The Ohio State University

UNIVERSITY LEAD INITIATIVE

Dr. Mike Benzakein
Assistant Vice President, Aerospace and Aviation

The challenges and the goals:

- The team
- System integration → vehicle sizing
- Batteries → energy storage
- Electric machines
- Thermal management
- The demonstration

WHY ARE WE DOING THIS?

- World population is growing ⟶ 10 Billion by 2100
- Commercial airplanes will double in the next 20 years, causing increased **CO_2** emissions that affect health across the globe.
- Goal is to have a carbon neutral environment by 2050.
- National Academy of Engineering has established that a reduction of a 20% in fuel burn and **CO_2** could be attained with electric propulsion.

Great Opportunities to help the environment, but challenges remain

THE TEAM

Wisconsin (University of Wisconsin-Madison)
- Electric Machines

The Ohio State University
- Center for Automotive Research—Batteries
- Center for High Power Performance Electronics—Power Electronics

University of Maryland
- Thermal Management

North Carolina A&T State University
- Thermal Management

Georgia Tech
- Systems Integration

NASA
- NEAT Test Facility

Case Western Reserve University (Est. 1826)
- Batteries

On hybrid electric propulsion, NASA asked Ohio State to lead a 5 year program to address these challenges

System Integration

Vehicle Sizing

Initial Sizing

1. Requirements
2. Electric Power Usage
3. ____________
4. ____________

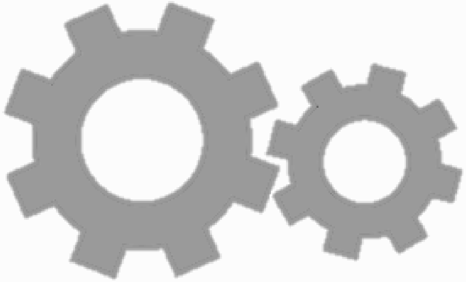
July 2017 – July 2018

Thermal Management Battery Definition

1. Iterate with battery testing
2. Trade battery life against density
3. ____________
4. ____________

Final Concept Definition

1. Update Scaling laws, and maps
2. Energy storage
3. ____________
4. ____________



Prelim. Sizing
July 2018

Resized vehicle
June 2019

Vehicle Design Frozen
June 2020

Vehicle Update
June 2021

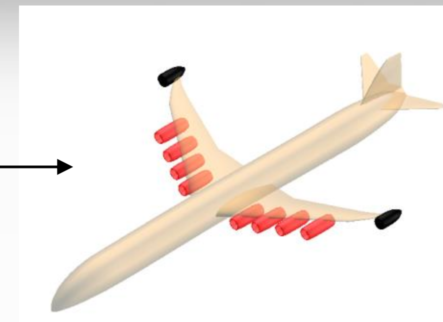
Vehicle Update
June 2022

Iterative cooperative process between Universities

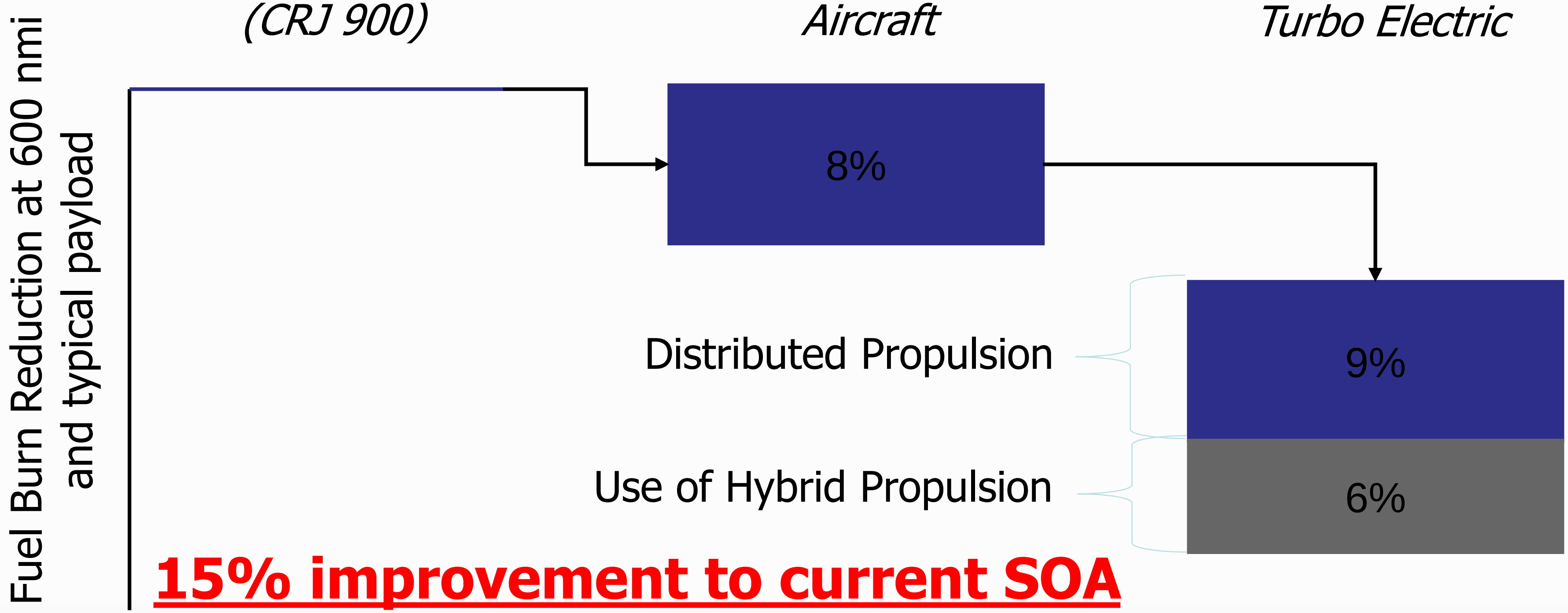
ULI Concept Benefits Assessment

Baseline Aircraft (CRJ 900)

Next Generation Aircraft



Distributed Hybrid Turbo Electric

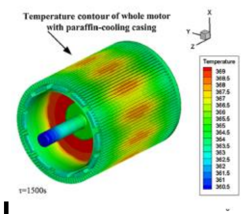


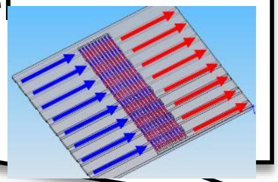
15% improvement to current SOA

*Assumes 200 Wh/kg batteries used at rate of 30% of overall propulsive power during climb and 20% during cruise

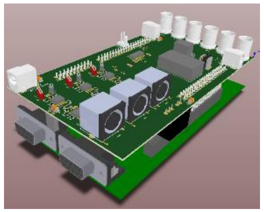
Technology Features

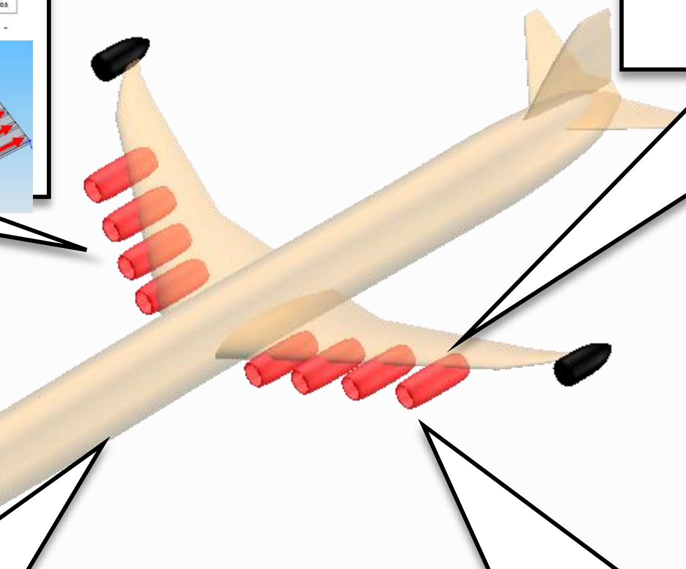
Tightly integrated TMS with phase change material for motor cooling and microchannel cooling





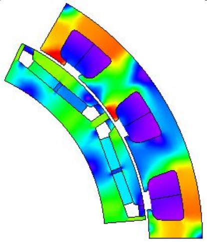
99% efficient inverter at ~25 kw/kg





Batteries for hybrid propulsion structurally integrated in the floor of the aircraft

>96% efficient motor at ~14kw/kg



Boundary Layer Ingestion

- Benefits under investigation at NASA, Whittle Lab at Cambridge, and Institute of Warsaw Aviation
- Evaluation bookkeeps at 2-10 10% benefit
- Will estimate here at 5%
- Added to current cycle benefits this at 15% + 5% = 20%

Preliminary evaluation of Hybrid Electric System is 20%

Whittle Laboratory

UNIVERSITY OF CAMBRIDGE

Where are we now?

