



NASA's Megawatt Electric Aircraft Propulsion Research and Development

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Seminar

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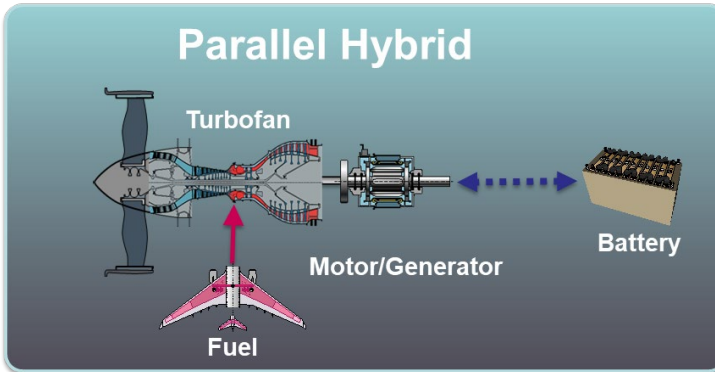
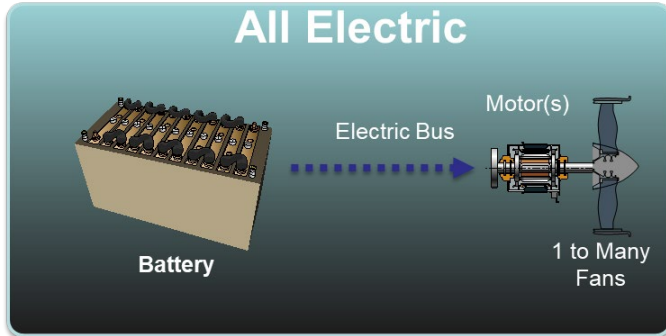
November 4th, 2022

Electric Aircraft Propulsion

Notional Electrification Spectrum

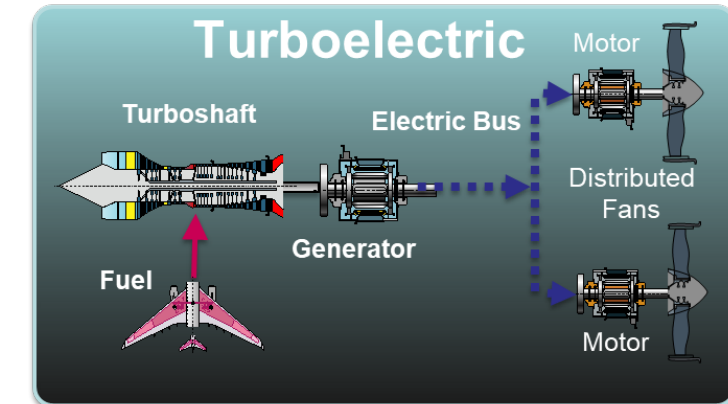
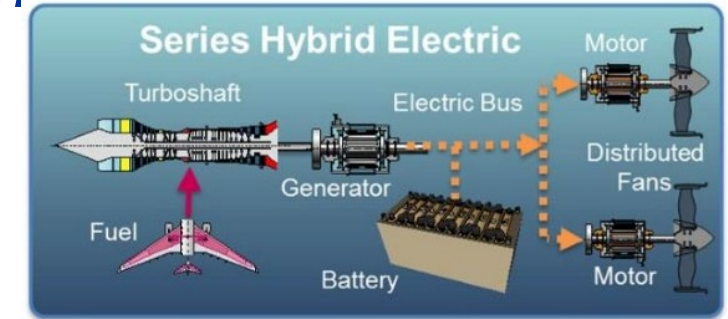
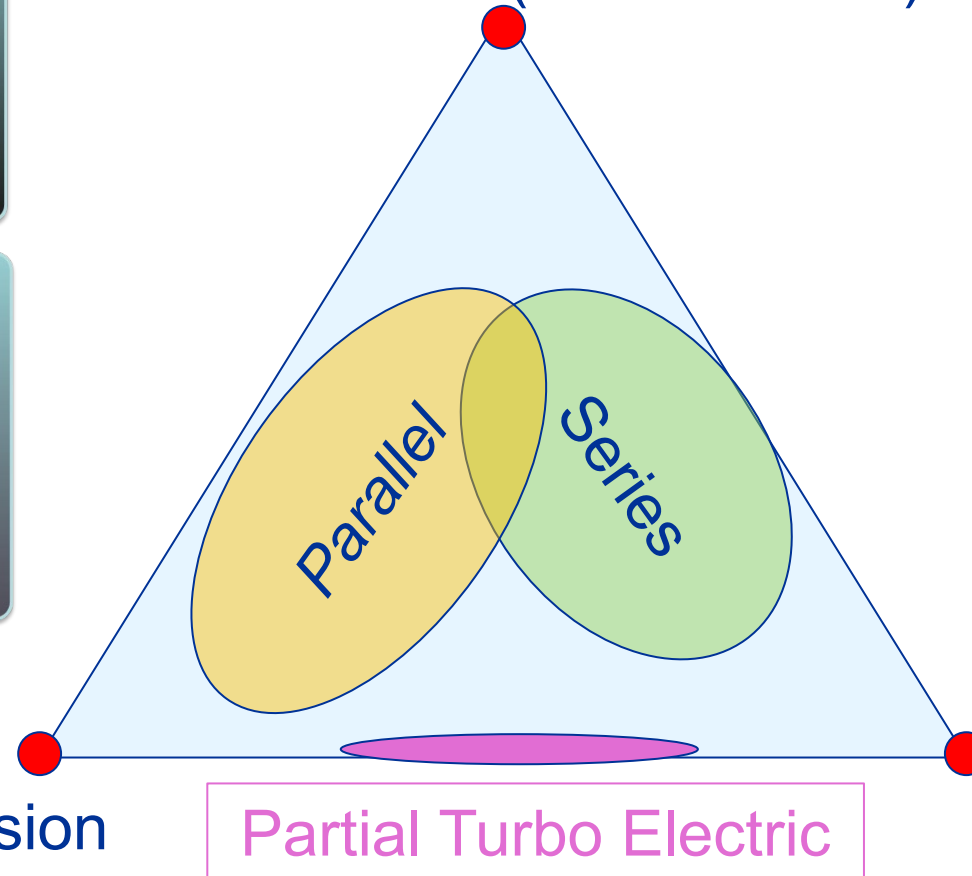
All Electric

- All batteries (no emissions)



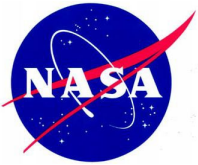
Conventional

- Fuel burning
- No electric propulsion

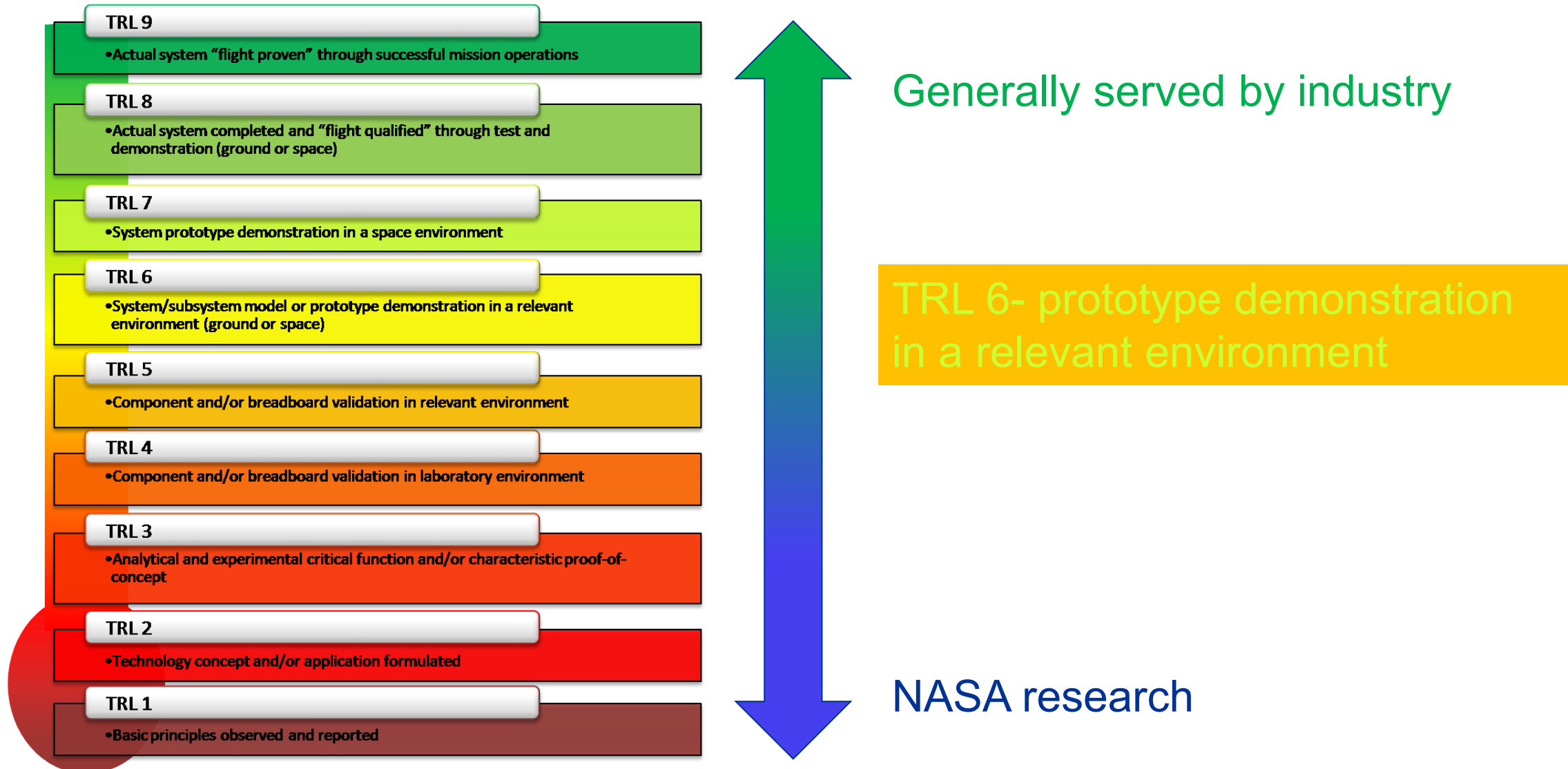


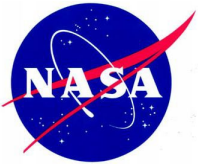
Turbo Electric

- Turbines only produce electricity
- No batteries



Technology Readiness Levels (Aeronautics)





NASA EAP REPRESENTATIVE ACTIVITIES

NASA has executed a plethora of EAP activities over the last 10 years and is in the process of advancing the future of sustainable flight. Work spans from fundamental research to flight demonstrations.



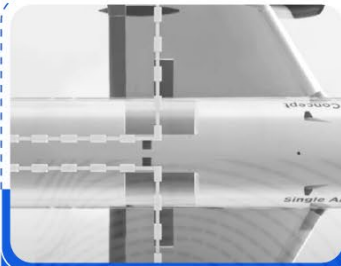
X-57, 100kW class flight demo of all electric distributed propulsion.



