

National Aeronautics and Space Administration



Electric Aircraft Technology Development Overview Briefing

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Mar. 14, 2018



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Outline



1. Brief review of terminology/systems to aid discussion
2. Missions and technology development – targeted vehicle classes
 - Single-Aisle Transports
 - Vertical Takeoff and Landing – Urban Air Mobility
 - Thin Haul Conventional Takeoff and Landing
3. Enabling Test Capabilities
4. Concluding Remarks

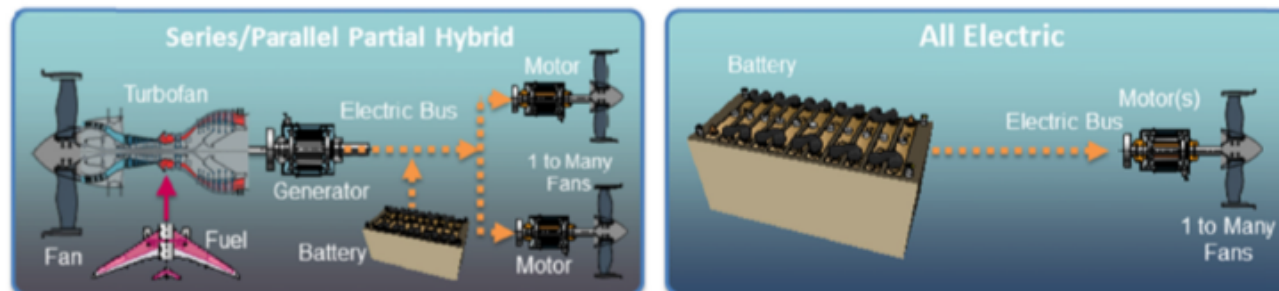
Electrified Aircraft Propulsion Concepts

Electrified Aircraft Propulsions systems use electrical motors to provide some or all of the thrust for an aircraft

- Turboelectric systems use a turbine-driven generator as the power source. Partially turboelectric systems split the thrust between a turbofan and the motor driven fans



- Hybrid-electric systems use a turbine-driven generator combined with electrical energy storage as the power source. Many configurations exist with different ratios of turbine to electrical power and integration approaches.
- All-electric systems use electrical energy storage as the only power source.



Benefits of Electrified Aircraft Propulsion Across Range of Missions



Improvements to highly optimized aircraft like single-aisle transports

- Potential fuel burn reduction estimated using turbo electric distribution to BLI thruster in addition to other benefits from improved engine cores or airframe efficiencies. Later developments could be more advanced electrical distribution and power storage.



Enabling new configurations of VTOL aircraft

- The ability to widely distribute electric motor driven rotors/propulsors operating from one or two battery or turbine power sources, enable new VTOL configurations with potential to transform short and medium distance mobility through 3x-4x speed improvement.



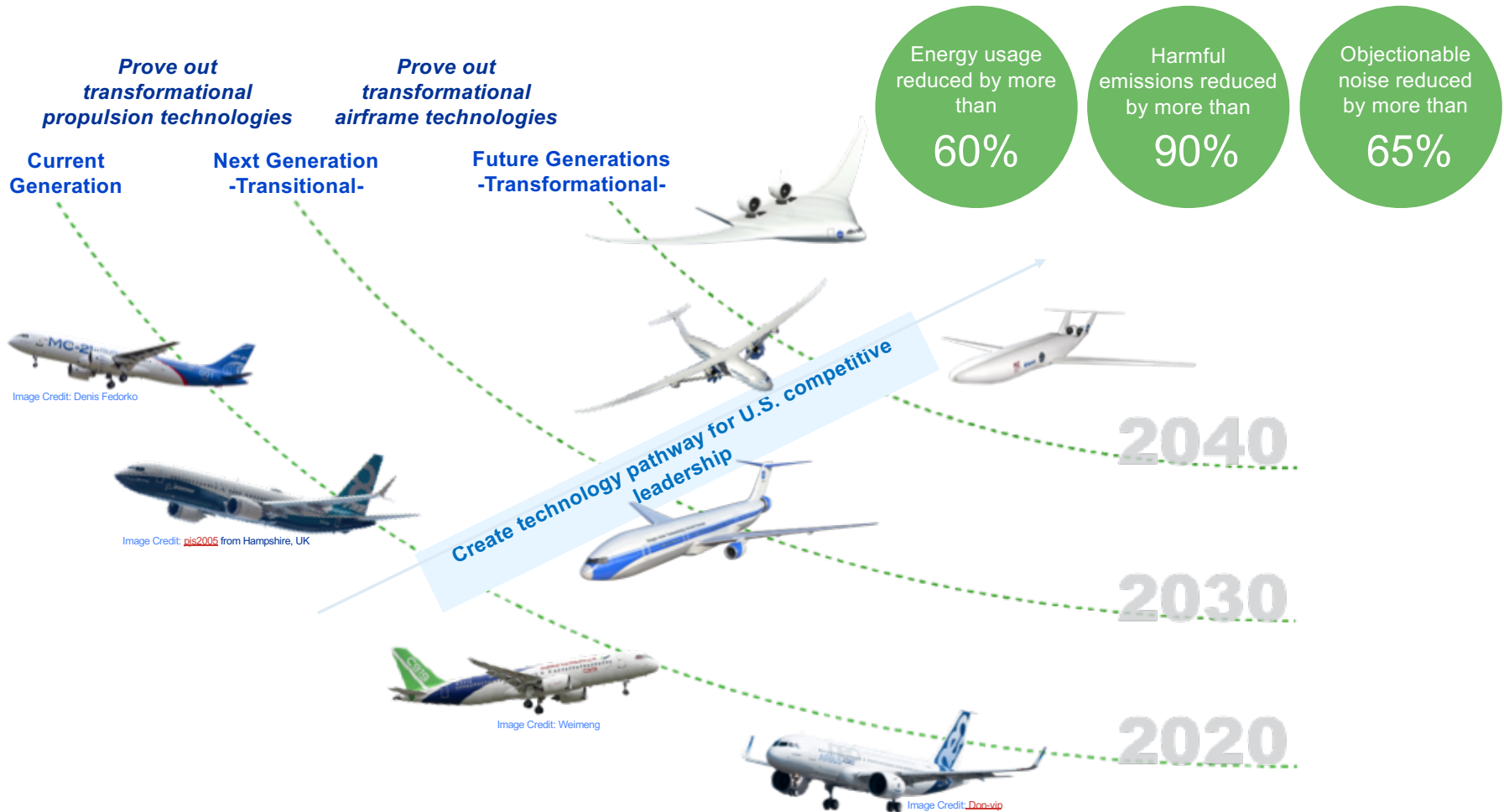
Revitalizing the economic case for small short range aircraft services