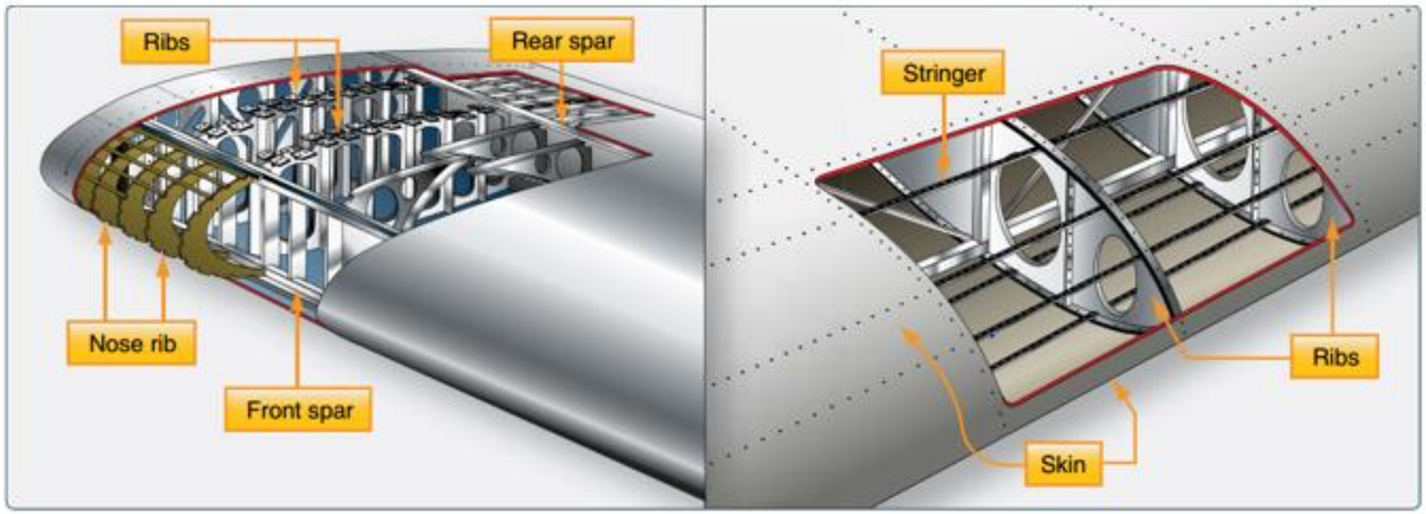
- **Better quantification and optimization of the use of structurally integrated batteries**
  - Continue to quantify how much structural integration improves the effective energy density
  - Identify best use of fixed and removable battery infrastructure
- **Assessment of integrated TMS architecture**
  - Selecting best concept
  - Minimizing impact to gas generators
- **Identify more optimized operating profiles**
  - Having even a small amount of battery power available for propulsion lets us independently control gas generator and fan

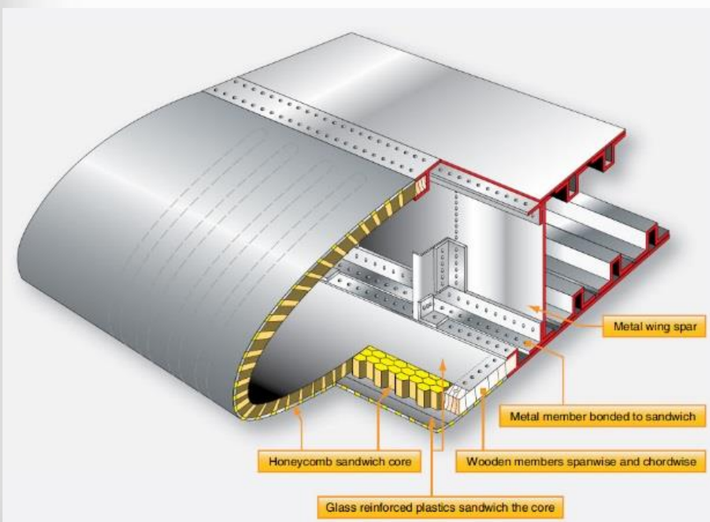
Batteries/Energy Storage

The Milestones

Task 1	System – level energy storage needs	**July 2018**
Task 2	Selection of commercially available battery cell technology	**July 2018**
Task 3	Performance models for cells with aging/life prediction capability	**July 2019**
Task 4	Thermal analysis of individual battery cells	**July 2020**
Task 5	Every storage system design reliability and management	**July 2021**
Task 6	System integration and prototyping	**July 2022**

Opportunity: Multifunctional Structural-integrated Battery



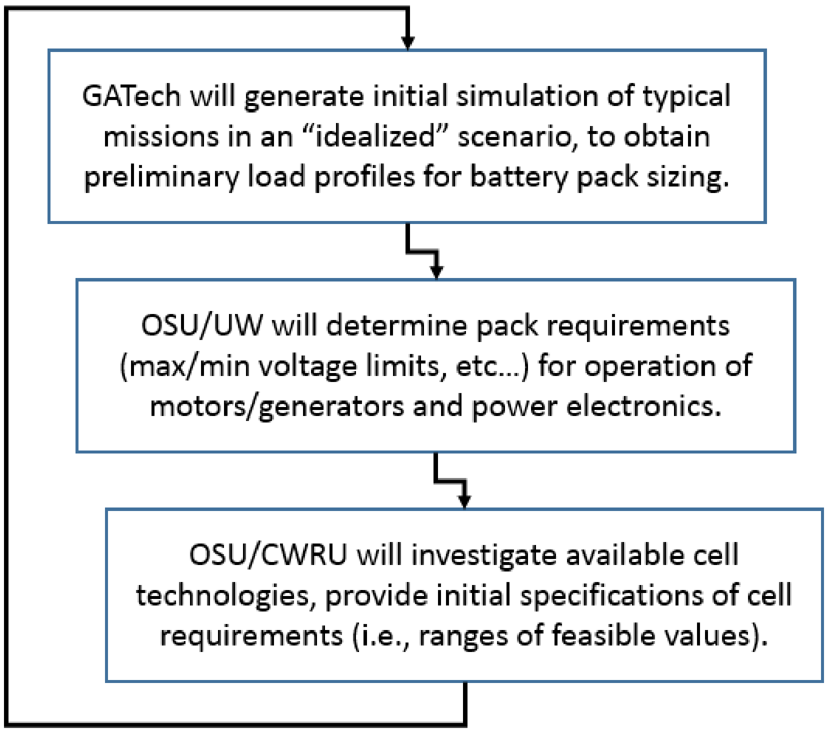


Honeycomb Structured Panels

- Floor panels
- Bulk Heads
- Control surfaces
- Tail cone
- Wing Panels (Leading and Trailing edges)

Define Pack Performance Requirements

- The activity will be conducted iteratively:



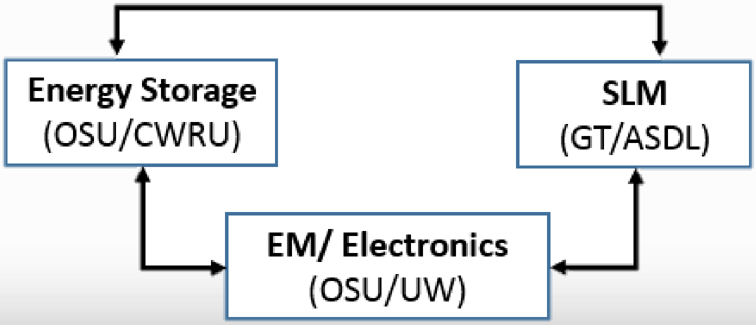
- This activity will be conducted in parallel with an evaluation and assessment of **high energy density Li-ion cell technologies**.

