Establishing Electrified Aircraft Propulsion Concepts

How AATT identified viable propulsion concepts and established foundational technologies

Dr. Cheryl Bowman
NASA Glenn Research Center

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Background: circa 2010 NRA Studies for Radical Benefits

Boeing, GE, GA Tech

NG, RR, Tufts, Sensis, Spirit

GE, Cessna, GA Tech

MIT, Aurora, P&W, Aerodyne

NASA, VA Tech, GT

NASA

Technology Trends:

- Tailored/multifunctional structures
- High aspect ratio/laminar/active structural control
- Highly integrated propulsion systems
- Ultra-high bypass ratio (20+ with small cores)
- Alternative fuels
- **Emerging hybrid electric concepts**
- Noise reduction by component, configuration, and operations improvements

Background: Electrified Aircraft Propulsion Studies pre-2014

NASA N3-X

- Fully Turboelectric, Hybrid Wing Body, 300 PAX
- ~70% fuel savings relative to CY2000 baseline
- ~20% fuel savings relative to Adv. HWB baseline
- Requires fully superconducting electrical systems and 5 -10 kV distribution, maturation of boundary layer ingestion

Boeing Sugar Volt

- Parallel hybrid, 150 PAX
- ~60% fuel savings relative to CY2005 baseline
- ~40% fuel savings relative to SUGAR Hi baseline
- Requires 750 W-hr/kg battery system, 1-5MW electric machines, and provides no in-flight energy efficiency benefit

ESAero ECO-150-100

- Fully Turboelectric, 150 PAX
- Increased Fan Area, High L/D wing
- ~40% fuel savings relative to CY2000 baseline
- Requires advance power components for savings relative to Adv. Baseline aircraft

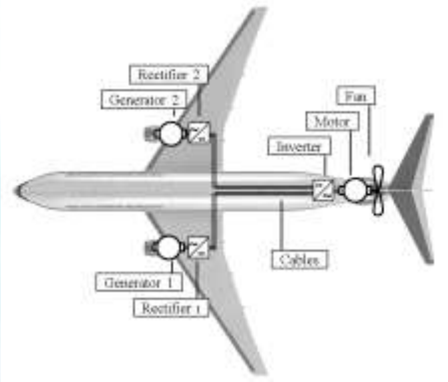
Technical Challenge: Are EAP Aircraft Viable for 2030-35?

Technical Challenge AATT.5.2 (FY14 to FY19)
Establish viable concept for 5-10 MW hybrid gas-electric propulsion system for a single-aisle class vehicle with reduced fuel burn, emissions and noise

- Can a 737-class hybrid gas-electric propulsion system close as flight worthy using current technology and achieve a net benefit to the aircraft metrics of **fuel burn/energy**, emissions, and noise?
- If not, what are the key performance parameters for closure and the new technology development requirements?

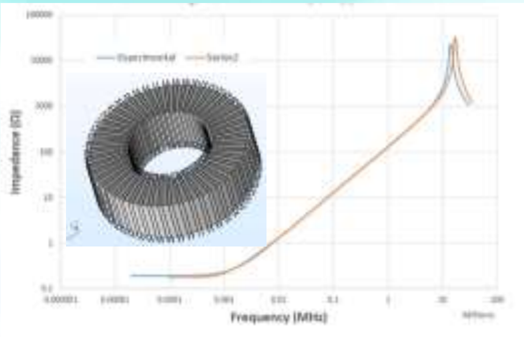
AATT Hybrid Gas-Electric Propulsion Sub Project (HGEP)

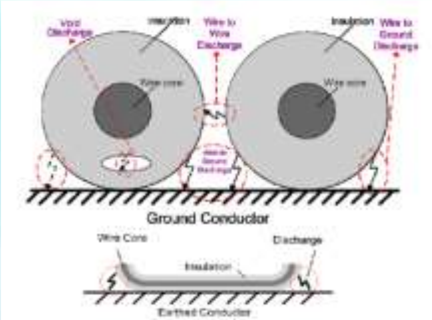
1. Detailed assessment *of reference design concept* through modeling and analysis



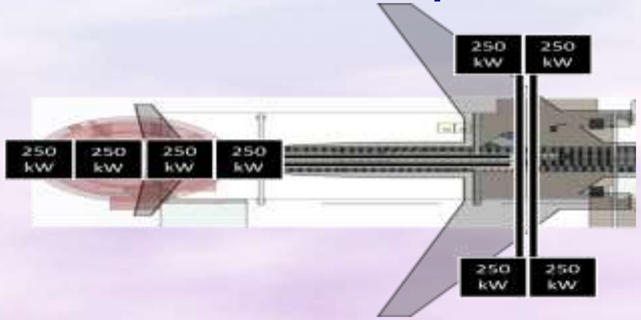
2. Select Component Demonstrations at *1-2 MW Level*

