ARMD Transformative Aeronautics Concepts Program

Convergent Aeronautics Solutions Execution Project

Compact Additively Manufactured Innovative Electric Motor (CAMIEM)

CAS Showcase 2019

November 13 - 14, 2019

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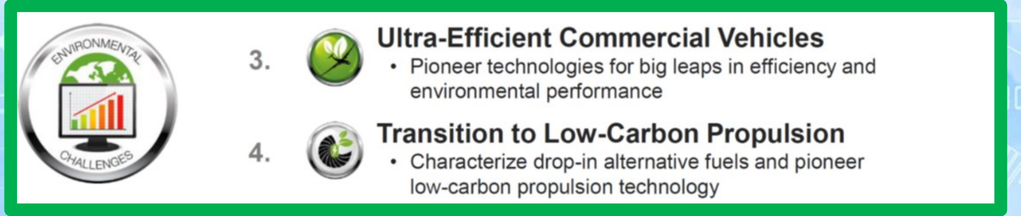
Images are credit NASA unless otherwise specified

Targeted – Big Questions

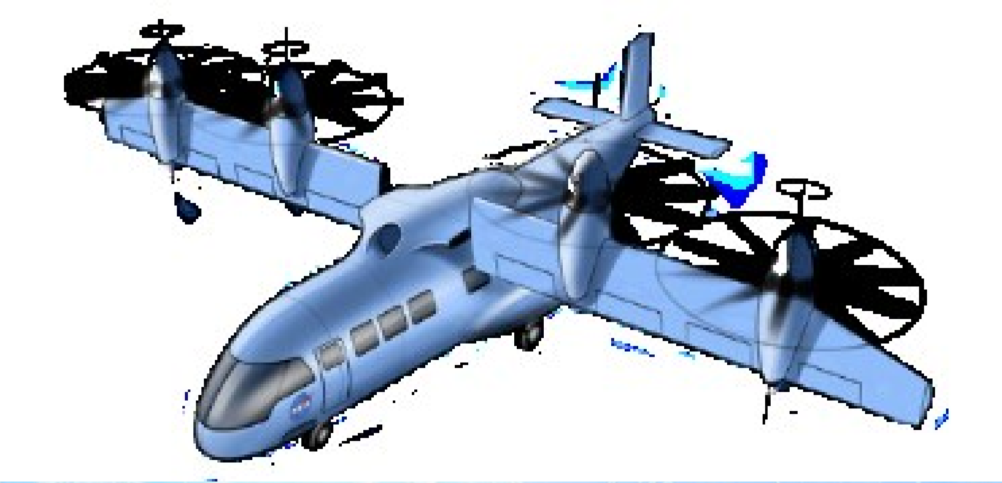
- **Can we enable cleaner, more fuel efficient aircraft using hybrid/electric propulsion?**
- **Can we dramatically increase the power density of electric machines?**
- **Focus Toward NASA Aeronautics Research Six Strategic Thrusts**



CAMIEM Big Question: Can emerging manufacturing technologies, namely Additive Manufacturing (AM), enable novel electric motor concepts for achieving the high power densities required for future hybrid propulsion?

Relevance to Aerospace

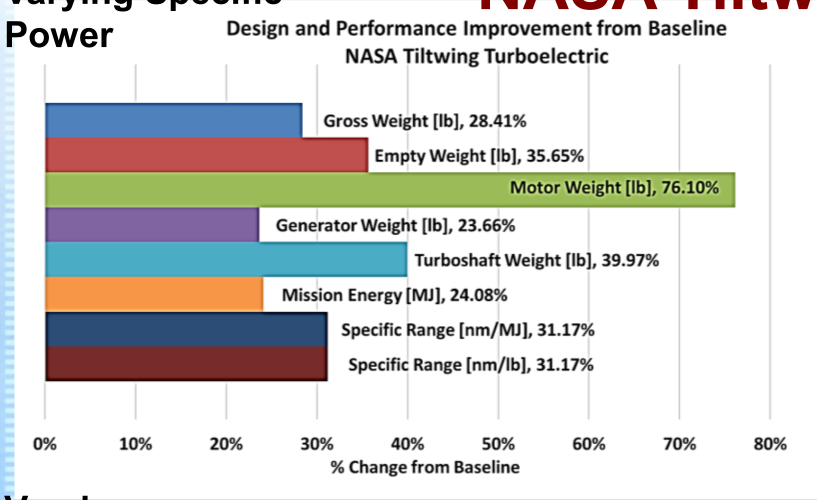
Urban Air Mobility



NASA 15 Passenger Tilt-wing

NASA Tiltwing Turboelectric

Varying Specific Power



Efficiency = 95%

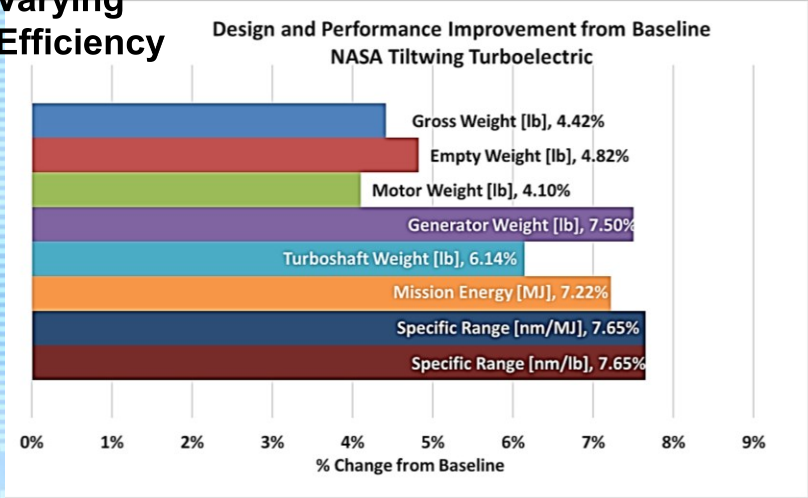
Specific power = 9.4 hp/lb (15.4 kW/kg)

Baseline Specific power = 3.13 hp/lb (5 kW/kg)

28.4% reduction in Gross weight

24.1% reduction in Mission energy

Varying Efficiency



- Increase in Power-to-Weight ratio by 1 hp/lb results in a gross weight reduction of ~500 lbs and an energy reduction of ~1330 MJ

Efficiency = 100%

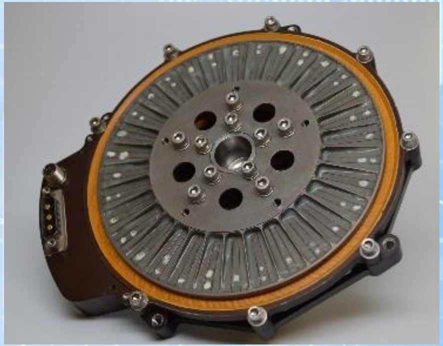
Specific power = 3.13 hp/lb (5 kW/kg)
Baseline Efficiency = 95%

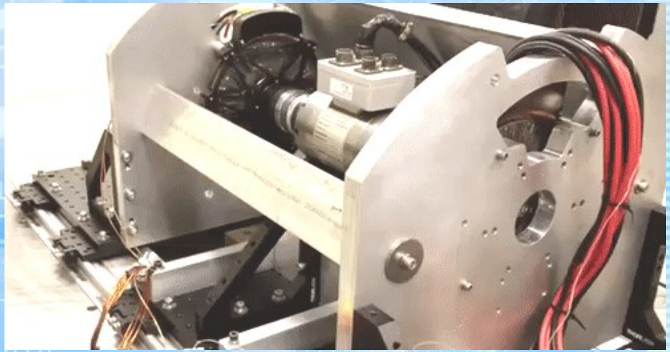
4.4% reduction in Gross weight

7.2% reduction in Mission energy

State of the Art (SoA) Motor

- **Motor Width: ~ 7.5"**
- **Total weight ~ 4lbs(1.8 kg)**

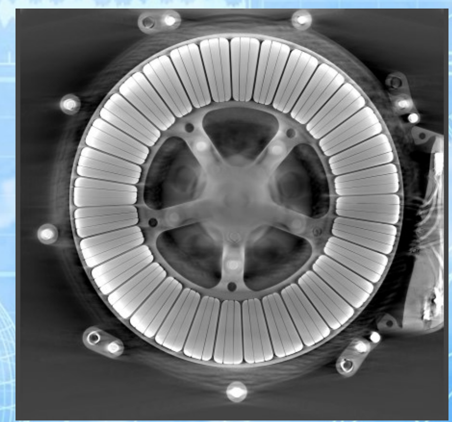


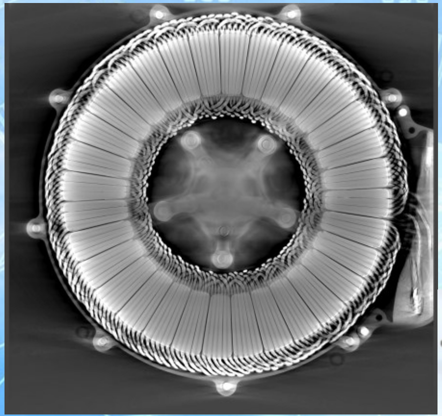


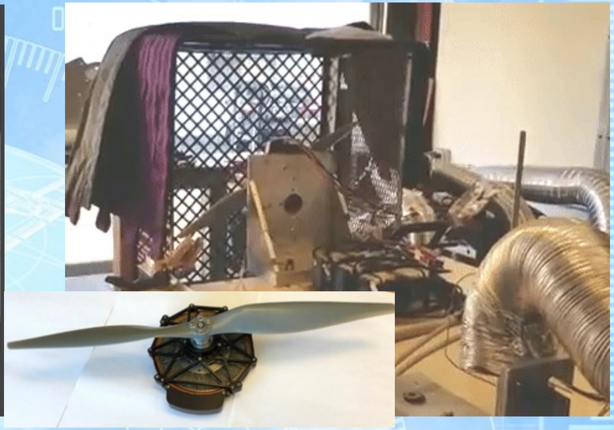
Performance Specs:

8.3 kW at 7500 rpm

- **94% efficient**
- **4.0 kW/kg power density (below max. allowable temp.)**

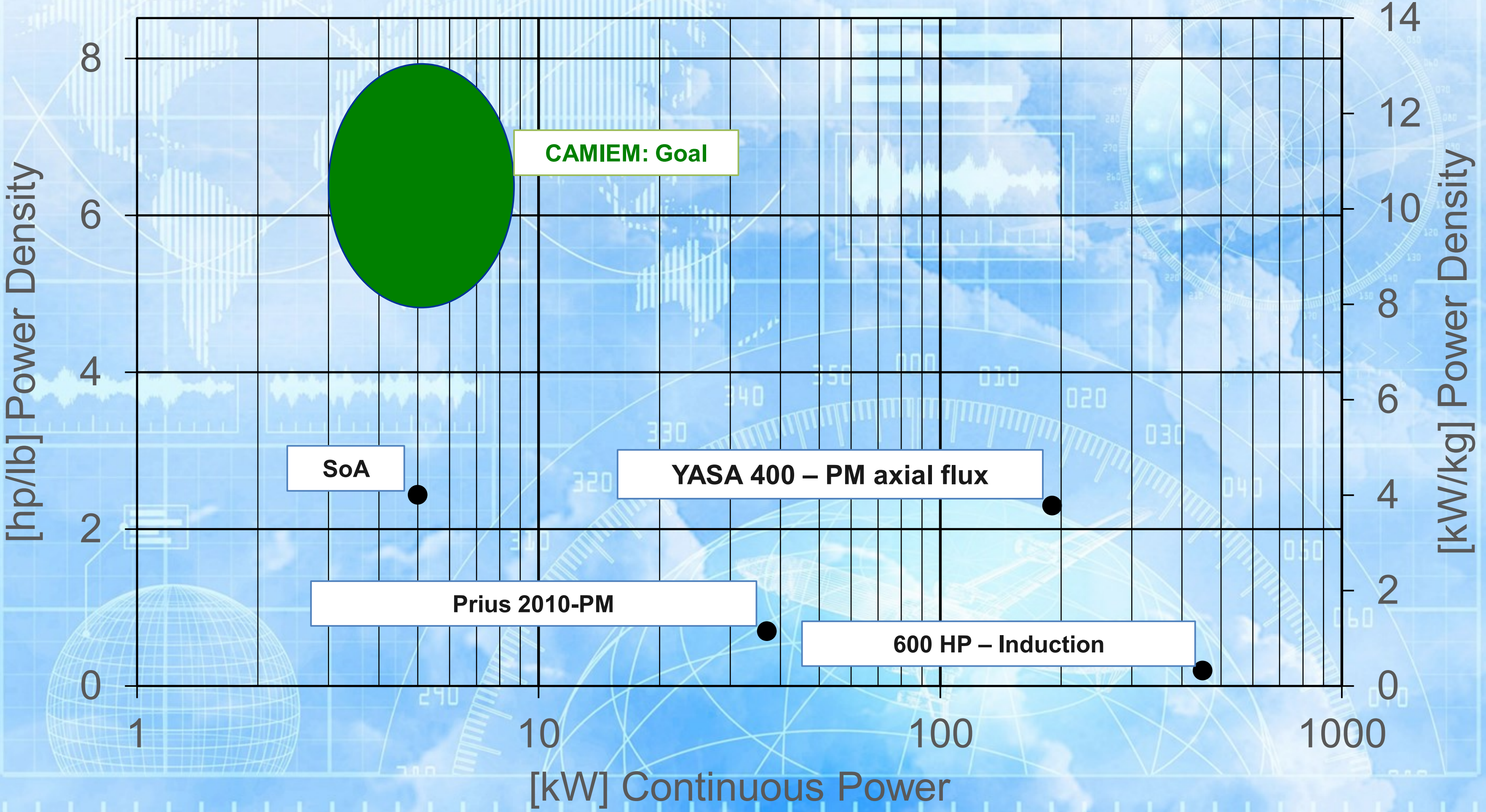






Already SoA due to compact design, halbach array of magnets, and high power density.