Revolutionary Vertical Lift Technology Studies of Electric, Hybrid, Turboelectric Concepts and Technology.

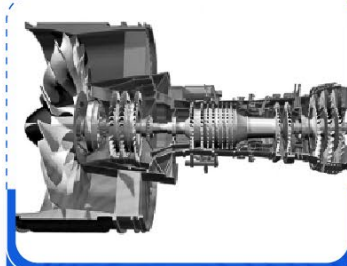


Electrified Powertrain Flight Demo – ground & flight demonstration of integrated MW-class powertrain.



Advanced Air Transport Technology/Propulsion & Power Subproject - powertrain technology

Transformational Tools & Technology – EAP materials & modeling.

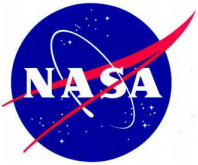


Hybrid Thermally Efficient Core (HyTEC)

Advanced turbine engine technologies in a high-power-density core.



SUSAN – A 20 MW hybrid-electric aircraft concept study featuring a single aft engine with distributed wing-mounted propulsors.



Sustainable Flight National Partnership

<https://www.nasa.gov/aeroresearch/sustainable-aviation-np/>

FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29
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Technology Readiness Target

Model Based Systems Analysis & Engineering

Sustainable Flight Demonstrator (SFD)

Flight Test

AATT - Transonic Truss Braced Wing

Technical Challenge (TC) Completion

Hi-Rate Composite Aircraft Manufacturing (HiCAM)

Mfg Demo & Structural Test

Hybrid Thermally Efficient Core (HyTEC)

Core Demonstration & Test

Electrified Powertrain Flight Demonstration (EPFD)

Flight Test

AATT - Electrified Aircraft Propulsion

Technical Challenge Completion

Achieve TRL 6 to support Industry Product Decisions

Leverage the Asset
—
Future Spirals

Planned

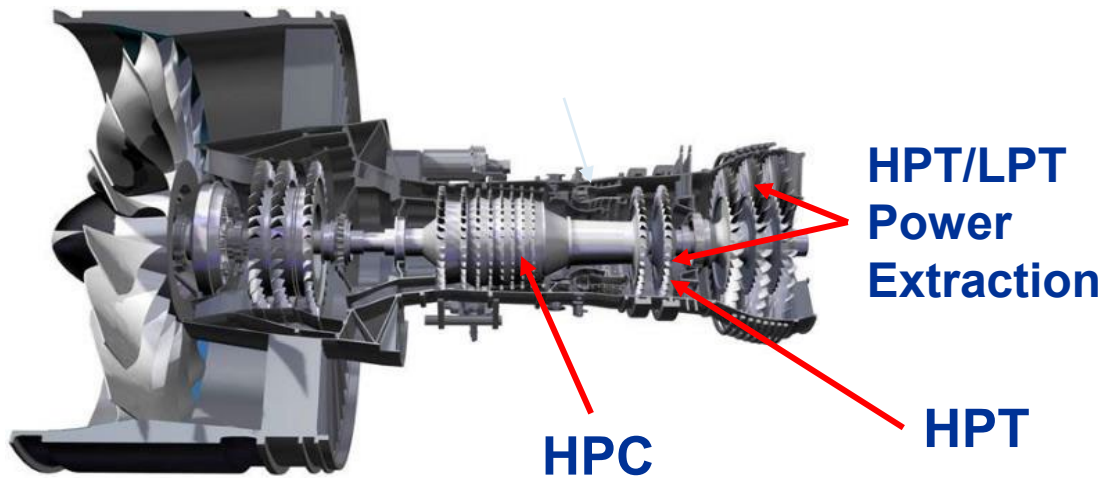
Notional

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Hybrid Thermally Efficient Core

Combustor & Sustainable Aircraft Fuel



Requirement

- Achieve a **5 to 10% fuel burn reduction** versus 2020 best in class.
- Achieve **up to 20% power extraction** (2 to 4 times current state of the art) at altitude.

Rationale/Impact

- Reduce engine core size and facilitate hybridization.
- Lower environmental impact and reduce end-user cost.
- Invest in aggressive, impactful small core turbofan technologies with development risk.
- Technology improvements for efficiency, durability, performance, and hybridization.

Approach

- Partner with industry to mature and demonstrate promising technologies

Accelerate development and demonstration of next generation small-core turbofan engine technologies



NASA Electrified Powertrain Flight Demonstration

Electrified Powertrain Flight Demonstration (EPFD) project:

- Partnership with U.S. industry to establish and demonstrate integrated megawatt-class powertrain systems.

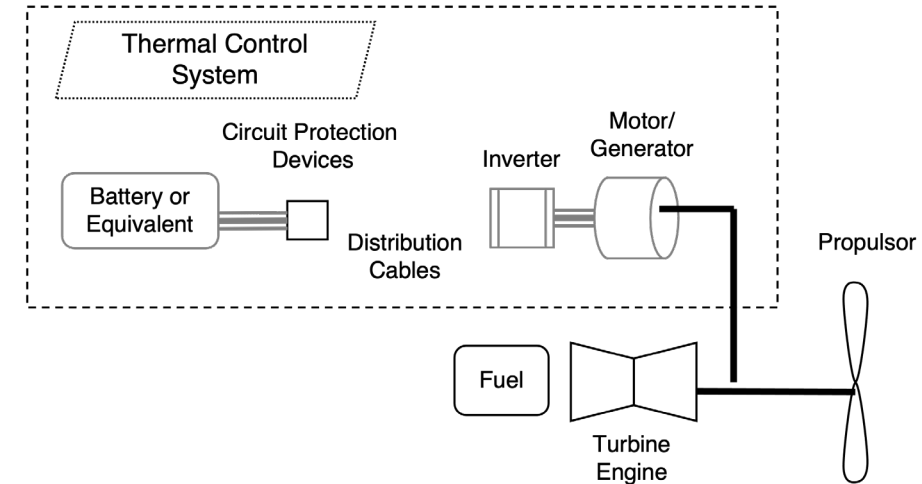
EPFD Goals:

- Accelerate US industry technology readiness and competitiveness
- Facilitate new aviation industry S – Curve for electrification
- 2030-2035 Entry Into Service: Next generation thin haul, regional and Single-Aisle markets



Regulations and Standards will play a large role:

- NASA is partnering with industry to identify the regulatory and standards gaps that may exist for the highest priority electric technologies and gather data to support future regulations and standards development.



Project Manager, Gaudy Bezoz-Oconnor (gaudy.m.bezos-oconnor@nasa.gov)
Deputy Project Manager for Technology, Ralph Jansen (ralph.h.jansen@nasa.gov).



EPFD Industry Partners

NASA has selected two U.S. companies to that will rapidly mature Electrified Aircraft Propulsion technologies through ground and flight demonstrations. *[Information from linked news articles below]*

GE Aviation, \$179 million.

- Partnered with Boeing to modify Saab 340B powered by GE CT7-9B turboprop engines
- Megawatt-class and multi-kilovolt hybrid-electric propulsion system tested in simulated altitude conditions at NASA NEAT facility
- Ground tests are a key step in technology development for a hybrid electric propulsion system for flight tests later this decade.

- [Link to cited news article GE 1](#)
- [Link to cited news article GE 2](#)

magniX, \$74.3million.

- Partnered with Air Tindi and AeroTEC
- Aims to demonstrate electric propulsion technology to power a hybrid De Havilland Canada Dash 7 aircraft, with first flight planned for mid-2020's
- The retrofitted aircraft will be powered by two PT6 engines and two magni650 electric propulsion units (EPUs)

- [Link to cited news article magniX 1](#)
- [Link to cited new article magniX 2](#)

POCs :

Project Manager, Gaudy Bezos-Oconnor (gaudy.m.bezos-oconnor@nasa.gov)

Deputy Project Manager for Technology, Ralph Jansen (ralph.h.jansen@nasa.gov)



EPFD Power System Technical Performance Objectives

Demonstrators are working at relevant operating points

Key Performance Parameter (KPP)#	Key Performance Parameter (KPP)	Full Success Single Aisle Part 25	Minimum Success 19 PAX Thin Haul Part 23
KPP-1	Total Power level of the Integrated MW-Class Powertrain System	2MW	500kW
KPP-2	Power Level of individual electrical components	1MW	250kW
KPP-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V	500V
KPP-4	Altitude Capability of the Integrated MW-Class Powertrain System	40,000 ft.	20,000 ft.
KPP-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg	0.5 kW/kg
KPP-6	End to End loss of the Integrated MW-Class Powertrain System	20%	
KPP-7	Mission Fuel Burn/Energy Reduction	4% for Part 25 Transport Aircraft	10% for Part 23 Transport Aircraft

POCs :

Project Manager, Gaudy Bezos-Oconnor (gaudy.m.bezos-oconnor@nasa.gov)

Deputy Project Manager for Technology, Ralph Jansen (ralph.h.jansen@nasa.gov)

Technical Performance Parameter (TPM)#	Technical Performance Parameter (TPM)	Full Success	Minimum Success
TPM-1	Total Power level of the Integrated MW-Class Powertrain System	1.5MW	500kW
TPM-2	Power level of individual electrical components	1MW	250kW
TPM-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V	500V
TPM-4	Altitude Capability of the Integrated MW-Class Powertrain System	30,000 ft.	15,000 ft.
TPM-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg	0.5 kW/kg
TPM-6	End to End loss of the Integrated MW-Class Powertrain System	20%	25%

Will be collecting relevant sets of data

- Integrated Ground System Development, Integration and Test
- Integrated Flight Systems Development , Integration and Test
- Flight Airworthiness/Safety and Mission Assurance

Demonstration of MW scale EAP that will help enable the next generation of aircraft



University Leadership Initiative

Electric Propulsion: Challenges and Opportunities *led by Ohio State University*

- Design, build and test 1 MW electric machine and thermal management system
- 14 kW/kg (active mass), 99% efficient
- Integrated 2 kV DC power electronics drive
- Airplane system and battery studies

CHEETA *led by University of Illinois*

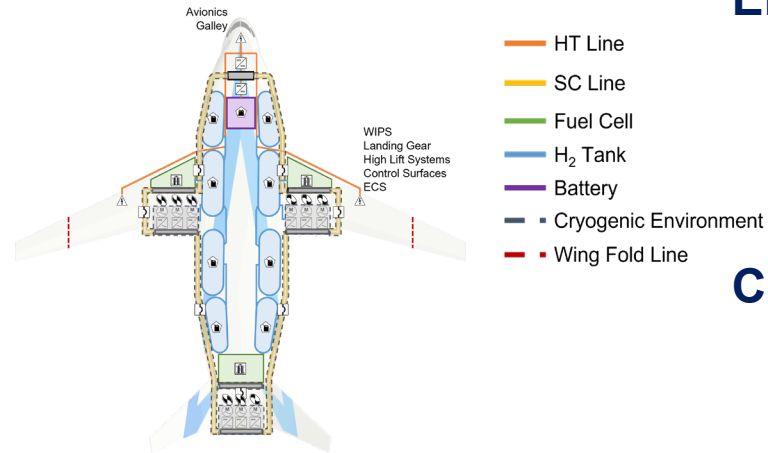
- Center for High-Efficiency Electrical Technologies for Aircraft
- Distributed propulsion architectures
- Energy conversion, generation and storage
- Superconducting machines

