Aircraft Electric Propulsion Systems: Applied Research at NASA

Sean Clarke, P.E.
Senior Systems Development Engineer, CEPT Principal Investigator
Aeronautics Research Mission Directorate, Armstrong Flight Research Center

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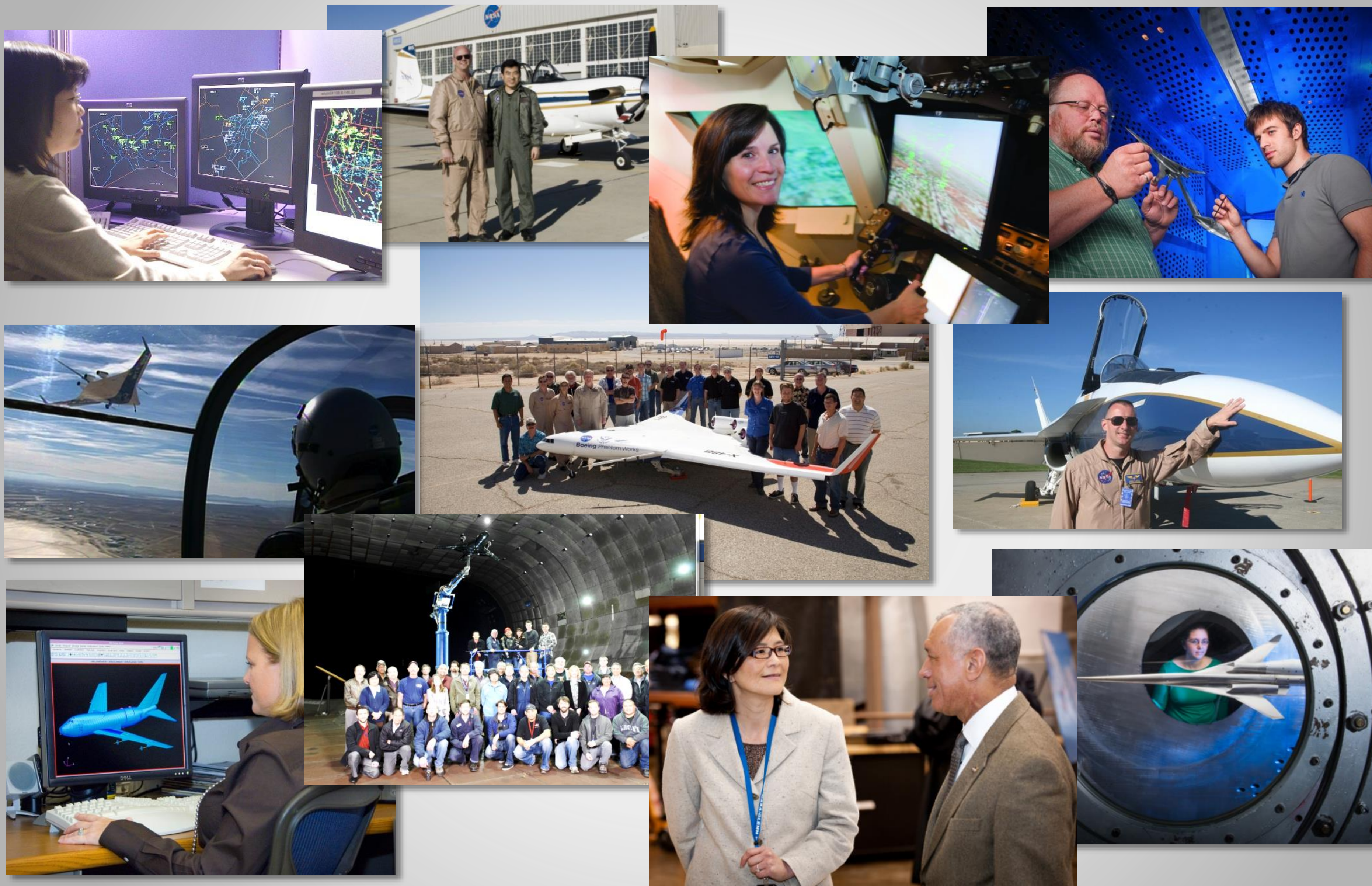
Graphic: NASA/Maria Werries

Who is NASA Aeronautics?

Engineers, pilots, managers, programmers -- we are proud of our legacy of technology contributions to aviation.



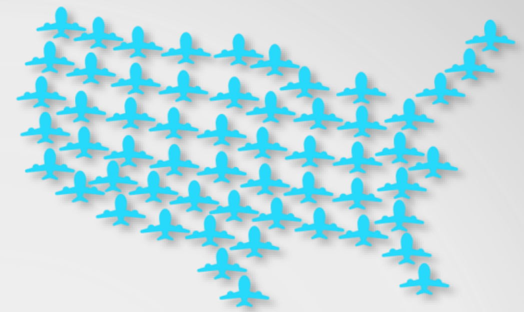
Why is aviation so important?

The air transportation system is critical to U.S. economic vitality.

