National Aeronautics and
Space Administration

Current Status and Future Plans for Electric Motors and Drives at NASA

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Session: Keynote
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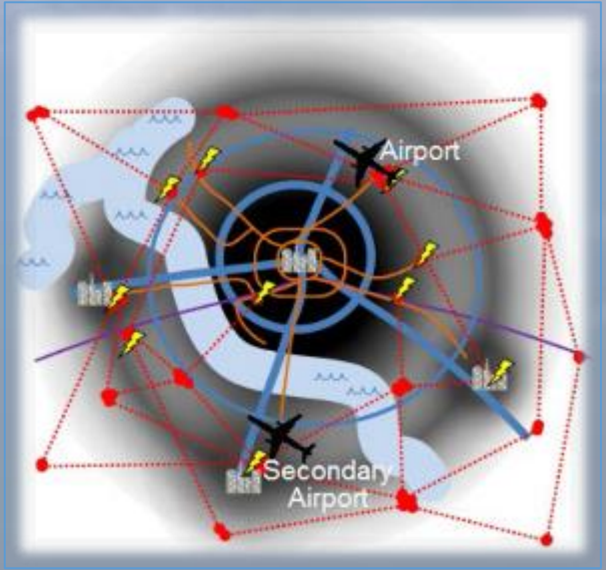
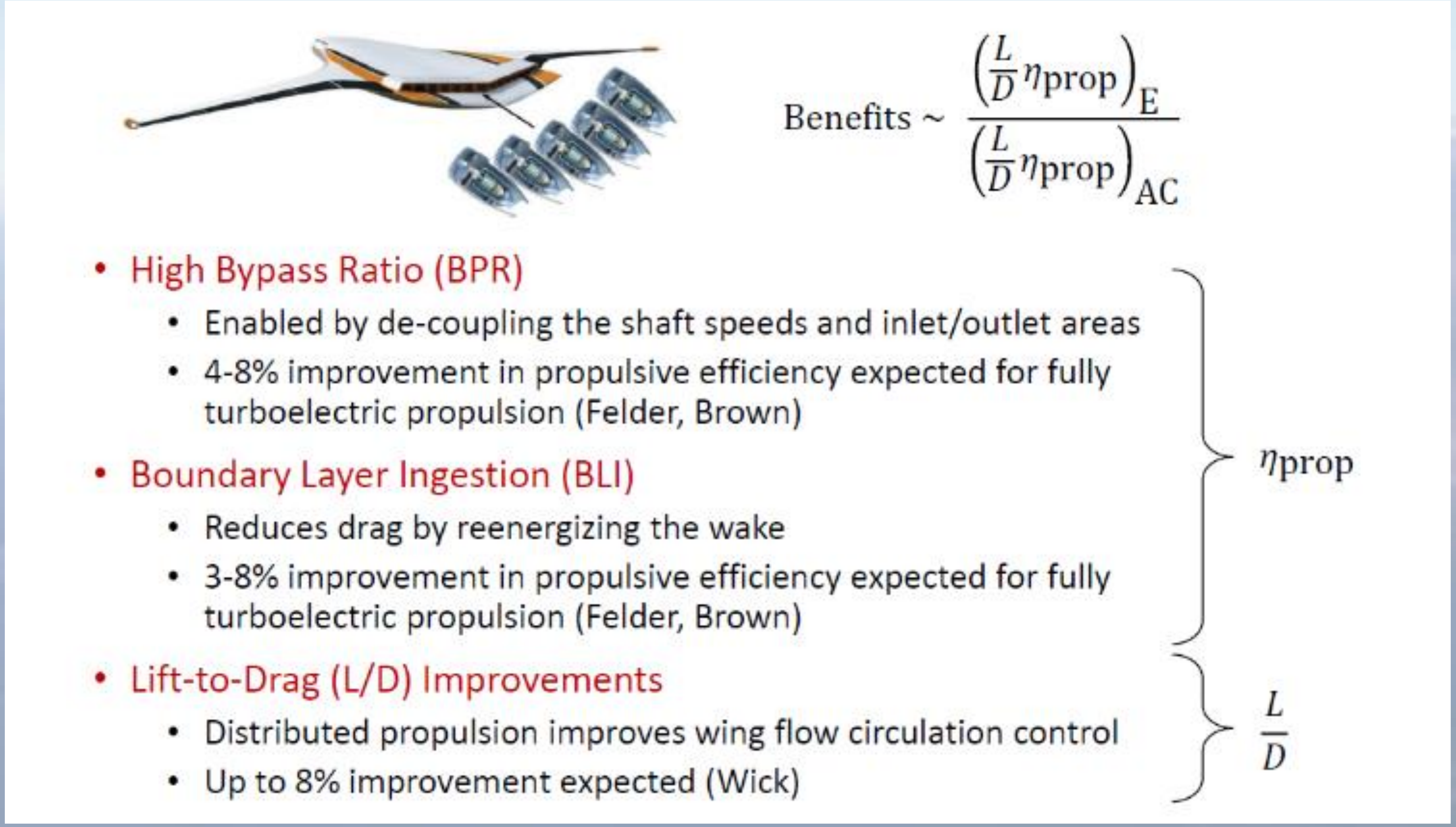
Why Electric Aero-Propulsion?

- Why electric?
  - Fewer emissions
  - Quieter flight
  - Fuel savings
  - New mobility options
  - Better utilization of infrastructure



Electric Aero-Propulsion Benefits



$$\text{Benefits} \sim \frac{\left(\frac{L}{D}\eta\text{prop}\right)_{\text{E}}}{\left(\frac{L}{D}\eta\text{prop}\right)_{\text{AC}}}$$

- High Bypass Ratio (BPR)
  - Enabled by de-coupling the shaft speeds and inlet/outlet areas
  - 4-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)
- Boundary Layer Ingestion (BLI)
  - Reduces drag by reenergizing the wake
  - 3-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)

ηprop

- Lift-to-Drag (L/D) Improvements
  - Distributed propulsion improves wing flow circulation control
  - Up to 8% improvement expected (Wick)

$\frac{L}{D}$

(Felder and Brown, NASA)

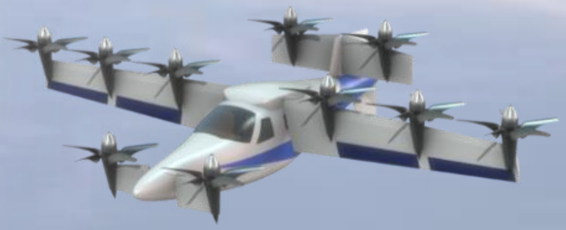
System Level Benefits Depend on Component, Powertrain, and Vehicle Optimization

Markets

- NASA is investing in research to enable Electrified Aircraft Propulsion (EAP).
  - NASA is working across a range of markets
  - The overarching strategy is to create enabling technology, demonstrate this technology in flight-test vehicles, and transfer the knowledge to industry for future products
  - Electrified aircraft propulsion has varying impact on air vehicle design depending on the key requirements of the market that the vehicle is intended to serve

Market: National/International

Impact: Fuel Burn/Emission Reduction



Market: On demand mobility

Impact: New mobility capability

Market: Regional

Impact: Revitalization of smaller routes

Electrified Aircraft Propulsion (EAP) – a 60,000 foot Perspective

(a range of vehicles and 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 on informing standards, regulations & design tools		NASA focus on 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

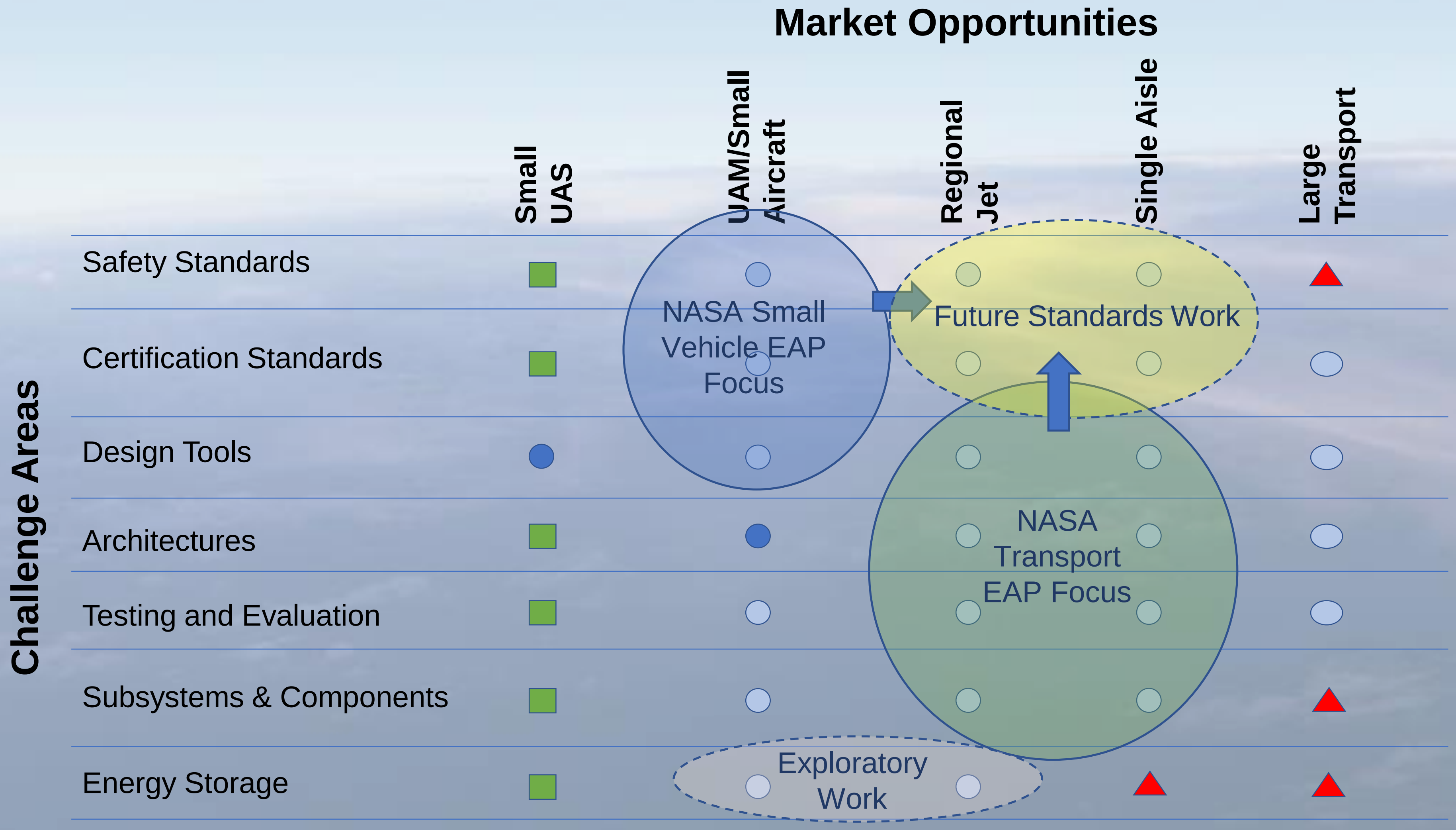
Transport Scale EAP

Energy & cost efficient, transport aviation

Leverage learning at smaller size to inform scale-up

Fundamental challenges span range of sizes

EAP Challenges Across Multiple Vehicle Classes



Market Opportunities

Challenge Areas

	Small UAS	UAM/Small Aircraft	Regional Jet	Single Aisle	Large Transport
Safety Standards	🟩	○	○	○	🔺
Certification Standards	🟩	○	○	○	○
Design Tools	●	○	○	○	○
Architectures	🟩	●	○	○	○
Testing and Evaluation	🟩	○	○	○	○
Subsystems & Components	🟩	○	○	○	🔺
Energy Storage	🟩	○	○	🔺	🔺

NASA Small Vehicle EAP Focus

Future Standards Work

NASA Transport EAP Focus

Exploratory Work

🟩 Existing or within reach

● Industry on track

○ Industry needs help

🔺 Significant need

EAP Ecosystem

	Electrical Energy Production	Electric Distribution	Energy Storage	Integrated Designs	System Testing & Evaluation	Certification	End User/ Buyer
DoD				✓	✓		✓
DOE	✓	✓	✓				
ARPA-E	ASCEND REEACH	CIRCUITS BREAKERS	✓				
FAA						✓	
NASA	Turbogen SOFC	Fault and Thermal	✓ SPACE	✓	✓	Flight Demos	
Engine Companies				✓	✓		
Airframers				✓	✓		
Operators							✓
Energy and Transport Industry	✓	✓	✓				

NASA Programs and Electrified Aircraft Content

Advanced Air Vehicles Program (AAVP)

Revolutionary Vertical Lift Technologies
<1MW

Advanced Air Transport Technologies
>1MW

Airspace Operations and Safety Program (AOSP)

Integrated Aviation Systems Program (IASP)

Flight Demonstrations & Capabilities
UAM
X-57
EPFD

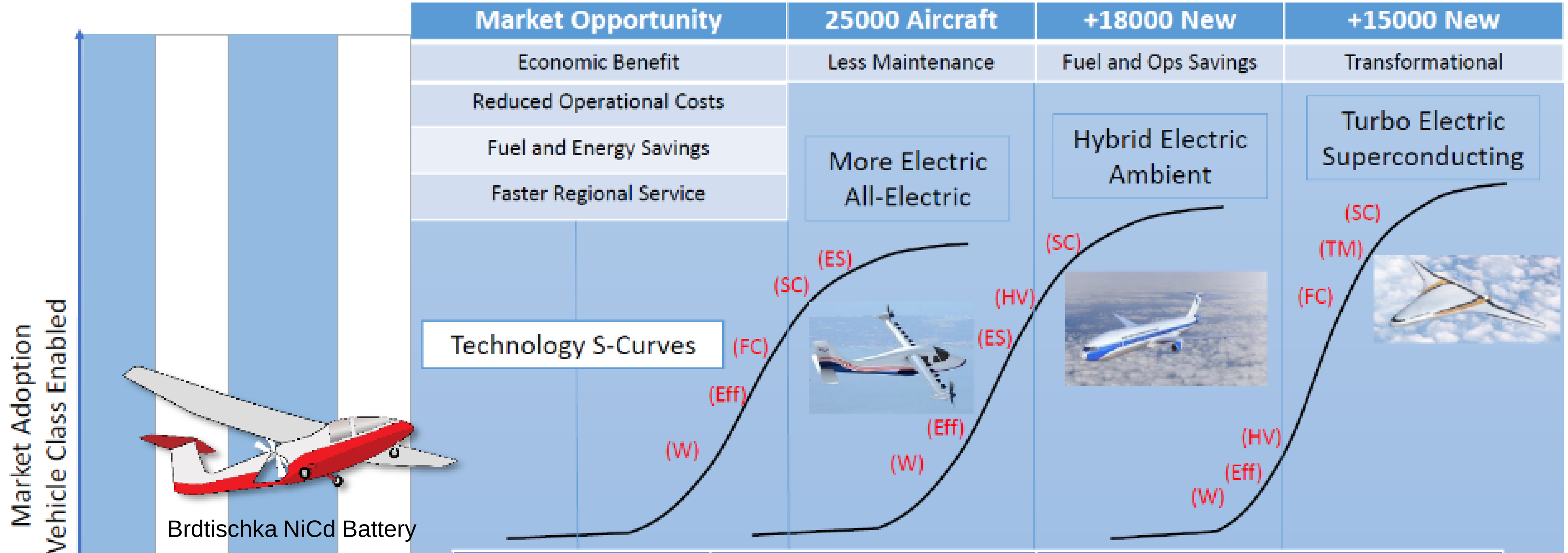
Transformative Aeronautics Concepts Program (TACP)

