The NASA Fixed Wing Project: Green Technologies for Future Aircraft Generations

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Project Manager
Fixed Wing Project
NASA Fundamental Aeronautics Program

Fedden Lecture
Cranfield University, Cranfield, United Kingdom
8 July 2014
Outline of Talk

• Introduction
• Future Challenges for Commercial Aviation
• NASA Fixed Wing Project and Subsonic Transport Metrics
• NASA Fixed Wing Project Research and Technology Portfolio Highlights
• Enabling Electric Propulsion for Large Aircraft
• Concluding Remarks
Why is aviation so important?
The air transportation system is critical to U.S. economic vitality

- **$1.3 TRILLION**
  TOTAL U.S. ECONOMIC ACTIVITY
  (civil and general aviation, 2009)

- **$47.1 BILLION**
  POSITIVE TRADE BALANCE
  (civil aviation, 2011)

- **10.2 MILLION**
  DIRECT AND INDIRECT JOBS
  (civil and general aviation, 2009)

- **5.2%**
  OF TOTAL U.S. GROSS DOMESTIC PRODUCT (GDP)
  (civil and general aviation, 2009)
Energy and Environmental Impact of Aviation

**U.S. commercial carriers burned 19.6B gallons of jet fuel; DoD burned an additional 4.6B (2008 data). At $3/gallon, fuel cost was $73B**

More than 250 million tons of CO₂ released each year into the atmosphere in U.S.

- **LTO NOx emissions affect local air quality; 40 of the top 50 U.S. airports are in areas that do not meet EPA standards for local air quality.**

- **Aircraft noise continues to be regarded as the most significant hindrance to system growth.**

- **In 2007, aircraft in the U.S. spent 213 million minutes taxiing and in ground holds – delays cost industry and passengers $32.9B.**

- **FAA has invested over $5B since 1980 in airport noise abatement programs for homes.**
Some Emerging Global Trends

China and India growing economically at unprecedented rates

Asia-Pacific will have the largest middle class

The world will be predominantly urban

Revolutionary technology development and adoption are accelerating
Why Are These Trends Important?

They drive global demand for air travel…

They drive expanding competition for high-tech manufacturing…

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

They drive resource use, costs, constraints and impacts…
How Do These Trends Affect Aviation?

Three mega-drivers emerge

Traditional measures of global demand for mobility – economic development, urbanization -- are growing rapidly

Severe energy and climate issues create enormous affordability and sustainability challenges

Revolutions in automation, information and communication technologies enable opportunity for safety critical autonomous systems
How is NASA Responding?

NASA Aeronautics research is organized around six strategic R&T thrusts

**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
The NASA Fixed Wing Project

Explore and Develop Technologies and Concepts for Improved Energy Efficiency and Environmental Compatibility for Sustained Growth of Commercial Aviation

- Early stage exploration and initial development of game-changing technologies and concepts for fixed wing vehicles and propulsion systems
- Commercial focus, but dual use with military
- Along with Environmentally Responsible Aviation (ERA) project focused on subsonic commercial transport vehicles
- Research vision guided by vehicle performance metrics developed for reducing noise, emissions, and fuel burn

Evolution of Subsonic Transports

- 1903
- DC-3
- B-707
- B-787
- 2000s
### NASA Subsonic Transport System Level Metrics

**Strategic Thrusts**

1. **Energy Efficiency**
2. **Environmental Compatibility**

<table>
<thead>
<tr>
<th>TECHNOLOGY BENEFITS*</th>
<th>TECHNOLOGY GENERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption† (rel. to 2005 best in class)</td>
<td>-33%</td>
</tr>
</tbody>
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* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines. N+2 values are referenced to a 777-200 with GE90 engines.

** ESA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

† CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used

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Research addressing revolutionary far-term goals with opportunities for near-term impact
N+3 Advanced Vehicle Concept Studies Summary

Advanced concept studies for commercial subsonic transport aircraft for 2030-35 Entry into Service (EIS)

Technology Trends:
• Tailored/multifunctional structures
• High aspect ratio/laminar/active structural control
• Highly integrated propulsion systems
• Ultra-high bypass ratio (20+ with small cores)
• Alternative fuels and emerging hybrid electric concepts
• Noise reduction by component, configuration, and operations improvements

Advances required on multiple fronts…
Fixed Wing Project Research Themes
Based on Goal-Driven Advanced Concept Studies

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<td>Goal-Driven Advanced Concepts (N+3)</td>
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| Research Themes with Investments in both Near-Term Tech Challenges and Long-Term (2030) Vision |

- SX/PM
- Rim 1500F
- Bore 1300F
Structural Concepts for Reduced Weight

Lightning Strike Testing of STAR-C2 (Smoothing, Thermal, Absorbing, Reflective, Conductive, Cosmetic) Material
Higher Aspect Ratio Wings

Boeing Truss-Braced Wing SUGAR Concept Testing in the NASA Transonic Dynamics Tunnel
Concepts for Reduced Airframe and Fan Noise

Advanced MDOF Aft-Duct Liner installed downstream of stator.

