Enabling Electric Propulsion for Flight

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www.nasa.gov
We Fly What Others Only Imagine – Hugh L. Dryden

Armstrong Flight Research Center
Criteria for Flight Research

1. Fits the national research agenda

2. Flight is the best (or only way) to obtain the relevant environment
   - Because research is sensitive to
     - Aerodynamic scaling or enthalpies that cannot be simulated on the ground
     - Properties of the natural atmosphere
     - Complexities that cannot be modeled

3. Appropriate for the government when
   - Results will have broad value and applicable to a class of applications
     - Unbiased testing is of national benefit
     - Technical or programmatic risk is too high for industry
     - Only required for NASA mission
Flight research doesn’t merely come at the end of the project, it actually informs the direction of the research and manufacturing. – National Research Council
Future Innovation Lies Between Disciplines

Boundary Layer Ingestion

Airframe Integration of Series-Hybrid

Propulsion Airframe Interaction

BWB Distributed Electric Propulsion

Structural Control of High Aspect Ratio Wings
Aeronautics Research Strategic 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
Aeronautics Mission Programs

**MISSION PROGRAMS**

- **Airspace Operations and Safety Program (AOSP)**
  - Safe, Efficient Growth in Global Operations
  - Real-Time System-Wide Safety Assurance
  - Assured Autonomy for Aviation Transformation

- **Advanced Air Vehicles Program (AAVP)**
  - Ultra-Efficient Commercial Vehicles
  - Innovation in Commercial Supersonic Aircraft
  - Transition to Low-Carbon Propulsion
  - Assured Autonomy for Aviation Transformation

- **Integrated Aviation Systems Program (IASP)**
  - Flight research-oriented, integrated, system-level R&T that supports all six thrusts
  - X-planes/test environment

**SEEDLING PROGRAM**

- **Transformative Aeronautics Concepts Program (TACP)**
  - High-risk, leap-frog ideas that support all six thrusts
  - Critical cross-cutting tool development

- **NARI Team SEEDLING PROGRAM**

**Armstrong Flight Research Center**

* Transition to Low Carbon Propulsion
Aeronautics Mission Programs

MISSION PROGRAM

Advanced Air Vehicles Program (AAVP)

AAVP

Ultra-Efficient Commercial Vehicles

Innovation in Commercial Supersonic Aircraft

Transition to Low-Carbon Propulsion

Assured Autonomy for Aviation Transformation
## Advanced Air Transport Technology Research

<table>
<thead>
<tr>
<th>Goals Metrics (N+3)</th>
<th>Noise</th>
<th>Emissions (LTO)</th>
<th>Emissions (cruise)</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 4 – 52 dB cum</td>
<td>CAEP6 – 80%</td>
<td>2005 best – 80%</td>
<td>2005 best – 60%</td>
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</tbody>
</table>

### Goal-Driven Advanced Concepts (N+3)

<table>
<thead>
<tr>
<th>Research Themes</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Theme 1 (2030): Lighter-Weight, Lower-Drag Fuselage</td>
<td></td>
</tr>
<tr>
<td>Research Theme 2 (2030): Higher Aspect Ratio Optimal Wing</td>
<td></td>
</tr>
<tr>
<td>Research Theme 3 (2030): Quieter Low-Speed Performance</td>
<td></td>
</tr>
<tr>
<td>Research Theme 4 (2030): Cleaner, Compact, Higher BPR Propulsion</td>
<td></td>
</tr>
<tr>
<td><strong>Research Theme 5 (2030): Hybrid Gas-Electric Propulsion</strong></td>
<td></td>
</tr>
<tr>
<td>Research Theme 6 (2030): Unconventional Propulsion-Airframe Integration</td>
<td></td>
</tr>
<tr>
<td>Research Theme 7 (2015): Alternative Fuel Emissions</td>
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*Achieving N+3 energy consumption goals will require Fixed Wing investment in all research themes and increased funding for hybrid electric propulsion*
Hybrid Electric Propulsion (HEP) Systems for Aviation

Low Carbon Propulsion
- NASA studies and industry roadmaps have identified hybrid electric propulsion systems as promising technologies that can help meet national environmental and energy efficiency goals for aviation.