$1.5 TRILLION

TOTAL U.S. ECONOMIC ACTIVITY

(civil aviation-related goods and services, 2012)



$75.1 BILLION

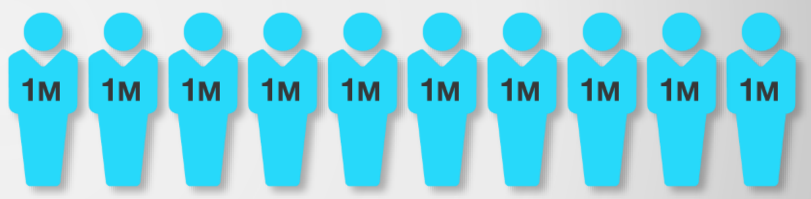
POSITIVE TRADE BALANCE

(aerospace industry, 2013)

11.8 MILLION

DIRECT AND INDIRECT JOBS

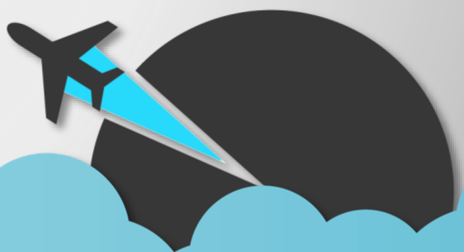
(civil and general aviation, 2012)



5.4% ($847.1 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%

OF GLOBAL CO_2

AND

5%

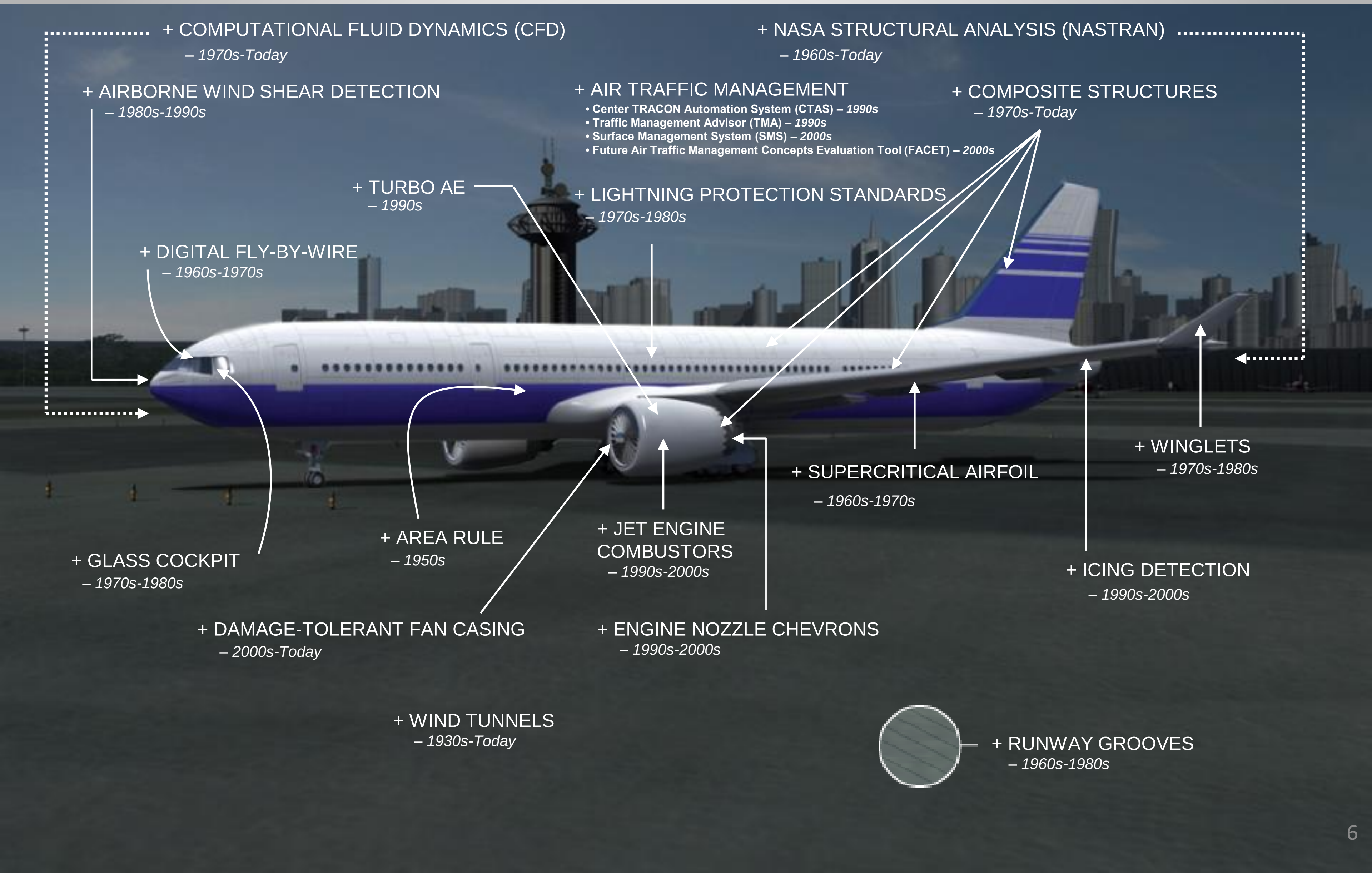
WARMING EFFECTS PROJECTED FROM AVIATION BY 2050

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

tech transfer →

Boeing 787

Boeing 747-8

16% to 20% more fuel efficient & reduced CO_2 emissions

28% to 30% reduction in NO_x emissions

30% to 60% smaller noise footprint

Source: Boeing

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

tech transfer →

P&W PurePower 1000G Geared Turbofan

CFM LEAP-1B

15% to 16% reduction in fuel burn/reduced CO_2 emissions

50% reduction in NO_x emissions

15 dB to 20dB noise reduction

Sources: CFM and Pratt & Whitney

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

tech transfer →

FEDERAL AVIATION ADMINISTRATION

SOUTHWEST.COM

- 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

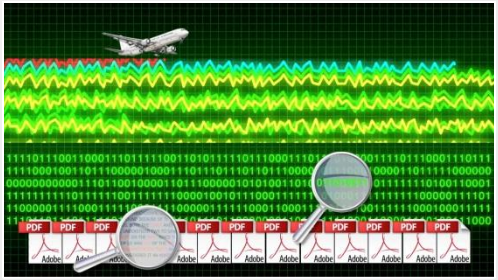
A lower sonic boom to possibly enable supersonic flight over land

