Overview of NASA Electrified Aircraft Propulsion Activities

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Ralph Jansen

Aeronautics Project Office

NASA Glenn Research Center

Community Outcomes and Benefits

Thrust 4: Transition to Low-Carbon Propulsion			
	2015	2025	2035
Community Outcomes	Introduction of Low-Carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Initial Introduction of Alternative Propulsion Systems	Introduction of Alternative Propulsion Systems to Aircraft of All Sizes
Benefits	• Sustainable alternative drop-in fuels begin to make a difference in fleet carbon reduction beyond that from efficiency gains • Scientific understanding of combustion emissions and environmental impact informs decisions on emissions standards • Experience and knowledge base established in electrified aircraft propulsion technology and design trades • Small aircraft markets enabled in part by electrified aircraft propulsion begin to open	• Advanced propulsion systems with optimized use of sustainable drop-in fuels that are economically produced in sufficient quantities to substantially reduce fleet carbon emissions • Certified small aircraft fleets enabled by electrified aircraft propulsion enter service, providing new mobility options • Initial application of electrified aircraft propulsion on large aircraft	• Sustainable alternative drop-in fuel use is the norm for advanced, optimized gas turbines and alternative propulsion systems • Small aircraft fleets with electrified propulsion are prevalent, providing improved economics, performance, safety and environmental impact • Large aircraft with cleaner, more efficient alternative propulsion systems substantially contribute to carbon reduction with growth in fleet operations

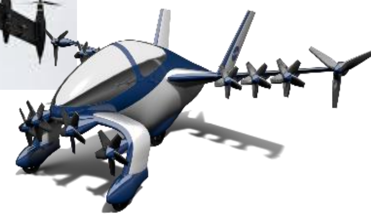
* Research horizons used in Federal Alternative Jet Fuel Strategy: <5 years (Near-term), 5-10 years (Mid-term), >10 years (Far-term)

Electrified Aircraft Propulsion Enables New Aircraft Designs

Potential EAP Benefits vary with Mission:

- Improvements to highly optimized aircraft like single aisle transports
  - 5-10% fuel burn reduction estimated using electrically driven BLI thruster is in addition to other benefits from improved engine cores or airframe efficiencies. Later developments could be fully electrified with split wing and more advanced electrical distribution and storage. Addresses Thrust 3 & 4.

- Enabling new configurations of VTOL aircraft
  - The ability to widely distribute electric motor driven 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 and cargo transport.

Aircraft Type A: 4-9 PAX CTOL

X-57 “Maxwell”

NASA X-57
Mod 4 Version

- Aero benefit demonstrated
  - Cruise-sized wing: enabled by DEP system for takeoff/landing performance
  - High-efficiency cruise propellers: electric motors mounted at wingtips
- Other benefits:
  - All-electric propulsion system: 40+ kWh battery, 240 kW across 14 motors
  - Fully redundant powertrain
- Potential upgrades beyond Mod 4
  - Hybrid power plants: fuel cell, range extender
  - Flight Controls integrated to DEP
  - Acoustic optimized power distribution

NASA Thin-Haul Commuter Concept

NASA
Thin-Haul
Commuter
Concept

- Total operating costs reduced up to 25%
- Initial EIS as early as 2025
- Tall Pole Technologies
  - Battery and Hybrid-Electric Propulsion
  - PAI optimized for 2000’ runways
  - Single-pilot flight systems enabling 2-pilot performance, safety
  - Revised airworthiness, pilot licensing, and operational regs. for full system benefit (e.g. Parts 23, 61, 91 & 135)

Aircraft Type B: VTOL with =>1 PAX

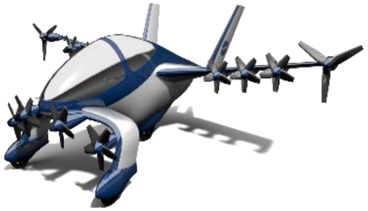
NASA Target Vehicle

- 3-4 place
- ~6000 lbs.
- ~120nm
- 150+kts cruise
- Low-noise/annoyance
- Small ground/air footprint in low-visibility
- Flight procedures, ATM for urban mobility
- High-speed charging
- All-weather ops./icing protection