IZEA (Integrated Zero-Emission Aviation) *led by Florida State University*

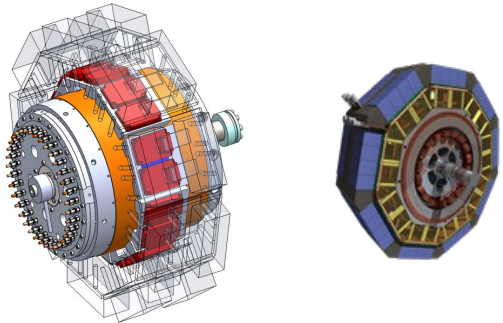
- Fuel cell technology
- Cryogenic liquid hydrogen fuel
- Electric machine, drive, power controls and thermal management
- Superconducting power transmission

Zero Emissions

- Program is gearing up for alternative solutions and energy sources
- Solicitation coming 2023

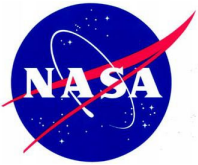


CHEETA Concept



MW Machine (U. Wisconsin) and
Power Electronics (OSU)

Diverse teams advancing NASA goals with highly innovative solutions



Take away

- Broad portfolio of work spread across many programs
- Relevant research from system to components to integration
- Engaged with both industry and academia

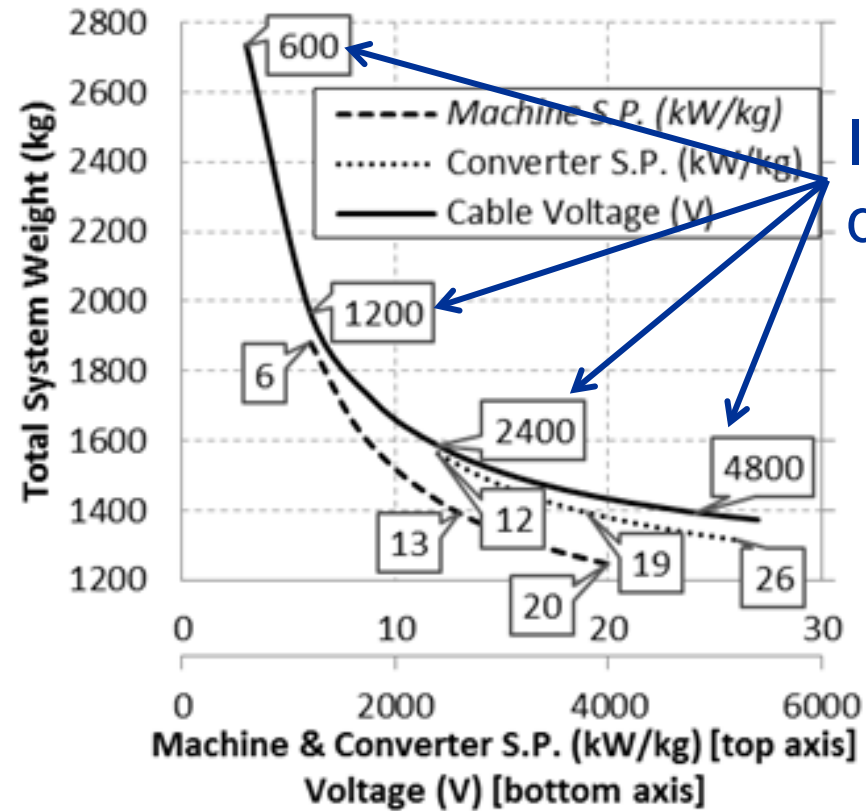
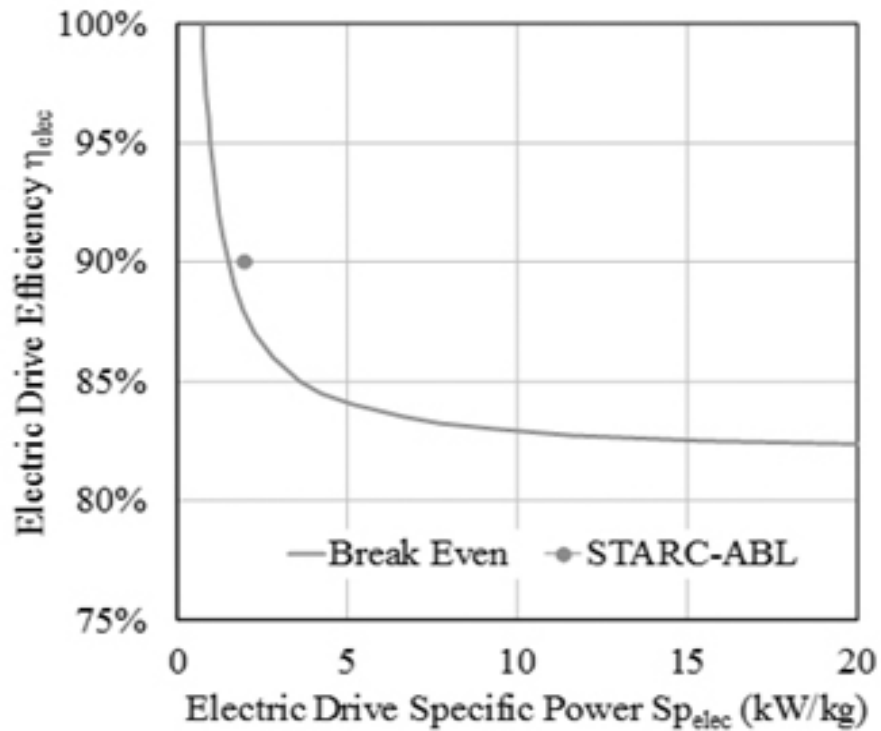


Advanced Air Transport Technology (AATT) Project Propulsion & Power Subproject -powertrain technology Advanced Air Vehicle Program

Electric Aircraft Portfolio



Mass is a problem



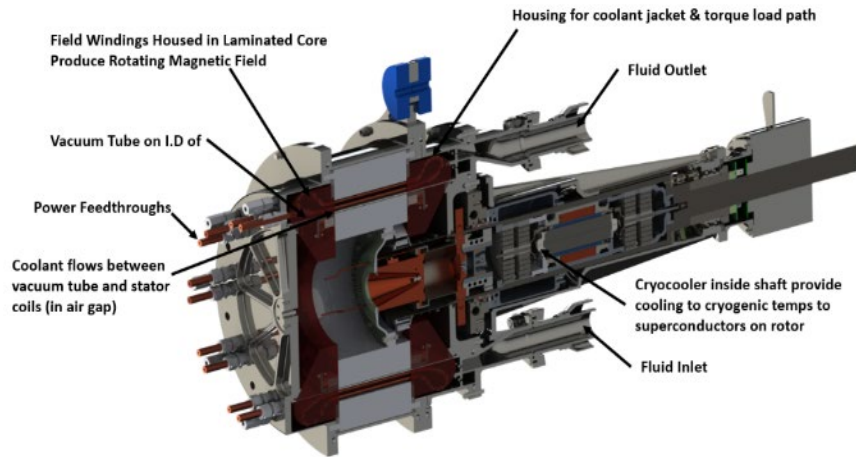
Increasing voltage
decreases mass

Note: Thermal systems also add mass along with energy storage

Haran, K. *Electrified Aircraft Propulsion: Powering the Future of Air Transportation*: Cambridge University Press, 2021.



High-Efficiency Megawatt Motor



Electric Machines

Ambient $>13 \text{ kW/kg}$, 96% efficient

- Ohio State University: Induction
- University of Illinois and Hinetics: Permanent Magnet
- University of Wisconsin (OSU-led ULI): Permanent Magnet

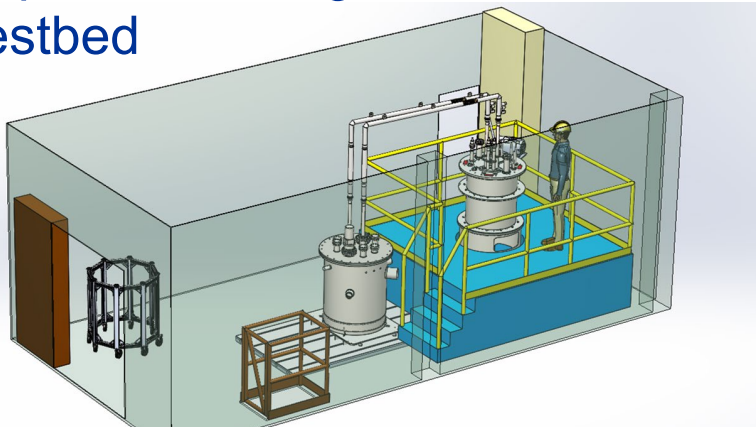
Partially Superconducting $>16 \text{ kW/kg}$, 98% efficient

- NASA High Efficiency Megawatt Motor Wound Field

Superconducting $>16 \text{ kW/kg}$, 99% efficient

- NASA addressing challenges for fully superconducting machines
- AC loss studies
- University of Illinois CHEETA program (ULI program)

Superconducting Coil Testbed



Still pursuing key performance parameters laid out in 2015-16 system studies

Super Conducting POCs: Mr. Gerry Brown (gerald.v.brown@nasa.gov) and Dr. Justin Scheidler (justin.j.scheidler@nasa.gov)

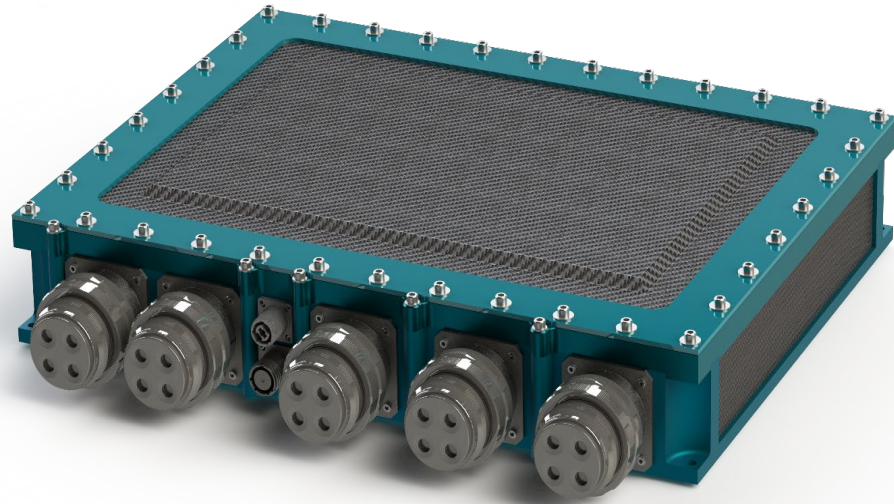


Power Converters

Advanced Power Converters

- Past efforts
 - Cryogenic
 - Ambient (silicon carbide – silicon/SiC hybrid and gallium nitride HEMT)
- Current efforts move toward altitude-capable:
 - GE flight-ready SiC inverter (SLIM) (19kW/kg, 99% efficiency)
 - NASA 250 kW low total harmonic distortion* controller/inverter (10 kW/kg, 99% efficient)