Transformative Tools & Technologies
Convergent Aeronautics Solutions
ULI

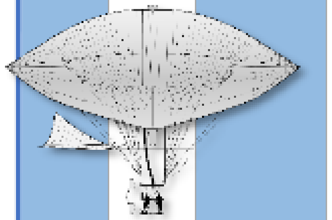
R&D is managed by identifying and seeking to overcome Technical Challenges

Technology Adoption S-Curves

Market Opportunity	25000 Aircraft	+18000 New	+15000 New
Economic Benefit	Less Maintenance	Fuel and Ops Savings	Transformational
Reduced Operational Costs			
Fuel and Energy Savings			
Faster Regional Service			



Brdtischka NiCd Battery



Tissandier Electric Motor Airship

Barrier	Why is this hard?	Why is this worth the investment?
Weight **(W)**	High power conductors are heavy	Light-weight components required for flight
Efficiency **(Eff)**	Requires high frequency/cryogenics	Reduces fuel required and thermal rejection load
Energy Storage **(ES)**	Only improves 2-6% / year	Directly impacts range and payload
High Voltage **(HV)**	Partial discharge at altitude	Enables flight-weight powertrain
Thermal Management **(TM)**	Low grade heat entrapment	Enables electric powertrain in composite body aircraft
Flight Controls **(FC)**	Mixed frequency integrated systems	Enables maximum performance and safety
Safety and Certification **(SC)**	Lack of flight history	Required for commercial operations

1883 1973 2000 2015 2025 2035 2045

Research addresses weight, efficiency, thermal, and fault management technology barriers.

Technology Maturation

Advancing Technical & Integration Readiness

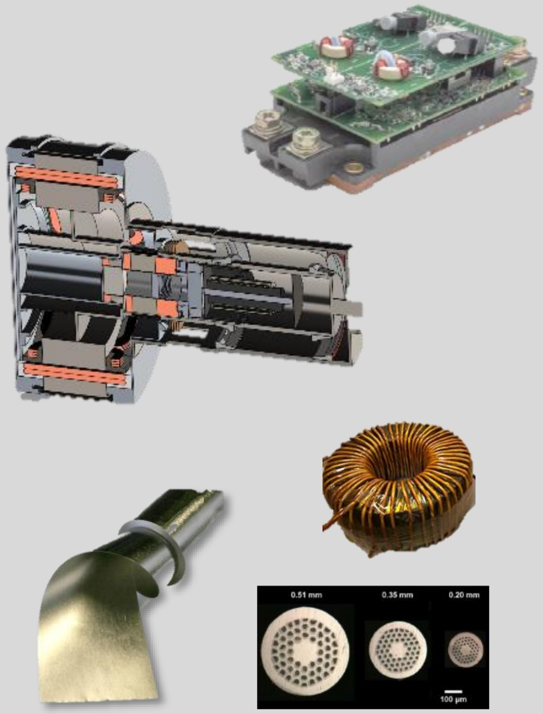
1

- Concept Vehicles
- Technology Gap Assessments
- Key Performance Parameter Identification
- Market Research
- FMECA Studies

TRL 1-2

2

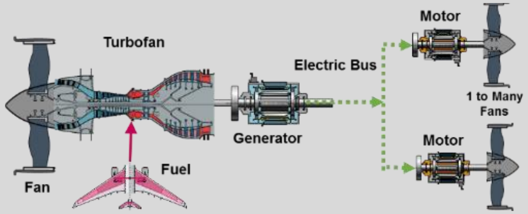
- Subsystems
- Components
- Devices
- Enabling Materials

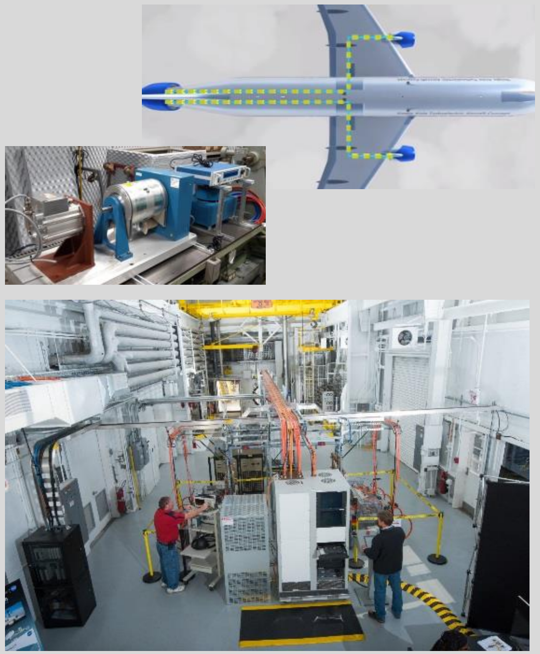


TRL ~3

3

- Ground Testing
- Integrated systems





TRL ~4

4

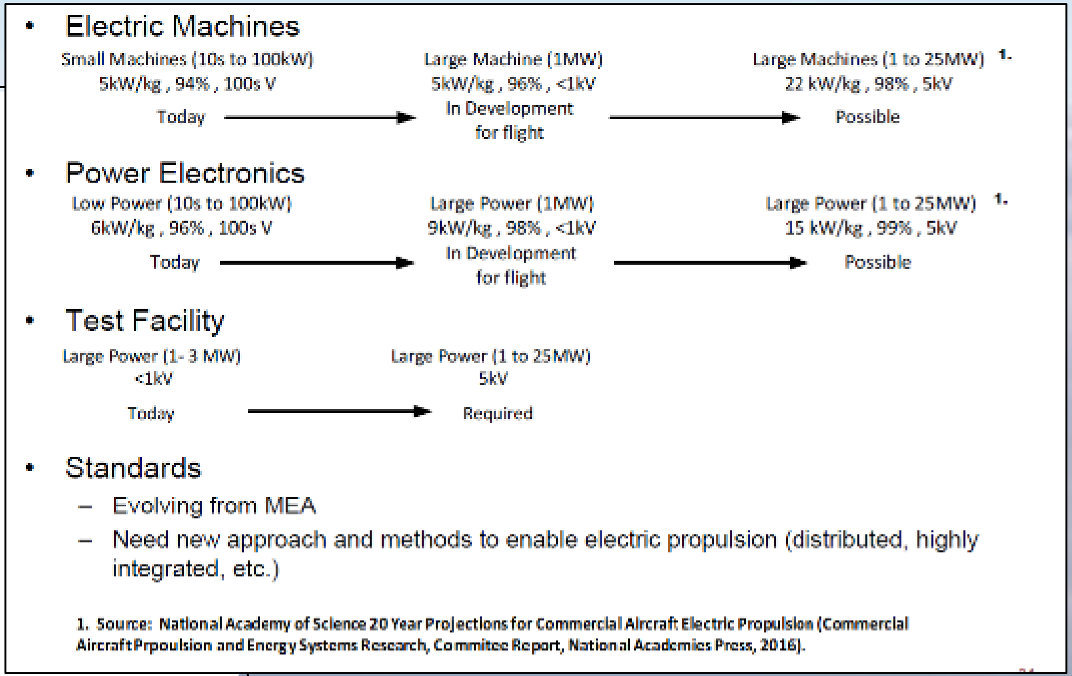
- Flight Experiments in relevant environment
- UAM Grand Challenges

- Key data informing product decisions
- Knowledge to support certification
- Learning to inform further fundamental research

TRL 5-6

Maturing System Level Benefits

- **BLI Power Saving Coefficient 15.8%** (($HP_{BLI} – HP_{Freestream}$)/ $HP_{Freestream}$)
- **Significant reduction** in **system fuel burn benefits** versus earlier results
  - **2.6% reduction in start of cruise (SOC) TSFC**
  - **2.7% reduction in economic mission block fuel**
  - **3.4% reduction in design mission block fuel**
  - Results are in comparison to advanced conventional configuration
- **Fuselage propulsor details**
  - Only a portion of the fuselage kinetic energy defect is ingested
  - BLI propulsor placed at most aft fuselage position
  - Driven by an all-electric motor with max power of 3500 HP
  - Electrical system modeled assuming ~12% total system losses
- **Partially turboelectric system is not a large weight penalty**
  - Downsizing of underwing engines enabled by turboelectric offsets the weight addition of electrical components and tailcone propulsor
- **Cable size/weight can become prohibitive if onboard voltage too low**
- **Electric system specific power based upon current AATT NRA efforts**



- Electric Machines

Small Machines (10s to 100kW)
5kW/kg , 94% , 100s V
Today → Large Machine (1MW)
5kW/kg , 96% , <1kV
In Development for flight → Large Machines (1 to 25MW) [1]
22 kW/kg , 98% , 5kV
Possible

- Power Electronics

Low Power (10s to 100kW)
6kW/kg , 96% , 100s V
Today → Large Power (1MW)
9kW/kg , 98% , <1kV
In Development for flight → Large Power (1 to 25MW) [1]
15 kW/kg , 99% , 5kV
Possible

- Test Facility

Large Power (1- 3 MW)
<1kV
Today → Large Power (1 to 25MW)
5kV
Required

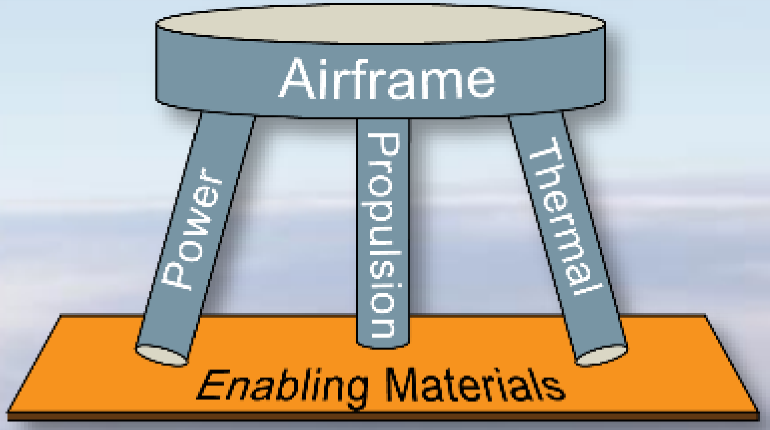
- Standards
  - Evolving from MEA
  - Need new approach and methods to enable electric propulsion (distributed, highly integrated, etc.)

1. Source: National Academy of Science 20 Year Projections for Commercial Aircraft Electric Propulsion (Commercial AircraftPrpoulsion and Energy Systems Research, Commitee Report, National Academies Press, 2016).

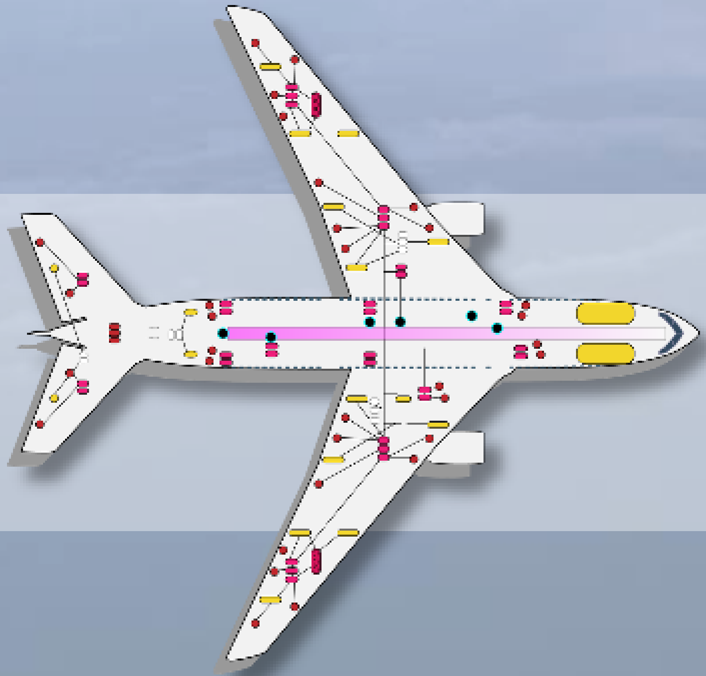
Increasing TRL, can decrease projected system benefits!

