Design and Test of a Structurally-Integrated Heat Sink for the Maxwell X-57 High Lift Motor Controller

Ryan Edwards & Andrew Smith
NASA Glenn Research Center

Presented By
Ryan Edwards

TFAWS
LaRC 2019

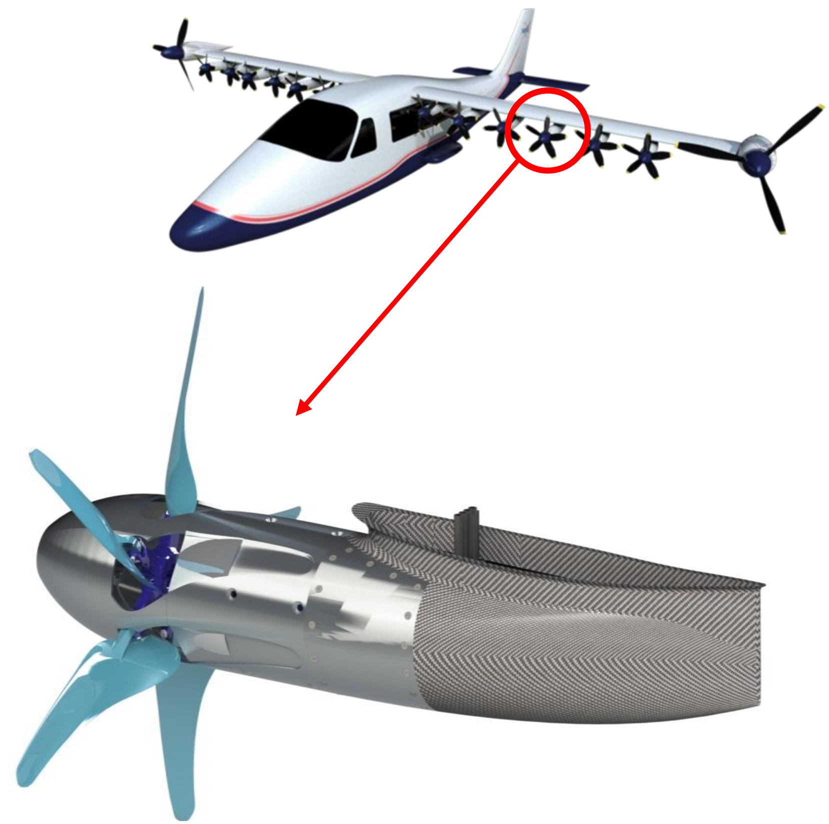
Thermal & Fluids Analysis Workshop
TFAWS 2019
August 26-30, 2019
NASA Langley Research Center
Hampton, VA

Background

X-57

- Fully Electric Aircraft Demonstrator
  - Two 60 kW Cruise Motors
  - Twelve 12kW High Lift Propulsors
    - Primarily used for lift augmentation for take-off and landing
  - Li Battery powered DC bus

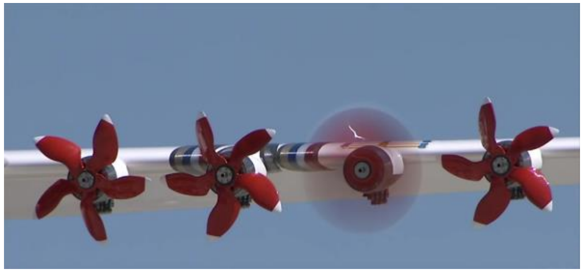
- Distributed High Lift System
  - Enables low profile wing shape, reducing unnecessary drag during cruise
  - Motor controllers and inverters are located in the nacelle with each motor
  - Inactive for majority of flight, driving the need for low mass and drag