Technologies

- ~6000 lbs. GTOW
- Electric & H-Electric DEP (~300-400 kw HEP)
- Simplified, augmented flight & trajectory control
- Fault tolerant propulsion, flight systems
- Ab-initio, single-pilot flight deck

Relevant NASA Experience/Concepts



Aircraft Type C Examples: Regional, Single Aisle, Larger Aircraft

NASA STARC-ABL

NASA
STARC-ABL

- Benefit – 7-12% net fuel burn reduction
- Supports 2035 EIS with current airport infrastructure
- Tall Pole Technologies
  - ≈ 3 MW non flight critical power system
  - BLI tail cone fan
  - 2 x 1.5 MW power extraction from turbines

NASA N3-X

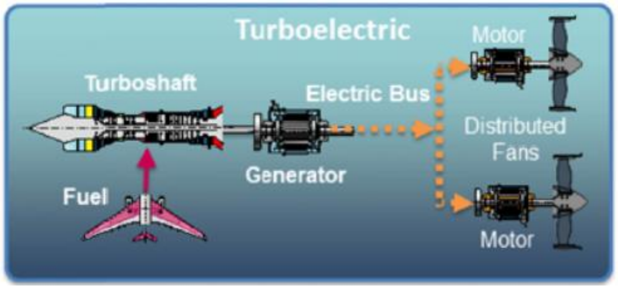
NASA
N3-X

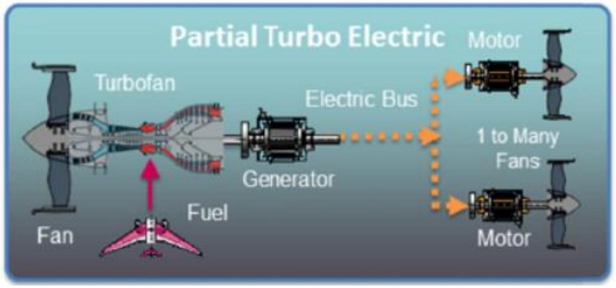
- Benefit – Maximum PAI, Propulsion benefits
- Numerous technical challenges, probable 2055 or later EIS.
- Tall Pole Technologies
  - ≈50 MW flight critical superconducting power system
  - Hybrid wing body
  - Many top mounted asymmetric BLI propulsors
  - 2x25 MW turbogenerators

Types of Electrified Aircraft Propulsion

Electrified Aircraft Propulsion (EAP) systems use electrical motors to provide some or all of the thrust for an aircraft

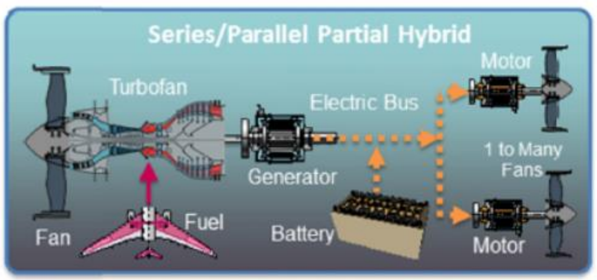
- Turboelectric systems use a turbine driven generator as the power source. Partially turboelectric systems split the thrust between a turbo fan and the motor driven fans.

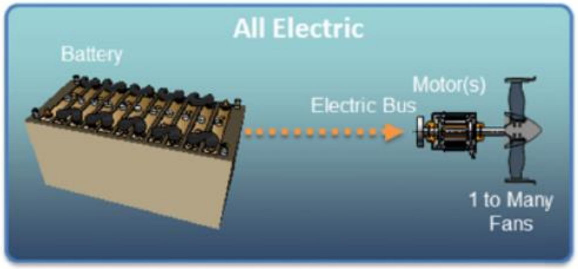




- Hybrid electric systems use a turbine driven generator combined with electrical energy storage as the power source. Many configurations exist with difference ratios of turbine to electrical power and integration approaches.

