Special Thanks to AFRC Researchers:

Kurt Kloesel, EE, AE
Propulsion Branch

Yohan Lin, AE
Vehicle Integration and Test Branch

Sean Clarke, EE
System Development Branch

Matt Redifer, AE,EE
System Development Branch

Jim Murray, AE
Aerodynamics Branch

Mark Moore, AE
NASA LaRC
Vehicle Systems Branch

National Aeronautics and
Space Administration

Enabling Electric Propulsion for Flight

Starr Ginn

Deputy Aero Director and Chief Engineer for Aeronautics Research

NASA Armstrong
Flight Research Center

www.nasa.gov

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

All of the new programs address more than one, or all, of the research thrusts.

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**

Armstrong Electric Propulsion Roadmap

FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20

1-2 MW Flight Project

Adv Air Transport Technology AFRC/GRC

Capturing Complexities of Hybrid Architectures

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

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

~2500lb

Spiral Development for MW scale

Team Seedling AFRC/LARC ESAero/Joby

Risk Reduction Testing for Airplane

Risk Reduction for kW airplane

LEAPTech

Leading Edge Asynchronous Propeller Technology

Primary Objective:

Coefficient of lift of ~5

Lessons to be Learned:

Battery weight/capacity/Test Time

Experience motor/motor controller/BMS

EMI

Propeller fatigue due to vortex shedding

Instrumentation for Safety and Research

Qualitative acoustics

Characterize open loop control

Testing capability for future wing designs

Photo Courtesy of Tom Tschida NASA AFRC

Convergent Aeronautics Solutions DEP Airplane

PHASE I

Requirements Definition, Systems Analysis, Wing System Design, Design Reviews

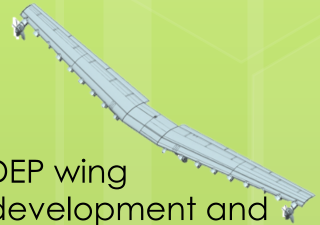
Ground validation of DEP highlift system

Flight testing of baseline Tecnam P2006T

Goals:

- Establish Baseline Tecnam Performance
- Test Pilot Familiarity

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

DEP System Level Impacts

Primary Objective

- Goal: 5x Lower Energy Use (Comparative to Retrofit GA Baseline @ High Speed Cruise)
- Minimum Threshold: 3.5x Lower Energy Use

Derivative Objectives

- 30% Lower Total Operating Cost (Comparative to Retrofit GA Baseline)
- Zero In-flight Carbon Emissions

Secondary Objectives

- 15 dB Lower community noise (with even lower true community annoyance) .
- Flight control redundancy, robustness, reliability, with improved ride quality.
- Certification basis for DEP technologies.
- Analytical scaling study to provide a basis for follow-on ARMD Hybrid-Electric Propulsion (HEP) commuter and regional turbo-prop research investments.

Primary Objective Basis

- Electric only conversion of the baseline aircraft results in a 2.9 - 3.3x efficiency increase (i.e. 28% to 92% motor efficiency).
- Integrating DEP results in an additional 1.2 - 1.5x efficiency increase.
- Minimum threshold is 2.9 x 1.2 = 3.5, with goal of 3.3 x 1.5 = 5.0 goal.

Spiral Development

From Ground to Flight

kW System Understanding

- 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 Restrictions
- 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

Advanced Air Transport Technology Research

Aircraft Hybrid Electric Propulsion

Power Level for Electrical Propulsion

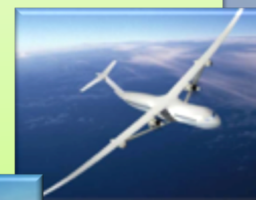
Projected Timeframe for Achieving Technology Readiness Level (TRL) 6

Technologies benefit more electric and all-electric aircraft architectures:

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

>10 MW

- Turbo/hybrid electric distributed propulsion 300 PAX



5 to 10 MW

- Hybrid electric 150 PAX
- Turboelectric 150 PAX

2 to 5 MW class

- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX
- All electric 50 PAX regional (500 mile range)

1 to 2 MW class

- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional
- All-electric, full-range general aviation

kW class

- All-electric and hybrid-electric general aviation (limited range)

Today | 10 Year | 20 Year | 30 Year | 40 Year

Ironbird – HEIST Hybrid Electric Integrated System Testbed

Integration and Performance Challenges are Studied so Larger, More Advanced Electric Propulsion 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

AirVolt Single String Propulsor System

Static and Dynamic Testing

- 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

Spiral Development

From kW to MW System Interfaces

kW System Integration

- EMI Concerns
- Pilot Input to autonomous Fly-By-Wire Propulsion Control
  - Flight control development for dep 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 flight airworthiness

Armstrong Electric Propulsion Roadmap

FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20

1-2 MW Flight Project

Adv Air Transport Technology AFRC/GRC

Capturing Complexities of Hybrid Architectures

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

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

~2500lb

Spiral Development for MW scale

Team Seedling AFRC/LARC ESAero/Joby

Risk Reduction Testing for Airplane

Risk Reduction for kW airplane

Small Business Initiative Research

Turbo-Generator

SBIR/METIS/Phase II

Lightweight turbine generator (40 kW)

ePHM

SBIR/ESAero/GA/Phase II

Fault tree and failure mode, effects and criticality analysis

HEIST

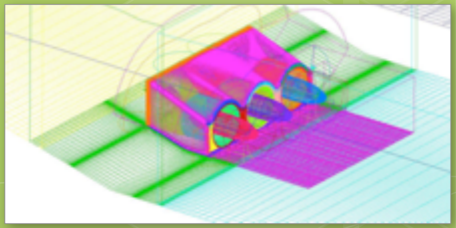
SBIR/ESAero/Phase III

IronBird instrumentation and data acquisition

Boundary Layer Ingestion Efficiency

LEARN/RHRC/Phase II

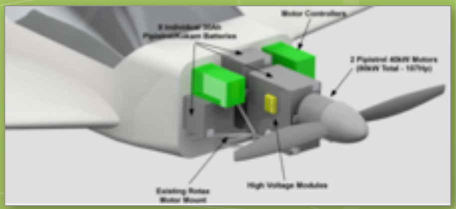
Characterize propulsion airframe interaction using closely spaced ducted electric motors



A/C Conversion Study

STTR/RHRC/Phase II

Modular flight testbed for studying various hybrid architectures



(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?

NASA