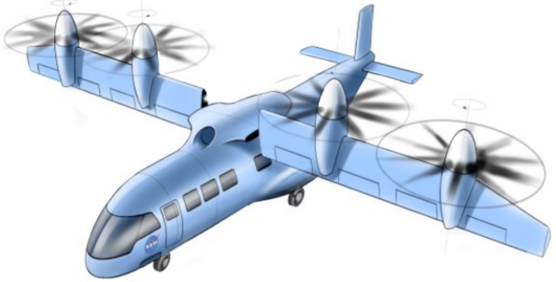

Overview of Electrified Aircraft Propulsion at NASA

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NASA Glenn Research Center

National Academy of Science - Aeronautics and Space Engineering Board

September 26, 2019 Irvine, California

Changing Landscape in Commercial Transport Market

Current market is growing and expanding

- Boeing and Airbus have strong product lines with significant numbers of orders (737MAX, 787, 777X, A320neo, A350)
- Strong demand for increased production rates are driving both airframe and engine companies

Interests in electrification of aircraft is rapidly growing

- Advances in battery technologies are motivating the industry to develop alternative propulsion system
- Short-haul / Thin-haul market interests are rapidly growing
- International competition is heating up
  - Airbus / Rolls Royce / Siemens announced partnership for electric aircraft in 2017

Potential Benefits of Electrified Aircraft Propulsion

Improvements to Highly Optimized Aircraft Such as Single-Aisle Transports

- Enables significant fuel burn reduction from alternative architectures and operational schemes in addition to other benefits from improved engine cores or airframe efficiencies

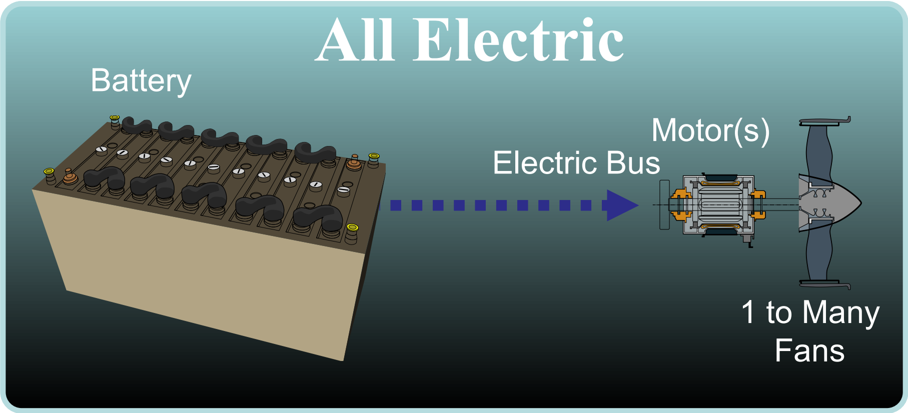
Helps Open Urban Air Mobility Market

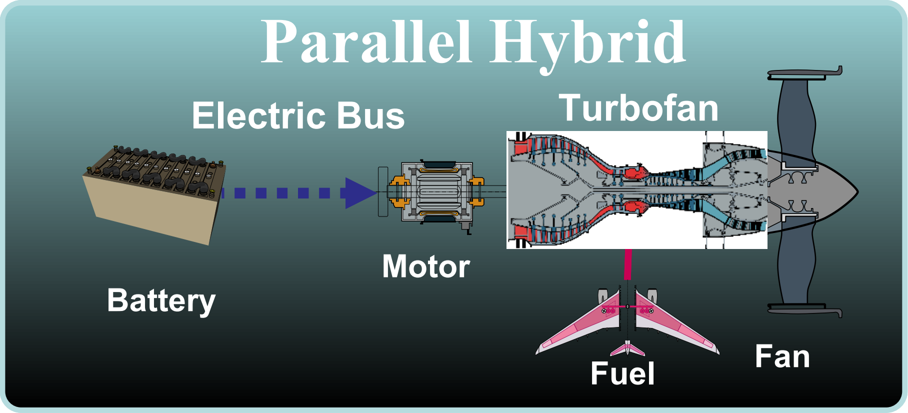
- Enable new VTOL configurations with the potential to transform transportation and services
- Lessons learned here will flow to larger vehicles

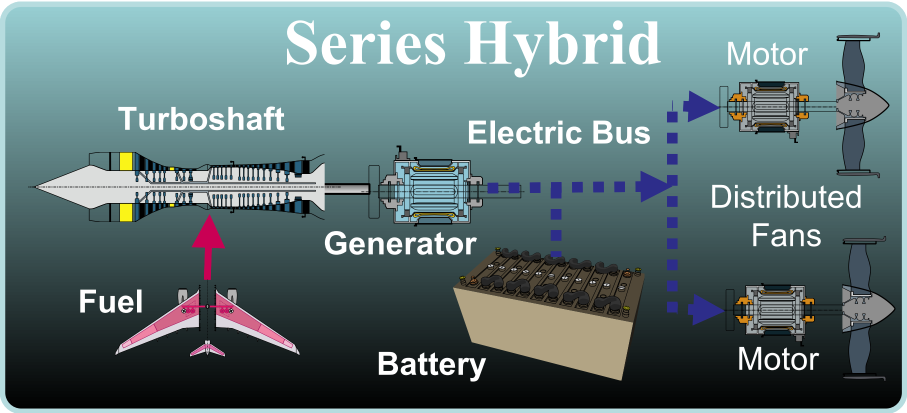
Revitalizing the Economic Case for Small Short-Range Aircraft Services

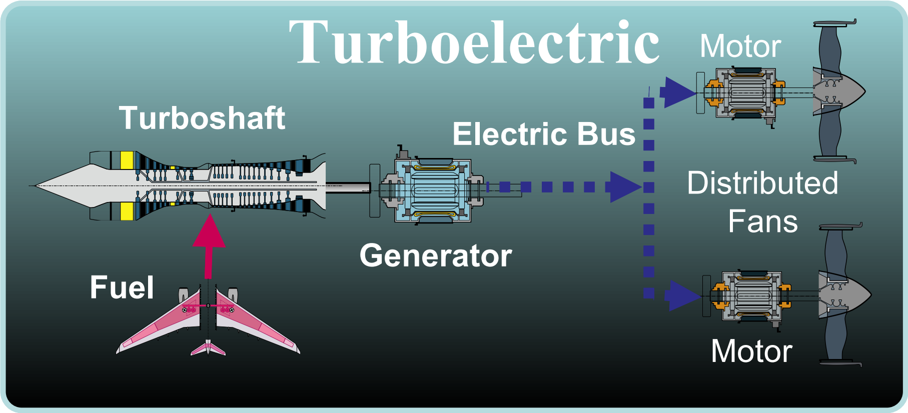
- The combination of electrified propulsion aircraft with higher levels of autonomous operations could reduce the operating costs of small aircraft operating out of community airports resulting in economically viable regional connectivity