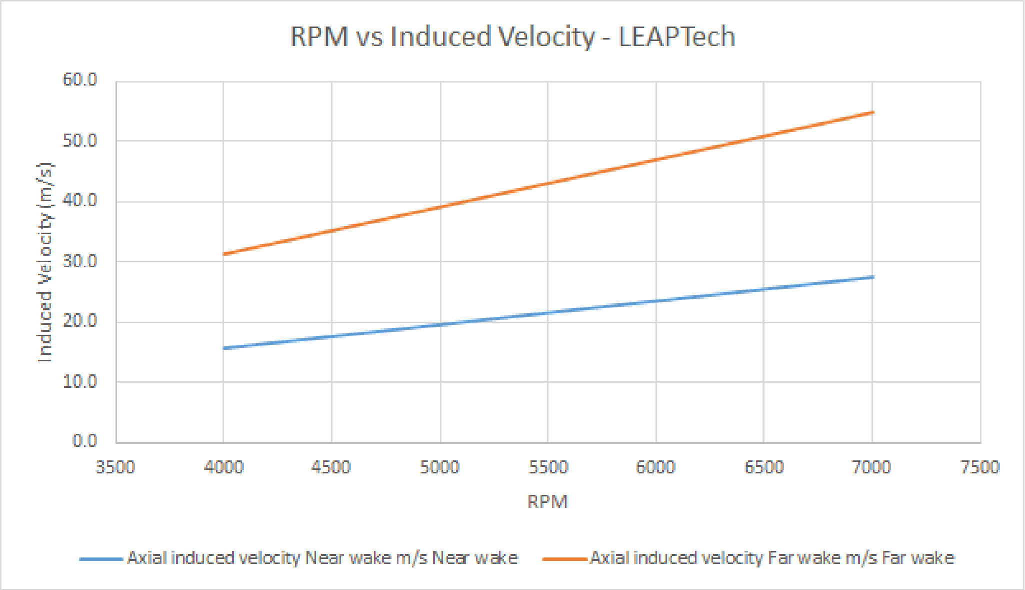


High Lift Propulsor Assembly

GIMC-HEIST Background

- Generalized Intelligent Motor Controller (GIMC)
- OML Cooled proof of concept for
  - 10-14 KW

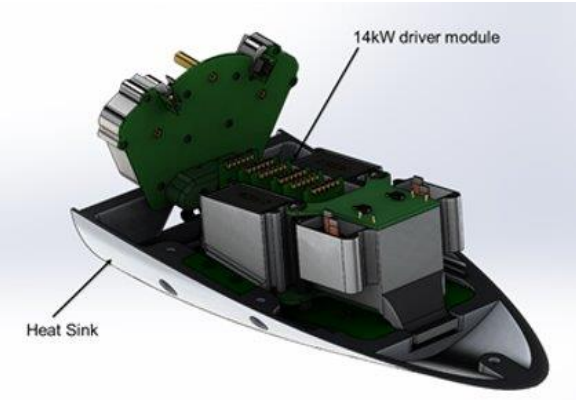




GiMC-Heist Test Configuration

Design Requirements

- Thermal
  - Dissipate controller and inverter waste heat for a 12 kW high lift system
  - Prevent components from exceeding their maximum operating temperatures
    - Particularly the High Power SiC MOSFETs
      - 100C Maximum Tj (150 C – 50 C de-rating)



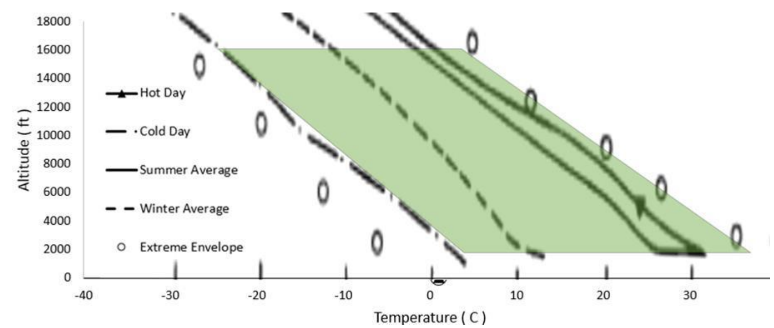
Environmental Requirements

- Qualification testing per DO-160G
- Worst Case Hot Environment
  - Stopped on runway with HLP at max power
    - 45C Ambient, 50 W/m^{2}C (Prop Wash) Convectio
- Worst Case Cold Environment
  - Cruise with HLP off
    - -25C Ambient, 110 W/m^{2}C Convection
- Qualification Test Margin
  - ±15C