** Addresses a sensitivity for high power density machines*

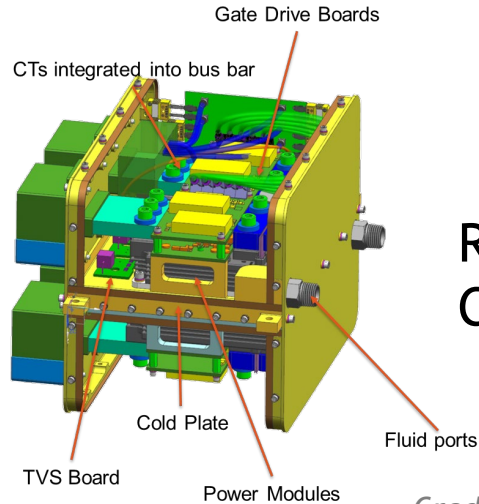


NASA 250 kW Inverter
Rendering

Flightweight DC power conversion key to many aircraft concepts

- POC: Mr. Dave Avanesian (david.avanesian@nasa.gov)

Fault Management and Safety



Raytheon
Circuit Breaker

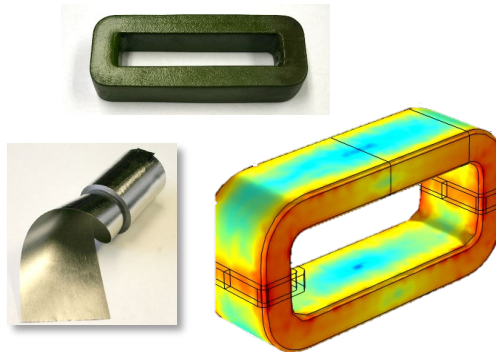
Credit: Raytheon Technologies

Circuit Breaker (MW scale, ~1kV, 1000A)

- Pratt and Whitney (P&W, RTX, and Collins Aerospace)
- General Electric Aviation (GEA and GE Research)
- Naval Post-Graduate School-POC: Dr. Rodger Dyson (rodger.w.dyson@nasa.gov)

Materials Studies

- Custom devices from NASA soft magnetic materials
- Lifetime modeling for insulations system



Power Quality Filtering

- Basic material to component
- Designed for advanced use with advanced power devices

Addresses key requirements for megawatt, kilovolt systems at altitude

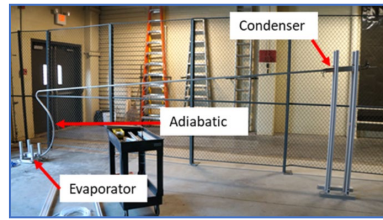
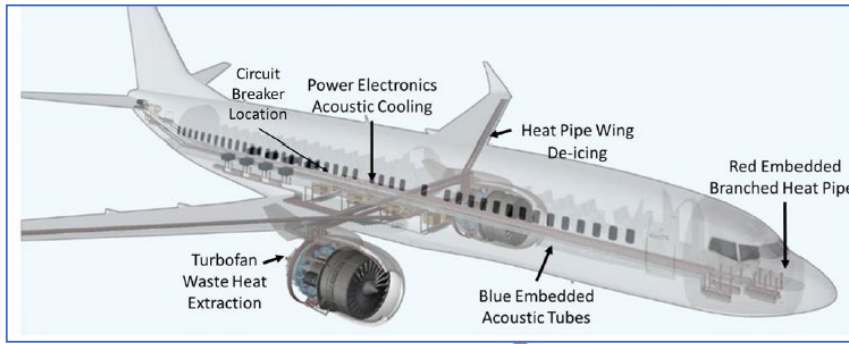
Thermal Management

- **Solid-State Exergy Amplification**

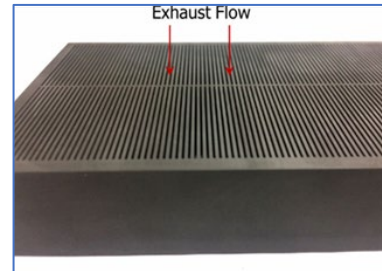
- No moving parts
- No pumped fluids
- No increased drag
- Maximize specific power
- Improve powertrain efficiency

- **Areas of Development**

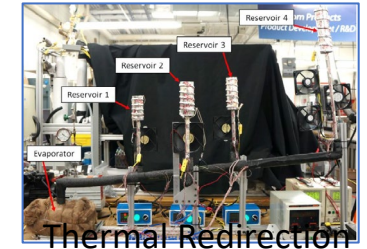
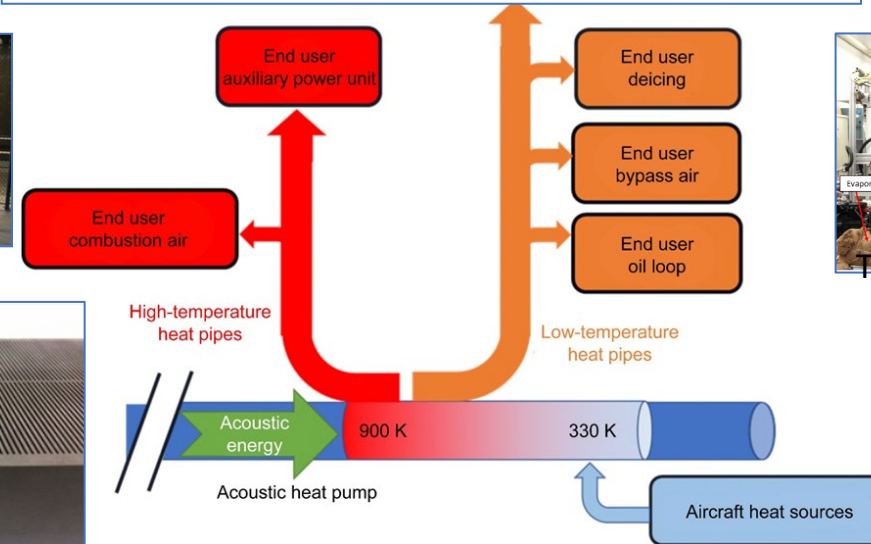
- Turbofan WHR HX
- Acoustic Heat Pump
- Oscillating Heat Pump (OHP)
- Thermal Transport
- Thermal Recycling
- Dynamic Thermal Redirection
- Gradient-based System Optimization



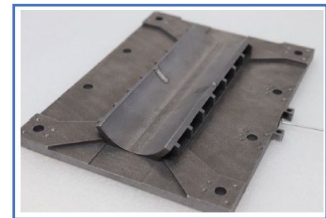
Thermal Transport



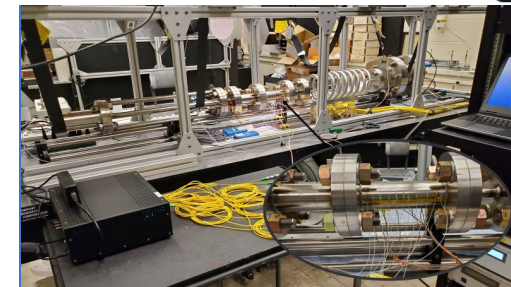
Waste Heat Recovery



Thermal Redirection



OHP Heat Collection



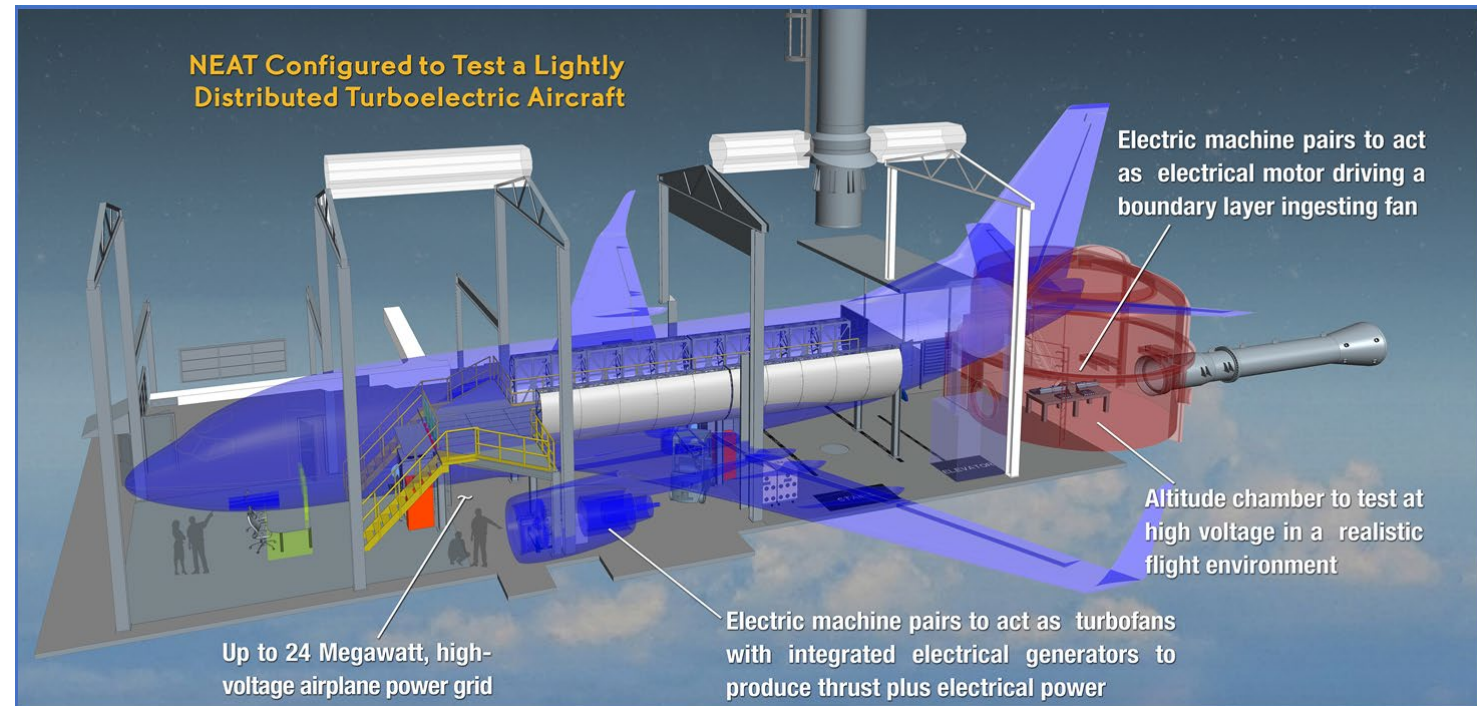
Acoustic Heat Pump

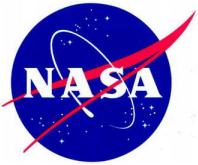
Simple, unique solutions for solving a complex distributed problem

