

Aircraft Transportation Electrification Eco-System and Technologies

Rodger Dyson
NASA Glenn Research Center
Cleveland, OH

2021 IEEE Transportation Electrification Conference and Expo
Short Course
June 21-25, 2021

Course Outline

- Background & Motivation
- Markets
- Government and Industry Eco-System
- Key Performance Parameters
- Propulsion Technologies
- Power Technologies
- Thermal Technologies
- Energy Source/Storage Technologies
- Flight Demonstration Vehicles
- Summary and Future Prospects

Why Electric Aero-Propulsion?

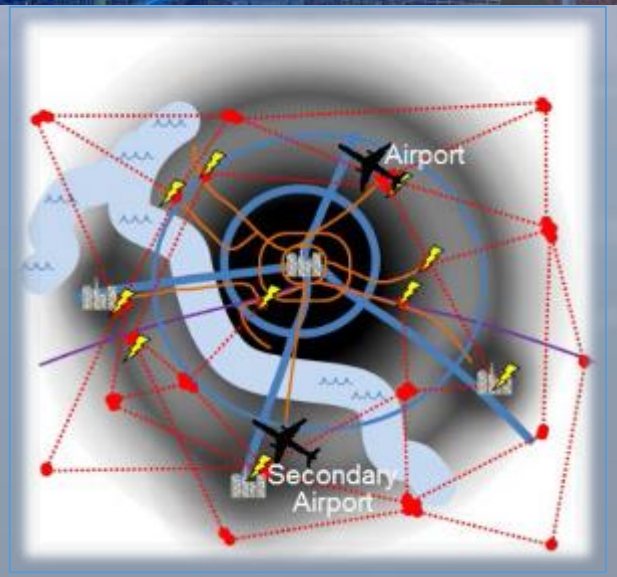
- Why electric?
  - Fewer emissions
  - Quieter flight
  - Fuel savings
  - New mobility options
  - Better utilization of infrastructure











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)

$\frac{L}{D}$

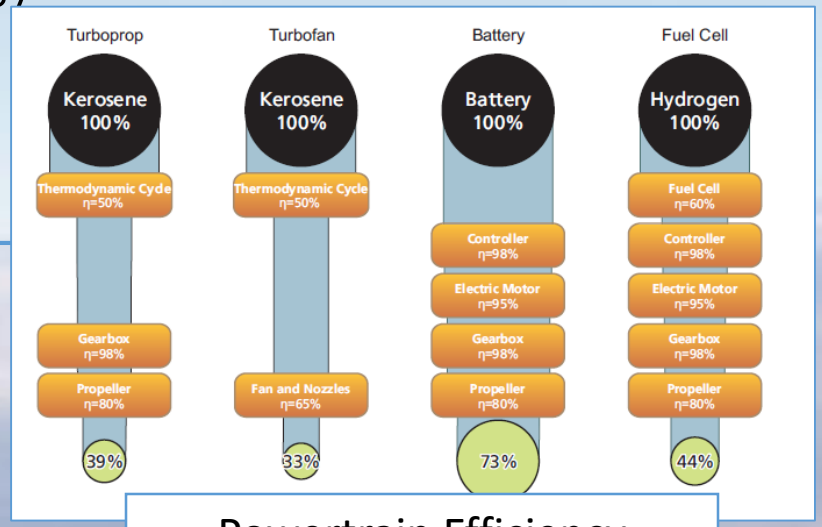
(Felder and Brown, NASA)

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

Electrically Enhanced Propulsion

Well to Wake Energy Benefit

- Fuel Savings
- Noise Reduction
- Carbon and NOx Reduction
- Mobility and Safety



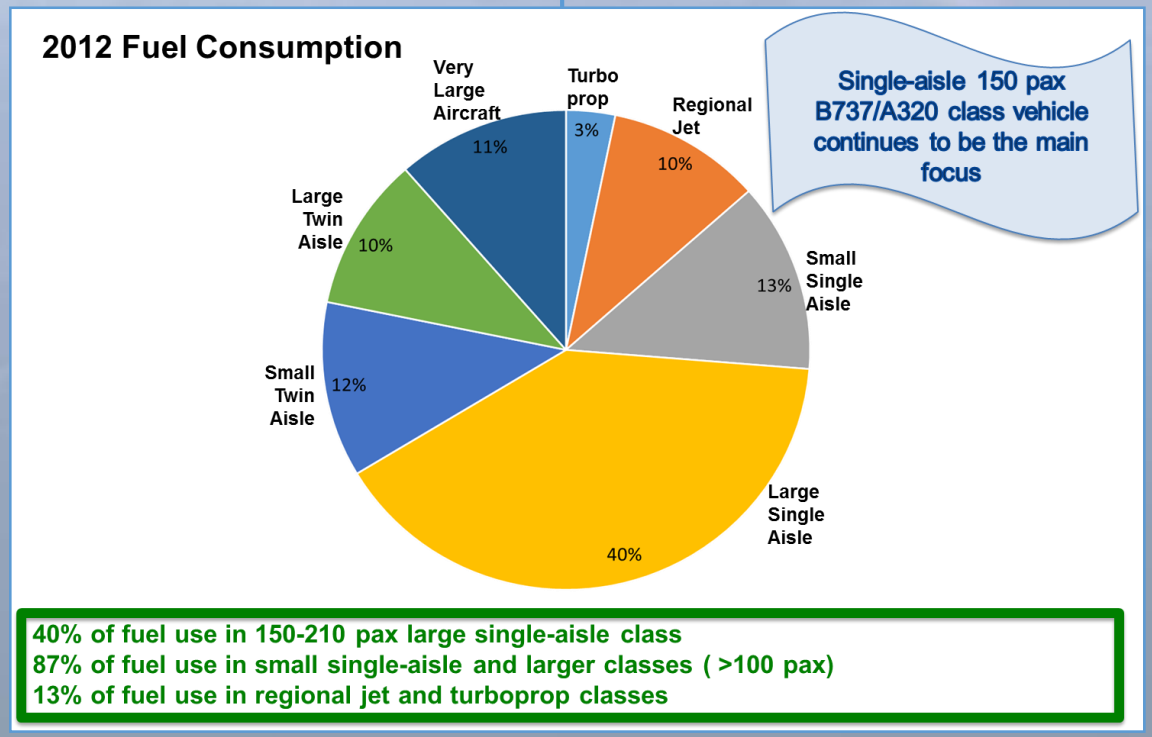
Powertrain Efficiency

39%, 33%, 21%, 13%
Well to Wake



System Benefit

3-5%
Well to Wake



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

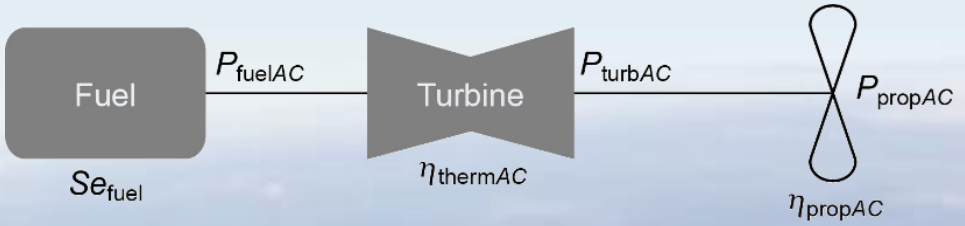


Market: Regional

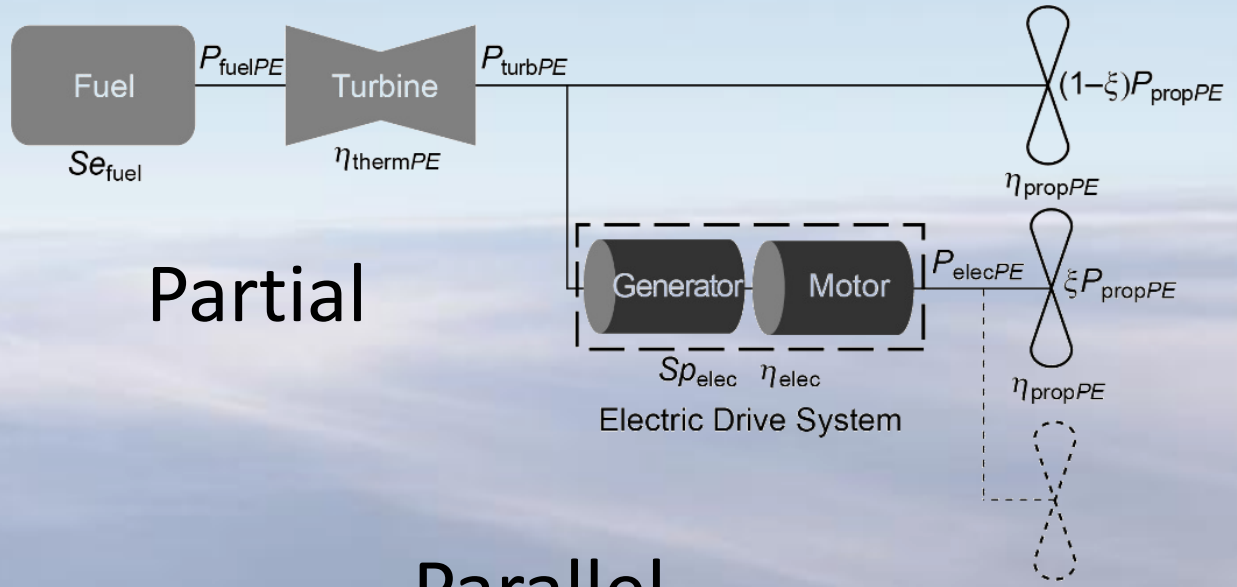
Impact: Revitalization of smaller routes

Electrified Propulsion System Definitions

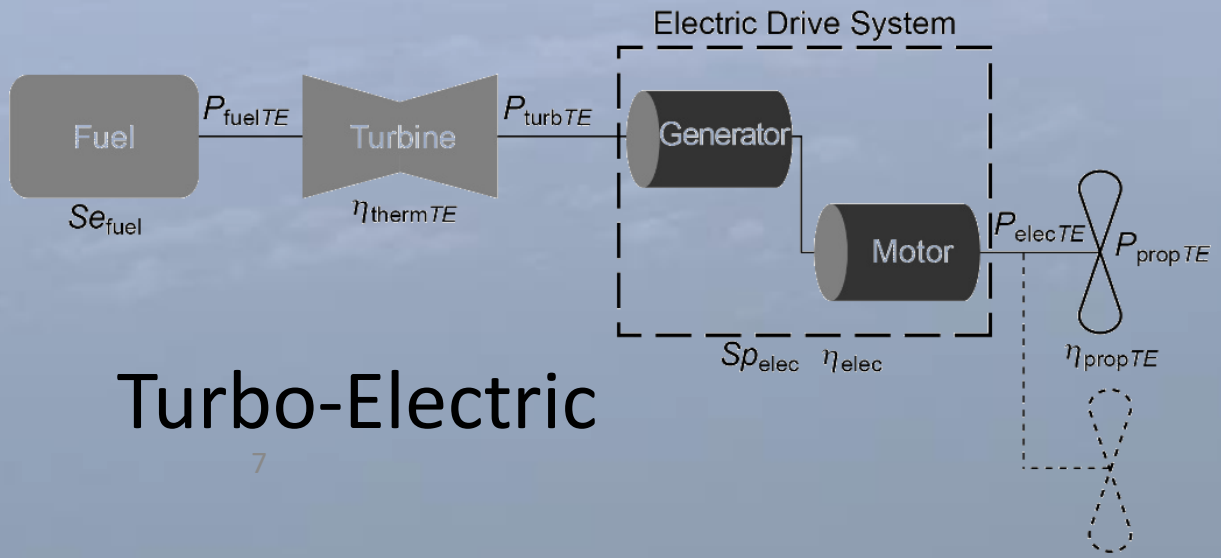
Conventional



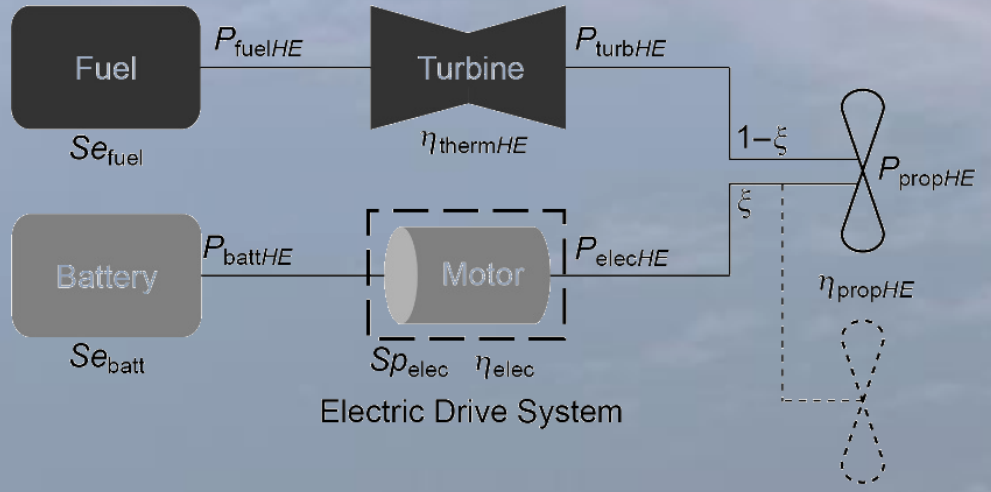
Partial



Turbo-Electric



Parallel



Electric Propulsion System Variables

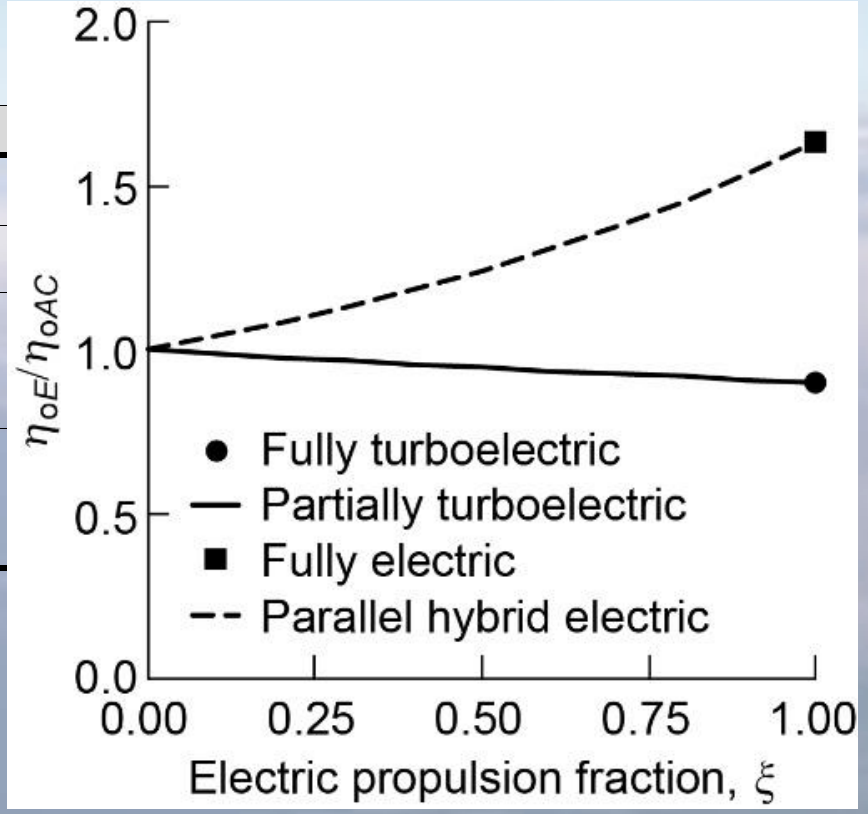
VARIABLES	DEFINITIONS
D, L, V	Drag, Lift, Velocity
$E_{batt,\ fuel}$	Energy of battery and fuel
ξ, α	Electric propulsion fraction, Ratio of takeoff to cruise power
$P_{batt,elec,fuel,prop,turb}$	Power of battery, electric drive, fuel, propulsion, and turbine shaft
$R_{batt.fuel}$	Range of battery-based, fuel-based aircraft
$Se_{batt,fuel}$	Specific energy of battery, fuel
Sp_{elec}	Specific power of electric drive
$W_{batt,I,f,elec,fuel,payload,OE}$ **w**	Weight of battery, initial/final aircraft, electric drive, fuel, payload, empty
$\eta_{elec,o,prop,therm}$	Efficiency of electric drive system, overall, propulsion, and thermal

Key Performance Parameters in RED

Ratio of Electrified to Conventional Efficiency

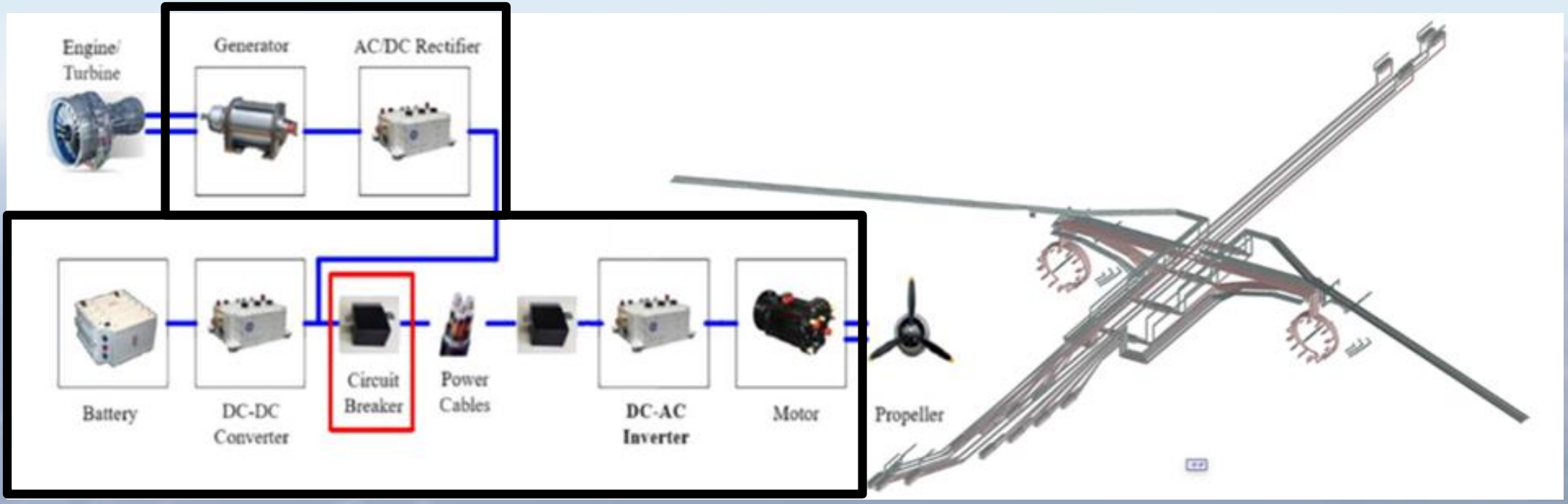
Aircraft Type	Overall Efficiency
Conventional Aircraft (AC)	$\eta_{oAC} = \eta_{propAC} \times \eta_{thermAC}$
Fully Turboelectric Aircraft (TE)	$\eta_{oTE} = \eta_{propTE} \times \eta_{thermTE} \times \eta_{elecTE}$
Partially Turboelectric Aircraft (PE)	$\eta_{oPE} = \dfrac{\eta_{propPE} \times \eta_{thermPE} \times \eta_{elecPE}}{(1-\xi)\eta_{elecPE} + \xi}$
Parallel Hybrid Electric Aircraft (HE)	$\eta_{oHE} = \dfrac{\eta_{propHE} \times \eta_{thermHE} \times \eta_{elecHE}}{(1-\xi)\eta_{elecHE} + \xi\eta_{thermHE}}$

Assume thermal efficiency is 55%
Electric drive efficiency is 90%



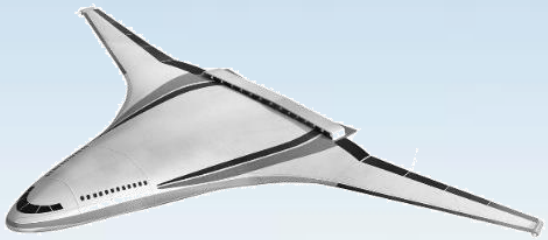
Costs of Electrified Aircraft Propulsion

- Added weight and losses of new propulsion system



Improved propulsive efficiency from high BPR and BLI, as well as increased L/D must be greater than the costs of electrified aircraft propulsion, and the balance of these benefits and constraints are presented here.

Aircraft Concepts with Electrified Propulsion



N3-X
300 PAX
7500 NM
-9% FB
BPR, BLI, L/D



STARC-ABL
154 PAX
3500 NM
-3% FB
BPR, BLI



PEGASUS
48 PAX
400 NM
-10% FB
BPR, BLI



X-57
2 PAX
86 NM
-80% EB
BPR, L/D

Different combinations of higher by-pass ratio, boundary layer ingestion, and lift improvements are employed for system level benefits.