Power, Propulsion, Thermal, and Airframe Integration

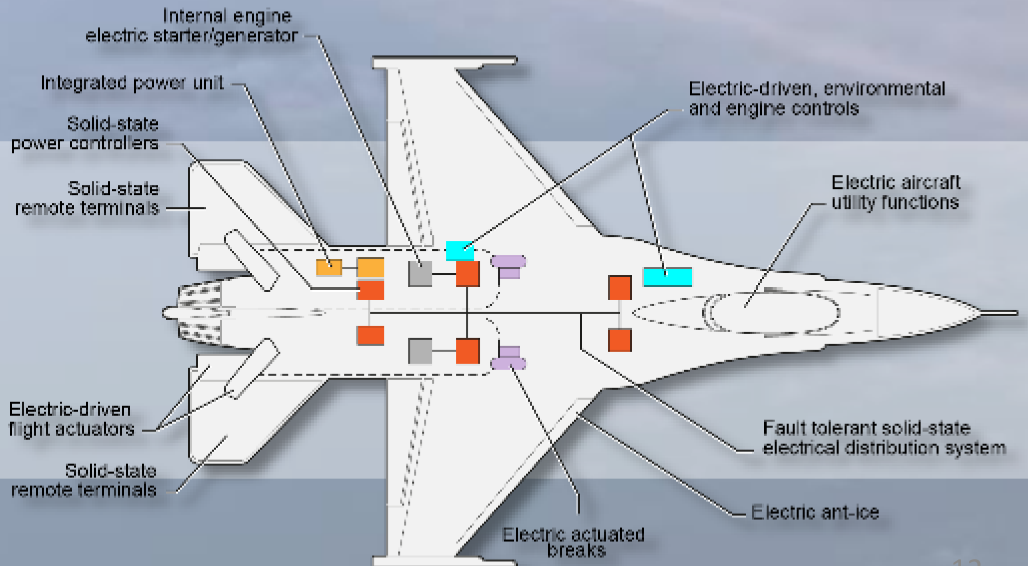
- **Challenge is to highly integrate all systems:**
  - improves fuel efficiency
  - reduces emissions
  - reduces low grade waste heat
  - reduces vehicle mass



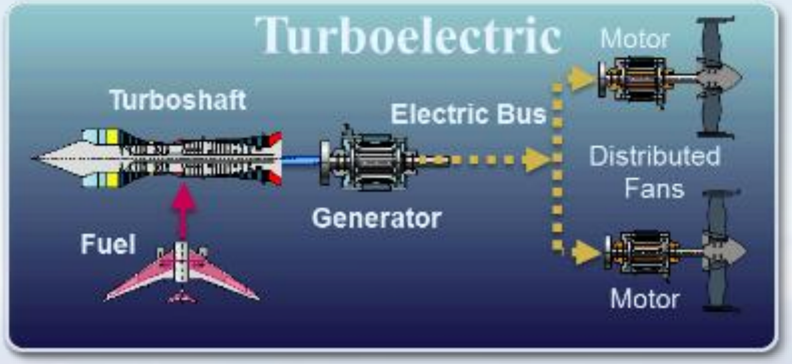
All components must integrate



PM and Induction Machine is a Near-term Technology



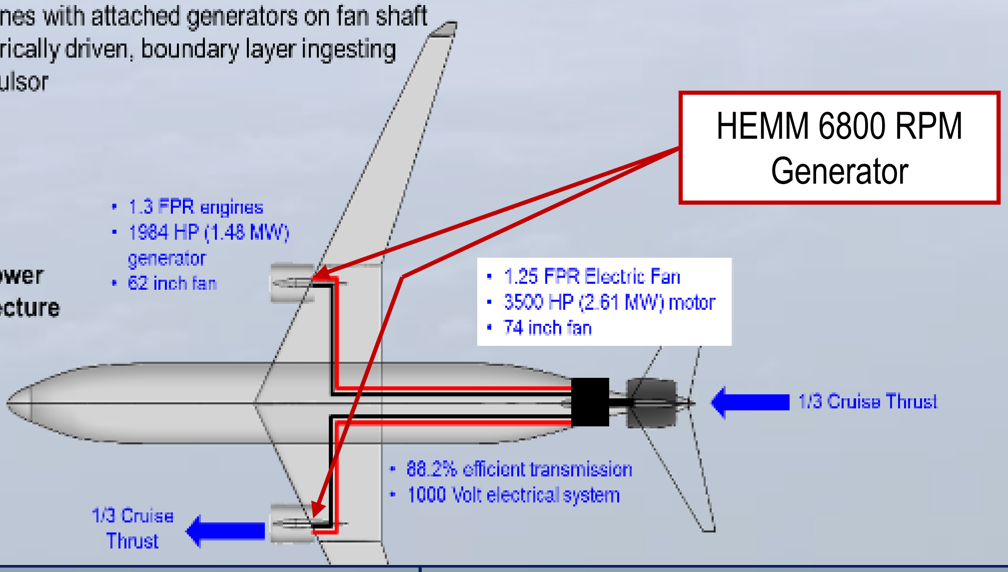
Electric Machine Integration



Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL)

- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted N+3 (Far-term) geared turbofan engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor

STARC-ABL Power System Architecture



HEMM 6800 RPM Generator

- 1.3 FPR engines
- 1984 HP (1.48 MW) generator
- 62 inch fan

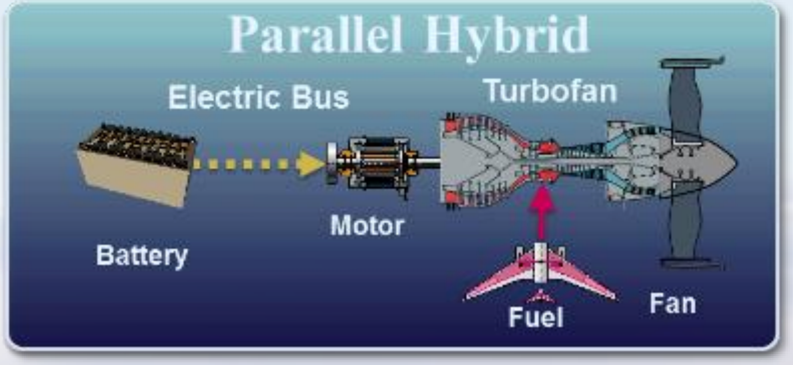
- 1.25 FPR Electric Fan
- 3500 HP (2.61 MW) motor
- 74 inch fan

1/3 Cruise Thrust

- 88.2% efficient transmission
- 1000 Volt electrical system

1/3 Cruise Thrust

Partial Turbo-electric Benefits From Efficient Generator

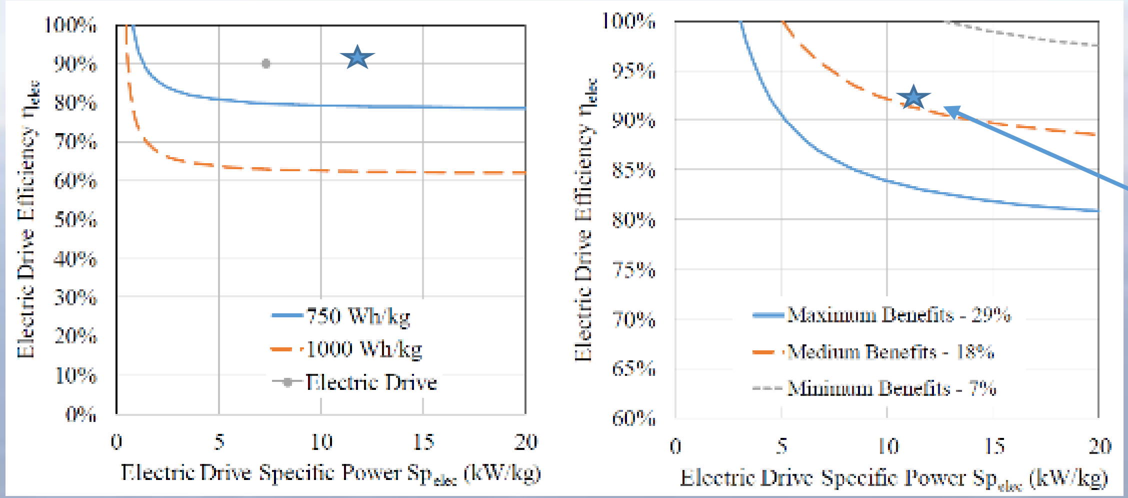


Parallel Hybrid Performance Improves with Energy Storage

Powertrain Technology Requirements

- MW-Scale Transport Class Powertrain Requirements:

Break-even Points

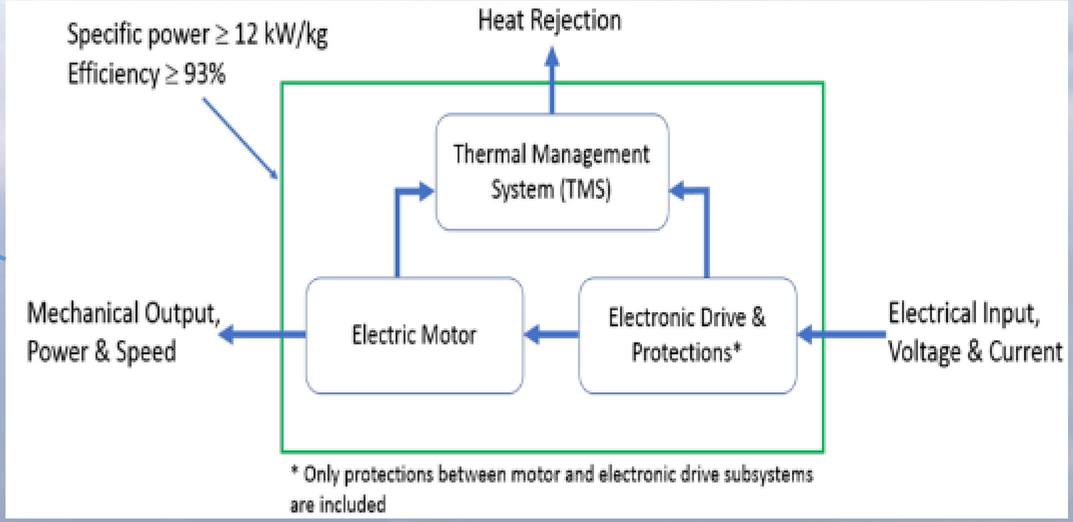


Parallel Hybrid

Turbo-electric

(Jansen, NASA)

ARPA-E ASCEND Powertrain



Specific power ≥ 12 kW/kg
Efficiency ≥ 93%

Heat Rejection

Thermal Management System (TMS)

Mechanical Output, Power & Speed

Electric Motor

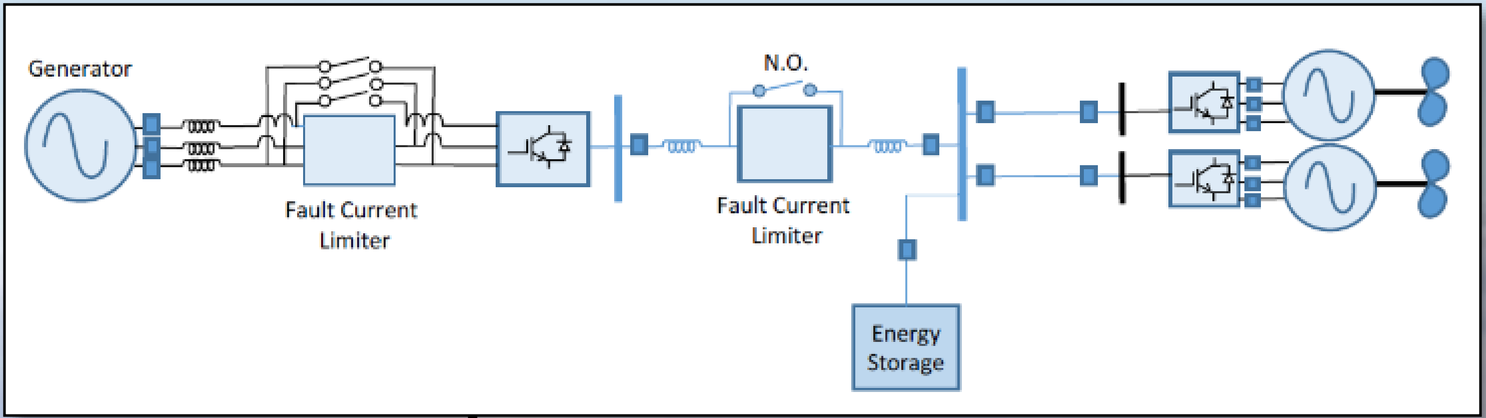
Electronic Drive & Protections*

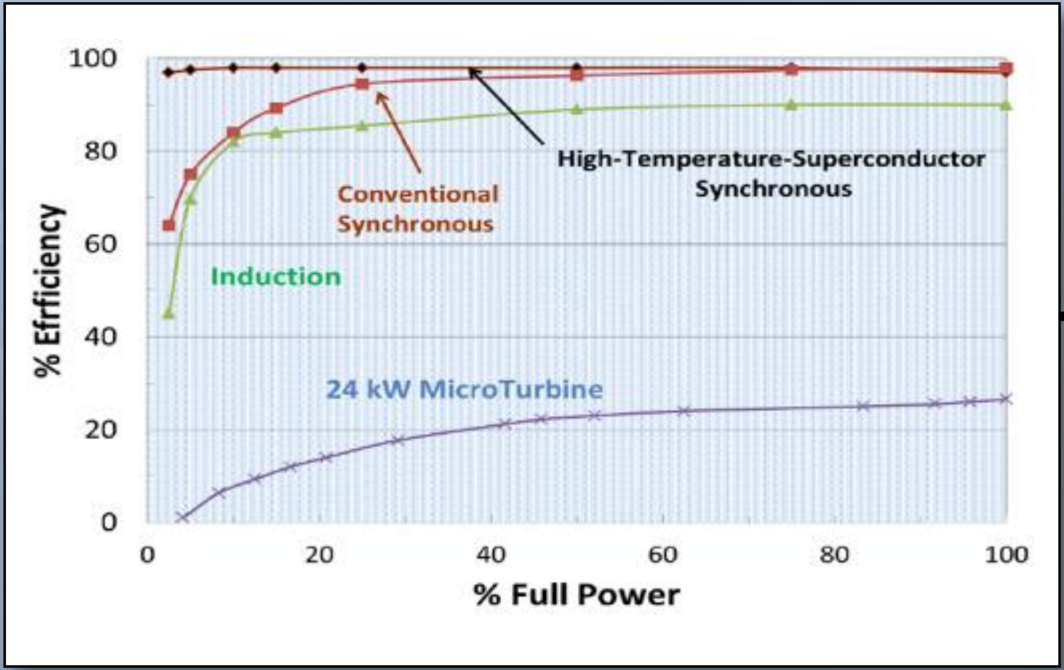
Electrical Input, Voltage & Current

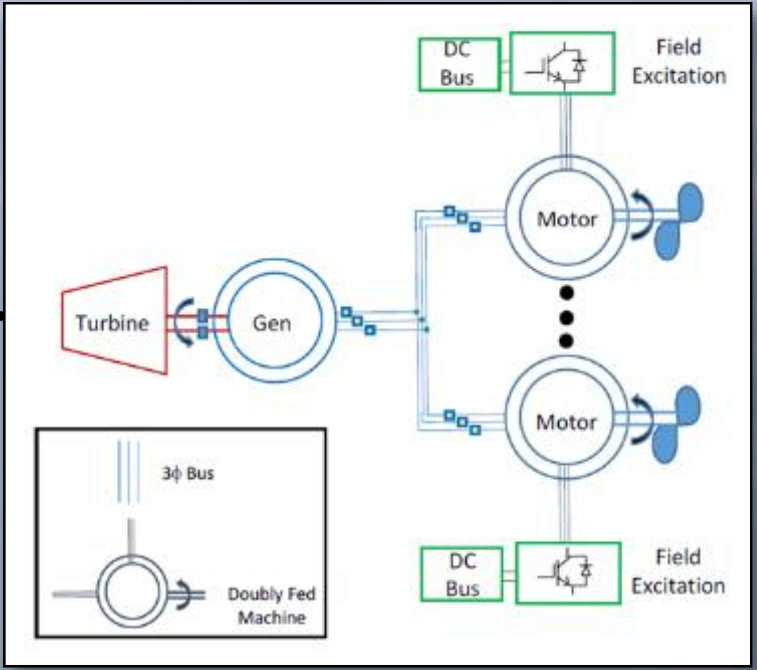
* Only protections between motor and electronic drive subsystems are included