Far-field Directivity Results Broadband SPL (2.5 to 3.5 BPF)
MDOF Liner (in Red) Follows Anticipated Trends in Aft Noise Reduction Compared To Hard-Wall (in blue)

Rig Tests of Advanced Multiple-Degrees of Freedom (MDOF) Acoustic Liner
Low Emissions and Low Noise Combustors

Combined Combustion Dynamics and Acoustics
Testing of Low NOx Multi-Point Injector

Acoustic Spool Dynamic P & T
High Pressure Ratio Small Core Gas Generators

Understanding and Mitigating Tip and Endwall Losses in Turbomachinery
Understanding Boundary Layer Ingesting Propulsion

Direct comparison of podded and integrated configurations

Low-Speed Wind Tunnel Testing of the MIT D8 Concept
Characterizing Emissions from Alternative Fuels

Alternative Aviation Fuel Flight Experiment
Electric Propulsion for Large Aircraft

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

• Why electric?
  – Less 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, less 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
Both concepts can use either non-cryogenic motors or cryogenic superconducting motors.
Benefits Estimated From Fixed Wing Studies

Boeing SUGAR (baseline Boeing 737, 2008 technologies)
- ~60% fuel burn reduction
- ~53% energy use reduction
- 77-87% reduction in NOx
- 24-31 EPNdB cum noise reduction

NASA N3-X (baseline Boeing 777-200)
- ~63% energy use reduction
- ~90% NOx reduction
- 32-64 EPNdB cum noise reduction
Boeing-GE “SUGAR-Volt” Hybrid Electric Propulsion

### Engine Specifications

<table>
<thead>
<tr>
<th>Engine</th>
<th>SUGAR FREE</th>
<th>Refined SUGAR</th>
<th>SUGAR Volt</th>
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<tbody>
<tr>
<td>CFM56</td>
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<tr>
<td>SLS Thrust (lbf)</td>
<td>27300</td>
<td>18800</td>
<td>18800</td>
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<tr>
<td>TOC Thrust (lbf)</td>
<td>5962</td>
<td>3145</td>
<td>4364</td>
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<tr>
<td>Cruise SFC (%)</td>
<td>Base</td>
<td>-29.7%</td>
<td>-49.0%</td>
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<tr>
<td>Bypass Ratio</td>
<td>5.1</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Fan Diameter (in)</td>
<td>61</td>
<td>86</td>
<td>80</td>
</tr>
<tr>
<td>Propulsion Sys Wt (lbs)</td>
<td>5257</td>
<td>7096</td>
<td>10475</td>
</tr>
<tr>
<td>Fuel Burn (%/seat)</td>
<td>Base</td>
<td>-38.9%</td>
<td>-63.4%</td>
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</table>

- **Advanced Composite Fan**: 1.35 PR, 89.4" fan, Advanced 3-D aero design, Sculpted features, low noise, Thin, durable edges
- **4-Stage Booster**: 59 OPR, 9 stages, Active clearance control
- **HPT**: 2-Stage CMC nozzles + blades, Next-gen ceramic, Active purge control, Next-gen disk material
- **LPT**: 8-Stage Highly Loaded Stages, CMC blades/vanes (weight)
- **Integrated thrust reverser/VFN**: Highly variable fan nozzle
ESAero ECO-150 and Dual-Use Split-Wing 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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<tr>
<td>TOGW</td>
<td>139,700</td>
<td>142,400</td>
<td>154,500</td>
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<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>
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<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>
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<tr>
<td>Motor hp/lb</td>
<td>2.46</td>
<td>Gen hp/lb</td>
<td>4.30</td>
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</table>

* At 3440 nm range

Fundamental Aeronautics Program
Fixed Wing Project
Low velocity core exhaust reduces noise.

Propulsors ingest boundary layer & fill center-body wake.

Many small fans give a large total fan area and very high effective bypass ratio.

Forward and aft fan noise shielding by airframe.

Electric power from generators distributed to multiple motor-driven propulsors.

Large efficient engines with freestream inlets drive superconducting generators.
Hybrid Electric Propulsion (HEP) Systems for Aviation

What is needed?