Phase	Duration (Seconds)	High Lift Controller Input Power (kW) 97.0% Efficiency	
		1 Motor	12 Motors
Taxi from NASA	600	-	-
TO Checklist	120	-	-
Cruise Runup	30	-	-
HLP Runup	30	11.4	136.7
Flight go/no-go	30	-	-
Ground roll	10	11.4	136.7
Climb to 1500'	90	5.7	68.4
Cruise Climb	540	-	-
Cruise	300	-	-
Descent to 1500'	450	-	-
Final approach	180	5.7	68.4
Go Around to 1500'	90	5.7	68.4
Approach pattern	90	-	-
Final approach	180	5.7	68.4
Rollout and turnoff	60	-	-
Taxi to NASA	600	-	-
Total (s, kWh, Wh)	3400	1.0	11.8

Mod 4 HLP Flight Profile

Environmental Temperature Extremes for Qualification Testing
-40C to +60C

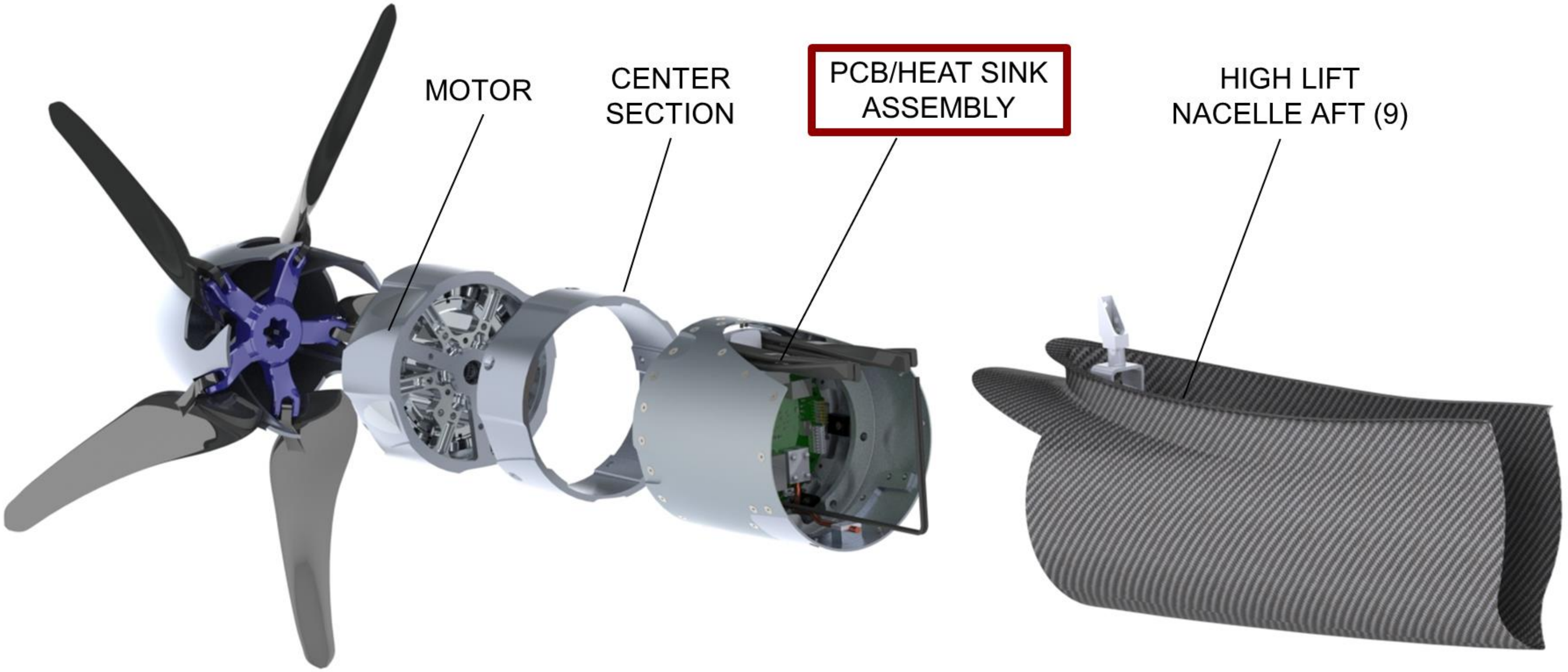


Temperature Profile for Edwards Air Force Base
Superimposed Envelope up to 15k ft