- POC: Dr. Rodger Dyson (rodger.w.dyson@nasa.gov)

NASA Electric Aircraft *Testbed* (NEAT)

- Can test megawatt (MW) systems test electrical systems at altitude
- Can test MW scale power systems, controls and in a variety of configurations:
- MW scale power levels complicates test run at kW or lower levels

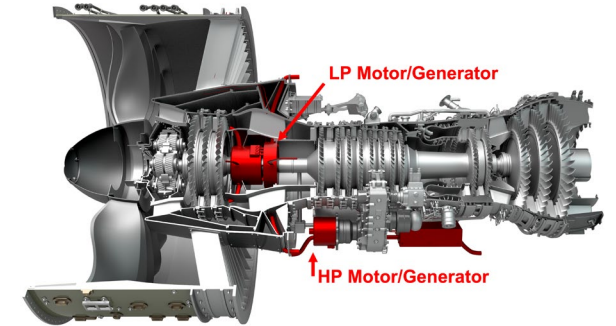




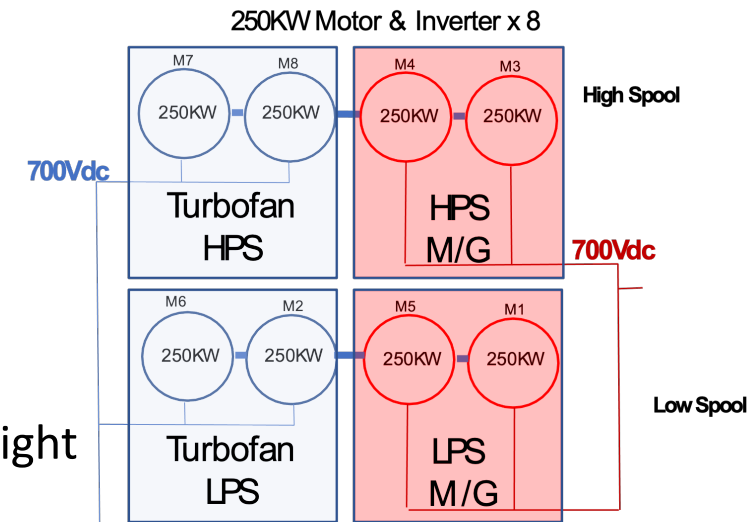
NEAT Tests



- **Turbine Electric Energy Management (TEEM):** Real-time demonstration of a control concept of optimizing the energy usage of a hybrid-electric propulsion system during transient operation.
 - Demonstrated the ability of TEEM to dynamically alter shaft speed to maintain the designed operating line performance during engine transient operations.
 - Demonstrated Addaptive Sliding Mode Inertia Controller and Scaling (ASMICS) algorithm.
- **STARC-ABL Controls Test:** Test of a control system design for the Single-aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion (STARC-ABL), a partially turboelectric Electrified EAP aircraft concept developed by NASA
- **NEAT MW EAP Power System Impedance Modelling:** Determining EAP system stability and transient response, providing guidance on power quality, providing insight into future standards development



Hybrid Turbofan Concept



NEAT TEEM Hardware Configuration

Answering questions about the utilization megawatts of electric power for propulsion

SABERS

(Transformative Tools and Technology (TTT) Project/Transformative Aeronautics Concepts Program)

OBJECTIVES

- 1 Meet energy density requirements needed to enable electric aircraft.
- 2 Optimize recharge speed for efficient turnaround time.
- 3 Avoid parasitic weight from excess packaging and cooling.
- 4 Increase safety with fully-solid design eliminating use of flammable liquids.
- 5 Combine materials technologies to achieve scalability.

NASA ADVANTAGES

Bi-polar stack design

Reduces safety containment weight and improves specific energy and power.

Patented holey graphene

Improves cathode electrical conductivity and the initial discharge capacity of the cell.

New sulfur-selenium combination

Improves cathode performance, reduces impedance, and creates a more stable discharge profile.

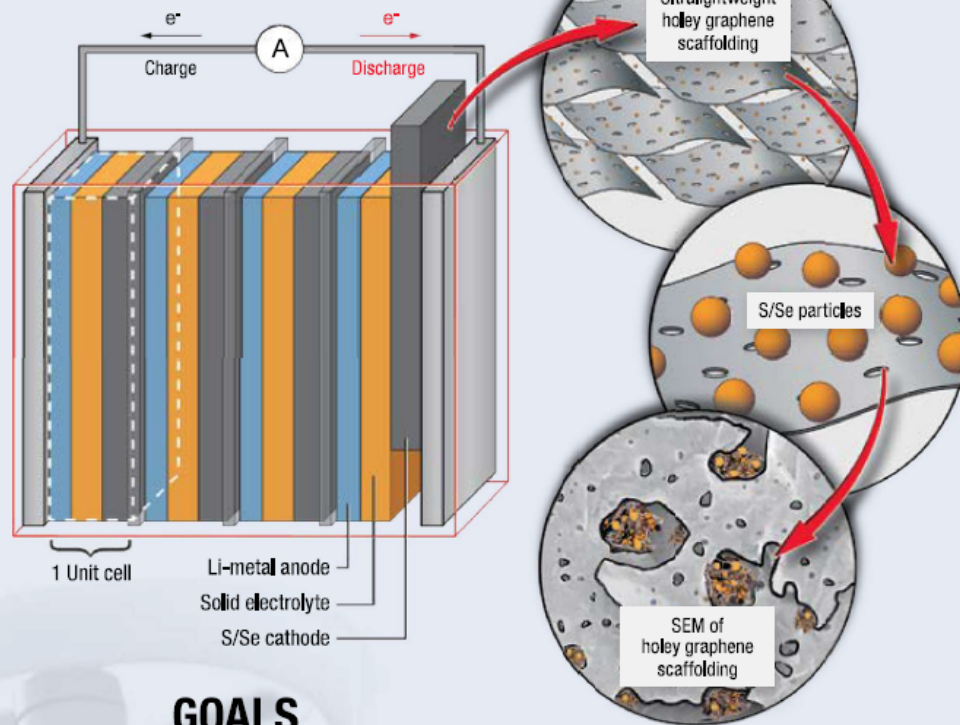
Computational modeling

Guides experiments to accelerate development time.

Collaboration

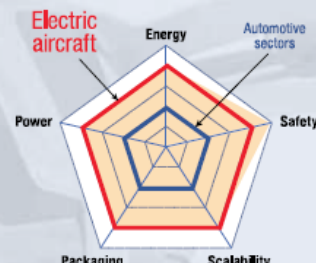
Engages expertise of multiple NASA centers and industry partners.

SOLID-STATE DESIGN

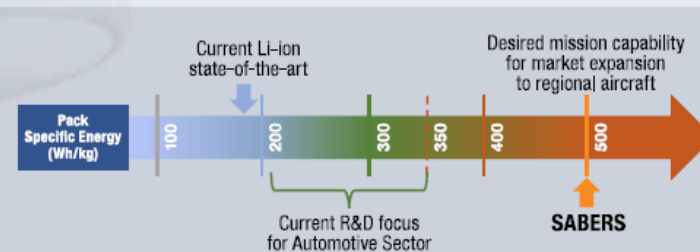


GOALS

Optimize composition ratio of solid-state electrolyte, active material, and conductive agent to significantly improve battery performance.



Performance Target: 500 Wh/kg battery



SABERS:
Solid-State Architecture
Batteries for Enhanced
Rechargeability and Safety

POCs:

Dr. Don Dombrush (donald.dornbusch@nasa.gov)

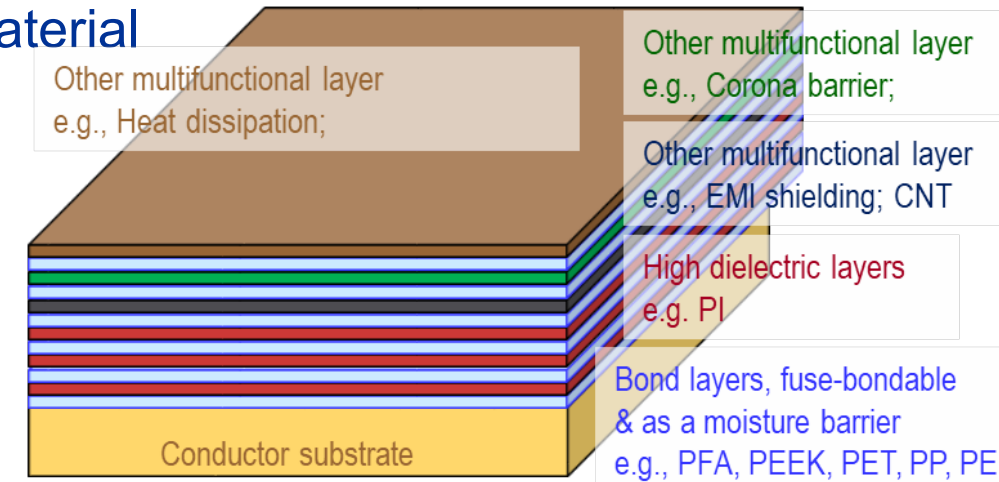
Dr. Rocky Viggiano (rocco.p.viggiano@nasa.gov)



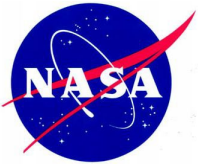
HV Electrical Materials

(Transformative Tools and Technology Project/Transformative Aeronautics Concepts Program)

- Cables and busbars are a primary focus, but may also apply to power electronics packing for EAP applications
- > 10kV, 51kft or higher (possible lunar applications)
- NASA developed Micro-Multilayered-Multifunctional Electrical Insulation (MMEI)
- Sustainable solutions
 - Develop non-fluorinated insulation materials
 - Boron nitride-polymer composites to create engineered material
 - Reduce mass/size of insulation
 - Boost thermal conductivity
 - Boost resilience to damage by partial discharge, corona etc.
 - Developing compound conductors to reduce weight



Creating lightweight, sustainable options for power transmission



Take away

- Directly address the mass issue in many key areas
- Addressing technology operational issues as well



Electric Machine Insulation

Electric machine key performance parameters

- >1 MW, >13 kW/kg, >96% Efficient (< 40kW of waste heat/MW)
- Significant thermal management problem