- The combination of battery powered aircraft with higher levels of autonomous operation to reduce pilot requirements could reduce the operating costs of small aircraft operating out of community airports resulting in economically viable regional connectivity with direct, high-speed aircraft services.



Subsonic Transport Technology Strategy

Ensuring U.S. technological leadership

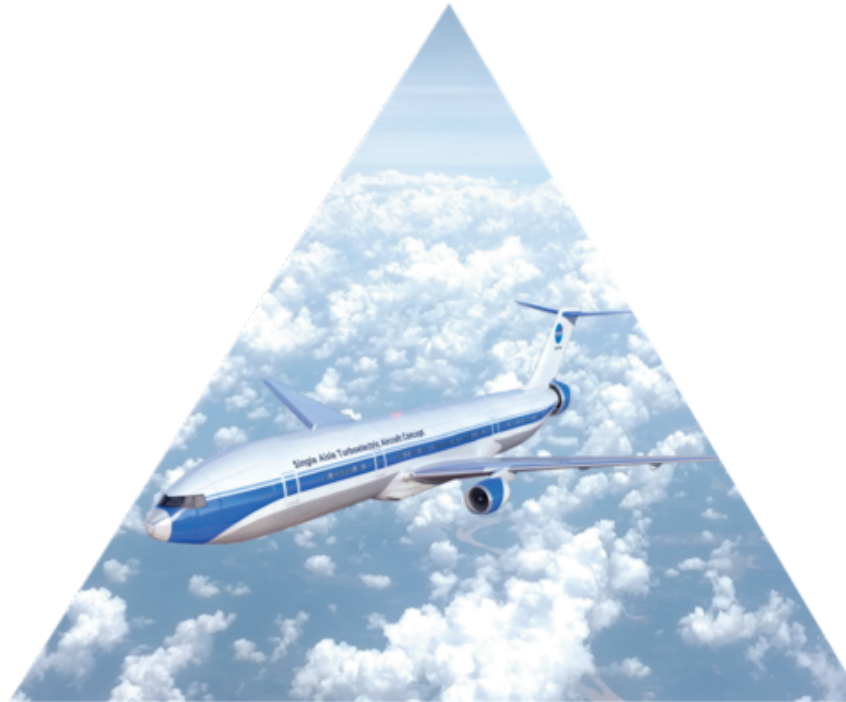


Transforming Propulsion – A Breakthrough Opportunity



Turbo-Electric Propulsion Architecture

Boundary-Layer
Ingesting Propulsor(s)



Ultra-Efficient “Small
Core” Turbofan

In whole or in part, transformational propulsion enables the next generation transitional subsonic transport configuration and enables future generation transformational subsonic transports

Electrified Aircraft Propulsion





Studies Targeting Regional Jets & Single Aisle Markets

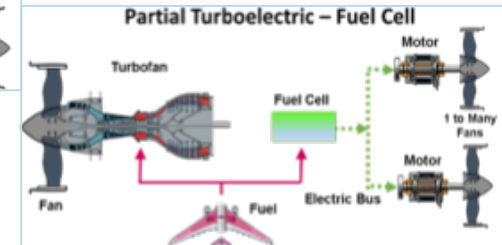
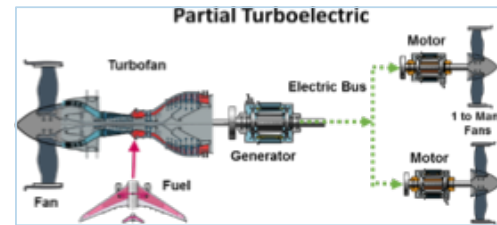
Partially and Fully Distributed Turboelectric Concepts



NASA STARC - ABL



Boeing/NASA SUGAR - FREEZE



NASA N3-X
(twin aisle)