On-Demand and Large Transport

All & Hybrid Electric, Distributed Propulsion

- On Demand Mobility
- Small Plane Focused

Enable New Aero Efficiencies

Power Sharing

Distributed Thrust Control

Certification Trailblazing





Energy & Cost Efficient, Short Range Aviation



SUGAR Volt

Turbo Electric, Distributed Propulsion

- Fuel Efficient Propulsion
- Transport Class Focused

Enable New Aero Efficiencies

High Efficiency Power Distribution

Power Rich Optimization

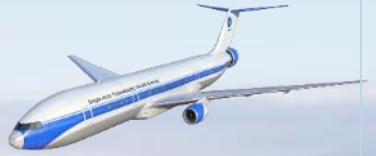
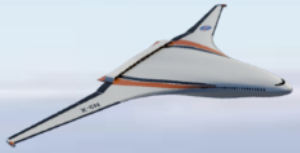
Non-flight Critical First Application



Energy & Cost Efficient, Transport Aviation

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

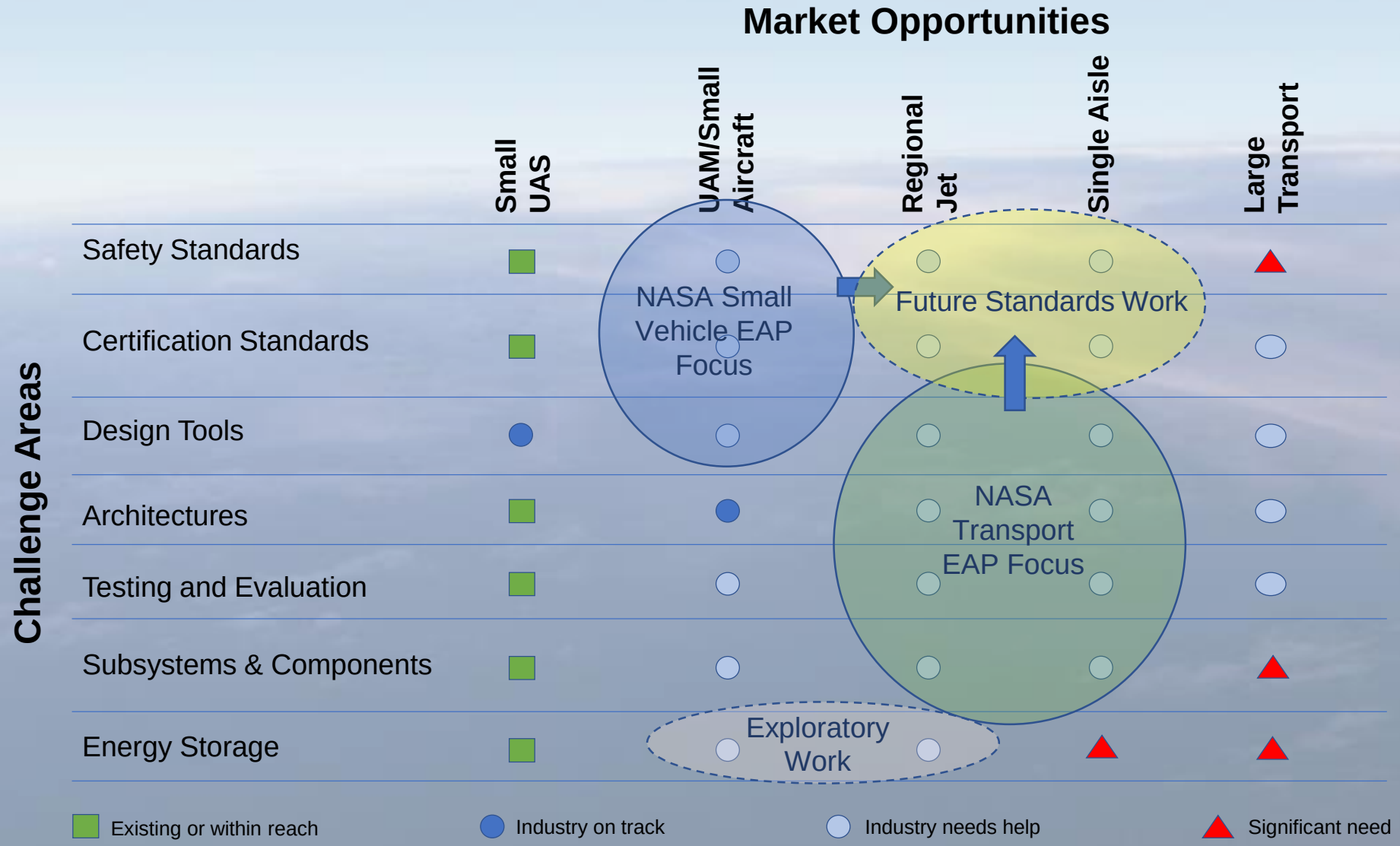
Transport Scale EAP

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



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

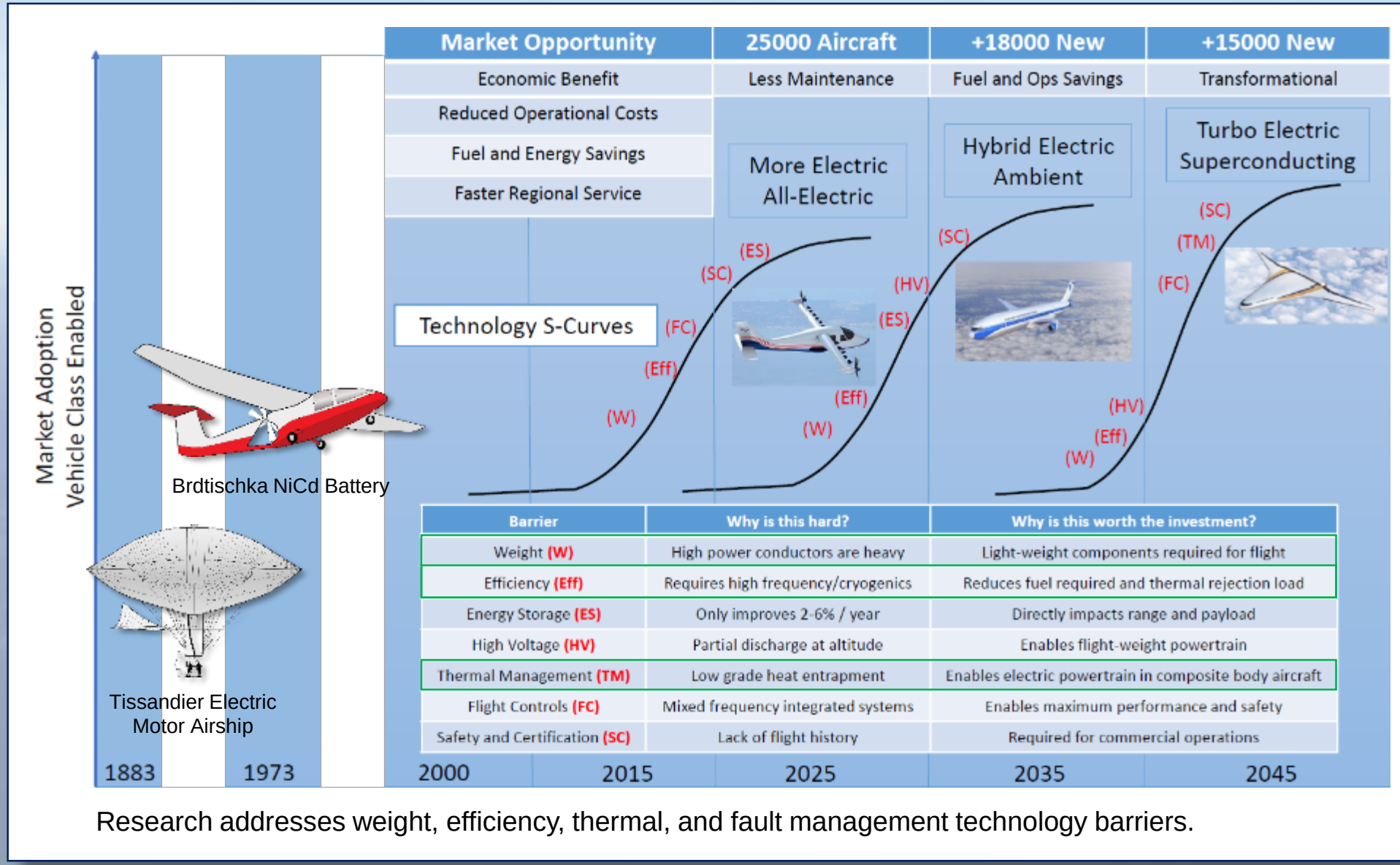


Transformative Aeronautics Concepts Program (TACP)

Transformative Tools & Technologies
Convergent Aeronautics Solutions
ULI

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

Technology Adoption S-Curves



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

Range of Required Machine Power

2015 → 2035

Largest Electrical Machine on Aircraft

Non-cryogenic | 100 kW | 1 MW | 3 MW | 10 MW | 30 MW | Superconducting

9 Seat
0.5 MW Total Propulsive Power
50-250 kW Electric Machines

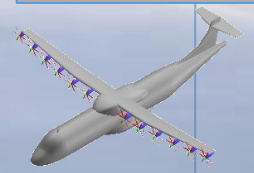


19 Seat
2 MW Total Propulsive Power
.1-1 MW Electric Machines

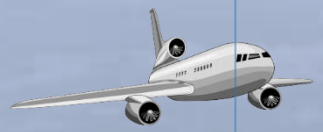


50 Seat Turboprop
3 MW Total Propulsive Power
.3-6 MW Electric Machines



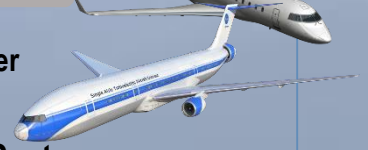


50 Seat Jet
12 MW Total Propulsive Power
.3-6 MW Electric Machines





150 Seat
22 MW Total Propulsive Power
1.5-2.6 MW Electric Machines



150 Seat
22 MW Total Propulsive Power
1-11 MW Electric Machines





300 Seat
60 MW Total Propulsive Power
3 -30 MW Electric Machines

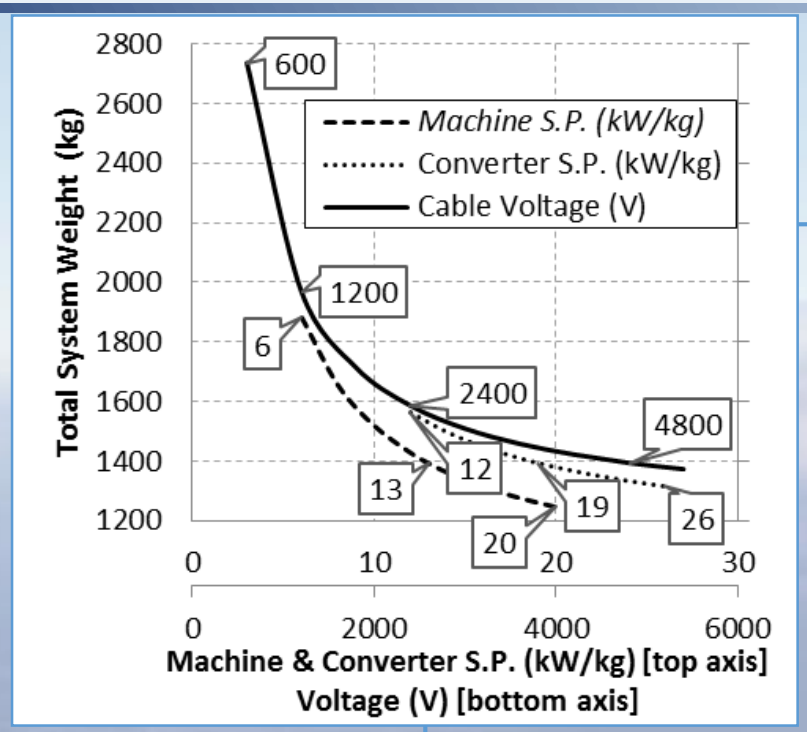


Left side of each power range bar is the smallest motor that yields overall aerodynamic efficiency increase for a partially electrified airplane

Right side is the size of a generator for a twin turboelectric system for a fully electrified airplane

PS–01758–1115

Vehicle Configuration Trade-offs

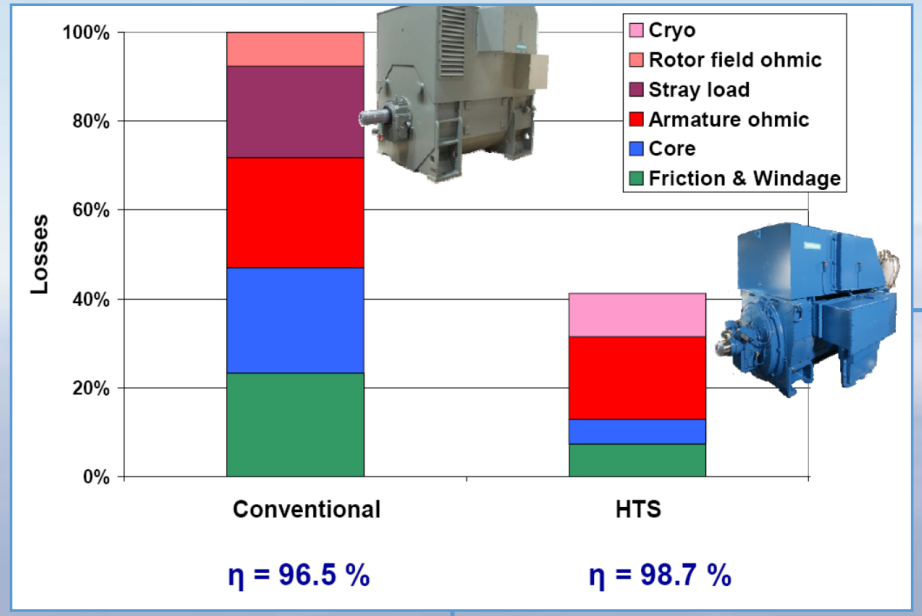


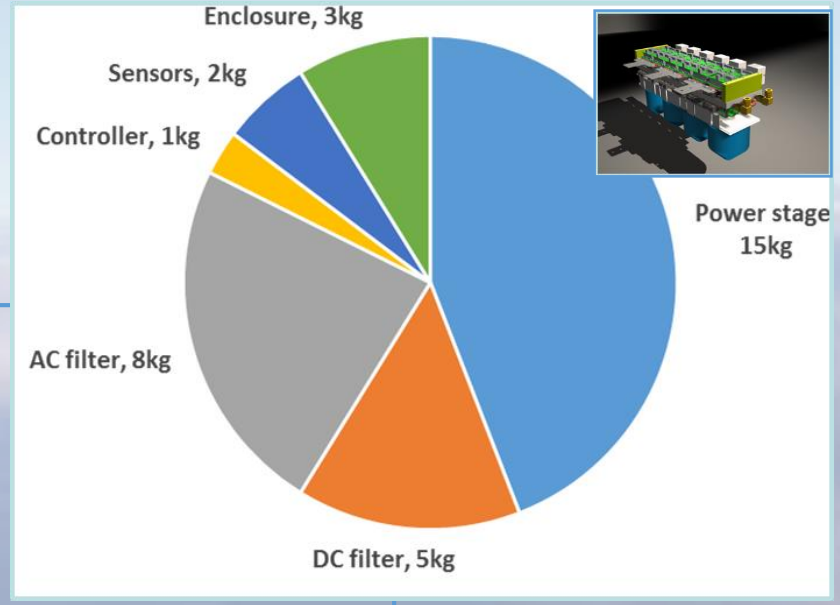
- Voltage vs. Efficiency
- Thermal vs. Mass
- Stability vs. Integration

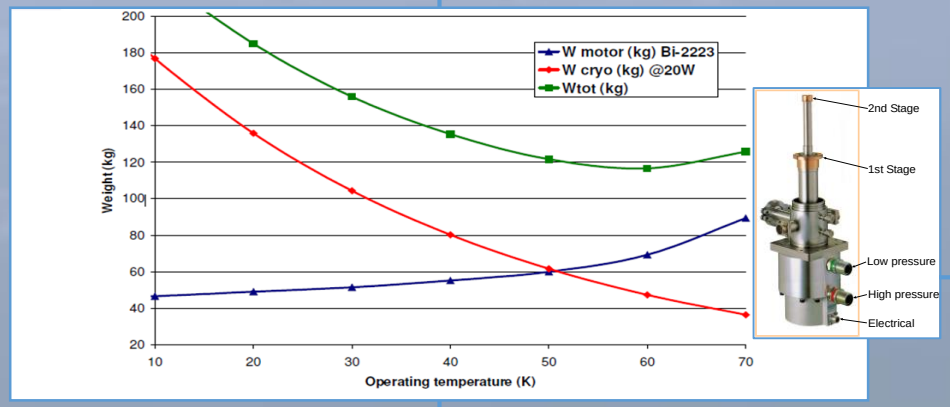
- Battery vs. Turbine Power
- Aerodynamics vs. Complexity

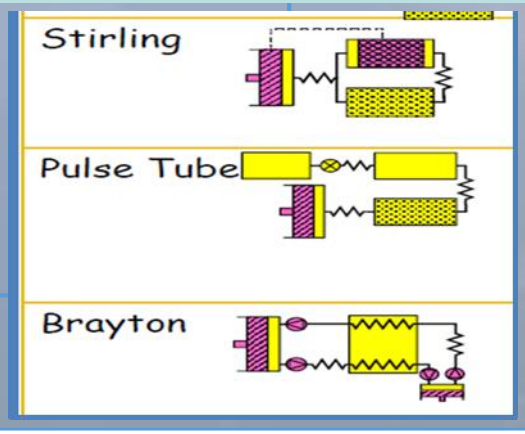
Energy Storage	Electrical Distribution	Turbine Integration	Aircraft Integration
Battery Energy Density	High Voltage Distribution	Fan Operability with different shaft control	Stowing fuel & batteries; swapping batteries
Battery System Cooling	Thermal Mgt. of low quality heat	Small Core development and control	Aft propulsor design & integration
	Power/Fault Management	Mech. Integration	Integrated Controls
	Machine Efficiency & Power	Hi Power Extraction	
	Robust Power Elec.		
Parallel Hybrid Specific	**Common to Both**		**Turboelectric Specific**

Powertrain System Optimization









An optimization of the whole system has to be done in order to reach the minimum weight and/or volume

Technology Maturation

Advancing Technical & Integration Readiness

1

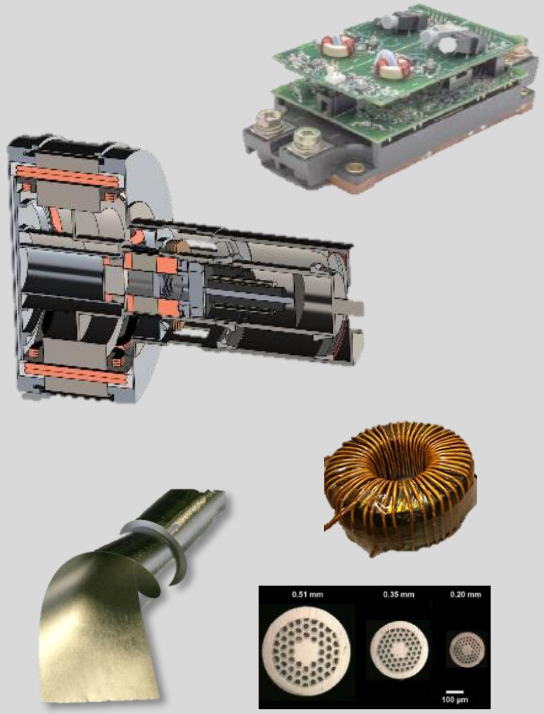
- Concept Vehicles
- Technology Gap Assessments
- Key Performance Parameter Identification
- Market Research
- FMECA Studies



TRL 1-2

2

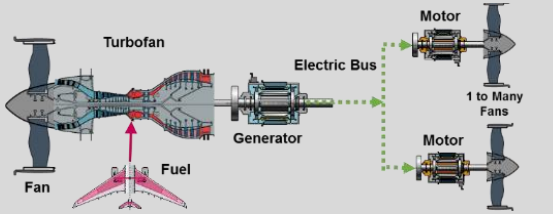
- Subsystems
- Components
- Devices
- Enabling Materials