Potential Benefits
- Energy usage reduced by more than 60%
- Harmful emissions reduced by more than 90%
- Objectionable noise reduced by more than 65%

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
Hybrid Electric Propulsion (HEP) Systems for Aviation

1-2 MW Class

Weight: 32,250 lb   Wingspan: 131ft   357 mph   60,000ft
"We are beginning to shift our focus to smaller classes – regional jets and turboprops." – Nateri Madavan, NASA Fixed Wing Project Scientist

**Hybrid Hopes**
Turbine-electric propulsion shows promise for keeping aviation's efficiency improvements going beyond 2030

Graham Warwick Washington

Hybrid propulsion systems have potential for reducing fuel consumption and emissions, which is critical for the aviation industry's sustainability goals. Armstrong Flight Research Center is exploring hybrid propulsion technologies that combine electric and traditional jet engines to achieve greater efficiency. The goal is to develop aircraft that can operate on both electric and jet power, allowing for reduced emissions and improved fuel efficiency.

**E-Propulsion**

E-Propulsion is an emerging technology that uses electric motors to drive the aircraft's propulsion system. This approach can offer significant advantages, including lower emissions, increased fuel efficiency, and quieter operation. NASA's Armstrong Flight Research Center is actively researching E-Propulsion systems to understand their potential for future aircraft applications.

**Future Developments**

The future of aviation propulsion appears promising, with advanced technologies like hybrid and E-Propulsion gaining attention for their potential to improve efficiency and reduce environmental impact. As research continues, we can expect to see more innovations in propulsion systems that help drive the aviation industry towards a more sustainable future.
**AirVolt Single String Propulsor System**

**Plug-and-Play Electric Propulsion Kit**
- Pipistrel Electro-Taurus Motor
  - 40 kW Peak, 53 hp
  - 30 kW continuous
  - 240 VDC

- Measurements
  - 500 lbf thrust
  - 500 ft*lbf torque
  - 0-40,000 RPM
  - 500 Amps

Acoustic signature

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**Going Electric**

**NASA Dryden is building testbeds to advance understanding of electric propulsion for aircraft.**

**Graham Warwick Washington**

Electric propulsion is not new, but it is now more attractive and affordable. Improvements in technology and performance could make it a viable alternative to traditional aircraft engines.

NASA Dryden is building testbeds to advance understanding of electric propulsion for aircraft. The goal is to design and test electric propulsion systems that can be used in various aircraft configurations. The testbeds will help validate the technology and demonstrate its potential for use in future aircraft.

NASA Dryden has identified several technologies that could be used in future electric propulsion systems. These technologies include electric motors, inverters, and energy storage systems. The goal is to develop a system that is efficient, reliable, and capable of providing the necessary power to the aircraft.

NASA Dryden is working with industry partners to develop these technologies. The goal is to create a system that is compatible with existing aircraft components and can be easily integrated into new or existing aircraft.

In addition to developing the technology, NASA Dryden is also working to identify potential applications for electric propulsion. This includes evaluating the system's performance in different flight conditions and determining how it can be used in various aircraft configurations.

This initiative is part of NASA's broader effort to advance the technology of electric propulsion. The goal is to design and test systems that can be used in a variety of aircraft, including commercial and military applications.

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**AVIATION WEEK & SPACE TECHNOLOGY**

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AVIATION WEEK & SPACE TECHNOLOGY

PUSHING THE BOUNDARIES
New Directions for Eco-Airplanes
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**AVIATION WEEK**

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SEPTEMBER 30, 2023
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**Armstrong Flight Research Center**

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**Pipistrel Electro-Taurus Motor**

- 40 kW Peak, 53 hp
- 30 kW continuous
- 240 VDC

**Measurements**

- 500 lbf thrust
- 500 ft*lbf torque
- 0-40,000 RPM
- 500 Amps

**Acoustic signature**

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AirVolt Single String Propulsor System

- Collect high-fidelity, high-bandwidth ground-based test data of motor, motor controller, battery system efficiencies, thermal dynamics and acoustics, independent of manufacturers
- 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
Ironbird – HEIST Hybrid Electric Integrated System Testbed

Integration and Performance Challenges are Studied so Larger, More Advanced Electric Propulsion System Testbeds Can Be Designed

- 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
- Discover incompatibilities
- Validate 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 effects
- Ironbird is controlled from a flight simulator
Ironbird – HEIST  Hybrid Electric Integrated System Testbed