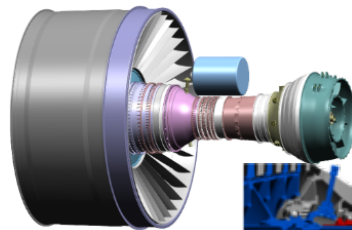


ECO-150

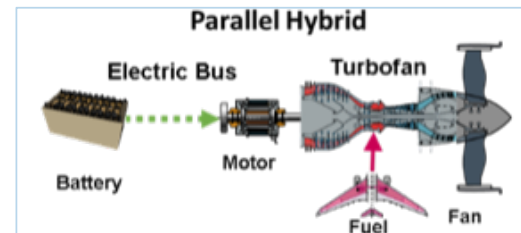
Parallel Hybrid Concepts



Boeing/NASA SUGAR - VOLT

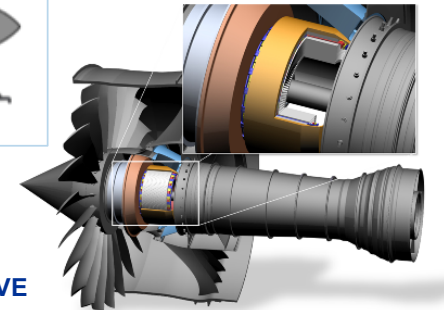


UTRC hGTF



Low Spool
High Spool

R-R LW EVE



Electrified Aircraft Propulsion Strategy for Single Aisle Aircraft



Initial Focus on Turboelectric Aircraft

Concept definition & system analysis

Novel integration and BLI

MW flight-weight electrical component development

Integrated system testing

Advanced cores with large power extraction

Potential Flight Demo

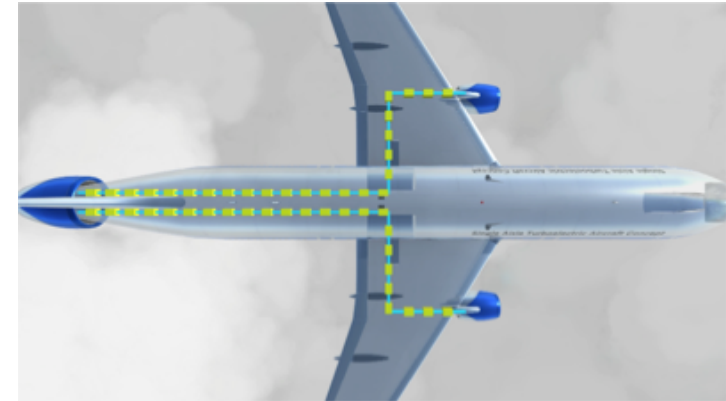
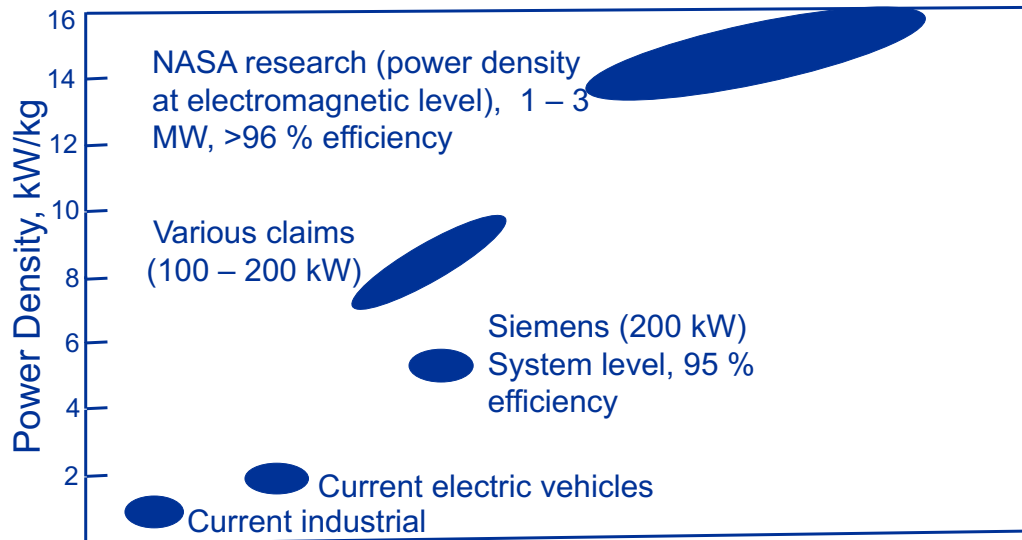
Single aisle aircraft entry into service in 2035 timeframe



Hybrid electric option to be considered with advances in battery technology

Development & Testing of MW Class Power System

High Power Density Electric Motor Development



Single-aisle Turboelectric Aircraft with Aft Boundary Layer Ingestion (STARC – ABL)

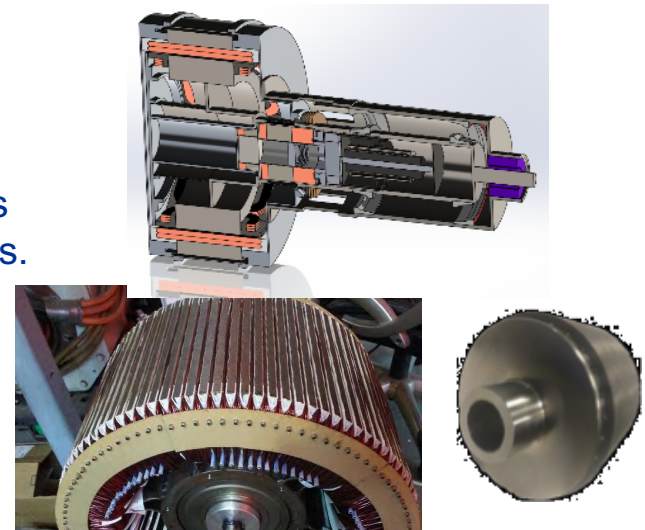
- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted turbine engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor
- Projected fuel burn savings for single-aisle missions