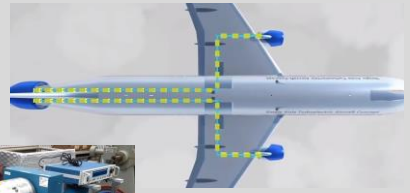


TRL ~3

3

- Ground Testing
- Integrated systems







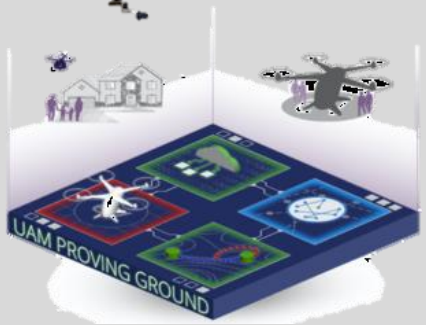


TRL ~4

4

- Flight Experiments in relevant environment
- UAM Grand Challenges



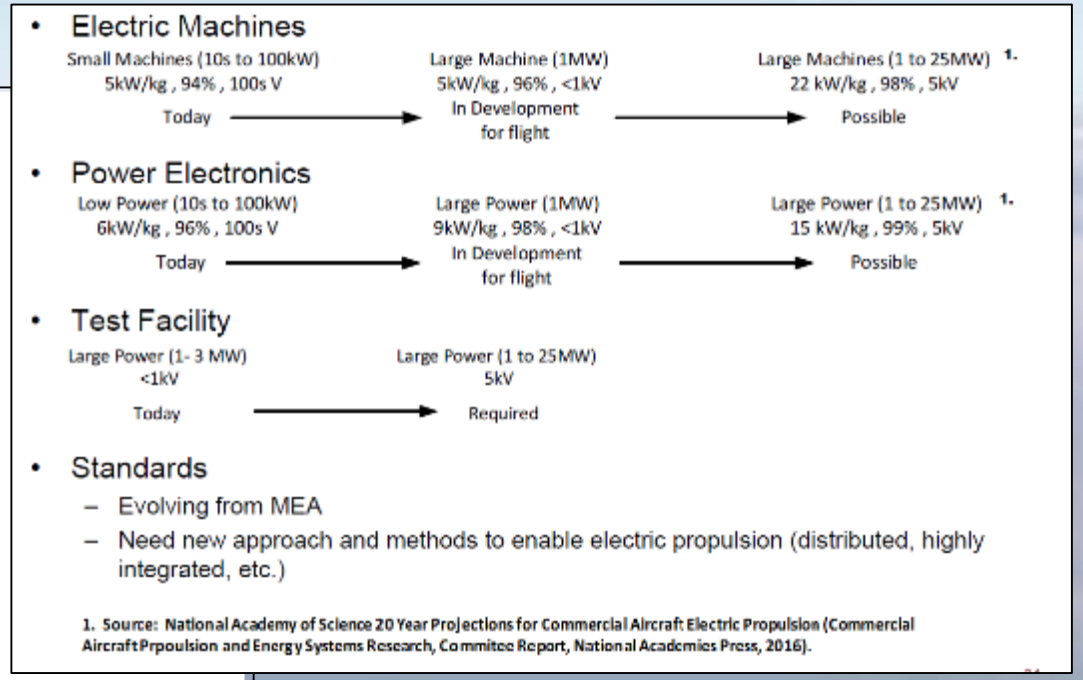


- Key data informing product decisions
- Knowledge to support certification
- Learning to inform further fundamental research

TRL 5-6

Maturing System Level Benefits

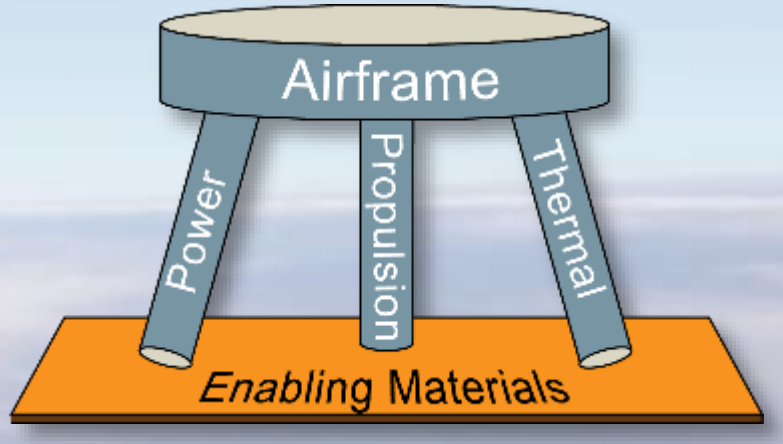
- **BLI Power Saving Coefficient 15.8%** $((HP_{BLI} - HP_{Freestream})/ HP_{Freestream})$
- **Significant reduction** in **system fuel burn benefits** versus earlier results
  - **2.6% reduction in start of cruise (SOC) TSFC**
  - **2.7% reduction in economic mission block fuel**
  - **3.4% reduction 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**



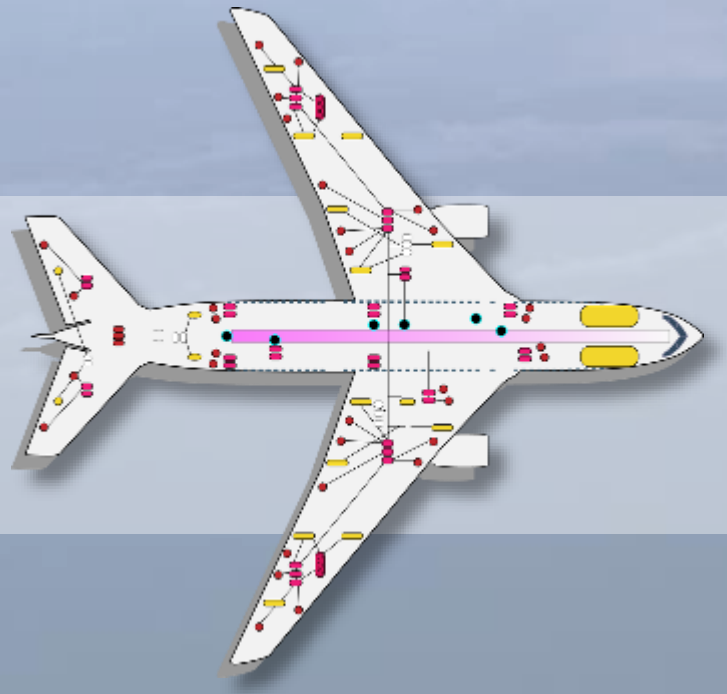
Increasing TRL, can decrease projected system benefits!

Power, Propulsion, Thermal, and Airframe Integration

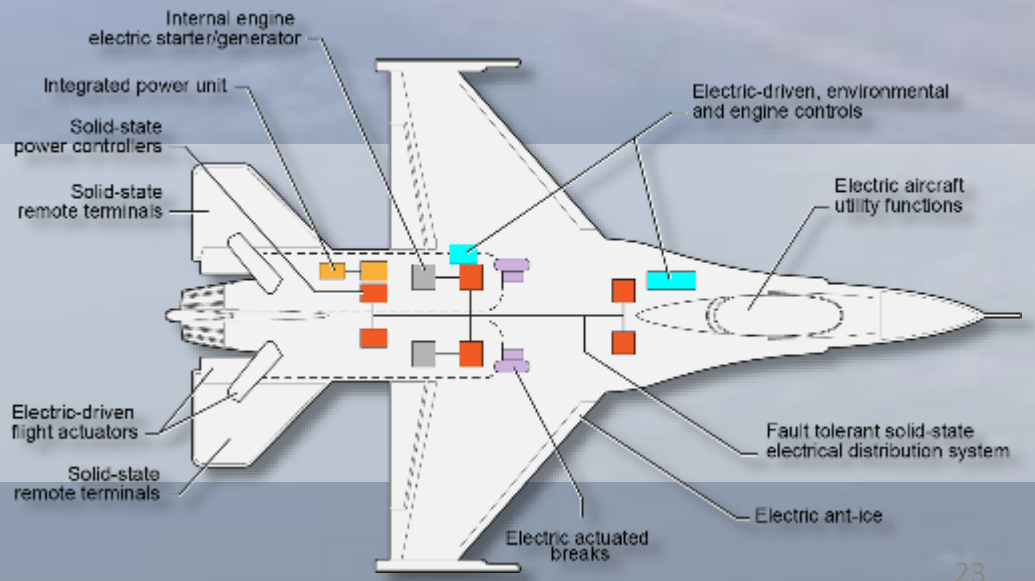
- **Challenge is to highly integrate all systems:**
  - improves fuel efficiency
  - reduces emissions
  - reduces low grade waste heat
  - reduces vehicle mass



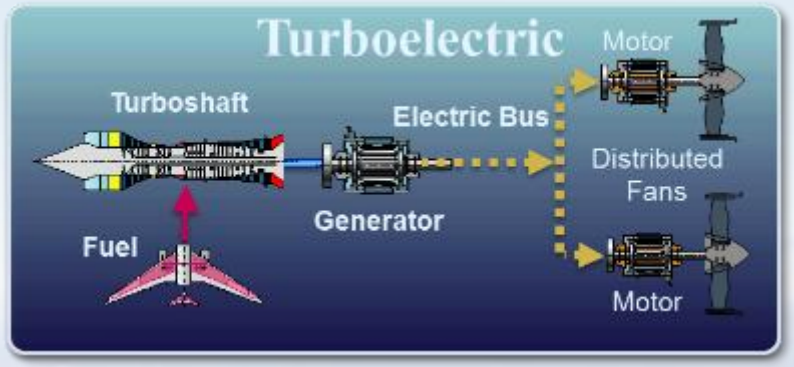
All components must integrate



PM and Induction Machine is a Near-term Technology



Electric Machine Integration



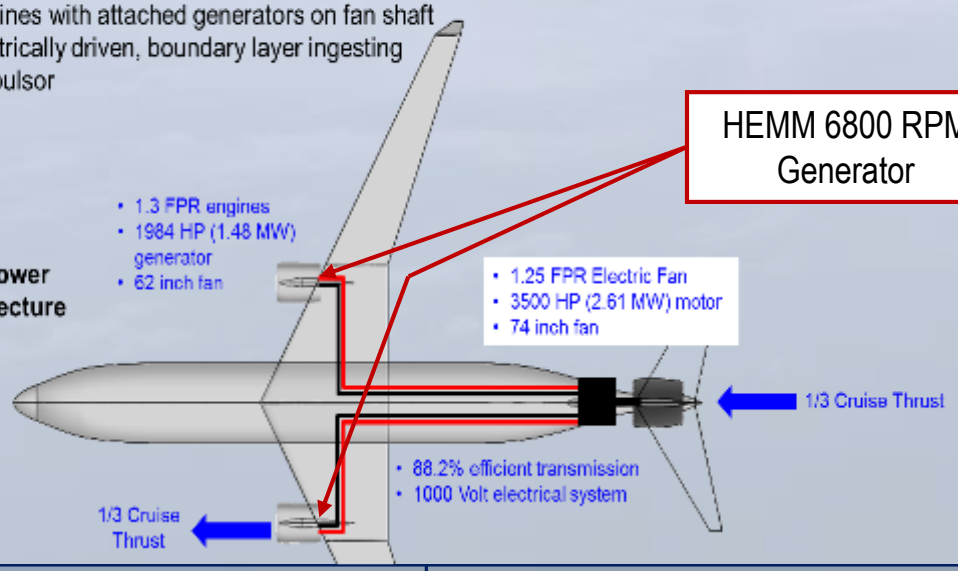
Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL)

- 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

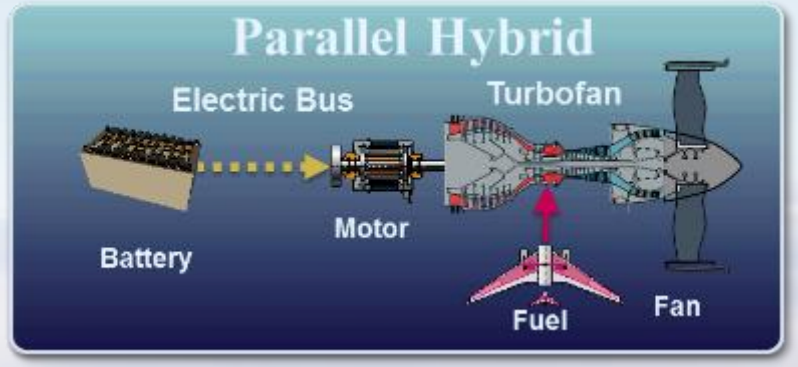


HEMM 6800 RPM Generator

STARC-ABL Power System Architecture



Partial Turbo-electric Benefits From Efficient Generator



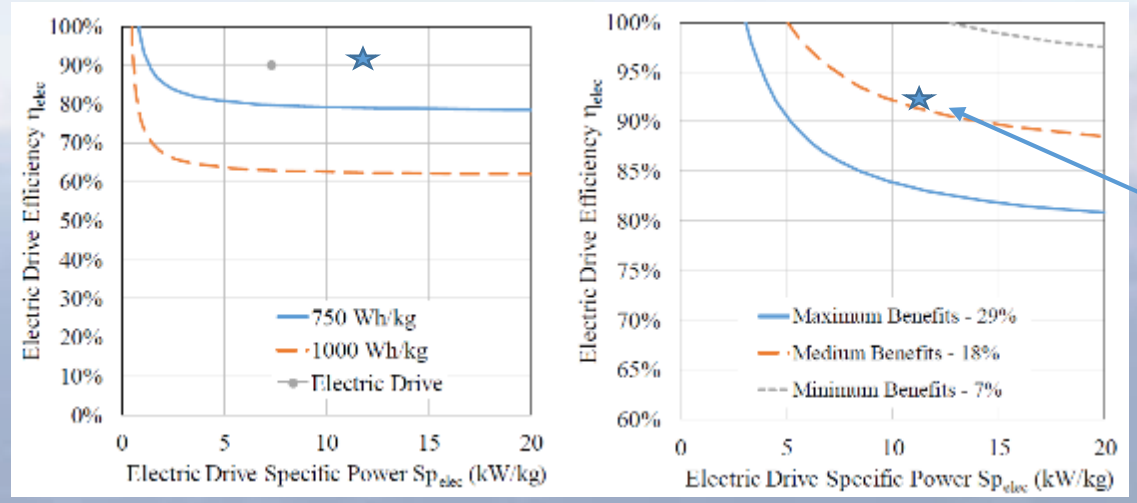


Parallel Hybrid Performance Improves with Energy Storage

Powertrain Technology Requirements

- MW-Scale Transport Class Powertrain Requirements:

Break-even Points

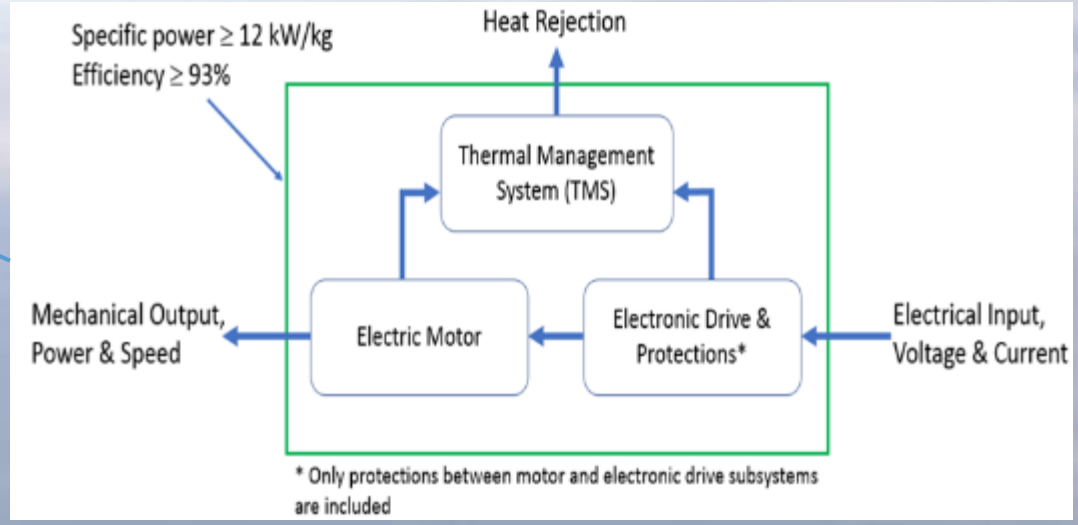


Parallel Hybrid

Turbo-electric

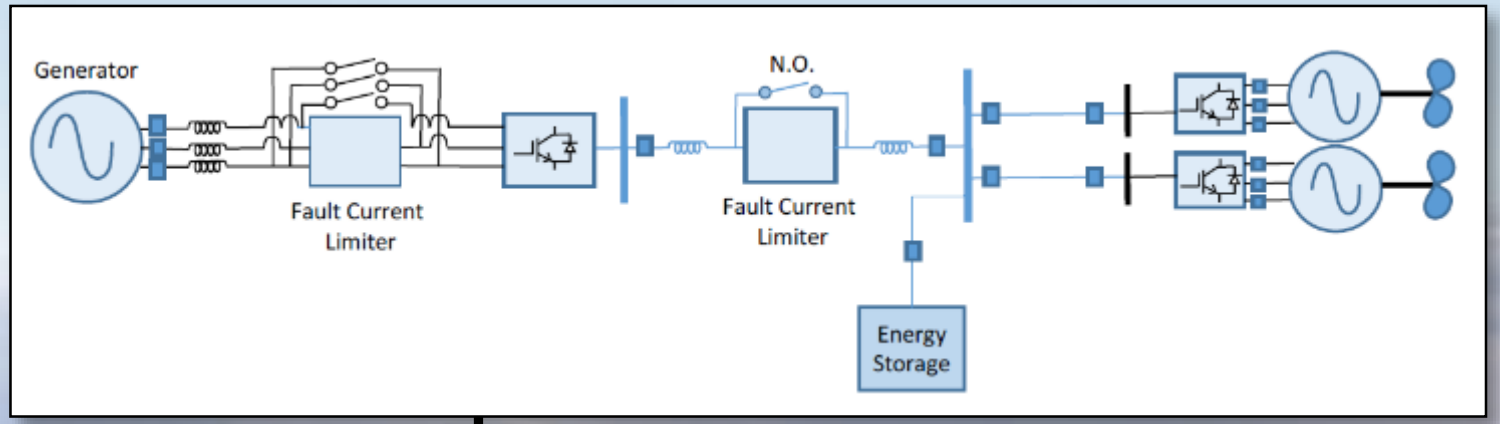
(Jansen, NASA)

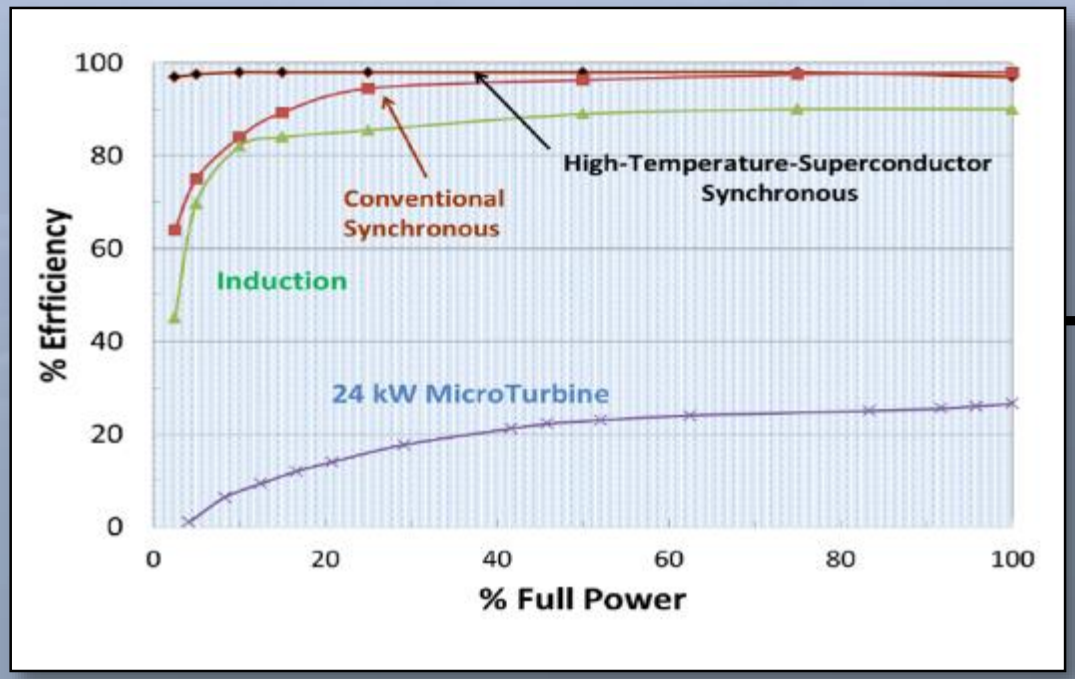
ARPA-E ASCEND Powertrain

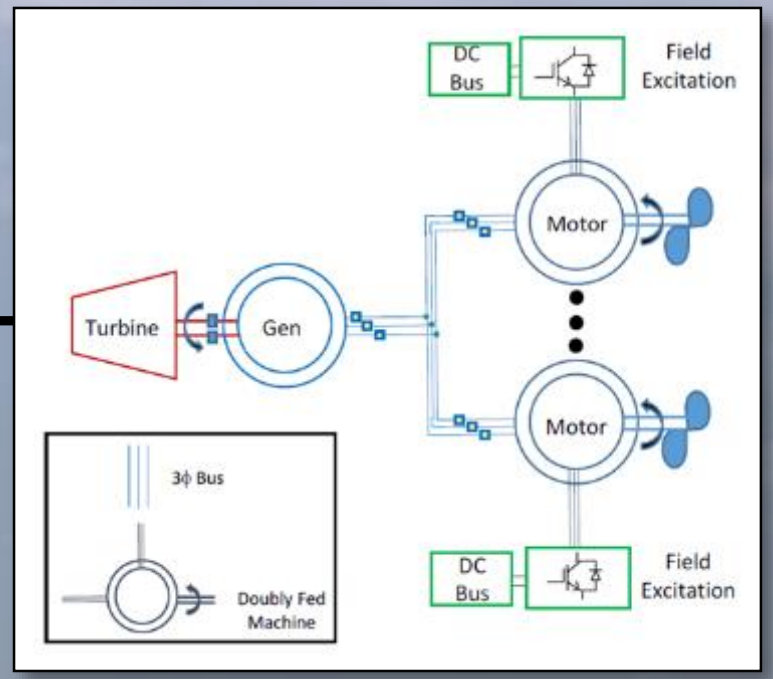


Electric Propulsion Machine Options

- 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

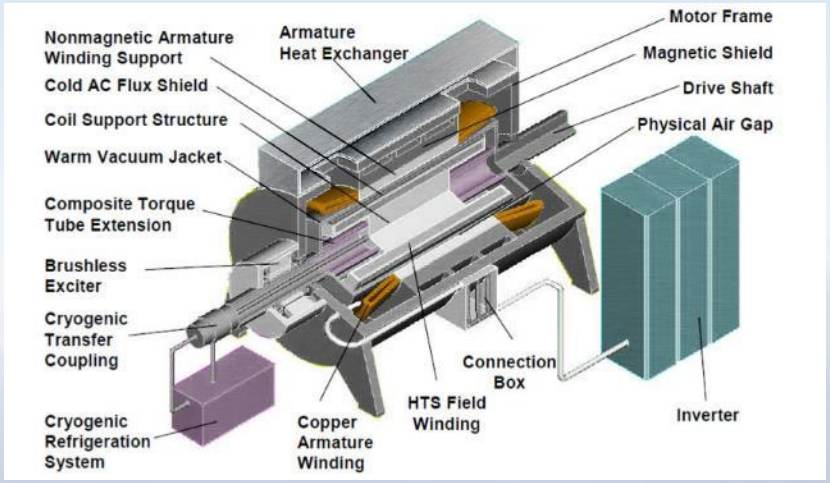
Ambient Inverter Requirements

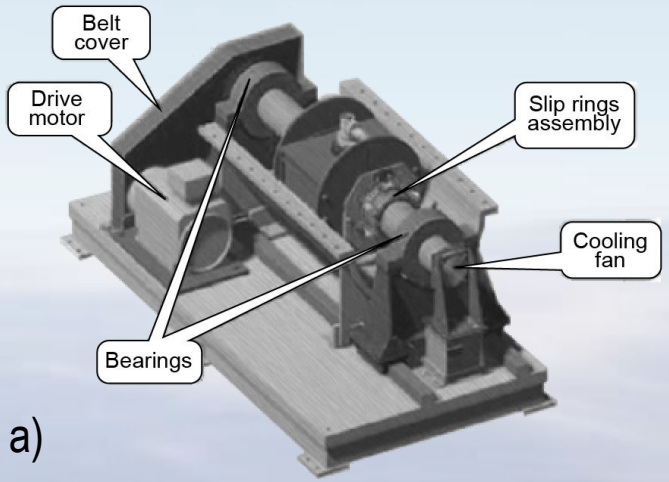
Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch Target	25	15.2	99.5