3. Maturation of key enabling *materials* and *subcomponents*

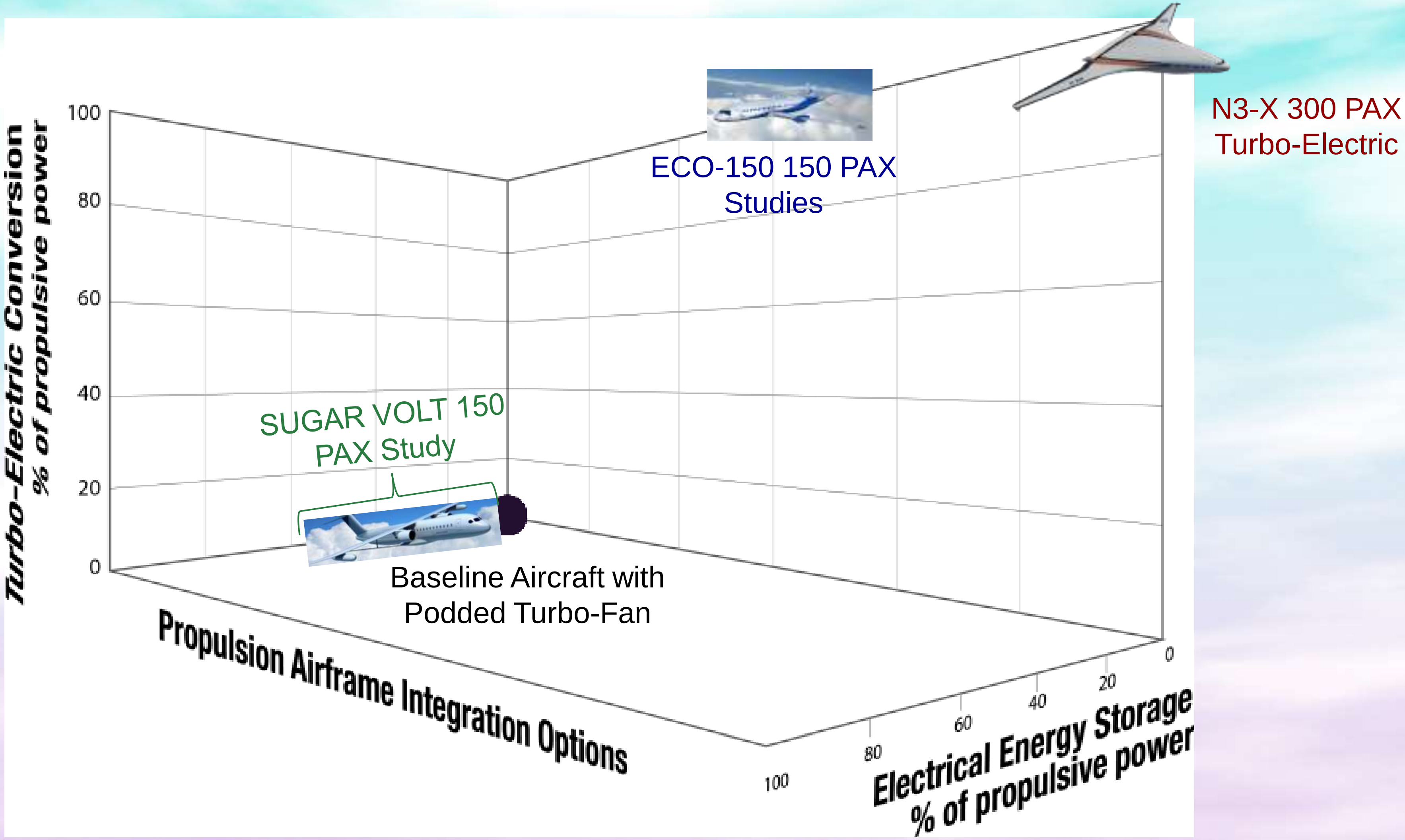




4. Integration Testbeds focusing on *hardware-in-the-loop* testing



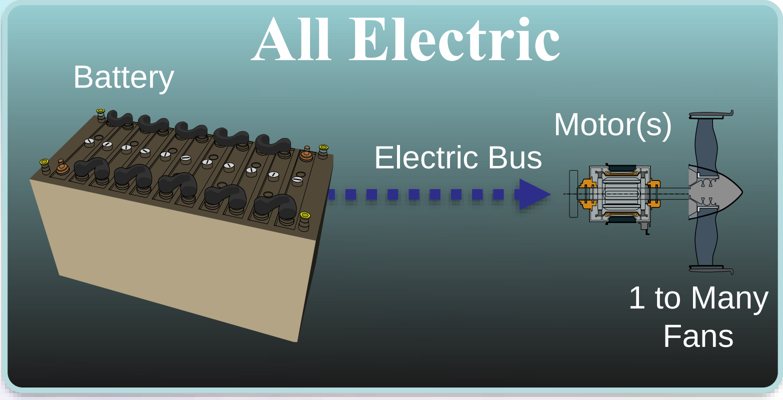
Expanding Trade Space for EAP Aircraft

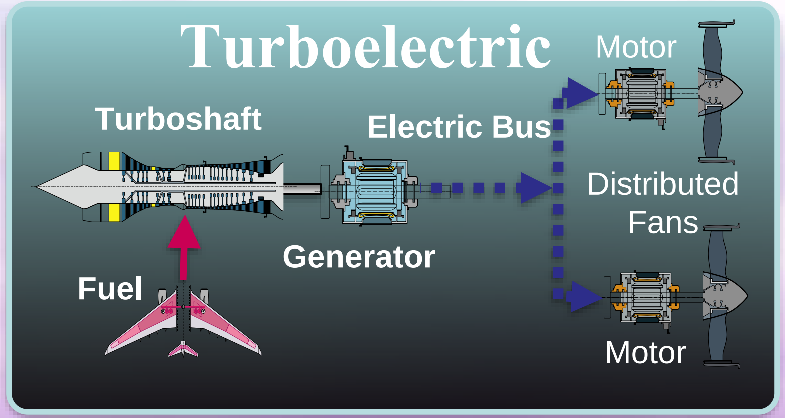


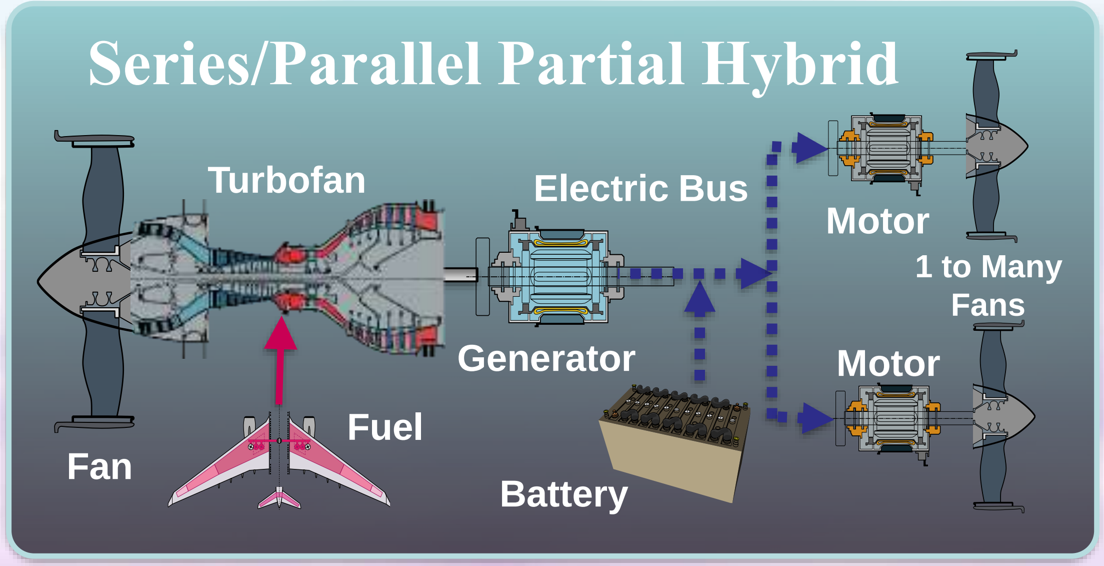
Expanding Trade Space for EAP Aircraft

Combined effort of HGEP Subproject and Systems Analysis and Integration (SA&I) teams including:

- Broad studies to explore vehicle size and integration trade space
- Point designs exploration for in depth analysis of vehicle level trades
- Exploring propulsion systems and propulsion-airframe integration







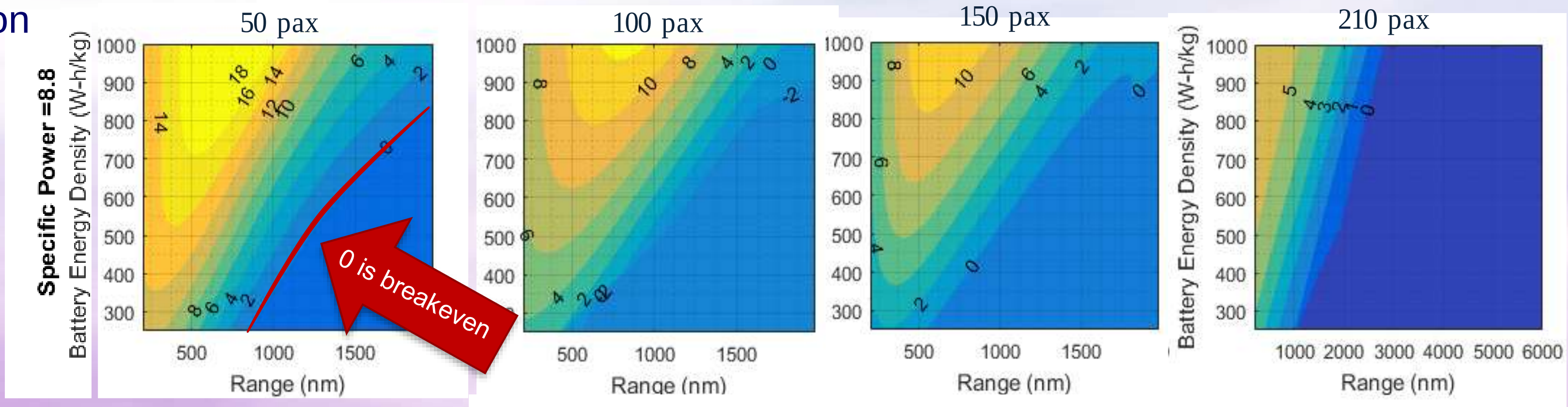
Georgia Tech ASDL Parametric Study Across Vehicle Sizes

GT HEAT DOE → Best Schedule for Range → Regress Surrogate Model → Evaluate Tech Level → Generate Entitlement Curve

Parameter	Minimum Setting	Maximum Setting
Battery Energy Density	250	1,000
Electric Drive System Efficiency	90	100
Electrical Drive System Specific Weight	2	30
Aircraft Technology Level	(current day)	High Tech
Gas Turbine Technology Level	(current day)	High Tech
Gas Turbine Engine Cycle	Optimized at Design Point	
Motor Rated Power	0	4,000
Hybridization Strategy	Optimized for Each Mission Length	
Mission Length	300	Design Range

General Trends for Parallel Hybrid:

- *Induced Drag* and *Battery Energy Density* are key drivers
- Benefits shows strong range dependency
- Trends similar for fuel, energy, and carbon emissions
- Sensitivity to machine specific power levels >6 hp/lb



These plots for 3MW motor with ~8.8 hp/lb

Parallel Hybrid: Electric Turbofan Engine Optimization

United Technologies Research Center Contract NNC14CA32C

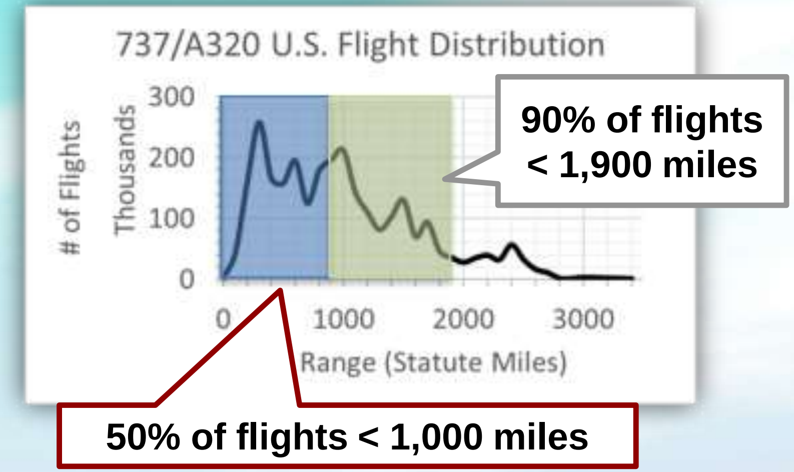
- Baseline is ~2035 advanced aircraft and advanced *conventional* Geared Turbo Fan (cGTF) Engine
- Hybrid Electric optimized Geared Turbo Fan (hGTF) Engine has core sized for cruise efficiency, electric boost power for take off and climb
- Overall Fuel Consumption reduced ~9% for 900nm mission
  - Max Cruise Thrust Specific Fuel Consumption reduced by 2%
  - Max Climb Thrust Specific Fuel Consumption reduced by 16%
- Overall Energy Improvement ~5%
- Potential for substantial ground/taxi emission reduction

- Still requires substantial energy storage and power component dev’t
- Electrical Energy Storage/Conversion, High Voltage Distribution, Engine Operability, and Thermal Management identified as highest risk technical challenges

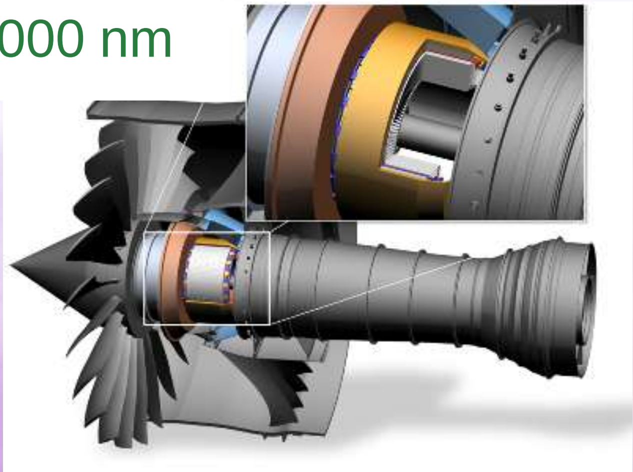
Parallel Hybrid: Electric Aircraft Mission Optimization