NASA Electric Aircraft Testbed (NEAT) for testing multi-MW level power system

MW-scale Electric Machines Research

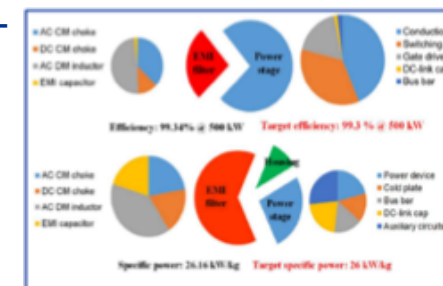
- Motors and/or generators (electric machines) are needed on all electrified aircraft.
- NASA is sponsoring or performing work to achieve power densities 2-3 times the state of the art for machines in the MW or larger class.
- Three major machine types are being developed: permanent magnet, induction, and wound field



	Continuous power rating, MW	Specific power goal, kW/kg	Efficiency goal, %	Motor type	Speed	Nominal dimensions
University of Illinois	1	13	>96	Permanent magnet	18,000	Cylinder 0.45 m by 0.12 m
Ohio State University	2.7	13	>96	Induction	2,500	Ring 1.0 m by 0.12 m
NASA Glenn Research Center	1.4	16	>98	Wound field	6,800	Cylinder 0.40 m by 0.12 m

MW-scale Converter Research

- Power converters are an essential component in most EAP aircraft concepts, as they are used to convert from ac to dc power, or vice versa
- NASA is sponsoring or performing work to achieve power densities 2-3 times the state of the art for converters in the MW or larger class.
- Silicon carbide and gallium nitride prototypes are being developed with conventional cooling as well as a cryogenically cooled converter



	Continuous power rating, MW	Specific power goal, kW/kg	Efficiency goal, %	Topology	Switch material	Cooling
General Electric	1	19	99	3 level	SiC/Si	Liquid
University of Illinois	0.2	19	99	7 level	GaN	Liquid
Boeing	1	26	99.3		Si	Cryogenic

Materials for Electrified Aircraft Propulsion

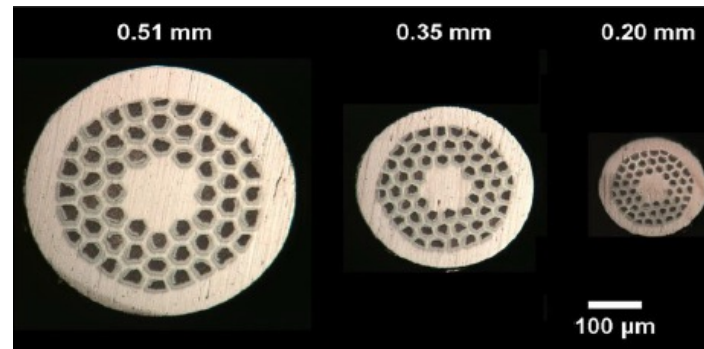
- New soft magnetic materials – improve performance of converter filters and electric machines
- Insulation – electrical insulation with better thermal transfer to improve electric machine performance
- High-Conductivity Copper/Carbon Nanotube Conductor – approach to reduce the mass of cables
- Superconducting Wire Development – AC superconductors which could be used for electric machines or distribution



25-mm by 1.6-km
spin cast ribbon



Transformer fabricated
from spin cast ribbon



Hyper Tech produced multifilament
MgB2 superconducting wires



CAPS idealized magnetic field test
capability for wire segments

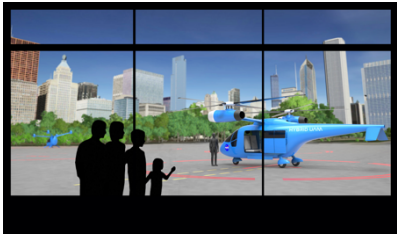
Urban Air Mobility – Vertical Takeoff & Landing (VTOL)



Move people inside congested urban areas from point to point using a VTOL air vehicle

Technologies

- Electric & hybrid-electric distributed electric propulsion (~300-400 kw HEP)
- Fault tolerant propulsion, flight systems
- Low-noise/annoyance
- Battery integration and safety
- High-speed charging
- Autonomous system capability
- Weather-tolerant operation
- High speed interoperable digital communications network
- Higher efficiency small gas turbine for hybrid electric



Significant commercial interest, initial commercial introduction likely to be in 2022 timeframe



NASA strategy under development – will influence initial & subsequent generations