Electric Propulsion Machine Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Single-fed Induction
- Double-fed Induction







(Beach, NASA)

MW Motor and Drive Development

NASA Sponsored Motor Research

- 1MW
- Specific Power > 8HP/lb (13.2kW/kg)
- Efficiency > 96%
- Awards
  - University of Illinois
  - Ohio State University

Ambient Motor Requirements

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

NASA Sponsored Inverter Research

- 1MW, 3 Phase AC output
- 1kV or greater input DC BUS
- Ambient Temperature Awards
  - GE – Silicon Carbide
  - Univ. of Illinois – Gallium Nitride
- Cryogenic Temperature Award
  - Boeing – Silicon CoolMOS, SiGe

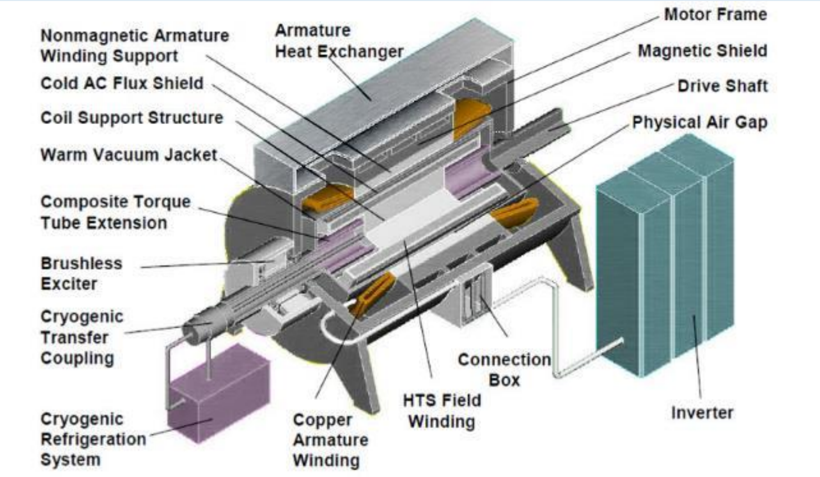
Ambient Inverter Requirements

Key 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

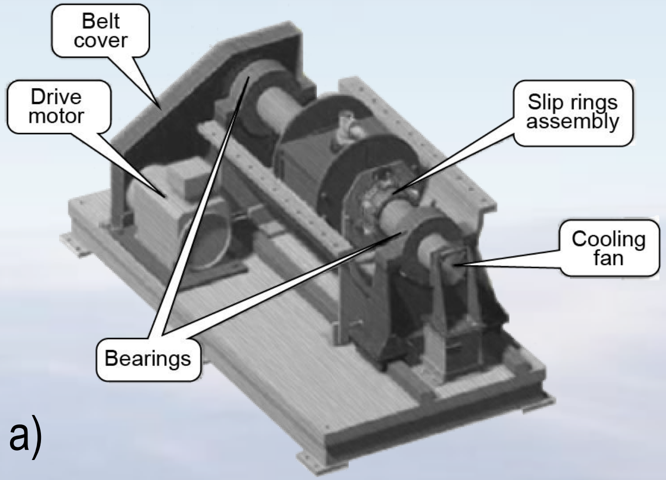
Cryogenic Inverter Requirements

Key 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

Related Prior DOE Effort and Recommendation

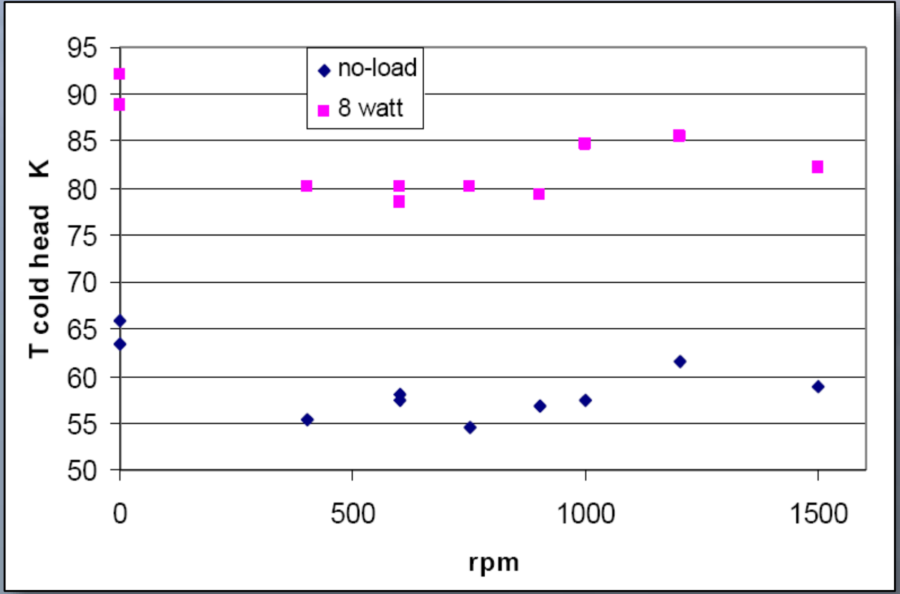


a)



b)

“**A pulse-tube cryocooler** is suitable for usage in a rotating environment. The demonstrated test rig allowed testing to 1500 rpm. There is no evidence that a pulse-tube based rotating cryocooler would not be successful at speeds exceeding 1500 rpm. Our belief is that the integration of the cryocooler into the rotor structure may be done for any rotational speed and such an integration will not increase the complexity of the rotor design.”

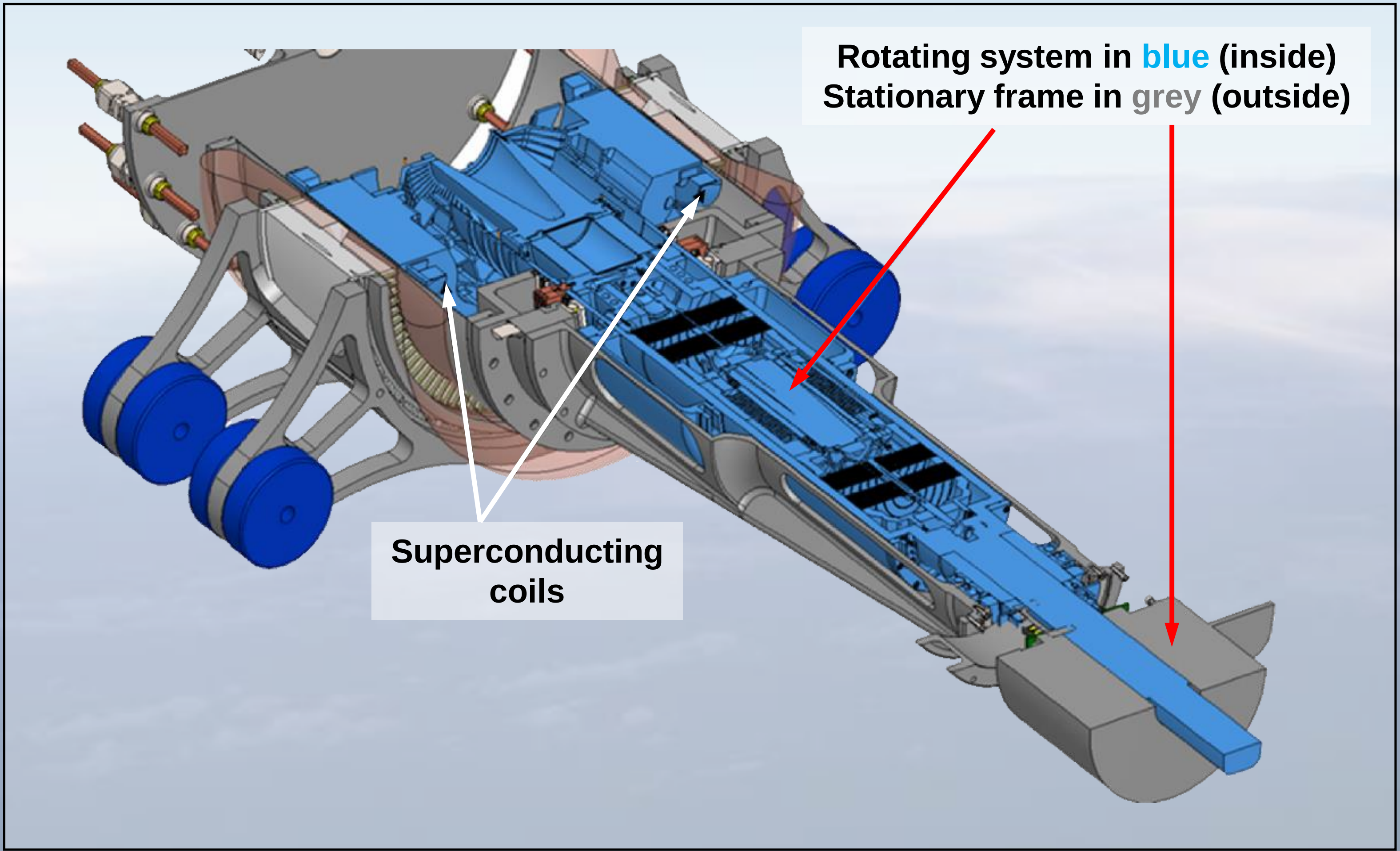


Development of Ultra-Efficient Electric Motors
April 2002- Sept. 2007
Reliance Electric Company
26391 Curtiss Wright Parkway, Suite 102
Richmond Heights, OH 44143
Date Published – May 2008

Prepared for the United States Department of Energy
Under Cooperative Agreement – No. DE-FC36-93CH10580
Baldor-DODGE-Reliance

Challenge: Design high aspect ratio symmetrical cryocooler for higher speed operation.
Solution: Redlich Alternator with Single-Stage Pulse-Tube Cooler

HEMM Thermal Loads (Cryogenic and Ambient)



Rotating system in blue (inside)
Stationary frame in grey (outside)

Superconducting coils

Component	Loss (kW)
Electromagnetic Losses	9.3
Stator Core	3.9
Stator winding (I^2R)	4.6
Stator winding proximity	0.8
Rotor core	0.009
Rotor coils	0
Other Losses	4
Cryocooler Power	2
Bearings	1
Vacuum Seals	1
Total Losses	13.5
Total Losses(+20% margin)	16.2

Under 50W Cryogenic Heat Load Expected

MW Class Electric Machine Testing

Problem

Efficient (>96%), high specific power density (>13 kW/kg) MW electric machines are an enabling technology for electric propulsion. NRA developed concepts which have shown great promise on paper are now being tested. These cutting edge machines, built at the University of Illinois and the Ohio State University have proven to be difficult to realize in hardware as the mechanical design implementation processes in first prototypes uncovered issues with design, fabrication and assembly.

Objective

Complete testing of both the Ohio State University and University of Illinois Electric MW machines and determine their true performance metrics.

Prior Progress

- Ohio State University has tested their inside-out external rotor induction machine to 440 kW at 1800 rpm and set a world record for power density at 4.5 kW/kg.
- The University of Illinois rotor was send back to the magnet vendor to be rebuilt a second time to correct for errors in the Halbach topology and poor magnet to shell adhesion. All other machine components are acquired, built, and ready for testing.

FY2020 Progress

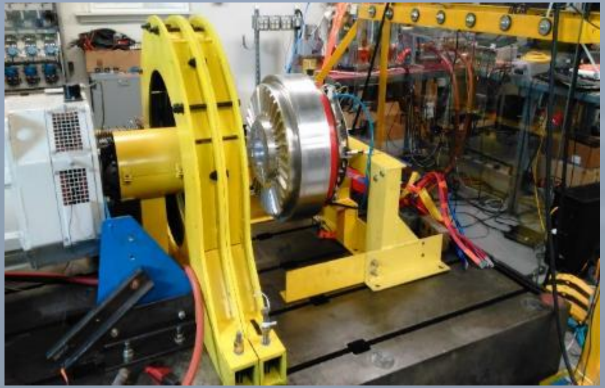
- Ohio State University, after a motor support failure during testing, has rebuilt their machine, made improvements to the electrical bus and inverter stacks, and modified the control system to better handle motor control under little or no mechanical load.
- Illinois has received their rotor from the magnet vendor and has completed machine assembly. The fundamental functionality of the stator is currently being assessed. This month (Oct '20), the motor will be slow speed tested at Illinois and then shipped to Collins Aerospace for load testing.

Significance

NASA NRA projects to develop novel MW class electric machines which can achieve aggressive performance metrics predicted as needed for transitioning to electrified aircraft propulsion moved closer to full speed and full load tests. These MW machines are pushing prior state-of-the-art power densities four fold and doubling typical efficiencies.