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



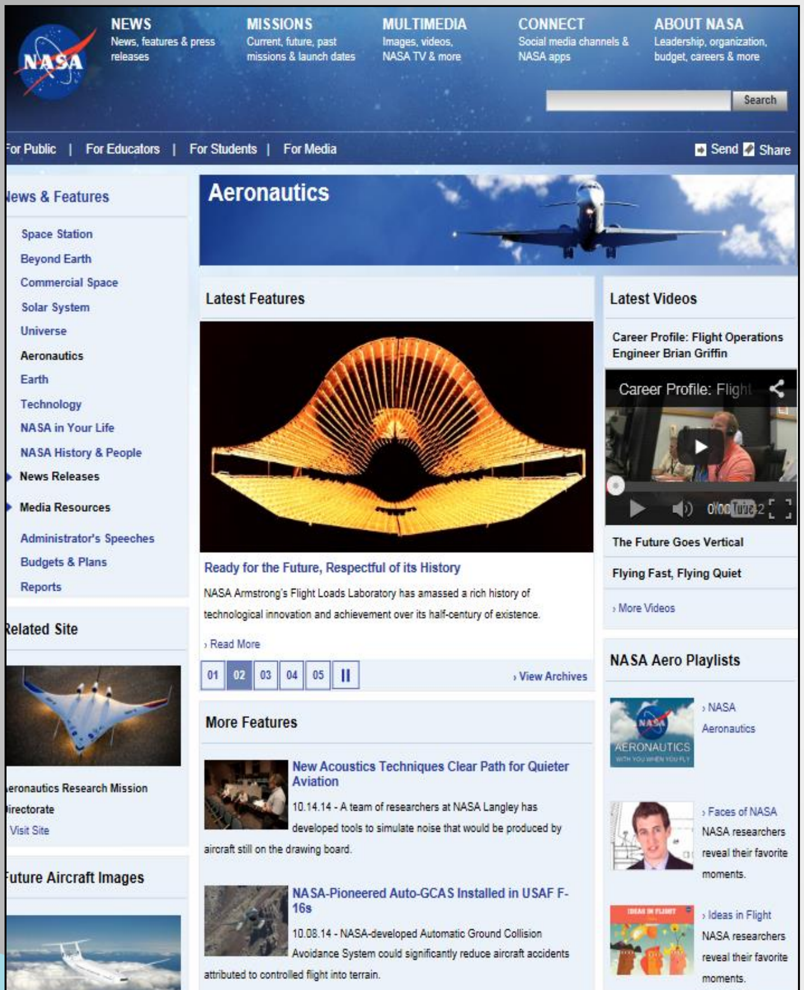
What is special about 2015?

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

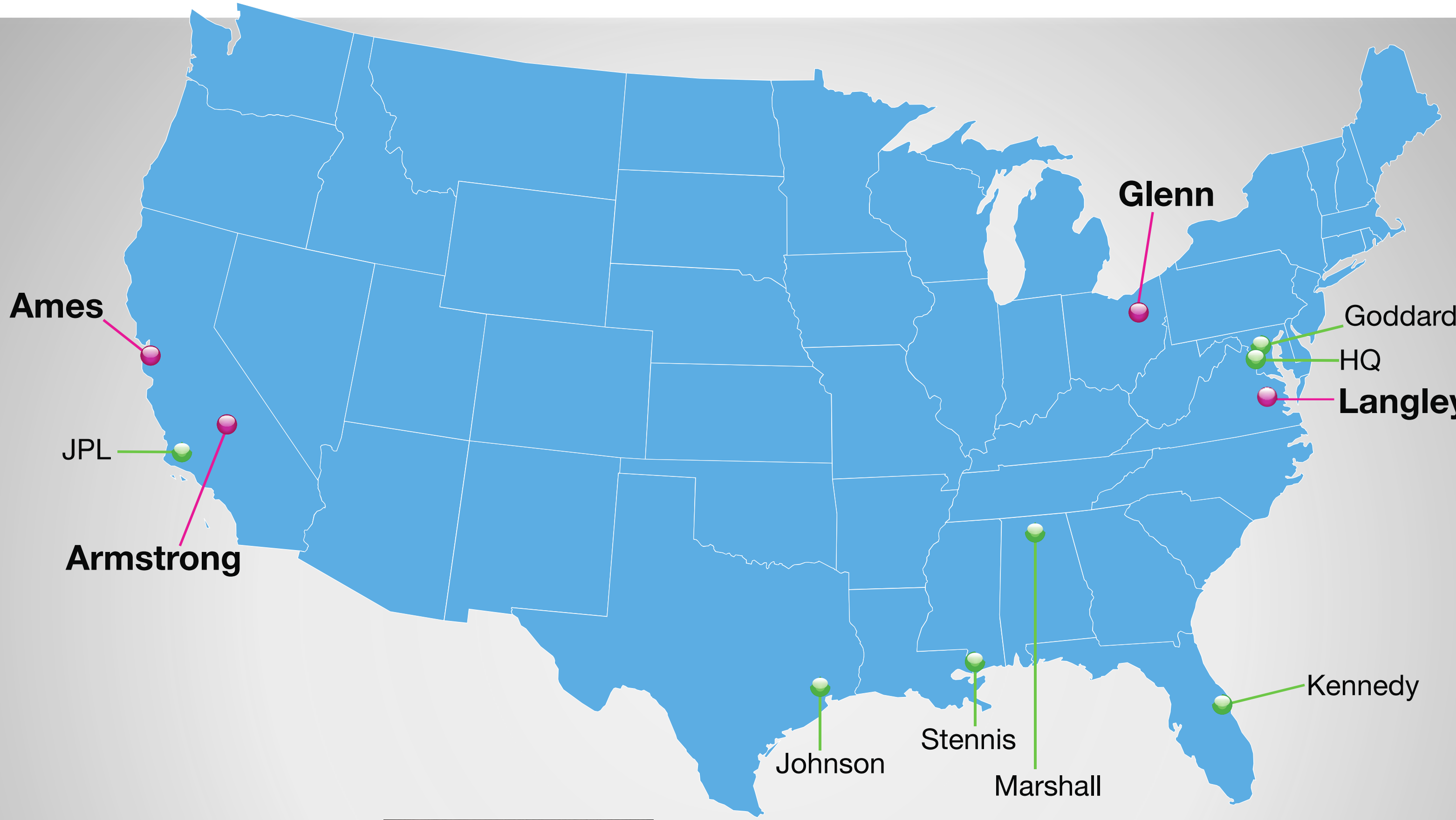
- Develop an integrated prototype of a real-time safety monitoring and assurance system