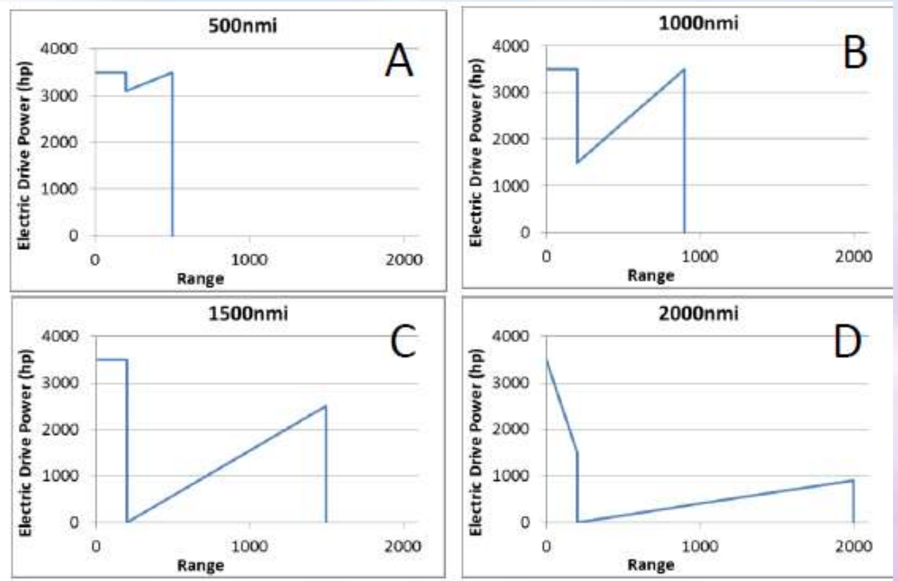
Rolls-Royce North American Technologies Contract NNC14CA29C

- Electrically Variable Engine™: variable pitch fan tightly integrated with electric machine
- Optimized electric power boost with mission
- Amortized fuel savings based on historic fleet usage data
- Found that mission objectives are important, *in addition to technology assumptions*



Projected fuel burn savings up to 20% for mission less than 1000 nm



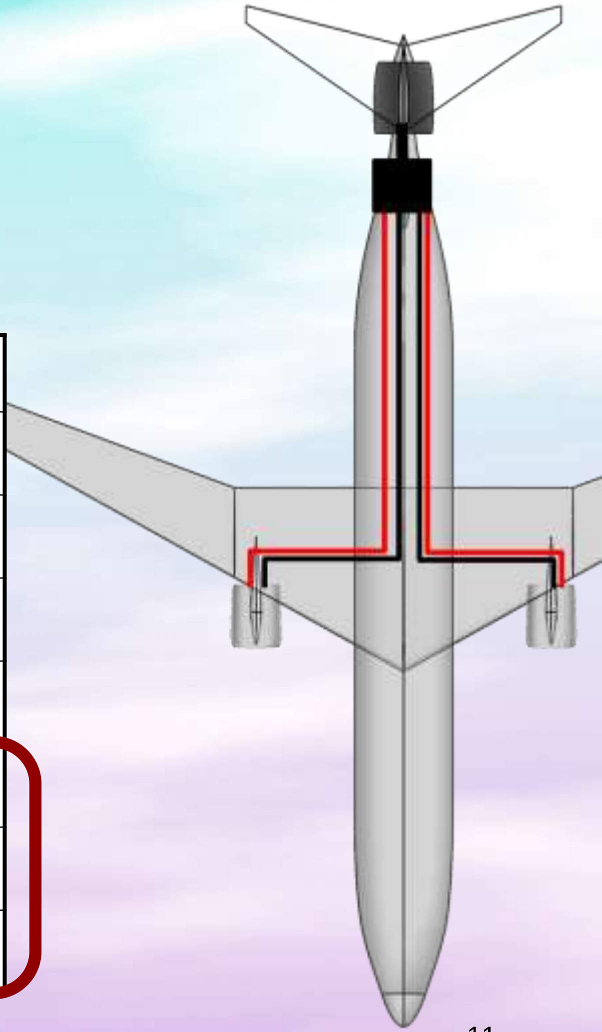


Beyond Parallel Hybrid: Introducing Distribution and PAI

Single-aisle **T**urboelectric **A**i**RC**raft with **A**ft **B**oundary **L**ayer propulsion (STARC-ABL)

- Results sensitive to both turbo machinery and electric machinery technology development assumptions
- Tight integration of the tailcone nacelle and vertical stabilizer required
- High voltage distribution is crucial
- BLI analysis validation required

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%**



FY2016 API Milestone for Concept Design

Initial three concept evaluations based on similar but different 2035 EIS, 737-class baseline aircraft. *Each concept resulted in overall vehicle-level benefits.*

Common Assumptions

- Non-superconducting electric powertrain targeting 20 year entry into service
- B737-class aircraft with moderate to high aspect wings, advanced composite structure
- High bypass turbine engines, small core
- Energy consumption comparisons “as loaded” on aircraft

Study Specific Assumptions / Results	**PH-1 UTRC**	**PH-2 RRNA**	**TE Aft BLI**	**Current SOA UAV / Marine**
E Machine Size (MW)	2.1 MW	1.9 MW	3.5 MW	100 kW / 10+MW
Elec. Machine Sp Power (kW/kg)	13	13	13	8-10 / 0.5
Powertrain Efficiency[1]	95%	96%	90%	93% / <90%
Elec. Energy Storage[2] (kW-hr)	1295	variable	-	variable
Energy Sp. Power (W-hr/kg)	1000	750	-	200

[1]Excluding Electrical Energy Storage [2]Net required for flight

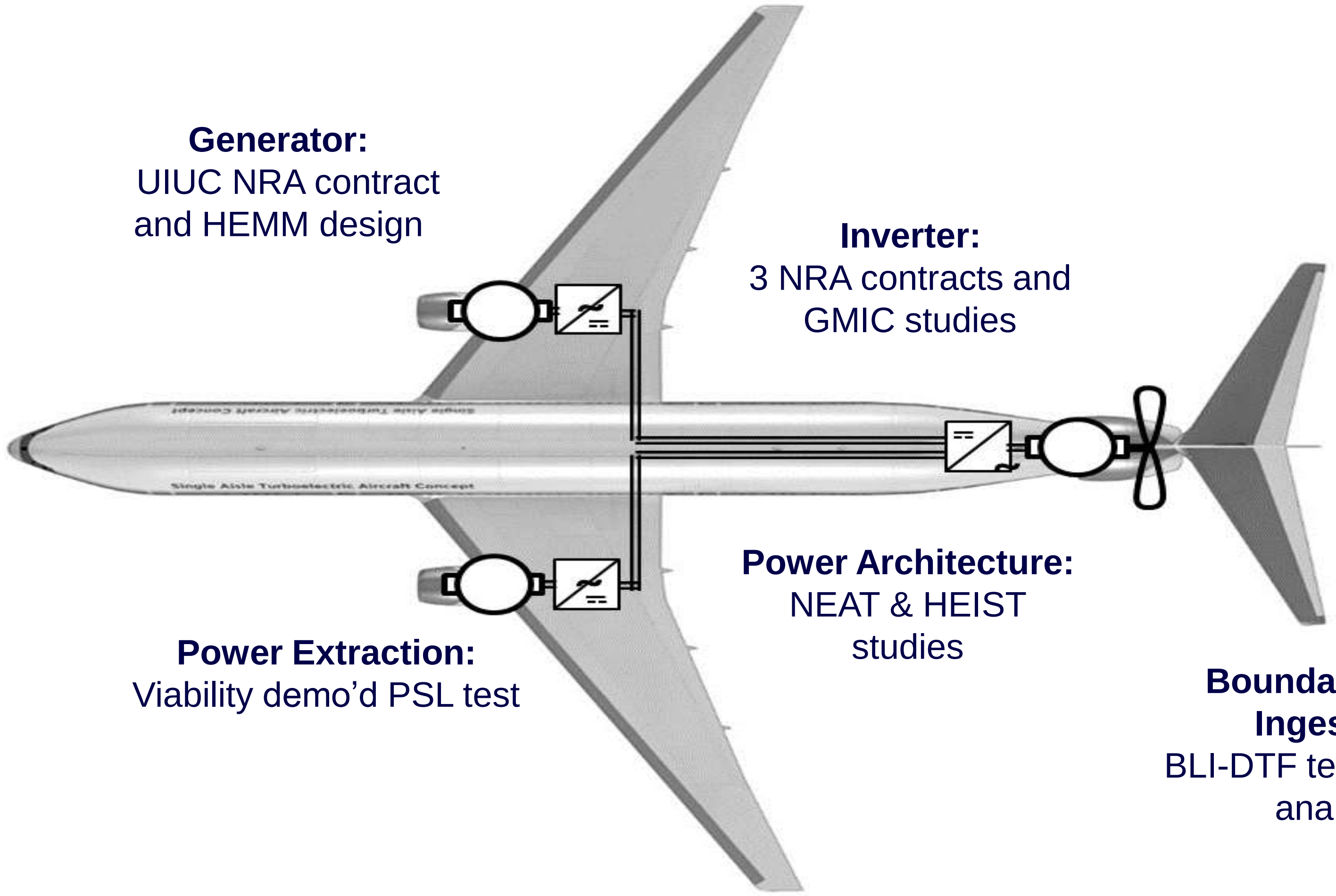
Continued Refinement of Concept Design (HGEP and SA&I)

- Completed two additional 1-year single aisle class concept studies to explore concepts beyond parallel hybrid
- Concepts from Boeing and Rolls Royce show potential fuel burn benefits of 4-5% over their references
- Batteries, when used, assumed battery pack specific energy density of 400 Wh/kg

Model	Type	TSFC $lb_m/hr/lb_f$	% Block Fuel Savings Econ	% Block Fuel Savings Design
N3CC-025	conventional	0.452	1.8	1.9
STAC-ABL	TE-AftFan	0.468	2.51	3.14
ECO-150-PMX	TE	-	2.75	5.3
ECO-150-PMX eOffset	TE + battery	0.536	3.05	1.02
HGEP Aft Fan Boost	TE + AftFan + battery	0.489	1.11	4.50