Battery Cells Requirements:

- Gravimetric energy density: Wh/kg
- Volumetric energy density: Wh/L
- Power density: kW/kg
- Charging & discharging characteristics
- Battery depth of discharge vs # of cycles
- Permissible steady-state and transient temperature thresholds
- Heat generation characteristics

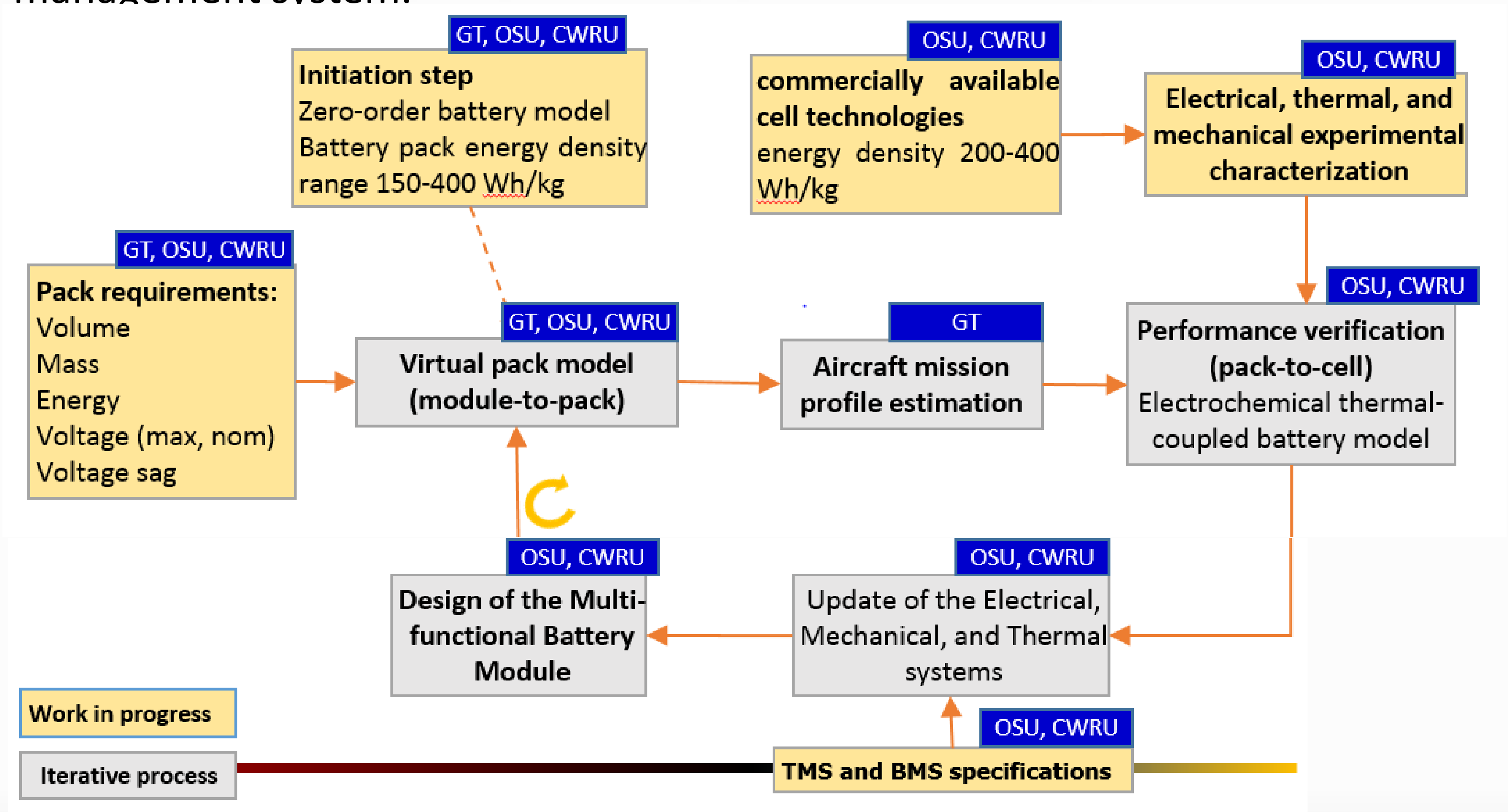
HV Electrical System Requirements:

- Max/min bus voltage
- Safety & Reliability (fault tolerance)
- Battery connectors/contactors availability
- Chip availability for BMS development
- EMI and compatibility requirements



Battery Pack Design Iterative Process

Design of a prototype of **high performance multifunctional smart structure-battery module** to enable safe on-board system-level distributed energy storage to power electric drive(s). The prototype will comprise structure-battery pack hardware along with an advanced battery management system.



Identify Commercially Available Cell Technology

- CWRU and OSU are investigating the availability of ***High Energy Density Lithium ion Cells***, to understand their attributes in terms of flexibility (and shape conformability), safety, reliability, energy density, life and thermal requirements.
- Current available cells have a specific energy density ≈ 250Wh/kg at 2C with an annual improvement of ≈8%.

Pouch cells

170-260 Wh/kg

- Kokam (Lithium-polymer, 130 - 265Wh/kg up to 50C, automotive / industrial application)
- Eagle Picher/Yardney (NMC, 125 – 135Wh/kg, aerospace application)
- XALT Energy (NMC, 220Wh/kg)

Cylindrical cells

240-270 Wh/kg

- Panasonic/Sanyo/Samsung (NCR, 260Wh/kg, automotive application)
- LG (IMR, 240-260 Wh/kg, automotive application)
- Efest (IMR, 270Wh/kg)

Pouch cells

300-400 Wh/kg

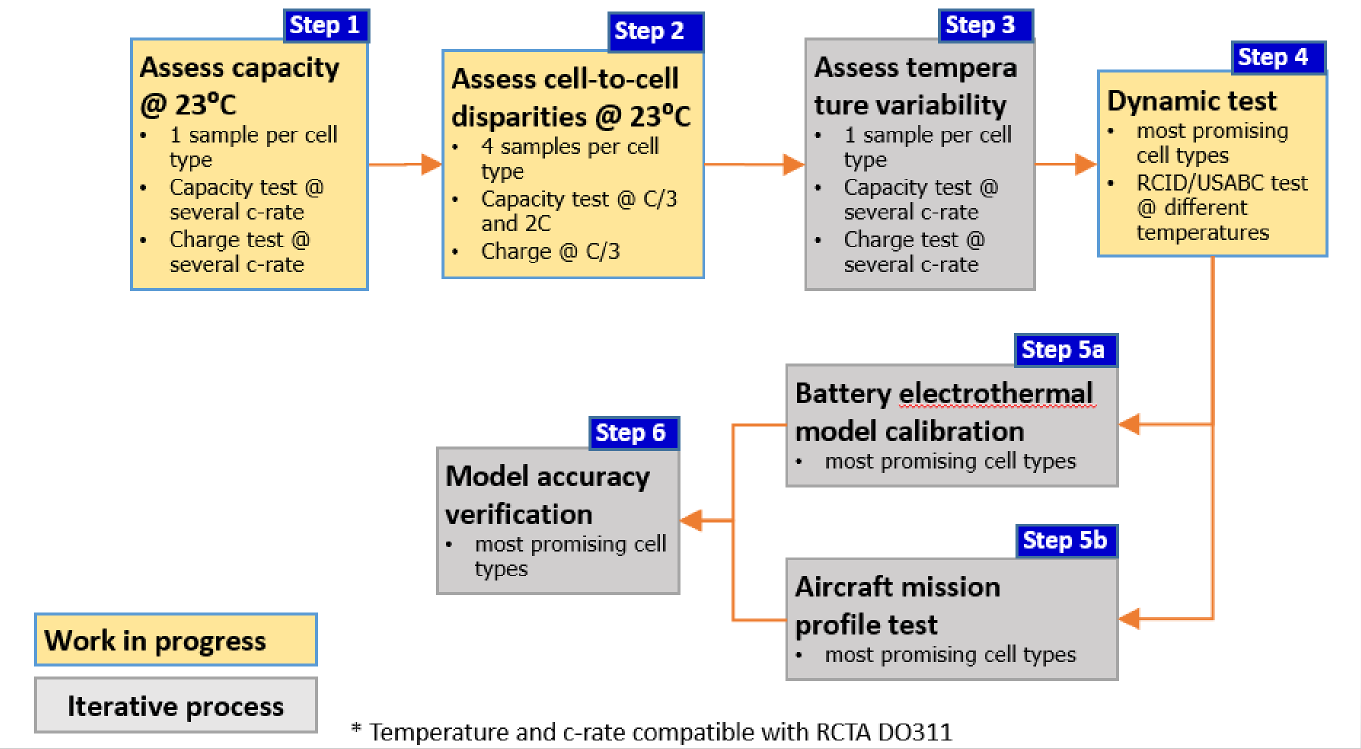
- American Lithium Energy (up to 400Wh/kg)
- Solid Power (Li-metal, ~325Wh/kg)
- Solid Energy Systems (Li-metal, 400 - 500Wh/kg)
- Sion Power (Li-S, 500Wh/kg)
- Oxis Energy (Li-S, 345Wh/kg)
- Envia Systems (Li-Si, 350Wh/kg)
- ~~Enevate Energy (Li-Si, 300Wh/kg)~~

Delivered and under testing

Procurement process

Electrical and Thermal Experimental Characterization

- All cell technologies under consideration will undergo a series of tests in order to identify the most suitable option. A general outline of the process is shown below.
- The specific characterization and life tests implemented would be based on available standards for batteries as well as past experience in research of energy storage systems.