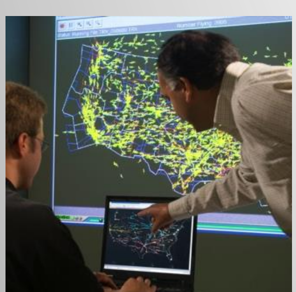
Assured Autonomy for Aviation Transformation

- Develop high-impact aviation autonomy applications

Where does NASA aeronautics research happen?

Aeronautics research takes place at four of NASA's centers.





AMES

ARMSTRONG

GLENN

LANGLEY

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

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

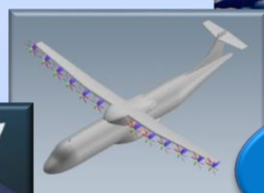
Superconducting Machines

- Turbo/hybrid electric distributed propulsion 300 PAX

>10 MW

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)

Power Level for Electrical Propulsion

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

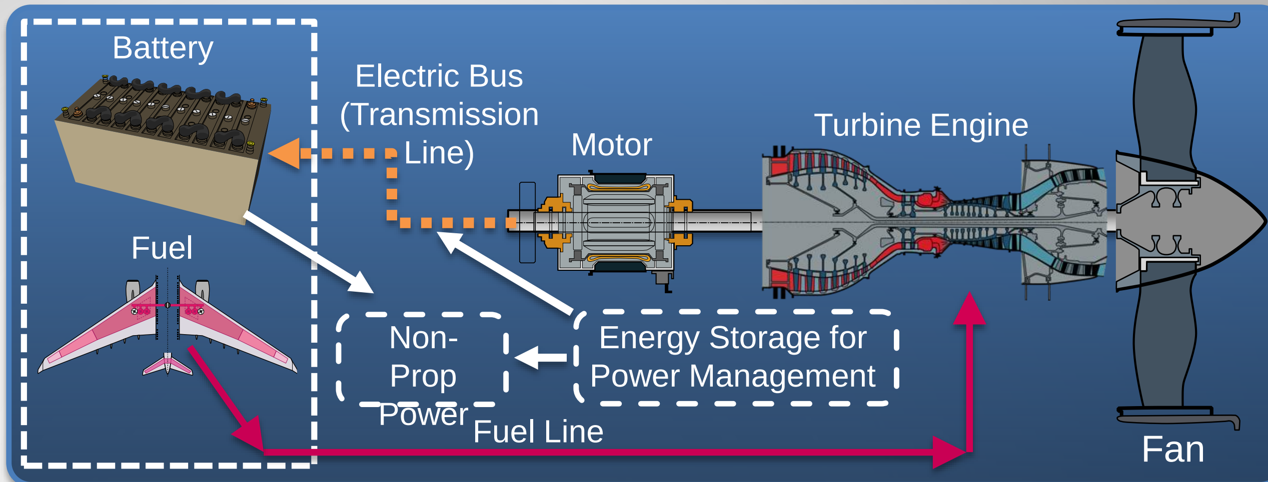
Hybrid Electric Propulsion Vehicles

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

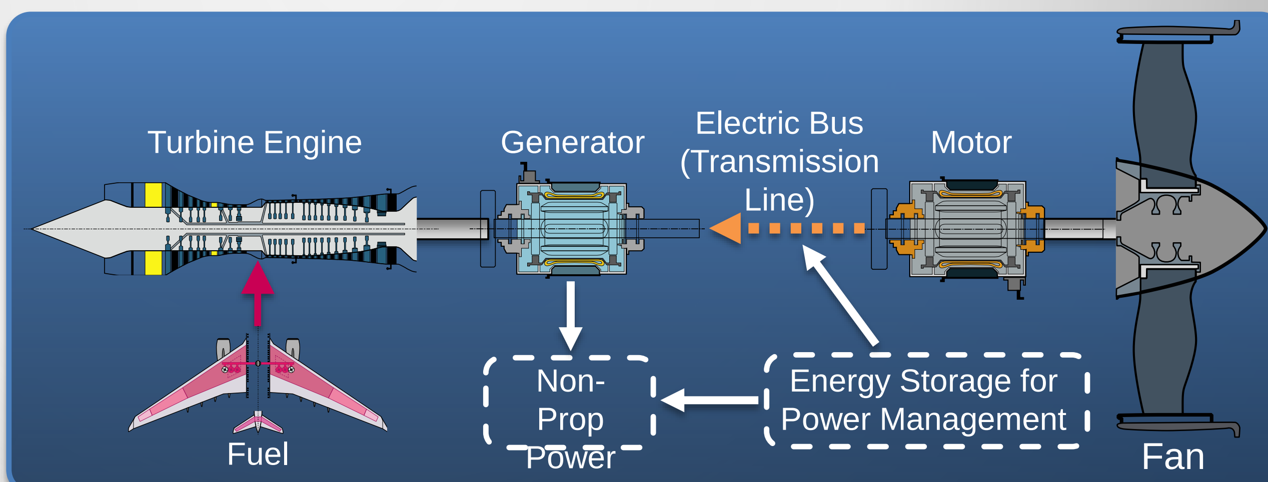
Possible Future Commercial Large Transport Aircraft Architectures