Disruptive: Leap Beyond Current SoA



Estimated Performance Improvements due to Additively Manufactured Iron Core Stator

- CAMIEM stator designs leverage material selection and additive manufacturing to increase max. temperature and the motor constant.
- $\Delta P_{specific}$ **1.68x improvement** was predicted via model calculations.

$$\Delta P_{specific} = \Delta K_m \cdot \sqrt{\frac{T_{stator\ max} - T_{ambient}}{\Delta R_{thermal}} \cdot \frac{\Delta\omega_{shaft}}{\Delta mass_{total}}}$$

$$\Delta P_{specific} = \mathbf{1.68} = 1.62 \cdot \sqrt{\frac{1.44}{1} \cdot \frac{1}{1.16}}$$

Stator Max. Temperature | Motor Constant, Km | **Predict: 68% increase in $P_{specific}$**

Material selections and demonstrations for temp. increase to >220°C from 160°C baseline

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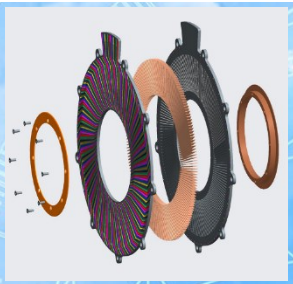

Iron core stator increases torque and motor constant

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Structural Components

- CAMIEM structural components leverage additive manufacturing to reduce mass and improve cooling.
- $\Delta P_{specific}$ **1.2x improvement** was predicted via model calculations

$$\Delta P_{specific} = \Delta K_m \cdot \sqrt{\frac{T_{stator\ max} - T_{ambient}}{\Delta R_{thermal}} \cdot \frac{\Delta \omega_{shaft}}{\Delta mass_{total}}}$$

$$\Delta P_{specific} = \mathbf{1.2} = 1 \cdot \sqrt{\frac{1}{0.75} \cdot \frac{1}{0.96}}$$

Save Mass | Improve Cooling | **Predict: 20% increase in $P_{specific}$**

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mass savings = -111 g (-6% of full motor)

mass cost = +4 g (+0.2% of full motor)

mass cost = +35 g (+1.7% of full motor)

Both contribute to cooling and thereby decreasing $\Delta R_{thermal}$ down to at least 0.75.

CAMIEM: Feasible Power Density Improvement

- Combined CAMIEM structural components feasible stator improvements that leverage additive manufacturing to increase the power density.
- $\Delta P_{specific}$ = **2x improvement is feasible**

$$\Delta P_{specific} = \Delta K_m \cdot \sqrt{\frac{T_{stator\ max} - T_{ambient}}{\Delta R_{thermal}} \cdot \frac{\Delta \omega_{shaft}}{\Delta mass_{total}}}$$

$$\Delta P_{specific} = \mathbf{2.0} = 1.62 \cdot \sqrt{\frac{1.44}{0.75} \cdot \frac{1}{1.12}}$$

Structural Components | Feasible Stator Improvements | **Predict: 100% increase in $P_{specific}$**

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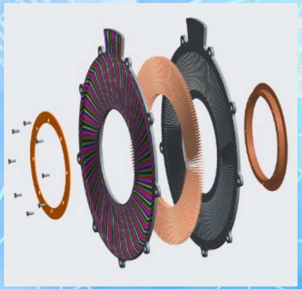

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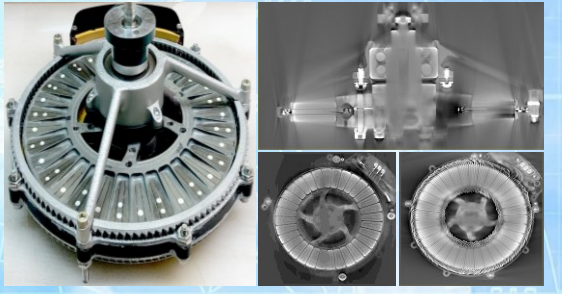
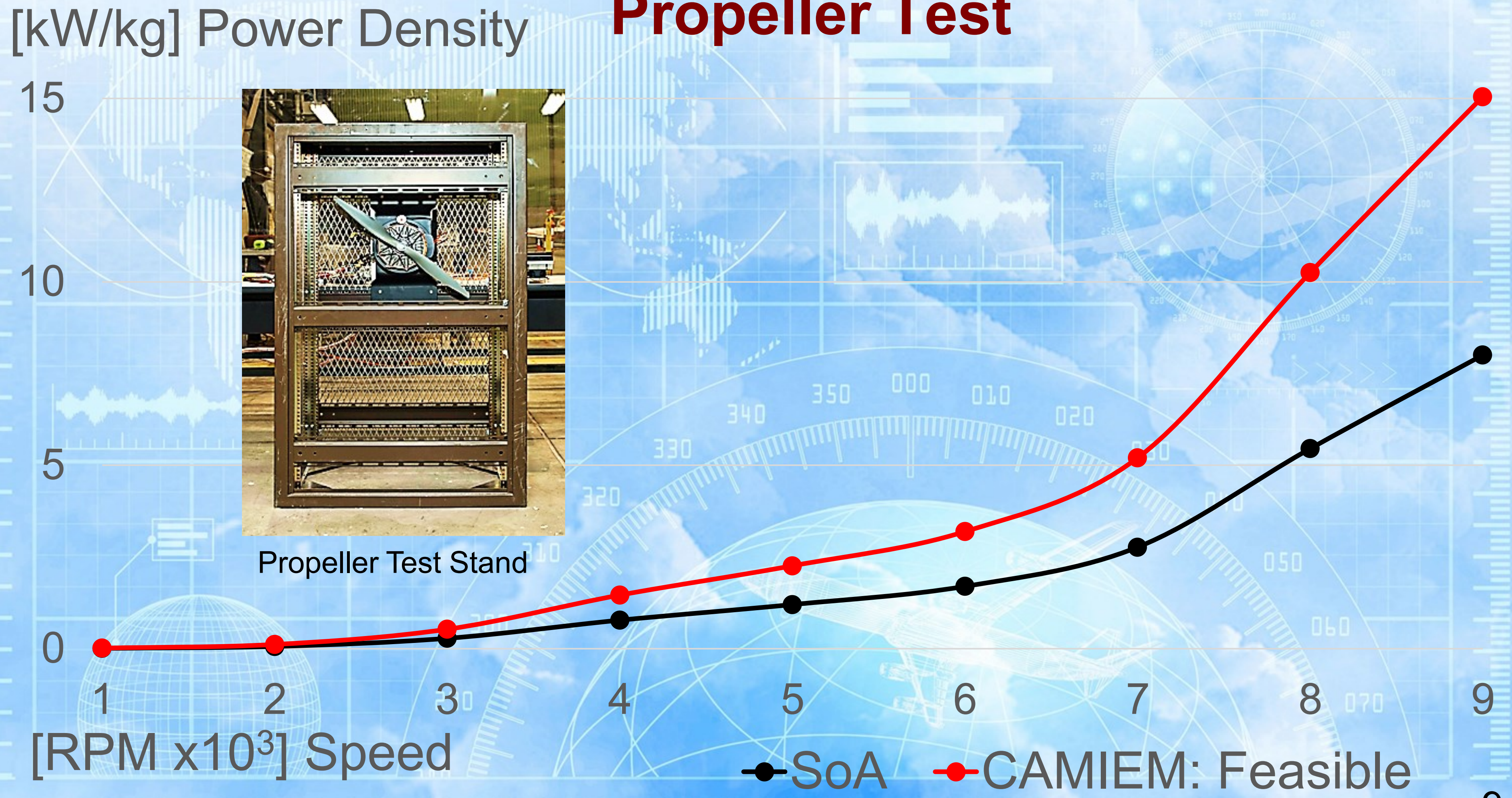
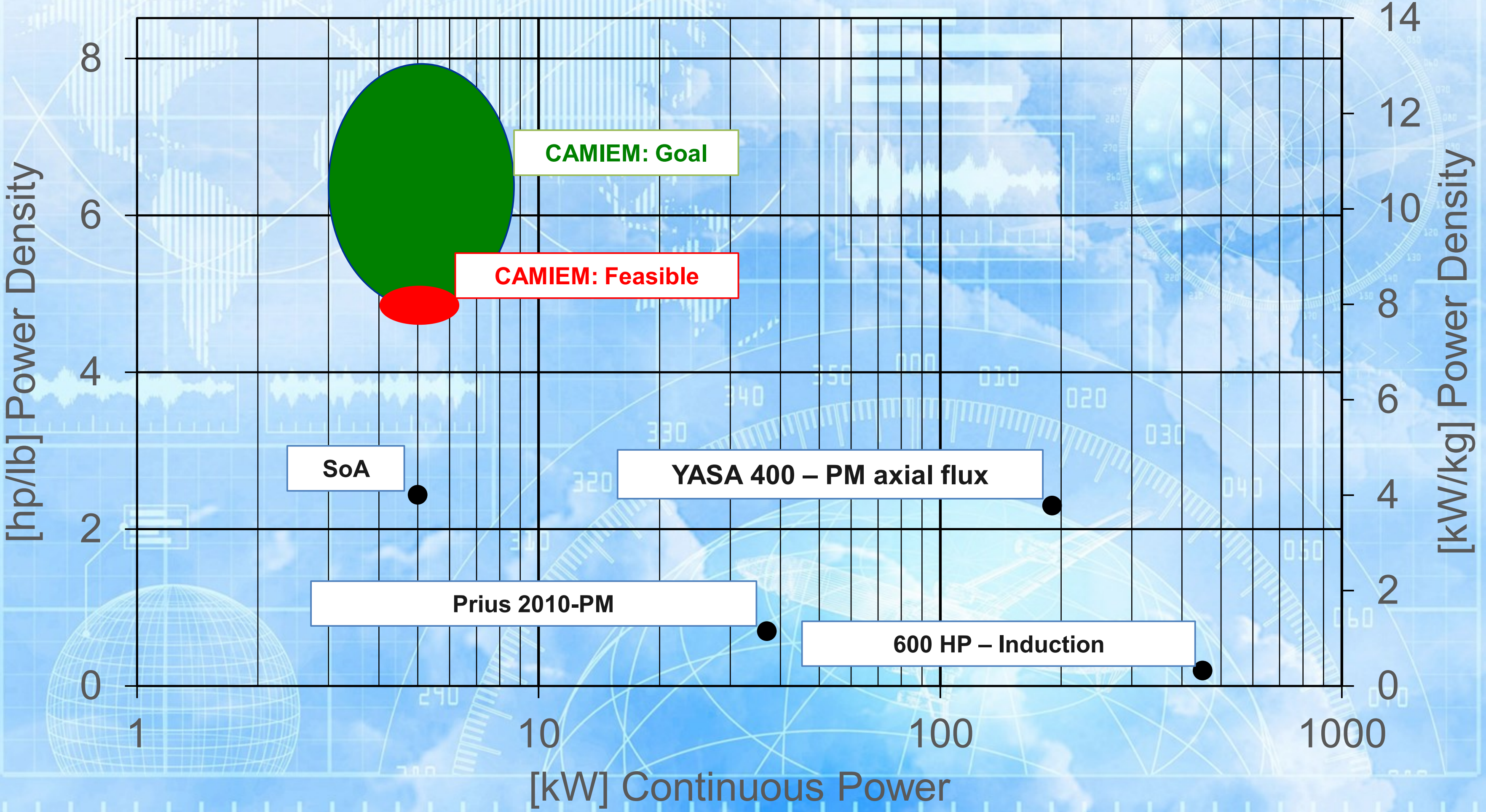


Propeller Test



Propeller Test Stand

Disruptive: Leap Beyond Current SoA



CAMIEM - Compact Additively Manufactured Innovative Electric Motor

Teaming - Partner Roles

NASA GRC
- Stator design and fabrication; direct printing of conductive layers and multi-material systems
- System analysis
- Electric motor testing

NASA LaRC
- Design and development of AM metallic structural components: rotors, housing, finned cooling ring for stator
- Computed tomography

NASA AFRC
- Electric motor testing in a propeller test stand

LaunchPoint Technologies
- Baseline electric machine
- Innovative electric machine designs
- Industry perspective on AM impact on design, cost, and fabrication

University of Texas El Paso
- AM of 3D electronic structures
- Printing of thermoplastic substrates with copper wire incorporation

Objective: Utilize AM methods to achieve new motor designs that have higher power densities and manufacturing benefits.