- All-electric systems use electrical energy storage as the only power source.





Current ARMD Electrified Aircraft Investments

The purpose of this section is to provide a top-level overview of the current ARMD investments categorized by Program and Aircraft Category that the investment relates to.

- The aircraft categories are::
  A. 4-9 passenger conventional takeoff and landing aircraft
  B. Vertical Takeoff and Landing with >1 passenger
  C. Regional jet size or larger and be commensurate with operations in the current airspace infrastructure

Advanced Air Vehicles Program (AAVP)

Integrated Aviation Systems Program (IASP)

Transformative Aeronautics Concepts Program (TACP)

What is NASA doing?

- Organized by Program and Type of Air Vehicle primarily addressed
  - Does not take credit for portion of small core, BLI, or systems in AATT which is relevant to large future EAP
  - Does not take credit for autonomy or airspace management work which is relevant to small EAP

	ARMD Technology Development (FY17)	ARMD Flight Test (FY17)
4-9 PAX CTOL	None *Possible ODM investment*	**IASP/FDC/X-57 FY17-20**
>1 PAX VTOL	**AAVP/RVLT/MDAO FY16-FY18** **4-6 PAX, VTOL** • *Possible leverage from AAVP/RVLT draft TC for UAS VTOL* • *Possible ODM investment*	None
RJ or SA	**AAVP/AATT/HGEP (TC FY15-19), Single Aisle**	None
proof of feasibility	**TAC/CAS**	Small UAS test of structural battery

- Additional small business and university investments in several areas through SBIR, STTR

Advanced Air Transport Technology Hybrid Gas Electric Subproject

Objective: Develop system concept and underlying technology for single aisle hybrid electric aircraft

Aircraft Type: Primary C, some elements aligned to A

Planned Schedule: Tech challenge FY15-19.

Element Name	Technology	Aircraft Focus	Aircraft Applicability
System Studies	Develop integrated aircraft, propulsion & power concept	C	C
Electric Machines	High power (MW), light, efficiency motors	C	A, B, C
Power Systems	High power, light, efficient power converters	A, C	A, B, C
Materials	Soft magnetics, insulation, conductors	A,C	A, B, C
Turbine/Generator Integration and Controls	Establish feasibility of turbogeneration	C	B, C
Boundary Layer Ingestion (BLI)	Confirm aft BLI benefits, develop technologies	C	C
Integrated Test Beds	HEIST, NEAT	A, C	A, B, C

IASP/FDC/X-57 Maxwell

Objective: Demonstrate aero benefits of DEP-enabled cruise sized wing
Aircraft Type: Primarily Aligned to 4-9 PAX EAP Aircraft
Planned Schedule: FY17-20

Element Name	Technology	Aircraft Focus	Aircraft Applicability
System Studies	Develop integrated electric propulsion flight demonstrator; Mod 4 expansion: hybrid powerplant, propulsion integrated flight controls,	A	A, B, C
Electric Machines	High power density (W/kg) motors, high-efficiency cruise propellers: electric motors mounted at wingtips	A	A, B, C
Power Systems	All-electric propulsion system (40+ kWh), 240 kW distributed among 14 motors, fully redundant powertrain	A	A, B, C
Materials	Li-Ion battery system, low emittance power distribution buses	A	A, B, C
Integrated Test Beds	HEIST, NEAT	C	A, B

TAC/CAS work with relevance to EAP*

Objective: Feasibility assessment of transformative concepts/solutions
Aircraft Type: Some elements aligned to sUAS, A, B, & C
Planned Schedule: CAS activities typically execute for 2–2.5 years

Element Name	Technology	Aircraft Focus	Aircraft Applicability
HVHEP	High voltage AC power distribution	C	A, B, C
MSHELLS	Structural battery	C	sUAS, A, B, C
LION	Battery Life Modeling	A-C	sUAS, A, B, C
FUELEAP	Solid Oxide Fuel Cell	A	A, B, C
CAMIEM	Additive Electrical Motor	A	sUAS, B
DELIVER	Cryo-cooled power electronics / motors	sUAS	sUAS, A, B, C

*Multidisciplinary efforts, significantly broader than EAP *per se*.