Hybrid Electric



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

Turboelectric



Estimated Benefits From Systems Studies

SUGAR (baseline Boeing 737–800)

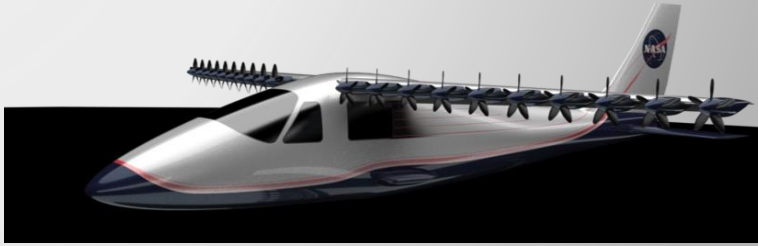
- ~60% fuel burn reduction
- ~53% energy use reduction
- 77 to 87% reduction in NOx
- 24-31 EPNdB cum noise reduction

N3–X (baseline Boeing 777–200)

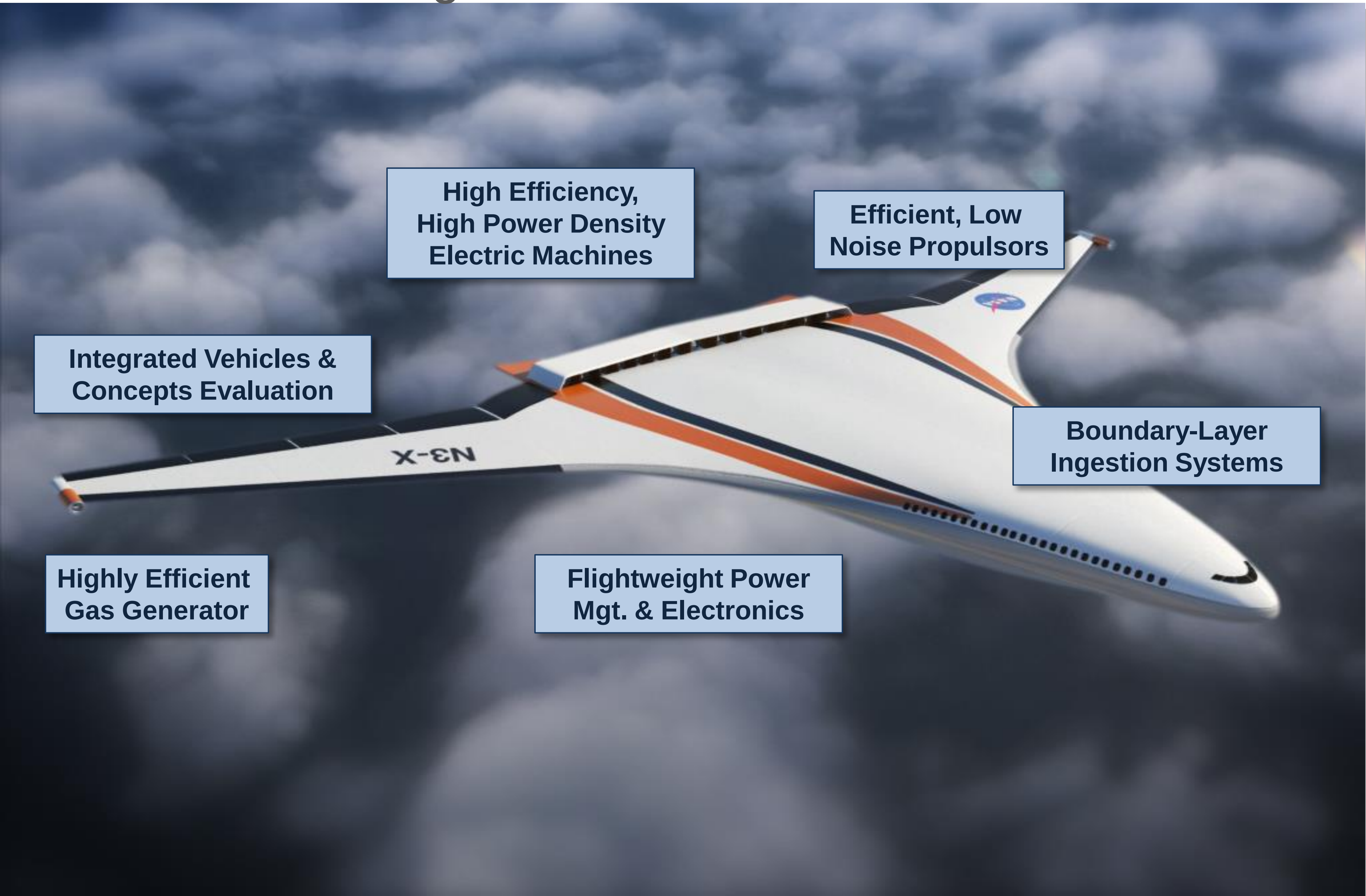
- ~63% energy use reduction
- ~90% NOx reduction
- 32-64 EPNdB cum noise reduction