Four Cardinal Electric Propulsion Architectures

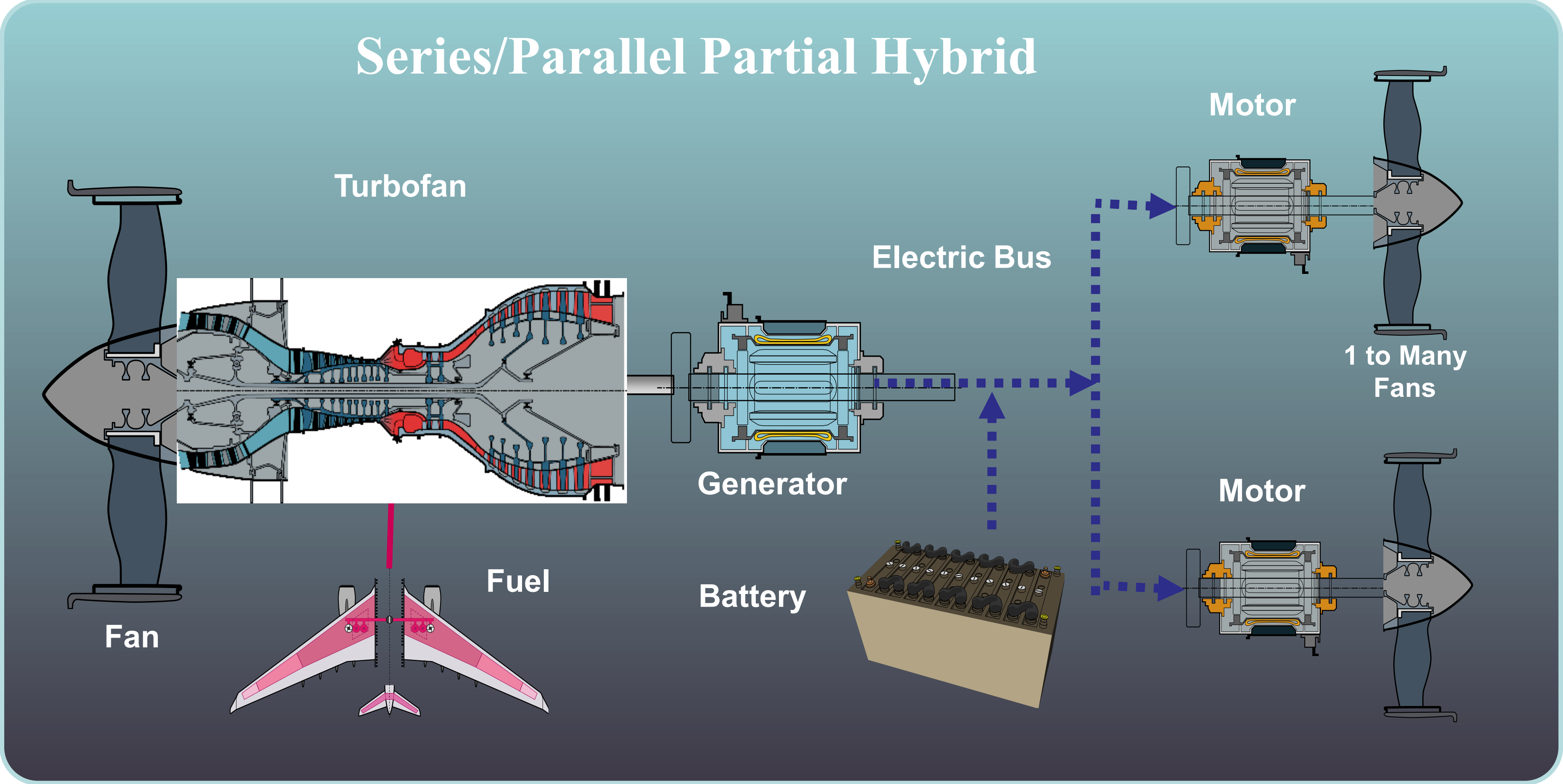








But Wait, There's More



Electrified Aircraft Propulsion – The Big Picture

A range of vehicles for a range of needs

	UAS	UAM	Small A/C	RJ	Single Aisle	Twin Aisle
						
Implementation Status	All electric vehicles in operation	All electric or hybrid applications being developed		Potential for hybrid or turbo-electric within 10 years		Significant progress needed for practical implementation
NASA Role	NASA research not needed	NASA focus: informing standards, regulations & design tools		NASA focus: enabling technologies, demonstrating benefits, addressing safety needs		Still too long term – not yet a NASA focus

Small Vehicle EAP

Energy & cost efficient, short range aviation

Transport Scale EAP

Energy & cost efficient, transport aviation

Leverage learning at smaller size to inform scale-up

Fundamental challenges span range of sizes

NASA EAP Strategy

All & Hybrid Electric, Distributed Propulsion
- On Demand Mobility
- Small Vehicle Focused

Turbo and Hybrid Electric, Distributed Propulsion
- Energy Efficient Propulsion
- Transport Class Focused

AATT/RVLT & IASP/X-57

Enable New Aero Efficiencies

Power Sharing

Distributed Thrust Control

Standards and Means of

AATT/AAVP & UEST/EAP/IASP

Enable New Aero Efficiencies

High Efficiency Power Distribution

Power Rich Optimization

Non-flight Critical First

Fundamental Challenges (e.g. materials)

Energy & Cost Efficient, Short Range Aviation

Leverage learning at smaller scale to inform scale-up

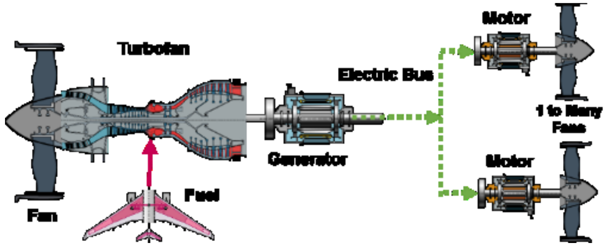
Energy & Cost Efficient, Transport Aviation

NASA Small Vehicle EAP

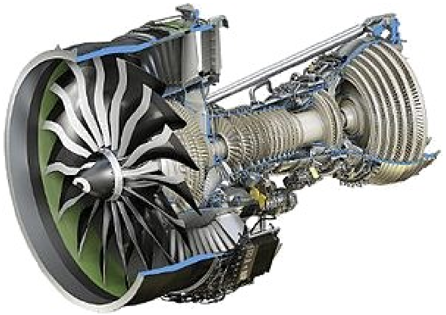
NASA Transport EAP

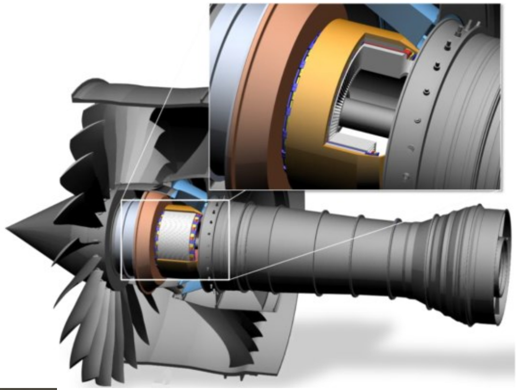
Multiple Aspects to Electrified Aviation Propulsion