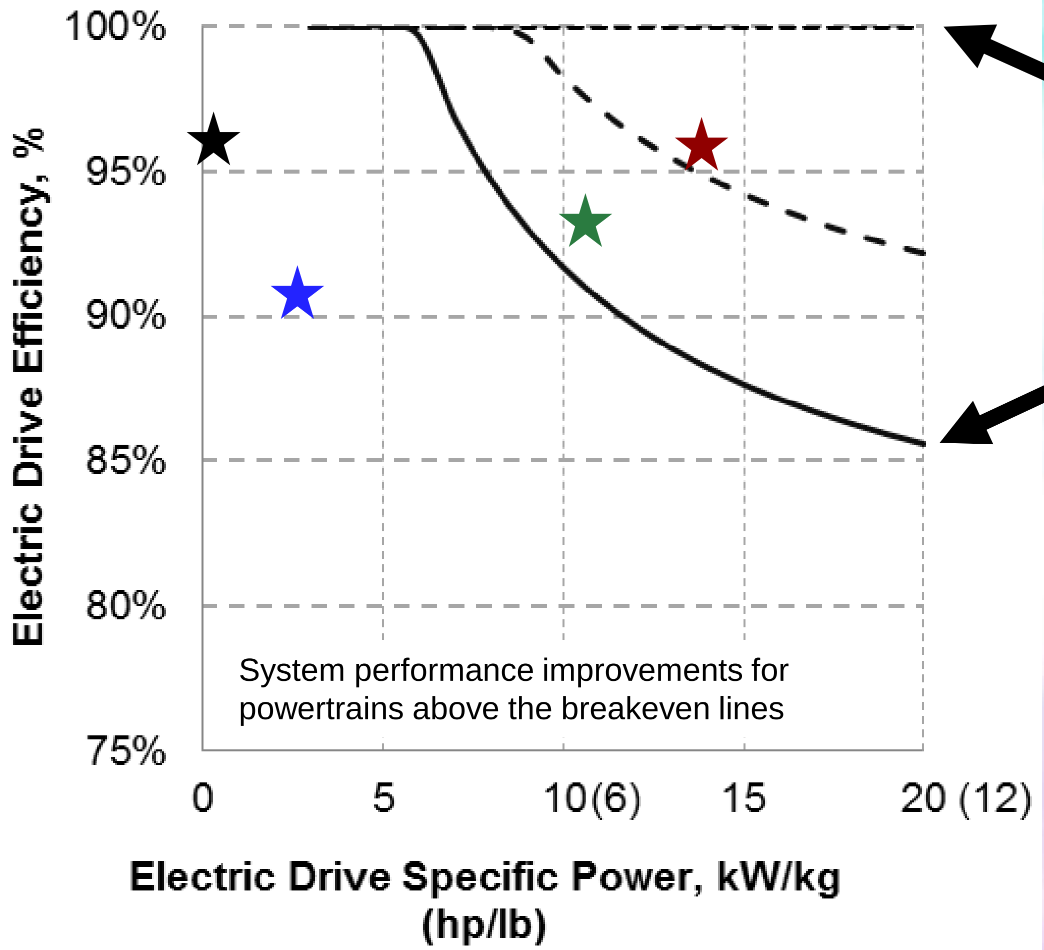
STARC-ABL Selected for Reference Concept

STARC-ABL provides anchor concept for component and system maturation



Breakeven Analysis Guiding Component Development Goals

Analysis for 3 levels of aircraft performance



Powertrains need both specific power and efficiency

Aircraft with minimal PAI system benefit require perfectly efficient components

Aircraft with large PAI system benefits require less aggressive component performance

Example Motor performance:

- Typical 1 MW Industrial
- 2008 Lexus Hybrid Automotive
- 2012 Launchpoint UAV
- 2014 NASA NRA target performance

NRA Sponsored Electric Machine Investment

Ambient Motor Targets:

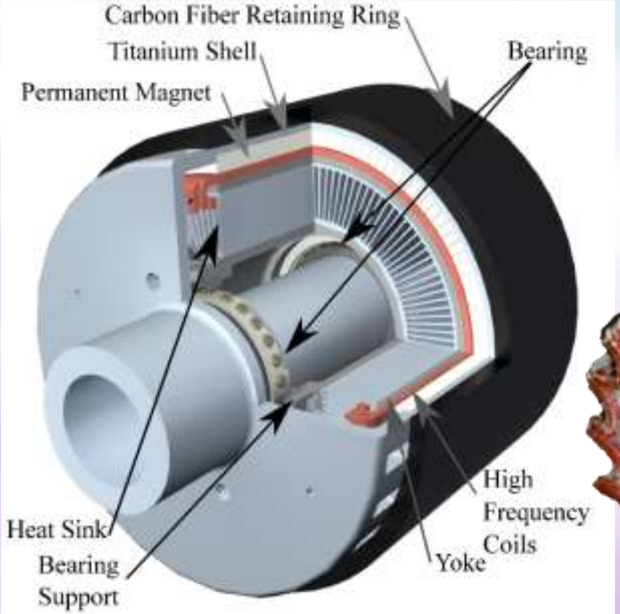
Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Goal	13.2	8.0	96

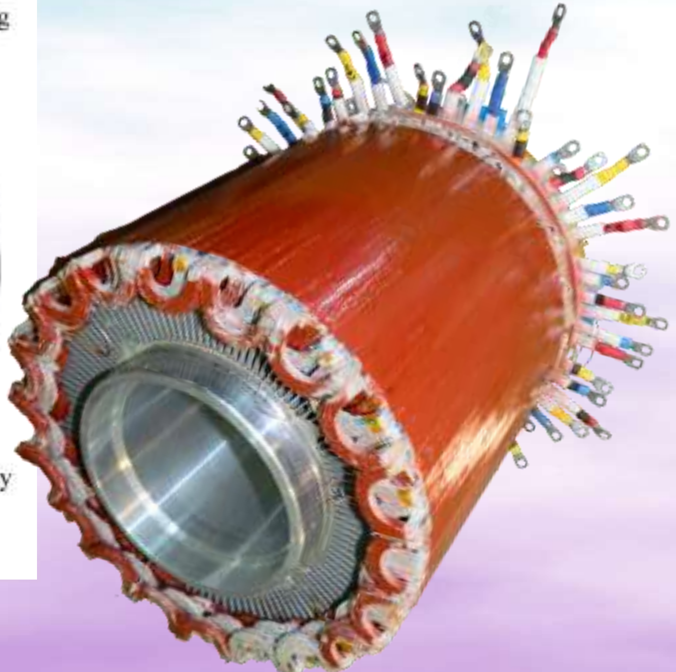
University of Illinois, P.I. Kiruba Haran

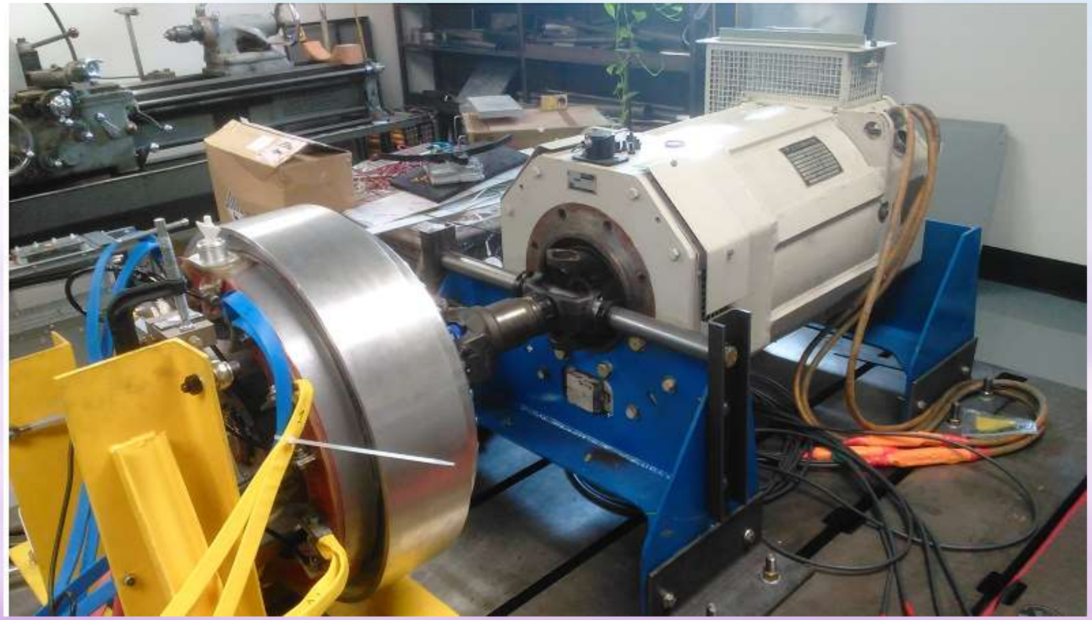
- Inside-out, permanent magnet design
- Composite structure casing
- High frequency drive for improved efficiency

Ohio State University, P.I. C.G. Cantemir

- Rim-driven Induction design
- Variable cross-section Al coils
- Setting records for induction motor performance
- Early proto-type being evaluated for trucks



