National Aeronautics and Space Administration

Hybrid-Electric and Distributed Propulsion Technologies for Large Commercial Air Transports: A NASA Perspective

Nateri Madavan
Associate Project Manager for Technology
Advanced Air Transport Technology Project
NASA Advanced Air Vehicles Program
NASA Ames Research Center, Moffett Field, California

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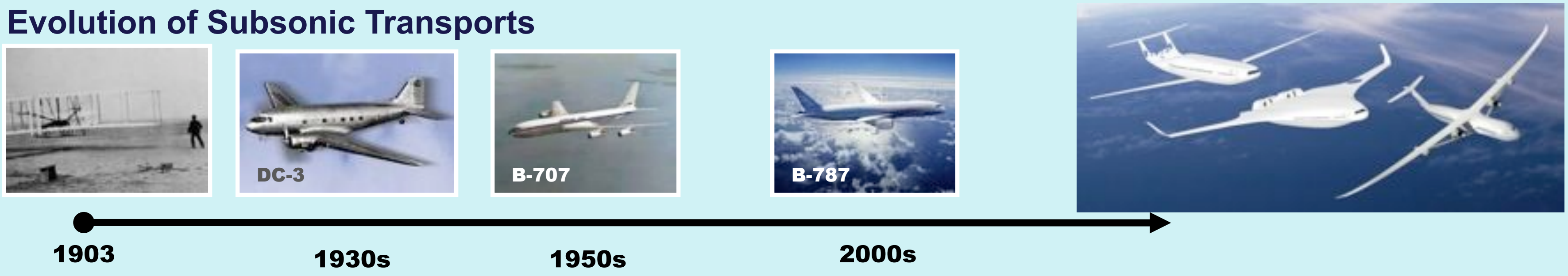
Advanced Air Transport Technology Project

Explore and Develop Technologies and Concepts for Improved Energy Efficiency and Environmental Compatibility for Fixed Wing Subsonic Transports

- Early stage exploration and initial development of game-changing technologies and concepts for fixed wing vehicles and propulsion systems
- One of two NASA Aeronautics projects (along with Environmentally Responsible Aviation (ERA) project) focused on subsonic commercial transport vehicles
- Commercial focus, but dual use with military
- Gen N+3 time horizon; ERA project horizon is Gen N+2
- Research vision guided by vehicle performance metrics developed for reducing noise, emissions, and fuel burn

Evolution of Subsonic Transports



The Case for Hybrid Electric Propulsion

- 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
- Advanced concept studies commissioned by NASA for the N+3/N+4 generation have identified promising aircraft and propulsion systems
- Industry roadmaps acknowledge need to shift in direction toward electric technologies
- Creative ideas and technology advances needed to exploit full potential
- NASA can help accelerate key technologies in collaboration with OGAs, industry, and academia

Estimated Benefits From Systems Studies

Boeing/GE 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

NASA N3X (baseline Boeing 777–200)

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

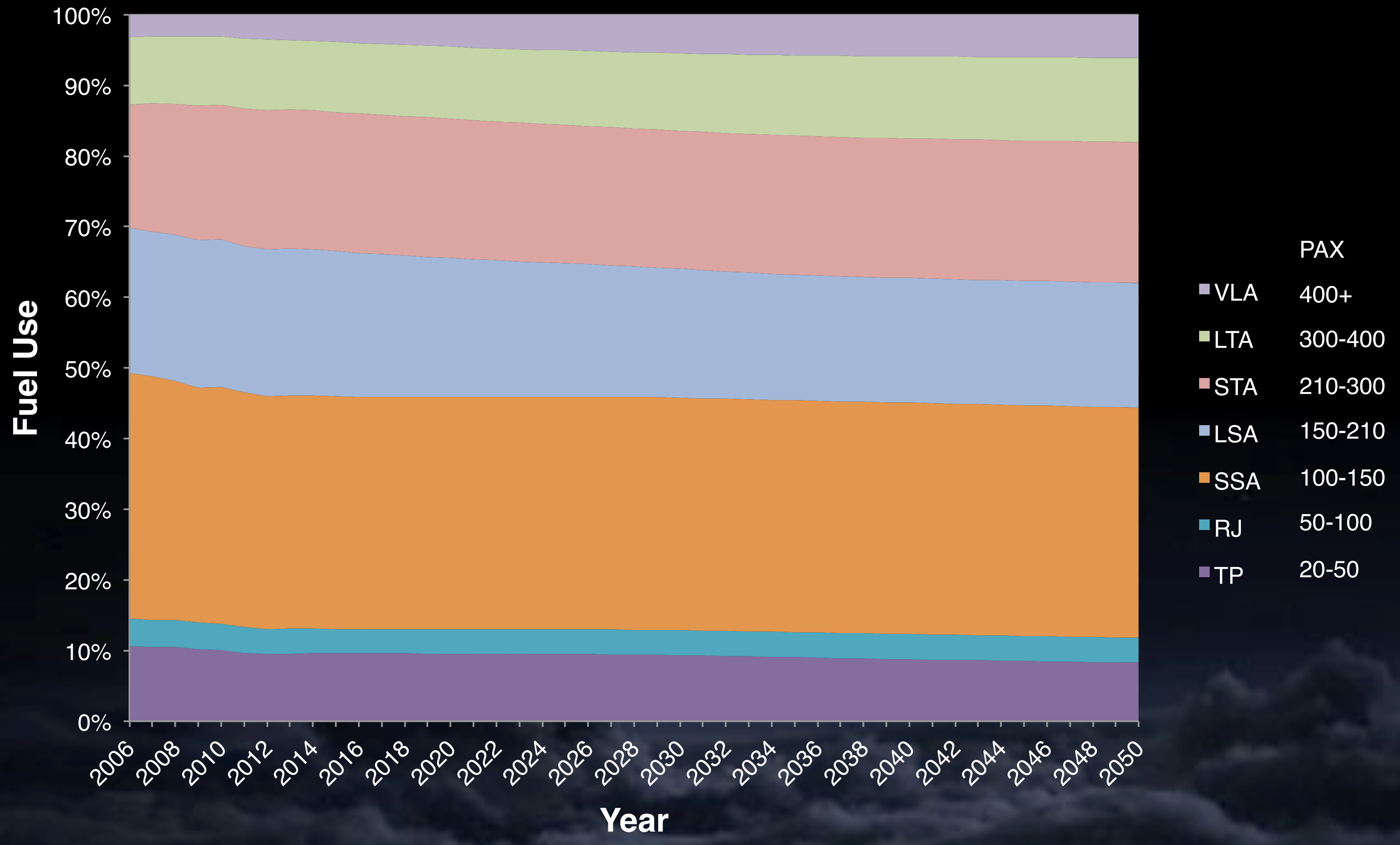
NASA CEPT for GA (baseline Tecnam P2006T)

- 5x lower energy use/cost and emission
- 15 dB lower community noise
- Propulsion redundancy, improved ride quality, and control robustness

The NASA Perspective

- Develop and demonstrate technologies that will revolutionize commercial transport aircraft propulsion and accelerate development of all-electric aircraft architectures
- Enable radically different propulsion systems that can meet national environmental and fuel burn reduction goals for subsonic commercial aircraft
- Focus on future large regional jets and single-aisle twin (Boeing 737-class) aircraft for greatest impact on fuel burn, noise and emissions
- Research horizon is long-term but with periodic spinoff of technologies for introduction in aircraft with more- and all-electric architectures
- Research aligned with new NASA Aeronautics strategic R&T thrusts in areas of transition to low-carbon propulsion and ultra-efficient commercial transports

Fuel Use by Vehicle Classes



Based on FAA Terminal Area Forecast (TAF) for US Operations; Courtesy of GA Tech

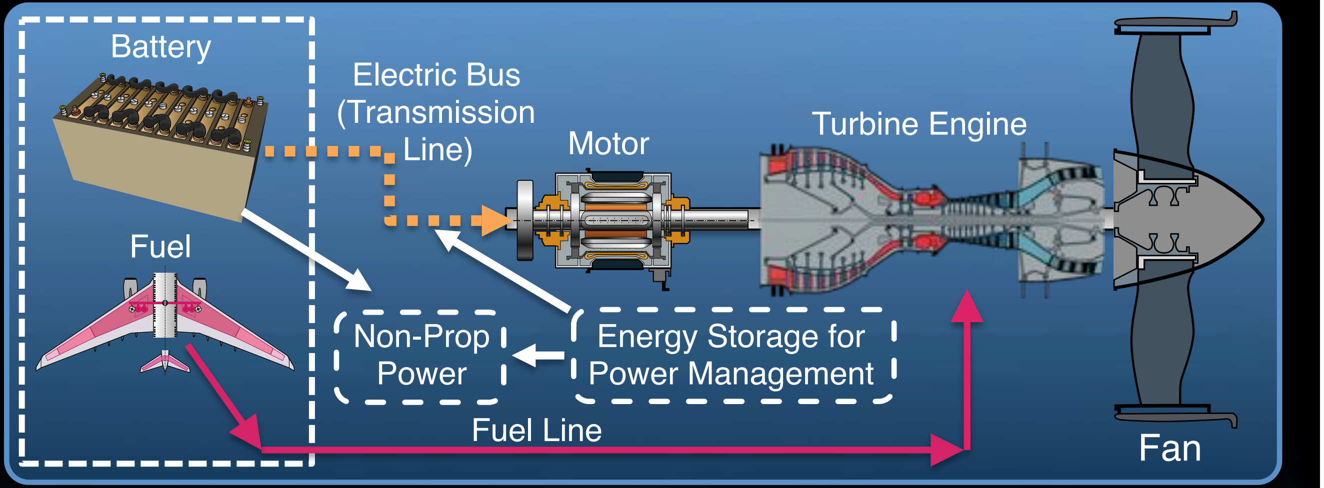
85% of fuel use is in small single-aisle (100-150 pax) and larger classes; regional jets and turboprops account for only 15% of fuel use