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



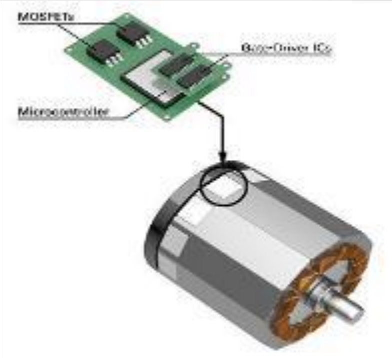
Flightweight Power Management and Electronics

- 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

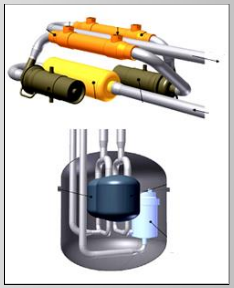
Superconducting transmission line

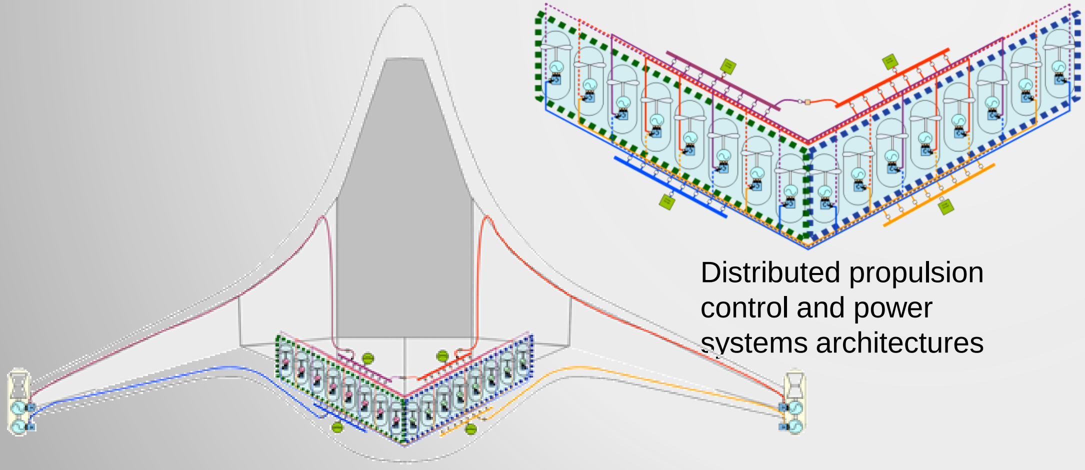
Lightweight power transmission

Integrated motor w/ high power density power electronics



Lightweight Cryocooler





Distributed propulsion control and power systems architectures

Lightweight power electronics

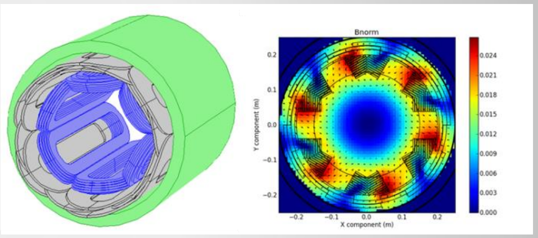
High Efficiency, High Power Density Electric Machines

- 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

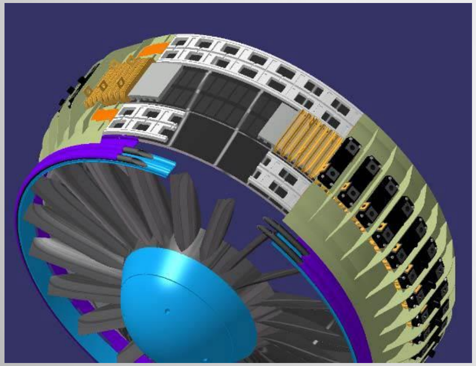
Low A/C loss superconducting filament

High thermal conductivity stator coil insulation

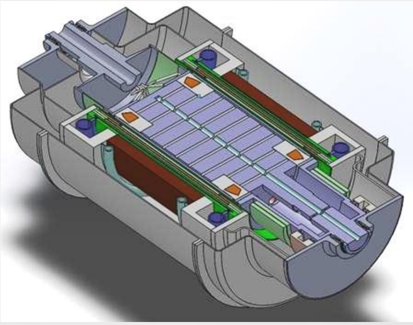
Superconducting electromagnetic model



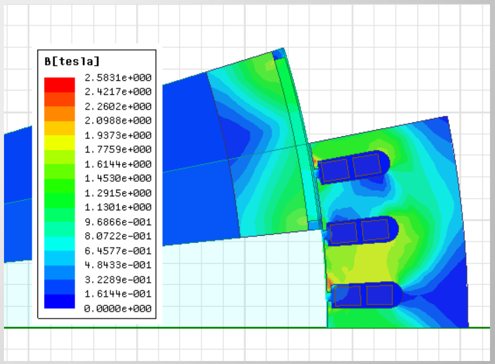
Normal conductor 1-MW rim-driven motor/fan