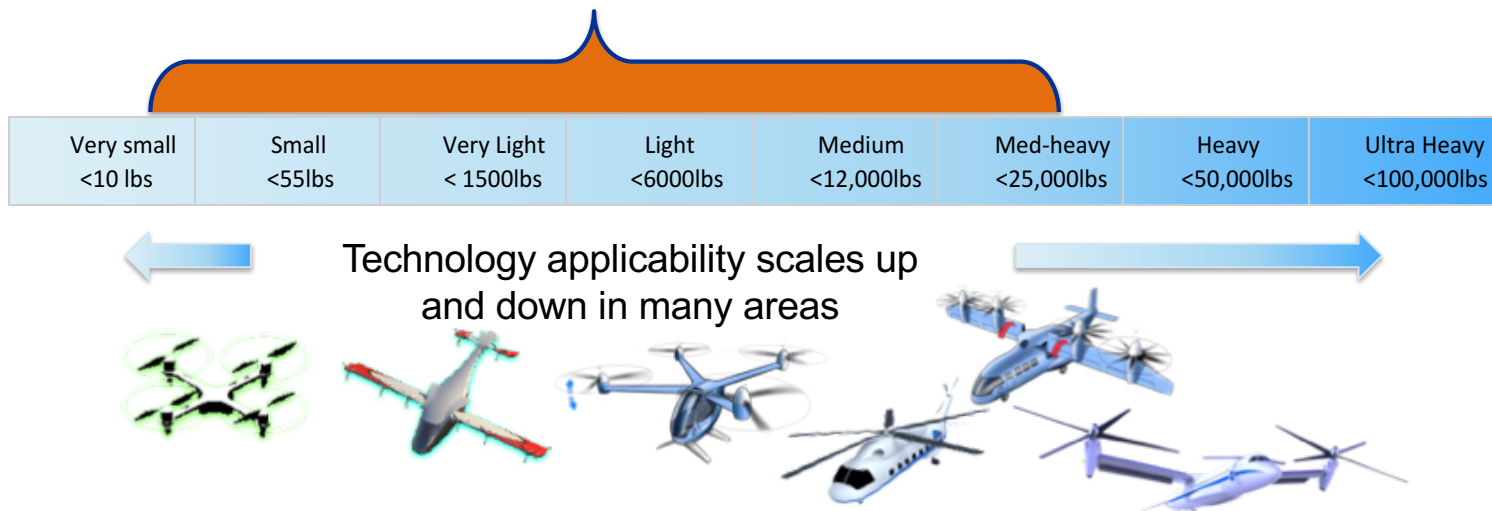
Electrified Propulsion for Vertical Lift

Overarching Vertical Lift Strategy

Enable a broad expansion of vertical lift applications

- Improve current configuration cost, speed, payload, safety, and noise
- Open new markets with new configurations and capability
- Capitalize on convergence of technology in electric propulsion, autonomy and flight controls

FY17+ NASA technology emphasis



NASA-developed VTOL Concept Vehicles for UAM

NOT “BEST” DESIGNS; NO INTENT TO BUILD AND FLY

06 Feb 2018

Objective: Identify NASA concept vehicles that can be used to focus/guide NASA research

- Open, publicly-available configurations
- Provide focus for trade studies and system analysis
- Push farther than current market trends
- Provide a range of configurations
- Cover a wide range of technologies and missions that are being proposed

Passengers	50 nm trips per full charge/refuel	Market	Type	Propulsion
1	1 x 50 nm	Air Taxi	Multicopter	Battery
2	2 x 50 nm	Commuter Scheduled	Side by Side (no tilt)	Parallel hybrid
4	4 x 50 nm	Mass Transit	(multi-) Tilt wing	Turboelectric
6	8 x 50 nm	Air Line	(multi-) Tilt rotor	Turboshaft
15			Lift + cruise	Hydrogen fuel cell
30			Vectored thrust Compound	

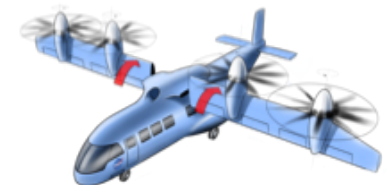
Quadrotor
“Air Taxi”



Side by Side
“Vanpool”



Tilt wing
“Airliner”



- Aircraft designed through use of NASA conceptual design and sizing tool for vertical lift, NDARC.
- Concepts described in detail in publication “Concept Vehicles for Air Taxi Operations,” by W. Johnson, C. Silva and E. Solis. AHS Aeromechanics Design for Transformative Vertical Lift, San Francisco, Jan. 2018.

Potential Research Areas for VTOL-enabled Urban Air Mobility



Passengers	50 nm trips per full charge/refuel	Market	Type	Propulsion
1	1 x 50 nm	Air Taxi	Multicopter	Battery
2	2 x 50 nm	Commuter Scheduled	Side by Side (no tilt)	Parallel hybrid
4	4 x 50 nm	Mass Transit	(multi-) Tilt wing	Turboelectric
6	8 x 50 nm	Air Line	(multi-) Tilt rotor	Turboshaft
15			Lift + cruise	Hydrogen fuel cell
30			Vectored thrust Compound	

PROPULSION EFFICIENCY

- high power, lightweight battery
- light, efficient, high-speed electric motors
- power electronics and thermal management
- light, efficient diesel engine
- light, efficient small turboshaft engine
- efficient powertrains

AIRCRAFT DESIGN

- weight, vibration
- handling qualities
- active control

OPERATIONAL EFFECTIVENESS

- disturbance rejection (control bandwidth, control design)
- all-weather capability
- cost (purchase, maintenance, DOC)

PERFORMANCE

- aircraft optimization
- rotor shape optimization
- hub & support drag minimization
- airframe drag minimization

ROTOR-ROTOR INTERACTIONS

- performance, vibration, handling qualities
- aircraft arrangement
- vibration and load alleviation