Progression of Electric Technology for Commercial Transport Aircraft

	Conventional Aircraft (i.e. B737, A320, etc.)	More Electric Aircraft (B787, A380, etc.)	All Electric Aircraft	Electric Propulsion Aircraft
Engine	• Gas turbine	• Gas turbine • Less hydraulic & pneumatic extraction	• Gas turbine • NO hydraulic & pneumatic extraction	• Electric propulsion
Hydraulic System	• Flight control • Landing gear • Utility actuation			
Pneumatic System	• De-ice • ECS			
Electrical Power System	• Motors • Lighting & Heating • Avionics • System controllers			

Possible Hybrid Electric Aircraft Configurations

Hybrid Electric



Battery

Electric Bus (Transmission Line)

Motor

Turbine Engine

Fuel

Non-Prop Power

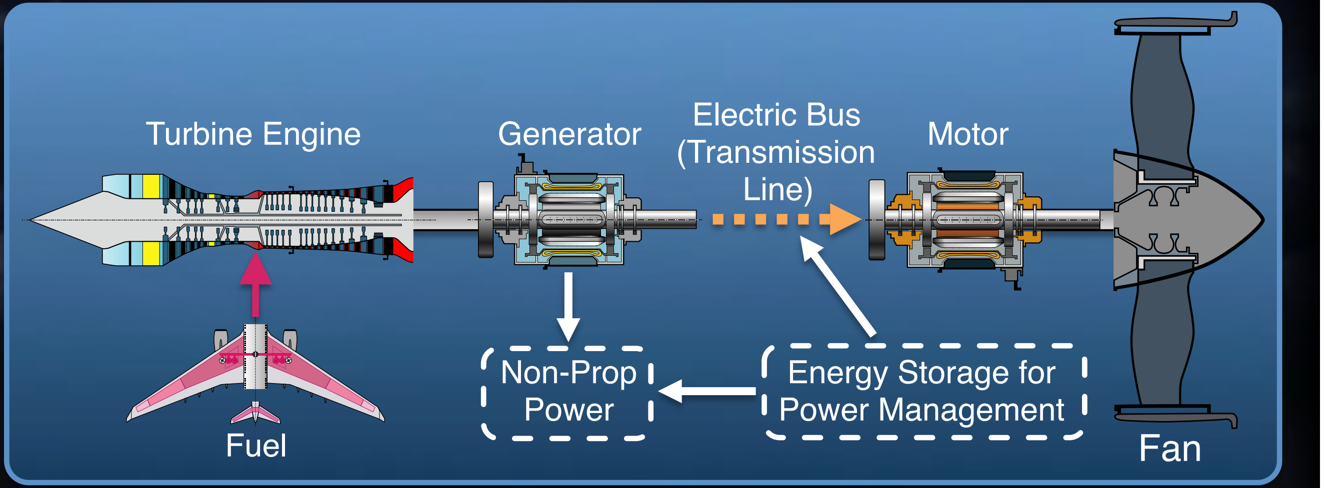
Energy Storage for Power Management

Fuel Line

Fan

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

Turbo Electric



Turbine Engine

Generator

Electric Bus (Transmission Line)

Motor

Fuel

Non-Prop Power

Energy Storage for Power Management

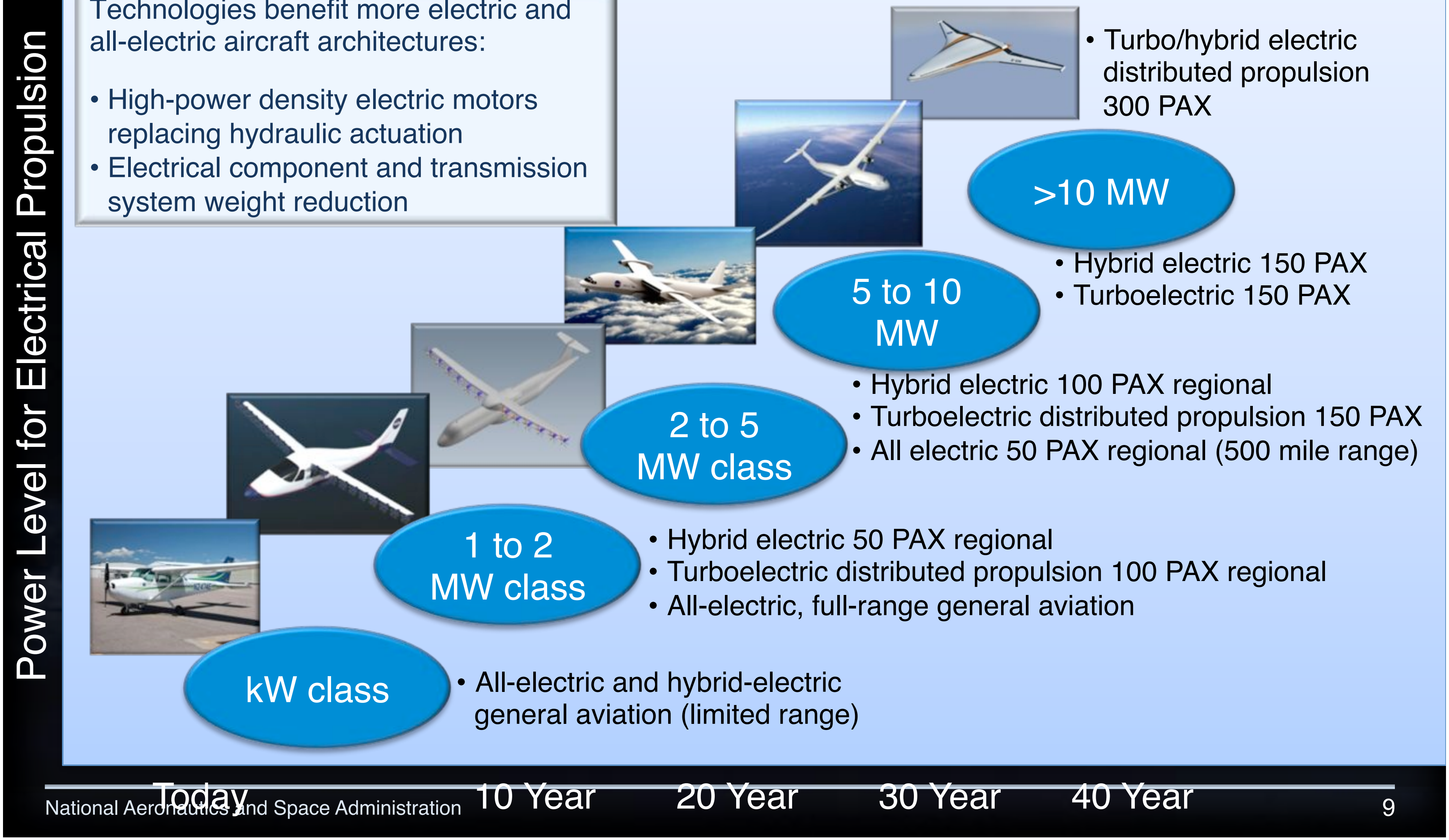
Fan

Hybrid Electric Propulsion Technology Projections

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



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

1 to 2 MW class
- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional
- All-electric, full-range general aviation