U. Illinois Composite-wrapped Halbach Array Rotor

U. Illinois assembled MW Machine ready for testing

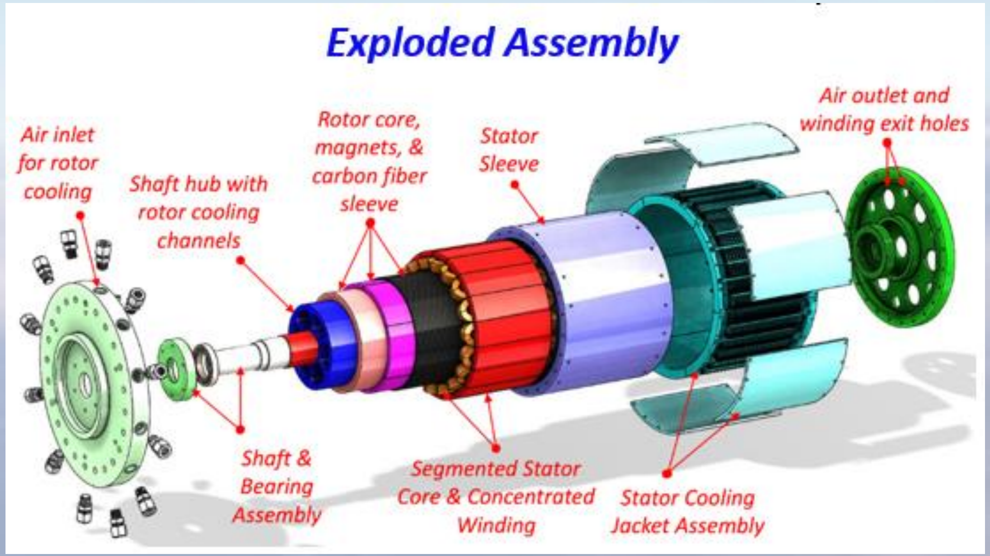


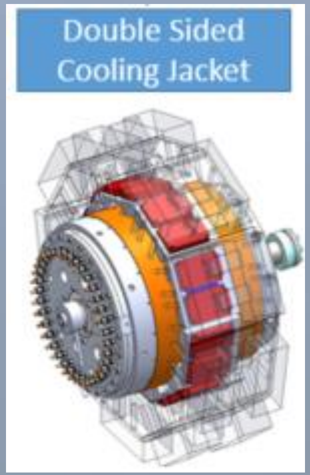
OSU MW motor connected to electric load machine

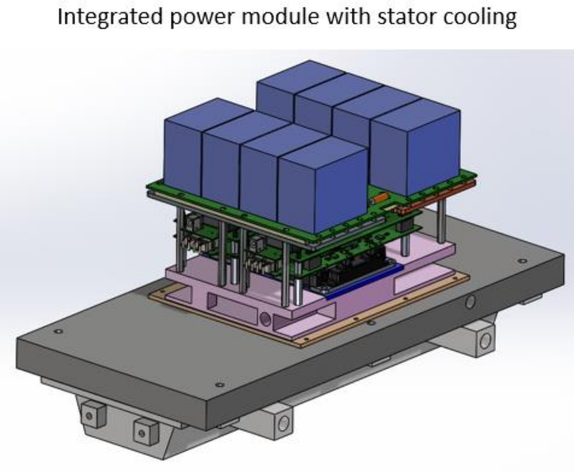
The Ohio State University ULI MW Motor Development

Integrated 1 MW Permanent Magnet Machine Design

- 200 kW risk reduction unit completed in April 2020
- Tested 200 kW for proof of concept
- MW development to be completed in Sept. 2021
  - Includes integration & system studies, along with power management
  - Advanced thermal management approach
  - Investigating advanced energy storage (batteries)
    - Characterizing commercial cells, including Li-Sulfur
    - Embedded redundancy/fault-tolerant functionalities
    - Self-diagnosis
  - Investigating advanced control concepts
- Culminate with testing at NASA's NEAT facility in 2022







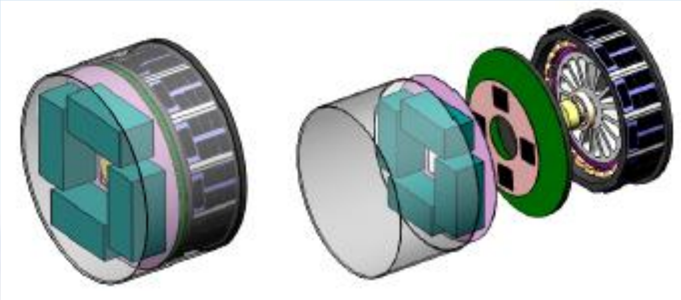
RVLT Motor Design Efforts – Goal: Improved Motor Reliability

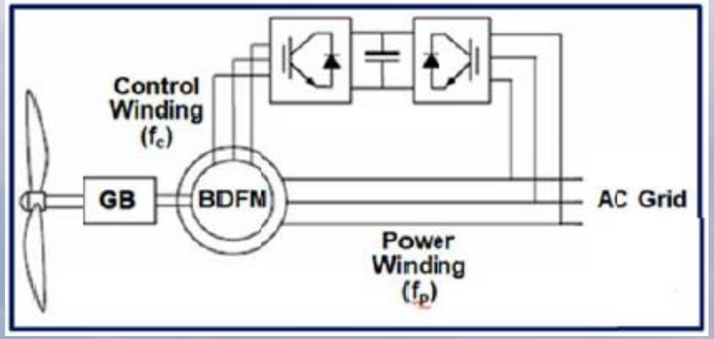
- **External Efforts[1]: 2 Contract Funded Design**

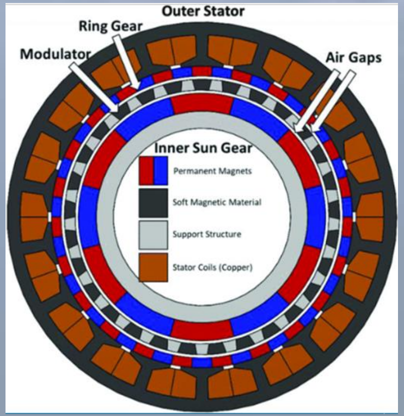
1) University of Wisconsin via OSU ULI
    - Integrated, fault-tolerant motor/drive design for RVLT quadcopter
2) Balcones Technologies vis Phase III NASA STTR
    - Developing Brushless Doubly-Fed Machine (BFDM) design for RVLT-class vehicle (100-200 kW)

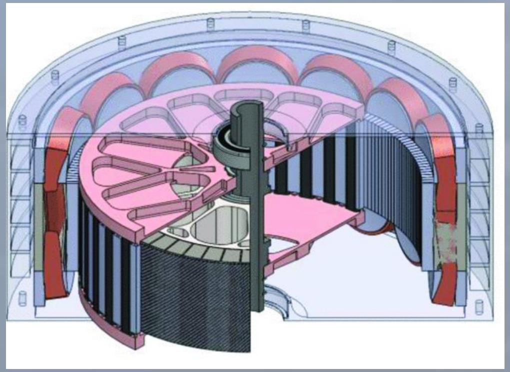
- **Internal Efforts[2]:**

1) Magnetically Geared Motors and Novel Designs
    - Exploring trade space of reliable motor topologies for UAM applications using in-house codes.
      Example: Outer Stator Magnetically Geared Motor
2) Winding Reliability Model Development
    - Developing modeling and experimental capability to explore/predict winding reliability









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1. J. Swanke, T. Jahns, “Reliability Analysis of a Fault-Tolerant Integrated Modular Motor Drive (IMMD) for an Urban Air Mobility (UAM) Aircraft Using Markov Chains.” 2021 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS).
2. T. F. Tallerico, Z. A. Cameron, J. J. Scheidler and H. Hasseeb, "Outer Stator Magnetically-Geared Motors for Electrified Urban Air Mobility Vehicles," 2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), New Orleans, LA, USA, 2020, pp. 1-25.

Low AC-loss Superconducting Cable Technology for Electric Aircraft Propulsion

Problem

Low AC loss superconducting cable development for the stators of motors and generators is one of the most essential technologies to enable us to develop NASA's turbo-electric propulsion for future aircraft.

Objective

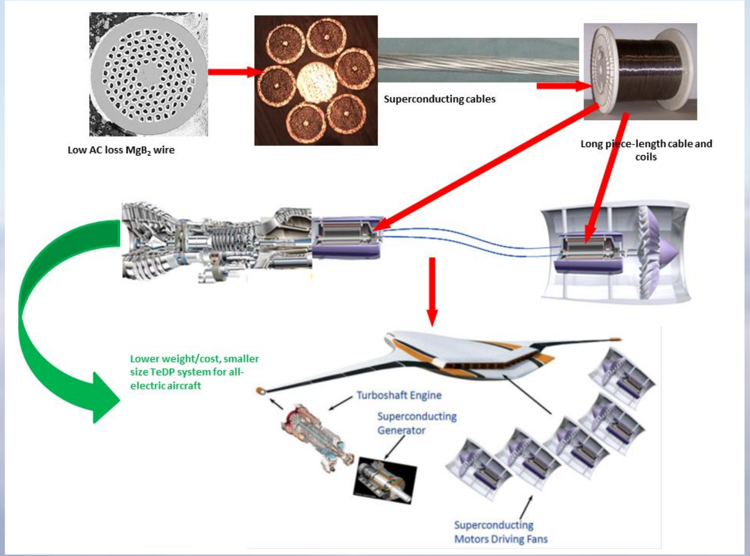
Design, fabricate and characterize new sets of MgB_2 superconductors with high superconductor current density, high superconductor fill factor, lower AC losses and in significant piece lengths (hundreds of meters). Cables will have low AC loss features: fine superconducting filaments (< 10 µm) and twisted strands.

Results

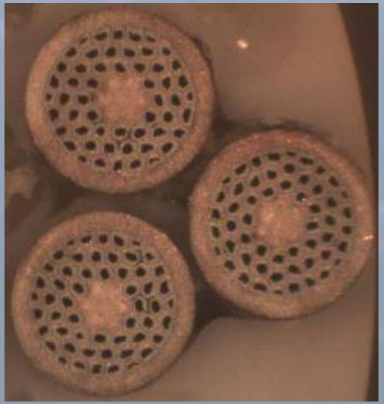
- Developed long length, low AC loss MgB_2 superconducting strands.
- Developed cables with improved cable engineering current density and with improved inter-strand contact resistance.
- Completed mechanical properties of MgB_2 cables.
- Analyzed superconductivity and AC losses of MgB_2 strands and cables.
- Completed a prototype stator coil (solenoid type) with MgB_2 cables.

Significance

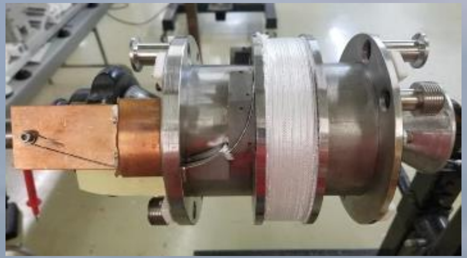
MgB_2 superconducting cable technology is the best route for producing conductors with higher current carrying capability and with significantly lower AC losses to enable more efficient stator configurations, resulting in reduced weight, size and cost of a turbo-electric distributed propulsion system for large transport aircraft.



Turbo-electric distributed propulsion system using SC motors and generators with low AC loss MgB_2 cables

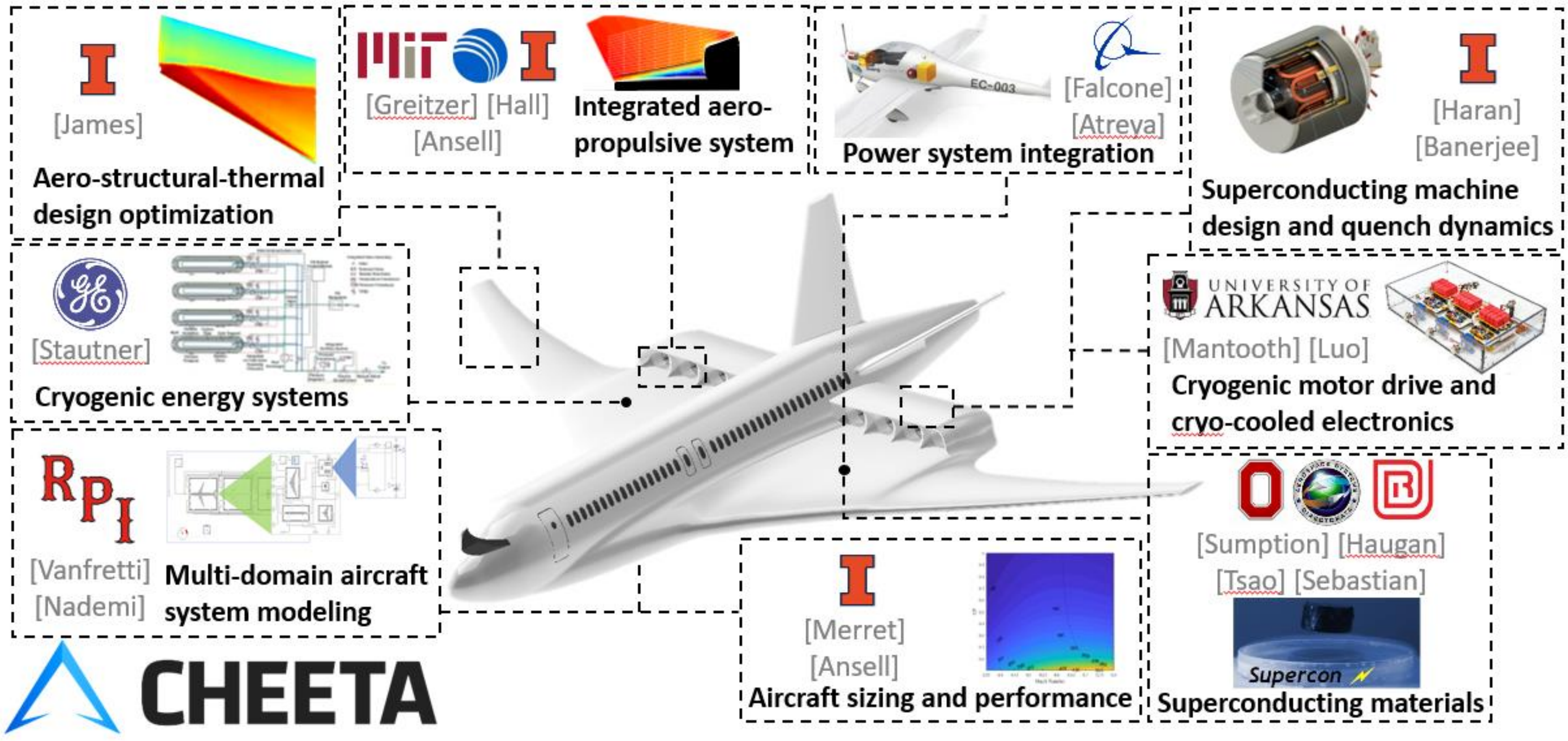


MgB_2 cables used for test coil



Test MgB_2 coil fabrication

University of Illinois NASA ULI Project



[James]