The Ohio State University

Electric Machines

Development Program

- 200 kW machine to be demonstrated in the laboratory – July 2020
- 1 mW machine to be demonstrated at NASA NEAT Facility – July 2022

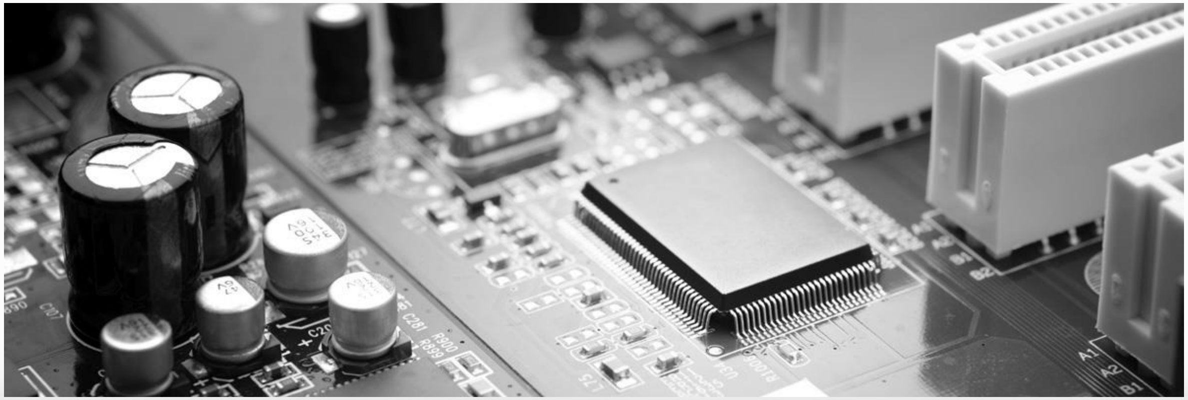
Team Effort

- The Ohio State University: Power Electronics
- University of Wisconsin: Electric Motor

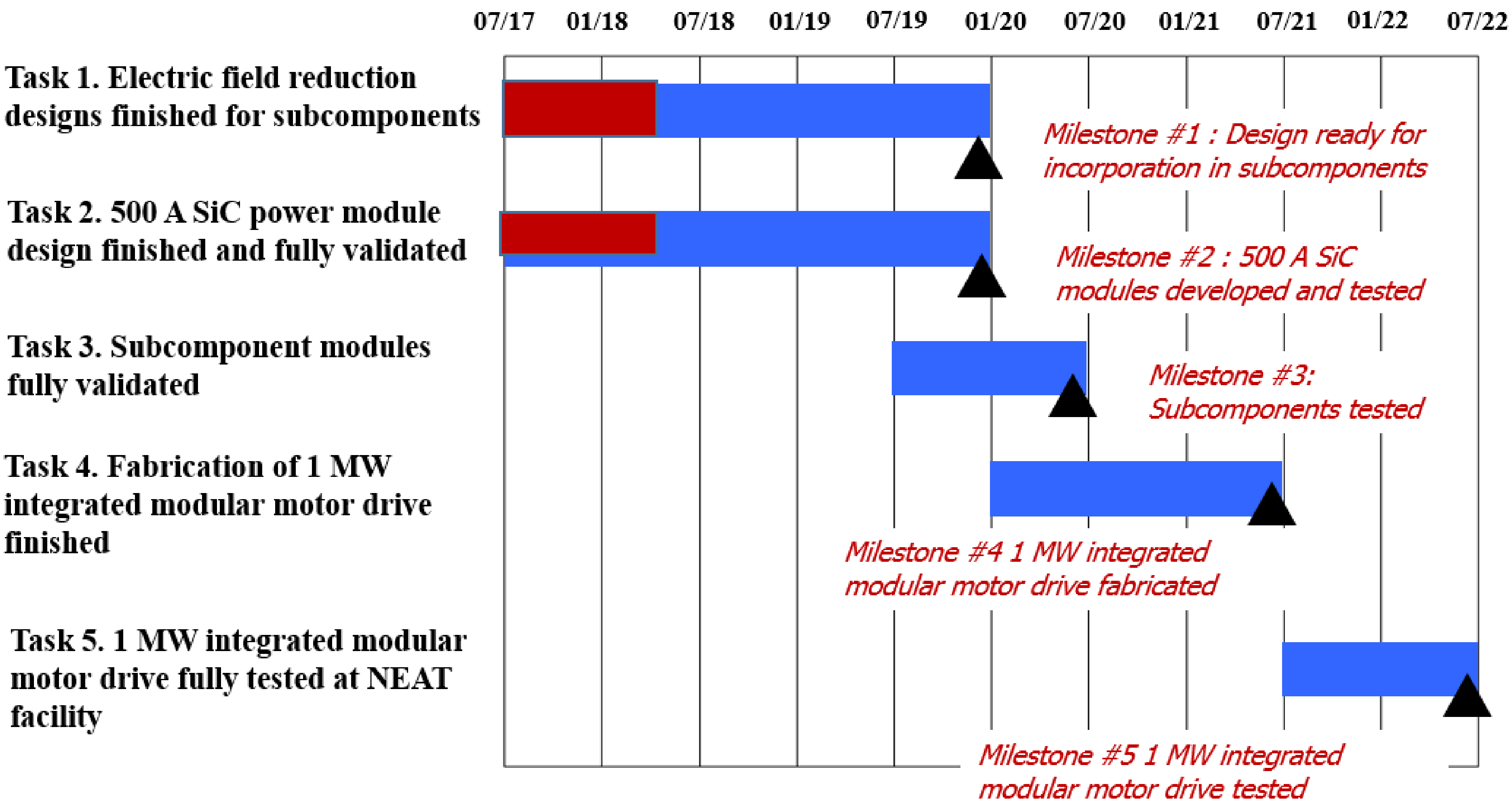
Power Electronics

Objectives:

- Develop 1 MW motor drive working with 2000 dc voltage in low pressure and high temperature environment while achieving a power density > 25 kW/kg
- Develop a system level control strategy for aircraft on board power system to improve system stability.

