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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) could be attained with electric propulsion.

Great **Opportunities** to help the environment, but challenges remain
THE TEAM

- Electric Machines
- Center for Automotive Research—Batteries
- Center for High Power Performance Electronics—Power Electronics
- Thermal Management
- Thermal Management
- Systems Integration
- Batteries
- NEAT Test Facility

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. ______________________

Iterative cooperative process between Universities

Prelim. Sizing
July 2018

Resized vehicle
June 2019

Vehicle Design Frozen
June 2020

Vehicle Update
June 2021

Vehicle Update
June 2022
ULI Concept Benefits Assessment

Baseline Aircraft (CRJ 900) → Next Generation Aircraft → Distributed Hybrid Turbo Electric

Fuel Burn Reduction at 600 nmi and typical payload:

- Distributed Propulsion: 8%
- Use of Hybrid Propulsion: 9% (15%)
- Distributed Propulsion: 6%

**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
- Batteries for hybrid propulsion structurally integrated in the floor of the aircraft
- >96% efficient motor at ~14kw/kg
- 99% efficient inverter at ~25 kw/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%
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
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:

- GATech will generate initial simulation of typical missions in an “idealized” scenario, to obtain preliminary load profiles for battery pack sizing.

- OSU/UW will determine pack requirements (max/min voltage limits, etc...) for operation of motors/generators and power electronics.

- OSU/CWRU will investigate available cell technologies, provide initial specifications of cell requirements (i.e., ranges of feasible values).

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

Energy Storage (OSU/CWRU) → SLM (GT/ASDL) → EM/Electronics (OSU/UW)
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%.

![Diagram showing energy density and providers]

- 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
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.

- **Step 1**: Assess capacity @ 23°C
  - 1 sample per cell type
  - Capacity test @ several c-rate
  - Charge test @ several c-rate

- **Step 2**: Assess cell-to-cell disparities @ 23°C
  - 4 samples per cell type
  - Capacity test @ C/3 and 2C
  - Charge @ C/3

- **Step 3**: Assess temperature variability
  - 1 sample per cell type
  - Capacity test @ several c-rate
  - Charge test @ several c-rate

- **Step 4**: Dynamic test
  - Most promising cell types
  - RCID/USABC test @ different temperatures

- **Step 5a**: Battery electrothermal model calibration
  - Most promising cell types

- **Step 5b**: Aircraft mission profile test
  - Most promising cell types

- **Model accuracy verification**: Most promising cell types

*Temperature and c-rate compatible with RCTA DO311*
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

Task 1. Electric field reduction designs finished for subcomponents

Task 2. 500 A SiC power module design finished and fully validated

Task 3. Subcomponent modules fully validated

Task 4. Fabrication of 1 MW integrated modular motor drive finished

Task 5. 1 MW integrated modular motor drive fully tested at NEAT facility

Milestone #1: Design ready for incorporation in subcomponents

Milestone #2: 500 A SiC modules developed and tested

Milestone #3: Subcomponents tested

Milestone #4: 1 MW integrated modular motor drive fabricated

Milestone #5: 1 MW integrated modular motor drive tested
Milestones / Deliverables

Task 6. Smart resistor validated at 10 kW bench level demonstration

Task 7. Modeling of electric system architecture completed

Task 8. Electrical power system control and protection strategy proposed

Task 9. Hybrid control strategy proposed to prevent engine stall at pulsed power load

Task 10. Full integration with aircraft control and optimization

Milestone #6 Validation of smart resistor concept at 10 kW

Milestone #7 Complete modeling of onboard electric power system

Milestone #8 Optimized control strategy for electric power system

Milestone #9 Control strategy to prevent engine stall at high pulsed power load

Milestone #10 Final system integration of onboard electric power system
Challenge I: Partial Discharge at High Altitude

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

- The chance of partial discharge increases significantly at low air pressure.
- Higher voltage (2 kV to 4.5 kV) will require a 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.

Detailed Challenges:
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
### Challenge 2: Power Loss and Thermal Management

#### Power module loss calculation

**Power module requirements and loss calculation assumption**

<table>
<thead>
<tr>
<th>Metrics and Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMMD maximum power</td>
<td>1 MVA</td>
</tr>
<tr>
<td>IMMD DC bus voltage</td>
<td>2000 V</td>
</tr>
<tr>
<td>IMMD switching frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>PWM modulation index</td>
<td>0.8</td>
</tr>
<tr>
<td>Module DC voltage</td>
<td>333 V</td>
</tr>
<tr>
<td>Module maximum power</td>
<td>166.67 kVA</td>
</tr>
<tr>
<td>Module Phase voltage</td>
<td>94.4 V rms</td>
</tr>
<tr>
<td>Module phase current</td>
<td>592 A rms</td>
</tr>
<tr>
<td>Die junction temperature</td>
<td>150 ºC</td>
</tr>
</tbody>
</table>

**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.

*The power loss calculation is based on the MOSFET die selection.*
Thermal Simulation at 1 MW

Thermal simulation settings:
- 75 °C coolant temperature
- 60 W power loss per SiC chip

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

<table>
<thead>
<tr>
<th>Flow Rate [LFM]</th>
<th>$T_{\text{max}}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>156</td>
</tr>
<tr>
<td>400</td>
<td>132</td>
</tr>
</tbody>
</table>