The Take-Aways

- **Electric Motors move Electric aircraft through the air**
  - Aviation pushes motor tech to the edge
  - Additive manufacturing can lead to improved motors
- **AM design space can be leveraged for electric motors**
  - Complex shapes are often enabled by AM
  - Lower up-front tooling and drawing costs to evaluate designs for custom aircraft
  - In the AM design space, complex thermal management components and some novel stator designs can be highly optimized for weight and performance
- **Legacy manufacturing techniques are inescapable**
  - AM is a compliment to legacy manufacturing techniques
  - Good topological optimization can lead to good designs, but not all will require additive manufacturing

The CAMIEM Team

Organization	Name	Role
Glenn Research Center	Michael Halbig	PI
	Mrityunjay "Jay" Singh	AM
	Valerie Wiesner	
	Greg Piper / Daniel Gorican	AM /Direct printing
	Derek Quade	Dynamometer
	Steven Geng	Motors and magnets
	Chip Redding	Design
	Chun-Hua “Kathy" Chuang	Insulator materials
	Peter Kascak	Electric motors
	Jeff Chin	System benefits
LaunchPoint Technologies	Michael Ricci	Baseline & innovative motor designs
	Brian Clark	
	Dave Paden	
Armstrong Flight Research Center	Ethan Niemen	Ground testing
	Otto Schnarr III	Electric propulsion ground testing
	Kirsten Fogg	
	Patricia Martinez	
Langley Research Center	Samuel Hocker	AM
	Christopher Stelter	
	Russell “Buzz” Wincheski	NDE
	Stephen Hales	Materials evaluation
	John Newman	Computational materials
University of Texas El Paso	Jose Coronel	Stator winding and cooling efficiency
	David Espalin	
	Ryan Wicker	

Also Summer Interns at GRC and LaRC.