EAP encompasses more than just electrical components:

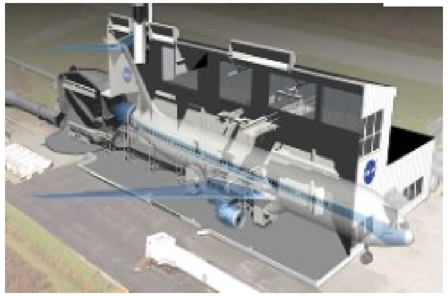


System Level
- Boundary layer ingestion
- Other propulsion airframe integration benefits
- Systems analysis tools
- Test capabilities





Electrical generation, storage and distribution
- Electrical power components (e.g. inverters, motors, generators & systems)
- Power storage
- Power extraction
- Electric System architectures

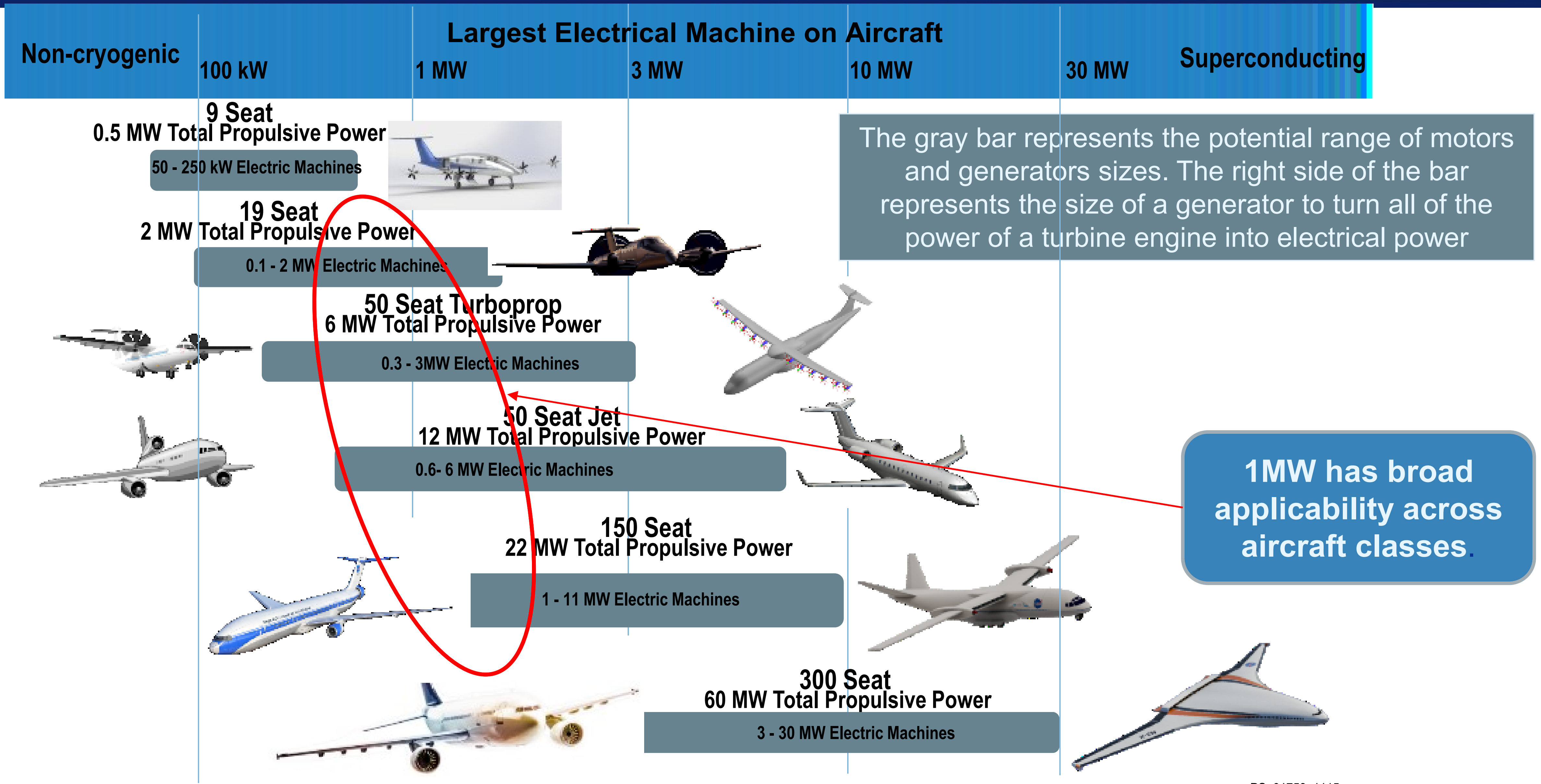


Coupled turbine systems
- Integrated Electrical Machines
- Small core turbomachinery
- New material systems

Electrified Aircraft Propulsion (EAP) – the suite of technologies and capabilities that will enable air vehicles to leverage benefits of electricity in their propulsion systems.

Electrified Aircraft Machine Power Requirements

Why 1MW+ Focus?



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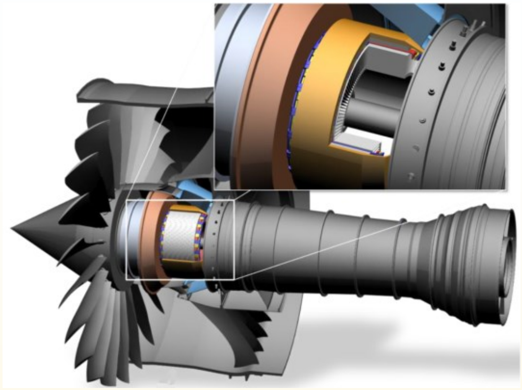
Electric Aircraft Propulsion – Potential Game Changer

Why 1MW+ is Important…

- 1MW power systems have broad applicability across aircraft classes, from small regional jets to single-aisle aircraft
- Opportunity to open new markets for U.S. industry as well as support U.S. competitiveness in existing markets



Why 1MW+ is Difficult...

- Existing MW+ electric ground power systems are efficient, but they are large and very heavy
- Reducing weight and addressing integration challenges is key for successful electrification of aircraft
- Smaller surface area to volume ratio and less thermal mass makes thermal management more challenging

Why EAP Flight Testing is Crucial…

- Flight research needed to advance EAP TRL by better understanding powertrain altitude performance, electrical & thermal integration challenges, & potentially turbine integration challenges.