Fully superconducting motor



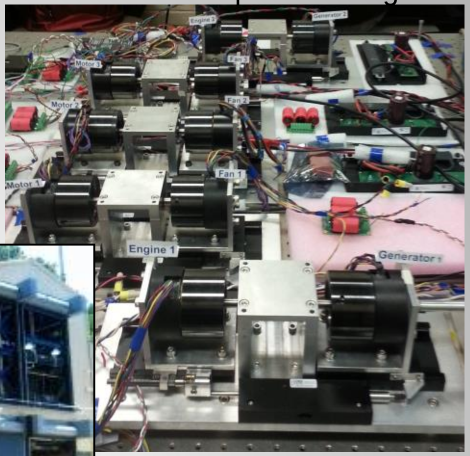
Flux density for rim-driven motor



Enabling System Testing & Validation

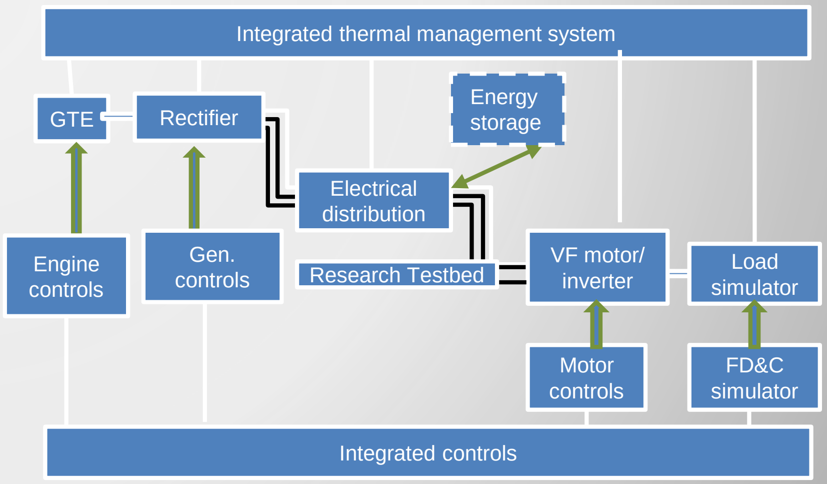
- Develop Megawatt Power System Testbed and Modeling Capability
- Key Performance Parameter-driven requirements definition and portfolio management
- Technology demonstration at multiple scales
- Identification of system-level issues *early*
- Develop validated tools and data that industry and future government projects can use for further development

hardware-in-the-loop electrical grid



Fully cryogenic motor testing NASA GRC

Eventual flight simulation testing at NASA Armstrong Flight Research Center



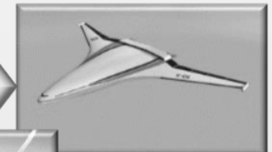
Projected Timeline to Tech. Readiness Level 6

Power Level for Electrical Propulsion

Technologies benefit more electric and all-electric aircraft architectures:

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

Superconducting Machines

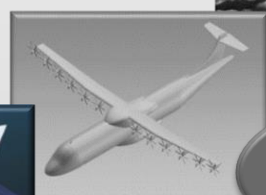


- Turbo/hybrid electric distributed propulsion 300 PAX

>10 MW

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

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

- 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.

Photo Courtesy of Tom Tschida NASA AFRC

First High Speed LEAPTech Test

Convergent Aeronautics Solutions DEP Airplane

PHASE I

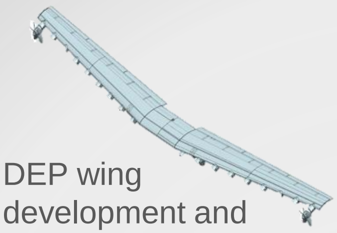
Requirements Definition,
Systems Analysis,
Wing System Design,
Design Reviews

Ground validation of DEP highlift system

Flight testing of baseline Tecnam P2006T

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).

<u>Achieves Primary Objective</u> of High Speed Cruise Efficiency

PHASE IV

Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

<u>Achieves Secondary Objectives</u>
- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Spiral Development

From Ground to Flight

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

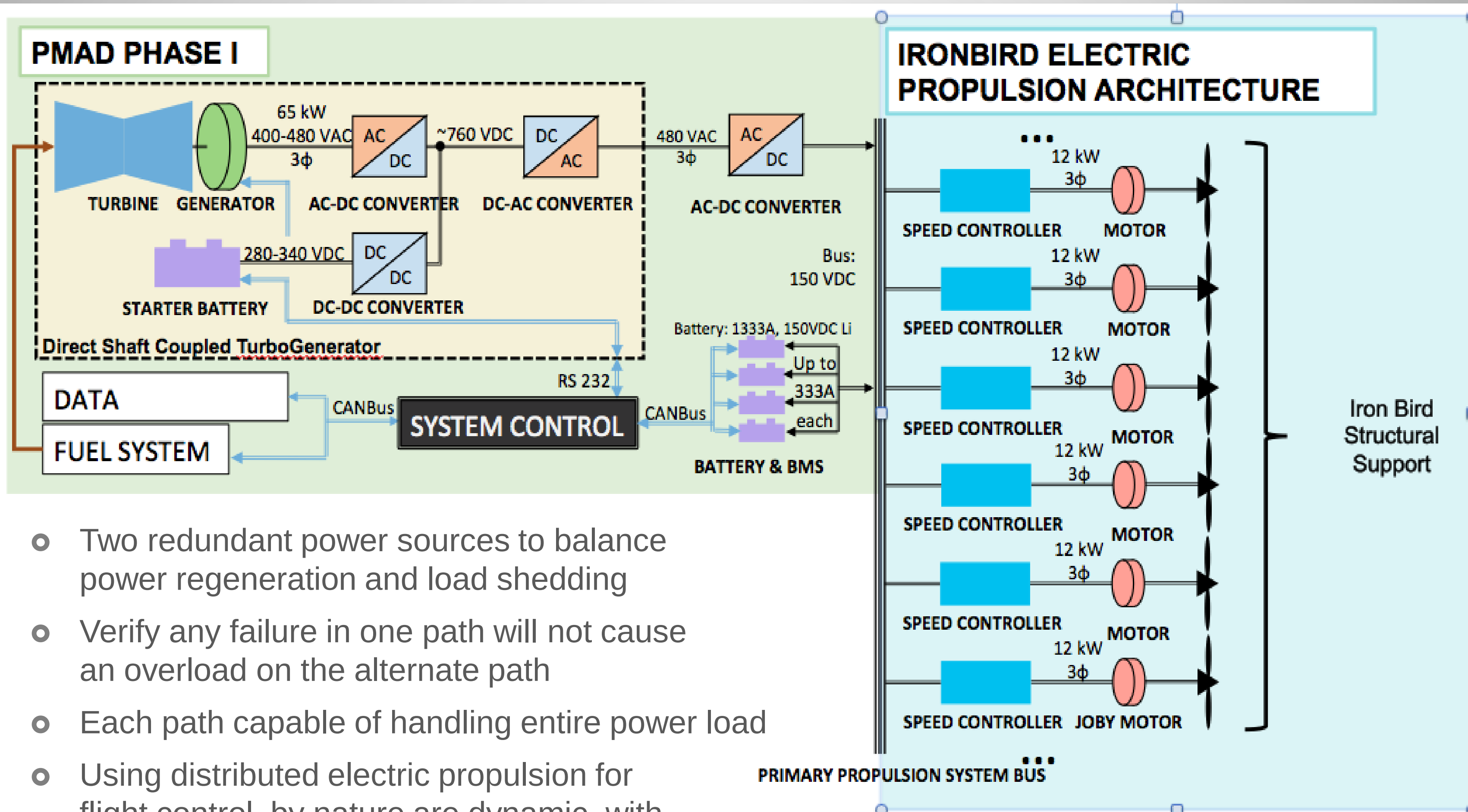
Hybrid Electric Integrated Systems Testbed (HEIST)