Revolutionary Vertical Lift Technology Tech Challenge

RVLT TC.2.1 Demonstration of an MDAO Process for Vertical Lift Vehicles

Aircraft Type: 4-6 PAX, VTOL

Planned Schedule: FY16-18

Objectives:

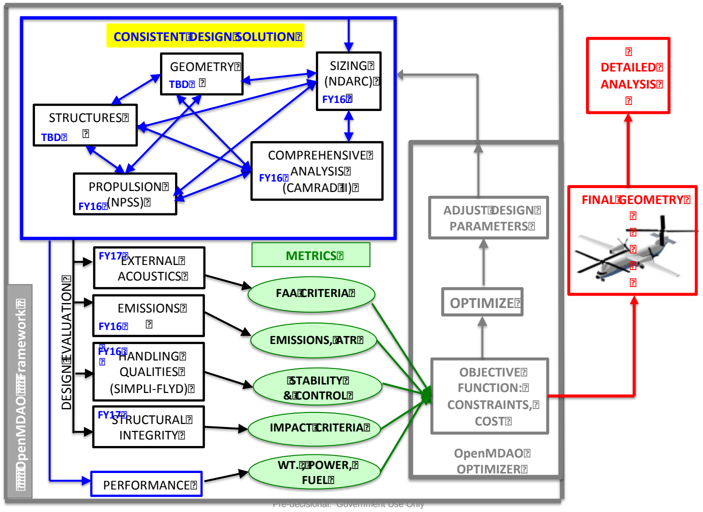
- New discipline tools integrated in a design optimization framework and low-noise, low-emission VTOL conceptual designs generated using a new MDAO process
- Development and Demonstration Metrics scores (measuring fidelity, scope, objective function, efficiency and design goals) within the range 15-20 at TC completion

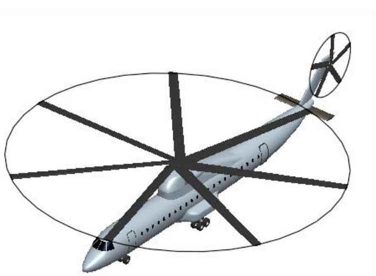
Technical Areas and Approaches:

- Develop integrated discipline modules that operate within a streamlined optimization framework
- Create conceptual designs of VTOL aircraft that meet emission and external noise metrics
- Verify aircraft and component designs using higher-fidelity analyses and experiments
- Assess the feasibility of testing promising VTOL designs in flight

Benefit/Pay-off:

- Ability to use formal optimization to assess configuration trades for multiple requirements /SIP Near/
- Cleaner, quieter VTOL configurations that serve as drivers for focusing and advancing technology /SIP Mid, Far/

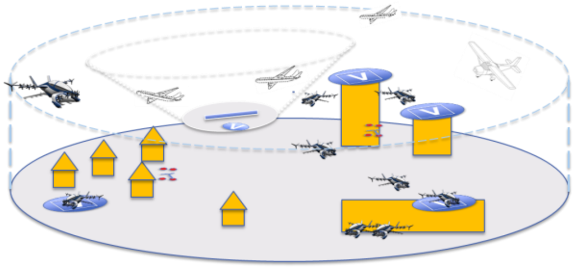




On Demand Mobility / Emerging Markets

NASA is uniquely qualified to *integrate these technologies* and *demonstrate the viability* of the Urban Aviation System concept

- *Deployable and scalable*
- *In partnership with stakeholders*



1. **Validated near-term operational capability of integrated system in *simulation and flight***
    - Low overall density of VMC/VFR operations, locally moderate ODM densities
    - Reliable and Increasingly capable flight deck automation for simplified vehicle operations
    - Preliminary cert-basis and standards for reduced fuel/energy reserves, flight-critical stability & trajectory augmentation, hybrid/electric propulsion, community noise
    - Initial, CNS capabilities/networks V2V, V2Ops, V2ATM