Advances and TRL Maturation Required in Key Technology Areas:

- Electric Machine Weight/ Efficiency
- Electric Power Distribution Weight/ Efficiency
- Turbine Engine Integration
- EMI Mitigation
- Thermal Management
- Energy Storage

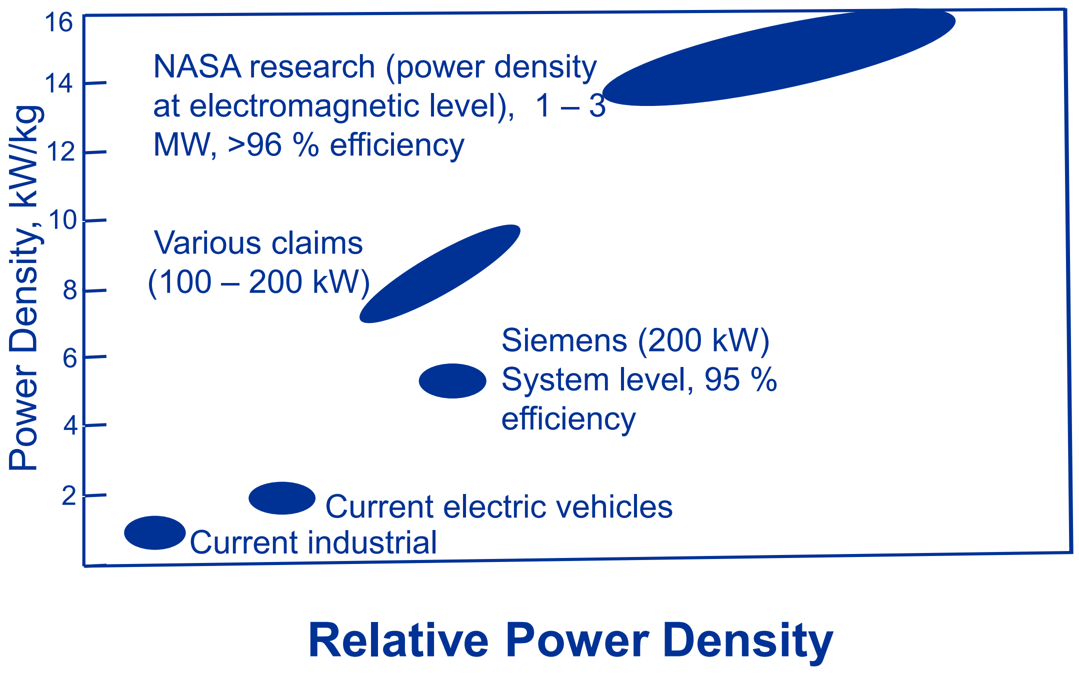
Technology Development for MW Class Power System

Electric Machines: Goal: >13kW/kg EM weight, >96% eff
- Design and subcomponent testing by UIUC, OSU, NASA GRC successful.
- Full scale build and test in plans.
- Three key machine types: PM, Induction, Wound Field

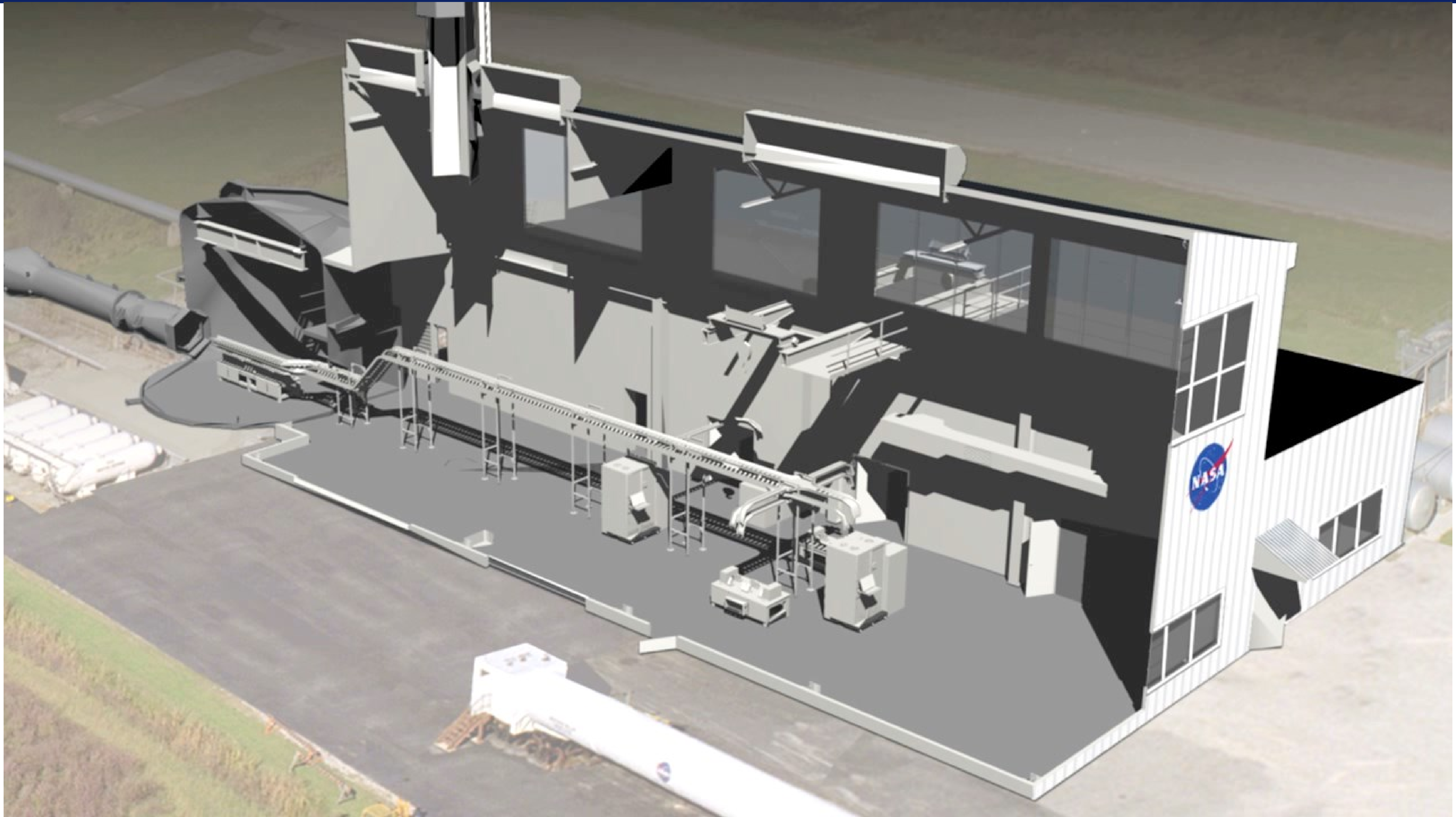
Inverters: Goal: >19kW/kg EM weight, >99% eff
- FY 18 Result: GE full scale prototype meets DO-160 and efficiency goal
- GE, University of Illinois, and Boeing on track to meet specific weight goal
- Portfolio covers key switch materials types: Silicon Carbide, Gallium Nitride, Silicon
- Portfolio also covers key architecture types.