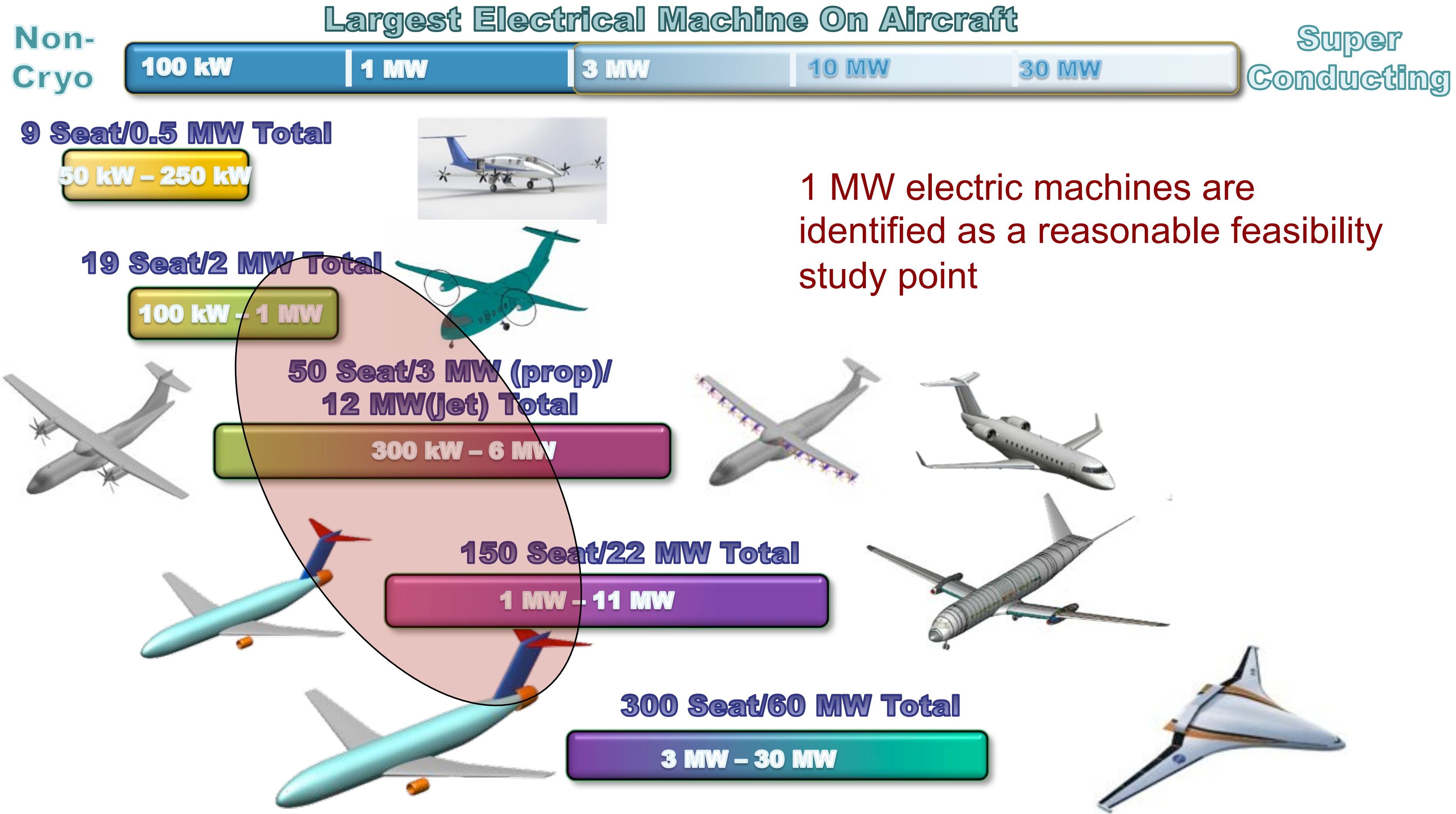
2 to 5 MW class
- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX
- All electric 50 PAX regional (500 mile range)

5 to 10 MW
- Hybrid electric 150 PAX
- Turboelectric 150 PAX

>10 MW
- Turbo/hybrid electric distributed propulsion 300 PAX

Electric Drives Tied to Aircraft Classes

Electric Drive Technology Development Impacts Propulsion & Vehicle Suite
Electric Drives enable distributed propulsion, improve concentrated propulsion



Largest Electrical Machine On Aircraft

Non-Cryo

100 kW | 1 MW | 3 MW | 10 MW | 30 MW

Super Conducting

9 Seat/0.5 MW Total

50 kW – 250 kW

19 Seat/2 MW Total

100 kW – 1 MW

50 Seat/3 MW (prop)/ 12 MW(jet) Total

300 kW – 6 MW

150 Seat/22 MW Total

1 MW – 11 MW

300 Seat/60 MW Total

3 MW – 30 MW

1 MW electric machines are identified as a reasonable feasibility study point

Transitioning to Electric Propulsion

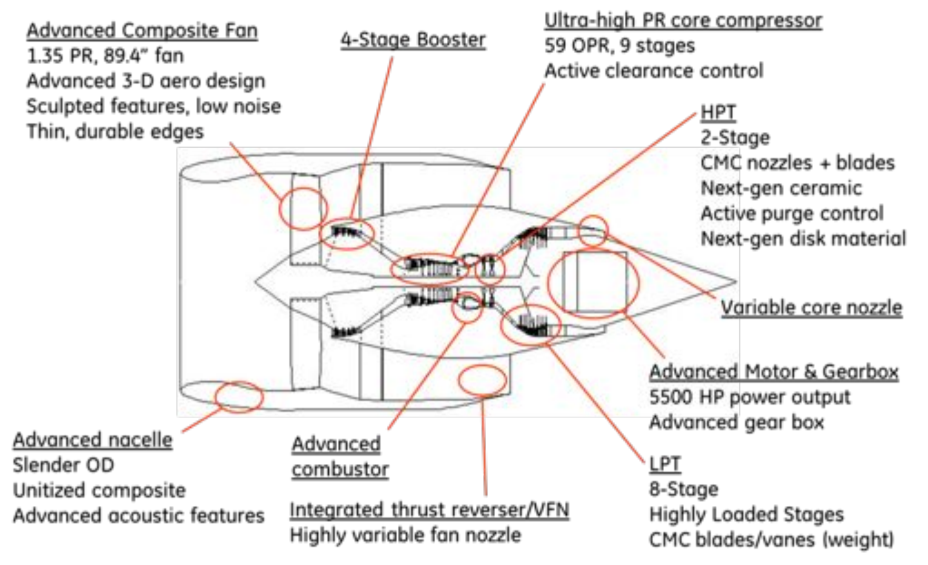
	Conventional	More Electric Architecture	All Electric Architecture	Hybrid Gas Turbine/Electric Propulsion		Electric Propulsion
				“Turboelectric Distributed” Gas Turbine Power, Decoupled Distributed Electric Propulsors	“Hybrid Electric” Gas Turbine and Electric Dual Power, Coupled Propulsor	
				Ambient Temperature or Cryogenic and Superconducting		
Propulsive Power Source	Gas Turbine	Gas Turbine	Gas Turbine	Gas Turbine + Electric	Gas Turbine + Electric	Electric
Non-Propulsive Power Source	Gas Turbine	Gas Turbine + Electric	Electric	Gas Turbine + Electric	Gas Turbine + Electric	Electric
Generation	< N	N, N+1	N+2,N+3	N+3, N+4		> N+4

Seeking spin-off or demo opportunities

Recommended NASA Investment Target

Hybrid-electric configurations and concepts

Boeing-GE “SUGAR-Volt” Hybrid Electric Propulsion Configuration



Advanced Composite Fan
1.35 PR, 89.4” fan
Advanced 3-D aero design
Sculpted features, low noise
Thin, durable edges

4-Stage Booster

Ultra-high PR core compressor
59 OPR, 9 stages
Active clearance control

HPT
2-Stage
CMC nozzles + blades
Next-gen ceramic
Active purge control
Next-gen disk material

Variable core nozzle

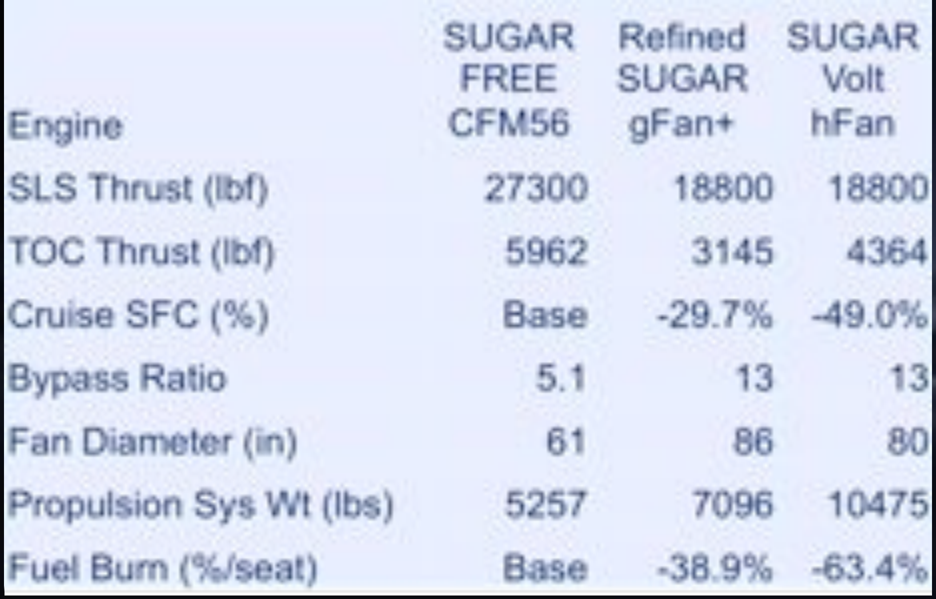
Advanced Motor & Gearbox
5500 HP power output
Advanced gear box

Advanced nacelle
Slender OD
Unitized composite
Advanced acoustic features

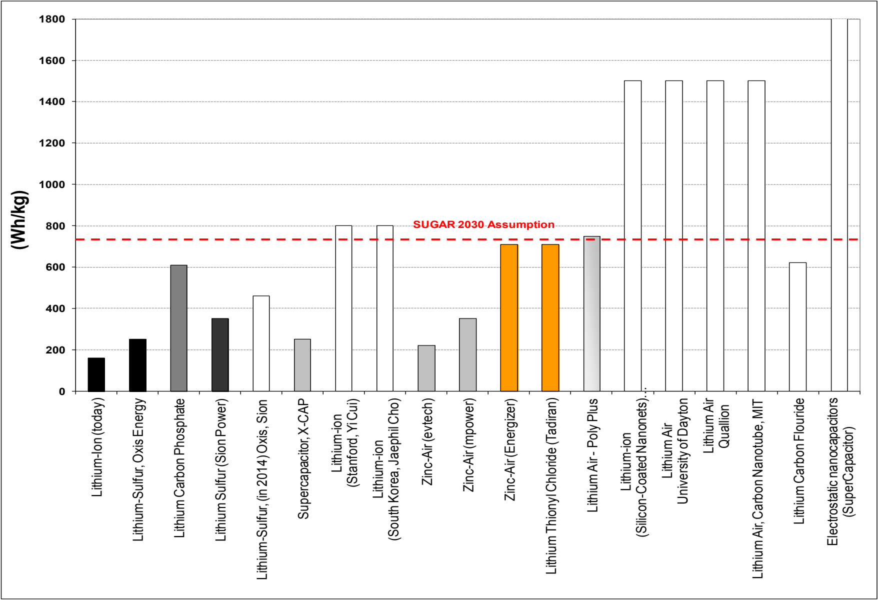
Advanced combustor

Integrated thrust reverser/VFN
Highly variable fan nozzle

LPT
8-Stage
Highly Loaded Stages
CMC blades/vanes (weight)