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



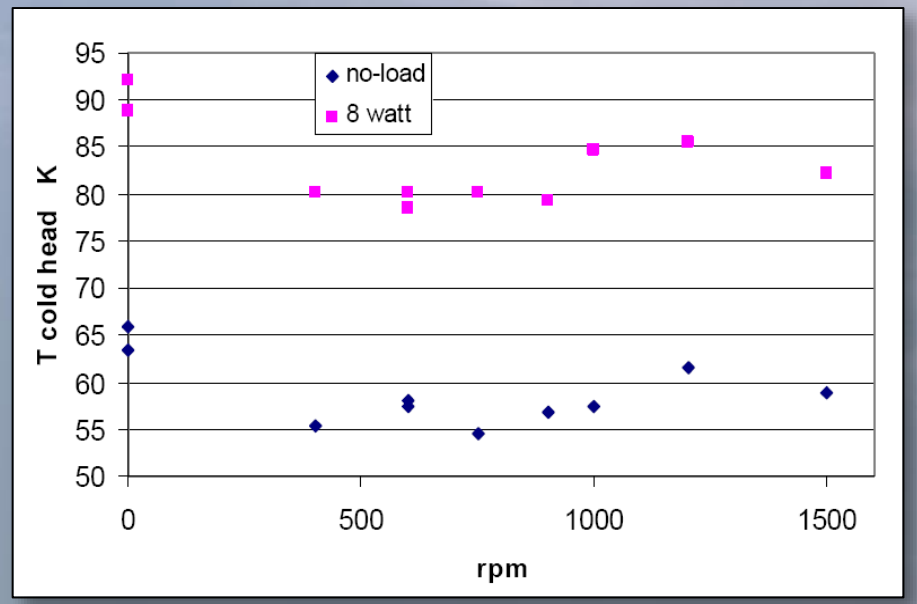


a)



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."

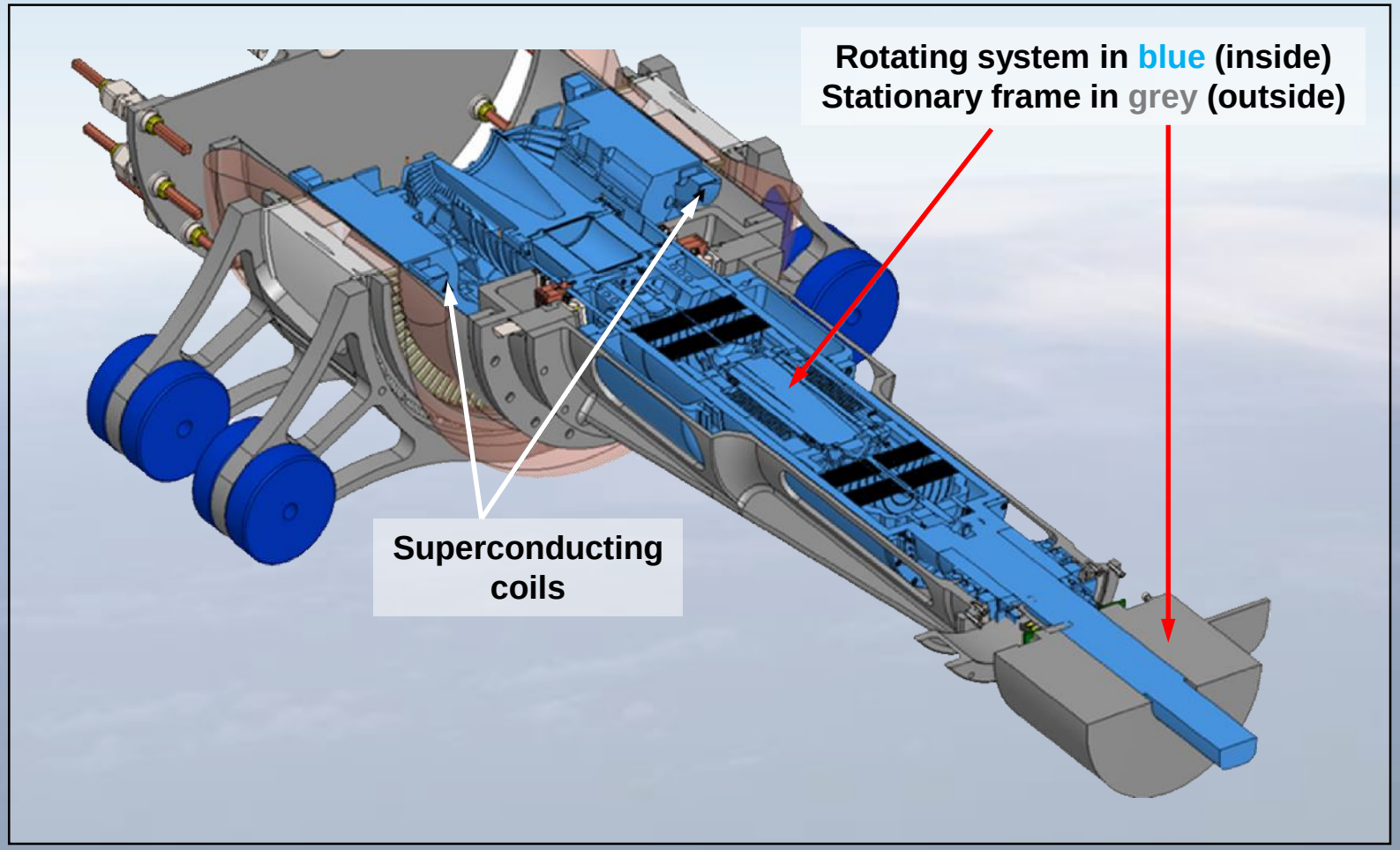


Development of Ultra-Efficient Electric Motors
April 2002- Sept. 2007
Reliance Electric Company
26391 Curtiss Wright Parkway, Suite 102
Richmond Heights, OH 44143
Date Published – May 2008

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)



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.

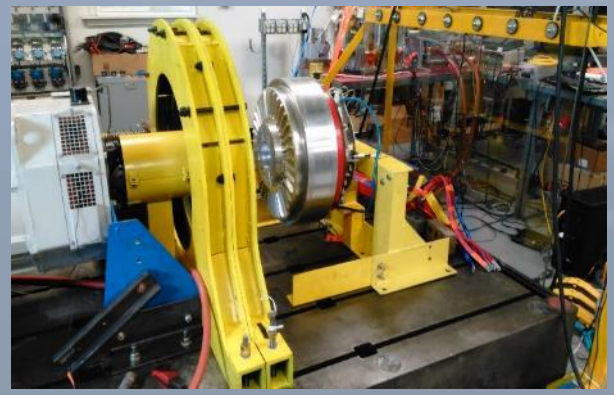
(Provenza, NASA)

U. Illinois Composite-wrapped Halbach Array Rotor





U. Illinois assembled MW Machine ready for testing



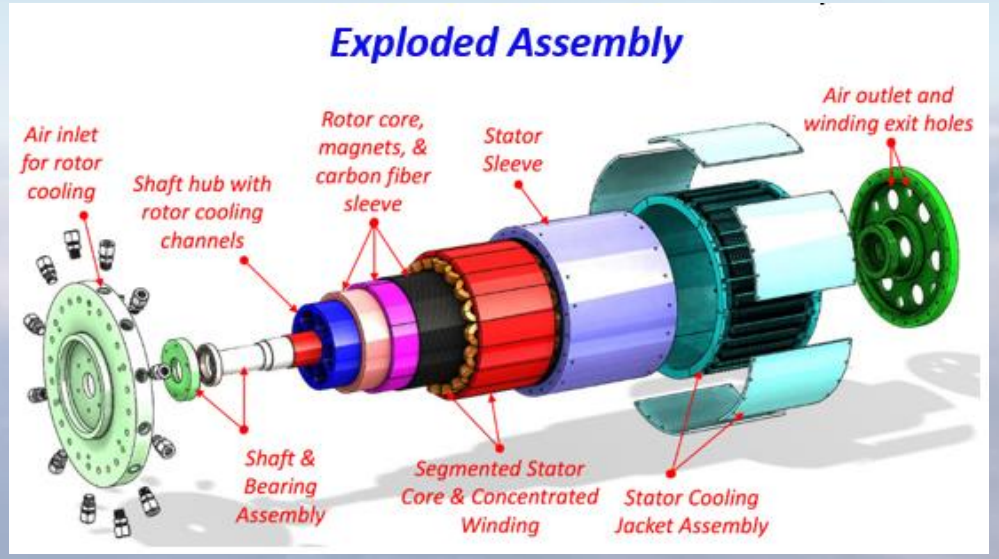
OSU MW motor connected to electric load machine

The Ohio State University ULI MW Motor Development

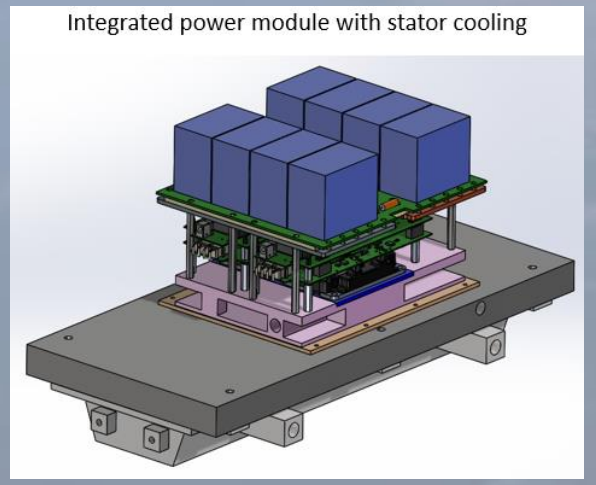
Integrated 1 MW Permanent Magnet Machine Design

- 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

(Taylor, NASA)





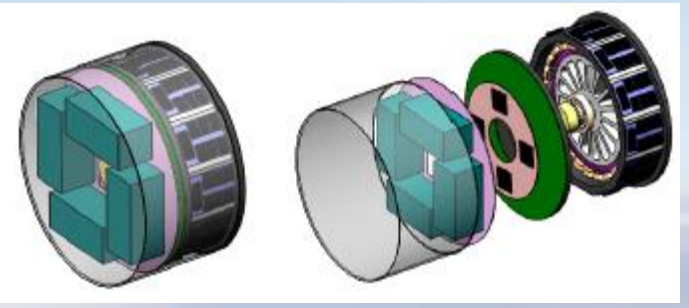


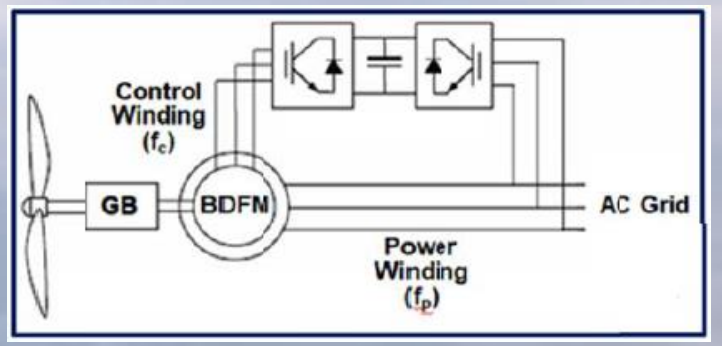
RVLT Motor Design Efforts – Goal: Improved Motor Reliability

- **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)

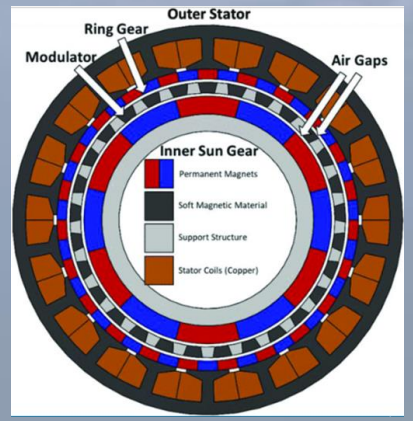


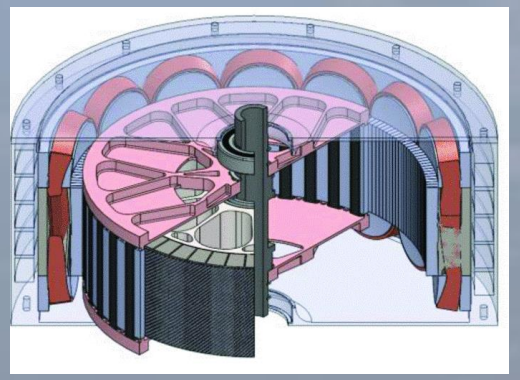


- **Internal Efforts[2]:**

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





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

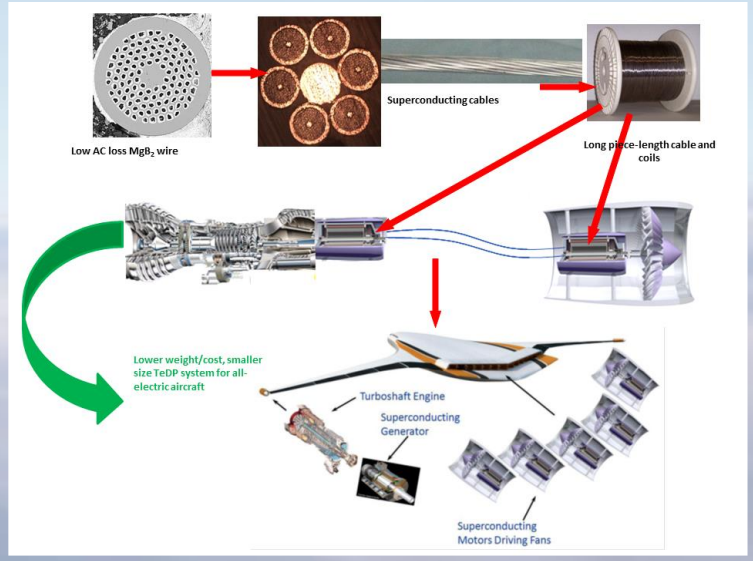
Design, fabricate and characterize new sets of MgB_2 superconductors with high superconductor current density, high superconductor fill factor, lower AC losses and in significant piece lengths (hundreds of meters). Cables will have low AC loss features: fine superconducting filaments (< 10 μm) and twisted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

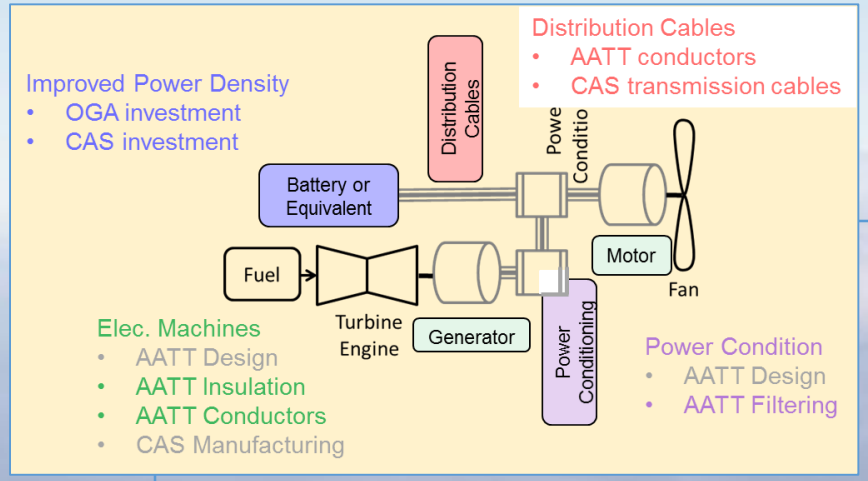


Test MgB_2 coil fabrication

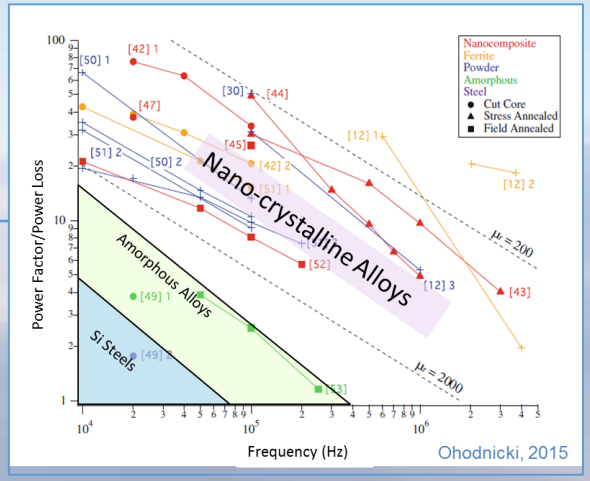
(Brown, NASA)