Stator composition

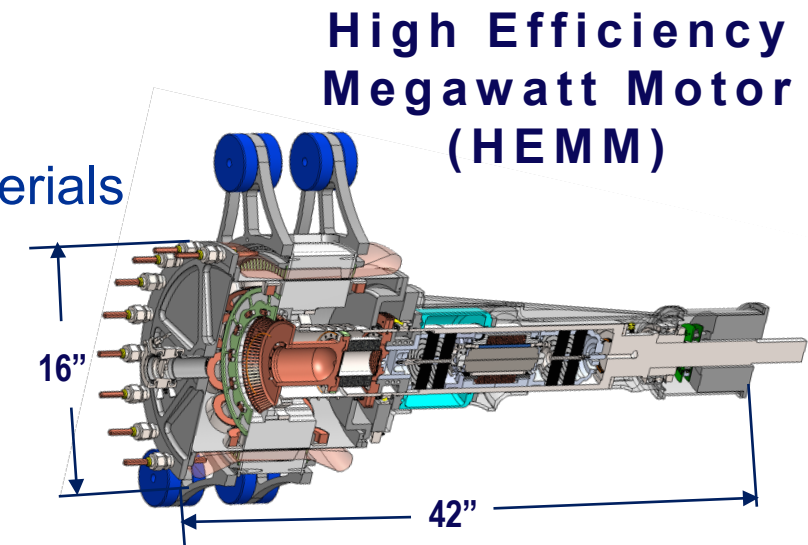
- Thermally conductive electrical conductor
- Several nonthermally conductive potting and electrical insulation materials
- Multi-material systems is a composite material

Targets

- Slot/slot liner (high voltage separator)-extruded polymer composites
- Wire insulation-polyimide/BNNS composites
- Potting materials and methods

Limitation of cooling

- Dielectric fluids are a common way of cooling a stator, not good thermal fluids
- Good thermal fluids have low dielectric breakdown strength
- Enabling: Material that supports coolant flow, has significant dielectric strength and thermal conductivity



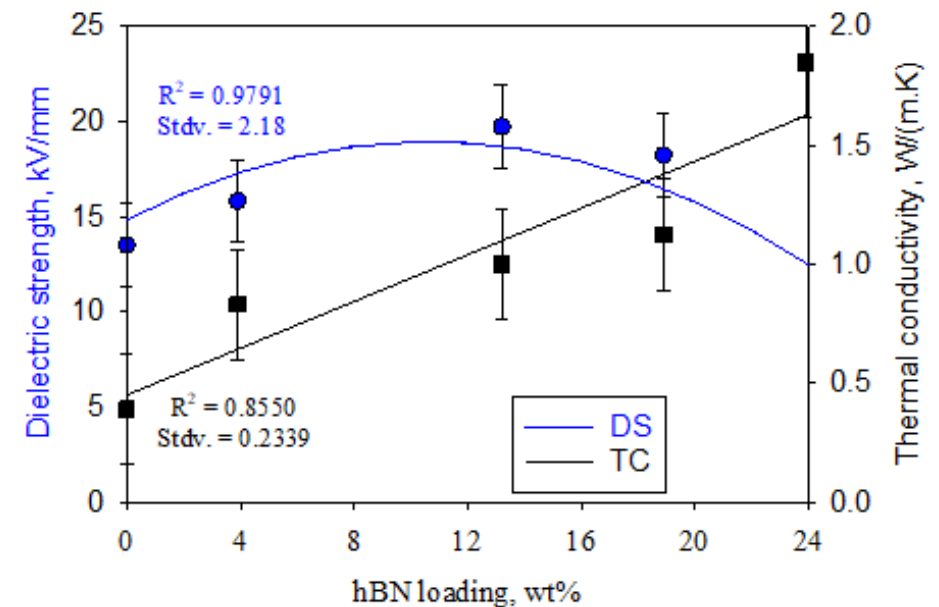
Extruded materials

- Extruded flexible polymer composite tapes have been demonstrated but other structures are possible
- Many different extrusion for possible including 3-D printer compatible filament extrusion possible
- 3-D printing of thermally conductive, electrically insulative heat exchanging stator teeth with integral fluid channels maybe useful



Williams, T. S., et al. Polyphenylsulfone-hBN Composite Insulation, IEEE International Conference on Dielectrics Conference Proceedings, Valencia, Spain, 5 – 9 July 2020,.

Flexible extruded PPSU (polyphenylsulfone)-hBN composite

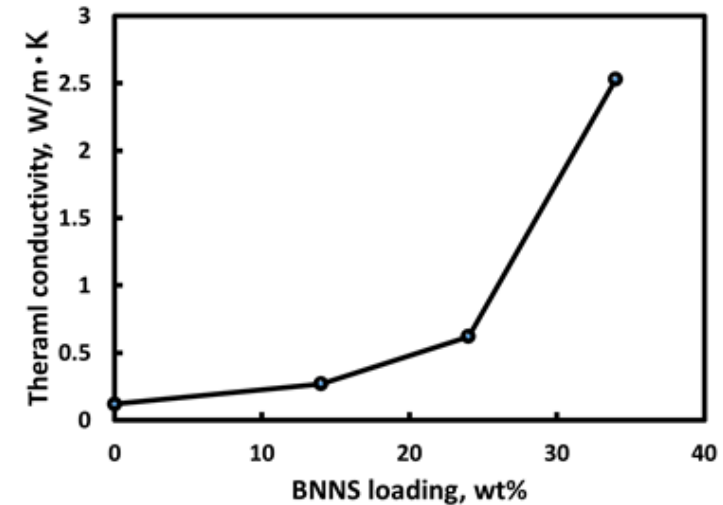
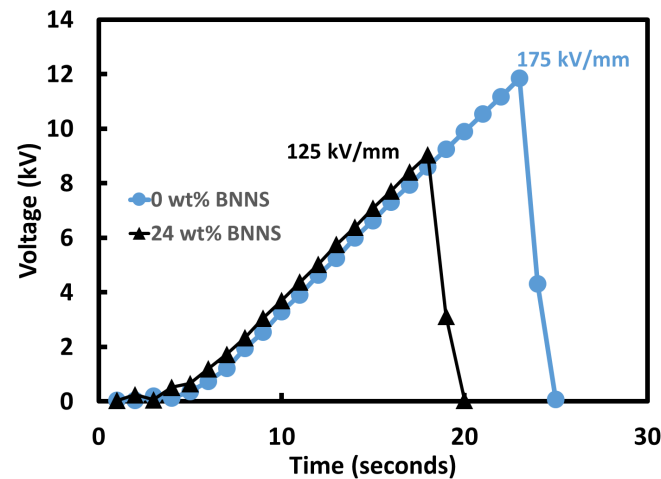
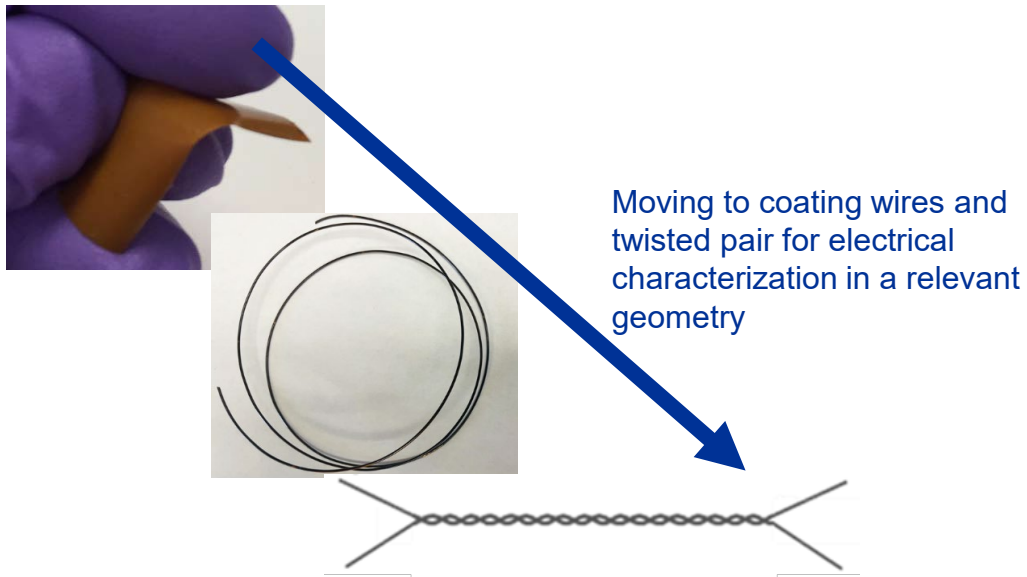


Williams, T. S., et al. "Fabrication of Extruded Polyphenylsulfone-Boron Nitride Composite Tapes," *Society for the Advancement of Material and Process Engineering neXus*, Virtual, 2021.

Flexible extruded polymer-hBN composites offer interesting solutions for electric machines

Polyimide-BN Nano Sheet Composites

- Retention of flexibility is critical for wire coatings
- ~30% reduction in dielectric strength
- Order of magnitude increase in thermal conductivity



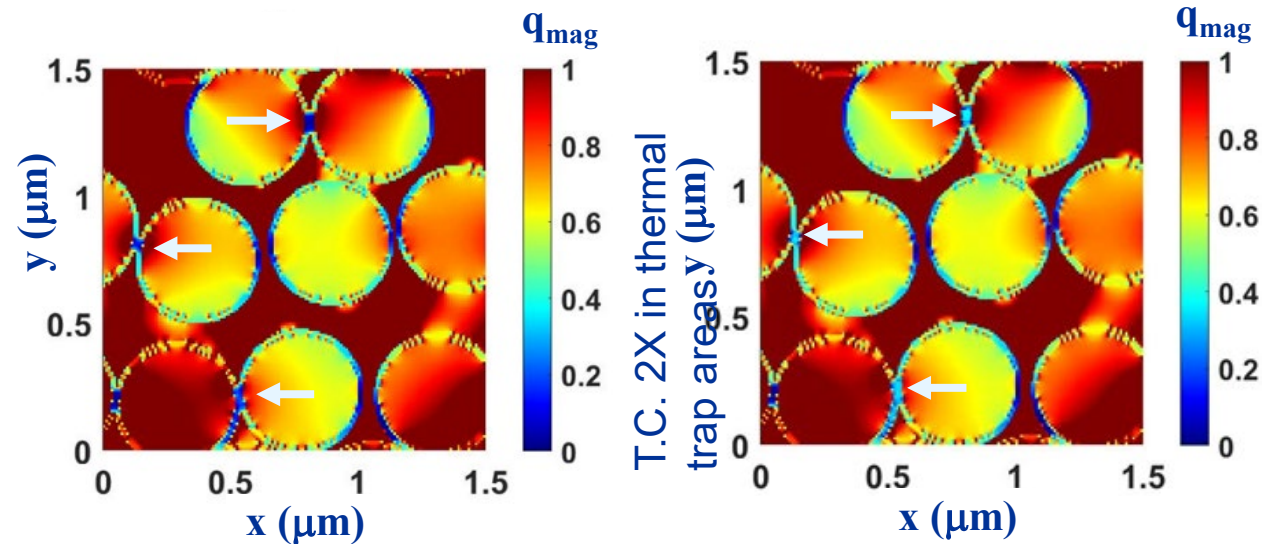
Woodworth, et al. "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*. 2021, p. 3275.