Engine	SUGAR FREE CFM56	Refined SUGAR gFan+	SUGAR Volt hFan
SLS Thrust (lbf)	27300	18800	18800
TOC Thrust (lbf)	5962	3145	4364
Cruise SFC (%)	Base	-29.7%	-49.0%
Bypass Ratio	5.1	13	13
Fan Diameter (in)	61	86	80
Propulsion Sys Wt (lbs)	5257	7096	10475
Fuel Burn (%/seat)	Base	-38.9%	-63.4%

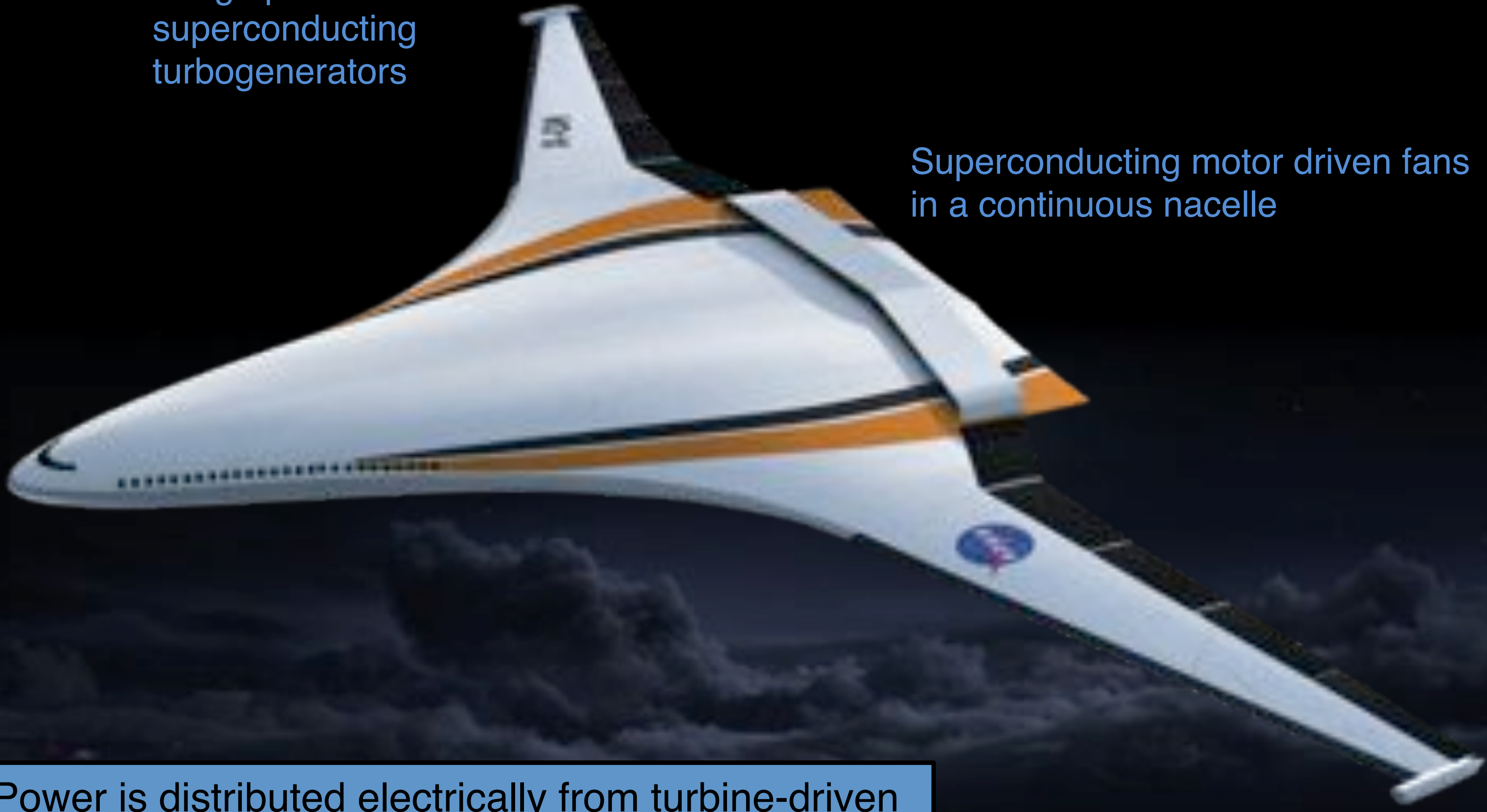


ESAero ECO-150 and Dual-Use Split-Wing Ambient Temperature Turboelectric Configuration

	ECO-150 (3-3)	DU-Civil (2-3-2)	737-700 (3-3)
TOGW	139,700	142,400	154,500
Propulsion Wt ("dry")	28,350	27,820	10,430
Payload*	30,000	30,000	24,000
Fuel*	28,900	28,900	46,612
Seat-Mile/ Gal	121	118	65
Motor hp/lb	2.46	Gen hp/lb	4.30

* At 3440 nm range

NASA N3X Distributed Turboelectric Propulsion System



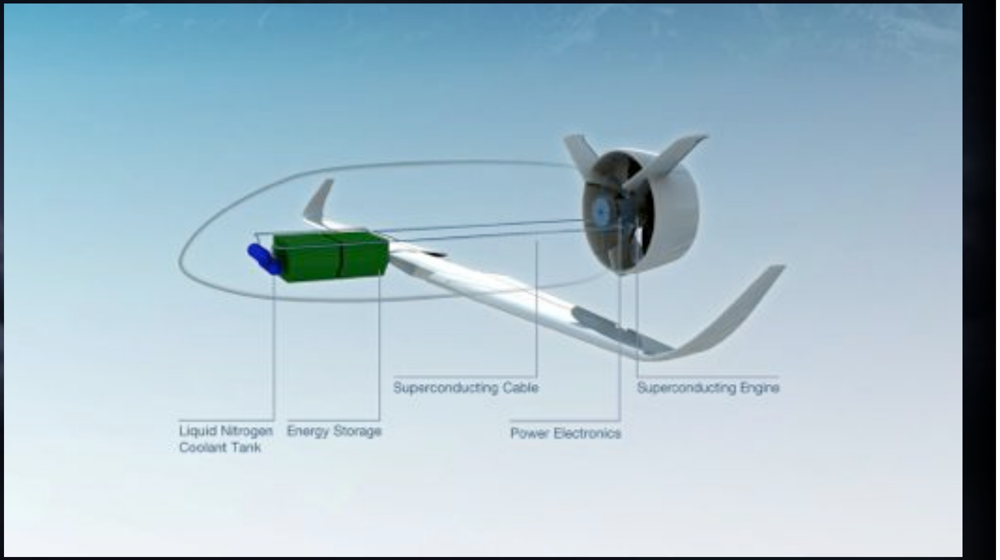
Power is distributed electrically from turbine-driven generators to motors that drive the propulsive fans.

NASA Convergent Electric Propulsion Technology (CEPT) Concept

Concept Flight Validation of Transformational Electric Propulsion Integration Capabilities through a Low Cost On-Demand Aviation Demonstrator as a Pathway to Ultra-Low Emission Commercial Aviation

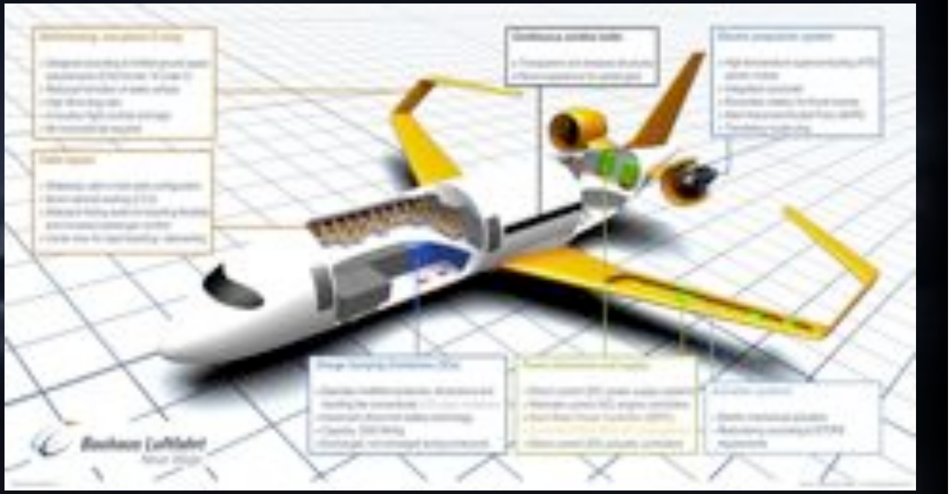
EADS VoltAir Concept

- EADS VoltAir all-electric 50 pax concept for 2035 EIS
- Displayed at the 2011 Paris airshow
- Next-gen Li-air batteries, two HTS electric motors driving two coaxial, counter-rotating shrouded propellers
- Easy battery swap for quick airport turnaround
- EADS predicts technology improvements will lead to HTS motors with power-to-weight ratios eventually exceeding gas turbines of today