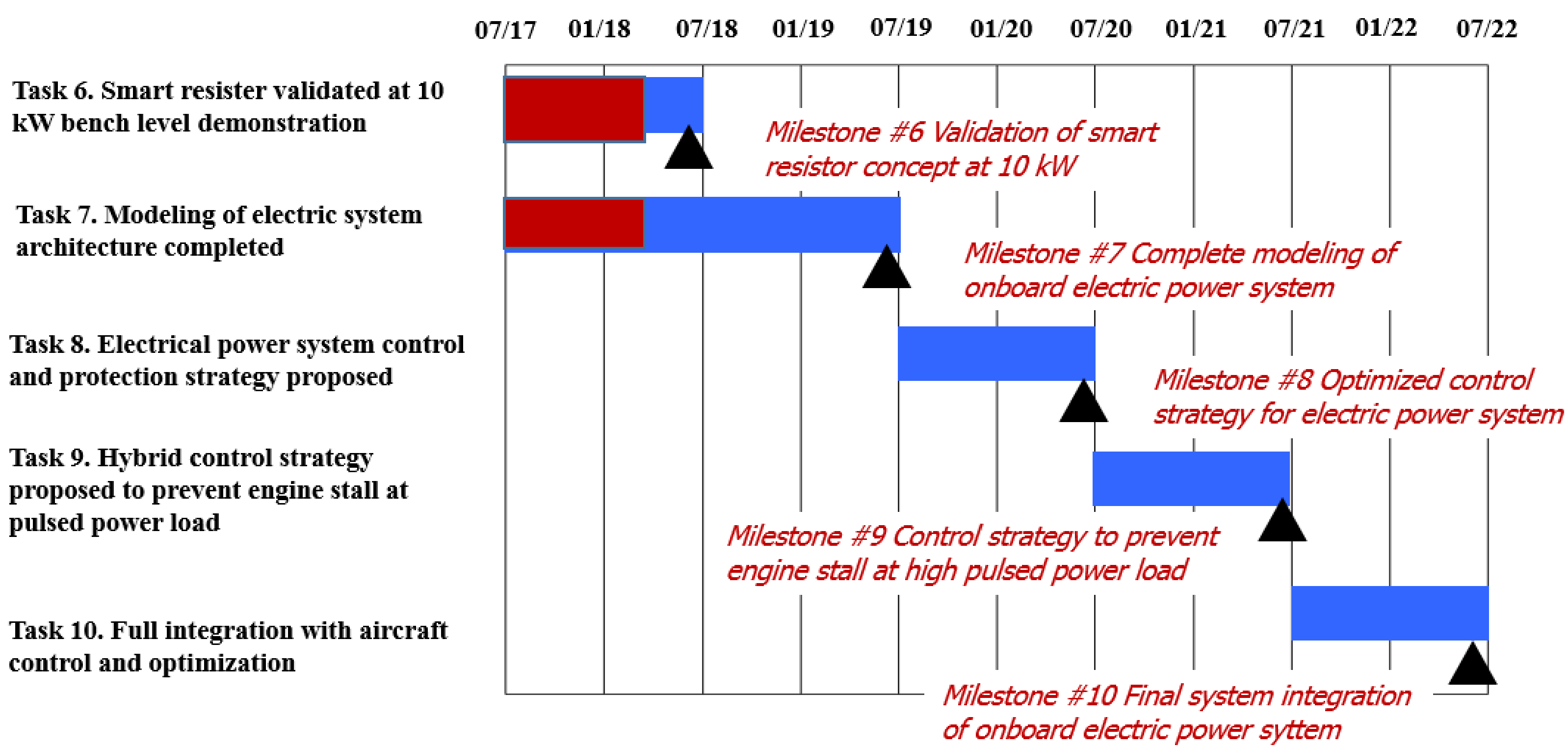


Milestones / Deliverables – Motor Drive

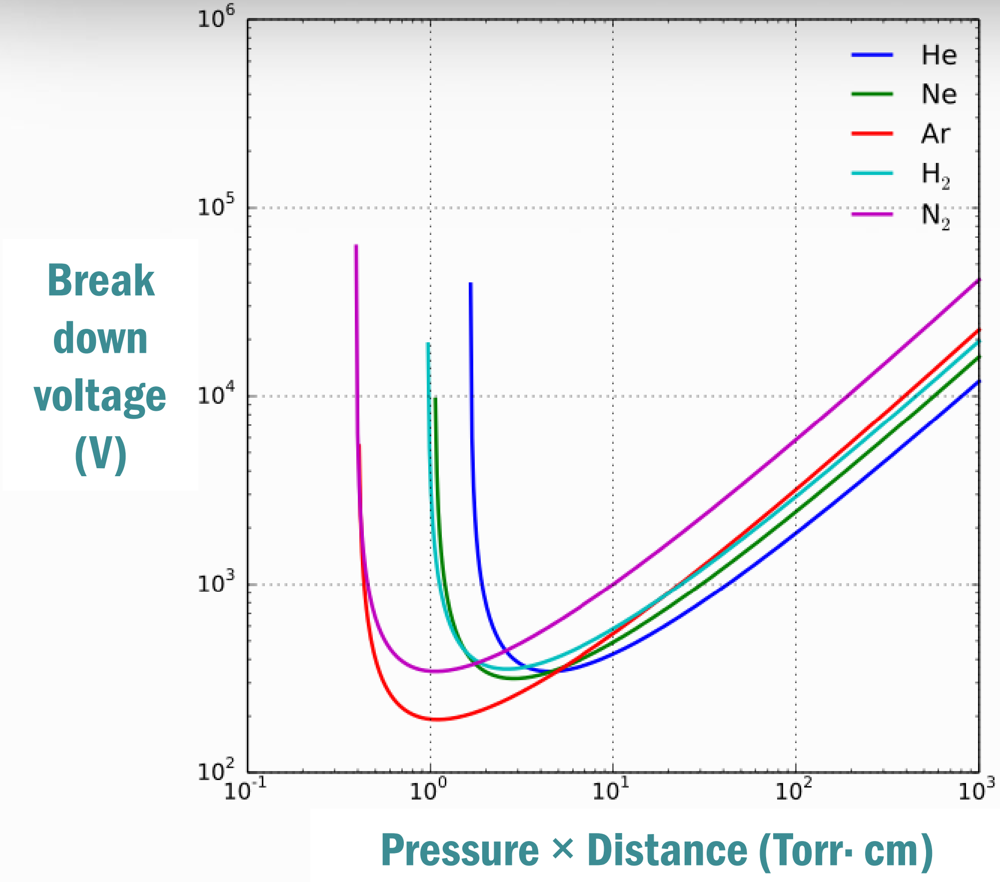


THE OHIO STATE UNIVERSITY

Milestones / Deliverables



Challenge I: Partial Discharge at High Altitude



The minimal onset voltage for partial discharge is around 300 V.

Detailed Challenges:

- **The chance of partial discharge increases significantly at low air pressure.**
- **Higher voltage (2 kV to 4.5 kV) will requirement significant increase of weight and size of insulation layers.**
- **Partial discharge pattern and mechanism at high dv/dt pulse width modulated (PWM) waveforms has not been adequately studied.**

Solutions and Approaches for Partial Discharge

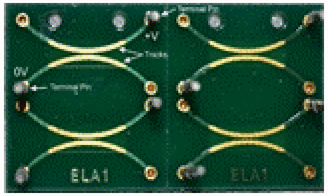
- **Systematic study of partial discharge at low air pressure in terms of voltage amplitude, dv/dt, temperature, humidity… and derive design and test guidelines**

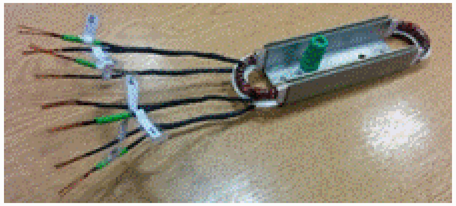
- **Modularized design and optimized grounding strategies to achieve low differential voltage for each circuit module**

- **Finite element analysis based electric field control to optimize the layout of power modules and power converters**

- **Evaluate existing power module designs that are rated at higher voltage**

- **Testing circuit samples with new insulation material and designs**






1.7 kV 300 A SiC Half Bridge

Challenge 2: Power Loss and Thermal Management

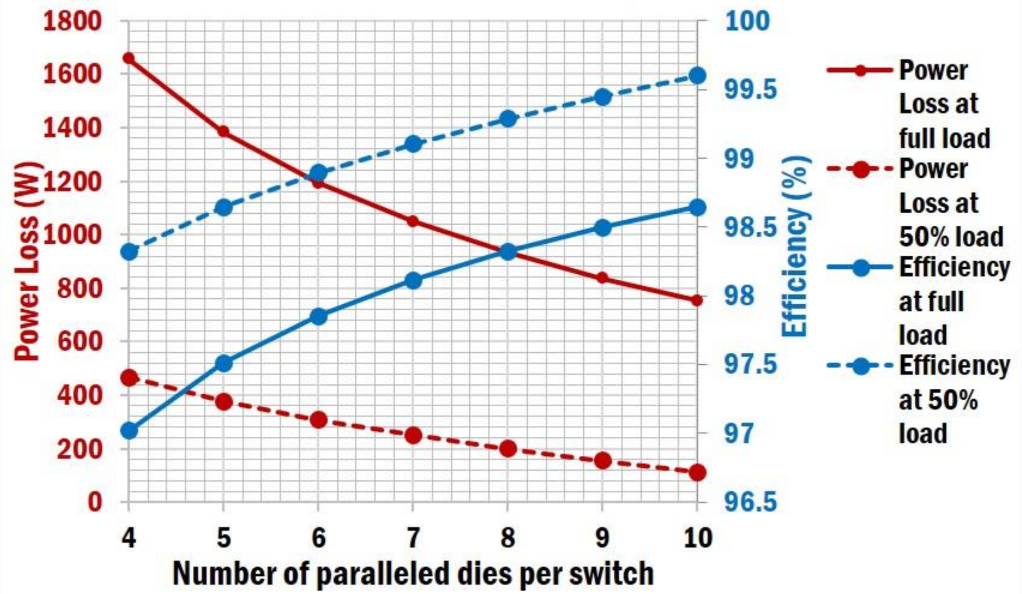
Power module loss calculation

Power module requirements and loss calculation assumption

Metrics and Parameters	Value
IMMD maximum power	1 MVA
IMMD DC bus voltage	2000 V
IMMD switching frequency	10 kHz
PWM modulation index	0.8
Module DC voltage	333 V
Module maximum power	166.67 kVA
Module Phase voltage	94.4 V rms
Module phase current	592 A rms
Die junction temperature	150 °C

*The power loss calculation is based on the MOSFET die selection.

