominantly urban.

Revolutionary technology development and adoption are accelerating.

Source: National Intelligence Council
Why are these trends important?

They drive “leapfrog” adoption of new technology and infrastructure…

They drive resource use, costs, constraints, and impacts…

They drive the need for alternative energy technologies…
Emissions reduction roadmap

- “Frozen technology” emissions
- Known technology, operations and infrastructure measures
- Biofuels and additional technology
- Carbon-neutral growth 2020
- Gross emissions trajectory
- Economic measures

- CNG 2020
- -50% by 2050

(schematic)

2005 2010 2020 2030 2040 2050
Glenn supports

**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

**Assured Autonomy for Aviation Transformation**
- Develop high-impact aviation autonomy applications
NASA Aeronautics Programs Today

Integrated Systems Research Program (ISRP)
National Aeronautics and Space Administration

NASA Aeronautics Programs (Proposed)
NAS...}
Research Themes

Lighter Weight Fuselage and Wings

Noise Reduction Technologies

Hybrid Gas Electric Propulsion

Compact Higher Bypass Propulsion

Propulsion Airframe Integration

Alternative Fuels Characterization
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**

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

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

- **20 Year**
  - 2 to 5 MW class
  - Hybrid electric 100 PAX regional
  - Turboelectric distributed propulsion 150 PAX regional

- **30 Year**
  - 5 to 10 MW
  - Hybrid electric 150 PAX
  - Turboelectric 150 PAX

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

**Projected Timeframe for Achieving Technology Readiness Level (TRL) 6**

- **Turboelectric**
  - Distributed propulsion 150 PAX

- **Hybrid electric**
  - 150 PAX
  - 100 PAX regional
  - 50 PAX regional

- **All electric**
  - Full-range general aviation
  - Regional (500 mile range)
  - 50 PAX regional
  - Distributed propulsion 100 PAX regional
  - Distributed propulsion 150 PAX regional
Electric Propulsion for Large Aircraft

- 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
Possible Future Commercial Large Transport Aircraft

Hybrid Electric

Both concepts can use either non-cryogenic motors or cryogenic superconducting motors.

Turbo Electric
Estimated Benefits From Systems Studies

N3–X (baseline Boeing 777–200)

• ~63% energy use reduction
• ~90% NOx reduction
• 32-64 EPNdB cum noise reduction

LEAPTech Wing Technology for GA (baseline Cirrus)

• 5 to 9x lower energy use/cost and emission
• 25 dB lower community noise
• Propulsion redundancy, improved ride quality, and control robustness
Highly Efficient Gas Generator

- 1500 °F capable disks, coatings, and noncontacting seals
- 2700 °F capable CMC turbine blades
- Low NOx fuel-flexible combustion
- Characterization of alternative fuels emissions
- Minimize losses due to large tip and hub seal cavity gaps of small size core
- Minimize cooling/leakage losses
- Assess system benefits and evaluate “smaller core” technology concepts for high-speed compressor demonstration

Smaller Core Size Research

Compressor exit corrected flow “core size” $W \sqrt{q_d}$

6.0 lbm/s vs. 2.1 lbm/s core size

Low NOx, fuel flexible combustor

Tip/endwall aerodynamic loss mitigation

1500 F, bonded hybrid disk concept
Technology Applications for Hybrid-Electric Vehicles
Power Systems Architectures

- Multikilovolt power system architecture and associated control system for transmission and use of multimegawatt power in aircraft
- Integrated thermal management and motor control schemes
- Enabling materials and manufacturing technologies
High-Power Density Motors

• 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

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

Flux density for rim-driven motor

Normal conductor 1-MW rim-driven motor/fan

Fully superconducting motor
Understanding Boundary Layer Ingestion Systems

- Assess net system-level benefits of propulsion-airframe integration concepts relative to podded engines.
- Measure boundary layer ingestion benefits of integrated propulsion airframe configuration relative to podded engine.
- Design highly coupled inlet/fan tolerant to continuous operation in distorted inflow.
- Test performance of highly coupled inlet/fan design required to achieve net system level benefits.

Distortion tolerance required for net vehicle system benefit

Reduced velocity in the boundary layer reduces inlet diffusion drag, but highly distorts inlet flow
Efficient, Low Noise Propulsor Systems

- Conceive and explore advanced propulsor architectures and technologies that alter the trajectory of noise and fuel burn trends for fans and open rotors to achieve future performance targets.

- Enhance analysis capabilities and acquire verification data to model nontraditional propulsion technologies and configurations.

- Maintain experimental facilities and capability to allow cutting-edge exploration of unique fan and open rotor system performance and associated physics.

Counter-rotating fans
Highly integrated, single core/Motor, multiple propulsors

Shrouded open rotor concept
Nontraditional low noise technologies

Open rotor noise prediction
Over-the-rotor acoustic treatment fan case
Acoustically treated “soft” vanes

Open rotor installed in NASA wind tunnel (2010)
Enabling System Testing

- 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

**Integrated thermal management system**

- GTE
- Rectifier
- Energy storage
- Electrical distribution
- Research Testbed
- VF motor/inverter
- Load simulator
- Motor controls
- FD&C simulator

**Integrated controls**

**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 HE systems
- Establish vehicle conceptual designs that span power requirements from GA (<1 MW) to regional jets (1-2 MW) to single-aisle transports (5-10 MW)
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, i.e., turbine coupled motors, propulsion modeling, power architecture, power electronics, thermal management and flight controls
- Multiplatform technology testbeds demonstrating
- Development of multiscale modeling and simulations tools
- Focus on future large regional jets and single aisle twin engine aircraft for greatest impact
Questions?