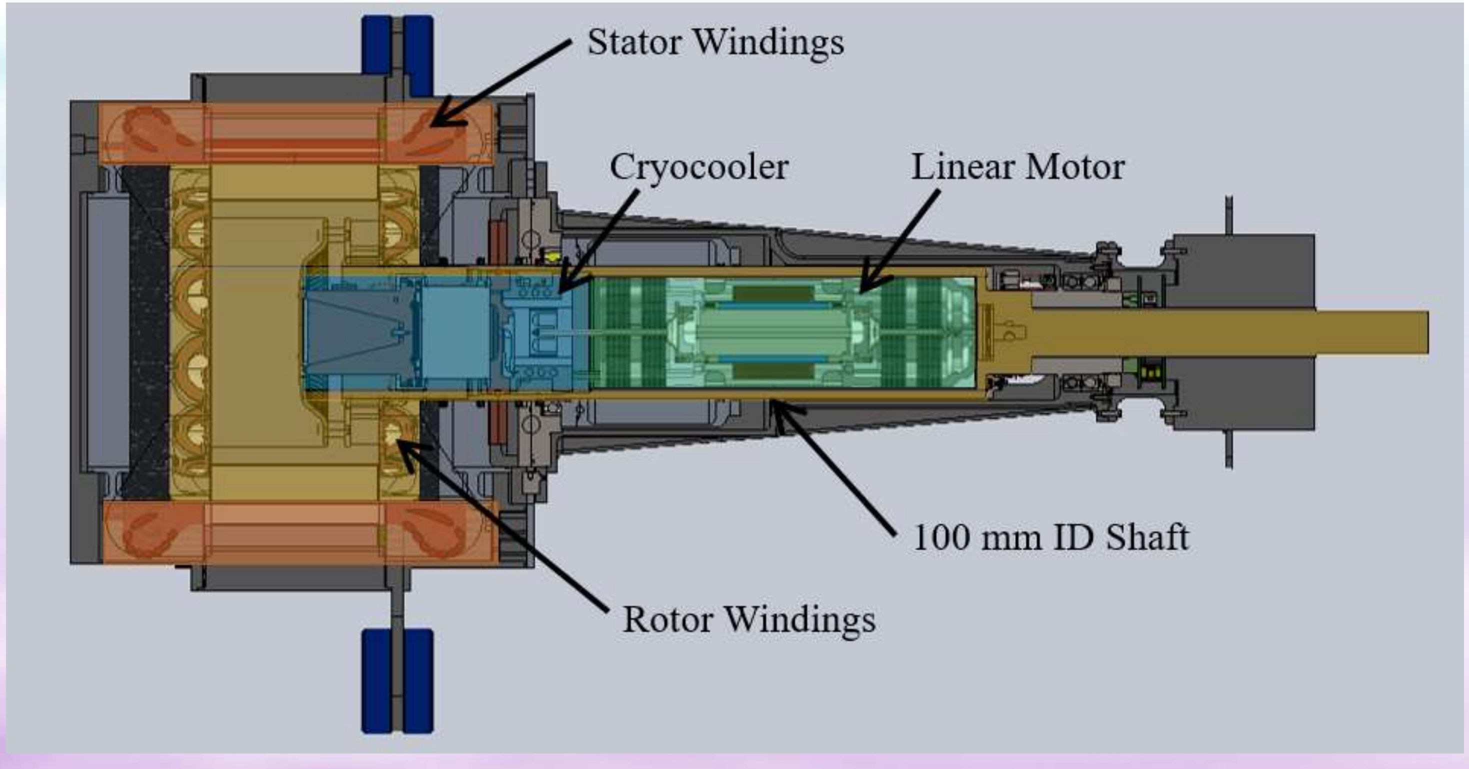




High Efficiency Megawatt Motor (HEMM)

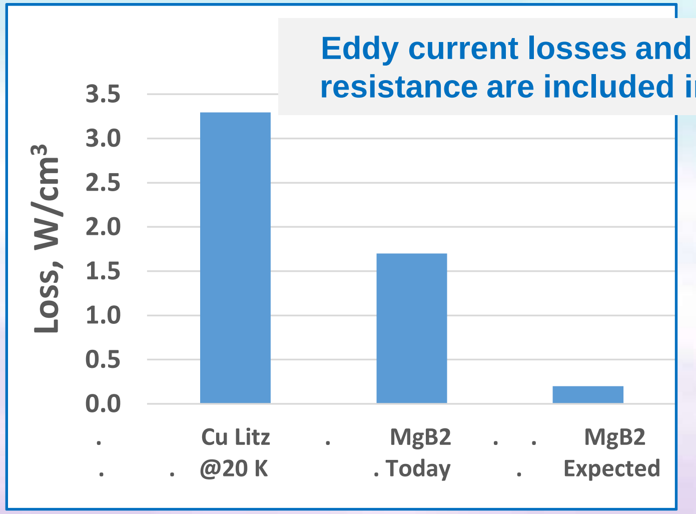
Leveraging NASA expertise to develop unique electric machine

- Started with ~year intensive analysis to explore features that pushed efficiency
- Using SOA superconducting materials in rotor windings
- On-board cryo-cooler leverages unique space expertise
- Building & testing subsystems to mature design

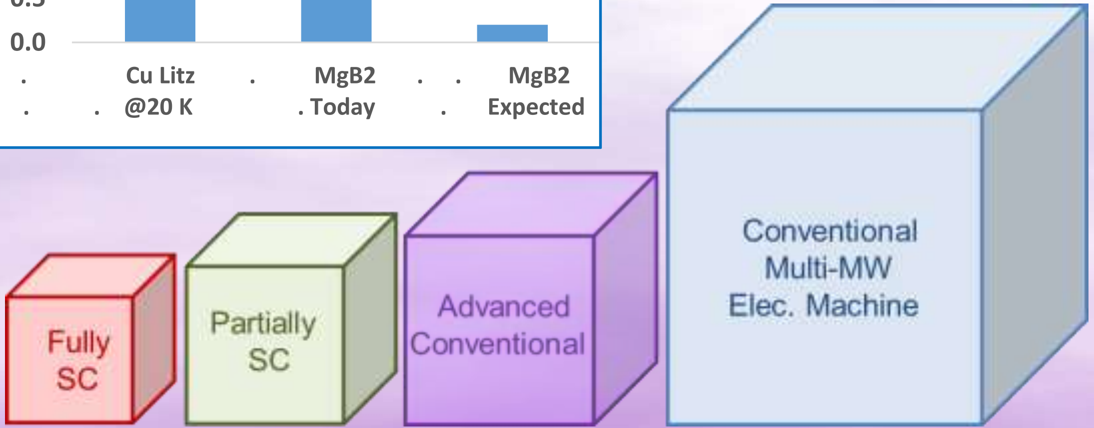


Fully Superconducting Machine Development

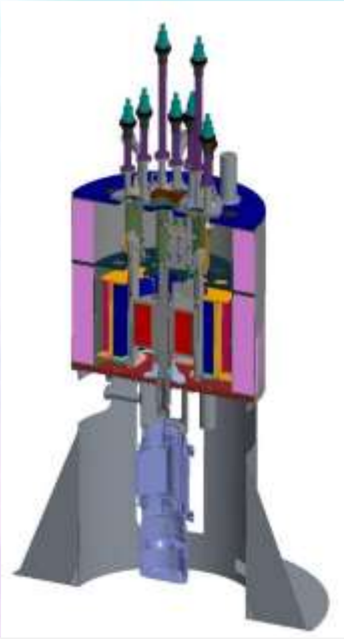
- Superconducting Technology has a dramatic impact on the volume, mass (specific power), and efficiency of electric machines
- NASA turboelectric aircraft studies have shown that an increase in efficiency from 96% to 99% would result in **additional 2%** fuel burn savings and improve thermal management by a **factor of 4**



Eddy current losses and magneto-resistance are included in Cu loss.



MgB_2 test article



Extending successful test rig design to lower temp (20K) and larger test section

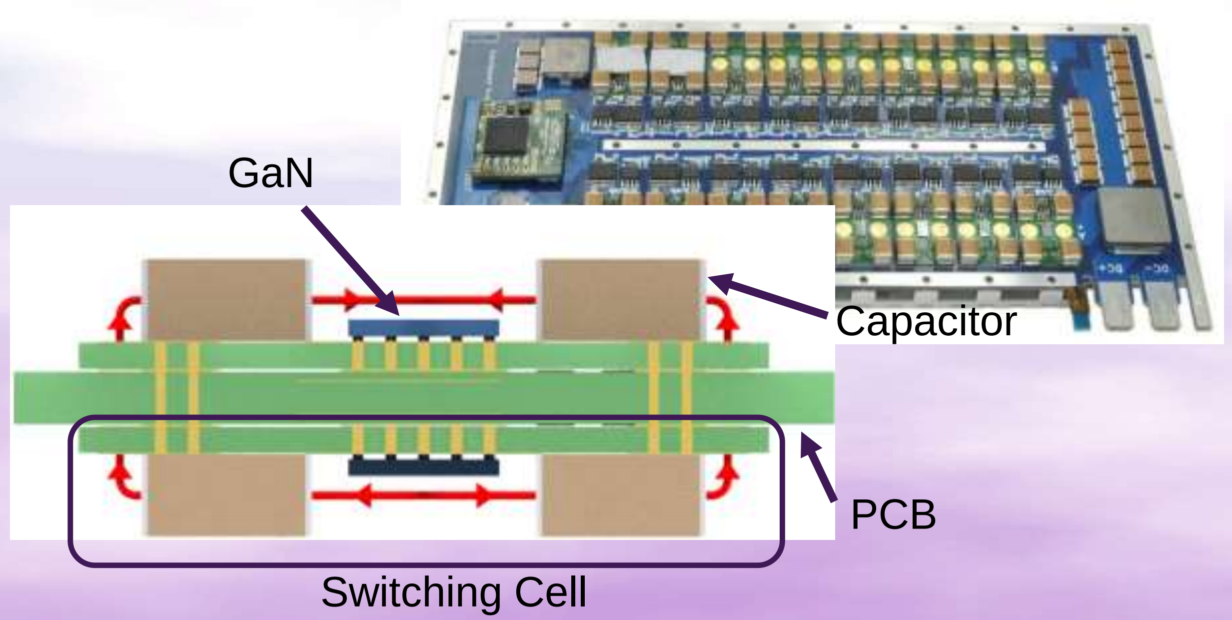
NRA Sponsored Power Electronic Investment

Ambient Inverter Targets:

Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch Target	25	15.2	99.5

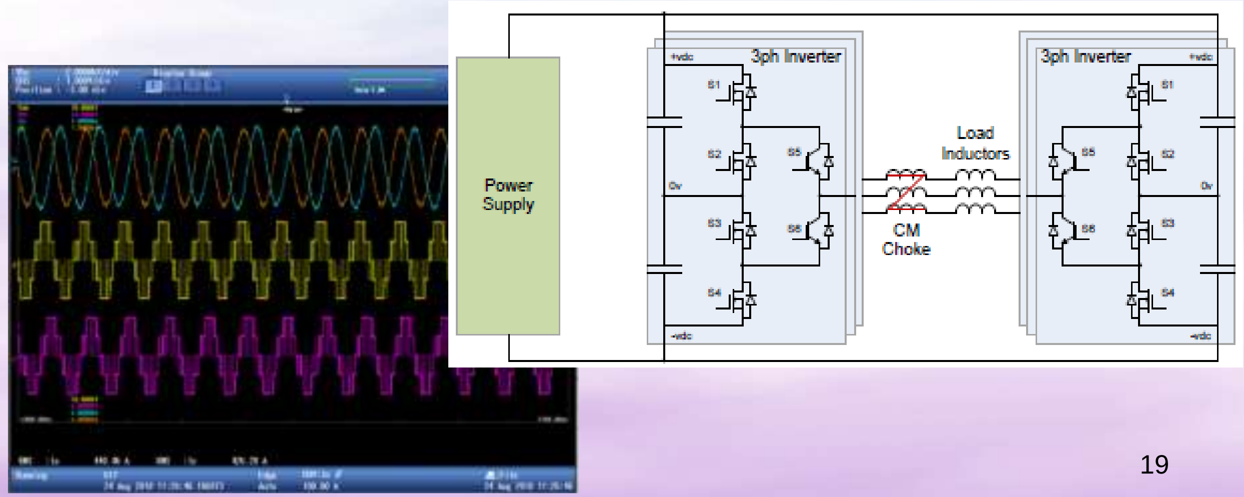
University of Illinois/Berkley, P.I. Robert Pilawa

- 9 level, low switch voltage stress
- High effective switching frequency
- Power loss distributed among switches
- Currently in final demonstration



GE Global Research Center, P.I Di Zhang

- Hybrid Si / SiC design
- 3 Level Topology
- Synergy with DOE investment to accelerate maturation
- Continuous operation at 1.26MVA, 18kVA/kg, and is10MVA/m3



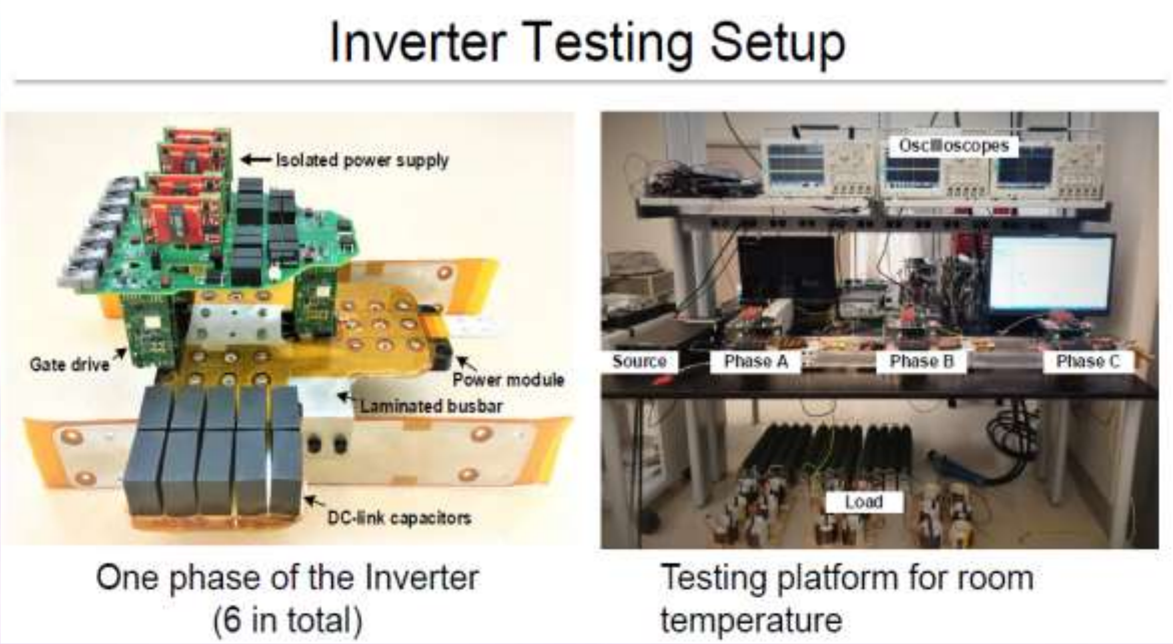
NRA Sponsored Power Electronic Investment

Cryogenic Inverter Targets:

Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	17	10.4	99.1
Goal	26	15.8	99.3
Stretch Target	35	21.3	99.4

Boeing, P.I. Shengyi Liu
supported by Univ. Tenn. Knoxville

- Documented cryogenic performance of Si, SiC, and GaN devices
- Demonstrated Si-based 200 kW inverter
- Demonstrated SiC-based 1MW inverter
- Designed to exceed 26 kW/kg, >99% efficiency at cryogenic operation



FY2018 API Milestone for Electric Machine Development

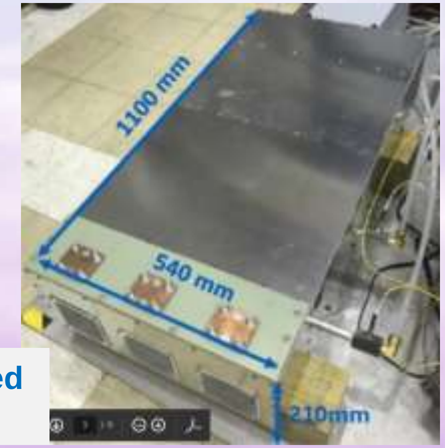
Component Performance Target:
13 kW/kg (8 hp/lb), > 96% efficiency

Results

- GE under NRA contract successfully demonstrated a full scale MW inverter which uses SiC MOSFETS. This converter produced 12 kW/kg and 99.1% efficiency
- University of Illinois under NRA cooperative agreement achieved 17.3 kW/kg and 98% efficiency in a subscale GaN inverter test
- University of Illinois subscale tests of a coreless, high frequency and high speed MW electric machine have shown feasibility of producing 13 kW/kg at 96% efficiency
- Ohio State University has tested their inside-out external rotor induction machine to 440 kW at 1800 rpm and claim to have set a world record for induction motor power density at 4.5 kW/kg

U. Illinois machine assembly and slow speed testing.

OSU MW motor connected to electric load machine.



Fully Assembled Converter

Component Development Driving Materials Research: Insulation

Better insulation required in EAP Electric Machines for improved thermal management and higher voltages

- Developing polymer composites (e.g. polyimide / boron nitride) with increased thermal conductivity while maintaining electrical, mechanical and durability characteristics.
- Extruding thin sheets and wire coatings for relevant form factors
- Developing stator potting techniques for fabrication of high power density motors

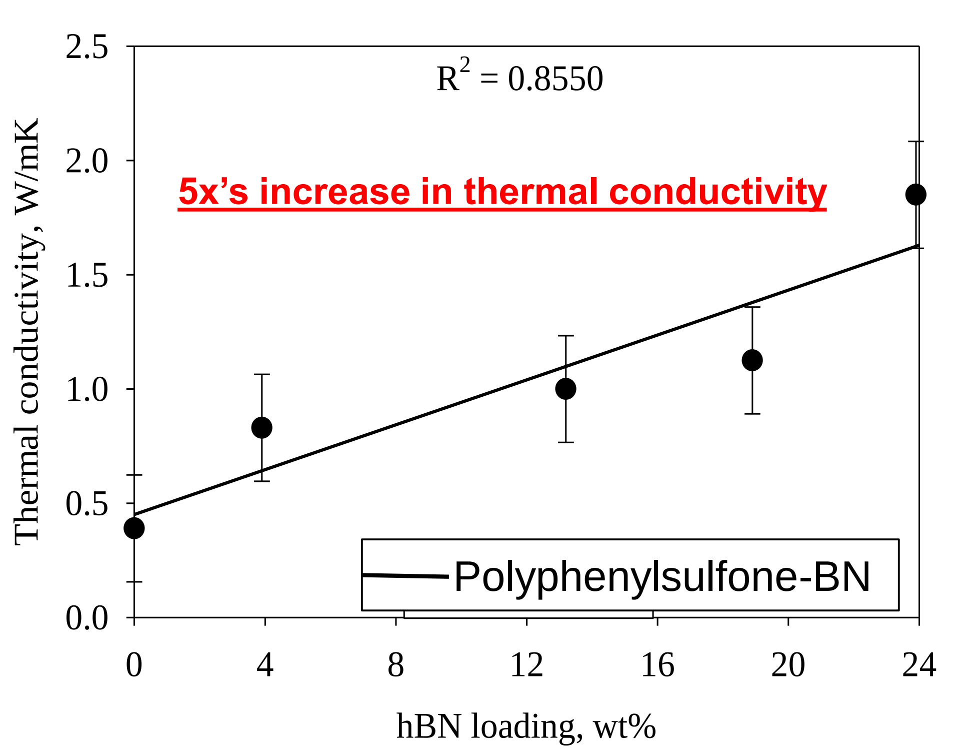
Future challenges include developing insulation with better durability to partial discharge events