ROTOR-WING INTERACTIONS

- conversion/transition
- interactional aerodynamics
- flow control

Quadrotor + Electric

Tiltwing + TurboElectric

Side-by-side + Hybrid

SAFETY and AIRWORTHINESS

- FMECA (failure mode, effects, and criticality analysis)
- component reliability
- crashworthiness
- propulsion system failures

NOISE & ANNOYANCE

- low tip speed
- rotor shape optimization
- aircraft arrangement/ interactions
- active noise control
- metrics and requirements

STRUCTURE & AEROELASTICITY

- structurally efficient wing and rotor support
- rotor/airframe stability
- crashworthiness
- durability and damage tolerance



Thin Haul Commuter (Conventional Takeoff & Landing)

NASA Flight Testing – X57 Aircraft

X-57 “Maxwell”

- Cruise-sized wing: enabled by distributed electric propulsion (DEP) system for takeoff/landing performance
- High-efficiency cruise propellers: electric motors mounted at wingtips
- All-electric propulsion system: 40+ kWh battery, 240 kW across 14 motors
- Fully redundant powertrain



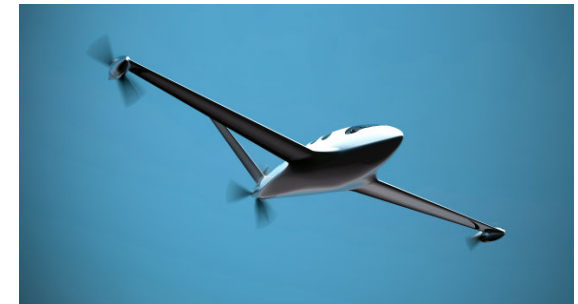
Current Effort:

- Demonstration of technologies & advanced concepts through flight tests
- Develop technologies to extend the range

Commercial (9-10 passenger)



Zunum Aero
(Hybrid electric)



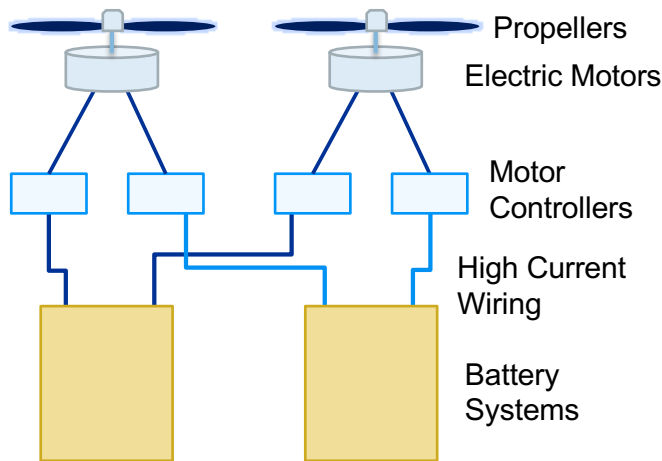
Eviation (all electric)

9-10 passenger, commercial
introduction planned for 2022 – 25
time frame



Distributed Electric Propulsion (DEP)

Distributed Electric Propulsion:
A system that distributes electric propulsion across the aircraft to yield significant benefits in aerodynamics, control and reliability.



Simplified X-57 Mod III Configuration
(typical DEP features)

Challenges for DEP systems including:

- Integration – Complex, highly distributed system
- Power Distribution – High voltage and current in very constrained areas
- Power Storage/Generation – Batteries or hybrid power plant
- Command/Control – Motor commands & management of varying power demands
- Thermal – High power systems can generate significant heat loads
- Mechanical – Rotating motors/wings, folding propellers, interacting load paths
- Weight – Primarily energy storage and/or power generation system
- Acoustics – Multiple interacting noise sources (aero-propulsive, motors, props)

X-57 efforts will enable:

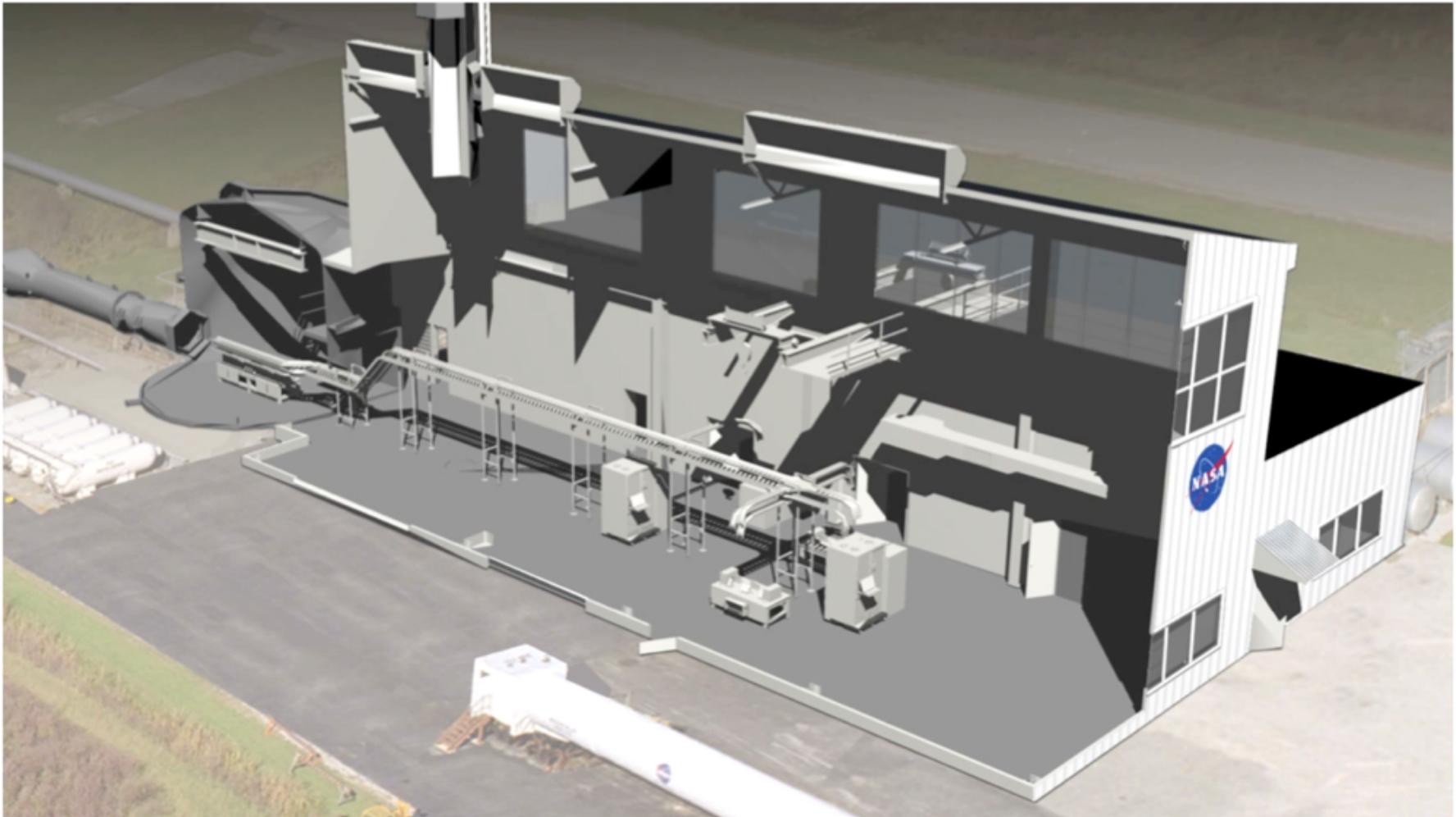
- Enhanced knowledge on interactions/integration including acoustics, power management, thermal loads, redundancy & failure modes, folding propeller operations, and propulsion airframe interaction
- Critical source information for technology development, integration, flight test documentation, and lessons learned – will inform/influence the development of certification standards (highly competitive industry not publishing their own work)

Essential Test Capabilities





NASA Electric Aircraft Testbed (NEAT)

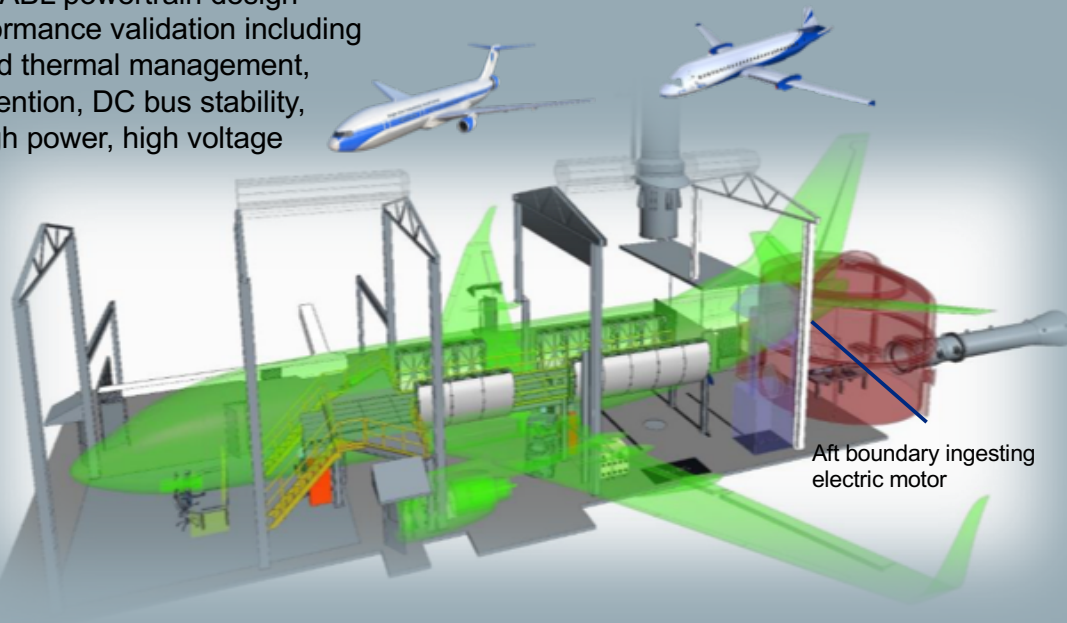




NASA Electrified Aircraft Technology (NEAT)

Problem

Hybrid electric STARC-ABL powertrain design requires full-scale performance validation including EMI mitigation, fault and thermal management, turbine surge/stall prevention, DC bus stability, flight-efficiency, and high power, high voltage component verification.