Single phase power loss and efficiency vs number of paralleled dies



Observation:

- **Efficiency is above 99% when at 50% load and more than 7 SiC chips are in parallel.**

Thermal Simulation at 1 MW

Thermal simulation settings:

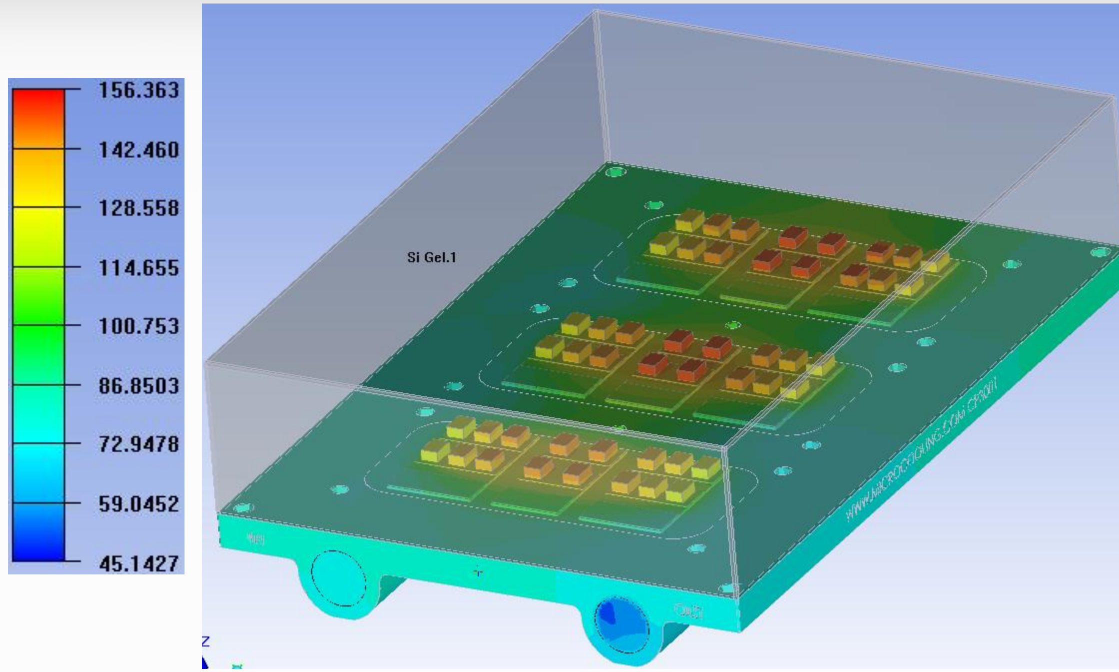
- 75 °C coolant temperature
- 60 W power loss per SiC chip

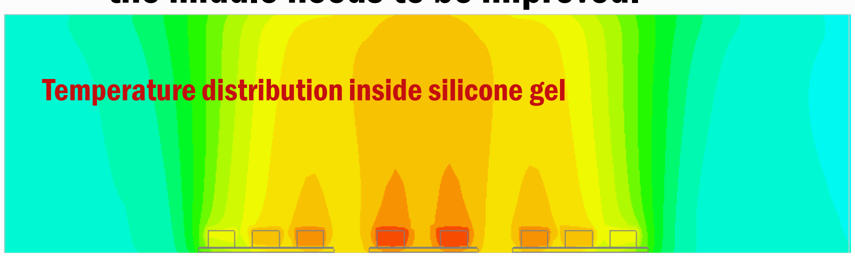
Observations:

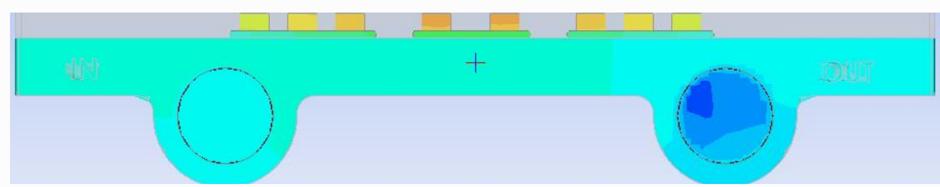
- Si Gel T_{max} is around 140 °C.
- Die maximum temperature:

Flow Rate [LFM]	T_{max} [°C]
200	156
400	132

- Thermal dissipation of the dies in the middle needs to be improved.







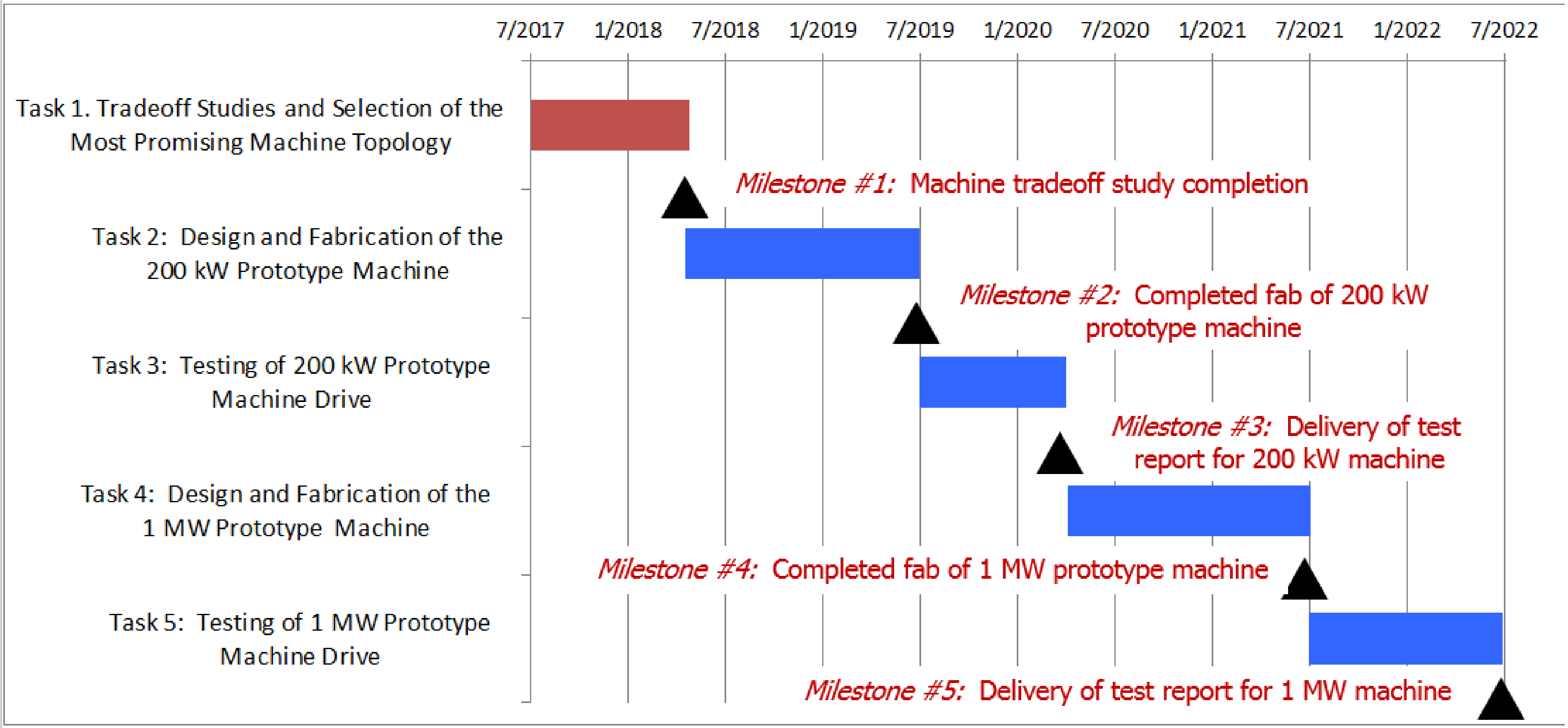
*45 C temperature is only present on edge of simulation area

With 200 LFM, the module will survive at 1 MW with small margin. The next step is to work with Univ. of Maryland for more advanced thermal designs.

Electric Motor

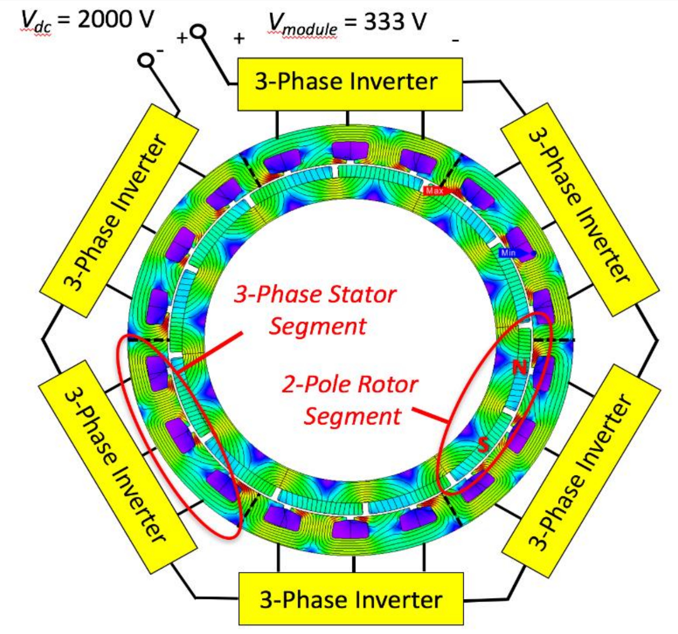
Develop, build and test a 1 mW motor with a specific power density > 14 kW/kg.