Aero-structural-thermal design optimization

[Greitzer] [Hall] [Ansell]

Integrated aero-propulsive system

[Falcone] [Atreya]

Power system integration

[Haran] [Banerjee]

Superconducting machine design and quench dynamics

[Stautner]

Cryogenic energy systems

[Mantooth] [Luo]

Cryogenic motor drive and cryo-cooled electronics

[Vanfretti] [Nademi]

Multi-domain aircraft system modeling

[Merret] [Ansell]

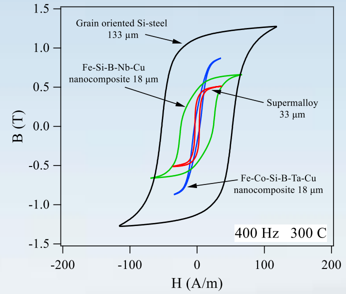
Aircraft sizing and performance

[Sumption] [Haugan] [Tsao] [Sebastian]

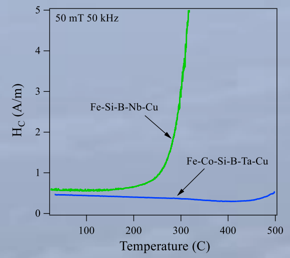
Superconducting materials

Alloy Development

High temperature nanocomposites



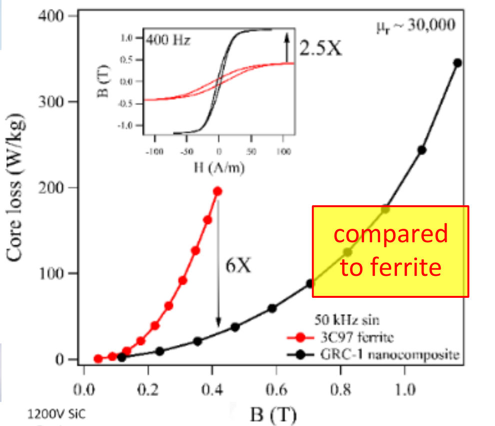
GRC alloy



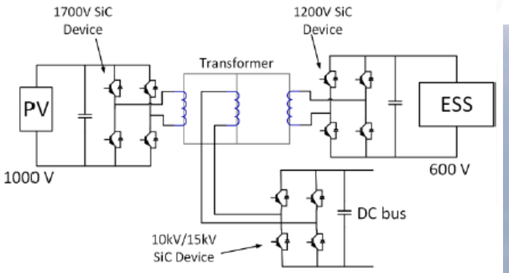
New alloy maintains room temperature performance of standard FeSi-based alloys, but extends useful range >300C

High permeability: choke/transformer

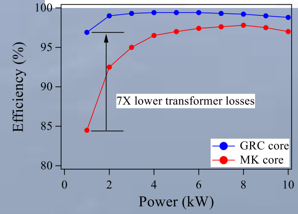
μ_r = 30,000



compared to ferrite



Three-Port Modular DC-DC Converter

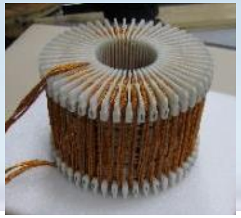


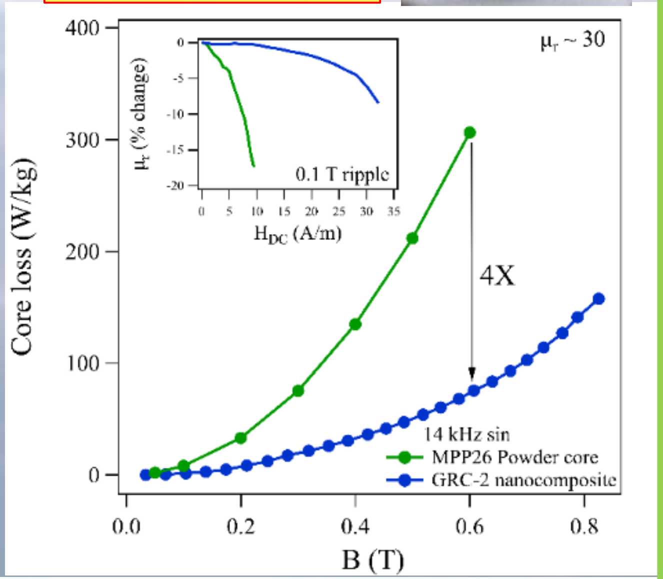
Not all commercial FeSi-based nanocomposites are high quality

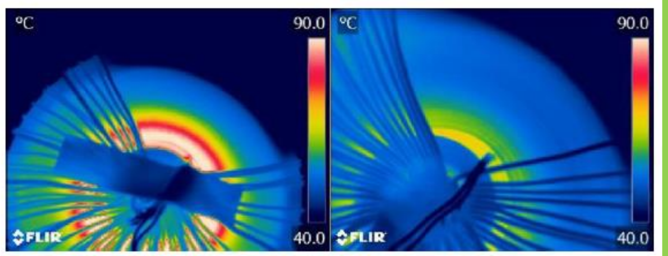
Low permeability: inductor

μ_r = 30 $L \sim \mu$

compared to best powder core material: better inductance linearity with bias and lower loss







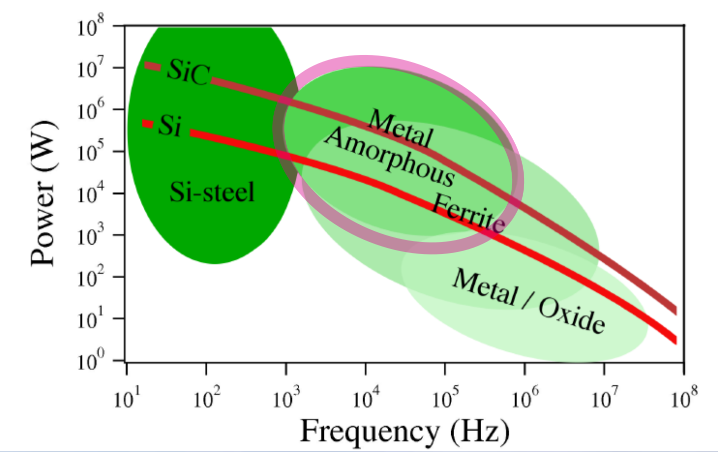
Spatially graded µ

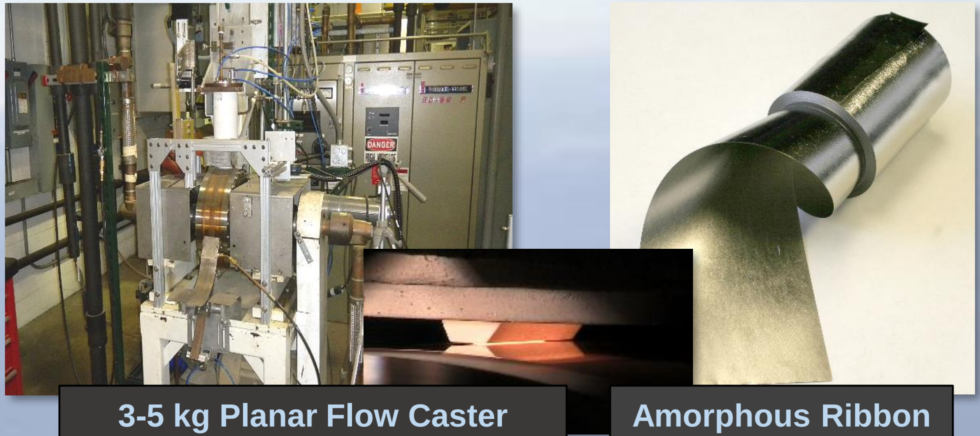
Byerly, et al. JOM **70** 2018

Alloys for both high and low permeability (µ) applications out-perform commercial soft magnetic materials in the 1-100 kHz range

GRC Soft Magnetic Core Development

- Targeting prototype core development for >10 kW power electronics
- Specialize in nanocomposite materials to leverage wide bandgap semiconductors in <1 MHz switching applications
- Able to process custom alloys from raw materials to wound cores

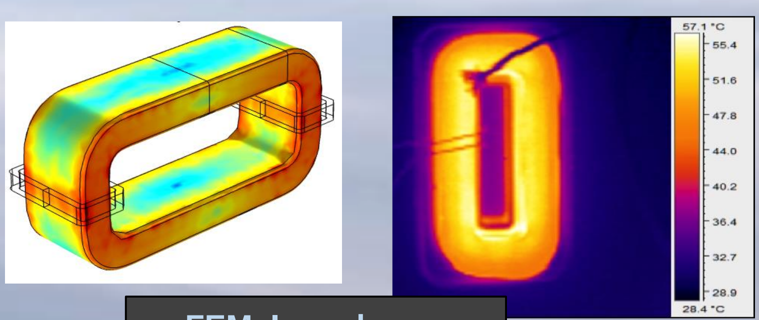




3-5 kg Planar Flow Caster

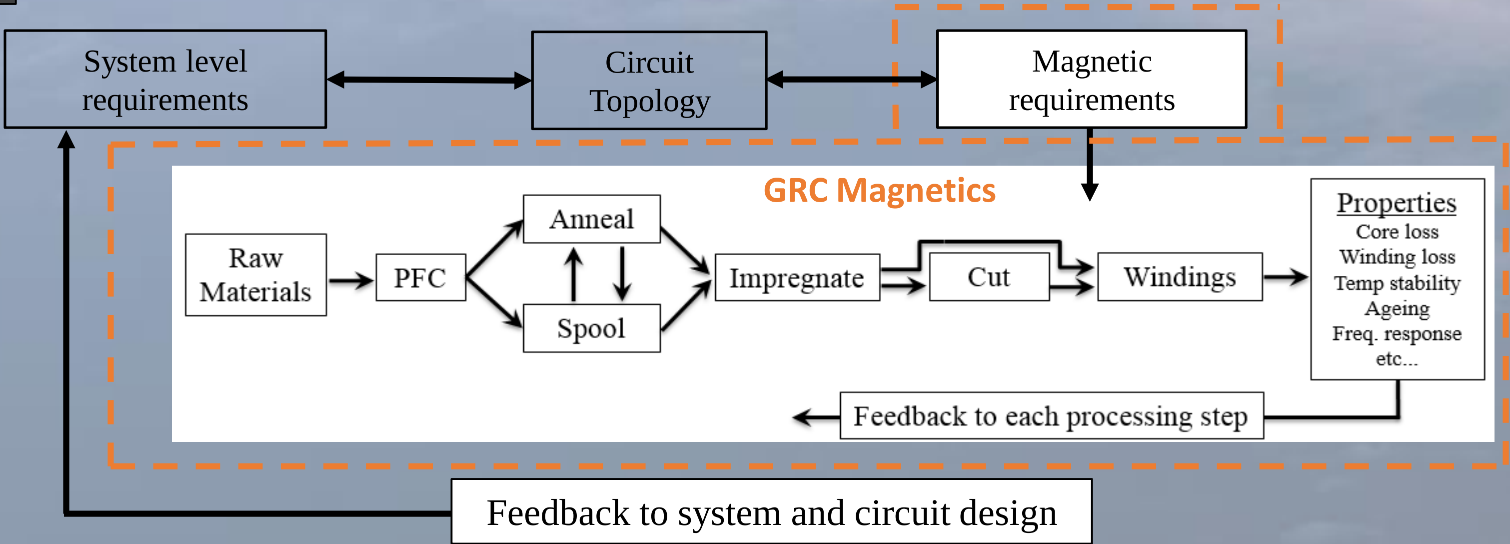
Amorphous Ribbon

Annealed, Impregnated, Powder Coated Core



FEM, Impedance, Losses

- Able to assist with (or develop) magnetics design with power electronic designers
- Can tune core permeability by induced anisotropy over wide range, enabling <u>gapless</u> cores with low loss
- Design iteration is key to success



System level requirements

Circuit Topology

Magnetic requirements

GRC Magnetics

Raw Materials

PFC

Anneal

Spool

Impregnate

Cut

Windings

Properties
Core loss
Winding loss
Temp stability
Ageing
Freq. response
etc...

Feedback to each processing step

Feedback to system and circuit design

Ultra-Light Highly Efficient MW-Class Cryogenically Cooled Inverter

Problem

Cryogenically cooled inverter development for improving power electronics converter performance is one of the most essential technologies to enable us to develop a complete superconducting machine driving system to achieve revolutionary advances in energy efficiency and environmental compatibility for future electric aircraft.

Objective

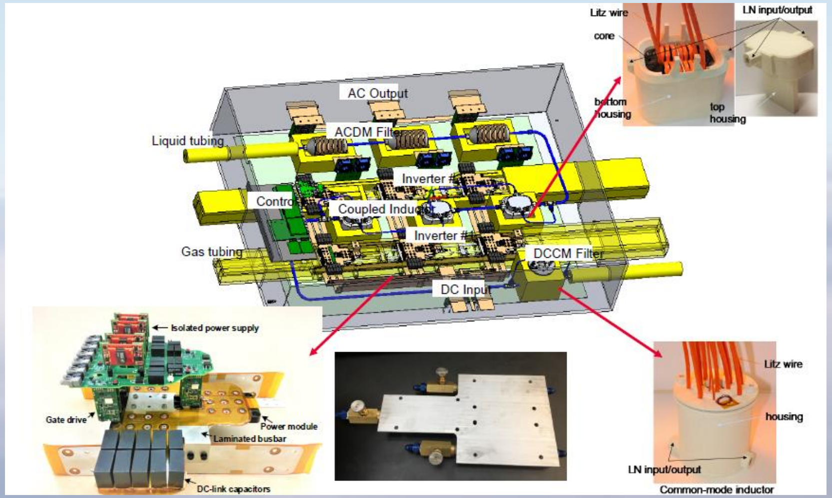
Design, build, test and demonstrate a cryogenically-cooled MW inverter system to achieve the technical objectives of 99.3% efficiency and 26 kW/kg specific power and meet the requirements of power quality and electromagnetic interference (EMI) compliance.