2. **Validated longer-term operational scalability and feasibility in simulation**
    - Scalability through high-fidelity human-in-the-loop and fast time simulation
    - Feasibility through piloted simulations and partners' economic analyses
    - Key aspects of scalable integrated system
        - Medium overall density of VFR-like operations in IMC, locally high ODM densities
        - ODM integration in NAS enabled by UAS- and UTM-derived capabilities, projected CNS
        - Comprehensive autonomy handles most vehicle operations, on-board pilot has simplified commercial pilot license and serves to accelerate operational approval
        - Full-electric aircraft highly-automated state-awareness, prognostication, adaptability
        - ODM fleet-level contingency robustness

Thoughts about Markets, Time, Cost to Entry

9 PAX and Smaller

- Potential Emerging Market
  - EAP with Automation may reinvigorate viability of thin-haul air routes.
  - EAP with Automation may make urban air taxies viable.
  - These emerging markets may grow very quickly, similar to the UAV market.
  - These markets have the potential to be truly transformative in our transportation systems.
- Time to Entry
  - Markets with high growth can attract venture capital and non-traditional companies which act quickly and leverage technologies from other industries.
  - Quick time from product concept to market is essential for these kinds of investments.
- Cost
  - Costs for smaller, shorter-term projects will be lower.
  - More small projects can be funded, so risk can be spread across several different approaches.
  - Cost share or partnerships may be important to get small companies started.

Single Aisle

- Large Viable Market
  - Single Aisle Transports are a large (multi billion$), viable, existing market with expected strong continuing sales.
  - New technologies generally need a 5-10% fuel burn benefit to justify investment. This is the range of benefit projected by initial studies for single aisle aircraft.
- Time to Entry
  - 20 years from concept to entry into service is common in this market.
  - In order to have a viable 2035 EIS system, the full-scale technology demonstration needs to be completed by the 2025 time frame.
- Cost
  - Costs in this class are higher than for small planes.
  - It is likely that only one technical path can be pursued at the X-Plane level in this area, so risk must be managed through the technical approach and ground testing of components.
  - Cost share with industry is likely to be required due to the magnitude of the combined ground and flight test effort.

Evolution of Thought within NASA

Large Plane: >80 PAX

GREATLY REDUCED TECHNOLOGY NEEDS ENABLE NEAR TERM FLIGHT FULL SCALE DEMO

Fuselage: HWB
Propulsion: Fully distributed
Power Distribution: 50MW, Superconducting, 7500V, FLIGHT CRITICAL
Power Source: Turbo generators
Infrastructure: Same air traffic

Fuselage: Tube and Wing
Propulsion: Partially distributed
Power Distribution: 3MW, 1,200V, not flight critical
Power Source: Turbo generators
Infrastructure: Same air traffic, airports

EXTREME PAI, BATTERY POWERED, LOW COST FLIGHT DEMO

Fuselage: Tube and Wing
Propulsion: Fully distributed
Power Distribution: 1MW, 600V, FLIGHT CRITICAL
Power Source: Batteries to 200miles, fuel to 500 miles
Infrastructure: Underutilized small airports, new charging stations

Fuselage: Fixed Wing VTOL
Propulsion: Fully distributed
Power Distribution: <1MW, <600V, FLIGHT CRITICAL
Power Source: Batteries to 100 miles
Infrastructure: Advanced air traffic, reduced or no pilot, new infrastructure

NEAR/ MID

GOAL:
2035 EAP EIS for Single Aisle

Activities:
2025 RJ or SA X-Plane Enabling R&D

GOAL:
New Aircraft Market

Activities:
Fixed Wing VTOL X-Plane Enabling R&D

MID/FAR TERM

Small and Large come together with full DEP and on-board electrical storage