Polyimide-BNNS composites are a viable option for motor applications with improved thermal conductivity

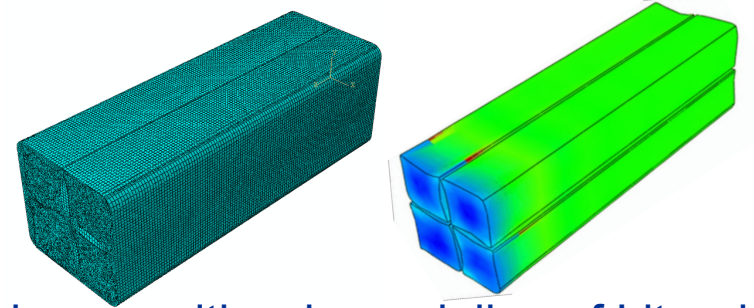
Potting and Microthermal Analysis

- Vacuum-assisted axial injection potting (VaAIP) process
 - Allows epoxy to flow along wires instead of through a bundle
 - POC: Eugene Shin (euy-sik.e.shin@nasa.gov)
- Thermal conductivity in potting materials
 - Usually achieved through micron sized fillers
 - Drives up viscosity
- Microthermal Analysis (AATT/TTT co-funded)
 - Thermal traps (no heat flow) between conductors
 - Simple 2X improvement in trap areas significantly improves heat flow

Combination of VaIP and low levels of nano fillers may enable significant thermal conductivity improvements



Thermal traps caused by SOA Materials



Developing a multiscale modeling of Litz wires utilizing NASMAT (NASA Multiscale Analysis Tool)

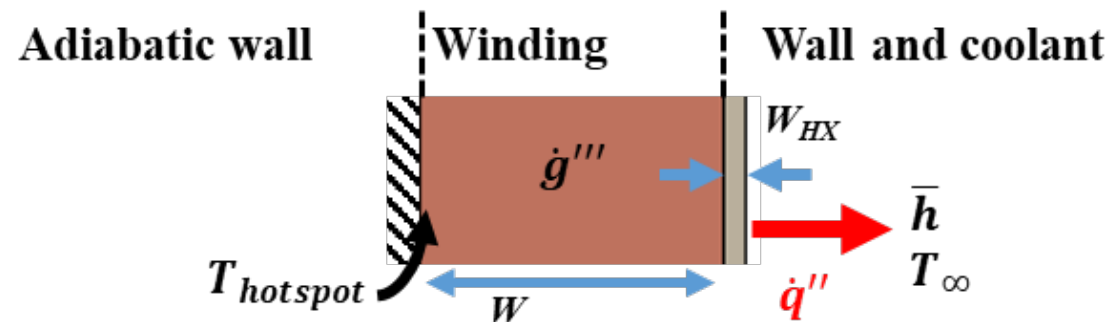
POC: Dr. Paria Naghipour (paria.naghipourghezeli@nasa.gov)

System Study

- 3-D printed direct winding heat exchangers
- BNNS infiltrated potting
- BNNS improved polyimide

Winding Insulation Component	Base Material	SOA Material (W/m-K)	Composite Material (W/m-K)
Encapsulation (Potting)	SOA Epoxy	1.3	1.7 *
Wire Insulation	Polyimide	0.1	2.5
Extruded 3D-DWHX**	PPSU	0.4	1.8

Printed direct winding heat exchangers (3D-DWHX 3-D)



*Shin, E. E., "Improved potting of Litz Wires for High Power Density Electric Motor," 2021 AIAA/IEEE EATS

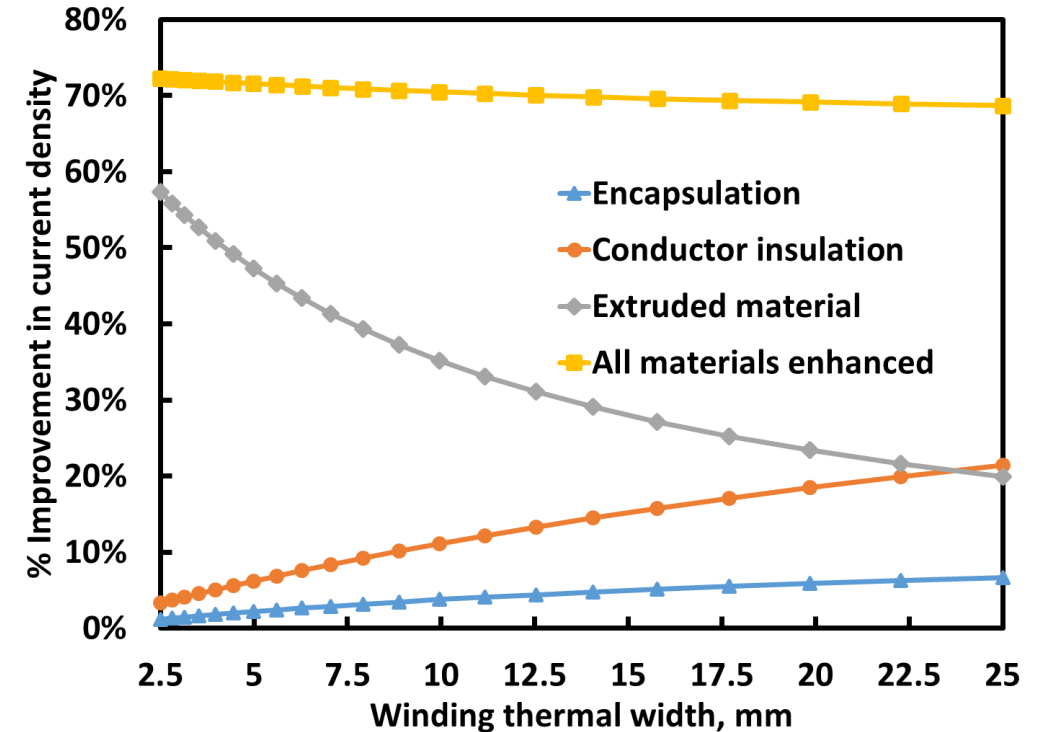
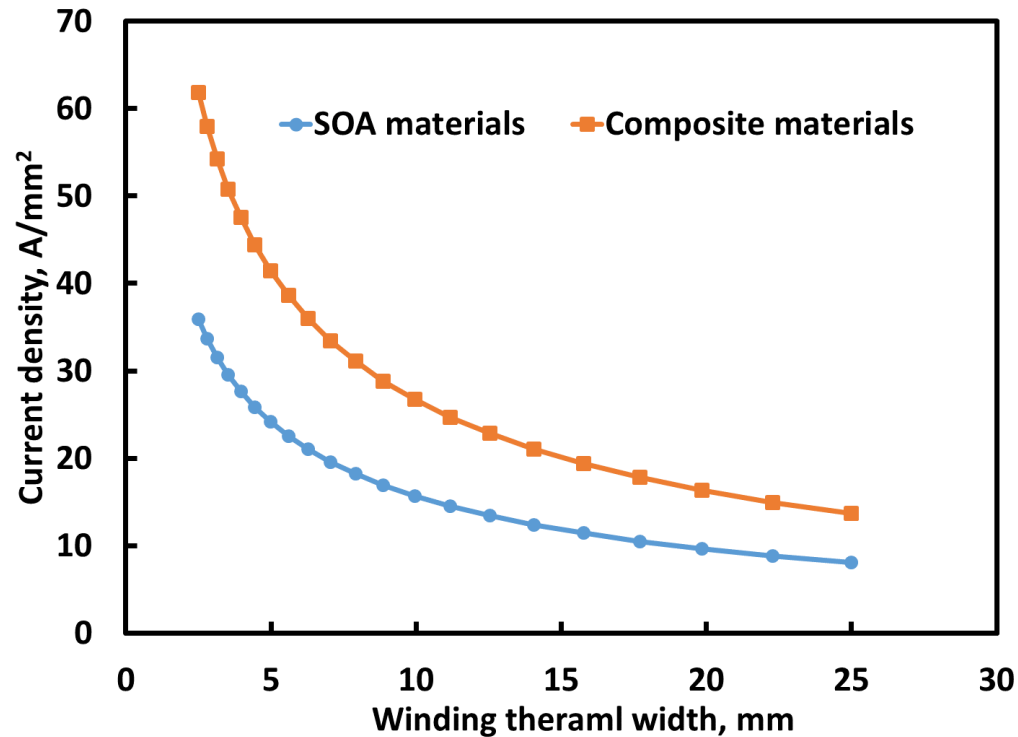
**Sixel, W., Liu, M., Nellis, G., and Sarlioglu, B., "Cooling of Windings in Electric Machines via 3-D Printed Heat Exchanger," IEEE Transactions on Industry Applications Vol. 56, No. 5, 2020, pp. 4718-4726.

Woodworth, et al. "Potential of Materials to Impact Megawatt-Scale Electric Machines," AIAA Propulsion and Energy 2021 Forum. 2021, p. 3275.



System Study

- Maximum current density was reached when the T_{hotspot} reached 220 °C



Woodworth, et al. "Potential of Materials to Impact Megawatt-Scale Electric Machines," *AIAA Propulsion and Energy 2021 Forum*. 2021, p. 3275.

Synergistic effects between the thermal conductivity individual components and system performance

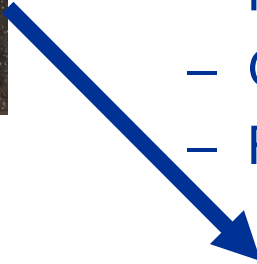


High Temperature RTM 3D Printing (AATT/TTT co-funded)

3D printed laser Sintered RTM

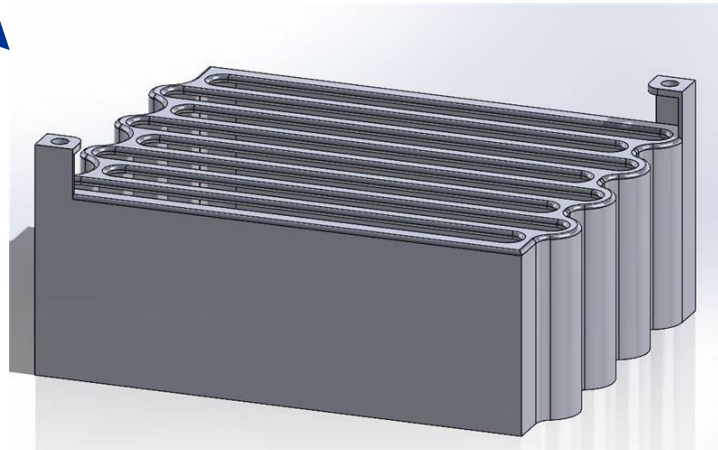


- High structural integrity
- Addition of BN increased thermal conductivity
- 3D printable opens many application
- Good candidate for battery packaging
 - Robust material that can survive thermal runaway events
 - Good thermal conductivity for thermal management
 - Requires nonflammable materials