Enabling Materials
- New soft magnetic material that will reduce EMI filter weight produced in lab and characterized. Agreements in work to move to industrial partner for production
- AC Superconducting wire created

Emerging Topics:
- Thermal management of waste heat from electrical system
- Light weight / reliable fault management of electrical system
- Batteries that are high performance, low cost, and safe

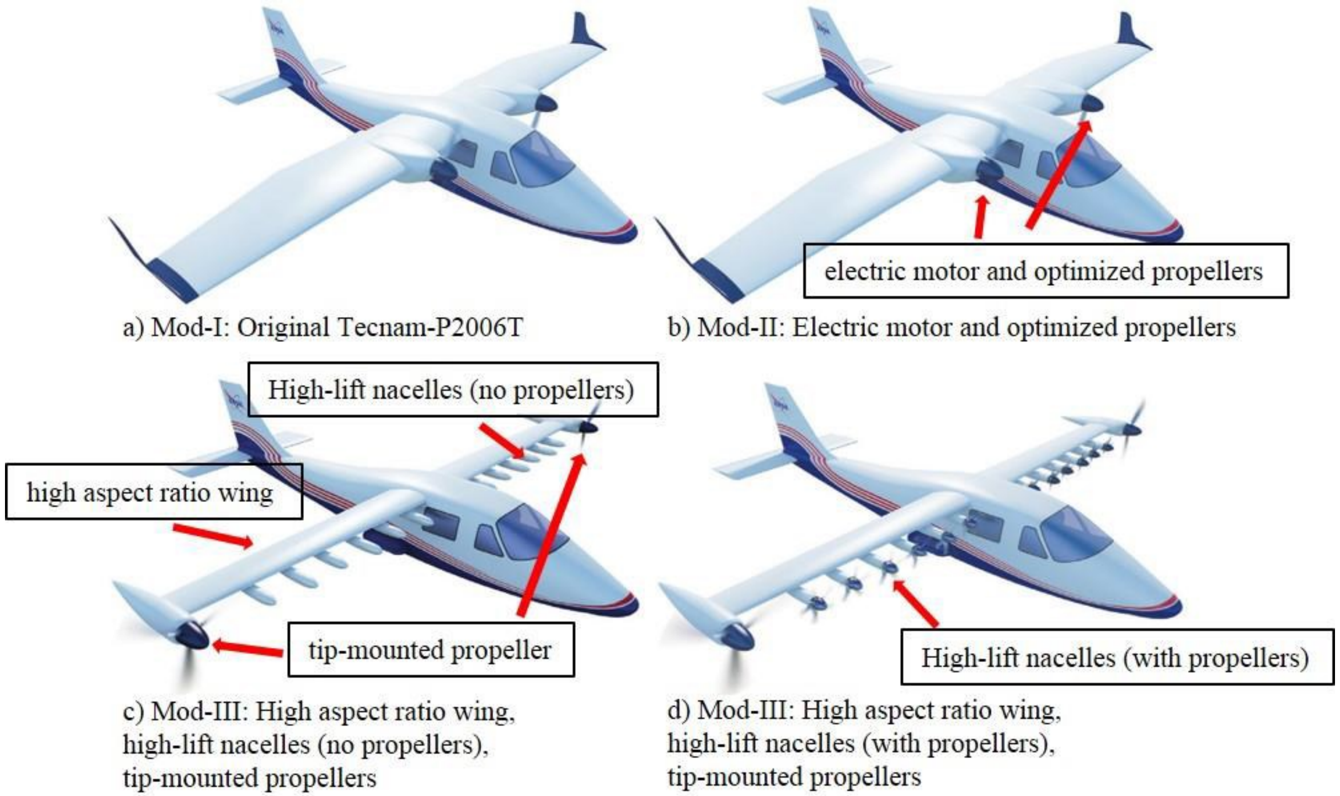


NASA Electric Aircraft Testbed (NEAT)



X-57 Maxwell

- Purpose is to explore all-electric EAP
  - Learning how to manage significant power in tight spaces
  - EMI!!!
  - Management of low grade heat in very temperature sensitive components
  - Battery packs are more than popping cells into a box
  - Many lessons will flow to UAM as well as commuter and regional fixed wing



EAP in Rotary Wing Aircraft

PERFORMANCE
aircraft optimization
rotor shape optimization
hub and support drag minimization
airframe drag minimization

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

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

Quadrotor + Electric

Tiltwing + Turboelectric

ROTOR-WING INTERACTIONS
conversion/transition
interactional aerodynamics
flow control

SAFETY and AIRWORTHINESS
FMECA (failure mode, effects, and criticality analysis)
component reliability and life cycle
crashworthiness
propulsion system failures
high voltage operational safety

Side-by-side + Hybrid

Lift+Cruise + Turboelectric

STRUCTURE AND AEROELASTICITY
structurally efficient wing and rotor support
rotor/airframe stability
crashworthiness
durability and damage tolerance
High-cycle fatigue

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

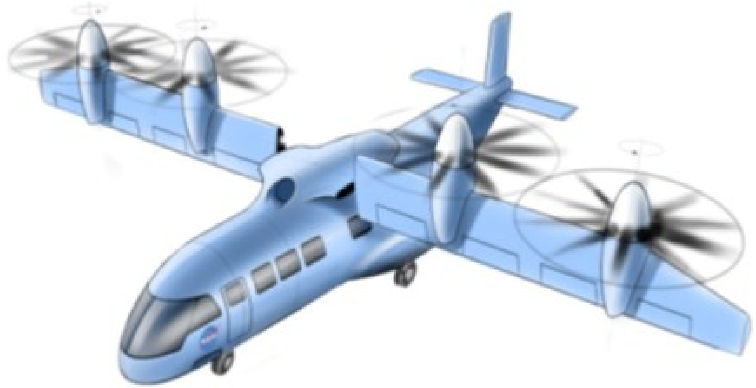
NOISE AND ANNOYANCE
low tip speed
rotor shape optimization
flight operations for low noise
aircraft arrangement/ interactions
cumulative noise impacts from fleet ops
active noise control
cabin noise
metrics and requirements

AIRCRAFT DESIGN
weight, vibration
handling qualities
active control

Multi-Discipline Optimization is Key

- Traditional aircraft design
  - Employs a lot of subsystem optimization and not as much system optimization.
  - Yields optimal subsystems but suboptimal vehicle

- Tilt-Wing Example (Goal minimize fuel)
  - Optimizing the wing only
    - Large, heavy wing at limit span
    - Suboptimal rotor design
  - Optimizing the propulsion only
    - Fixed wing span limits propulsion changes
  - Fully Coupled Optimization
    - Wing and propulsion found optimum not available when to subsystem optimization
    - Lowest fuel burn
    - AND the peak power is the lowest.