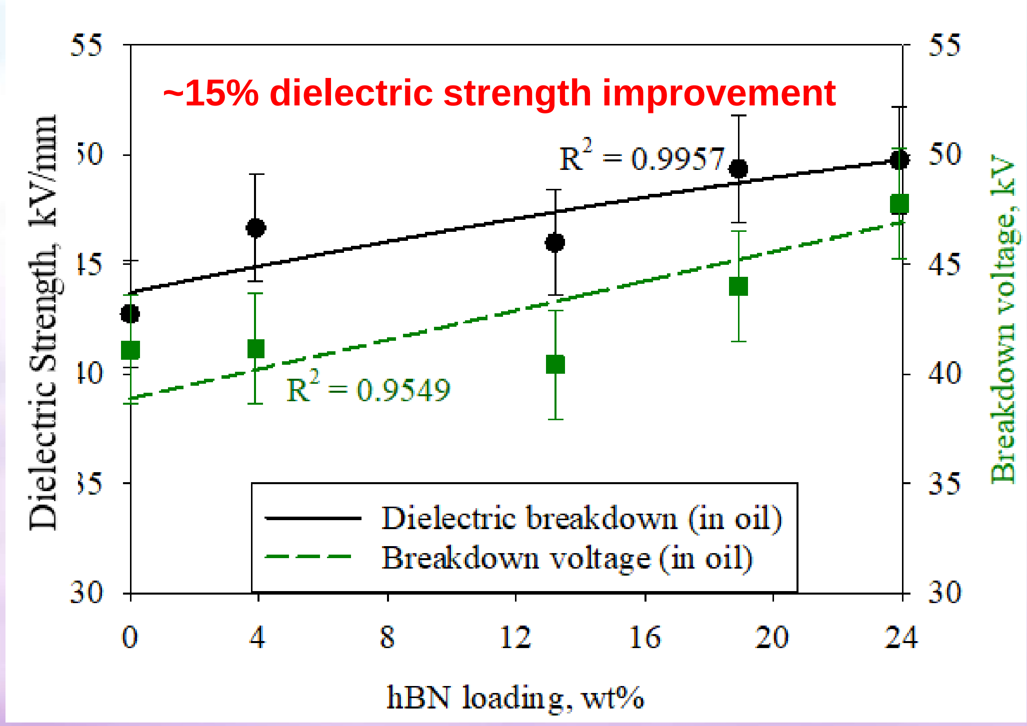
Flexible tape infuse with BN

Developing practical potting techniques for fine, twisted "Litz" wire

Component Development Driving Materials Research: Insulation

- Terrestrial medium and higher voltage machines rely on in-organic insulation such as mica, not conducive to fine or twisted wires
- Typically adding conductive particles to polymers increase thermal conductivity but reduces dielectric strength
- NASA materials engineers are developing flexible composites which improve thermal conductivity and improve dielectric strength and breakdown voltage

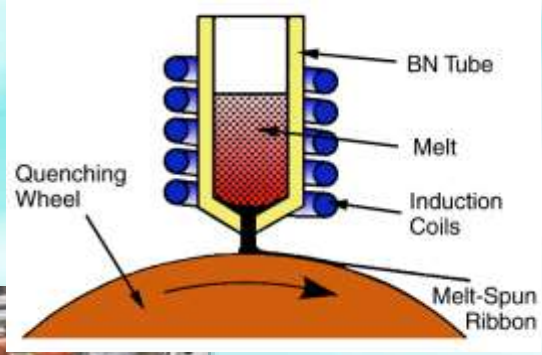




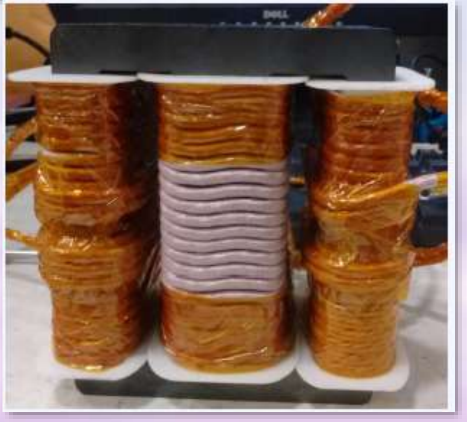
Component Development Driving Materials Research: Magnetics

Soft magnetic devices key throughout electric power system in filtering, transforming, and electric machines

- New material required to match target EAP power frequency ranges



NASA has taken EAP-relevant alloy class from lab to component application



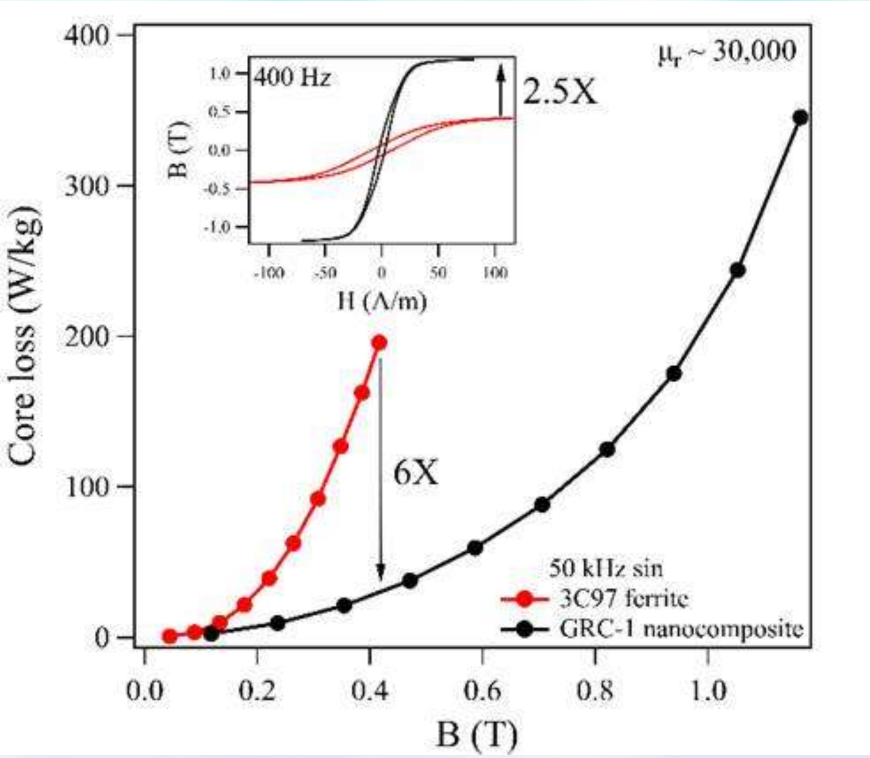
Component Development Driving Materials Research: Magnetics

NASA has taken EAP-relevant alloy class from lab to component application

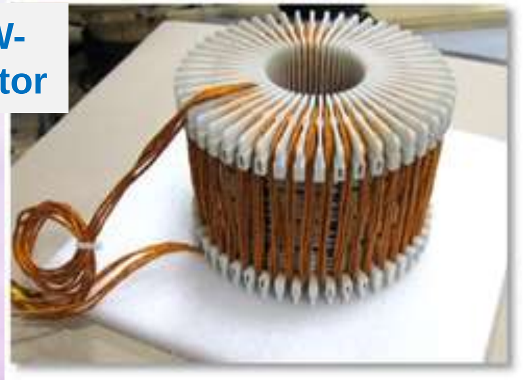
- Patented new alloys being transitioned to industry
- Full range of modeling, processing and characterizing capability to enable custom components

Magnetic Material performance demonstrated:

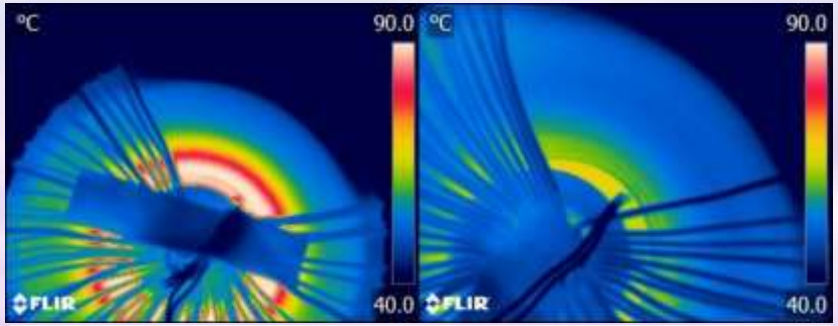
- Increased operating temperature from 150 to 400C
- Replaced MW class inductor with 87% lighter unit
- Doubled performance of 10 kW power transformer
- 500W transformer 38% lighter, 1% more efficient



Lighter MW-Class Inductor



Filter inductor for CAS motor controller project



Graded-permeability core (right) produces less heat

Integrated System Testing focused on Distributed Propulsion

Distributed Electric Propulsion (DEP) R&D

- Precursor work to X-57 Flight Demonstrator let to the development of distributed hybrid electric system testbed (HEIST) and Airvolt propulsor test stand at AFRC
- HEIST design complete:
  - 265 kW with a 65 kW turbogenerators and battery
  - Distributed propulsors along a wing
  - Aerodynamic feedback using dynamometers
  - Piloted simulation to design and study future DEP flight controls
- Airvolt Propulsor Test Stand
  - Supports airworthiness standards for certifying electric motors for flight
  - Used for X-57 cruise motor testing in 2017