- Conceptual designs of aircraft and propulsion systems
- Higher power density generators and motors
- Flight-weight power system architectures and simulations
- Higher energy density energy storage systems (non-NASA)
- Extensive ground and flight testing

Spinoff Technologies Benefit More/All Electric Architectures:
- High power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

Projected Timeframe for Achieving TRL 6

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<tr>
<th>Power Level</th>
<th>Today</th>
<th>10 Yr</th>
<th>20 Yr</th>
<th>30 Yr</th>
<th>40 Yr</th>
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<tr>
<td>kW class</td>
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<td>1-2 MW class</td>
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<td>2-5 MW class</td>
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<td>5-10 MW</td>
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<td>40 Yr</td>
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(Power level for single engine)
# Progression of Electric Technology for Commercial Transport Aircraft (NASA Projection)

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<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>
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<tr>
<th>Generation</th>
<th>&lt; N</th>
<th>N, N+1</th>
<th>N+2, N+3</th>
<th>N+3, N+4</th>
<th>&gt; N+4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current industry focus</strong></td>
<td>on more/all electric architectures for commercial transports</td>
<td><strong>Recommended NASA Investment Target</strong></td>
<td>(with likely adoption of common technologies for more/all electric architecture in N+2/N+3 timeframe)</td>
<td></td>
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</tbody>
</table>
NASA HEP Technology Investment Strategy

MW Size Motors

Today

4 hp/lb (6.6 kW/kg)

Non-Cryogenic

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

25 hp/lb (41.1 kW/kg)

Cryogenic, Superconducting

4 hp/lb (6.6 kW/kg), partially superconducting

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

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

Fundamental Aeronautics Program
Fixed Wing Project
Cranfield University
Turboelectric Distributed Propulsion Vehicle Study

• Thanks to the generosity of John Murnin, a Scottish space enthusiast, who bequeathed half of his estate to NASA.

• NASA awarded Cranfield University a grant to identify advanced TeDP vehicle configurations, and evaluate vehicle and propulsion system performance
  – Review and summarize prior distributed propulsion concepts studies
  – Investigate electric propulsion and power systems
  – Explore new and or advanced classes of TeDP
  – Techno-economic, environment and risk analysis (TERA)

• Opportunity to collaborate and jointly improve simulation and analysis capabilities for distributed propulsion concepts
Concluding Remarks

- Addressing the environmental challenges and improving the performance of subsonic aircraft
- Undertaking and solving the enduring and pervasive challenges of subsonic flight
- Understanding and assessing the game changers of the future
- Strong foundational research in partnership with industry, academia, and other Government agencies
- Exciting challenges for an industry that was deemed as being “mature”
# Impact of NASA Research Over the Years

## Boeing 787

- **NASA’s work on these technologies**
  - Advanced composite structures
  - **Chevrons**
  - Laminar flow aerodynamics
  - Advanced CFD and numeric simulation tools
  - Advanced ice protection system

- **Was transferred for use here**

- **Benefits**
  - 20% more fuel efficient
  - Reduced CO₂ emissions
  - 28% lower NOₓ emissions
  - 60% smaller noise footprint

- **824 confirmed orders through August 2012**

## Boeing 747-8

- **NASA’s work on these technologies**
  - Advanced composite structures
  - **Chevrons**
  - Laminar flow aerodynamics
  - Advanced CFD and numeric simulation tools

- **Was transferred for use here**

- **Benefits**
  - 16% more fuel efficient
  - Reduced CO₂ emissions
  - 30% lower NOₓ emissions
  - 30% smaller noise footprint than 747-400

- **106 confirmed orders through August 2012**

## P&W PurePower 1000G Geared Turbofan

- **NASA’s work on these technologies**
  - Low NOₓ, Talon combustor
  - Fan Aerodynamic and Acoustic Measurements
  - Low noise, high efficiency fan design
  - Ultra High Bypass technology
  - Acoustics Modeling and Simulation tools

- **Was transferred for use here**

- **Benefits**
  - 16% reduction in fuel burn
  - Reduced CO₂ emissions
  - 50% reduction in NOₓ
  - 20dB noise reduction

- **Proposed for Airbus A320NEO, Bombardier C-Series, Mitsubishi Regional Jets**

## CFM LEAP-1B

- **NASA’s work on these technologies**
  - Compression system aerodynamic performance advances
  - Low NOₓ, TAPS II combustor
  - Low pressure turbine blade materials
  - High-pressure turbine shroud material
  - Nickel-aluminide bond coat for the high pressure turbine thermal barrier coating

- **Was transferred for use here**

- **Benefits**
  - 15% reduction in fuel burn
  - Reduced CO₂ emissions
  - 50% less NOₓ
  - 15dB noise reduction

- **Proposed for Airbus A320NEO, Boeing 737MAX**

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**Source:** Boeing

**Source:** Pratt & Whitney

**Source:** CFM
# Impact of NASA Research Over the Years

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## CFM LEAP-1B

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## What goes on this chart 20 to 30 years from now?

- 50% reduction in NOₓ
- 20dB noise reduction

## Fundamental Aeronautics Program

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Source: Boeing

Source: Pratt & Whitney

Source: CFM