Design Process

- Initially greatly over weight
  - HEIST was prepackaged (multiple thermal interfaces)
  - Separately designed thermal, structural, and power electronics
- Rapid redesign process
  - Weekly iterations
    - Quick turnaround analysis tools
  - In house controller design greatly increased electronics efficiency
    - Enabled by subsystem cooperation
- Structural Thermal design iterations
  - Competing requirements
  - Very low mass margins

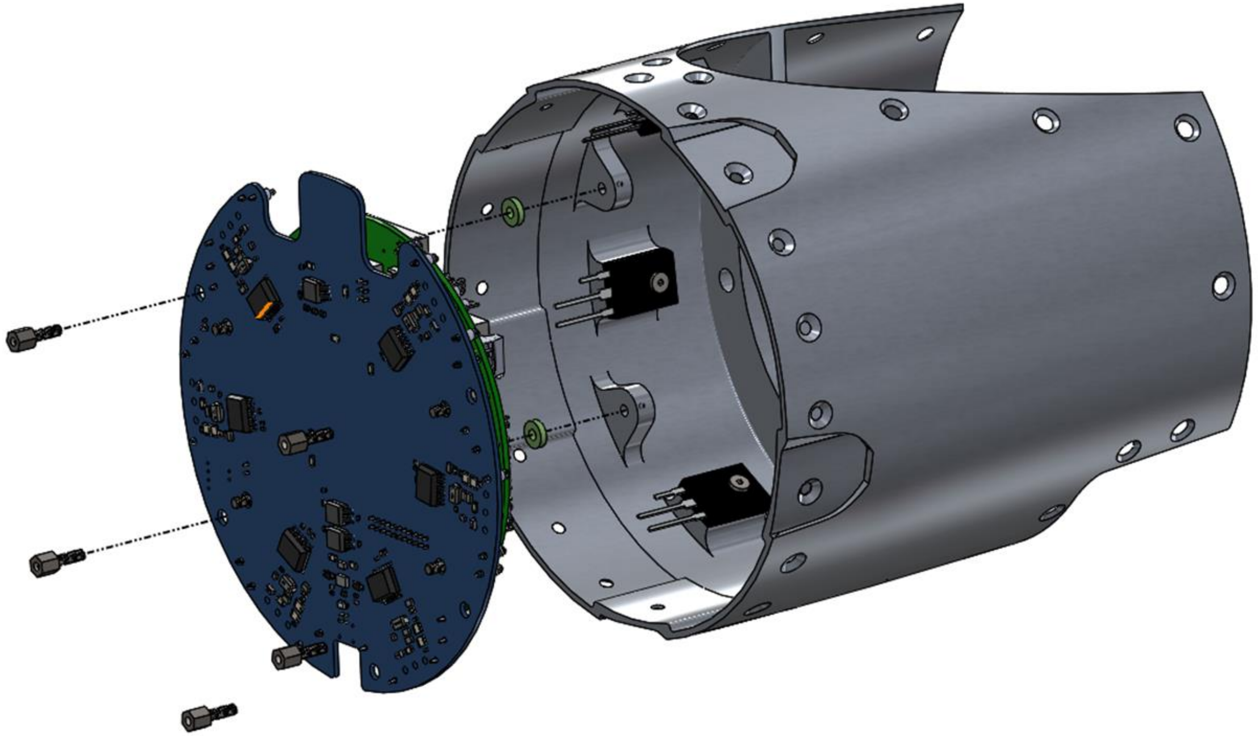
GIMC Design



MOTOR
CENTER SECTION
PCB/HEAT SINK ASSEMBLY
HIGH LIFT NACELLE AFT (9)

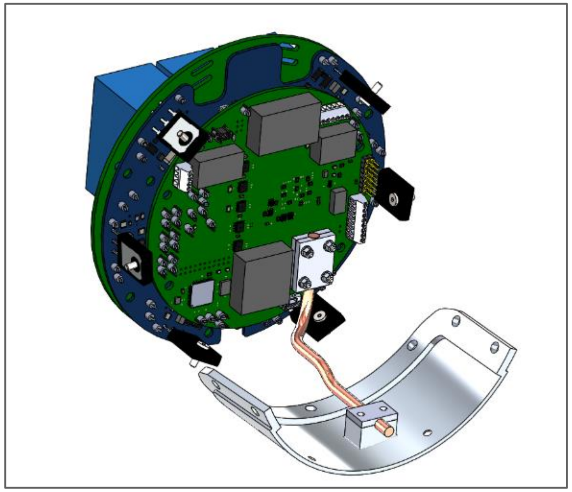
High Power Electronics Thermal Design

- **High Power Electronics**
  - Thermally sinked to external flow
  - Aluminum external sink conforms to OML
  - SiC MOSFETs are distributed around the circumference of the sink to minimize temperature gradient
  - Designed External Sink Surface Area
    - 640 cm^2