Bauhaus Luftfahrt Ce-Liner Concept

- All-electric concept for 2035 EIS
- 200 Pax capacity
- C-Wing design based on Kroo and McMasters (Stanford/Boeing/UWA)
- Twin HTS electric motors supplied by advanced Li-ion batteries
- Cargo containers for batteries will quick allow airport turnaround with no recharging time
- Predict battery technology will allow 700 nm range by 2030, 1000 nm by 2035, 1600 nm by 2040
- Company also has the Claire Liner concept vehicle – box-wing, extreme STOL aircraft with laminar flow and integrated wing fans

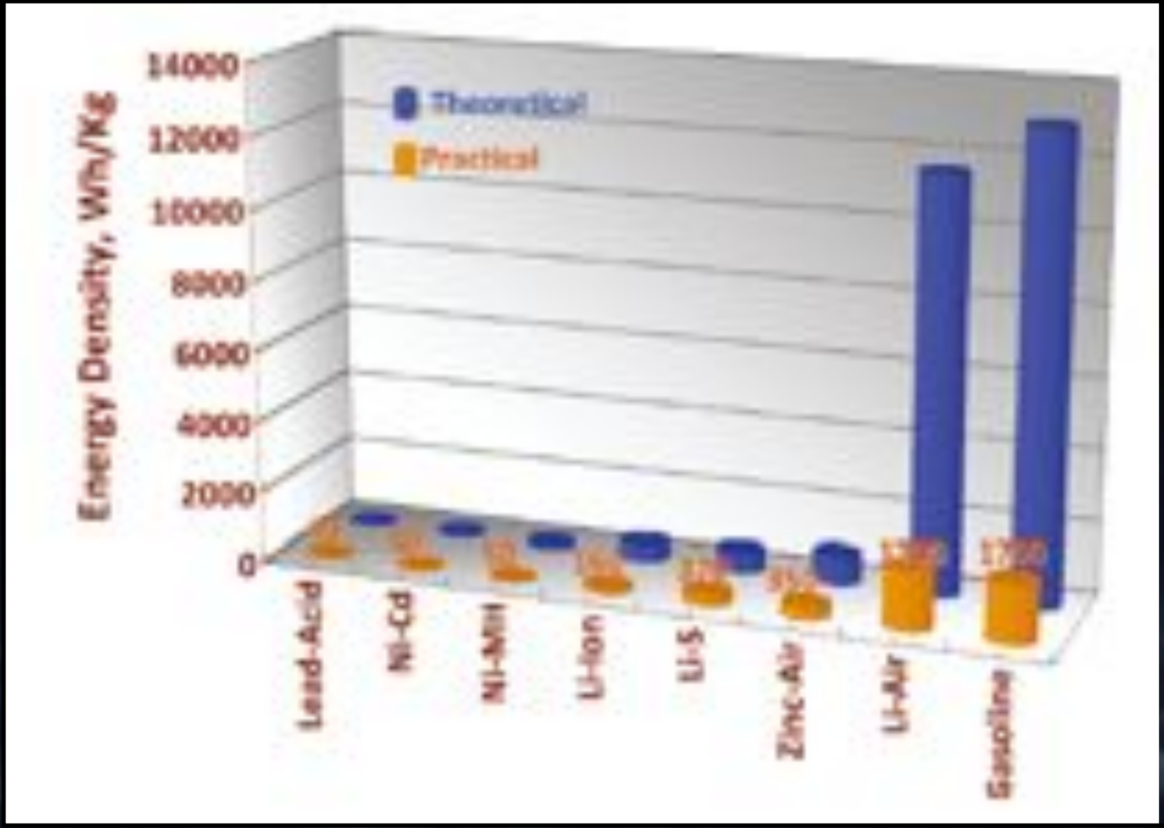


EADS/Rolls-Royce eConcept

- EADS/RR distributed hybrid-electric propulsion concept for 2050 EIS
- Single large turbine engine embedded in tail generates electricity to six ducted fans (20+ effective BPR)
- Turbine engine drives hub-mounted bidirectional superconducting motor
- Structural stator vanes used to extract power and circulate cryo coolant
- Advanced Li-air batteries for storage; anticipate 1000 Wh/kg energy densities achievable in 20 years
- Turbine+battery power for takeoff and climb; batteries recharged during cruise and during gliding descent with windmilling fans; turbine power during landing
- Cranfield and Cambridge U partners

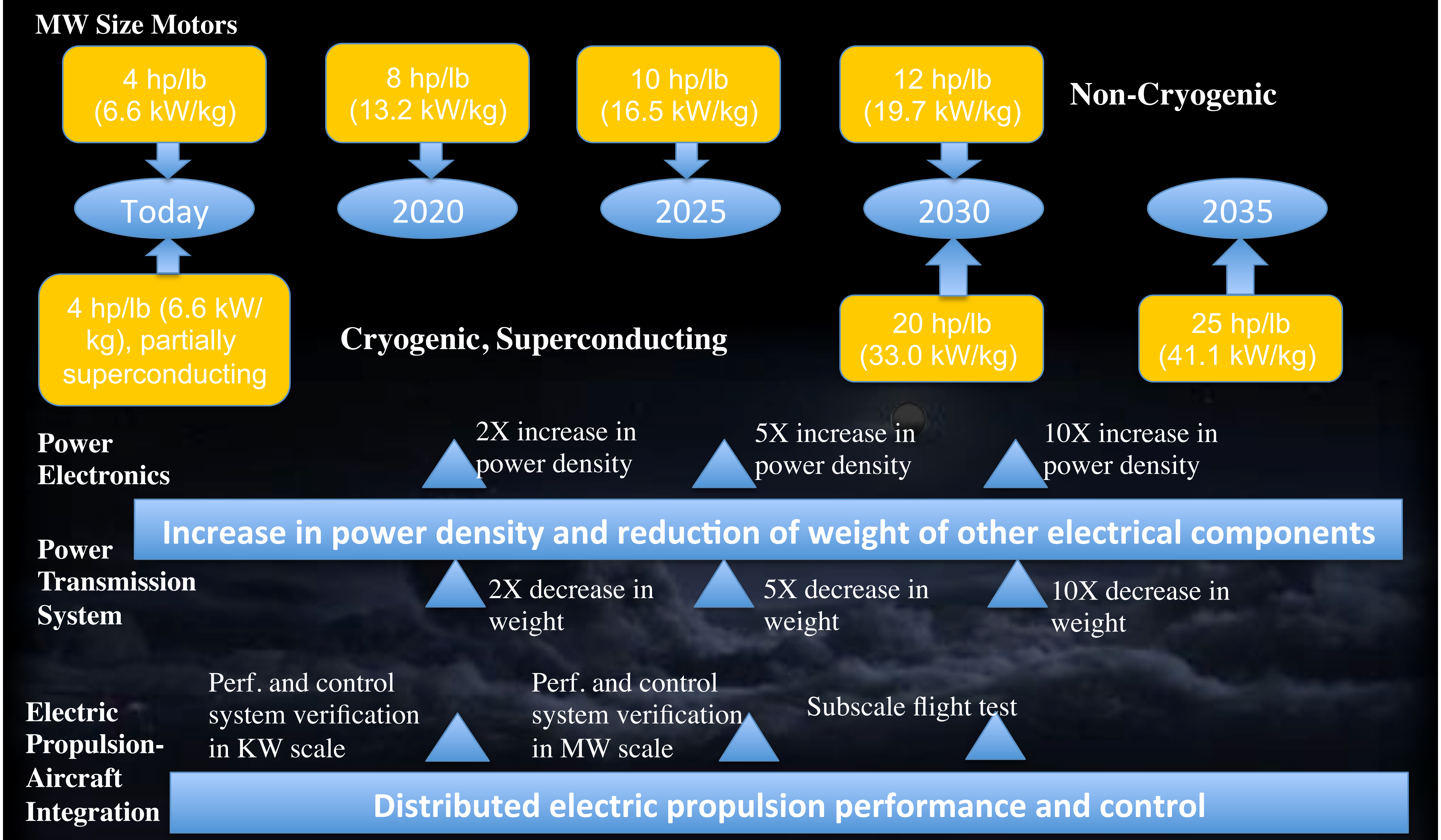
Hybrid-electric propulsion research portfolio

Battery Technology: Beyond Li-Ion



**Practical values for Li-Air, Li-S and Zn-Air are optimistic projections.
Significant technical challenges must be overcome to achieve these values.**