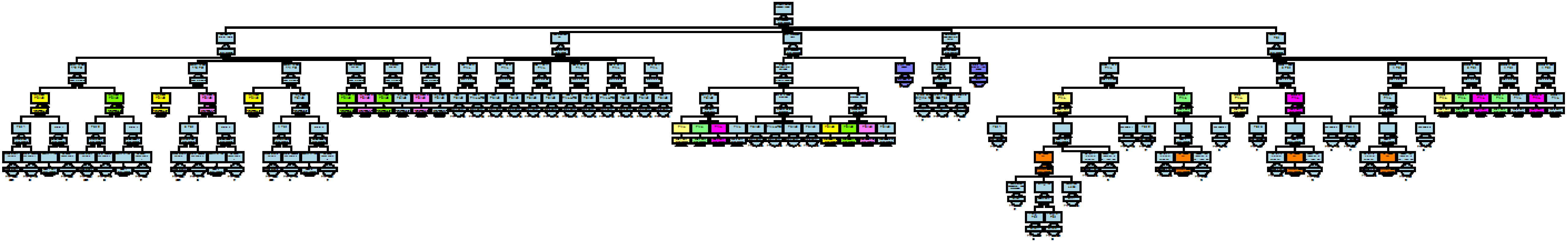


Aircraft Sizing Optimization Results

Parameter		Baseline	Wing Only	Prop Only	Fully Coupled
Maximum takeoff weight	lbm	13761	13621	12456	12588
Fuel weight	lbm	1705	1592	1490	1440
Wing weight	lbm	820	1658	820	1418
Propulsion system weight	lbm	4252	3409	3290	2867
Rotor/propeller diameter	ft	11.73	15.34	*11.73*	14.57
Wingspan	ft	52.5	*65.62*	52.5	62.83
Peak Power @ T/O	Hp	3450	*2950*	2600	2500

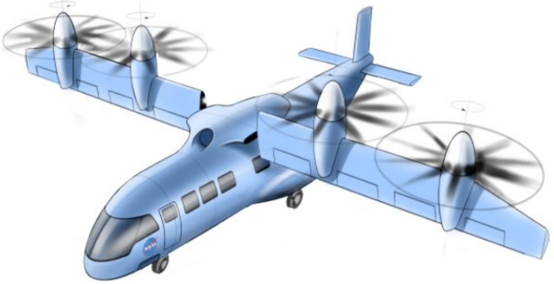
FMECA Analysis Critical for EAP

TILT-WING FAULT TREE DIAGRAM



3A2	Convert HVDC Electrical energy to shaft torque	9.24E-05	Motor #1 fails to provide output torque	Motor #1 Failure	All	Motor #1 fails to provide output torque.	Interconnecting shaft transfers torque from other motors to prop-rotor #1.	25% loss of propulsion system power. Aircraft handling qualities affected. Insufficient power available to control aircraft in OMI avoid region. Loss of control of aircraft if failure occurs while aircraft is in OMI region.	Visual & audible warning provided to pilot	Limited flight envelope, Pilot diverts to alternate landing location and executes roll-on landing above 25 kts.	I	1.00	2.000E-01	Assumed to be in hover/OMI avoid region 20% of the time	1.85E-05

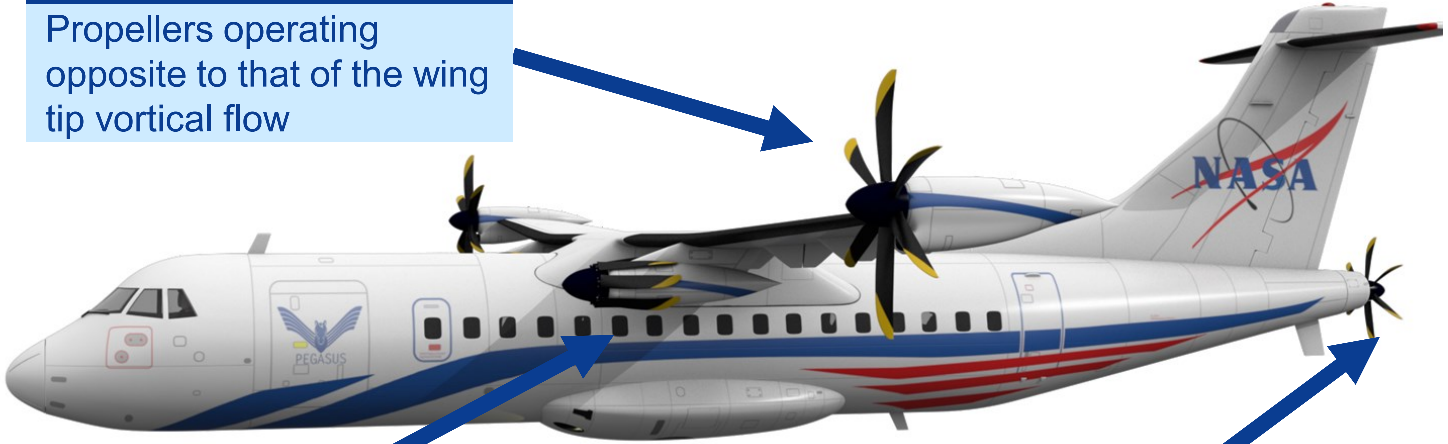
More rotors can mean more redundancy and so increased safety, or it can just mean more opportunities for a single critical fault to happen and so reduced safety



PEGASUS Concept Design

Wingtip: Parallel Hybrid Electric

Propellers operating opposite to that of the wing tip vortical flow

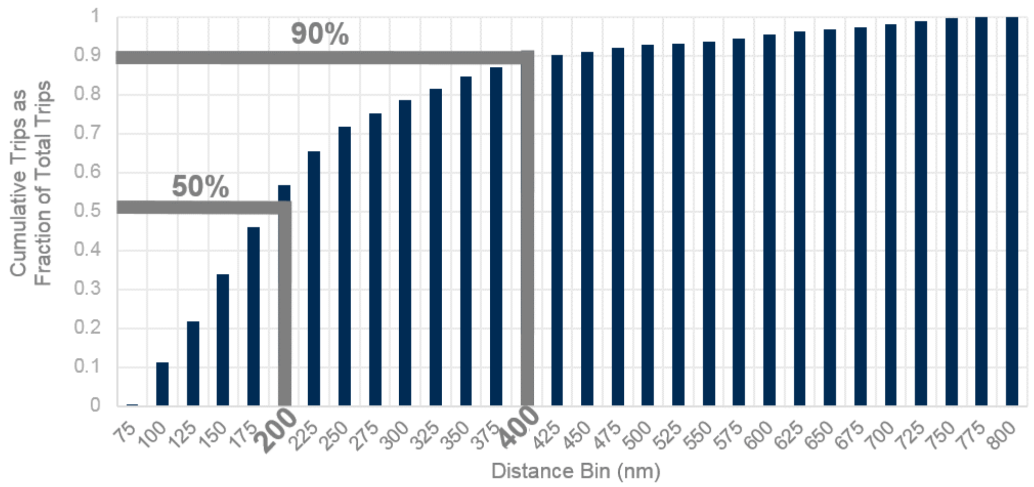


Inboard: All Electric

Folded at cruise to reduce lift losses due to propeller swirl

BLI: All Electric

Ingests the fuselage boundary layer to reaccelerate the flow



Two Missions

- All-electric: 200 nm (50% of trips)
- Hybrid electric: 400 nm (90% of trips)