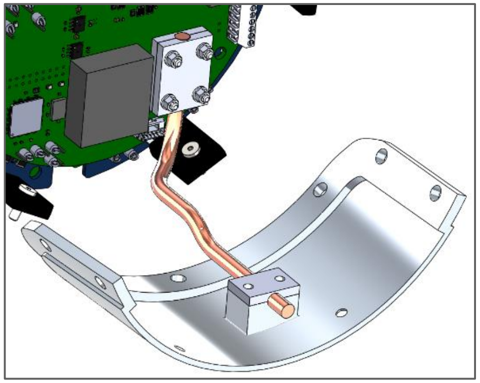


Low Power Electronics Thermal Design

- **Low Power Electronics (LPE)**
  - Two copper thermal planes on each PCB to distribute heat
    - 1.4 mil (1 oz copper)
  - PCBs are thermally linked together through aluminum standoffs which are in contact with the thermal planes
  - Secondary Low Power Heat Sink with heat pipe conductor
    - Low Power Sink is thermally insulated from High Power Sink with G10 standoffs
    - Sintered Wick Copper Heat Pipe
      - Water working fluid
      - 27W Capacity
      - 30 to 120C Temperature range
  - Additional convection to internal nacelle environment

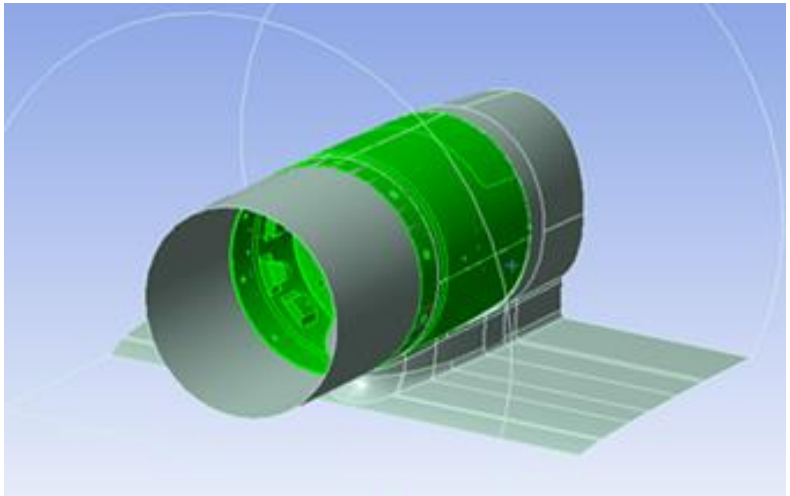


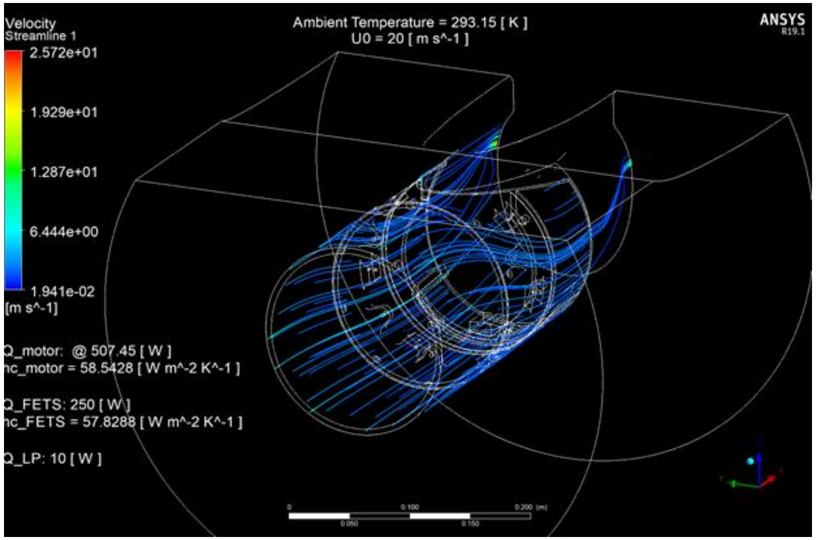
Low Power Electronics with G10 spacers



Low Power Heat Sink and Heat Pipe

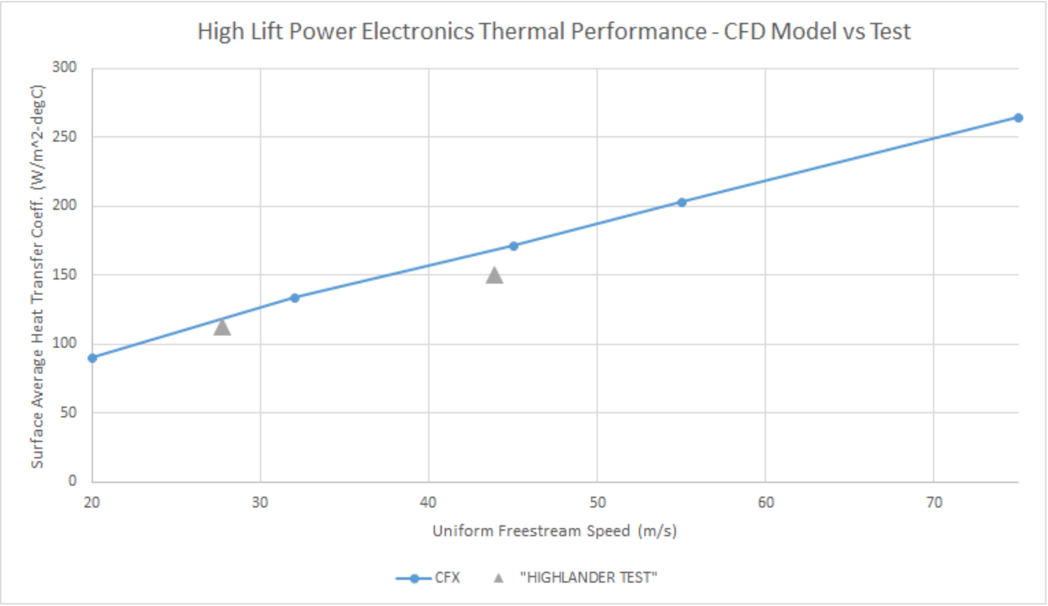
Convection Heat Transfer Characterization

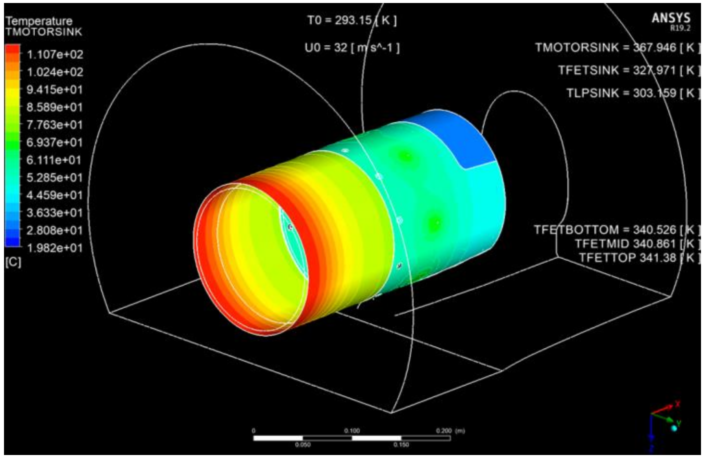




- **RANS (SST) Turbulence Model**
  - Enhanced wall treatment for heat transfer
  - Design points based on uniform inlet temperature, speed, and dissipated power.