NASA Technology Investment Strategy



MW Size Motors

4 hp/lb (6.6 kW/kg) → Today

8 hp/lb (13.2 kW/kg) → 2020

10 hp/lb (16.5 kW/kg) → 2025

12 hp/lb (19.7 kW/kg) → 2030

Non-Cryogenic

2035

4 hp/lb (6.6 kW/kg), partially superconducting → Today

Cryogenic, Superconducting

20 hp/lb (33.0 kW/kg) → 2030

25 hp/lb (41.1 kW/kg) → 2035

Power Electronics

2X increase in power density

5X increase in power density

10X increase in power density

Increase in power density and reduction of weight of other electrical components

Power Transmission System

2X decrease in weight

5X decrease in weight

10X decrease in weight

Electric Propulsion-Aircraft Integration

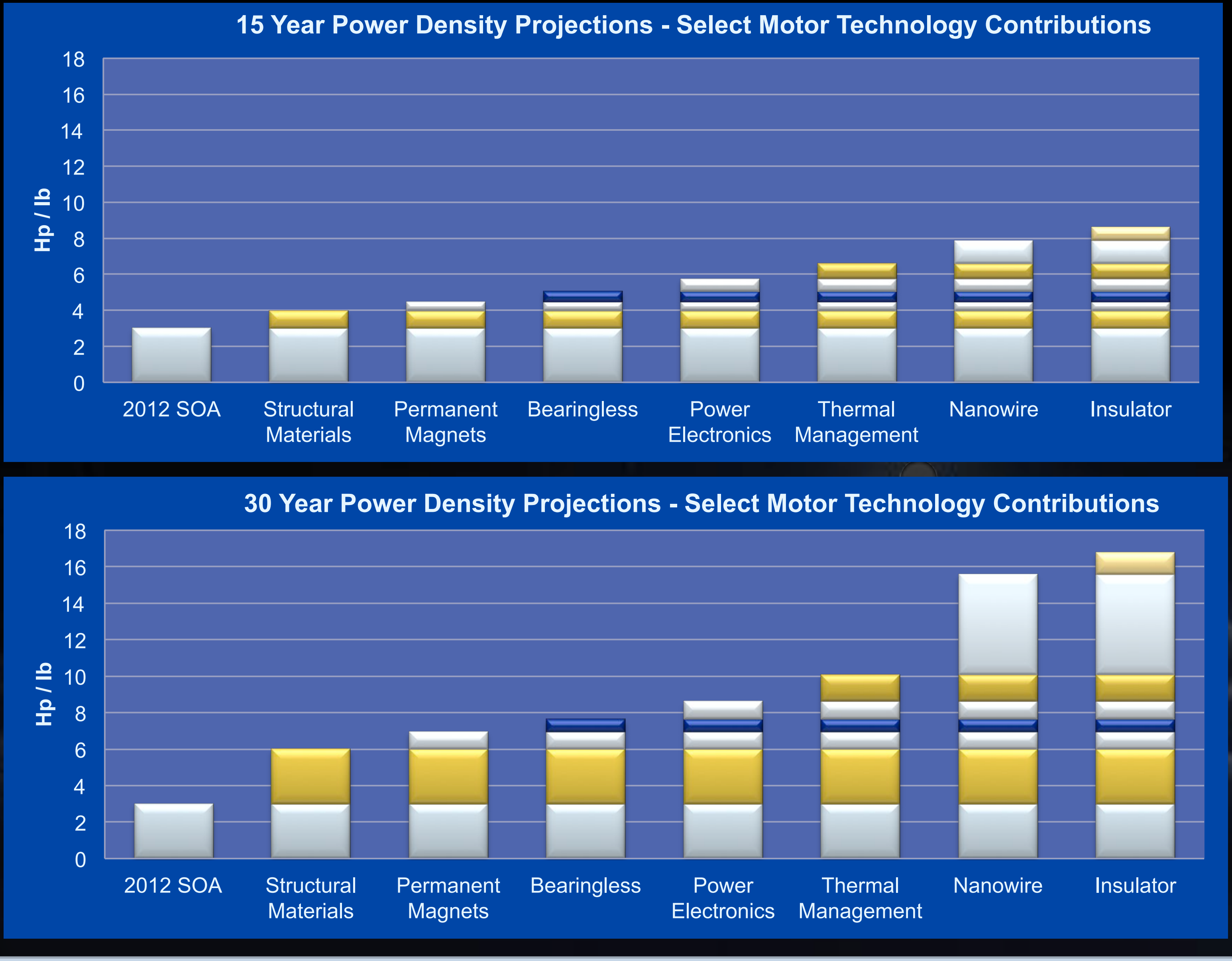
Perf. and control system verification in KW scale

Perf. and control system verification in MW scale

Subscale flight test

Distributed electric propulsion performance and control

Projected Power Density Increase – 1-10MW Motors



In addition to advances in individual technologies, integration of functions can offer further increase in power density

Enabling Technologies for Hybrid-Electric Propulsion

- Electric Machine Architectures
  - Alternate topologies for higher efficiency and power density
  - Ironless or low magnetic loss
  - Concepts that allow motor to be integrated into the existing rotating machinery (shared structure)
  - Concepts that 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 with a pressurized LH2 source
  - Flight qualification of new components

- Cryocoolers
  - Flightweight systems for superconducting and cryogenic machines, converters, and transmission lines

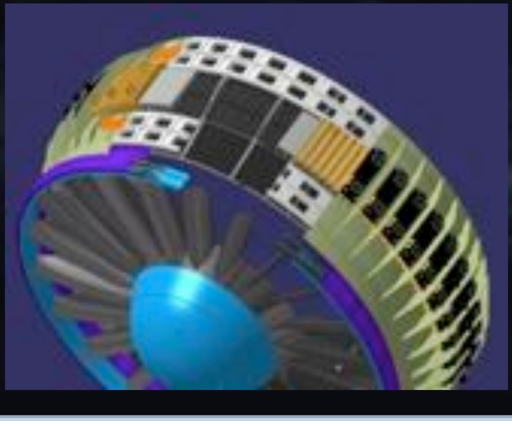
Enabling Technologies for Hybrid-Electric Propulsion

- 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 swappable
- Thermal management
  - Cooling for electric machines with integrated power electronics
  - Advanced lightweight cold plates for power electronics cooling
  - High performance lightweight 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 500kW and above range
  - Regenerative power-absorbing propeller and ducted-fan designs for efficient wind-milling

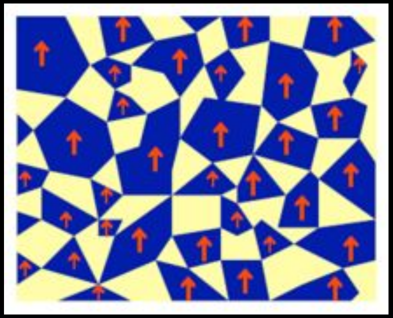
High Efficiency, High Power Density Electric Machines

- Cryogenic, superconducting motors for long term
- Normal conductor motors for near and intermediate term
- High power to weight ratio is enabling
- Materials and manufacturing technologies advances required
- Design and test 1-MW noncryogenic electric motor starting in FY2015; fully superconducting motor in FY2017

Normal conductor 1-MW rim-driven motor/fan



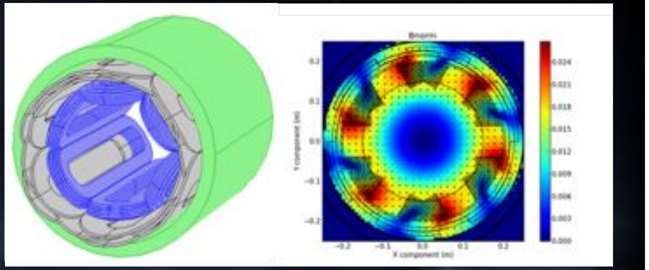
Nanoscale ultra-high strength low percent rare-earth composite magnets



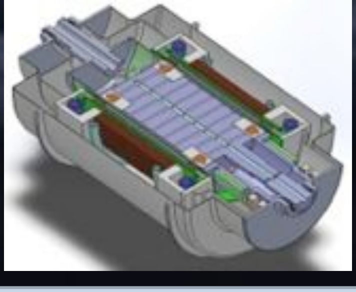
High thermal conductivity stator coil insulation