Electric Powertrain Materials

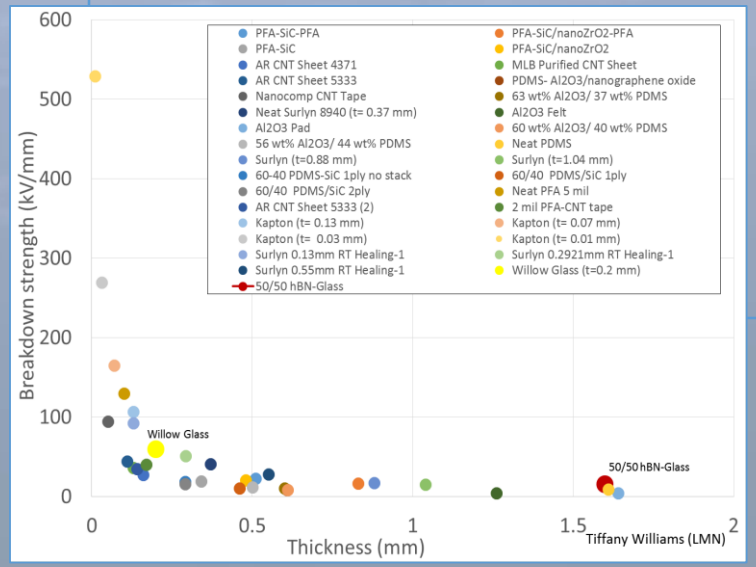
Power System Weight Drivers



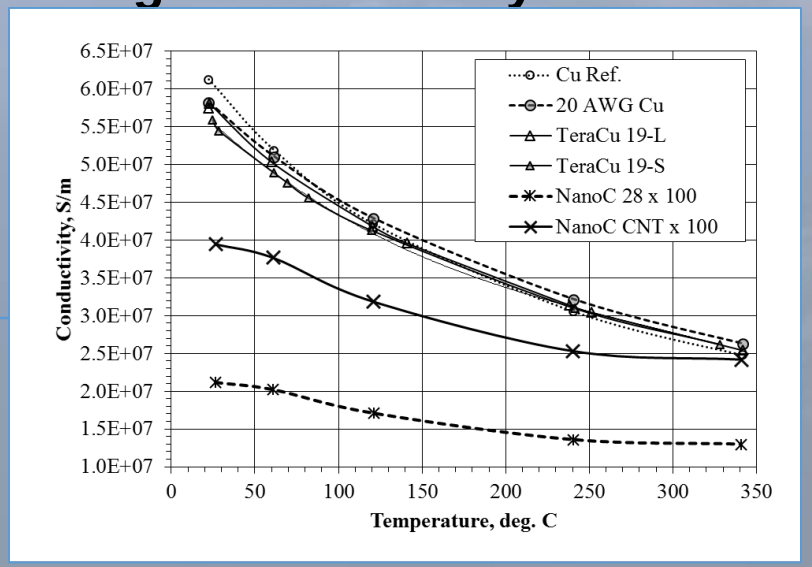
Magnetic Materials



Insulation Materials

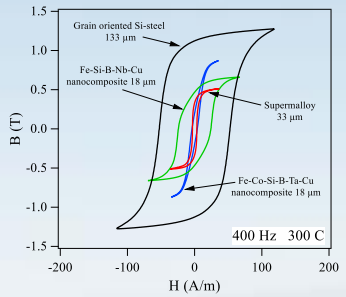


High Conductivity Materials

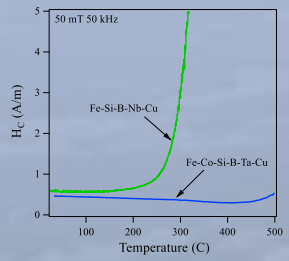


Alloy Development

High temperature nanocomposites



GRC alloy

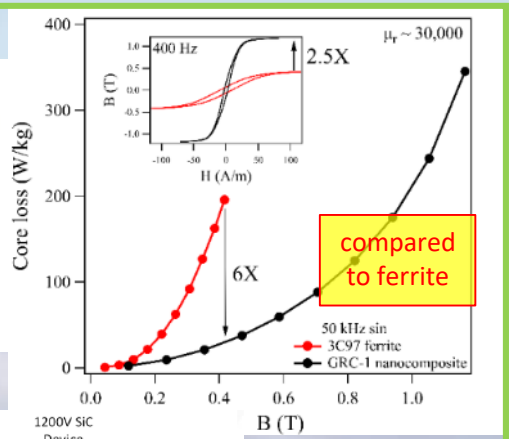


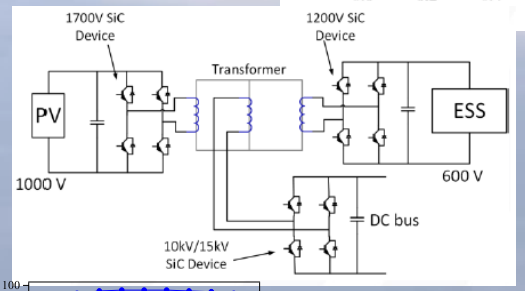
New alloy maintains room temperature performance of standard FeSi-based alloys, but extends useful range >300C

High permeability: choke/transformer

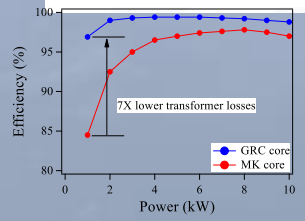
μ_r = 30,000







Three-Port Modular DC-DC Converter

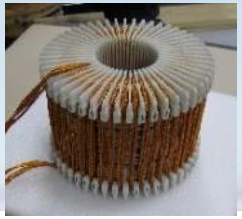


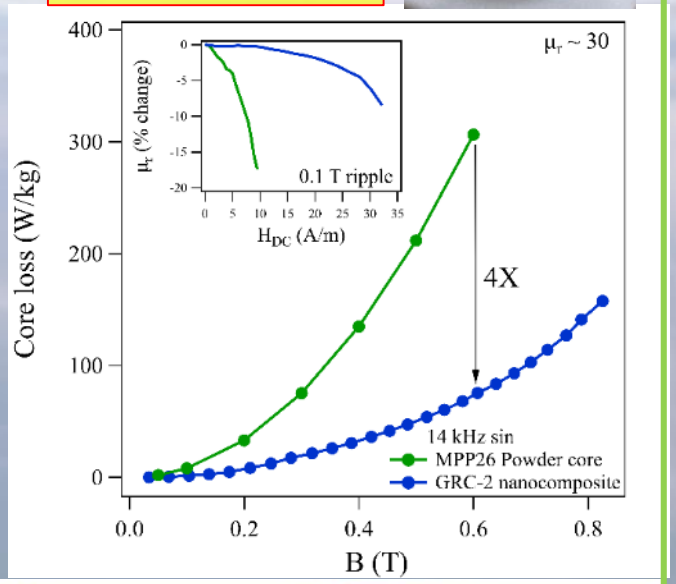
Not all commercial FeSi-based nanocomposites are high quality

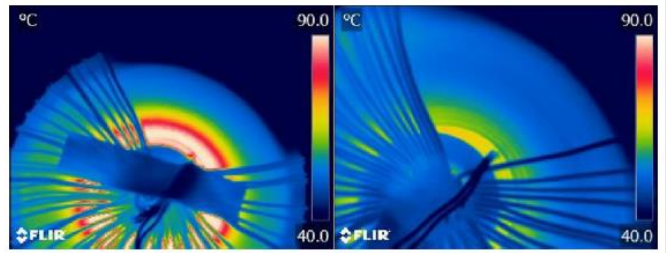
Low permeability: inductor

μ_r = 30 $L \sim \mu$

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







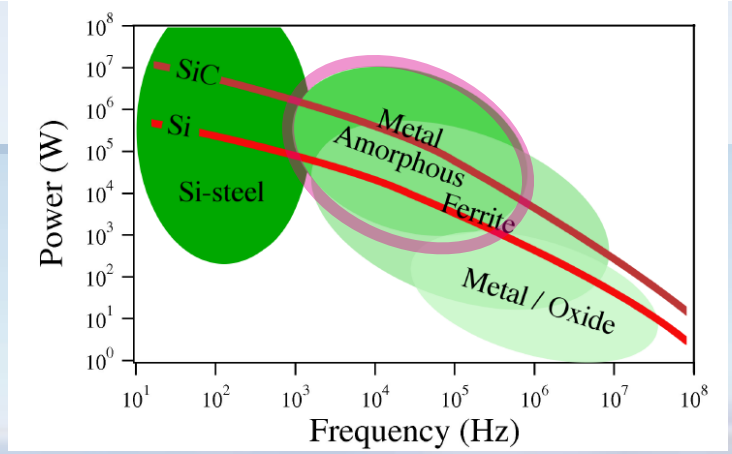
Spatially graded μ

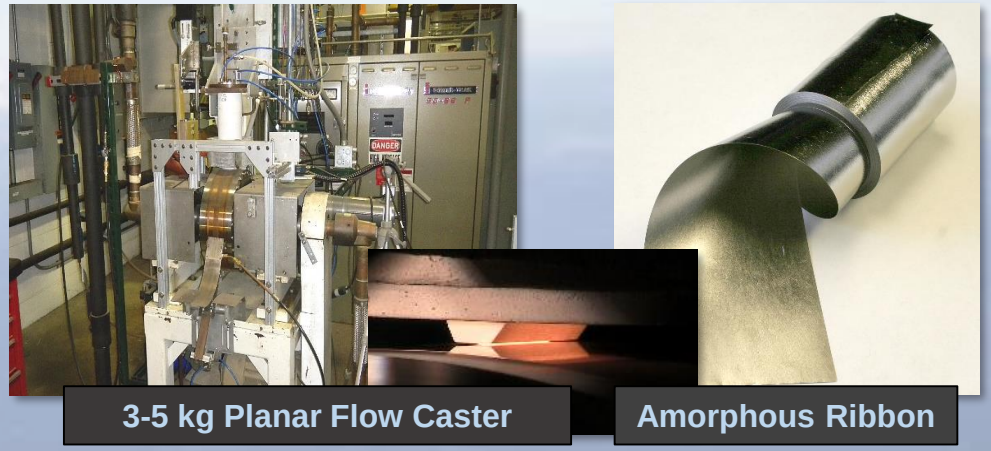
Byerly, et al. JOM **70** 2018

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

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



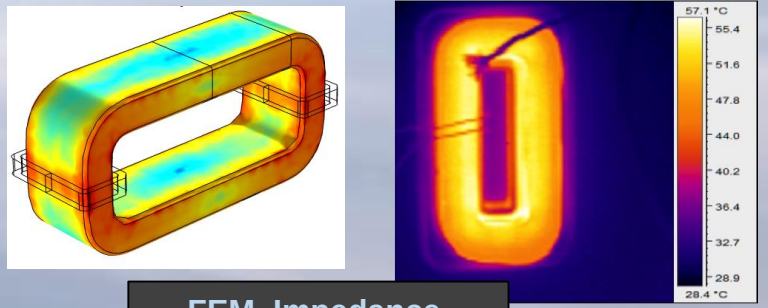


3-5 kg Planar Flow Caster

Amorphous Ribbon

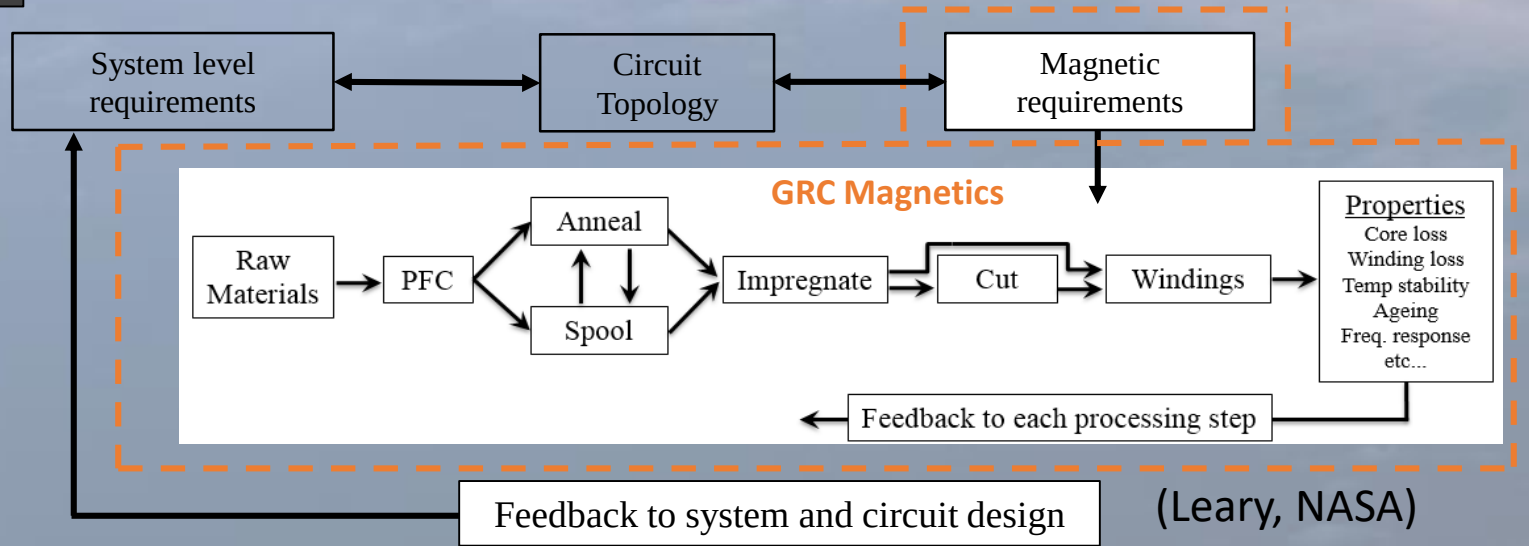


Annealed, Impregnated, Powder Coated Core



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 gapless cores with low loss
- Design iteration is key to success



(Leary, NASA)

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

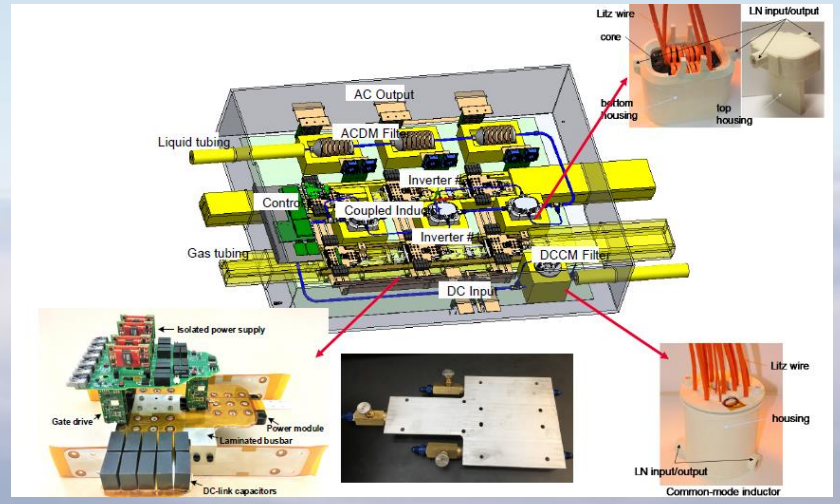
Design, build, test and demonstrate a cryogenically-cooled MW inverter system to achieve the technical objectives of 99.3% efficiency and 26 kW/kg specific power and meet the requirements of power quality and electromagnetic interference (EMI) compliance.

Results

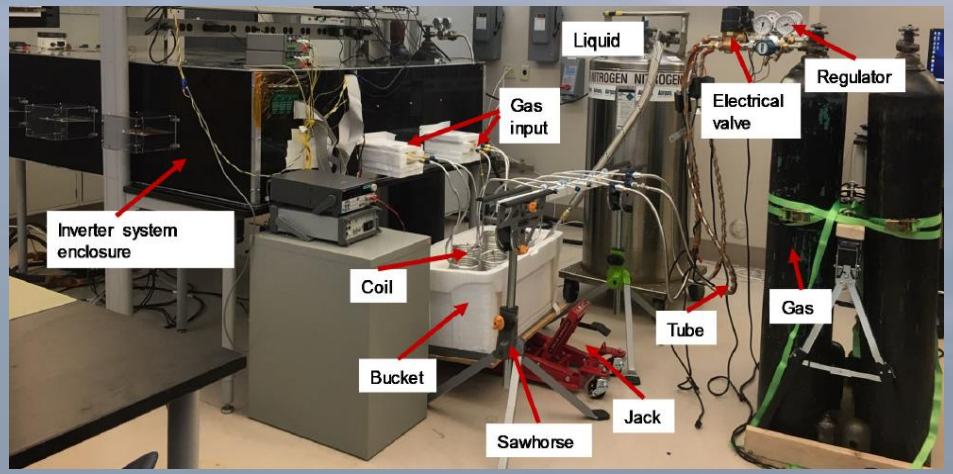
- Designed and built 1 MW protype consisting of two paralleled 500 kW inverters, and completed dual liquid and gaseous nitrogen cooling system to accommodate the requirements of power stage and filters.
- Successfully tested at 1 kV DC bus voltage input and rated 1 MVA power with cryogenic cooling. AC 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

(Choi, NASA)

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

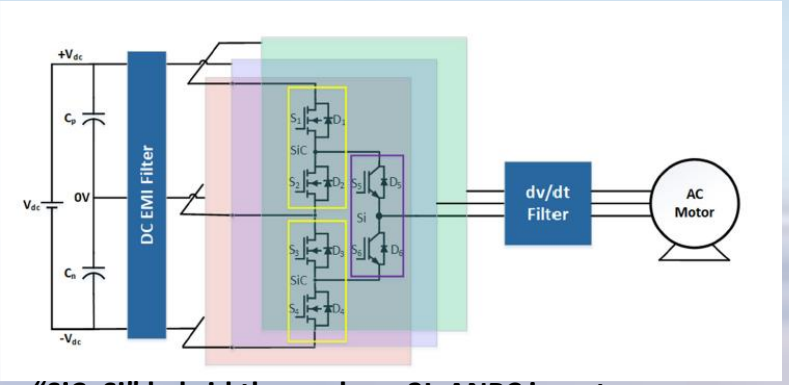
- Develop and demonstrate high voltage SiC MW inverter with altitude capability.
- Retire risks for 2 kV+ DC system for 30+ kft altitude at ambient temperature.
- Retire vibration risk.

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



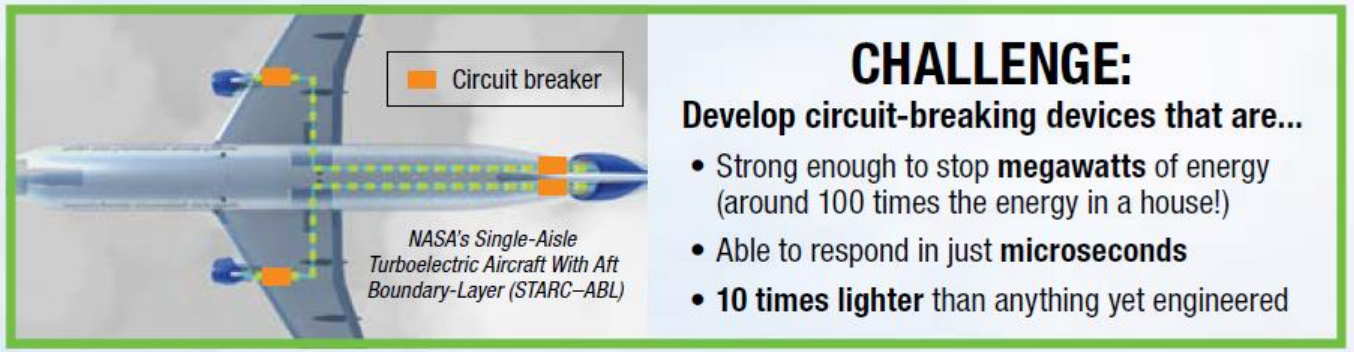
Gen3 inverter in altitude chamber

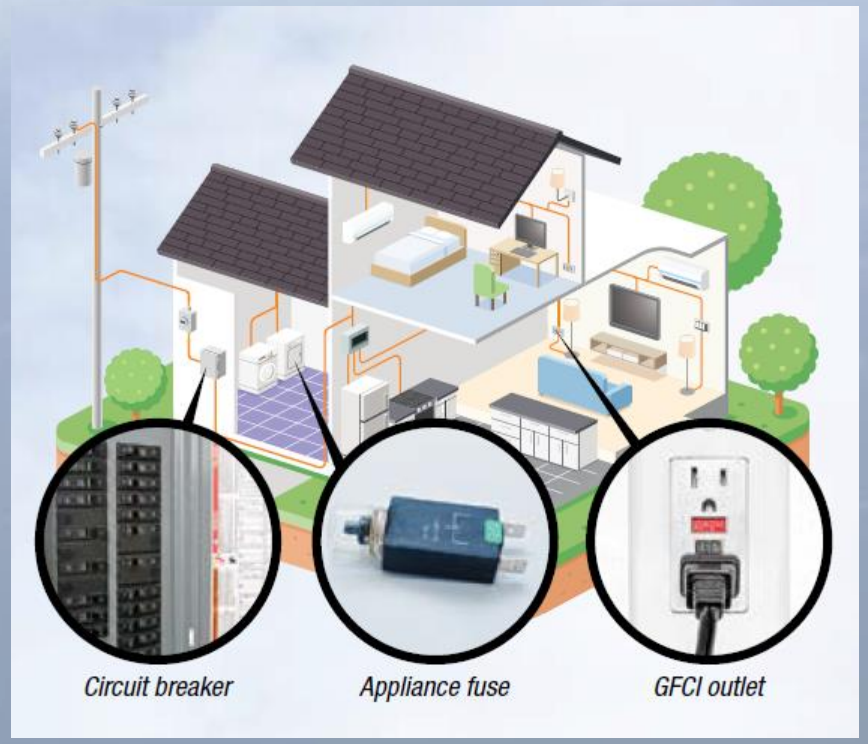


dv/dt filter inductor tested for altitude

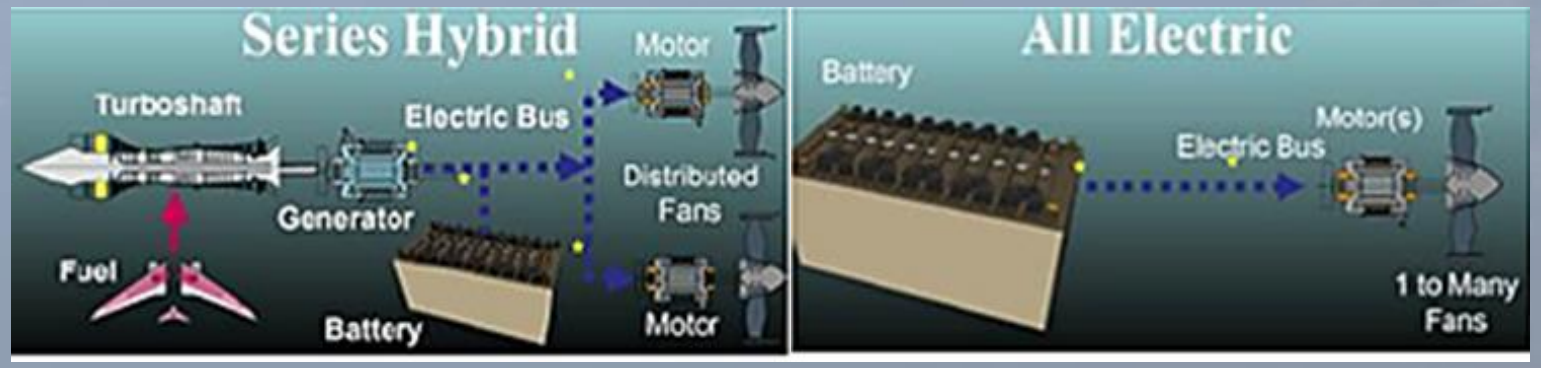
(Choi, NASA)