BACK-UP Slides

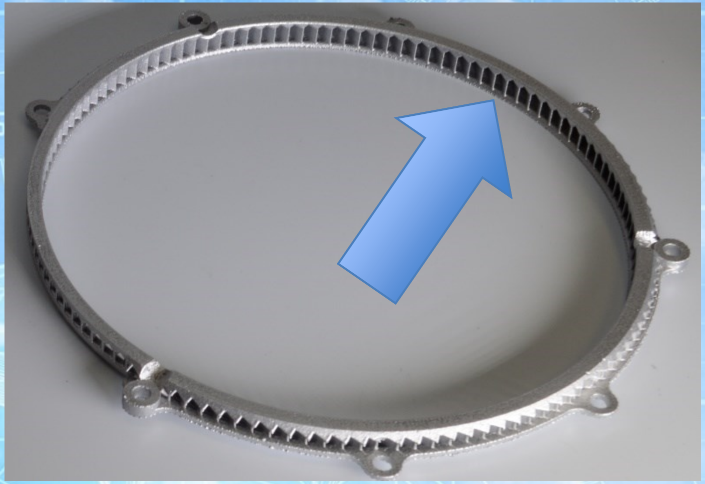
Heat Sink Design Iterations

Xtreme challenge or impossible without AM

Heat sink ring: Design1

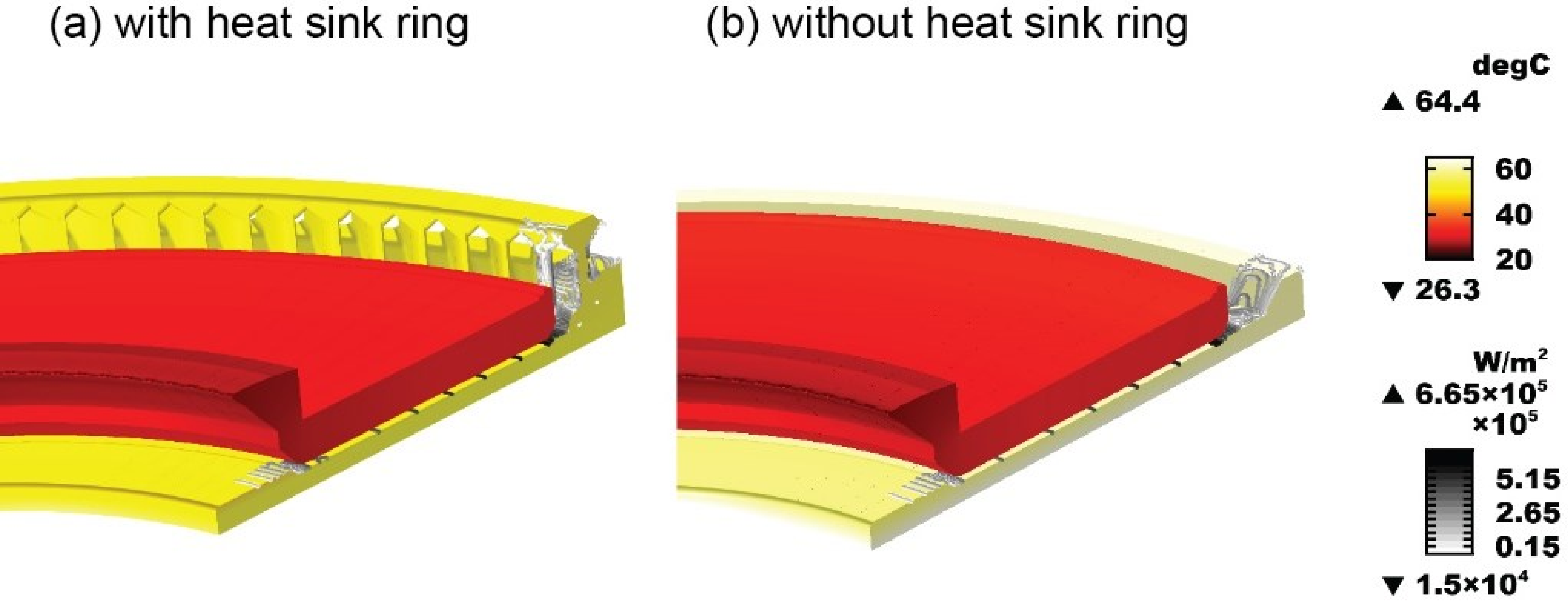
0° fin angle

Design2 with airfoil fins

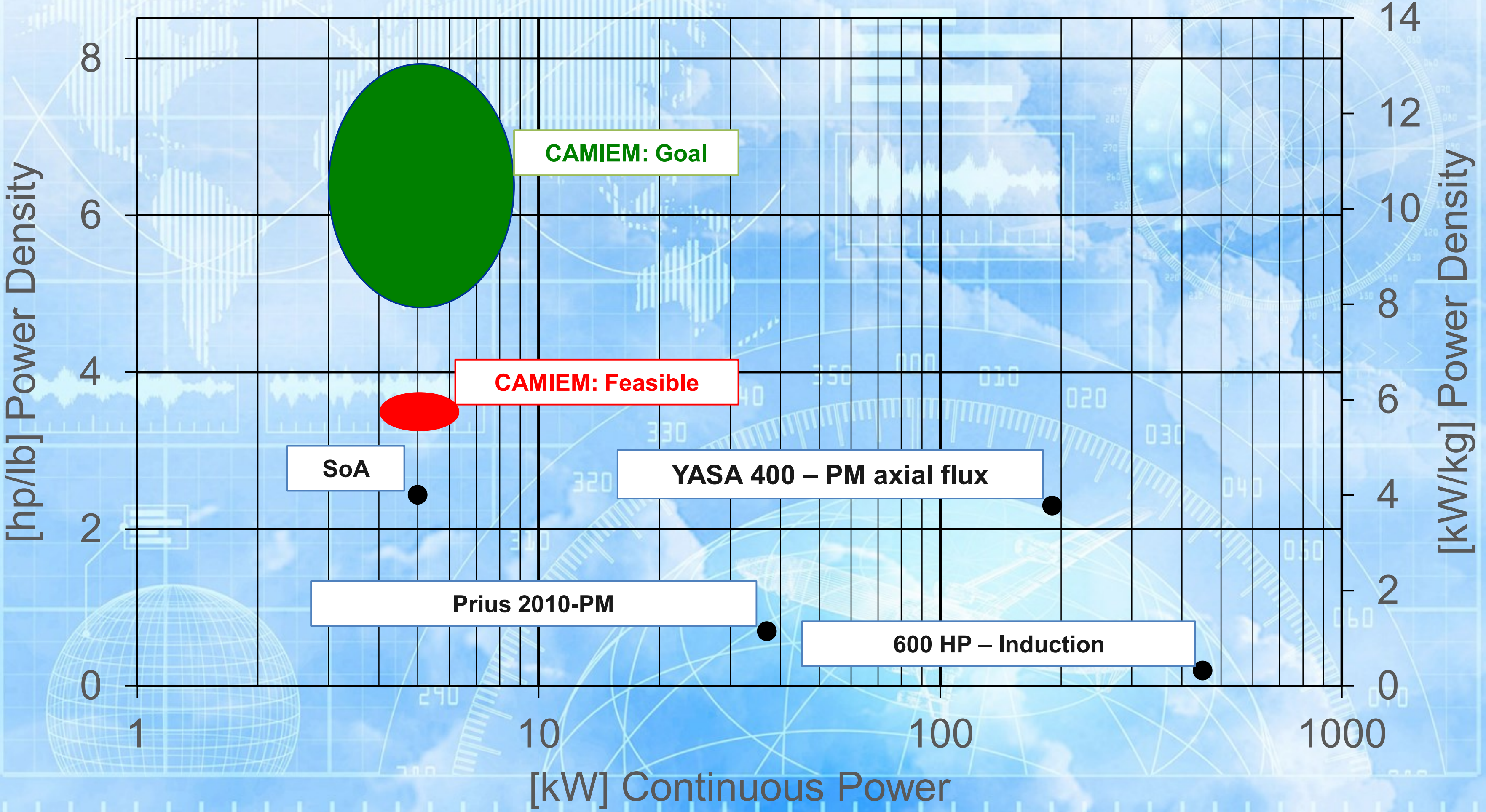


45 ° airfoil angle

Model for Heat Sink Ring Benefit to Thermal Management

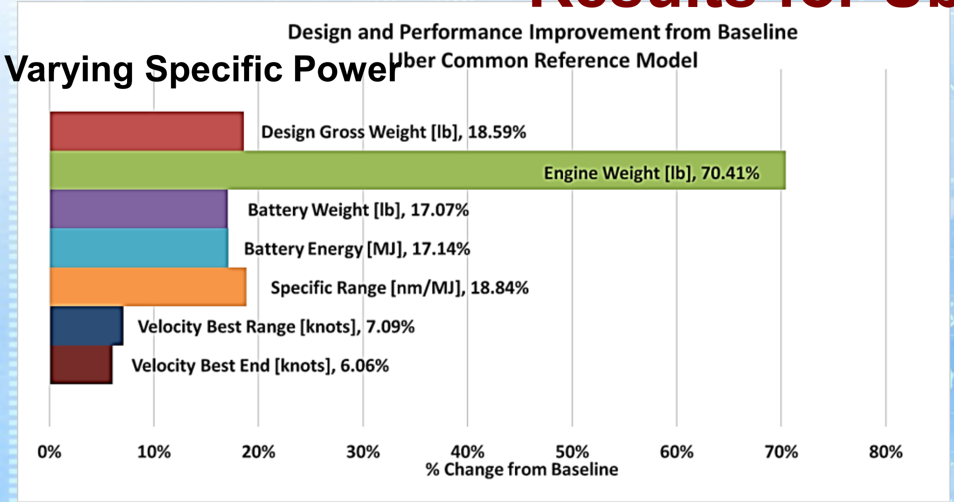


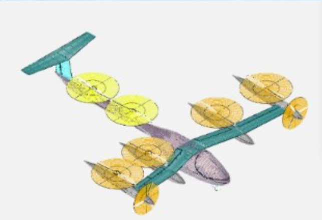
Disruptive: Leap Beyond Current SoA



Results for Uber eCRM-002

Varying Specific Power





Efficiency = 95%

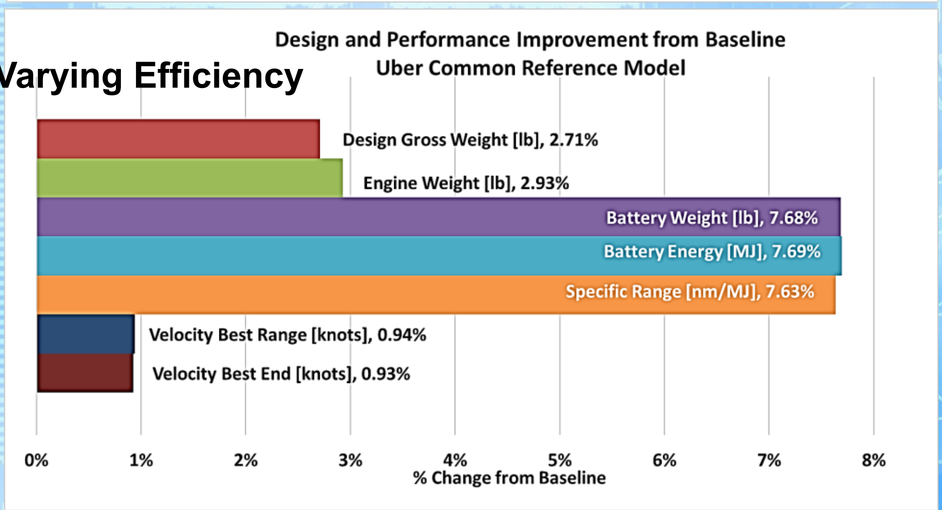
Specific power = 9.4 hp/lb (15.4 kW/kg)

Baseline Specific power = 3.13 hp/lb (5 kW/kg)

18.6% reduction in Gross weight

17.1% reduction in Battery energy

Varying Efficiency



- Increase in Power-to-Weight ratio by 1 hp/lb results in a gross weight reduction of ~300 lbs and an energy reduction of ~27 MJ

Efficiency = 100%

Specific power = 3.13 hp/lb (5 kW/kg)
Baseline Efficiency = 95%

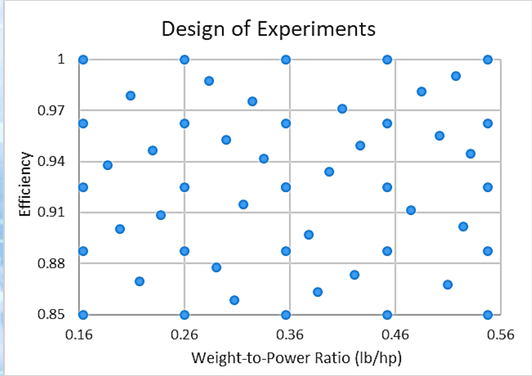
2.7% reduction in Gross weight

7.7% reduction in Battery energy

System Studies

System studies looked at benefits from improved motor performance within the ranges of:

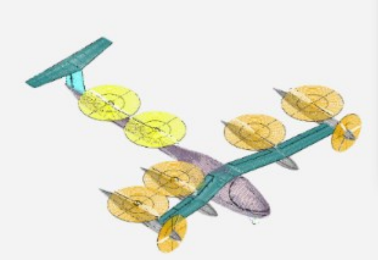
- 85-100% efficiency
- 3.13 - 15.00 hp/lb power density.



- Urban Air Mobility – Georgia Tech Analysis (under a CAS contract to work with FY17 initiated Activities including CAMIEM):

Georgia Tech Aerospace Systems Design Laboratory

Uber Elevate



- VTOL, 4 PAX
- 1100 lbs max payload; 7000 lbs max TOGW
- 60 mi design range, 25 mi nominal trip distance
- 8 rotors with 2 rotors at each tip

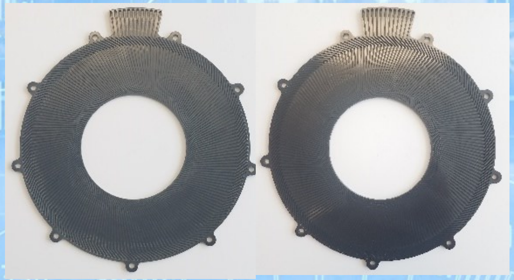
NASA 15-Passenger Tilt Wing

- 15 PAX, tiltwing
- 4 x 731 hp (545 kW) high-speed/low torque motors
- 3000 lbs payload; 14,039 lbs max TOGW
- 400 nmi design range

Comparison of Methods to Obtain Outside Fabrication for Channeled Plates for GRC Stators

Concept A - Stator Plates from Cobalt-Iron Alloy

Concept B - Stator Plates from Cirlex



Concept B - Stator Plates from Ultem1010

Fabrication Method	**Machine/EDM**	**Machine/Mill**	3D Print/FDM
Fabrication Time	**4+ months**	**3 months**	1 week (92.3% reduction)
Fabrication Costs	**$21,400**	**$19, 870**	$1,000
Material Costs	**$600**	**$330**	$0 (included in fab.)
Total Costs	**$22,000**	**$20,200**	$1,000 (95.0% reduction)

Currently relying on machined stator plates.

Conclusions

- AM enables innovative component designs to be pursued.
- Motor component fabrication will rely on single and/or combined utilization of AM, conventional, and machining.
- Multi-material AM and hybrid manufacturing is feasible for complex component fabrication but full motor fabrication on a single machine is not currently achievable.
- 1.75x increase in power density and 2x increase in torque density projected (CAMIEM effort). Further increases achievable.
- AM offers additional benefits (e.g. higher efficiencies, faster fabrication times, and reduced costs, and, more rapid component iterations).
- The CAMIEM Activity only scratched the surface of what AM can offer toward new designs and manufacturing of electric motors.
- Designing a motor from scratch to fully take advantage of AM can offer more significant benefits.

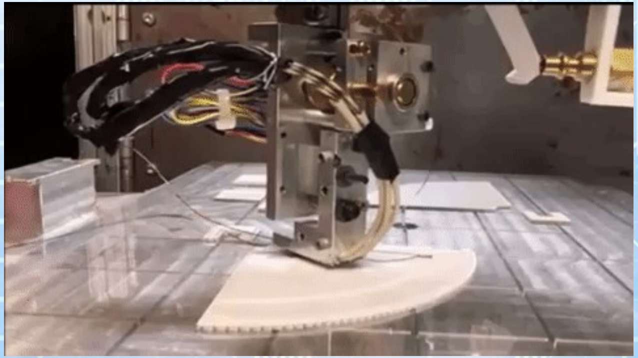
CAMIEM - Top Level Summary

- CAMIEM addressed two key emerging areas within NASA:
  1. Advanced manufacturing => additive manufacturing.
  2. Electrified aircraft and urban air mobility.
- CAMIEM investigated the feasibility of additive manufacturing to enable new higher performance electric motor designs.
- CAMIEM resulted in the first demo of additively manufactured components and motor configurations.
  - New motors based off of SOA power dense motor that operates at 7500 rpm.
  - New design can provide about 2x torque, power, and power density.
- CAMIEM results show and Panel Review agrees feasibility achieved. √

Outline

- CAMIEM intro and feasibility study
- System benefits
- Additively manufactured components
- Evaluation of the baseline and modified motors
- Summary/Conclusions

Wire Embedded Stator



Cartridge heated embedding demonstration

- Kapton coated Litz wire necessary to prevent dielectric breakdown and Eddy current losses

Ultrasonic embedding horn

20 kHz Ultrasonic system

PC substrate

Demonstrations were made with 30 AWG Kapton™ coated litz wire on polycarbonate

Pressing process needed to further densify the stator

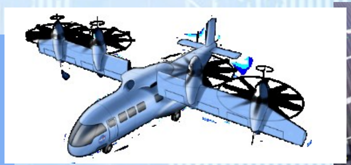
Final stator

- Challenges with feeding wire through ultrasonic horn of required 14 AWG wire.
- Challenges with overprinting polycarbonate onto embedded wire.
- AM of a wire embedded stator needs further development to be achievable.

Images credit: University of Texas @ El Paso

Sustainable Transportation Stakeholders

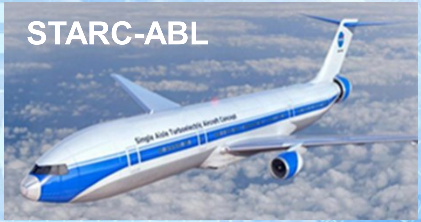
Urban Air Mobility

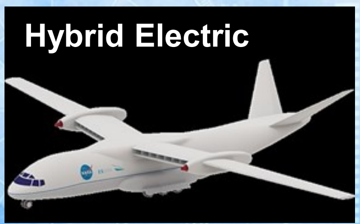


NASA 15-PAX tiltwing aircraft

Uber Elevate

Large Single Isle Transports



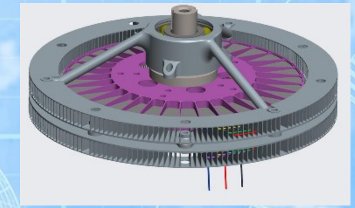


Greased Lightning GL-10

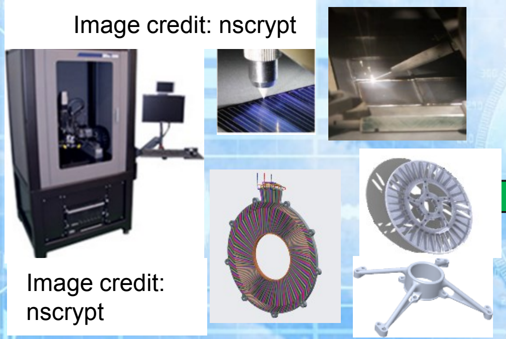
Feasibility Assessment

Baseline Motor

Baseline Motor Testing
for baseline performance



Innovative Motor Design



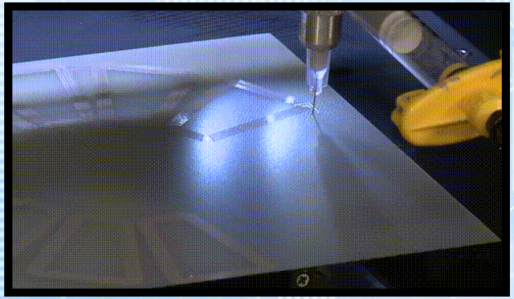
Additive Manufacturing Processes and Advanced Components

Testing of “New” Motor Configurations to Determine Improved Performance

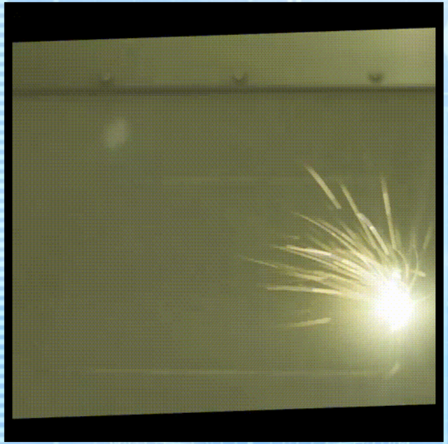
Aircraft Level System Studies

Feasibility Assessed and Benefits Determined

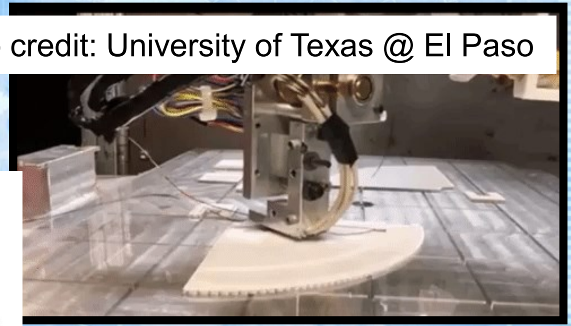
Additive Manufacturing Processes Being Applied to Motor Fabrication



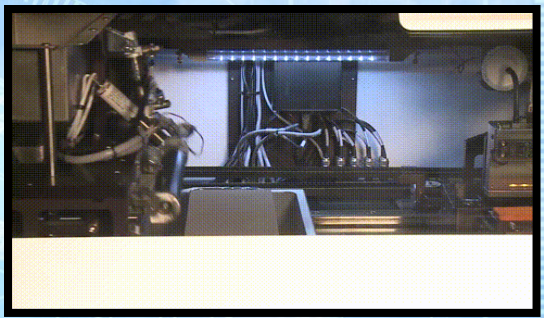
Direct Write Printing



Selective Laser Sintering



Wire Embedding



Binder Jet 3D Printing

System Studies

System studies looked at benefits from improved motor performance e.g. ~2-3 times increase in power density and 1-5% increase in efficiency.