Low A/C loss superconducting filament

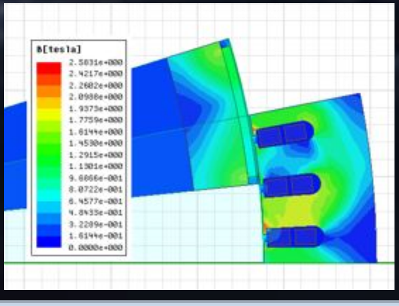
Superconducting electromagnetic model



Fully superconducting motor

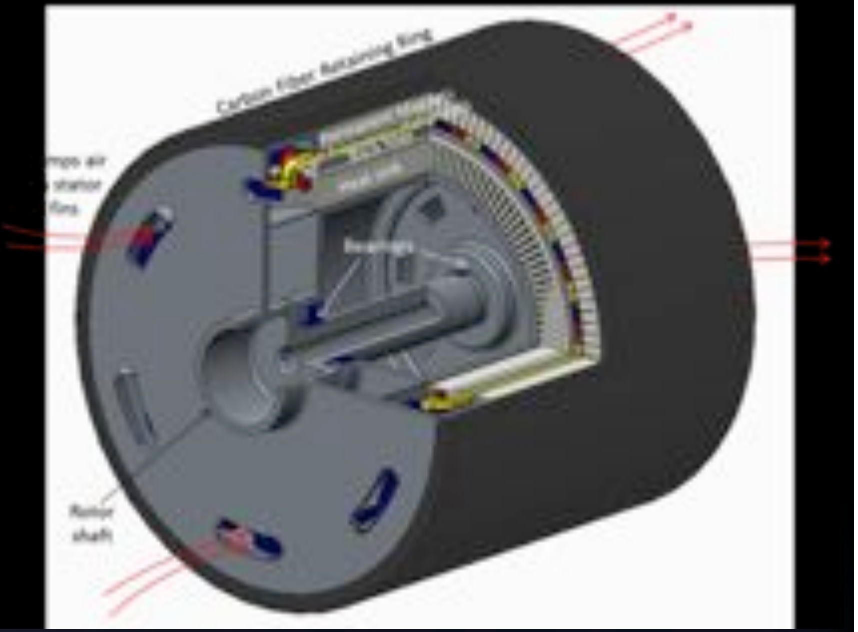


Flux density for rim-driven motor

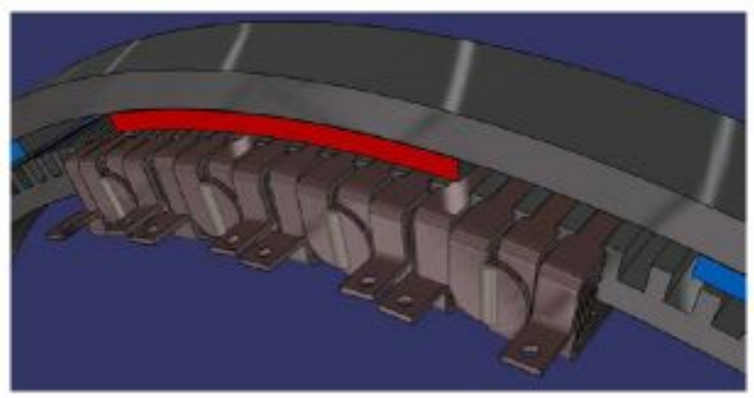


High Power Density MW Class Non-Cryogenic Motor

- Design and test scalable high efficiency and power density (96%, 8 hp/lb) MW-class non-cryogenic motor for aircraft propulsion
- U of Illinois, UTRC, Automated Dynamics
  - Migrate from from traditional “metal-intense” to composite and silicon-intense design
  - High fundamental frequency (10X conventional)
  - High pole-count, ironless motor with composite roto
  - Modular, air-core armature
  - Modular, passively cooled drive with wide-band-gap devices integrated with motor

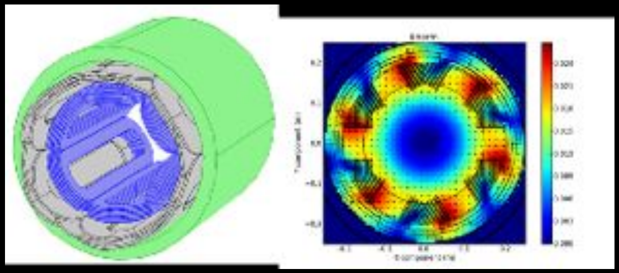


- Ohio State University
  - Design a motor for integration on LPT spool of CFM56 class engine
  - Reversed (ring) concept with cooling based on Variable Cross-Section Wet Coils (VCSW) coil design with integrated, direct cooling
  - Extensive design trade-space analysis and testing of motor concept at three power levels

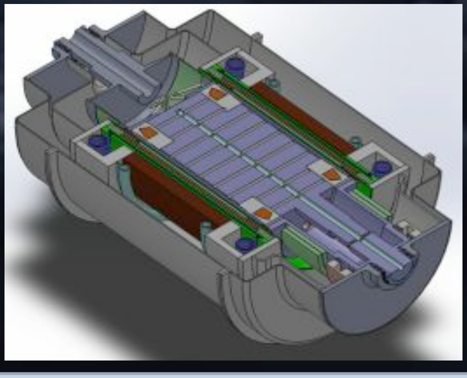


High Efficiency, High Power Density Superconducting Machines

- Advance SOA for crucial components to minimize power loss and enable thermal management
- Detailed concept design completed of 12MW fully superconducting machine achieving 25 hp/lb
- In collaboration with Navy, Air Force, Creare, HyperTech, Advanced Magnet Lab, U of FL
- Fabricating and testing superconducting machine components at laboratory scale
- Developing system for FY17 fully superconducting electric machine test at 1 MW design level



AML model for magnetic fields



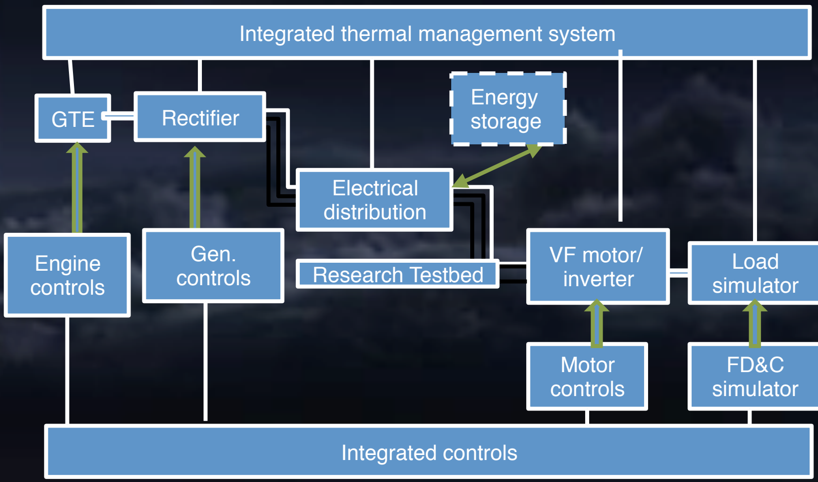
Enabling System Testing and Validation

- Develop Megawatt Power System Testing and Modeling Capability
- Key Performance Parameter-driven requirements definition and portfolio management
- Technology demonstration at multiple scales
- Early identification of system-level issues
- 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



Integrated thermal management system

GTE

Rectifier

Energy storage

Electrical distribution

Engine controls

Gen. controls

Research Testbed

VF motor/ inverter

Load simulator

Motor controls

FD&C simulator

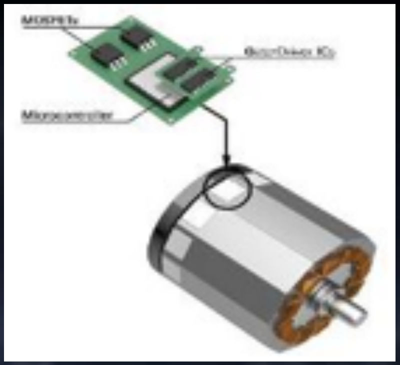
Integrated controls

Flight-weight Power Management and Electronics

- Multi-KV, Multi-MW power system architecture for aircraft applications
- 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