Project Schedule including Milestones / Deliverables

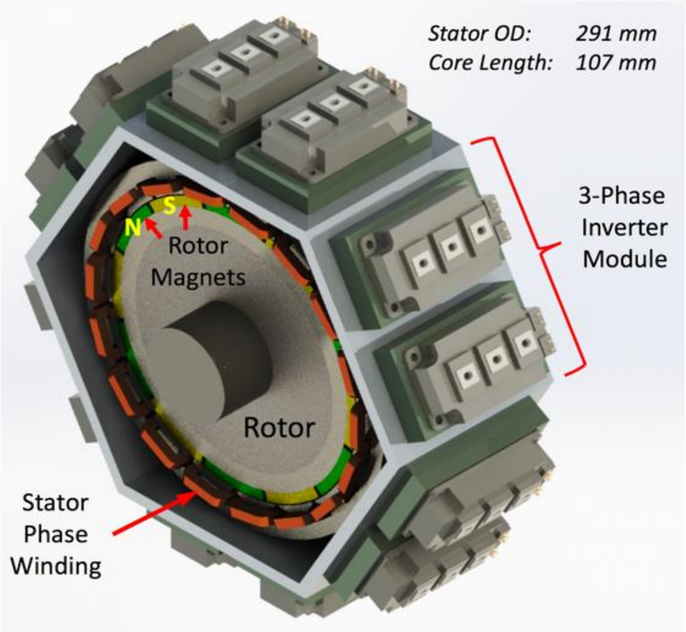


Design Concept for 1 MW Integrated Motor Drive

Proposed IMD Configuration



Rendered Drawing of IMD

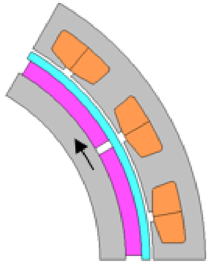


- 12-pole PM machine stator grouped into six 3-phase floating-wye groups, each excited by a 6-switch full-bridge inverter with SiC switches
- Inverters connected in series, so each inverter dc link voltage is 333 Vdc, totaling to 2000 Vdc

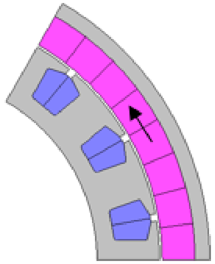
IMD configuration offers key advantages including enhanced high voltage compatibility at high altitudes and fault tolerance

High Power Density Machine Candidates for Tradeoff Study

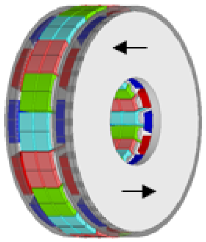
Inner Rotor Surface PM (SPM)



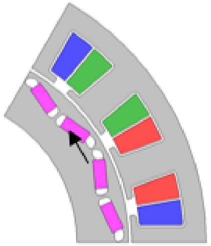
Outer Rotor SPM



Axial-Flux SPM

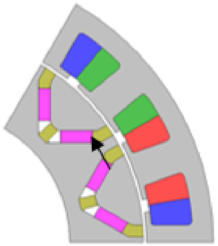


Classic Interior PM (IPM)

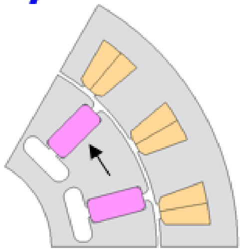


	Inner Rotor Surface PM (SPM)	Outer Rotor SPM	Axial-Flux SPM	Classic Interior PM (IPM)
Merits	• Simple electromagnetic configuration • Concentrated windings	• No magnet containment issue	• No rotor yokes required, reducing mass and core losses • Add stator/rotor stacks to increase power	• Magnets inside rotor simplify containment • Reluctance torque
Challenges	• Magnet containment reduces power density • Risk of high losses in rotor magnets	• Cantilevered rotor leads to complex bearing design • Poor access to stator windings for cooling	• Mechanical alignment critical with multi-stator/rotor • Magnet containment and leakage at both inner and outer rotor diameter	• High speed complicates structural/electromag-netic design tradeoffs

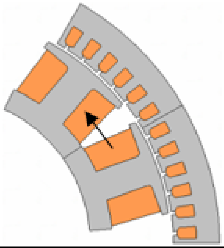
Dual-Phase IPM



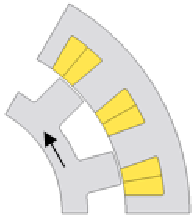
Spoke IPM



Wound-Field SM

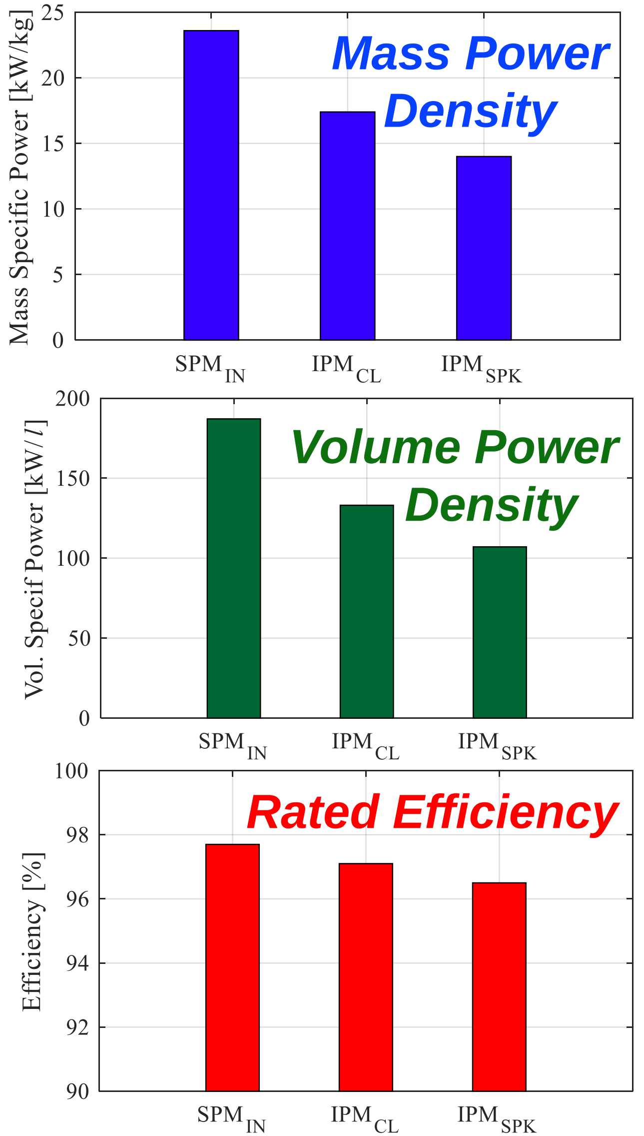


Switched Reluctance



	Dual-Phase IPM	Spoke IPM	Wound-Field SM	Switched Reluctance
Merits	• Decouples structural and electromagnetic design issues	• High magnet flux concentration	• Freedom from magnet demag. & temp. limits • Adjustable field control	• No magnets • Simple, robust rotor structure • Appealing fault tolerance
Challenges	• Low saturation flux density • Dual-Phase material availability is uncertain	• Complicated structural/elec-tromagnetic design tradeoffs • Demagnetization concerns	• High field winding losses • Rotor excitation adds mass and volume	• High torque ripple • High core losses • More complicated control