Power Management and Distribution Research

- **Embedded Flight Control Computer** will Host
  - **Distributed Propulsion Electronic Controller**: Translate thrust targets with simulated pilot inputs into individual thrust commands for each of the propulsors, controlling roll and yaw
  - **Power Management Algorithm**: Manage the loading of the power generator, the real-time capacity of the energy storage buffer (e.g., battery system) and the power demand of the collection of propulsors
  - **Peek Seeking Control**: Use real-time measurements and quickly adapt to environmental changes, to reduce drag, increase performance and energy savings
HEIST  Modular Architecture to Allow for Multiple Configurations (TeDP/Hybrid/All-electric; serial; or parallel buses)

- 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
Aeronautics Mission Programs

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- **NARI Team SEEDLING PROGRAM**

* Transition to Low Carbon Propulsion
Aeronautics Mission Programs

Seedling Program

National Aeronautics Research Institute (NARI)

Early-Stage Innovative and Novel Concepts to Revolutionize the Future of Aeronautics
Leading Edge Asynchronous Propeller Technology

July 7, 2014

Electrifying Aviation

Light aircraft are early targets for the efficiency and safety benefits touted for electric propulsion

Graham Warwick Atlanta

Aviation did not enter the Jet Age overnight, and a decades-long journey to the next propulsor paradigm may already be underway. At NASA, the exploration has begun with plans for ground and flight tests to determine whether hybrid and distributed electric propulsion could be the next disruptive shift in civil aviation.

Personal air vehicles around electric propulsion and increasing autonomy, beginning this updated exploration with small unmanned aerial systems (UAS) (e.g., mQAM-30) and light aircraft.

“Why are electric motors so efficient?” asks Mark Moore, advanced concepts engineer at NASA Langley Research Center, who is working on the LiFePO4. “With whom efficiency, poor maintenance and high running costs of smaller aircraft, electric propulsion is attractive.”

Electric motors are more efficient than turbines or propellers even in hightax regimes. Electric motors have lower noise and vibration, and they are quiet, compact and ready to be integrated into the aircraft. However, with new emissions and energy costs that are much lower than for aviation fuel, electric propulsion presents new design challenges.

“Electric propulsion presents new design challenges. The electric motor and transmission system need to be integrated into the aircraft, and it needs to be designed to be efficient and safe,” Moore says.

The Electric Aircraft Propulsion Systems (EAPS) project is exploring the potential of electric propulsion for small unmanned aerial systems (UAS) and light aircraft. The project aims to develop and demonstrate electric propulsion systems that can meet the requirements of small UAS and light aircraft.

The EAPS project is led by the Electric Aircraft Propulsion Systems (EAPS) project, a collaboration between NASA Langley Research Center, the University of Washington, and the University of Colorado Boulder.

The project is building a prototype electric propulsion system that will be tested on a small UAS. The system will include an electric motor, a battery pack, and a control system.

The EAPS project is expected to complete its testing in 2016, and the results will be used to inform the development of electric propulsion systems for future aircraft.

Armstrong Flight Research Center

Team – NASA LaRC, AFRC, ARC, industry partners Joby Aviation and ESAero.
LEAPTech

Leading Edge Asynchronous Propeller Technology

Armstrong Flight Research Center

Team – NASA LaRC, AFRC, ARC, industry partners Joby Aviation and ESAero.
LEAPTech
Leading Edge Asynchronous Propeller Technology

Lessons to be Learned

- Battery weight and capacity versus HP and test time
- Experience with motor/motor controller/BMS
- Hoping for a coefficient of lift of ~5
- Power loss and voltage spike due to line length
- Propeller fatigue due to vortex shedding from neighbor propeller
- What is the minimum set of data to achieve objectives
- Aeroelastic frequency measurement
- Qualitative acoustics
- Characterize open loop control
- Testing capability for future wing designs
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NARI Team

* Transition to Low Carbon Propulsion

Armstrong Flight Research Center
Aeronautics Mission Programs

Transformative Aeronautics Concepts Program

Convergent Aeronautics Solutions Project

TACP

High-risk, leap-frog ideas that support all six thrusts

Critical cross-cutting tool development
Convergent Electric Propulsion Technologies Sub-Project
Early Flight Evaluation Allows Timely Exposure to Benefits and Issues