Results

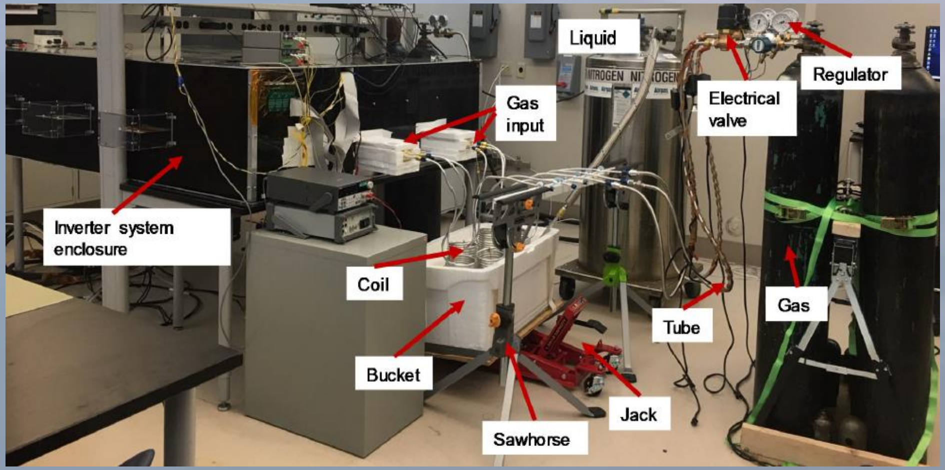
- Designed and built 1 MW protype consisting of two paralleled 500 kW inverters, and completed dual liquid and gaseous nitrogen cooling system to accommodate the requirements of power stage and filters.
- Successfully tested at 1 kV DC bus voltage input and rated 1 MVA power with cryogenic cooling. AC output current showed good waveform quality with low THD. The currents between two 500 kW inverters were well balanced as well.
- At half power, the tested efficiency of power stage was 99.2%, and the efficiency with both power stage and filter was 98.9%.
- For lack of suitable Si (or GaN) modules for cryogenic temperature, strategically decided to use SiC MOSFET and this change caused slower switching (i.e., increasing filter weight), resulting in the specific power of 18 kW/kg.
- Published six *IEEE journal* papers and 21 renowned conference papers.

Significance

- Enable MW-level power conversion and interfacing with superconducting machines.
- Achieve ultra-high efficiency and specific power over the state of art technology.
- Demonstrate the scalability for large commercial air transport vehicle application.



Integrated inverter system



1 MW inverter testing setup with cryogenic cooling

SiC Lightweight Inverter for Megawatt Power Phase 4

Problem

High voltage 2 kV+ DC system enables lightweight high-efficiency power distribution systems for future hybrid electric aircraft. High voltage altitude capable inverters are essential for such a system.

Objective

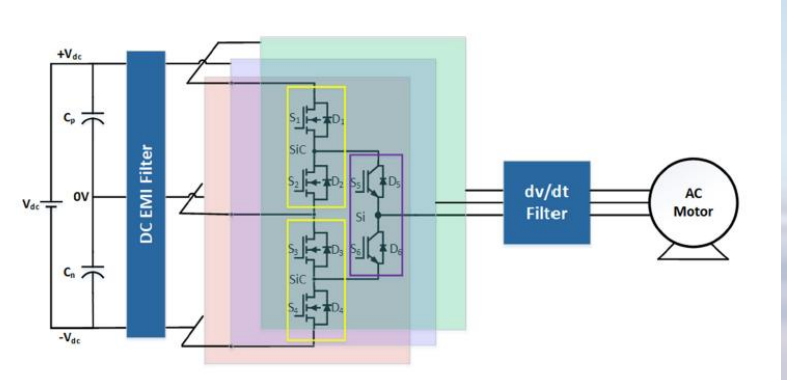
- Develop and demonstrate high voltage SiC MW inverter with altitude capability.
- Retire risks for 2 kV+ DC system for 30+ kft altitude at ambient temperature.
- Retire vibration risk.

Results

Subtask	Status	Deliverable
Develop and test altitude capable components	Complete	Components passed altitude screening test and ready for inverter build
Gen3 altitude ready inverter design	Complete	Inverter design ready to be built
Sea level test of Gen3 inverter	Complete	• Validate power capability of Gen3 inverter • Capture EMI performance of Gen3 inverter
Altitude chamber test of Gen3 inverter	In progress, testing at altitude	• Establish testing capability for high voltage inverter at altitude • Validate altitude capability of Gen3 inverter
Altitude integration test at NASA NEAT	In progress, in preparation	Gen3 inverter tested with motor generator at NEAT
Gen4 flight ready inverter design	In progress	Design of Gen4 inverter to meet shock and vibration and EMI requirements

Significance

Components are developed for high voltage altitude capable inverter. Ongoing work continues to retire risks of employing high voltage inverter in future hybrid electric aircraft.

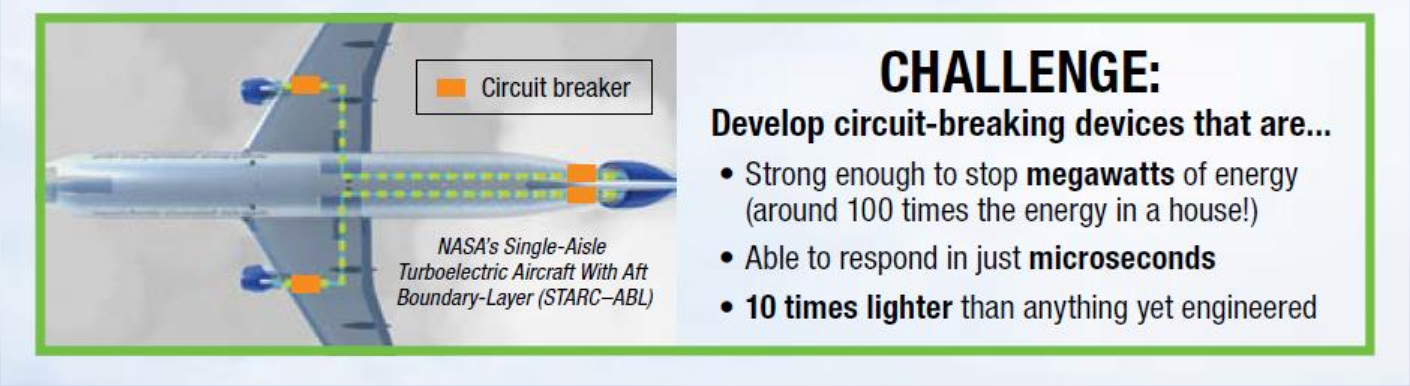


"SiC+Si" hybrid three-phase 3L-ANPC inverter

Gen3 inverter in altitude chamber

dv/dt filter inductor tested for altitude

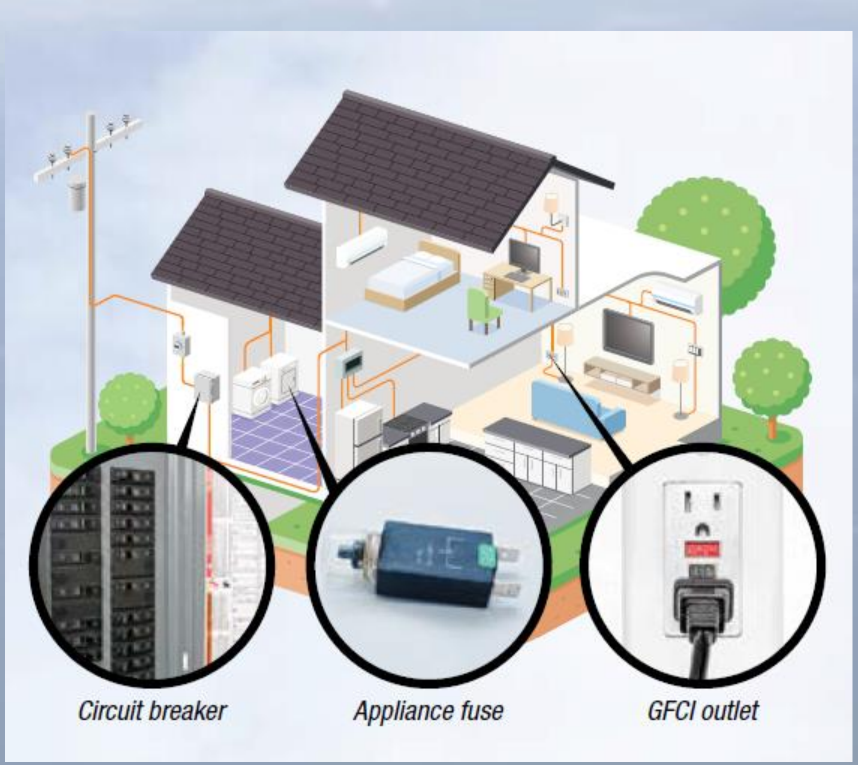
Fault Management Challenge

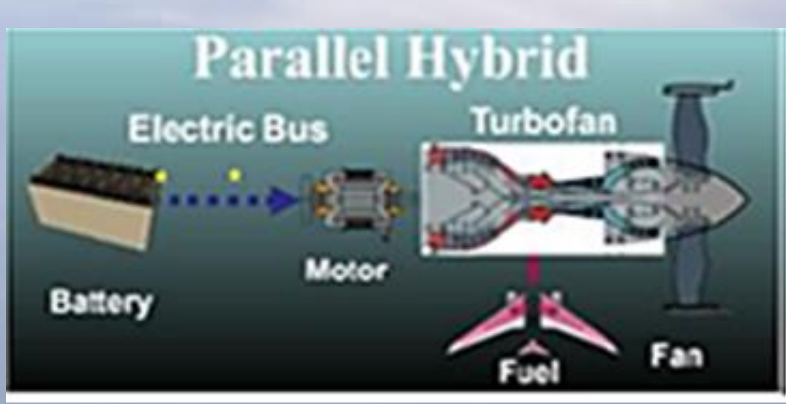


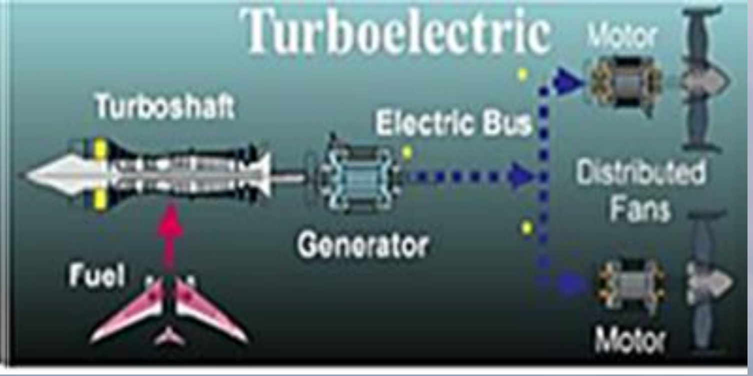
CHALLENGE:

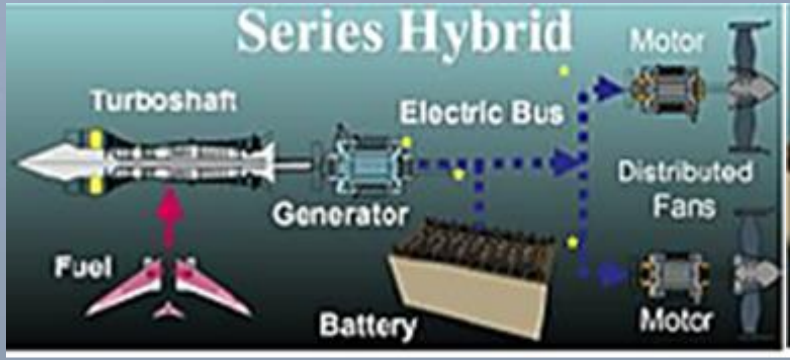
Develop circuit-breaking devices that are...

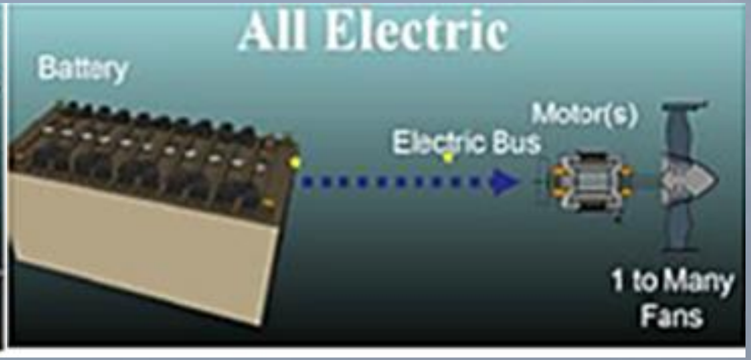
- Strong enough to stop **megawatts** of energy (around 100 times the energy in a house!)
- Able to respond in just **microseconds**
- **10 times lighter** than anything yet engineered