Fault Management Challenge

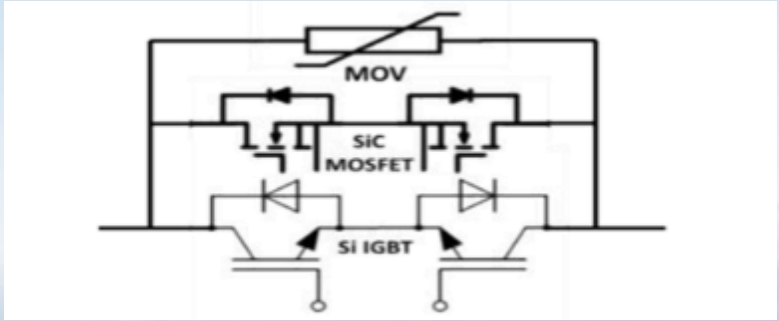




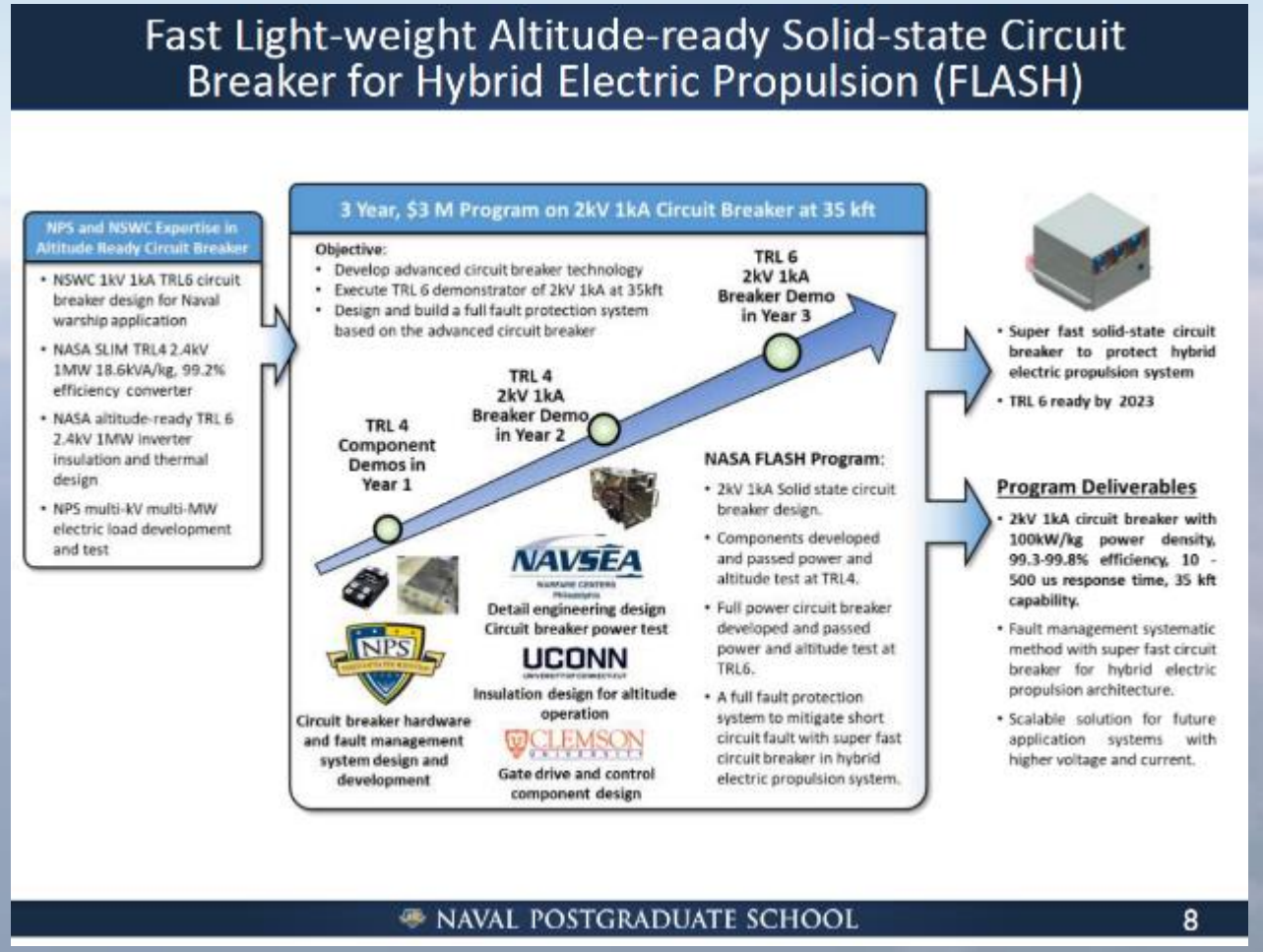




Ultra-Fast, Light-Weight Breaker System



- 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.



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)".

Fault Management Thermal and Mass Impact

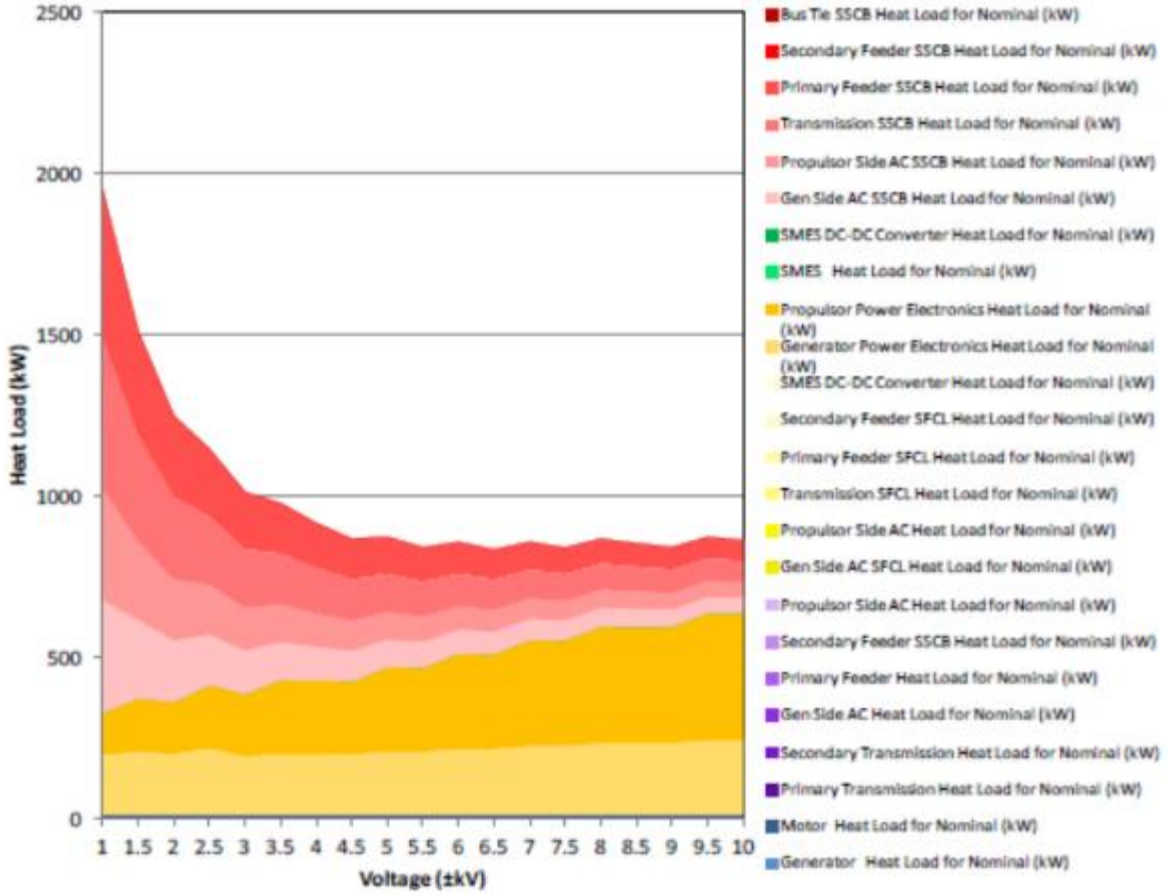
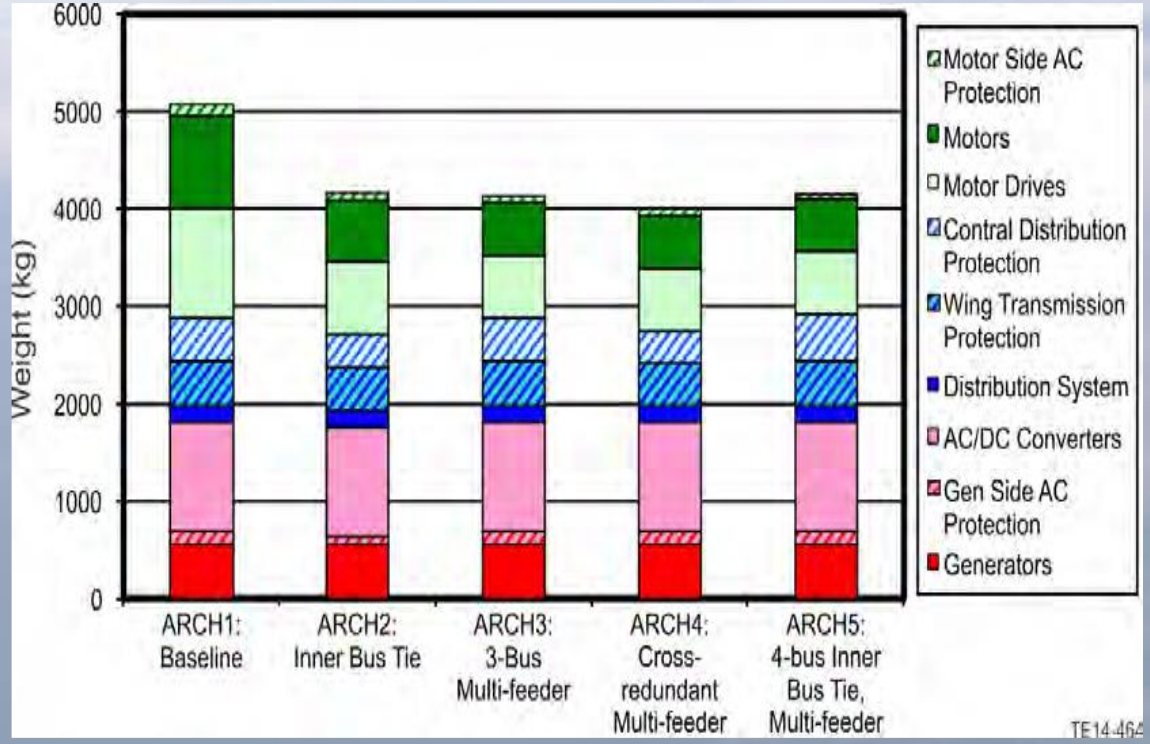
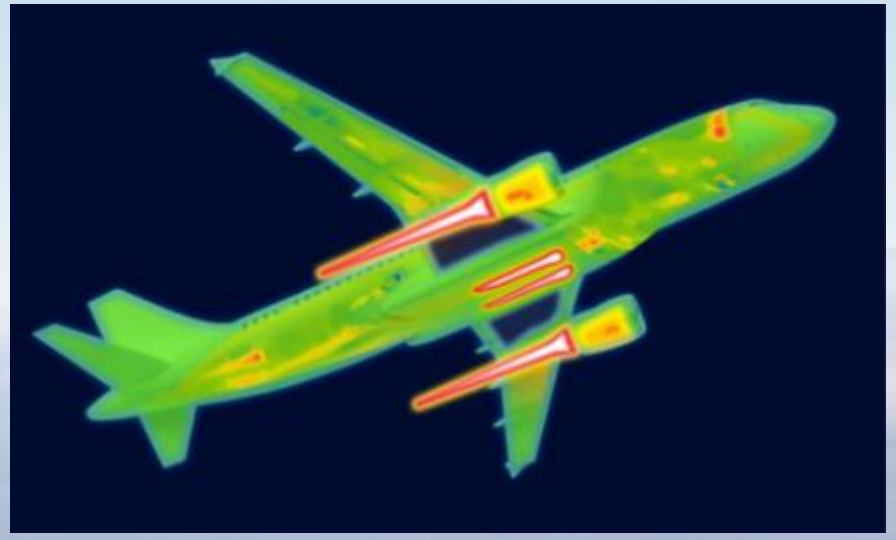


Figure 150.—Heat from Devices during 10 MW Nominal Operation for Baseline Configuration and Losses.



(Mike Armstrong, Rolls-Royce NASA RTAPS Study)

High Exergy and Low Exergy Heat Sources





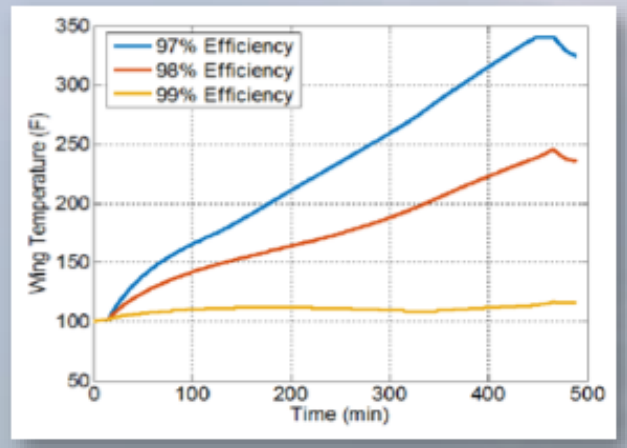
Beneficial Uses of Higher Exergy Waste Heat from Powertrain		
Sink Location	Sink Temperature (C)	Benefit
Engine Core	600	Recuperates engine and powertrain heat for efficiency
Engine By-pass	100	Increases thrust with P-51 effect
Outer Mold Line	200	De-icing, Anti-icing, Turbulent Boundary Layer Mgmt
Auxiliary Power Unit	400	Provides electrical power from waste heat
Cabin	40	Provides cabin heating without bleed air from turbine
Battery	20	Maintains batteries above freezing
Oil Coolant Loop	100	Smaller heat exchanger required due to higher temp.
Ram Air	100	Smaller heat exchanger required due to higher temp.

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

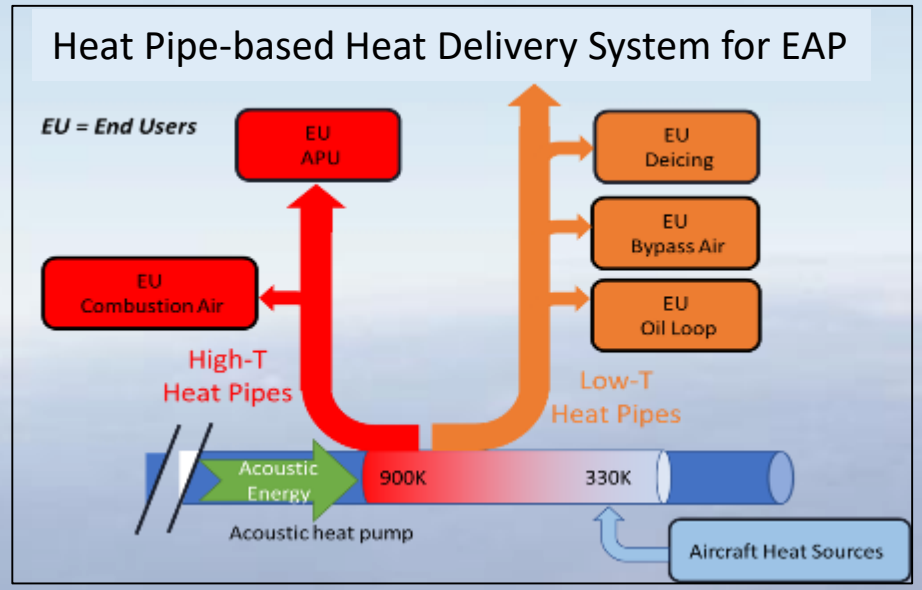
Mode	Limits	Scale
Electrical	Voltage, Copper Mass and Heat	I^2R
Mechanical	Lubrication, Vibration, Heat, Mass	$0.5\ \tau\omega^2$
Fluid	Freezing, Pump, Impurities, Heat, Mass	$\dot{m}\ C_p$T
Phase Change/Vapor	Gravity, Orientation, Distance, Freezing	<1 m
Acoustic	Design Challenge, Some Heat	$0.5 * pv^2$



P.C. Krause

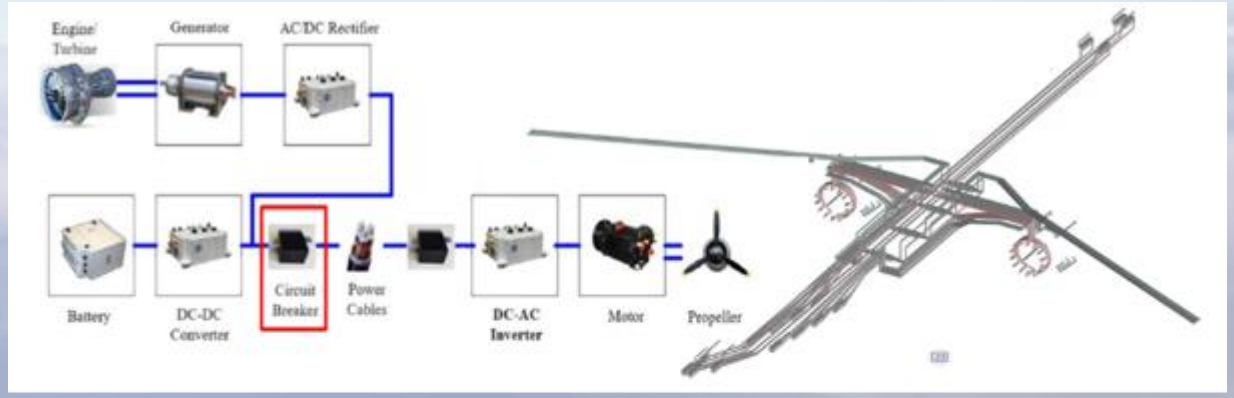
50kW to >800kW of low-grade thermal heat trapped within composite aircraft body

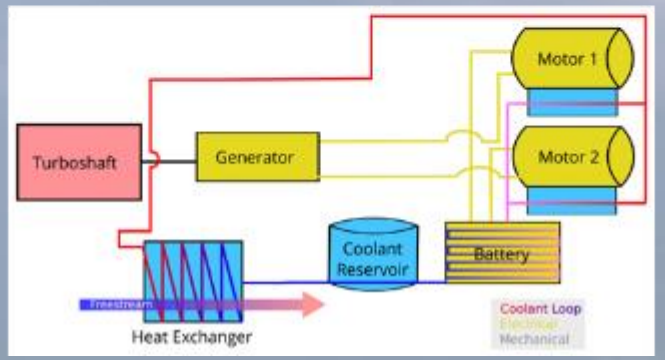
Dynamic Real-Time Exergy Optimization



Advanced Cooling Technologies (Tarau)

Naval Postgraduate School (Zhang)



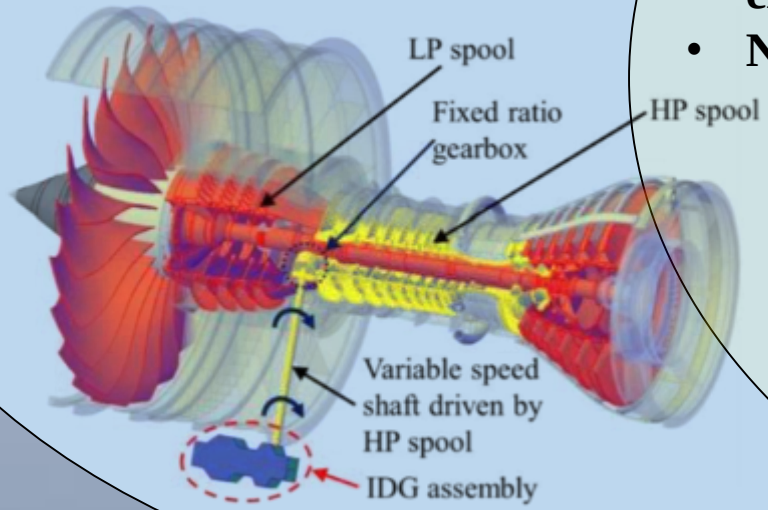


University of Michigan (Breilje)

TMS Integration

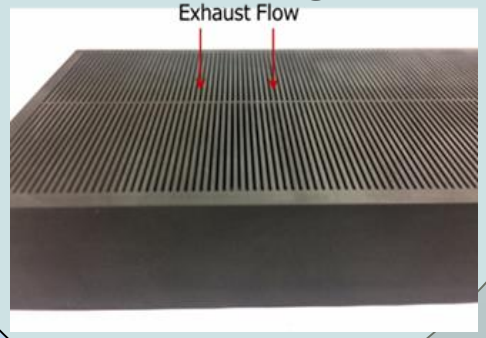
Turbofan TMS eTC

- **Multifunctional Liner TRL 4 test of system - ANCF**
- **AI designed lightweight heat exchanger**