- **Single Aisle Long Haul Transports:**
  - **Sugar Volt**
  - **STARC-ABL**

If changes to motor design yield:	Sugar Volt - Change in Mission Fuel Burn:	STARC-ABL - Change in Mission Fuel Burn:
P/W increase from 5 hp/lb to 15 hp/lb	-0.18%	-1.98%
Increase in efficiency from 95% to 97.5%	-2.67%	-1.28%

- **All Electric Aircraft**
  - **X-57**

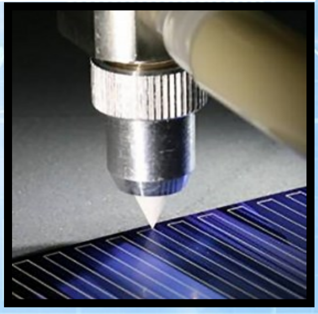
- **3x Power Density increase in all motors would result in ~200lb savings**
- **Increase in range 6.6%**

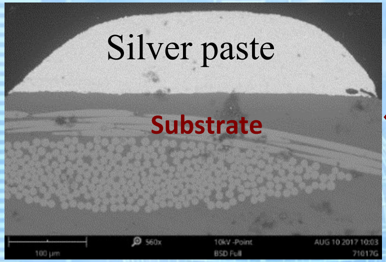
Multi-Material Stators

- Wire embedded stator
- Direct printed stator

Silver Paste Selection and Print Optimization

Images credit nScrypt 3Dn-300



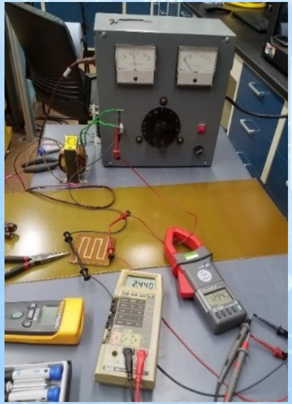


PLAIN PASTE			
Paste Composition	Conductivity [Ωm]^-1	Max Temp (°C)	Vendor Resistivity
CL-11190 (Heraeus)	4.86×10^7	300	N/A
CB028 (DuPont)	3.54×10^7	175	7 – 10 (mΩ/sq/mil)
CL20-1127(Heraeus)	2.78×10^7	300	N/A
CB100 (DuPont)	1.91×10^7	175	>7.5×10^{-8} Ωm
Ag-PM100 (Applied Nanotech)	1.10×10^7	300	>5×10^{-8} Ωm
Kapton™ (DuPont)	4.74×10^6	225	<5 (mΩ/sq/mil)

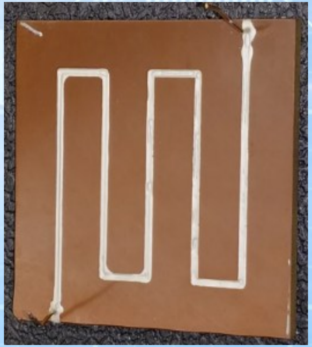
Down-selected to a silver paste with highest electrical conductivity and temperature capability.

Direct Printed Silver Coils - High Current Test

Direct Printed Silver Coils - High Current Test

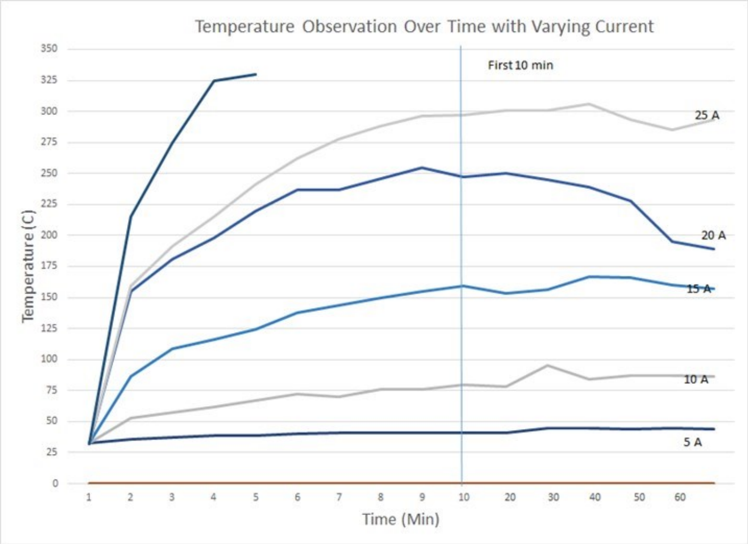


Test Set-Up



Printed Coil

Coil Heated under High Current



Up to 30 Amp current test in an uncooled benchtop test.

Stator temperature capabilities far exceed that of the baseline motor.

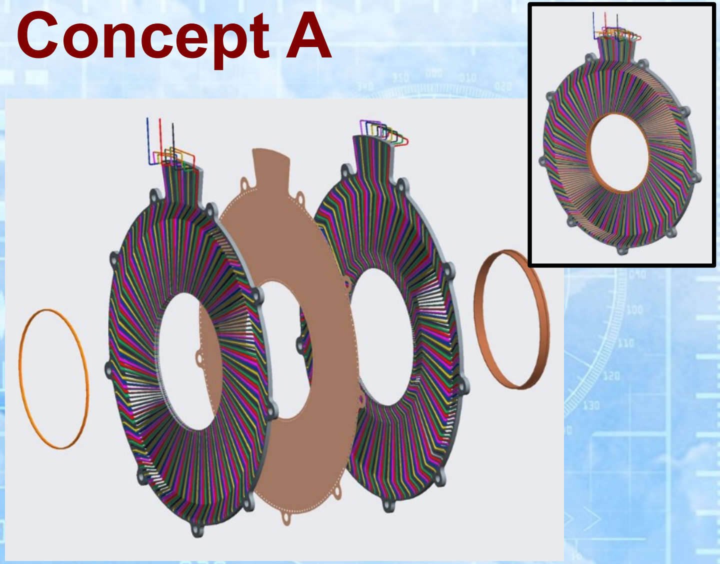
Direct Printed Stator - Concept A

Benefits of Concept A and B Designs

- Higher magnetic flux, torque, and motor constant (K_m).
- Higher temp. capability, 220°C and >250°C instead of 160°C for baseline stator.

- Higher torque with iron core.
- Direct printed silver coils with high fill.
- Significant reduction in costs and labor.

Cirlex™ Middle insulation layer



Outer Rings

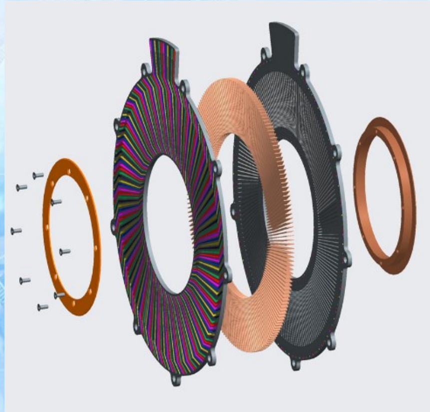
Upilex™ Spin Coatings

Concept A - Stator Plates from Cobalt-Iron Alloy

Details of machined features

Direct Printed Stator - Concept B

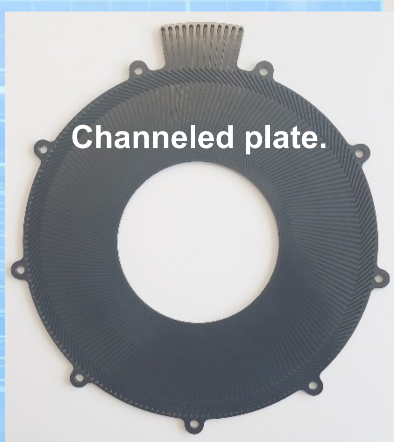
- High temperature polymer plates machined to form pockets for iron wedges and channels for the coils.
- No coating required.
- Lighter weight and higher temp. than Concept A.
- Discrete iron wedges for lower magnet attraction and lower eddy current losses.
- All assembly sub-elements available.



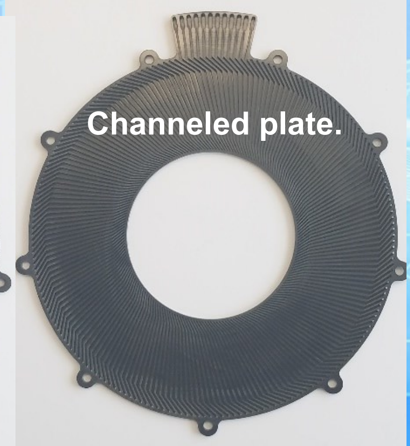
Polymer sections form pockets and channels.

Channeled plate bottom surface with iron wedge integration.

Outer Rings



Channeled plate.



Channeled plate.

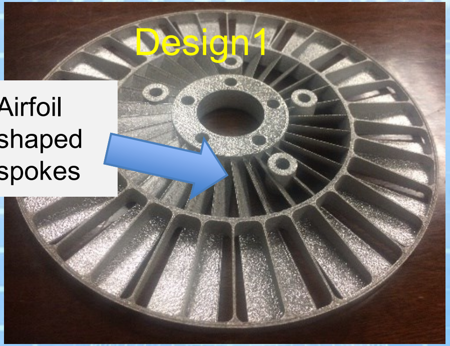
Direct Printed Stator - Concept B
3D Printing with High Temp. Material

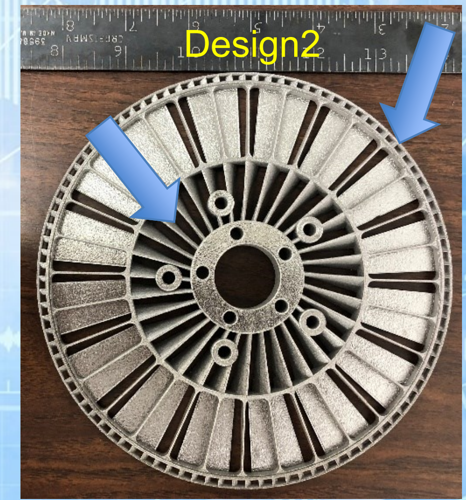
Additive Manufacturing from Extem™ (Tg of 311°C) (left) and Ultem™ 1010 (TG of 217°C) (right) FDM filament.

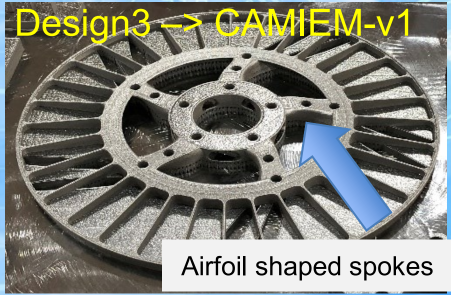
Low cost and rapidly manufactured sub-components may be possible with further advancements or alternate AM processes.

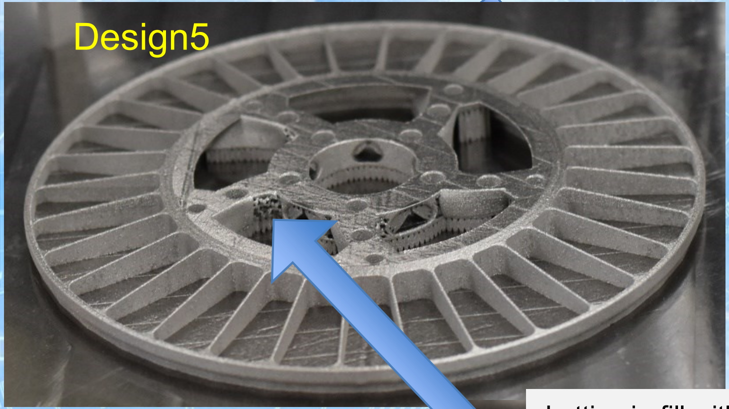
Rotor Component Design Iterations

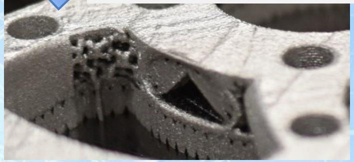
Xtreme challenge or impossible without AM











Metallic Structural Components

- Additive Manufacturing of rotors, housings, and finned cooling rings

Cost Estimate Comparison

Rotorplate

Additive Manufacturing: CAMIEM-v2 design

Total Manufacturing Time: 20 hrs

8 hrs to print. 12 hrs to post-process.