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

Temperature distribution inside silicone gel

*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

- **Task 1.** Tradeoff Studies and Selection of the Most Promising Machine Topology
- **Task 2.** Design and Fabrication of the 200 kW Prototype Machine
- **Task 3.** Testing of 200 kW Prototype Machine Drive
- **Task 4.** Design and Fabrication of the 1 MW Prototype Machine
- **Task 5.** Testing of 1 MW Prototype Machine Drive

- **Milestone #1:** Machine tradeoff study completion
- **Milestone #2:** Completed fab of 200 kW prototype machine
- **Milestone #3:** Delivery of test report for 200 kW machine
- **Milestone #4:** Completed fab of 1 MW prototype machine
- **Milestone #5:** Delivery of test report for 1 MW machine
Design Concept for 1 MW Integrated Motor Drive

Proposed IMD Configuration

- 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

Rendered Drawing of IMD

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)**
- Simple electromagnetic configuration
- Concentrated windings

**Outer Rotor SPM**
- No magnet containment issue

**Axial-Flux SPM**
- No rotor yokes required, reducing mass and core losses
- Add stator/rotor stacks to increase power

**Classic Interior PM (IPM)**
- Magnets inside rotor simplify containment
- Reluctance torque

**Merits**
- **Inner Rotor Surface PM (SPM)**
  - Simple electromagnetic configuration
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- **Classic Interior PM (IPM)**
  - Magnets inside rotor simplify containment
  - Reluctance torque

**Challenges**
- **Inner Rotor Surface PM (SPM)**
  - Magnet containment reduces power density
  - Risk of high losses in rotor magnets

- **Outer Rotor SPM**
  - Cantilevered rotor leads to complex bearing design
  - Poor access to stator windings for cooling

- **Axial-Flux SPM**
  - Mechanical alignment critical with multi-stator/rotor
  - Magnet containment and leakage at both inner and outer rotor diameter

- **Classic Interior PM (IPM)**
  - High speed complicates structural/electromagnetic design tradeoffs

**Dual-Phase IPM**
- Decouples structural and electromagnetic design issues

**Spoke IPM**
- High magnet flux concentration

**Wound-Field SM**
- Freedom from magnet demag. & temp. limits
- Adjustable field control

**Switched Reluctance**
- No magnets
- Simple, robust rotor structure
- Appealing fault tolerance

**Merits**
- **Dual-Phase IPM**
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  - Adjustable field control

- **Switched Reluctance**
  - No magnets
  - Simple, robust rotor structure
  - Appealing fault tolerance

**Challenges**
- **Dual-Phase IPM**
  - Low saturation flux density
  - Dual-Phase material availability is uncertain

- **Spoke IPM**
  - Complicated structural/electromagnetic design tradeoffs
  - Demagnetization concerns

- **Wound-Field SM**
  - High field winding losses
  - Rotor excitation adds mass and volume

- **Switched Reluctance**
  - High torque ripple
  - High core losses
  - More complicated control
Finalist Machine Predicted Performance Metrics – 20,000 rpm

- 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**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner SPM</td>
<td>200</td>
<td>51.6</td>
<td>42.5</td>
<td>23.6</td>
<td>5.35</td>
<td>187.1</td>
<td>97.7</td>
</tr>
<tr>
<td>Classic IPM</td>
<td>200</td>
<td>44.6</td>
<td>57.4</td>
<td>17.4</td>
<td>7.51</td>
<td>133.1</td>
<td>97.1</td>
</tr>
<tr>
<td>Spoke IPM</td>
<td>170</td>
<td>45.2</td>
<td>71.7</td>
<td>14.0</td>
<td>9.34</td>
<td>107.1</td>
<td>96.5</td>
</tr>
</tbody>
</table>
Team Members and Roles in the Project

Power Electronics
OSU

Electric Machines
U Wisc

Thermal Management
Patrick McCluskey
Univ of Maryland

John Kizito
North Carolina A&T

System Integration
GA Tech

Battery and Energy Storage
Case Western
OSU
**Milestones/Deliverables**

<table>
<thead>
<tr>
<th>Key Milestone</th>
<th>Target</th>
<th>Actual</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of Viable Cooling Technologies</td>
<td>June 2018</td>
<td></td>
<td>Documentation on the selection and modification of cooling technologies for use in aerospace applications.</td>
</tr>
<tr>
<td>200 kW system preliminary thermal design</td>
<td>June 2019</td>
<td></td>
<td>Integrated thermal design for the 200 kW electric propulsion system, including cooling power, COP, and reliability.</td>
</tr>
<tr>
<td>200 kW system testing and final modified design</td>
<td>June 2020</td>
<td></td>
<td>Testing and final design of cooling system to be integrated into the 200 kW system</td>
</tr>
<tr>
<td>1 MW system preliminary thermal design</td>
<td>June 2021</td>
<td></td>
<td>Integrated thermal design for the 1 MW electric propulsion system.</td>
</tr>
<tr>
<td>1 MW system testing and final modified design</td>
<td>June 2022</td>
<td></td>
<td>Testing and final design of cooling system to be integrated into the 1 MW system.</td>
</tr>
</tbody>
</table>
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.
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
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