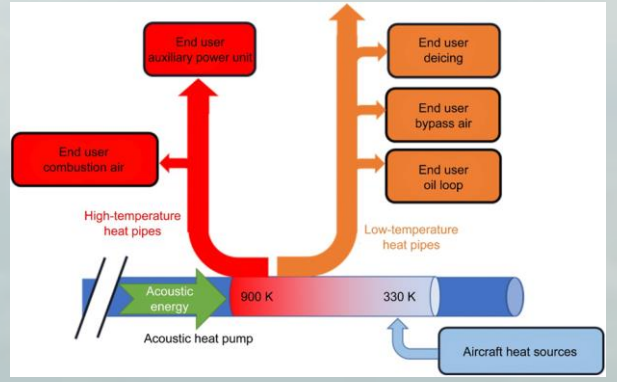


Propulsion and Power Interface

- **Graphite Compact heat exchanger**
- **N+3 Aircraft/Engine**



Powertrain TMS TC
TRL-4 FY23 Powertrain Demo





Aircraft Energy Sources

Jet Fuel is Light-Weight and Low-Cost



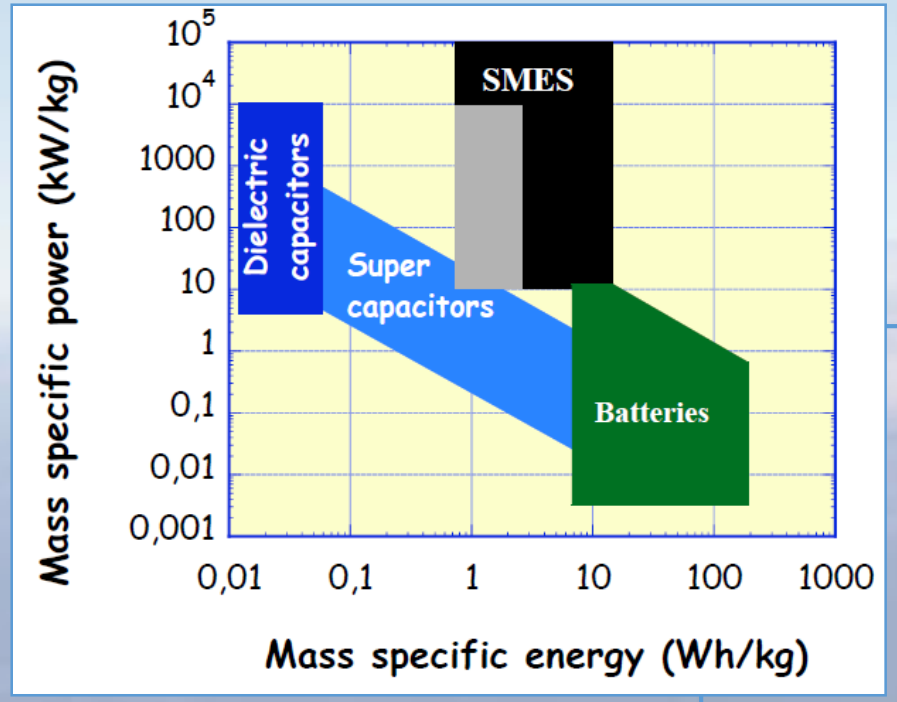


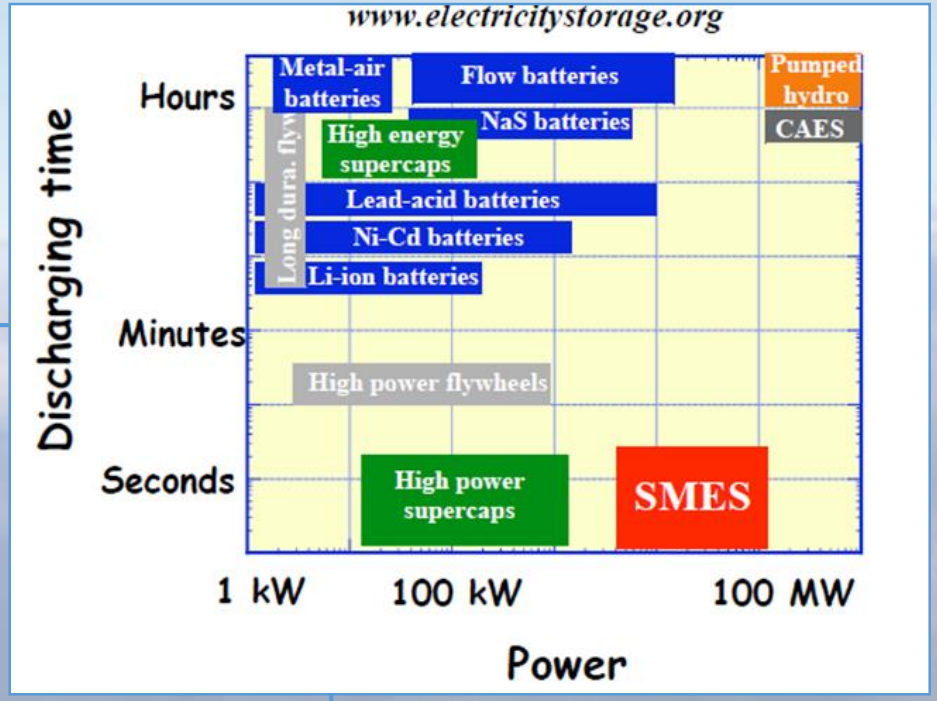
❑ 1 kg coal	8 kWh
❑ 1 kg wood	4 kWh
❑ 1 kg oil	10 - 12 kWh
❑ 1 kg natural gas	10 - 14 kWh
❑ 1 kg enriched uranium(~2% burnup)	600 000 kWh
❑ 1 kg of water - 1000 m fall	0.003 kWh ⬅
❑ 1 kg Pb battery	0.03 kWh
❑ 1 kg lithium battery	0.2 kWh

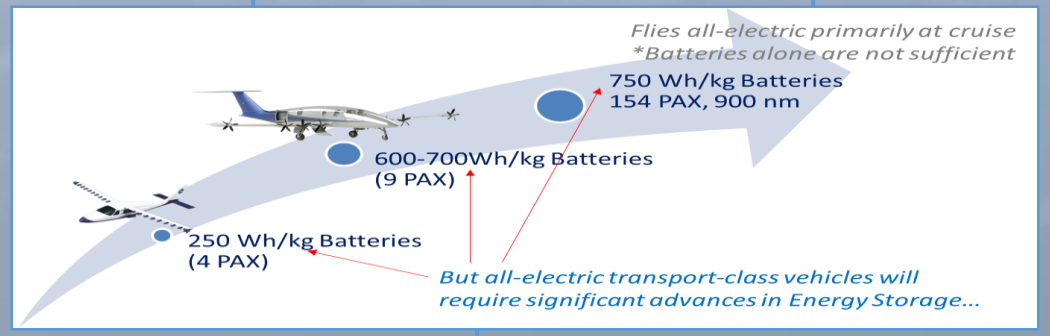
(1 kWh : kinetic energy of a 10 ton truck at 100 km/h)

Required mission power level determines energy source

Aircraft Energy Storage

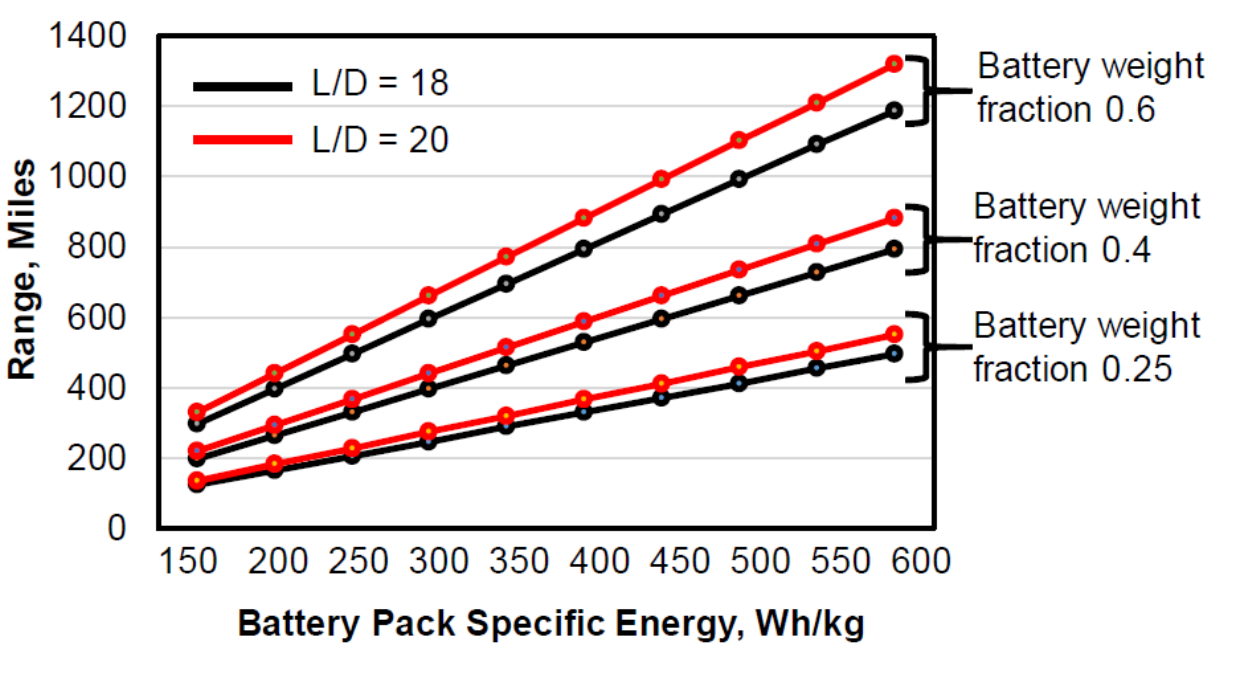






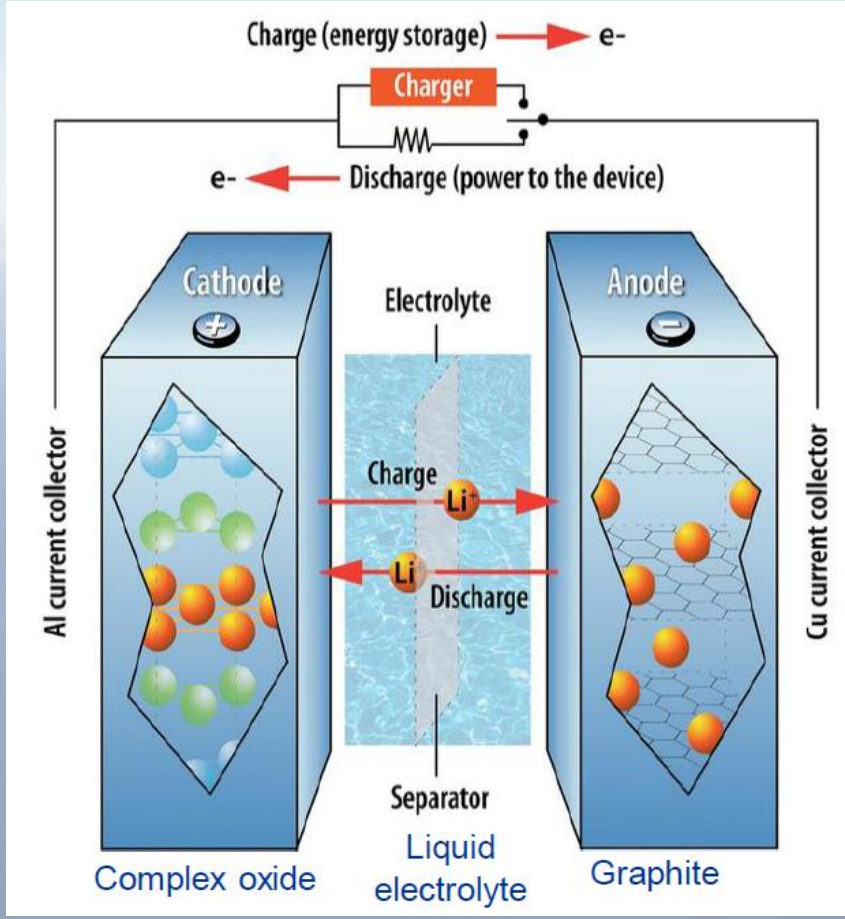
Can choose high energy or power, mass is a challenge

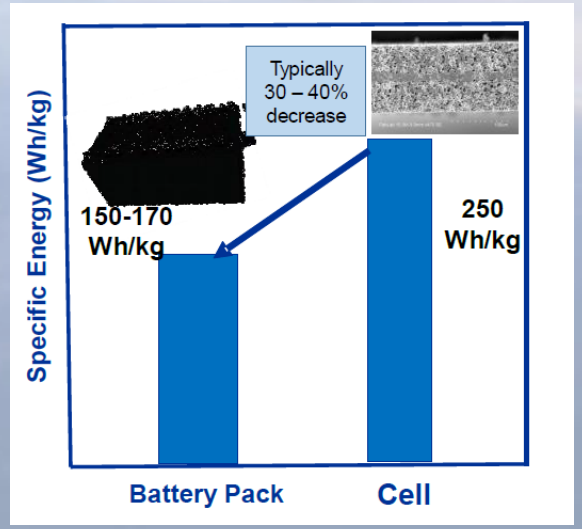
Battery Performance and Impact

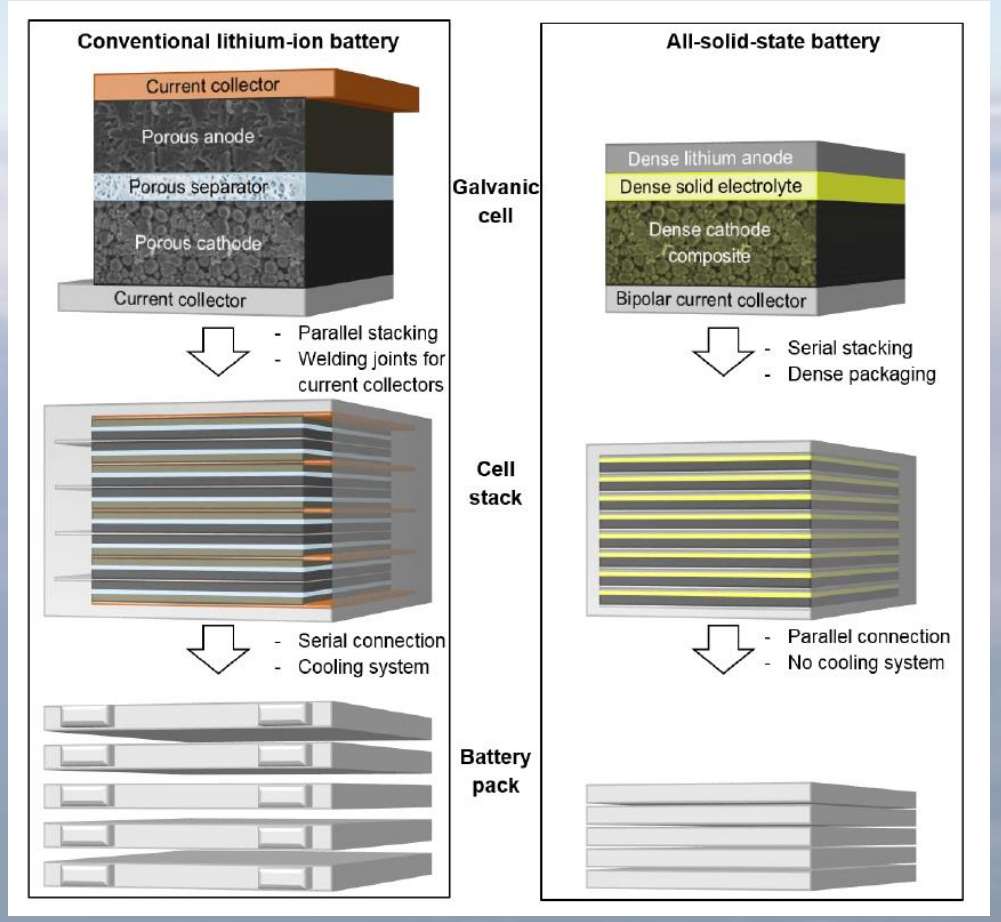


Anode	Cathode	Theoretical Cell Specific Energy (Wh/kg)
Graphite (SOA)	NMC (SOA)	615
Si	NMC (SOA)	952
Li metal	NMC (SOA)	755
Si	Sulfur (Li_2S)	1550
Li metal	Sulfur	2500
Li metal	Air (oxygen)	3500 - 5200