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

Hybrid Electric Integrated Systems Testbed (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

AirVolt

Single-String Electric Propulsor Test Stand

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

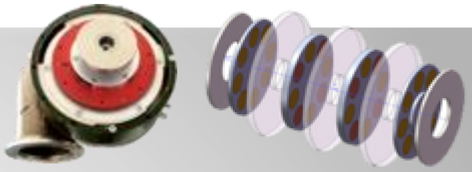
- EMI Concerns
- Pilot Input to autonomous Fly-By-Wire Propulsion Control
  - Flight control development for propulsion coupled pitch, yaw and roll
  - Emergency Recover
- Understand cooling systems for motors and batteries
- System controllers for bus architectures with multiple power sources
- Verification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

Small Business Initiative Research

Turbo-Generator

SBIR/METIS/Phase II

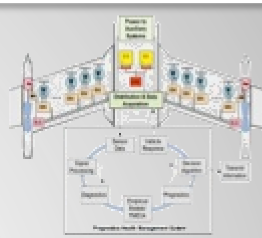
Lightweight turbine generator (40 kW)



ePHM

SBIR/ESAero/GA/Phase II

Fault tree and failure mode, effects and criticality analysis



HEIST

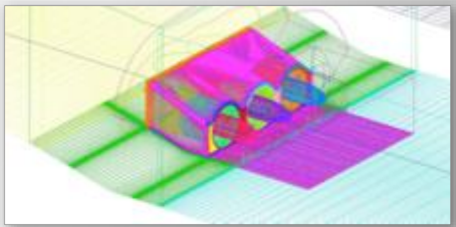
SBIR/ESAero/Phase III

IronBird instrumentation and data acquisition

Boundary Layer Ingestion Efficiency

LEARN/RHRC/Phase II

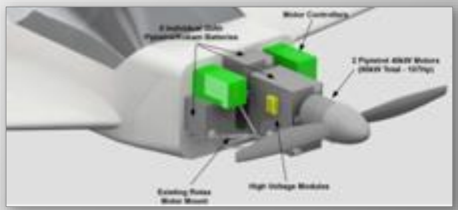
Characterize propulsion airframe interaction using closely spaced ducted electric motors



A/C Conversion Study

STTR/RHRC/Phase II

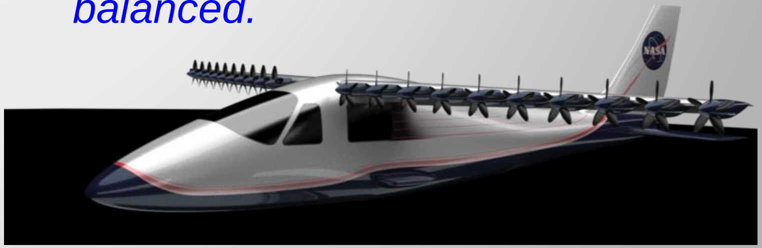
Modular flight testbed for studying various hybrid architectures



Technologies that can enable or accelerate hybrid, turbo- and all electric Aircraft

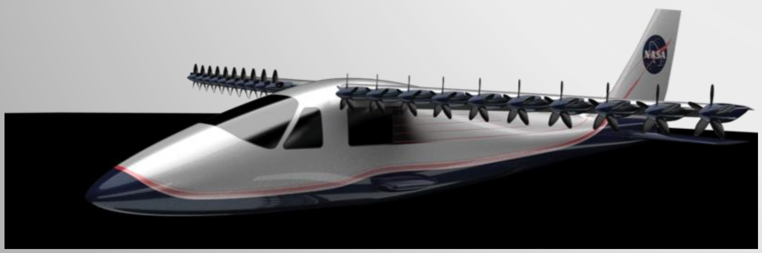
- Electric Machine Topologies:
  - Higher efficiency designs: reduce the losses in the motor through better topologies without sacrificing power density
  - Ironless or low magnetic loss
  - Concepts which allow motor to be integrated into the existing rotating machinery (shared structure)
  - Concepts 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)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