2017 Demonstrator
- 400 empg/pax efficiency
- 80% reduction in life cycle GHG emissions
- 40% reduction in total operating cost
- 25 dB reduction in community noise

Distributed Electric Propulsion Integration Approach
- Tight aero-propulsion coupling increases effective $C_{L_{\text{max}}}$ from 1.8 to ~5.0
- Wing loading is increased from 17 lb/ft$^2$ to ~50 lb/ft$^2$, with the same stall speed and field length performance capability
- Electric motors don’t experience power lapse with altitude
- Inner span propellers can be stopped and folded back at cruise
- This permits the inner propellers to be optimized for ultra low noise at takeoff/landing, without cruise penalty
Convergent Electric Propulsion Technologies Sub-Project

Critical Cross-Cutting Tool Development

- Tool validation
  - Conceptual design process
  - MDAO optimization capability
  - Acoustic benefits
  - Aeroelastic effects
  - Use challenge problems to focus development and demonstrate capabilities

- Propulsion effects are largely ignored during aerodynamic modeling, which greatly limits investigation of tightly coupled aero/propulsion technologies
  - Develop a rapid, medium-fidelity aerodynamic analysis of distributed propulsion interaction with lifting surfaces suitable for parametric analysis
Spiral Development

From kW to MW at lower costs

**kW System Understanding**
- Tool validation
- System complexities
- Weight restrictions
- Volume restrictions
- Heat restrictions
- Dynamic aero loading
- Battery requirements for flight profiles
- Environmental effects; cold, hot, gust, airflow variables on inlets
- DEP crossflow characterization and aero/propulsion interaction for stall margins and cruise
- EMI concerns
- Pilot input to fly-by-wire propulsion control
- Emergency recover
Armstrong Electric Propulsion Roadmap

<table>
<thead>
<tr>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
</tr>
</thead>
</table>

- **Adv Air Transport Tech**
- **PMAD Research & Integrated Systems IronBird**
- **Convergent Aeronautics Solutions**
- **Team Seedling**

- **Risk Reduction Testing for Airplane**
- **~2500lb**
- **Spiral Development for MW scale**
- **1-2 MW Flight Project**
- **Capturing Complexities of Hybrid Architectures**
- **Risk Reduction for kW airplane**
## Small Business Initiative Research

<table>
<thead>
<tr>
<th>Category</th>
<th>Project Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SBIR/METIS/Phase II</strong></td>
<td>Lightweight turbine generator (40 kW)</td>
</tr>
<tr>
<td><strong>ePHM</strong></td>
<td>Fault tree and failure mode, effects and criticality analysis</td>
</tr>
<tr>
<td><strong>HEIST</strong></td>
<td>IronBird instrumentation and data acquisition</td>
</tr>
<tr>
<td><strong>Boundary Layer Ingestion Efficiency</strong></td>
<td>Characterize propulsion airframe interaction using closely spaced ducted electric motors</td>
</tr>
<tr>
<td><strong>A/C Conversion Study</strong></td>
<td>Modular flight testbed for studying various hybrid architectures</td>
</tr>
</tbody>
</table>

**Additional Projects:**
- **SBIR/ESAero/GA/Phase II**
- **SBIR/ESAero/Phase III**
- **LEARN/RHRC/Phase II**
- **STTR/RHRC/Phase II**
(The purpose of flight research) is to separate the real from the imagined problems and to make known the overlooked and the unexpected.

— Hugh L. Dryden

Questions?
The first thing we want to do is test the technology in small aircraft. In long term the drive system will also be used in large-scale aircraft. “It may be small but it’s a start on the road to the VoltAir.” – EADS (Cri-Cri), 2011 25 years to Transport

The packaging of old ideas using new technologies. The question is how to enable this creative wackiness to thrive within an industry that is increasingly averse to risk, and with a customer base that is increasingly unwilling to fund R&D that does not promise to deliver near term capabilities. – Avweek, October 2012

“Real Scientists” steered clear of such low-payoff frontiers, preferring to focus on research that could yield useful technologies and solve well-defined problems in the near-term. However, play it safe research aimed at achieving technology evolution rarely leads to revolutionary break-throughs. – Frontiers of Propulsion Science (Rutan), 2009