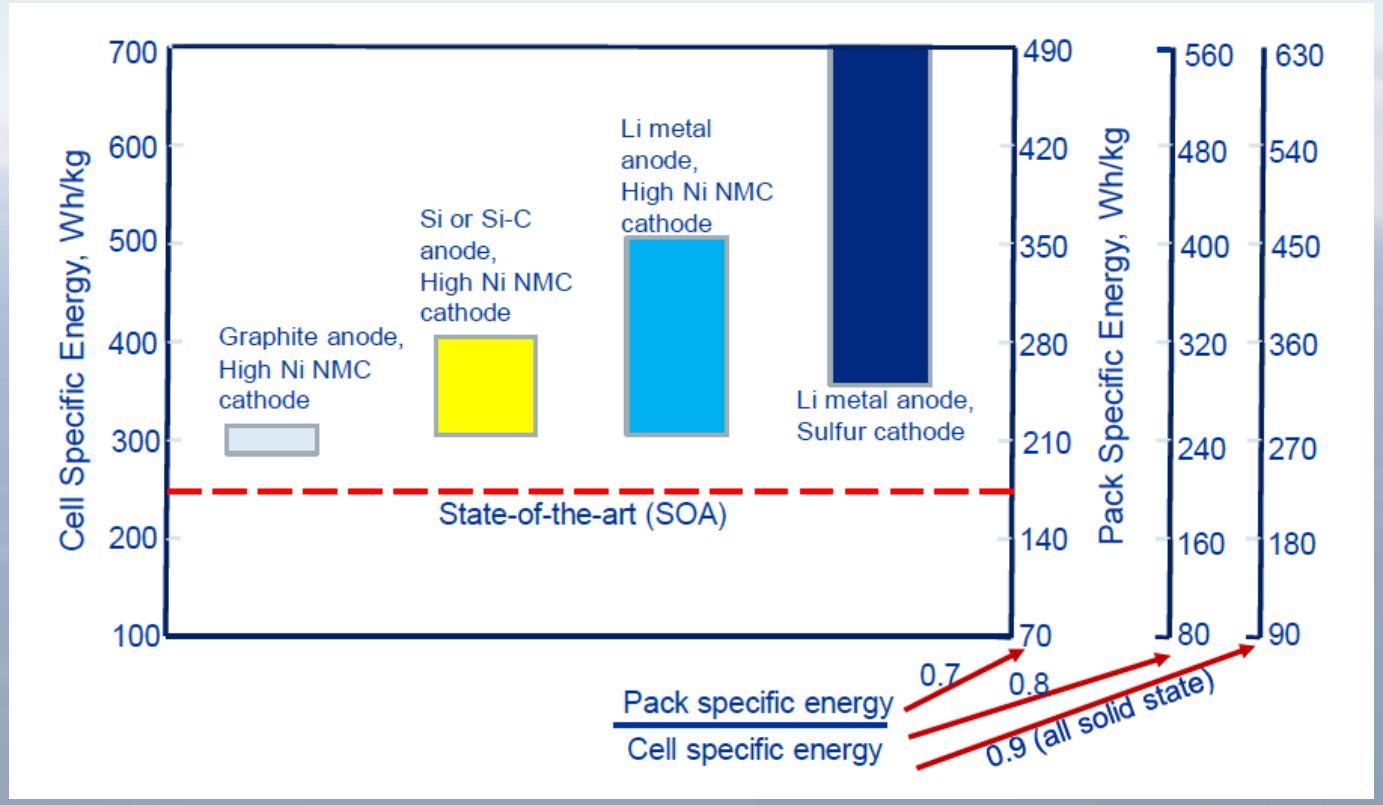
Solid-State Energy Storage

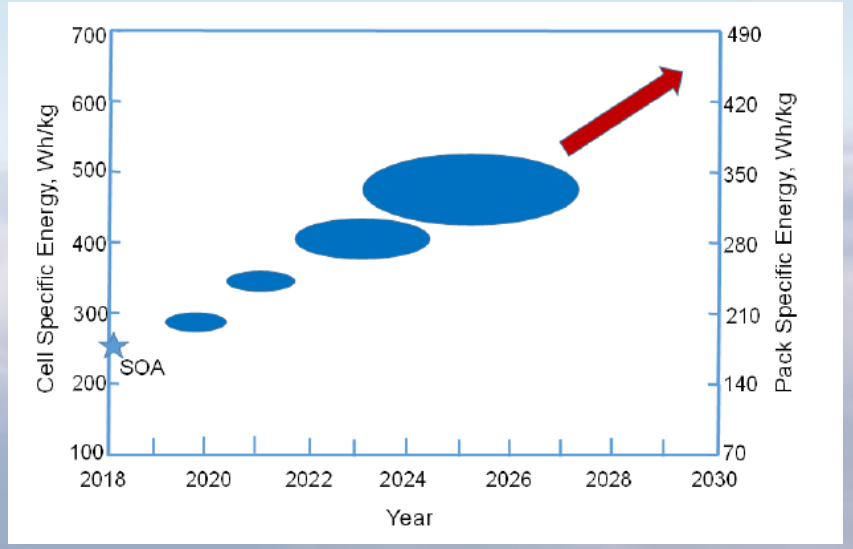


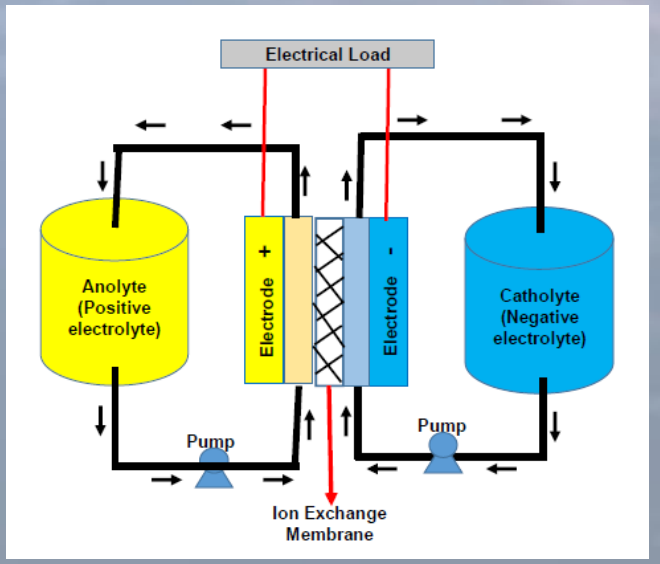




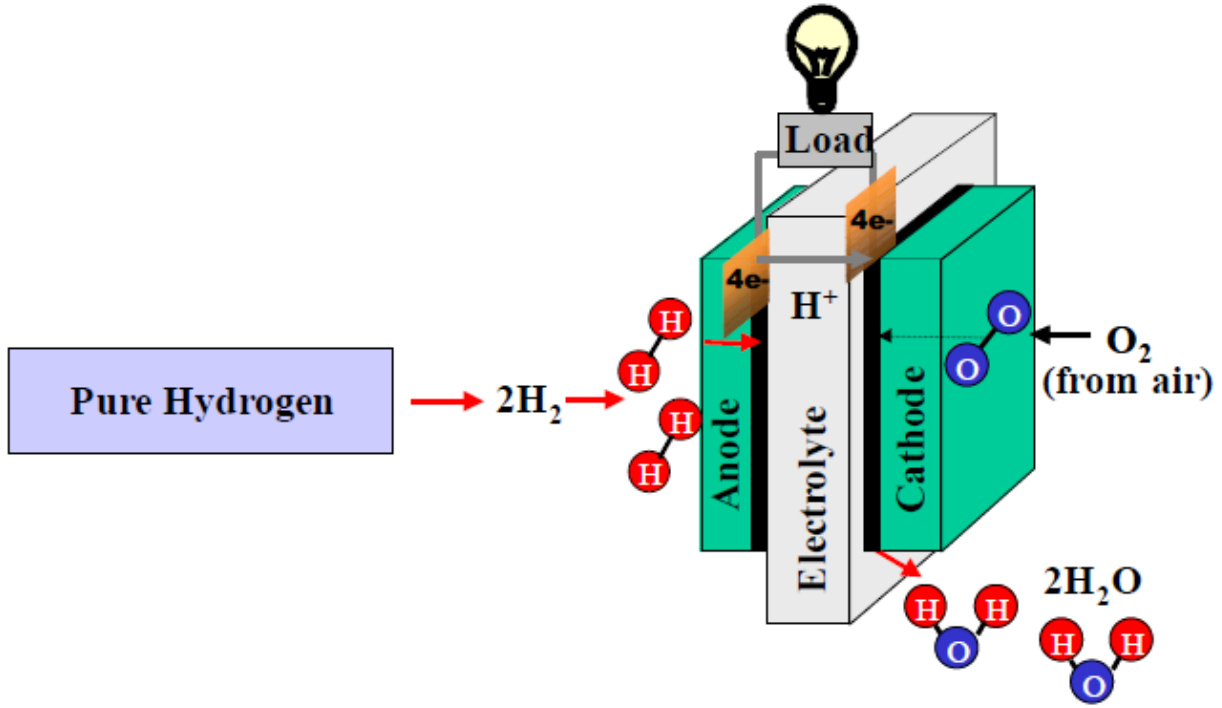
Battery Packaging and Improvement

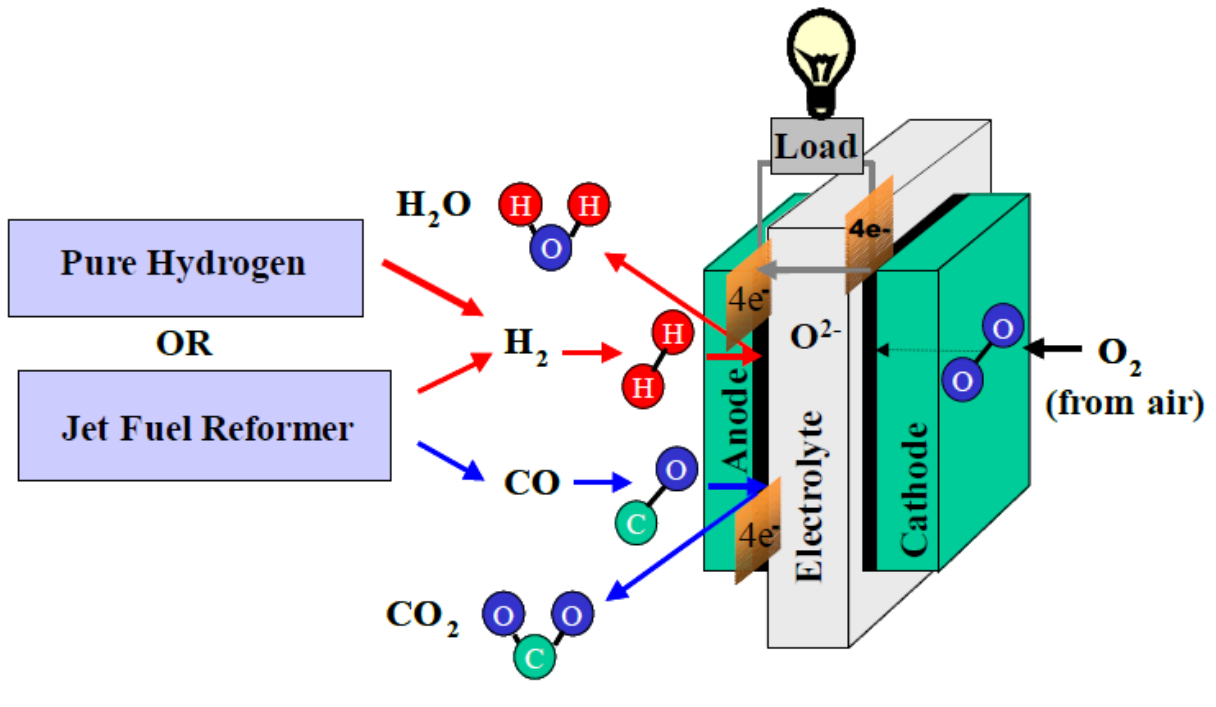




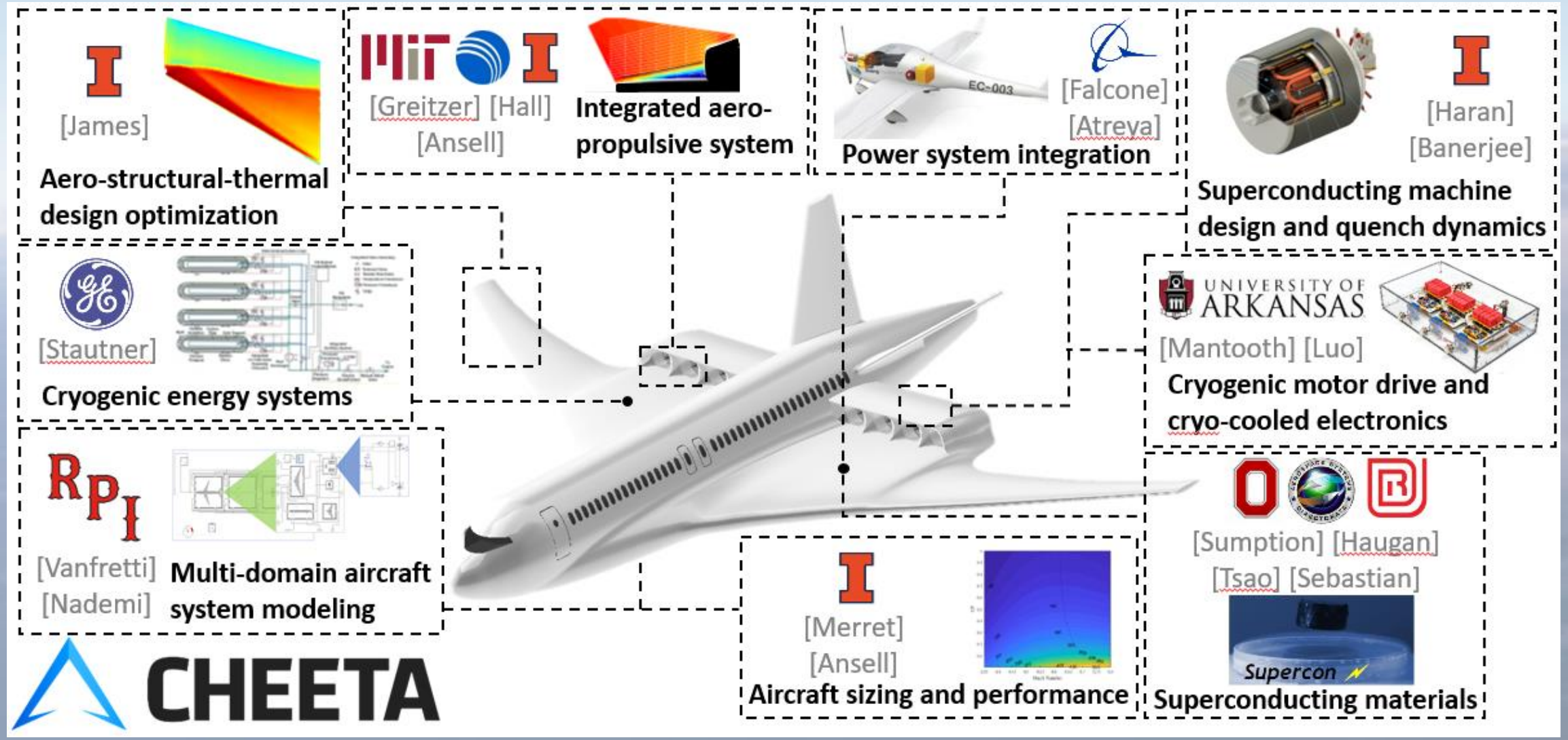


Hydrogen / CNNF / SAF Alternative Fuel Options





University of Illinois NASA ULI Project



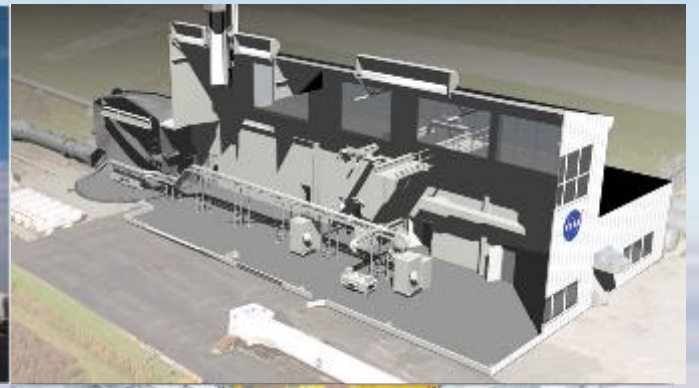
(Provenza, NASA)

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





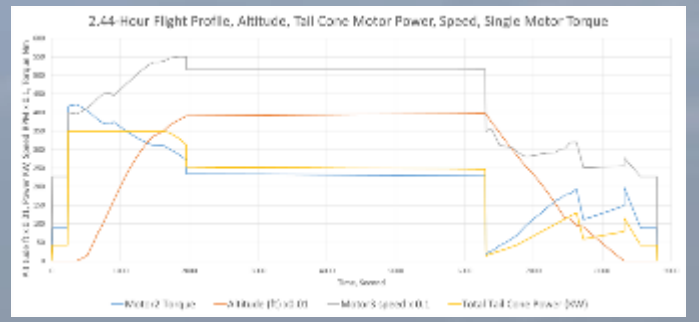


TRL maturation:

- **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.**

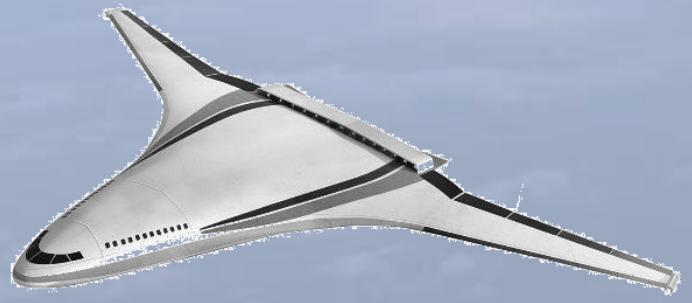


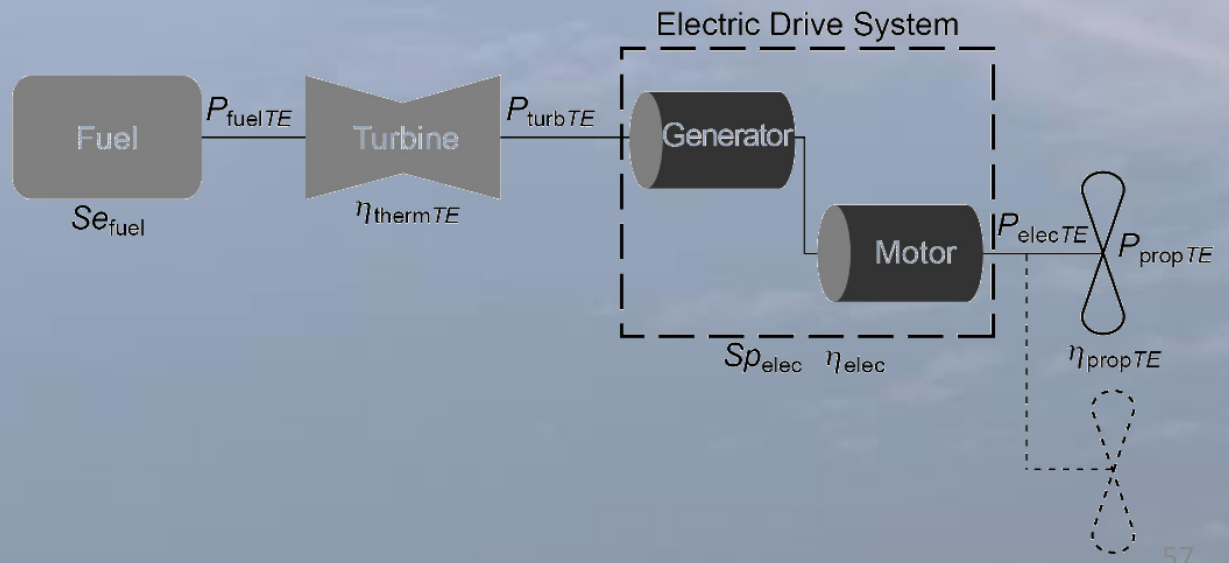
Vehicle Summary

- EAP for commercial transport include a wide range of PAI and drive train options.
- Bounding analyses provide starting point for detailed studies
- KPPs for the drive system are specific power, efficiency, and electric propulsion fraction.
  - Drive system is everything between the turbine and propulsor
- Equations compare benefits and costs of EAP relative to conventional aircraft and help to establish component KPPs.

Fully Turbo-electric Aircraft

- The requirement that the electric drive system must provide power for takeoff results in tougher requirements on specific power than for partially turboelectric aircraft.

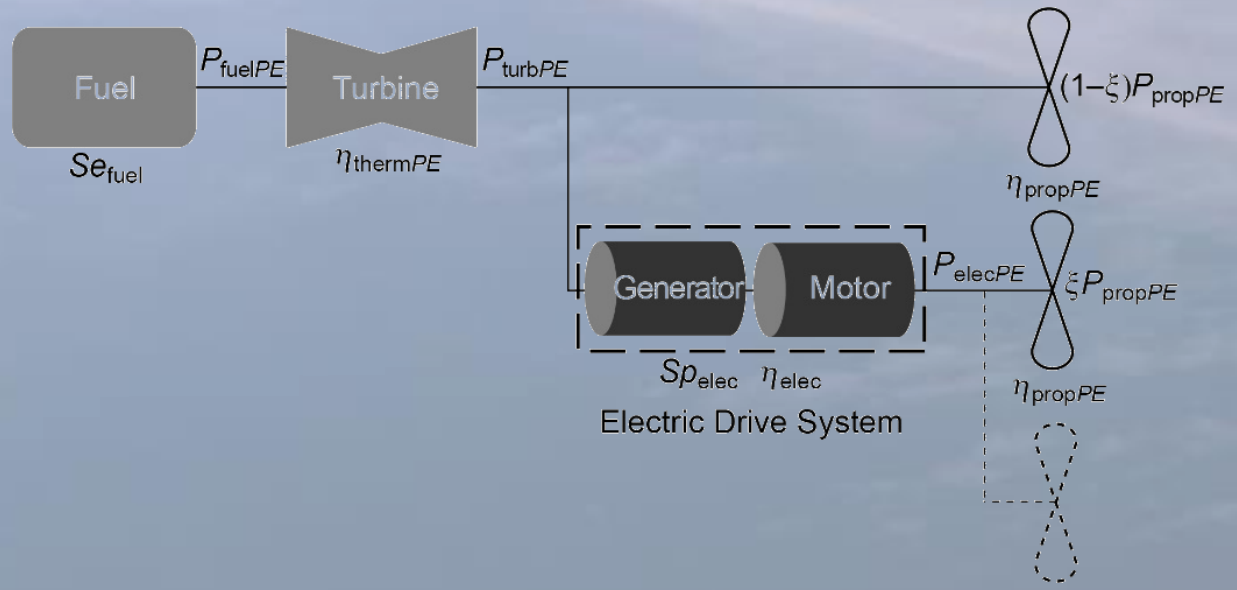




Partially Turbo-electric Aircraft

- Assuming propulsive benefits that scale with electric propulsion fraction, a higher electric propulsion fraction relaxes the requirements of the electric drive system, since the higher aero and propulsive benefits cancel the costs of the electric drive system.

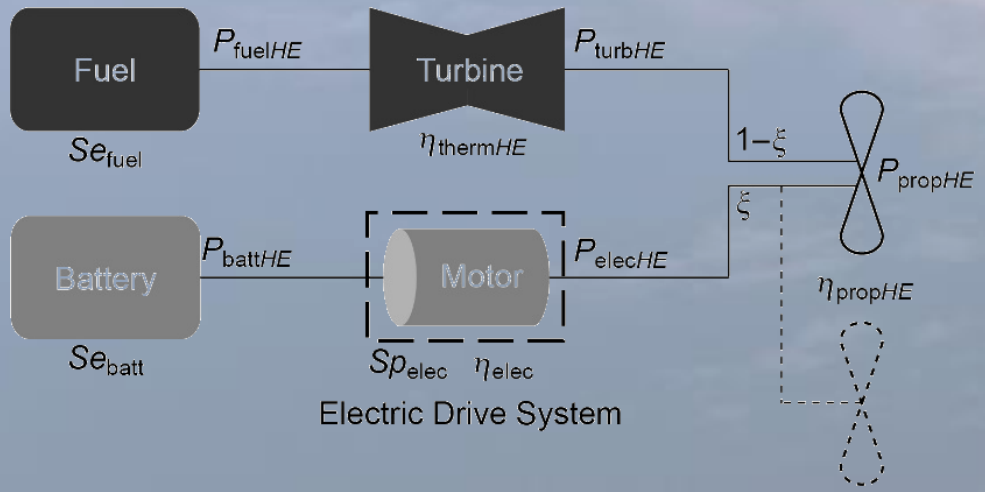




Parallel Hybrid Electric Aircraft

- Is better suited to shorter range flights.
- Improving battery specific energy will make hybrid electric configurations more feasible.
- Assuming constant aero and propulsive benefits, increasing the electric propulsion fraction increases the demands on the electric drive system because of the added battery weight.





All-Electric Aircraft

- The breakeven curves are very sensitive to the propulsive benefit assumptions.
  - The breakeven analysis is sensitive to the component weight assumptions. Here it was assumed that the ratio of OEW to initial aircraft weight remains constant.
  - In general, at low specific power, the efficiency of the electric drive system dominates. But increasing specific power above a certain level yields diminishing returns.



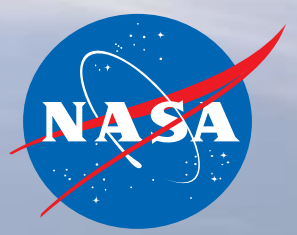


Vision

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.


iTEC2021


NASA