Wasted Titanium : ~300 cm^3

(un-usable powder loss & support volumes)

Total Cost : ~$1000 per plate

CNC – LaunchPoint (baseline) design

Total Manufacturing Time: 20 hrs. at LPT

Wasted Titanium : (V_{Billet} – V_{Part}): ~350 cm^3

Total Cost: $825.5 per plate

Housing

Additive Manufacturing: 4-leg design

Total Manufacturing Time: ~18 hrs

15 hrs to print. 3 hrs to post-process.

Wasted Aluminum : ~100 cm^3

(un-usable powder loss & support volumes)

Total Cost : ~$300 per housing

CNC – LaunchPoint (baseline) design

Total Manufacturing Time: 28 hrs at LPT

Wasted Aluminum : (V_{Billet} – V_{Part}): ~1,350 cm^3

Total Cost: $310 per housing

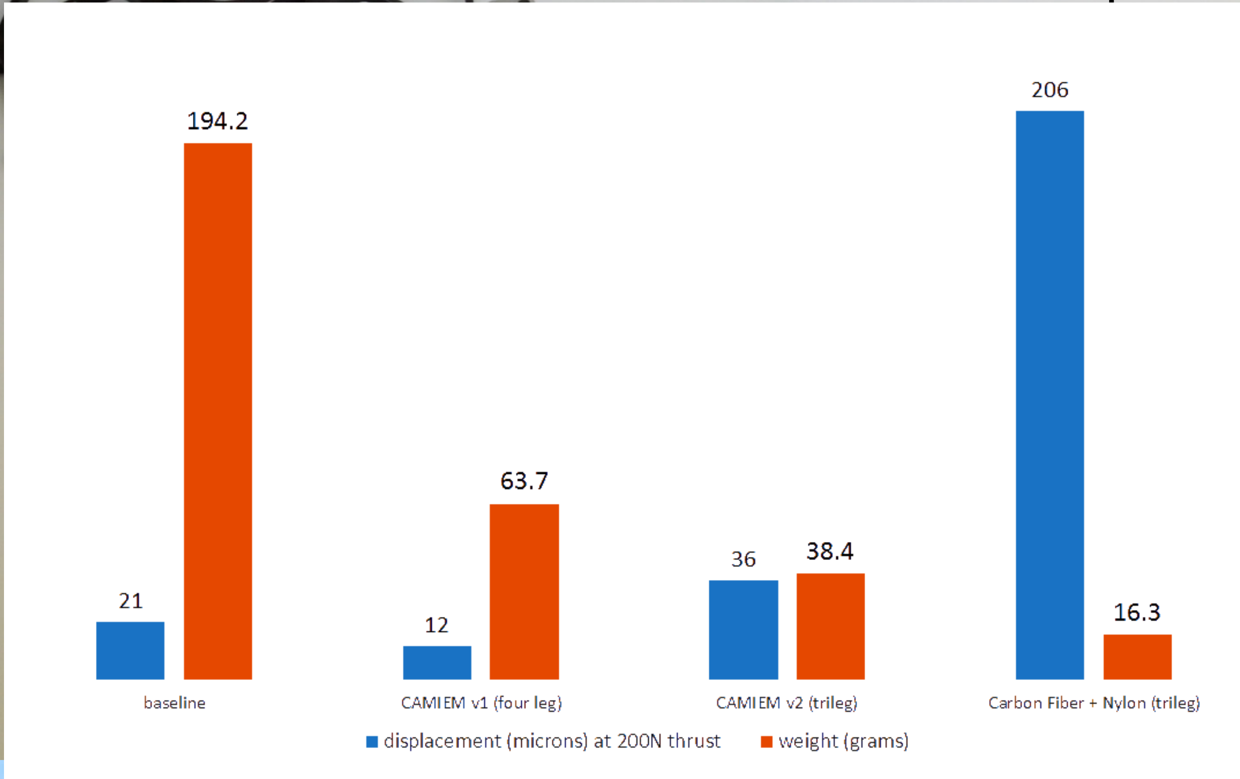
Housing Design Evolution

Factor of 3-10 reduction in mass

Factor of 1.25-2.7 lower fastener count

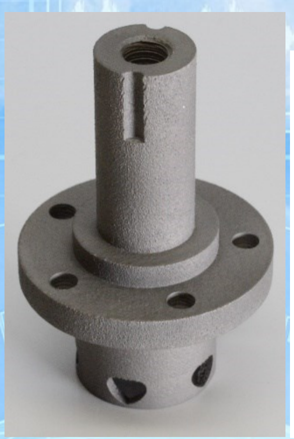
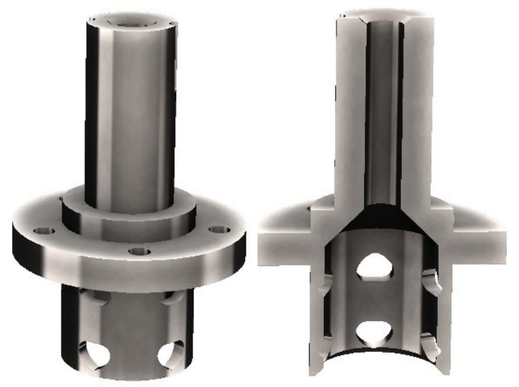
Stiffness can be improved by ~2x

eduction



Shaft Design Weight Reduction



Mass of baseline stainless shaft: 160.9 grams

Mass of LaRC titanium printed shaft: 76.1 grams

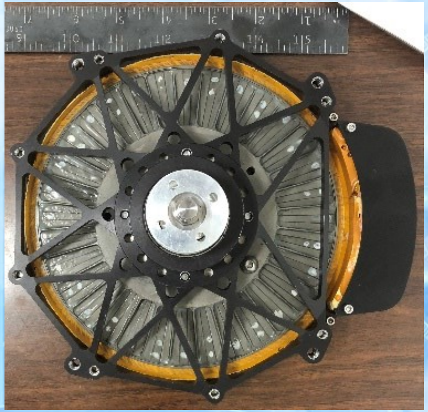
53 % Mass savings

Baseline and New Motor Configurations Testing

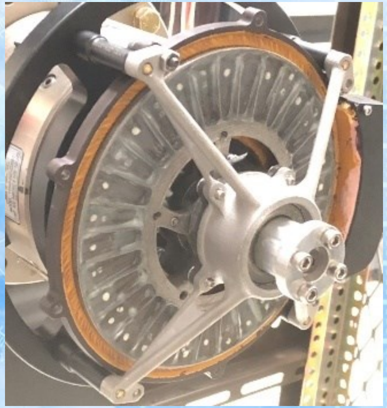
- Prop Motor Testing
- Dynamometer Motor Testing

Testing of Motor Configurations

Prop motor testing:
- Baseline Motor
- Version 1 Motor: Structural parts – with additively manufactured mod. 1 rotors and 4 legged housing.



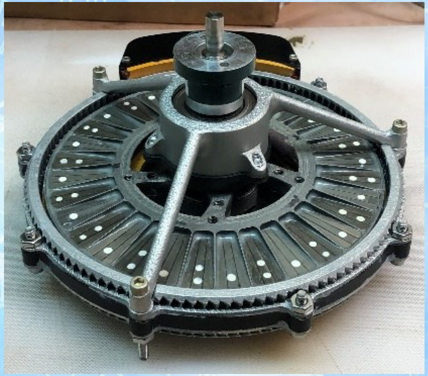
Baseline Motor



CAMIEM V1. Motor

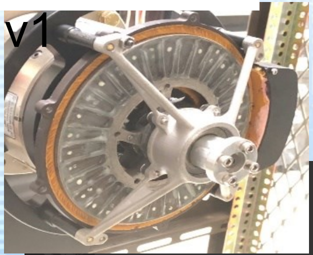
Dynamometer motor testing:
- Baseline Motor
- Version 2 Motor: Structural parts – with additively manufactured mod. 2 rotors, 3 legged housing, and fined stator cooling ring.

CAMIEM V2. Motor

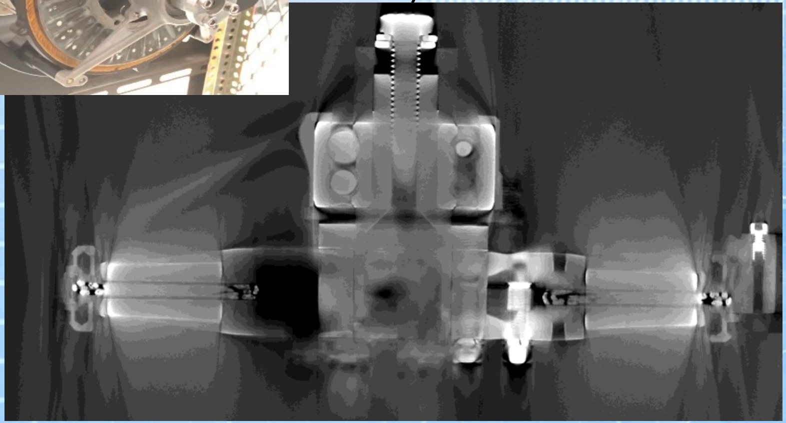


CAMIEM-V1 and V2 Motor Configurations

CAMIEM-v1

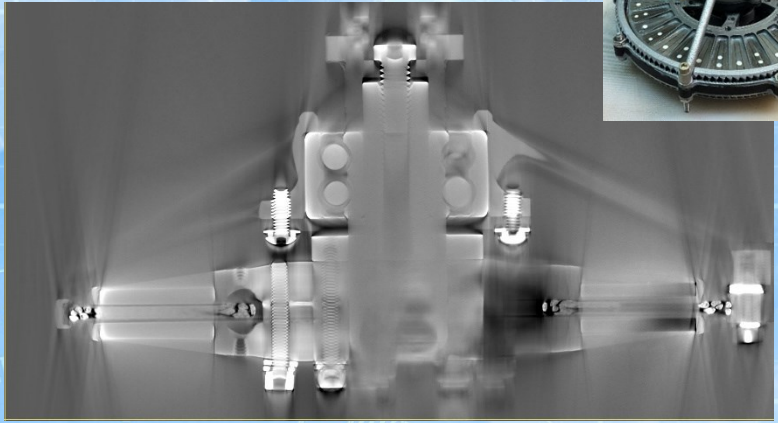


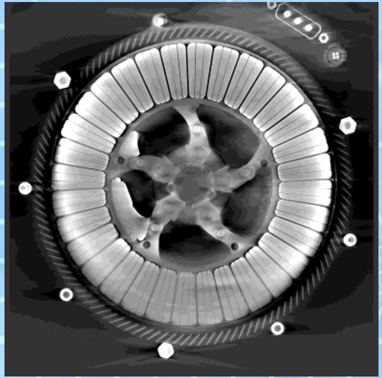
Mass = 1833 g (7% less mass)

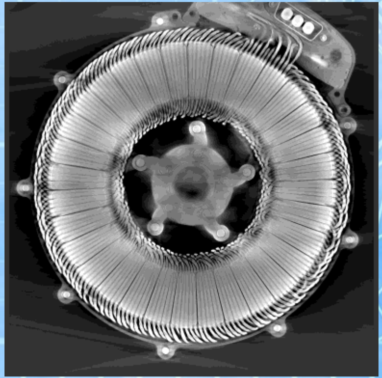


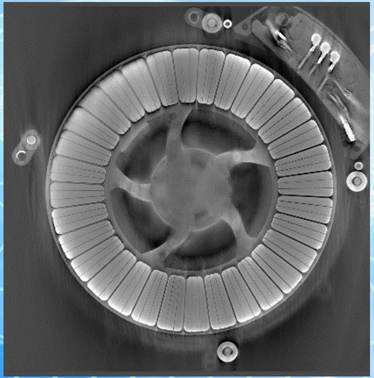
CAMIEM-v2

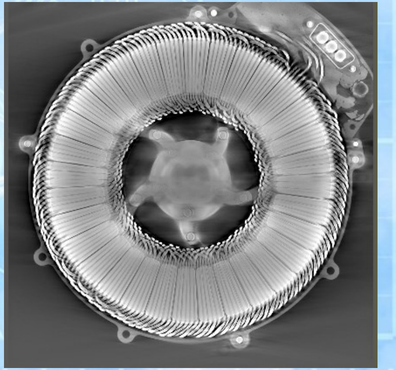
Mass = 1870 g (5% less mass)
Total heat sink mass = 92 g