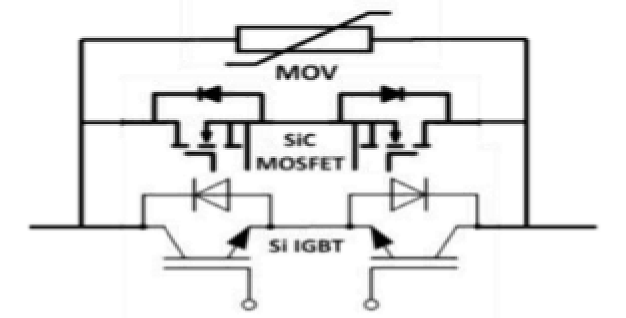


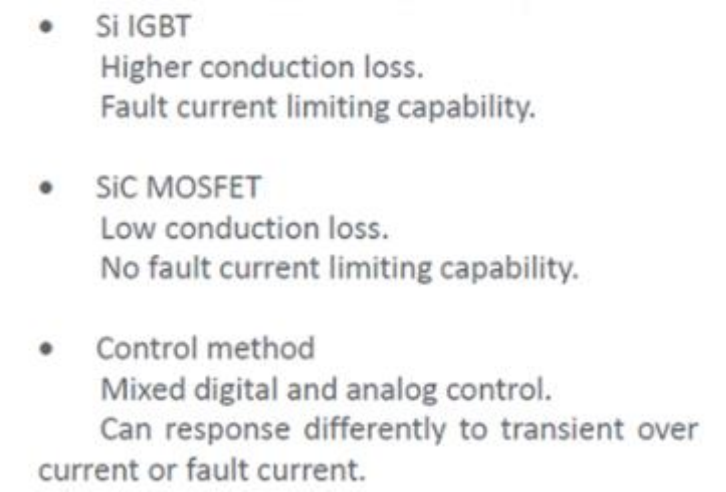




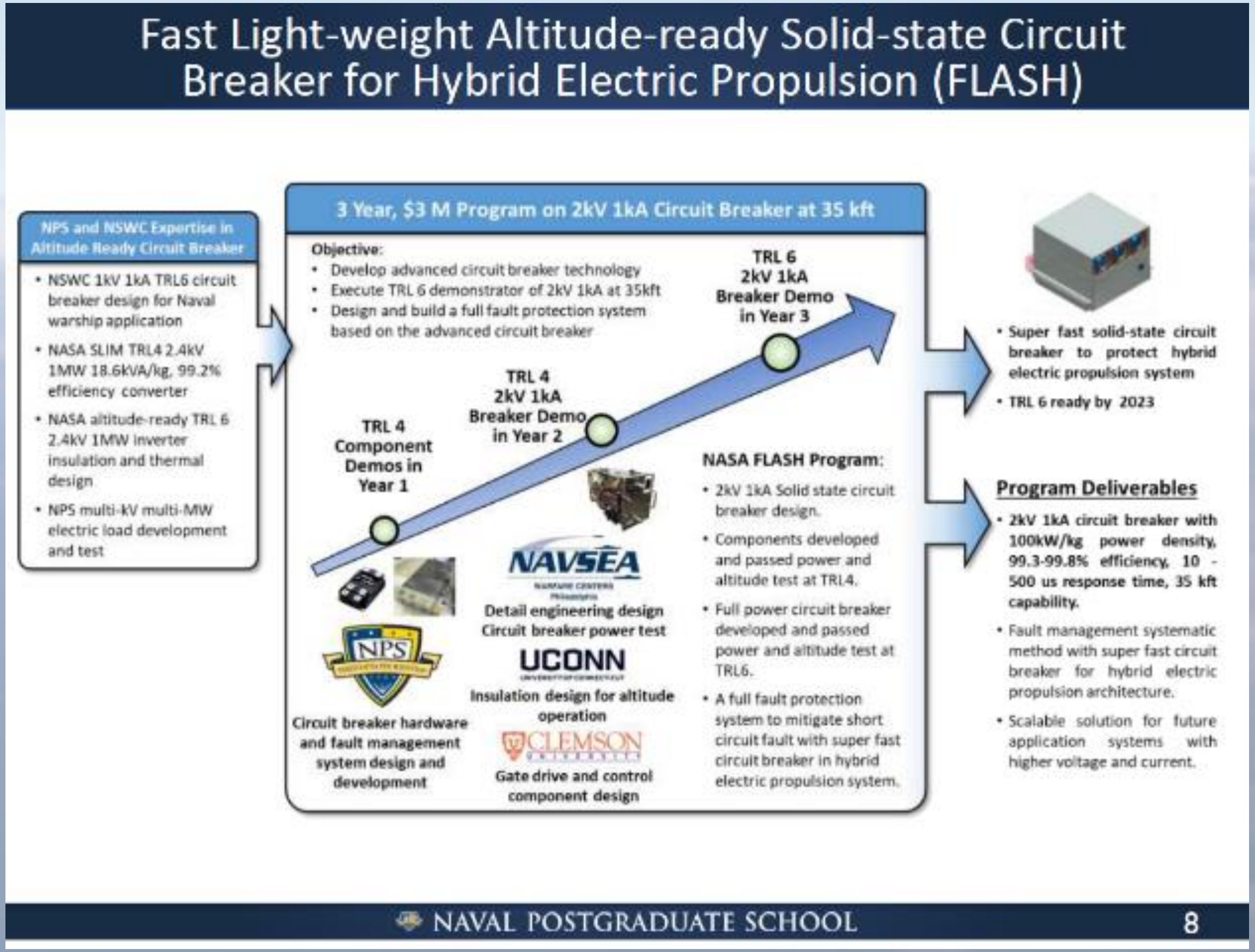


Ultra-Fast, Light-Weight Breaker System





- Si IGBT
  Higher conduction loss.
  Fault current limiting capability.
- SiC MOSFET
  Low conduction loss.
  No fault current limiting capability.
- Control method
  Mixed digital and analog control.
  Can response differently to transient over current or fault current.



Fast Light-weight Altitude-ready Solid-state Circuit Breaker for Hybrid Electric Propulsion (FLASH)

NPS and NSWC Expertise in Altitude Ready Circuit Breaker

- NSWC 1kV 1kA TRL6 circuit breaker design for Naval warship application
- NASA SLIM TRL4 2.4kV 1MW 18.6kVA/kg, 99.2% efficiency converter
- NASA altitude-ready TRL 6 2.4kV 1MW inverter insulation and thermal design
- NPS multi-kV multi-MW electric load development and test

3 Year, $3 M Program on 2kV 1kA Circuit Breaker at 35 kft

Objective:

- Develop advanced circuit breaker technology
- Execute TRL 6 demonstrator of 2kV 1kA at 35kft
- Design and build a full fault protection system based on the advanced circuit breaker

TRL 4 Component Demos in Year 1

TRL 4 2kV 1kA Breaker Demo in Year 2

TRL 6 2kV 1kA Breaker Demo in Year 3

Circuit breaker hardware and fault management system design and development

Detail engineering design Circuit breaker power test

Insulation design for altitude operation

Gate drive and control component design

NASA FLASH Program:

- 2kV 1kA Solid state circuit breaker design.
- Components developed and passed power and altitude test at TRL4.
- Full power circuit breaker developed and passed power and altitude test at TRL6.
- A full fault protection system to mitigate short circuit fault with super fast circuit breaker in hybrid electric propulsion system.

- **Super fast solid-state circuit breaker to protect hybrid electric propulsion system**
- **TRL 6 ready by 2023**

Program Deliverables

- **2kV 1kA circuit breaker with 100kW/kg power density, 99.3-99.8% efficiency, 10 - 500 us response time, 35 kft capability.**
- Fault management systematic method with super fast circuit breaker for hybrid electric propulsion architecture.
- Scalable solution for future application systems with higher voltage and current.

NAVAL POSTGRADUATE SCHOOL 8

Naval Postgraduate School (Zhang)

Fault Condition Response Times

- Megawatt DC bus power is essentially a high power arc welder if a fault condition is not managed quick enough.

Fault Type	Effect	Response Time Required
IGBT over-current	Damaged circuit	< 500 us
Arcing	Damaged equipment	<1 ms
Over-heating	Damaged plane	<10 ms

Ultra-fast, flight weight, medium voltage circuit breakers will protect passengers, equipment, and circuitry so the aircraft can still be used under a full range of fault situations including:

- **Environment**
  - lightning, bird-strike, wind sheer, turbulence vibration, cosmic ray
- **Operation**
  - engine stall, tail strike, microwave interference
- **Design**
  - insulation fail, rotor burst, equipment failure, fatigue crack, control/software issue

Machine and Fault Management Integration

Machine Type	Fault Management	Specific Power (kw/kg)	Efficient (%)	Benefit	Challenge
PM	SSCB Open Circuit High Voltage	>6	>95	Light-weight and efficient	Fast fault management required – Needs SSCB or advanced controls Low inductance
Induction	De-energizes on open circuit	>4.7	>92	Simple construction Hybrid CB can be used High Inductance	Slower response time Thermal Loads
Wound Field	Rotor field quick cut-off	>5	>96	Highly controllable Hybrid CB can be used Medium Inductance	Rotor thermal management
Partial SC Wound Field	Rotor field quick cut-off	>15	>98	Highly controllable Hybrid CB can be used Medium Inductance	Rotor thermal management

Fault Management Technology Options

	Mechanical	Solid-State	Hybrid
Device to break current	Mechanical Switch	Semiconductor Devices	Semiconductor Devices and Mechanical Switch
Benefits	Low Conduction Loss	Super-fast response time (<10 us) Simple structure	Low conduction loss Fast response time (1-5 ms)
Limitations	Slow Response Time (50 ms)	**High conduction loss (~0.5%)**	Complexity

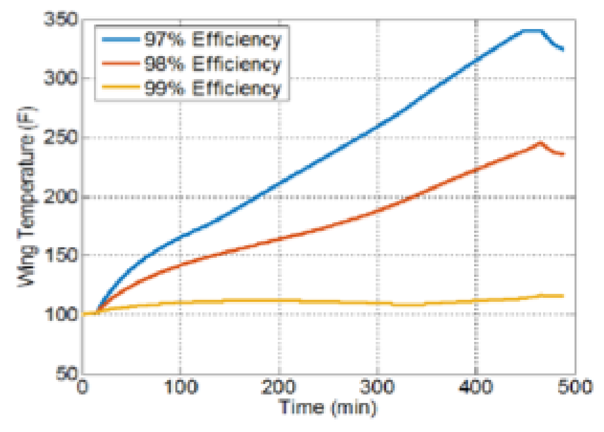
“All [aerospace] machines are PM (radial inner rotor, radial outer rotor, and axial flux)”.

Electric Aircraft Thermal Challenge

Current proposed solutions include:

- Ram air HX
  - – adds weight and aircraft drag
- Convective skin cooling HX
  - – adds weight, drag, and inefficient
- Dumping heat into fuel
  - – limited thermal capacity
- Dumping heat into lubricating oil
  - – limited thermal capacity
- Active cooling
  - – adds weight and consumes engine power
- Phase change cooling
  - –adds weight and limited thermal capacity
- Heat pipe, pumped multiphase, vapor compression
  - – adds weight and consumes engine power

Mode	Limits	Scale
Electrical	Voltage, Copper Mass and Heat	I^2R
Mechanical	Lubrication, Vibration, Heat, Mass	$0.5\ \tau\omega^2$
Fluid	Freezing, Pump, Impurities, Heat, Mass	$\dot{m}\ C_p\mathrm{T}$
Phase Change/Vapor	Gravity, Orientation, Distance, Freezing	<1 m
Acoustic	Design Challenge, Some Heat	$0.5 * pv^2$



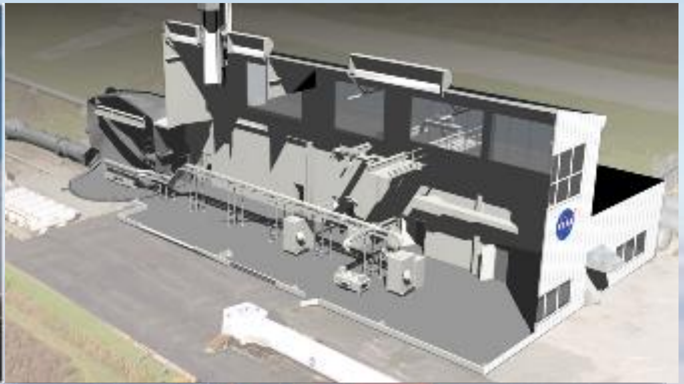
P.C. Krause

50kW to >800kW of low grade thermal heat trapped within composite aircraft body

Technology Readiness Level Testing Challenge

Reconfigurable Powertrain Testbed for Fault Testing

- Located at NASA Glenn Plum Brook Station in the recently refurbished Hypersonic Tunnel Facility (HTF)
- Supports full-scale megawatt powertrain testing under actual flight scenarios with cryogenic fuel, high voltage, large wingspan, electromagnetic interference, and high altitude

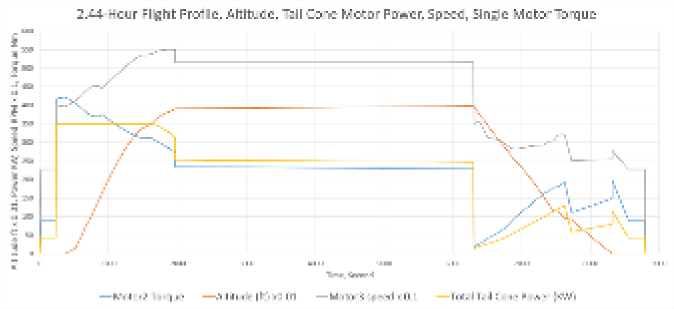


TRL maturation:

- **High voltage bus architecture –**
  Insulation, geometry, 600V up to 4500V
- **High power MW Inverters, Rectifiers-**
  Commercial, In-House, NRAs
- **High power MW Motors, Generators-**
  Commercial, In-house, NRAs
- **System Communication –**
  Aircraft CAN, Ethernet, Fiber-optics
- **System EMI Mitigation and Standards –**
  Shielding, DO-160G, MIL-STD-461
- **System Fault Protection –**
  Fuse, Circuit Breaker, Current Limiter
- **System Thermal Management –**
  Active/Passive, Ambient/Cryo
- **Altitude Integration-**
  Cosmic, creepage, partial discharge

Powertrain Lessons Learned:

- **EMI shielding is critical for safe and proper operation of the powertrain even with DO-160G compatible equipment.**
- **Federated fault response with localized feedback/controls are important for orderly shutdown sequencing.**
- **System interactions between components must be tested to account for common modes, grounding loops, and resonant conditions**
- **Optical fiber and digital instrumentation are required for robust communication and sensors**
- **Higher voltage and current present new issues such as insulation resistance breakdown and power quality challenges when operating near rated equipment limits**
- **Shielding throughout the powertrain limits the ability to acquire data from transducers forcing calculated software measurements.**



Summary and Vision

Feasible Vehicle Class Driven by Powertrain Specific Power and Efficiency and Integrated Vehicle Design Optimization

Power, Propulsion, Thermal, and Airframe Integration Key

- Electric Aero-Propulsion is enabled by new class of powertrain technologies you are developing!
- Future high power space missions to lunar and Martian surface require similar capability and required soon!
- Many national and international development efforts
- Recent powertrain technology advancements indicate MW-scale electric propulsion will be a reality soon.