Hybrid Electric Integrated Systems Testbed (HEIST) at AFRC

Flight Simulators Connected to HEIST

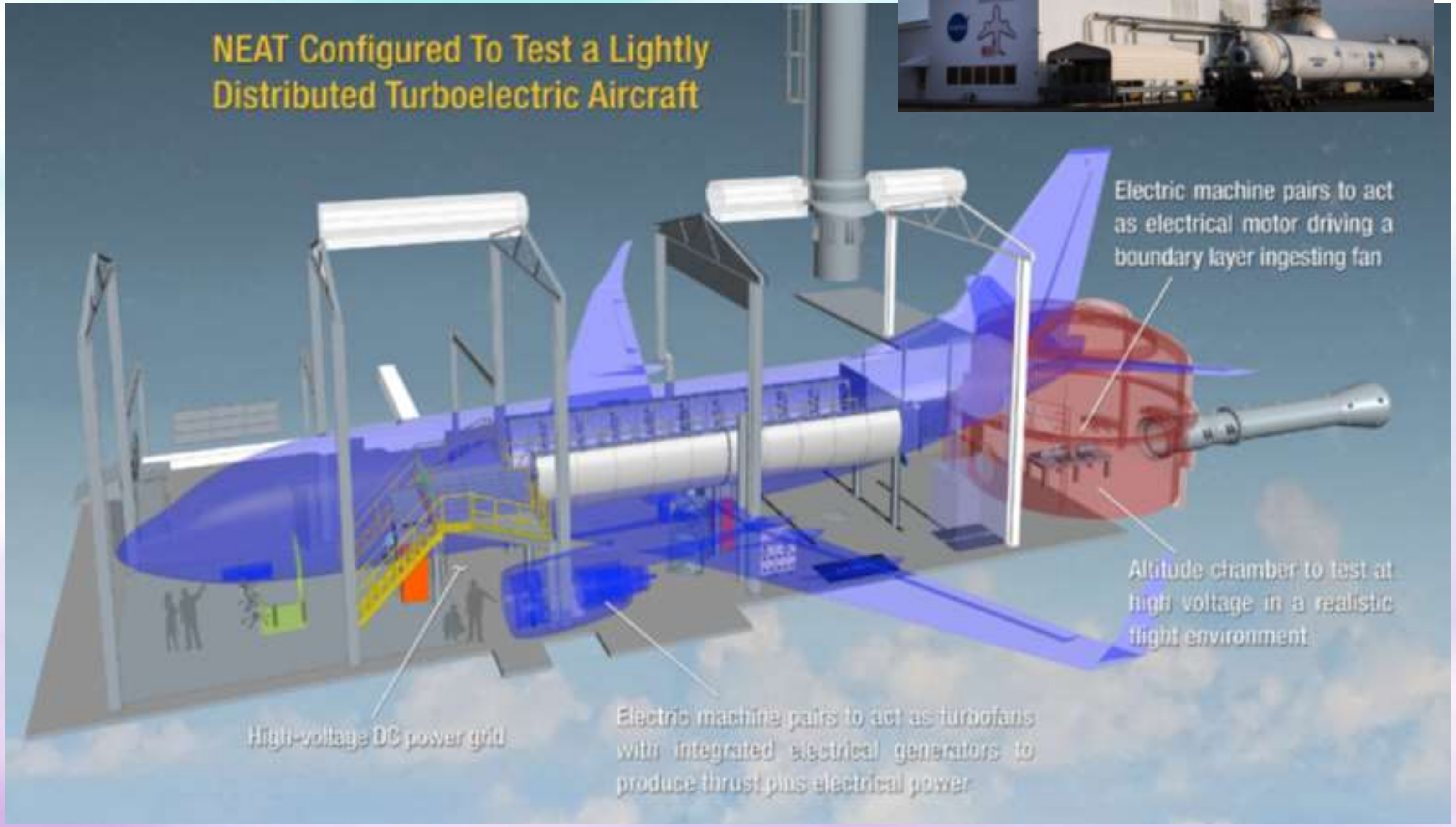
X-57 Cruise Motor on Airvolt Test Stand

Distributed propulsion provides new opportunities for propulsion efficiencies requiring aerodynamic, system, and flight control research

Integrated System Testing focused on Propulsive Powertrain

NASA Electric Aircraft Testbed (NEAT)

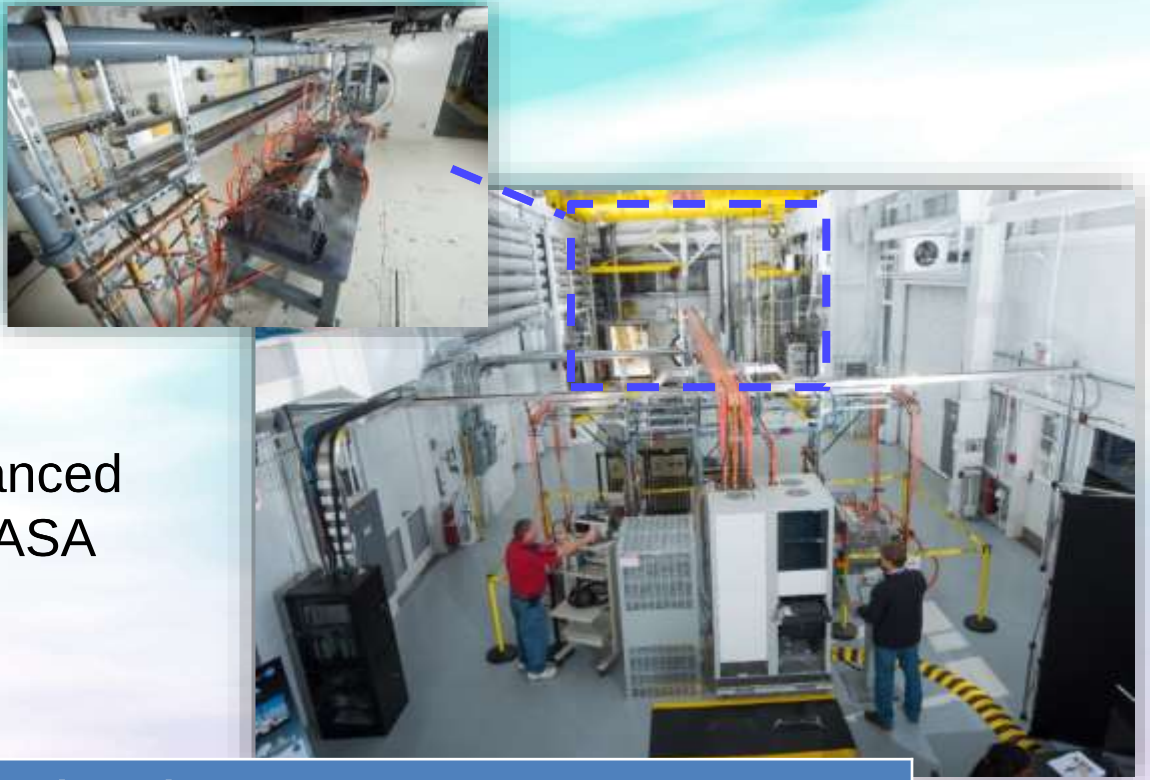
- From conception to operations in three years
- 20x25 ft. altitude chamber
- MW, kV power class
- Uses 250 kW electric machines as powertrain building blocks
- TC 5.2 Tests Complete:
  - ✓ 125 kW Single String Tests
  - ✓ 500 kW STARC-ABLE
  - ✓ Partnered component testing at Altitude



FY2019 API Milestone for System Testing

Target: Representative electrified aircraft powertrain designed, assembled and tested in the NEAT testbed

- Simplified powertrain for Boeing 737-class Electrified Vehicle tested at 500kW exploring EMI, thermal, impedance, latency, conformity, and reflections
- Partnered with General Electric to test an advanced electric machine at altitude conditions in the NASA Electric Aircraft Testbed.



Requirements for Green Exit Rating	
Representative electrified aircraft powertrain	**✓Two complementary tests completed:** • **Full powertrain at 500kW** • **Partial powertrain at full-scale power (MW class)**
Commercial off-the-shelf (COTS) non-flightweight components	**✓ World class testing of advanced components capable of altitude operation**

EAP Technical Challenge: The World is On-Board

Several aircraft system studies anchored with notable technology maturation from the material level up through system demonstration have established path forward

- NASA investment in EAP has expanded beyond one AATT subproject

- Advanced Research Projects Agency–Energy's Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) which expands NASA investment goals from machines & inverters into powertrain drives

- There have been three Electric Aircraft Technology Symposiums (EATS 2018, 2019, 2020) co-sponsored by AIAA and IEEE
- Numerous companies have announced plans for all-electric or hybrid electric demonstrators

Team Members

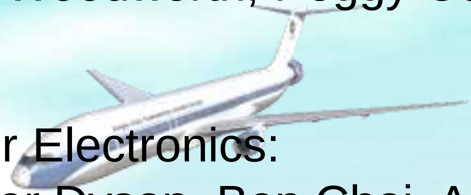
Tech Challenge Definition:
Rubén Del Rosario, Rich Wahls

System Analysis & Integration:
Bill Haller, Mark Guynn, Jim Felder,
Ty Marien

Electric Machines:
Gerry Brown, Andy Provenza,
Yaritza De Jesus-Acre

Insulation Materials:
Marisabel Lebron-Colon, Andy Woodworth

Subproject Management:
Amy Jankovsky, Ralph Jansen, Rodger Dyson,
Andy Woodworth, Peggy Cornell



Power Electronics:
Rodger Dyson, Ben Choi, Andy Provenza,
Dave Avanesian

Magnetic Materials:
Alex Leary, Randy Bowman

HEIST and NEAT Testbeds:
Kurt V. Papathakis, Kurt J. Kloesel, Yohan
Lin, Rodger Dyson

Partnerships Highlights

- NASA and GE heavily partnered with non-reimbursible SAA test programs at NEAT and 50/50 cost share contract to develop a flight ready inverter. This partnership has served to accelerate US competitiveness, and accelerated NASA's capability readiness for kV, MW testing at altitude
- NASA, AFRL and GE partnered in a non-reimbursible SAA to test MW power extract under altitude conditions at PSL
- NASA-Navy Superconducting Team demonstrated the key components of a turbo-Brayton design (recuperator, counter-flow heat exchanger) towards 80% reduction in the weight of cryocoolers used in superconducting machine applications
- NASA-DOE funded partnership with NETL, Carnegie Mellon Univ., NC State Univ., and Eaton Corporation successfully developed and built improved 1 MW inverter

Technology Transition Success Stories:

- NASA-DOE funded partnership with NETL, Carnegie Mellon Univ., NC State Univ. and Eaton Corporation, under the DOE SuNLaMP project, produced a photovoltaic transformer core which out-performed a commercial core by having more than a 2X lower energy loss and 99% efficiency. This represents a significant advancement in the state of the art for soft magnetic materials and will be leveraged to support NASA's goals for hybrid electric aircraft.
- HGEP sponsored work in passively cooled motor control power electronics baselined for X-57 cruise motors
- OSU motor licensed by Cummins for BEV Class 8 Semi-Truck for 2020 product introduction
- UTRC/UTAS engaged in performing testing of U of Illinois motor; cost share provided as facility upgrades to accommodate motor. UTAS's electric drive integrated systems labs (ISL) and 125 kW motor drives, developed for and flying on the Boeing 787 Dreamliner, used to drive U of Illinois motors that were developed under NRA contract.

ULI Collaborations…

- Close relationship and coordination with Ohio State-led team on Thrust 4 work in electrified propulsion technologies. Developing a MW EAP electric machine, power electronics, advanced thermal management and plan to test at NEAT
- Close relationship and coordination with Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA). Developing a LH2 hybrid wing body plane concept powered by a fuel cell and featuring a fully electric, superconducting propulsion system.

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