Results

Completed the assembly of a STARC-ABL powertrain including turbo-generation and tail-cone thruster machine pairs, ARINC 664 communication protocol, 600VDC multi-bus, NPSS turbine and ducted fan with closed loop torque feedback, power regeneration, thermal management system and facility integration.

Successfully operated a 600VDC STARC-ABL powertrain configuration with approximately 460kW tail-cone thrust power with representative turbine and ducted fan performance maps through a representative flight profile.

Objective

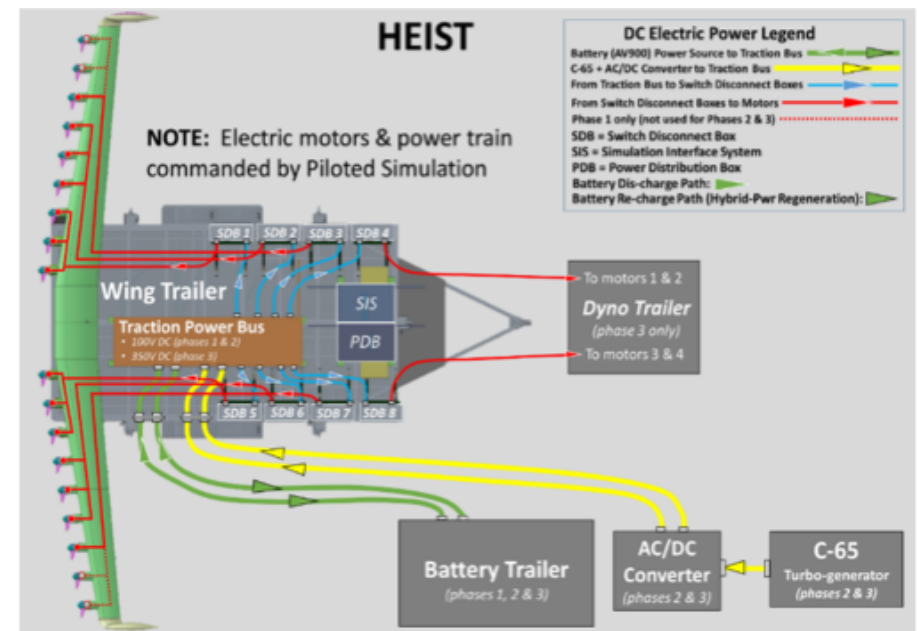
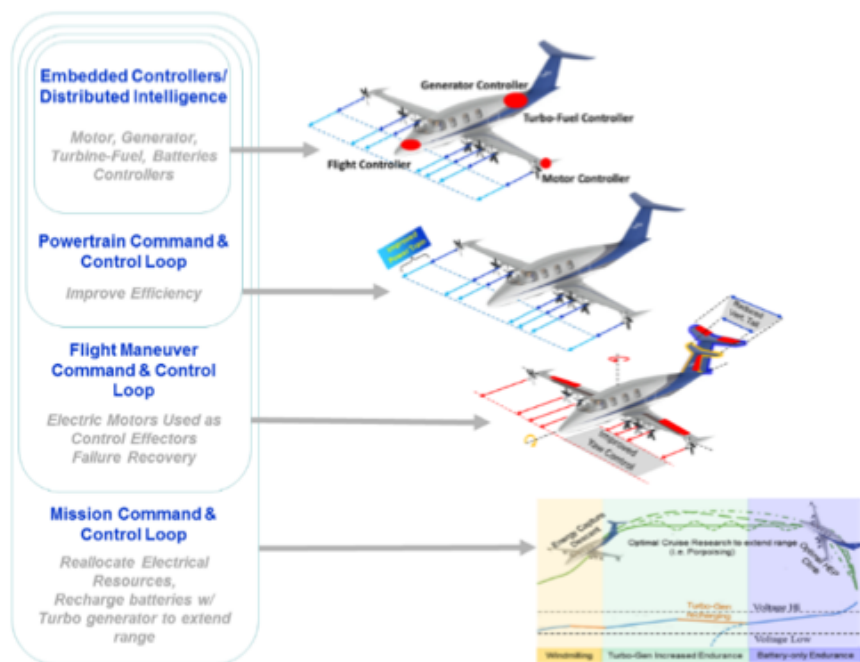
Establish a 500kW STARC-ABL powertrain with COTS equipment and demonstrate operation of the powertrain through a complete flight-profile with NPSS turbine and ducted fan emulation.

Significance

This powertrain is the first operational powertrain that is representative of the STARC-ABL vehicle and it enables model validation to establish concept viability, demonstrates power/propulsion/communication/thermal integration at the MW scale, and guides the optimization of the powertrain control dynamics.

Hybrid Electric Integrated Systems Testbed (HEIST)

- Being developed to study power management and transition complexities, modular architectures, and flight control laws for turboelectric distributed propulsion technologies using representative hardware and piloted simulations
- Configured in the fashion of an iron bird to provide realistic interactions, latencies, dynamic responses, fault conditions, and other interdependencies for turboelectric distributed aircraft, but scaled to the 200 kW level.
- Power and voltage levels that would be considered subscale for a commercial transport, but test capability extends to the entire airplane system and can exercise all aspects of flight control, including cockpit operations.



Concluding Remarks

- Electrified propulsion technology development well underway.
- Specific technologies for development driven by the integrated propulsion systems and the propulsion systems driven by mission requirements
- Continuing to advance technologies and knowledge applicable to variety of missions and systems as well as those critical to enabling the systems