Finalist Machine Predicted Performance Metrics – 20,000 rpm

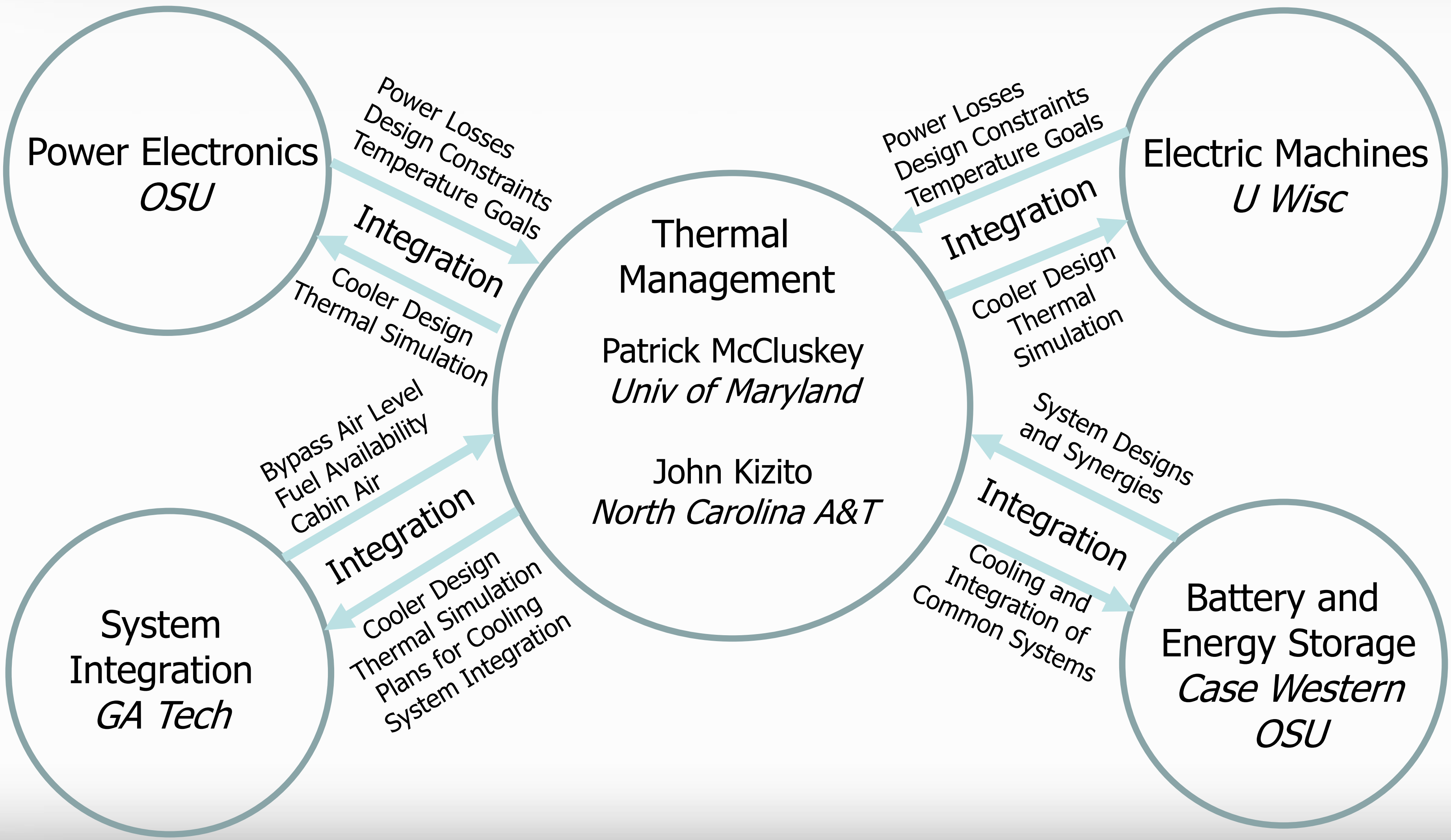


	Tip Speed	Sheer stress *[kPa]*	Active Mass *[kg]*	Mass Specific power *[kW/kg]*	Active Volume (*l*)	Vol. Specific power *[kW/l]*	Efficienc y *[%]*
Inner SPM	200	51.6	42.5	23.6	5.35	187.1	97.7
Classic IPM	200	44.6	57.4	17.4	7.51	133.1	97.1
Spoke IPM	170	45.2	71.7	14.0	9.34	107.1	96.5

- Inner rotor SPM machine predicted to deliver highest values of 3 key metrics
- Classic IPM is penalized by tradeoff between structural strength and magnet shorting by thick rotor bridges
- Spoke IPM is penalized by rotor structural strength issues requiring lower tip speed

Inner Rotor SPM machine achieves the highest metrics among finalists

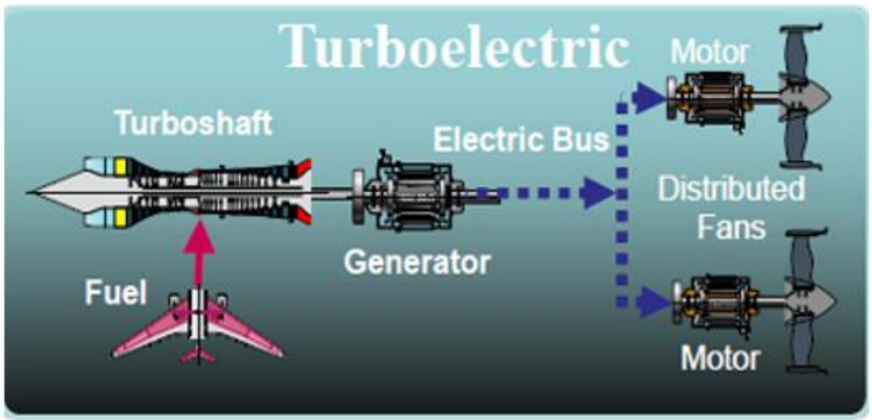
Team Members and Roles in the Project

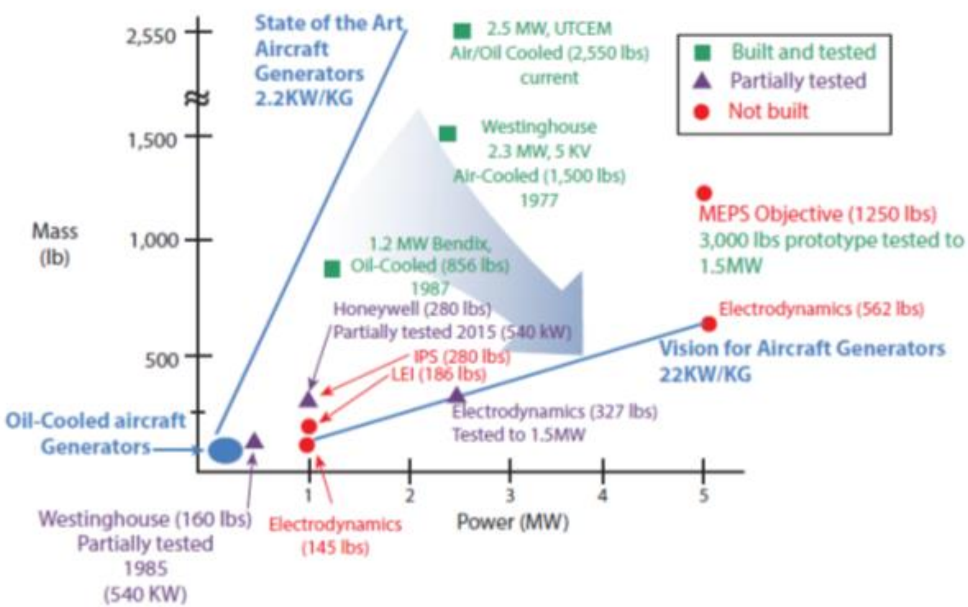


Milestones/Deliverables

Milestone and Timeline Information (date range)			
Key Milestone	Target	Actual	Comments
Development of Viable Cooling Technologies	June 2018		Documentation on the selection and modification of cooling technologies for use in aerospace applications.
200 kW system preliminary thermal design	June 2019		Integrated thermal design for the 200 kW electric propulsion system, including cooling power, COP, and reliability.
200 kW system testing and final modified design	June 2020		Testing and final design of cooling system to be integrated into the 200 kW system
1 MW system preliminary thermal design	June 2021		Integrated thermal design for the 1 MW electric propulsion system.
1 MW system testing and final modified design	June 2022		Testing and final design of cooling system to be integrated into the 1 MW system.

Overview of Thermal Challenge





- 1 MW motor at 93.5% efficient = 65 kW heat
- 1 MW power module at 98% efficient = 20 kW heat
- Need high heat flux cooling system that is reliable in aerospace applications.

Summary and Conclusions

Novel cooling solutions are being developed to address the combined challenges of:

- Higher heat loading
- Aerospace Environment (low pressure, high and low g-forces)

These cooling solutions are being

- Integrated between the electric machines, batteries, and power electronics
- Integrated between the cooling system and the other systems
- Compatible with the available incoming air and heat exhaust mechanisms

This program will develop and integrate these techniques for both 200 kW and 1 MW electric propulsion engines

The Demonstration

NEAT – NASA Electric Aircraft Test Bed

- Terrific Facility
- On line since summer 2016
- Incorporates altitude chamber
- Ohio State faculty and students closely connected to NASA on planning and operation

THE PRODUCT

- A MegaWatt System
- Will be demonstrated at the NASA NEAT Facility in Plumbrook, Ohio in 2022.
- Will provide the right building blocks to power the commercial airplanes of the future.
- Will lead creative new technologies for the nation and put us in a leadership position in the world:
  - Electrical Machines and Batteries for commercial and military aircraft
  - Innovative advanced airplane systems
  - Great motivation and education for students and faculty