Reserves

- Reserves operating on all gas
  - 200 nm mission: ~50% time in reserves
  - 400 nm mission: ~40% time in reserves

PEGASUS Results

400 nm Design Mission	Conventional Concept	PEGASUS	Difference
Cruise Altitude (ft)	25,000	20,000	
Cruise Mach	0.43	0.45	
Cruise Speed (ktas)	259	276	6.5%
Total Engine Weight (lb)	3675	5558	51%
TOGW (lb)	35,539	53,041	49%
Wing Area (ft^2)	586	700	19%
Battery Weight (lb)	0	13,131	
Mission Fuel (lb)	1421	903	-36%
Mission Energy (kW-hr)	7663	6186	-20%

The beginning of the STARC-ABL Concept

- The **S**ingle-aisle **T**urboelectric **A**i**RC**raft with **A**ft **B**oundary **L**ayer propulsion (STARC-ABL) concept was unveiled at **2016 SciTech**
- Initial results indicated the concept provides a significant fuel burn
- System details (from original analysis)

Parameter	Units	N3CC	STARC-ABL	% Change
MTOW	lb	129260	133370	3.2%
OEW	lb	73690	80480	9.2%
Wing Area	sq. ft	1220	1680	37.7%
Thrust (total, SLS)	lb	41020	35280	-14%
SOC TSFC	lb/hr/lb	0.437	0.373	**-14.6%**
900 nm Block Fuel	lb	5930	5529	**-6.8%**
3500 nm Block Fuel/seat	lb	22050	19350	**-12.2%**

Very encouraging results, but contains a very significant flaw in inlet drag accounting

Updating Boundary Layer Methodology

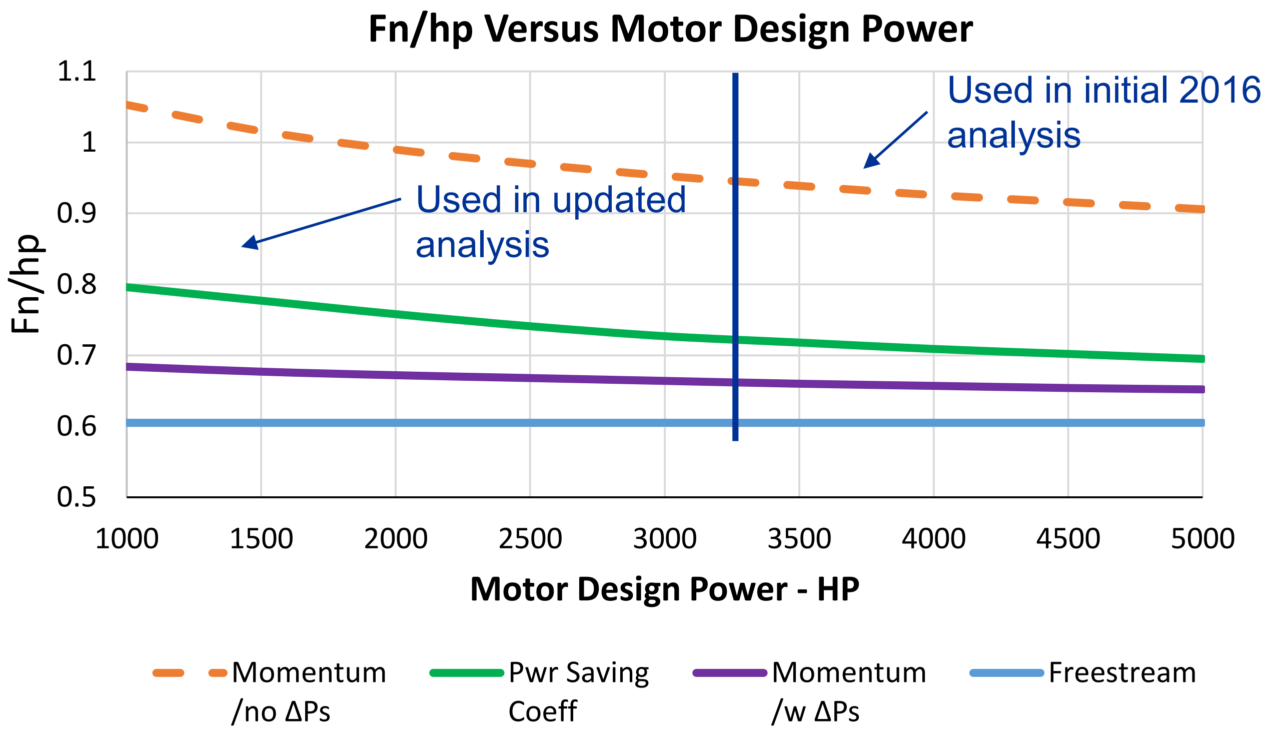
Two methods were investigated in the updated analysis:

1. Add ΔPs Term

- Add drag due to difference between inlet and nozzle static pressure to the momentum drag term
- Assumes no effect of propulsor on flow over the tailcone (superposition)

2. Power Saving Coefficient (PSC) [Justin Gray's PhD Thesis]

- Uses powered CFD to get integrated solution with tailcone thruster
- Includes effect of propulsor on the aircraft as well as aircraft on the propulsor
- Optimizes the shape of the fuselage tailcone and propulsor nacelle to maximize combined performance
- Benefits for full integration is about **twice** that non-integrated approach



Fully integrated method shows twice the BLI benefit of superposition method

Updated STARC-ABL Results

- Incorporating the updated BLI modeling significantly reduced the benefits of the STARC-ABL

Parameter	Units	N3CC	STARC-ABL	% Change
MTOW	lb	134880	134700	-0.10%
OEW	lb	77780	78510	0.90%
Wing Area	sq. ft	1120	1130	1.4%
Thrust (total, SLS)	lb	43320	42820	-1.2%
SOC TSFC	lb/hr/lb	0.48	0.468	**-2.6%**
900 nm Block Fuel	lb	6410	6240	**-2.7%**
3500 nm Block Fuel	lb	23360	22550	**-3.4%**