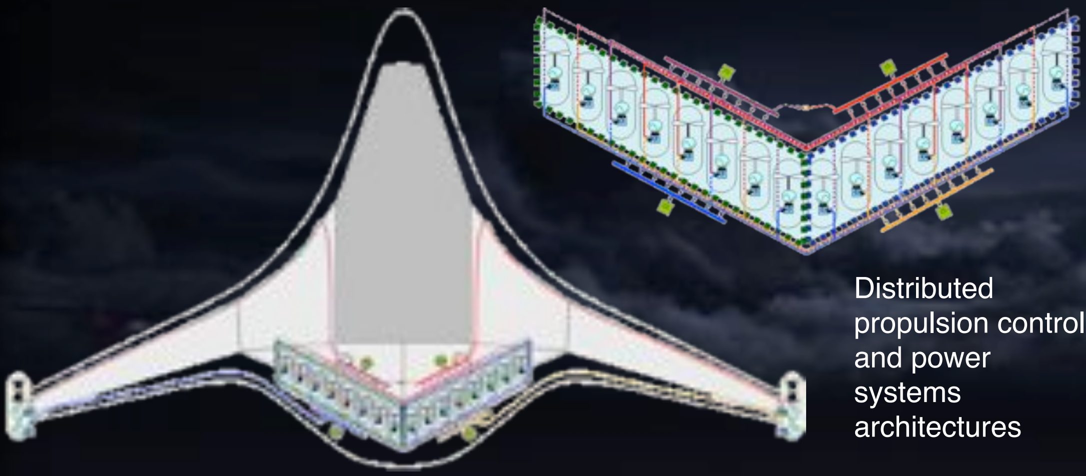
Superconducting transmission line

Lightweight power transmission



Integrated motor with high power density power electronics

Lightweight Cryocooler

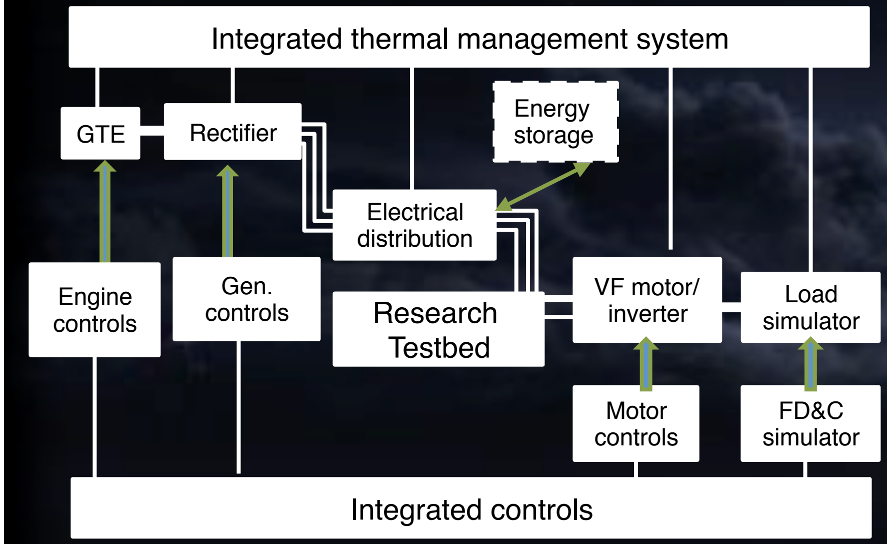


Distributed propulsion control and power systems architectures

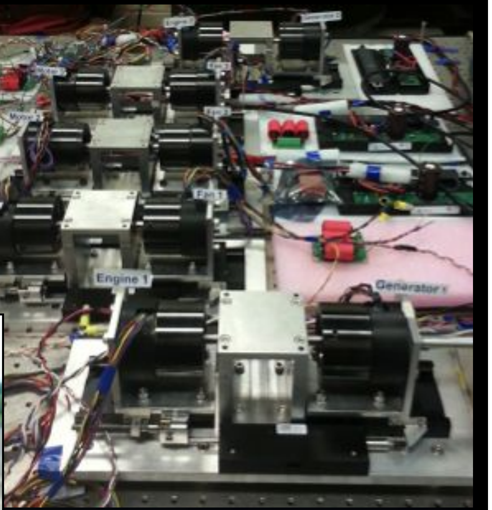
Lightweight power electronics

System Testing and Validation

- Use system-level simulation capability to emerge requirements.
- Demonstrate technology at appropriate scale for best research value.
- Integrate power, controls, and thermal management into system testing.
- Validated tools and data that industry and future government projects can use for further development.


Integrated thermal management system
GTE
Rectifier
Energy storage
Electrical distribution
Engine controls
Gen. controls
Research Testbed
VF motor/ inverter
Load simulator
Motor controls
FD&C simulator
Integrated controls

Propulsion Electric Grid Simulator—hardware-in-the-loop electrical grid

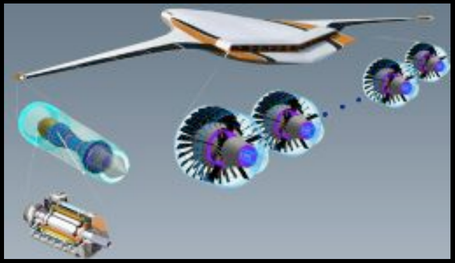


Fully cryogenic motor testing Glenn/SMIRF

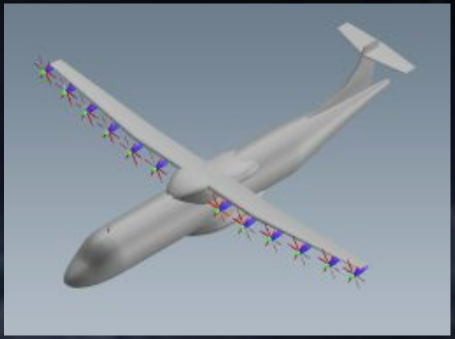
Eventual flight simulation testing at NASA Armstrong Flight Research Center

Integrated Vehicles and Concept Evaluations

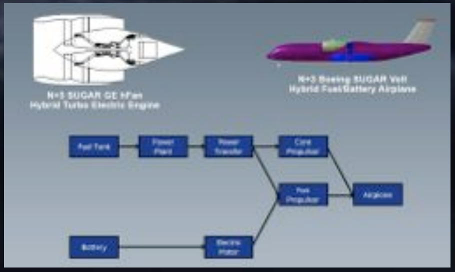
- Determine design requirements and trade space for hybrid electric propulsion vehicles
- Identify near-term technologies that can benefit aircraft non-propulsive electric power
- Enhance analysis capabilities to model non-traditional vehicle configurations with hybrid electric systems
- Establish vehicle conceptual designs that span power requirements from general aviation (<1 MW) to regional jets (1-2 MW) to single-aisle transports (5-10 MW)



GTE/generator,
distribution
and motor drive



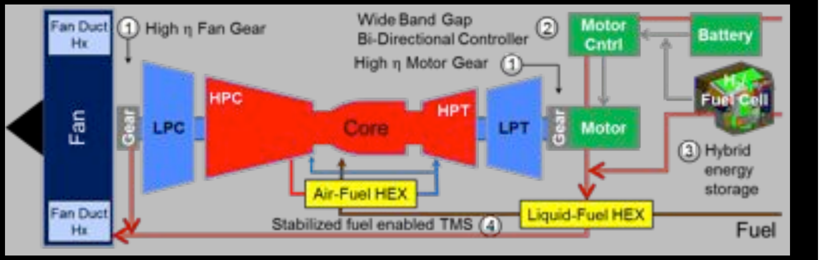
Fully electric GA/
commuter



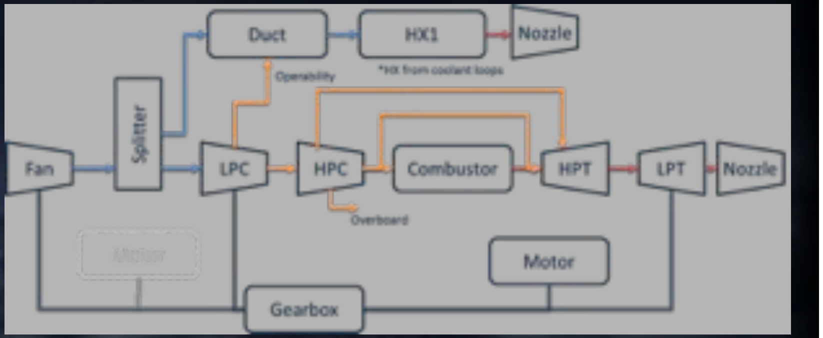
GTE and energy
storage (battery)

Hybrid Electric Propulsion System Conceptual Design

- Hybrid-electric geared turbofan conceptual design
  - UTRC, Pratt and Whitney, UTC Aerospace Systems
  - High Efficiency Drive Gear integrating high speed motor and low pressure turbine
  - Bi-directional flow of power
  - Hybrid battery/fuel cell for high density energy storage
  - Combined fuel/fan thermal management system

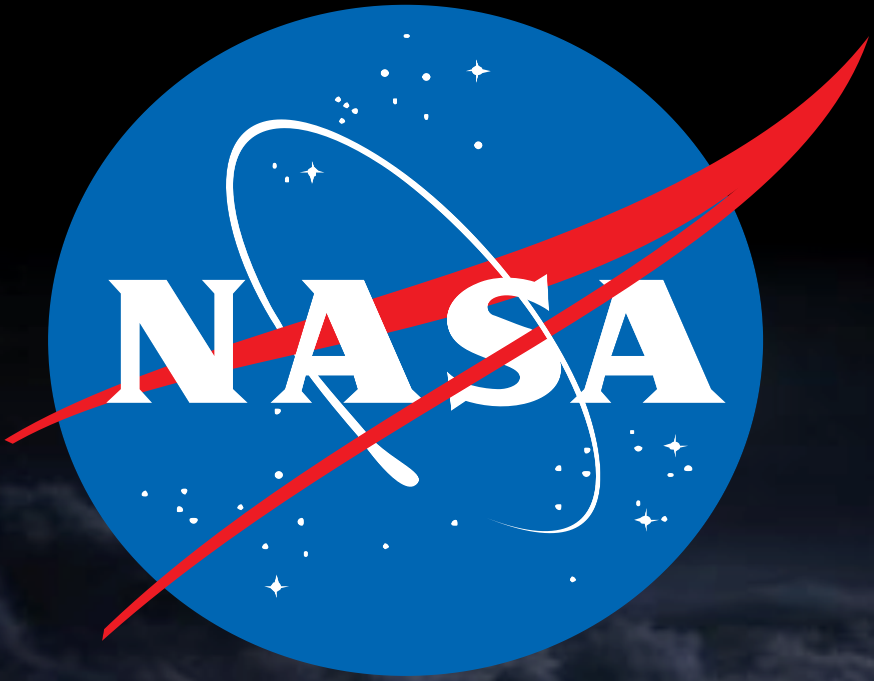


- Hybrid-electric geared turbofan conceptual design
  - Rolls Royce, Boeing, GA Tech
  - Identify best performing architecture based on engine cycles, motor, power conversion, energy storage, and thermal management
  - Innovative integration of novel gas turbine cycles and electrical drives
  - Potential side effects of system design considerations
  - Provide roadmap and technology maturation plan



Looking to the Future…

- Exciting challenges for an industry that was deemed “mature”
- Conceptual designs and trade studies for electric-based concepts
- Tech development and demonstration for N+3 MW class aircraft
- Development of core technologies - turbine coupled motors, propulsion systems modeling, power architecture, power electronics, thermal management, and flight controls
- Multiplatform technology testbeds demonstrating
  - Fully superconducting motor
  - 8 hp/lb (2x SOA) non-cryogenic electric motors
  - 2x power density increase for power electronics
  - Performance and control system verification for distributed electric propulsion at kW scale
- Development of multi-scale modeling and simulations tools
- Focus on future large regional jets and single aisle twin-engine aircraft for greatest impact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