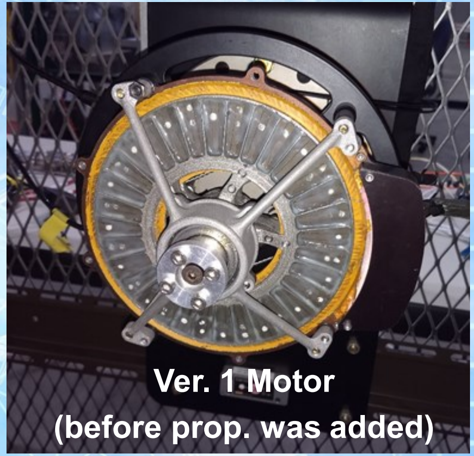




Motor Testing in Prop Test Stand - Testing Summary

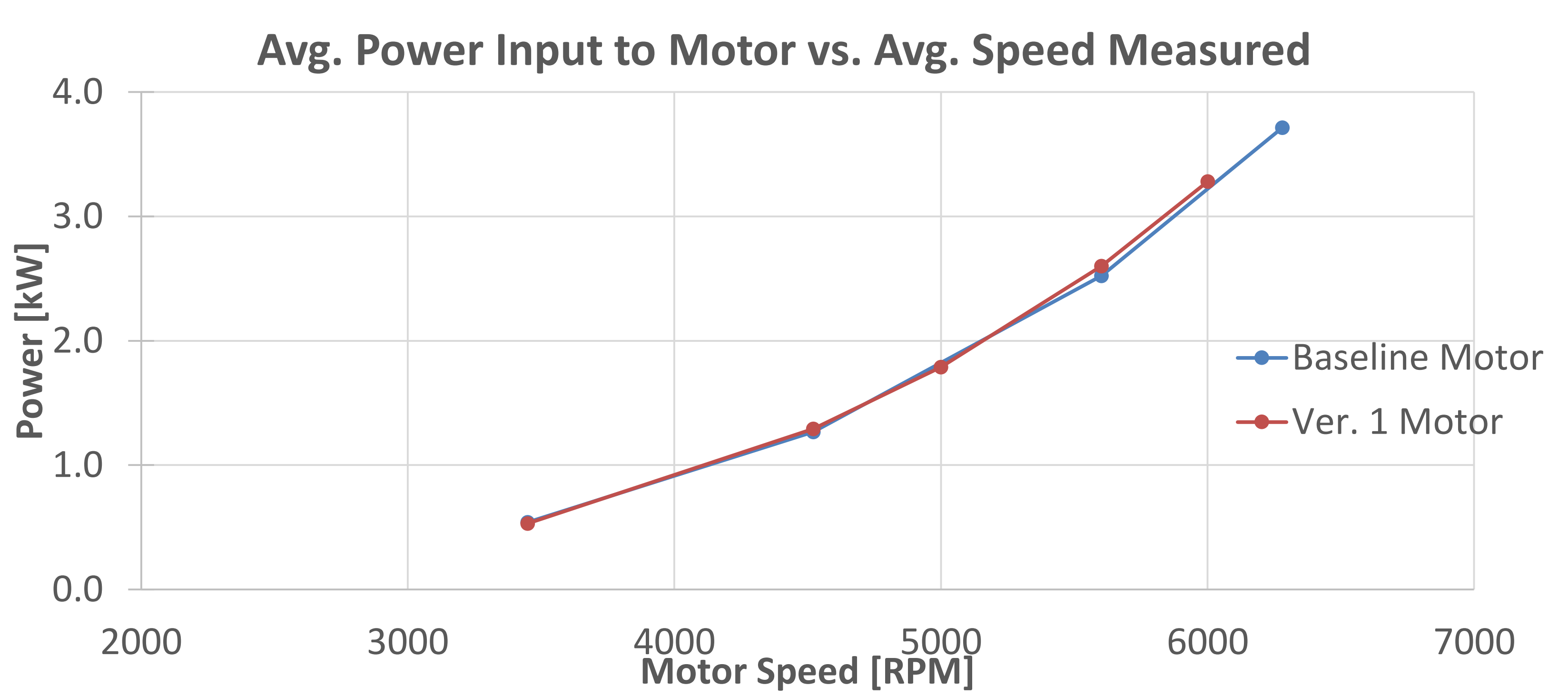
- Baseline motor
  - Conducted a speed sweep up to 7500 RPM with prop to identify keep-out speeds
  - Conducted stair-step to collect power consumption, temperature, and estimate torque
- CAMIEM Version 1 motor
  - Following successful speed sweep without prop, conducted stair-step **with prop** up to 6000 RPM to compare to baseline data
- For each test, measured:
  - Stator temperature vs. speed at thermal equilibrium
  - Electrical power consumption (measured with 2-Wattmeter method)
  - Propeller speed

Baseline Motor



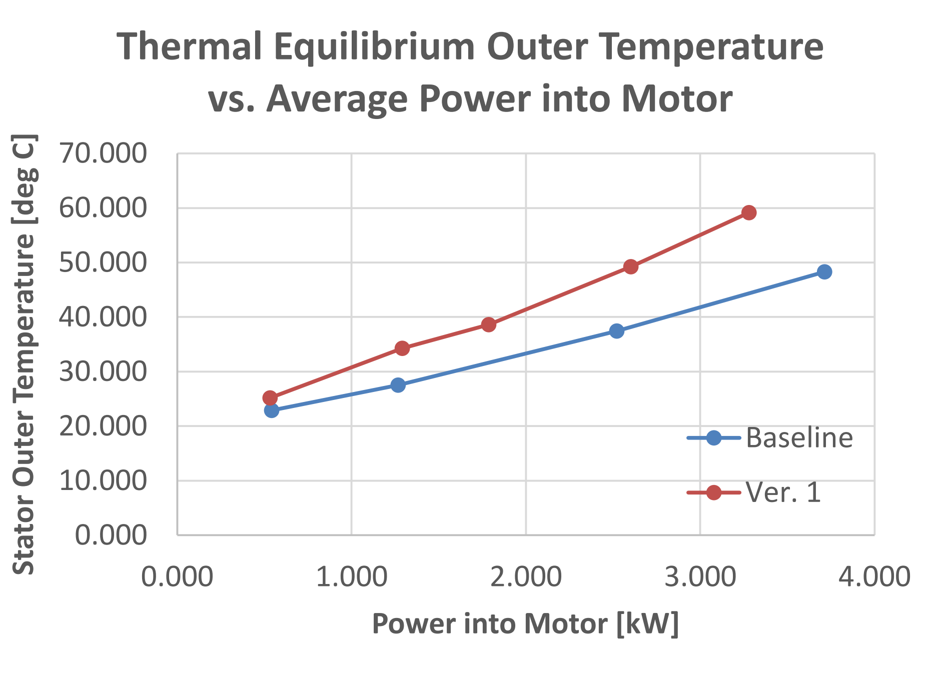
Ver. 1 Motor
(before prop. was added)

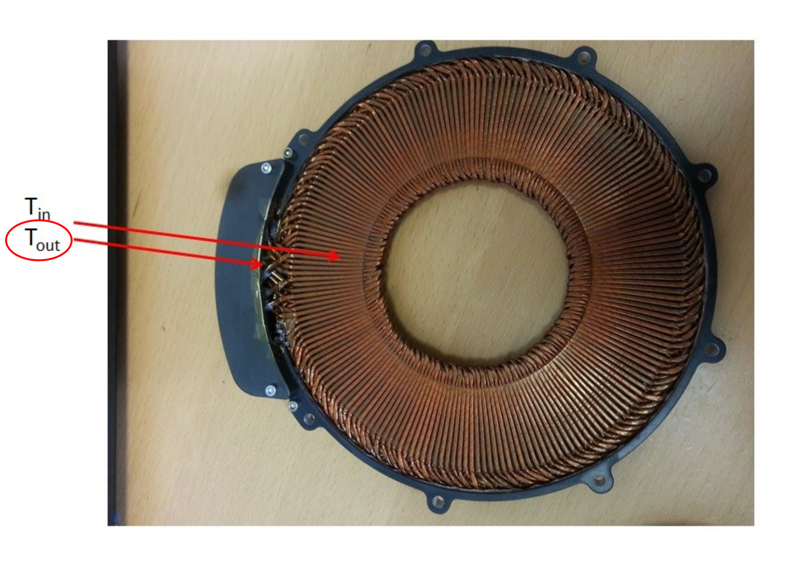
Power Input to Motor



The Version 1 motor consumed slightly more power than the baseline. Assuming power output is dependent on propeller only (same for each speed for both motors), at 6000 RPM the Ver. 1 was approximately 96.6% as efficient as the baseline.

Stator Temperature (Outer Diameter)



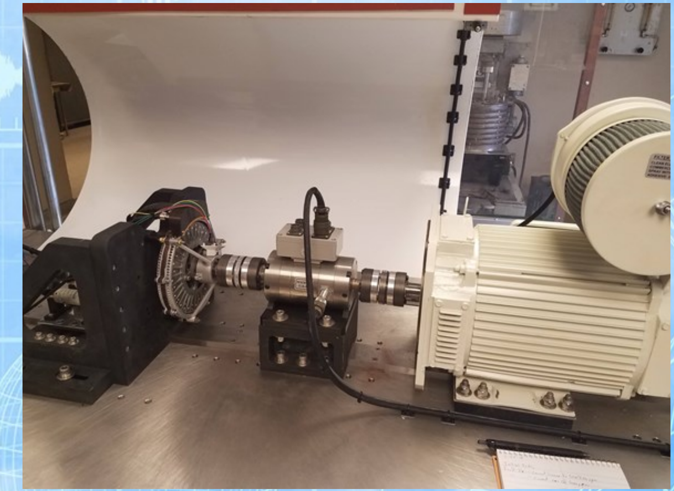


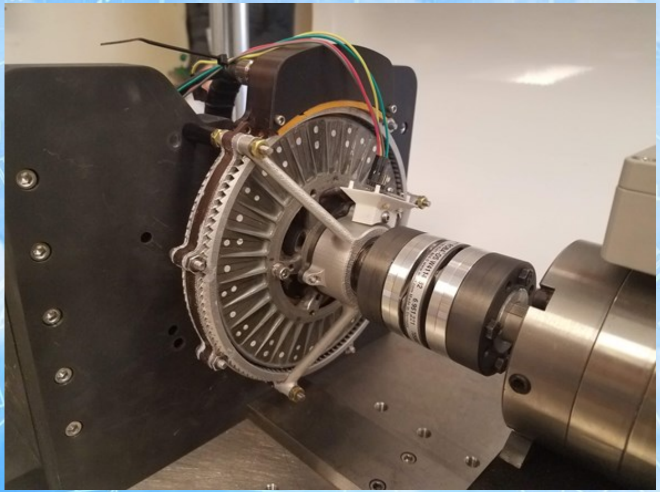
Demonstrates steady-state thermal behavior of the motors when spun with prop. Ambient temperature (measured by same thermocouple before power-up of motor) was 17°C for the baseline and 21°C for the Version 1

Dyno Testing of Ver. 2 Motor

CAMIEM Version 2 Motor

- Motor was installed, firmware updated, Lab View control updated, and shaft alignment checked.
- Motor was successfully spun at low rpm.
- As torque was applied to the motor, balance issues would cause a fault/stop. The motor needs to be professionally balanced. Limited testing was conducted.





Unable to get to higher RPMs due to balancing challenges.

Comparison for Baseline and CAMIEM Concepts A and B

Baseline and predicted CAMIEM motor performance metrics

- These predictions are for CAMIEM motors with all the final components for the structural parts (rotors, housing, finned cooling ring, and shaft) and concept A and B stators.