STARC-ABL fuel savings now in the 3% range

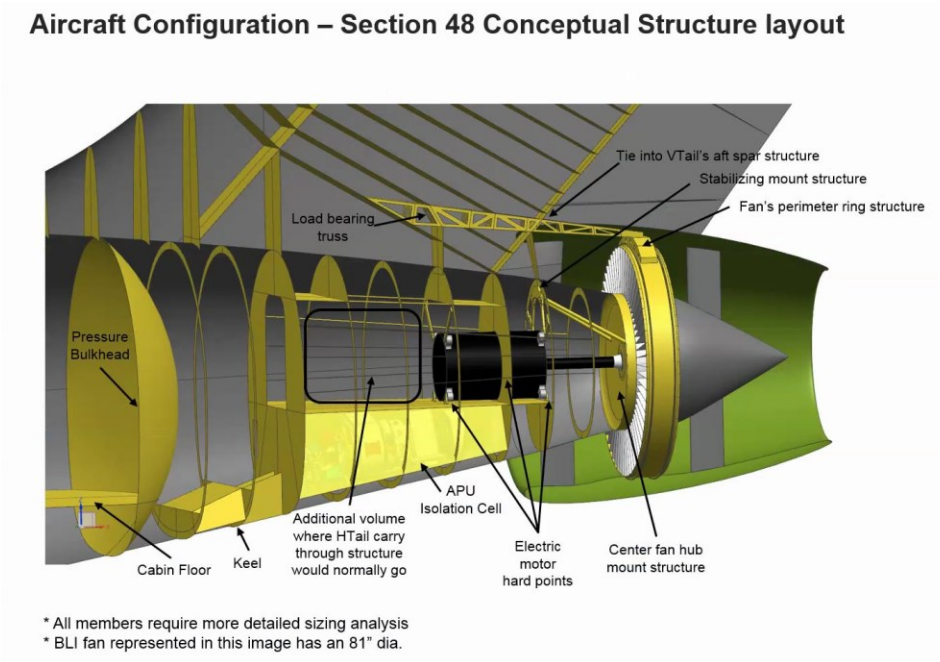
External Assessment of STARC-ABL By Aurora

Parameter	Units	Aurora N3CC-01	Aurora N3ST-01	% Change
MTOW	lb	134,827	131,069	-2.8%
OEW	lb	76,009	73,325	-3.5%
Wing Area	sq. ft	1151	1161	0.8%
Thrust (total, SLS)	lb	43320	42820	-1.2%
SOC TSFC	lb/hr/lb	0.437	0.434	**-0.7%**
900 nm Block Fuel	lb	7388	7327	**-0.8%**
3500 nm Block Fuel	lb	24364	23429	**-3.8%**

- Aurora Flight Sciences conducted independent assessment of the STARC-ABL
- Aurora used their own tools and methods to develop their version of the N3CC (N3CC-01) and STARC-ABL (N3ST-01)
- Aurora's Mission Fuel Burn:
  - Design mission savings: 3.8%
  - Econ mission savings: 0.8%
- Differences from NASA results likely due to differences in assumptions outside key technologies and different tools and methods

Aurora results tell us that our results are in the right range

Other Tailcone BLI Concepts



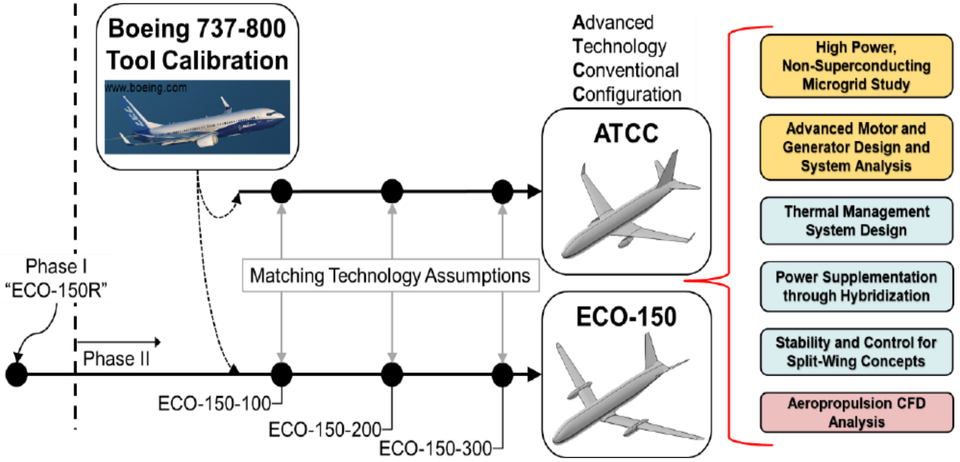
- Boeing/Rolls-Royce/GaTech
  - Transonic, Truss-braced, High Wing
  - 1772 lb battery used during T/O and climb to "cruise size" the turbofan engine core to reduce cruise TSFC
  - 1.5 MW generator on each engine power BLI tailcone thruster
  - Results:
    - Design mission fuel savings: **4.5%**
    - Econ mission fuel savings: **1.1%**

Mild Hybridization can reduce long range mission fuel burn but at the cost of short range mission fuel burn

ESAero ECO-150-300 Fuel Savings from Unexpected Source

- Comparisons are relative to a Advance Technology Conventional Configuration (ATCC) baseline developed in parallel
- ECO-150-300 is 100% turboelectric
- 3-D powered CFD validated split-wing aerodyamics.
- Propulsion system TSFC is **4% HIGHER** than ATCC
- Cruise L/D is **14% higher**
- GTOW 5.7% lower
- Results in lower total thrust in all flight segments
- Yields an **11.5% reduction** in design mission and **9.2% reduction** in 900 nm econ mission fuel burn

A "worse" propulsion system can yield a better airplane



Vehicle Comparison (3,500 nmi Mission)	2035 ATCC	2035 ECO-150-300	Difference %
Takeoff Gross Weight (lbm)	148,056	139,606	-5.7%
TSFC @TOC (lbm/lbf/hr)	0.4780	0.4977	4.1%
Cruise L/D @ICA	18.84	21.53	14.3%
Design Mission Block Fuel (lbm)	28,492	25,215	-11.5%
Specific Range (nmi/lbm)	0.1108	0.1220	10.2%
LTO NOx Emissions (g/kN)	41.45	36.12	-12.9%
Cruise NOx Emissions (kg/hr)	28.96	24.91	-14.0%

Summary

- NASA EAP is exploring ways to use electrified propulsion to enable new configurations previously impossible and improve overall vehicle efficiency from all-electric UAM application up to turbo-electric single-aisle transport class aircraft
- Some of the lessons we have learned
  - Don't turn shaft power into electricity unless it is used for something that can not be done with direct shaft drive
  - Optimize at the system level and not at the subsystem level
  - Always look for the unexpected. A propulsion concept that increased the cruise TSFC would appear to be a non-starter until it turns out that it enables a much more efficient airframe
  - Always look for the "ANDs". In the UTRC/Pratt&Whitney NRA E-Taxi was a free AND of a hybrid system that could drive the fans without starting the engines. This ended up contributing a significant portion of the total fuel savings
  - Lighter electrical machines aren't always better. Efficiency has a weight of its own
  - Even seemingly simple tasks can be harder than they look. Battery packs look relatively straight forward until one cell has a thermal run-away, catches the rest of the pack on fire and burns up your test facility

Questions