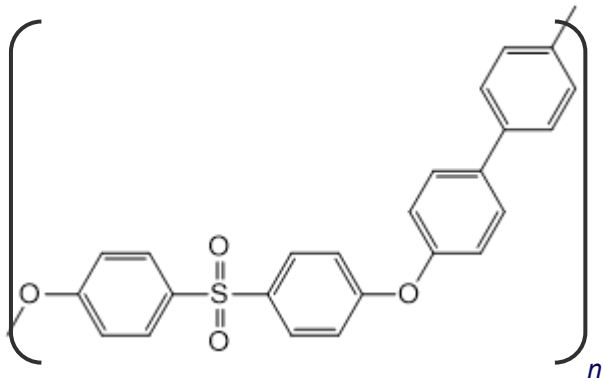
3D printable battery packaging
concept

Credit SUSAN Electro-fan Activity

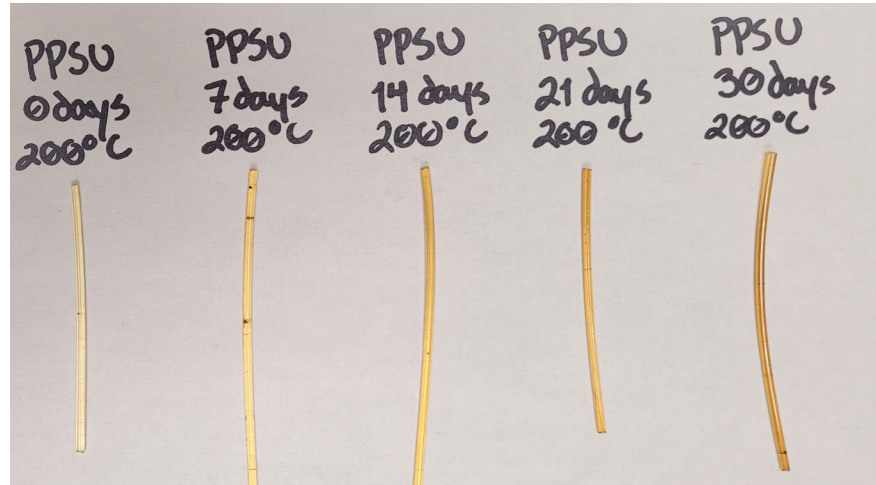


Additive manufacturing of high performance materials is enabling

Ageing analysis of high-temperature polymers - PPSU

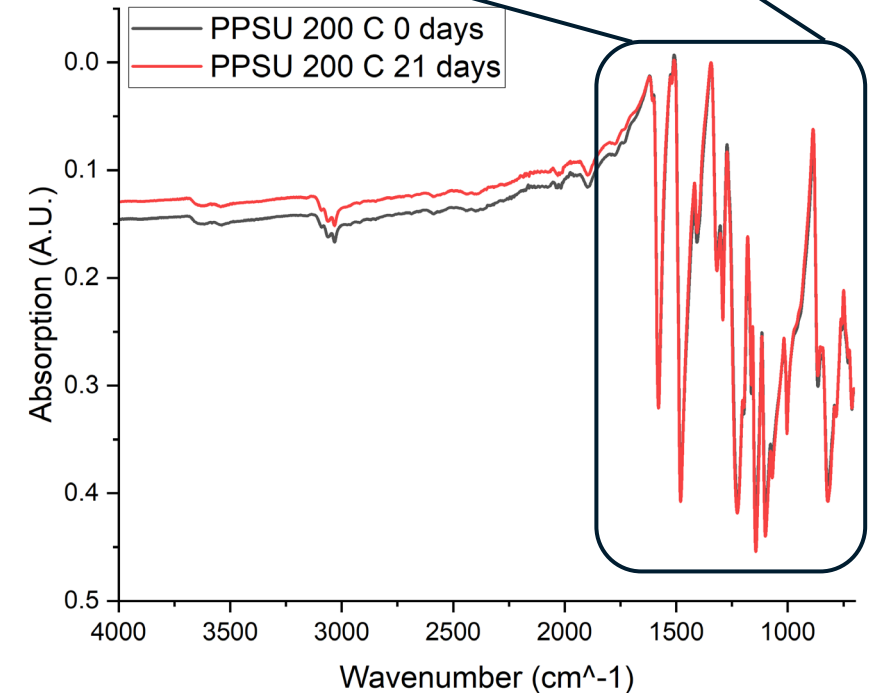
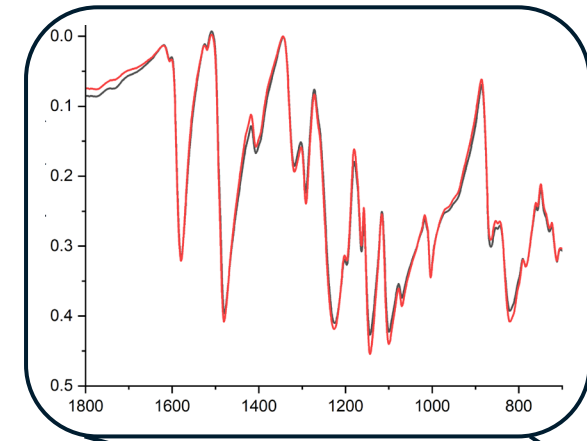


PPSU repeating unit



Thermal ageing of PPSU at 200 °C has clear effects on its color, traditionally an indicator of some mode of degradation

- PPSU resists traditional ageing chemical analyses due to its non-oxidative degradation mechanism
 - FT-IR (pictured right of slide) indicates no formation of carbonyl or hydroxy structures typically observed in ageing materials
- PPSU not thermo-mechanically stable when accelerated aging > 200 °C, limiting scope of available ageing conditions
 - Tensile specimens do not retain shape after aging, work to enhance stability ongoing



Understanding ageing is an critical part of materials development



Concluding thoughts

- Wide range investments in different technologies
- Investments have significant depth to match the breadth

Please contact me If you have seen something in this presentation and you want to know more!

Andrew Woodworth

Phone: 216-433-3544

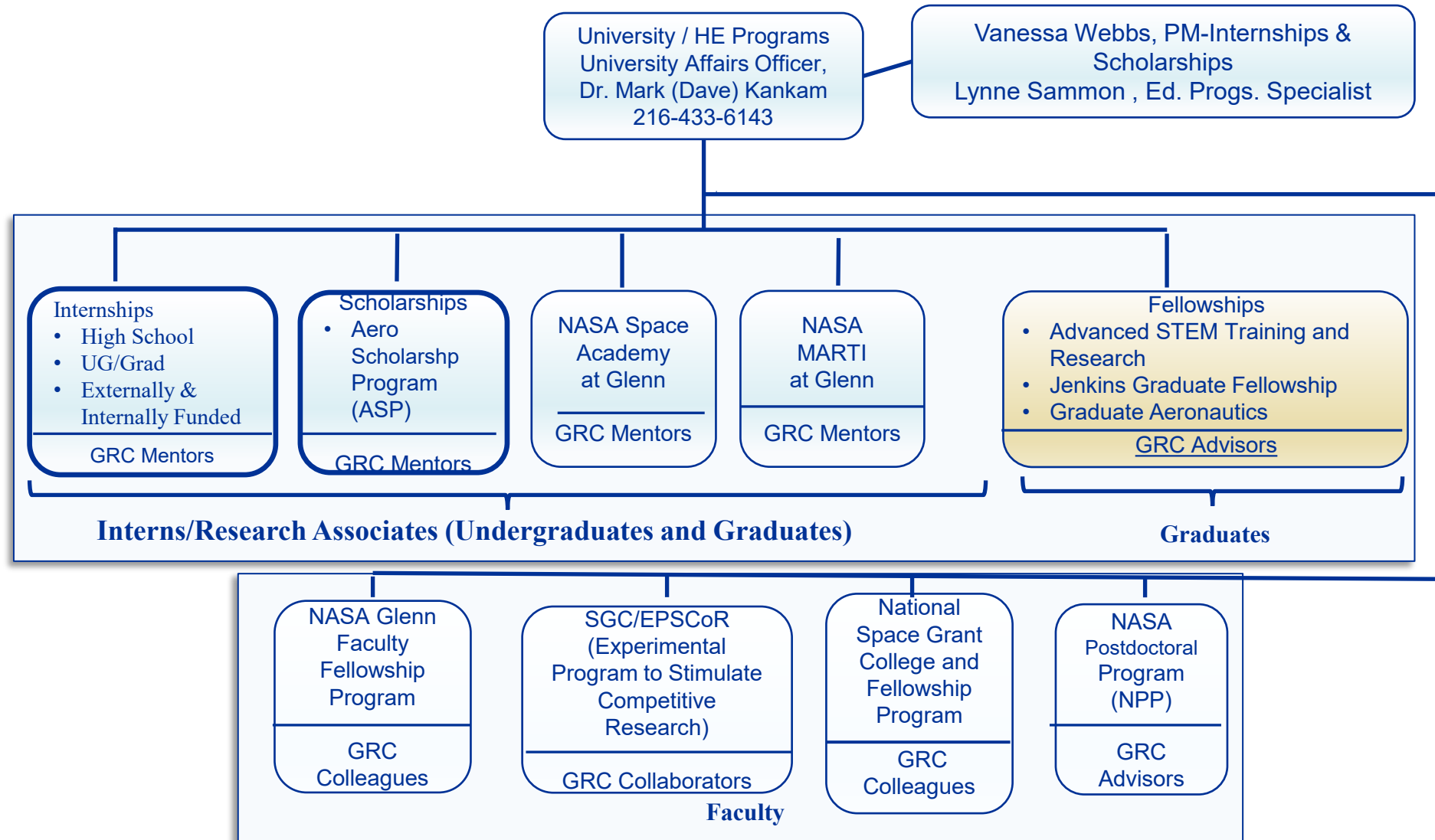
Email: andrew.a.woodworth@nasa.gov

You can also follow our developments at:

<https://www1.grc.nasa.gov/aeronautics/eap/>



University/Higher Education Programs – Pathways for Collaboration



MARTI – Multidisciplinary Aero Research Team Initiative



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- Glenn Office of Education Website (For Program Details):
<http://www.nasa.gov/centers/glenn/education>



Noteworthy Websites for Faculty/ Student Engagements

*NIFS Application → OSSI (One Stop Shopping Initiative)

- <http://intern.nasa.gov/>

*NASA Glenn STEM

- <https://www.nasa.gov/centers/glenn/stem> (One Stop)

*NASA Postdoctoral Program (NPP)

- <https://npp.usra.edu/>

*NASA Glenn Faculty Fellowship Program (NGFFP)

- <https://www.nasa.gov/centers/glenn/stem/nasa-glenn-faculty-fellowship-program>

*NASA Space Technology Graduate Research Opportunities (NSTGRO)

- <https://www.nasa.gov/directorates/spacetech/strg/nstgro>



Noteworthy Websites for Faculty/ Student Engagements

*National Space Grant College & Fellowship Program /EPSCoR

- <https://www.nasa.gov/stem/epscor/home/index.html>

*NASA Solicitation & Proposal Integrated Review & Evaluation System (NSPIRES)

➤ Includes information on:

○ NASA MUREP Institutional Research Opportunity (MIRO)

- <https://nspires.nasaprs.com/external/>

* NASA Research Announcements (NRAs)

➤ Includes Education Opportunities in NASA STEM (EONS)

- <https://nspires.nasaprs.com/external/solicitations/solicitationAmendments.do?method=init&solId={F257E429-24AC-EE13-09E6-45812E0D1314}&path=open>