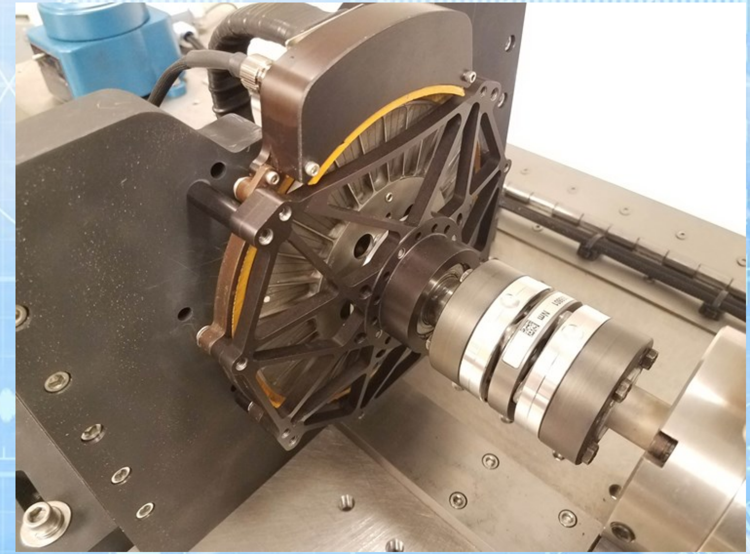
Baseline

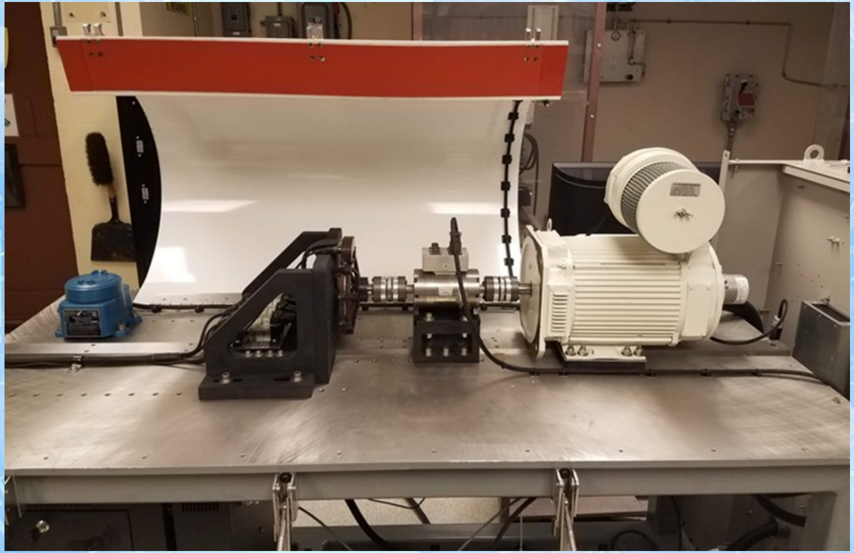
	Baseline Motor	CAMIEM Concept A	CAMIEM Concept B
Maximum Power [W]	8330	13300	16300
Maximum Torque [N*m]	11	17	21
Mass [kg]	2.0	2.5	2.3
Specific Power [kW/kg]	4.0	5.3	7.0

Concepts A and B (with relevant stator)

The baseline and predicted CAMIEM motor performance metrics predict an increase in maximum power (x1.96), maximum torque (x1.96), and power density (x1.75).

Baseline Motor Tested in Dyno

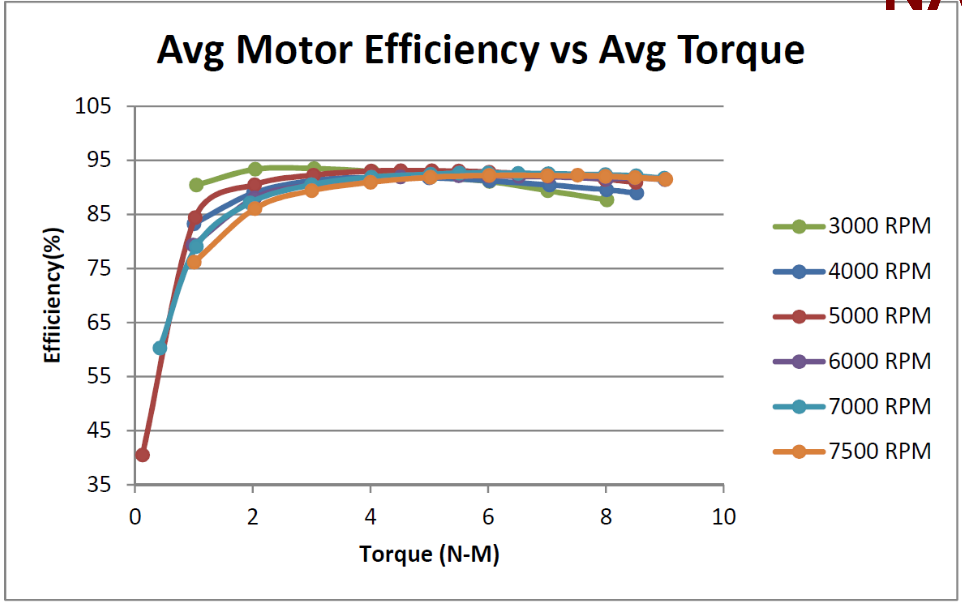


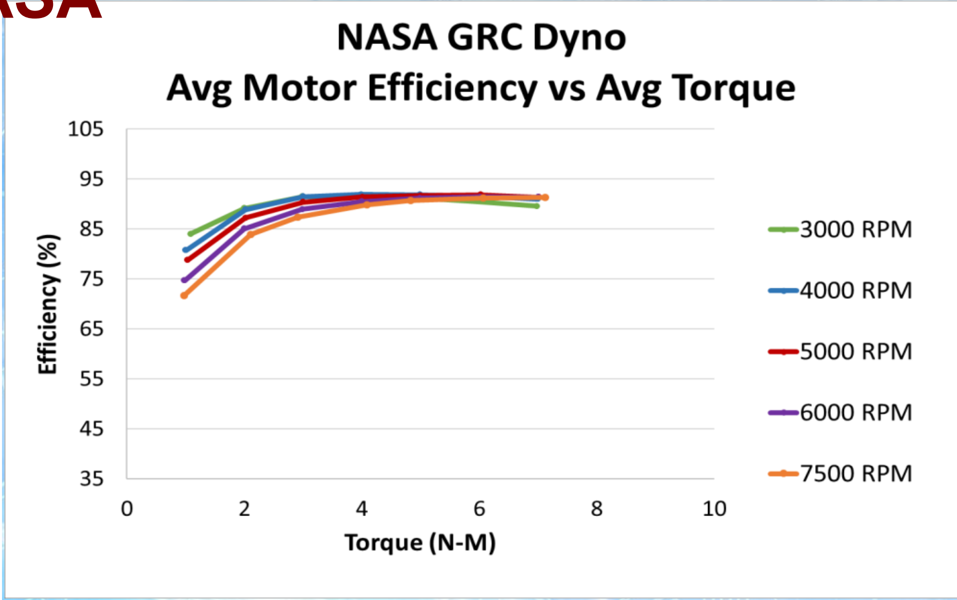


Baseline motor

- The power, motor efficiency, and motor temperature were determined to provide motor efficiency curves at various rpms (from 3000 to 7500 rpm) and torque settings (from 1 to 7 N m).

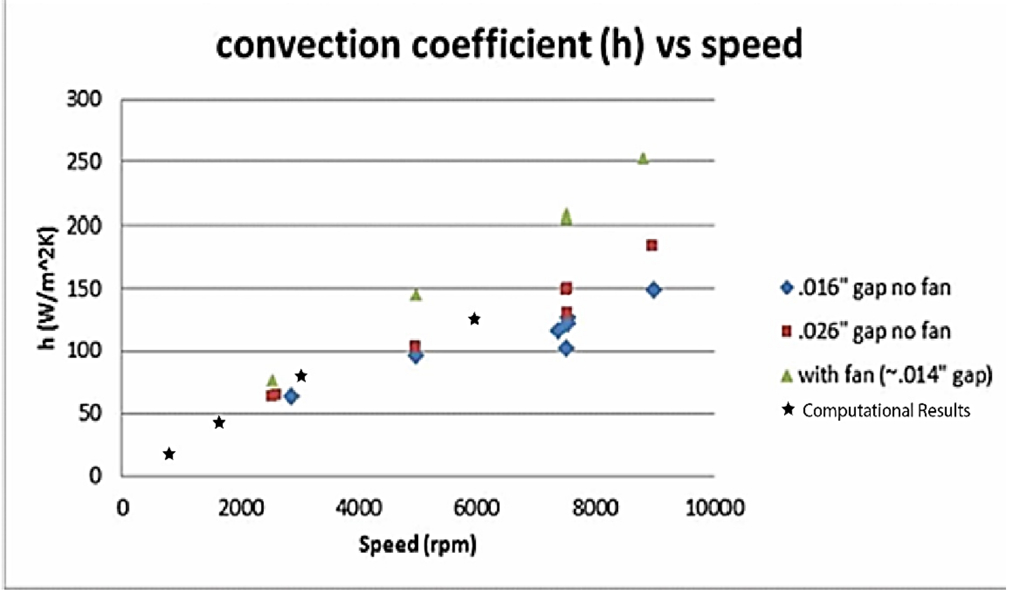
Baseline Motor Tests on the Dyno System When at LaunchPoint and at NASA



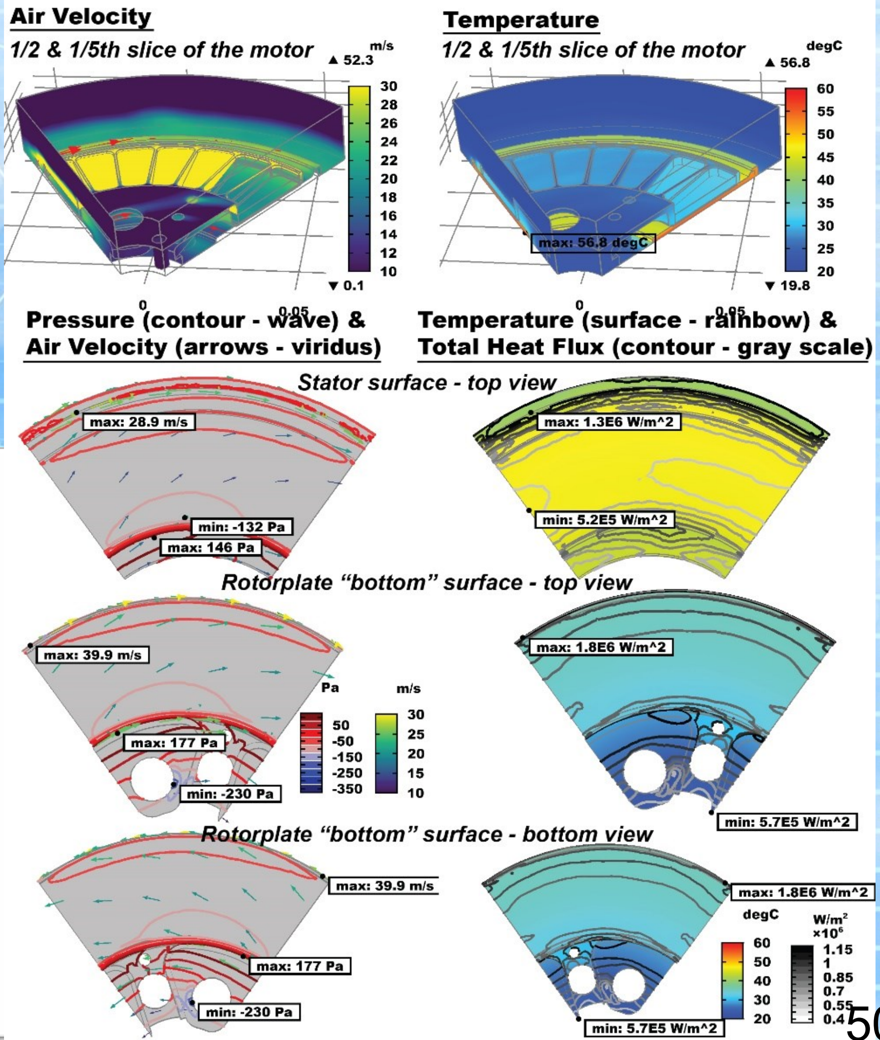


Good agreement in motor efficiency for all rpms for both the LaunchPoint Technologies and GRC tests. Motor efficiencies mapped and corresponding motor power determined.

Experimental vs Computational Convection Coefficient vs Speed Results



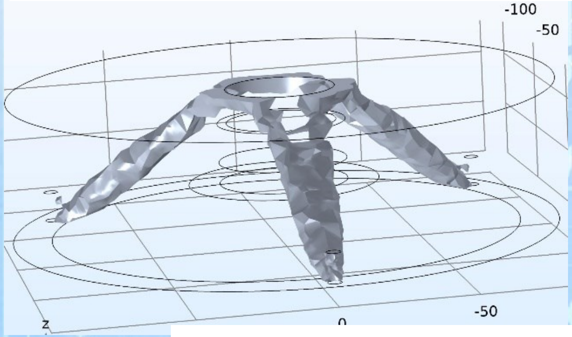
Launchpoint "baseline" SoA - (no CUT)



Housing Design Iterations

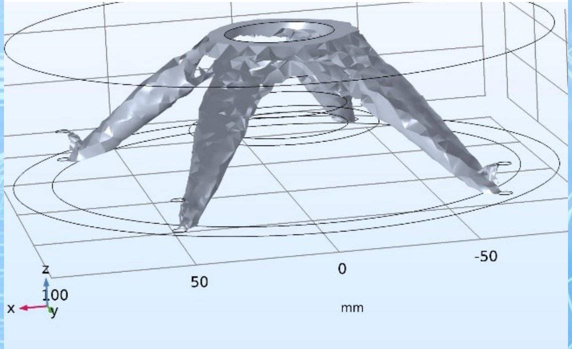
Topologically Optimized for Propeller Condition: minimize mass & deflection

3-legged



3-legged housing printed

4-legged



4-legged housing printed