Convection Heat Transfer Characterization

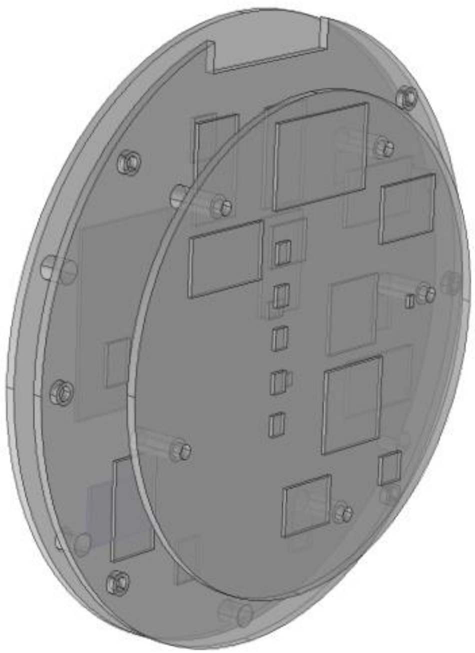




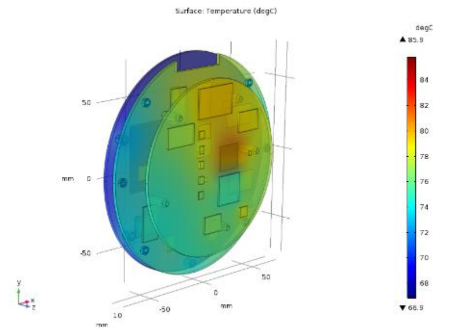
Printed Circuit Board Thermal Analysis & Model

- All boards have two 2oz copper thermal layers
  - 1.4 mil thickness
  - Additional ground and bus planes will help distribute heat
- Thermal vias located throughout boards
- Heat Pipe interface boundary
  - 65C
- High Temperature Sink boundary
  - 72C
- Natural Convection
  - 5W/m^{2}C @ 60C

- Majority of active components have maximum operating ambient air temperature limits
  - Results show we can keep all components below their maximum ambient temperature limit
    - Conservative due to actual component maximum operating temperature being higher than ambient operating temperature



PCB Thermal Model Component Results



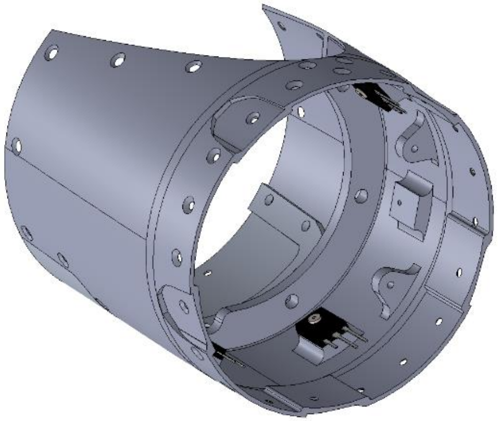
Component	Part	Qty	Pwr (mW) ea	Pwr (mW) Tot	Max Operating Temp	Model Temp	Notes
Capacitor	B32778G1206K000	3	83	249	105	69.9	
Current Sensor	LA 100-P	2	240	480	85*	74.3	Ambient Max
Total			323	729			

Component	Part	Qty	Pwr (mW) ea	Pwr (mW) Tot	% Output of Max	Max Operating Temp	Model Temp
Gate to Source Resistor	RT1206BRD075KL	6	10	60		155	78.9
6V Zener	MMSZ5233B-7-F	6	32.53	195.18		150	78.9
6V Zener Current Limiting Resistor	ERJ-14NF3321U	6	97.59	585.54		155	78.9
HS Driver PS	ATA00H18S-L	4	80.02	240.07	13%	85	77.6
LS Driver PS	ATA00H18S-L	4	240.07	240.07	40%	85	78.7
Opto Driver	ACPL-339J-500E	6	240	1440		95 (amb)	78.9
Gate Resistors		12	10	120		155	78.9
Total			710.22	2880.87			

Component	Part	Qty	Pwr (mW) ea	Pwr (mW) Tot	% Output of Max	Max Operating Temp	Model Temp	Notes
ADC Buffer Amp	AD620BRZ-R7	5	31.2	156		85	78.7	
5V CVTR	SD02S1205A	1	27.6	27.6	6%	98.2*	77.7	Derated Ambient Temp
3.3V Delfino CVTR	JTE0624S3V3	1	472.824	472.82	43%	82.8*	79.8	Derated Ambient Temp
12V CVTR	ISB0124D12	1	28.08	28.08	15%	92*	79.3	Derated Ambient Temp
DAQ Chip	AD7606BSTZ-RL	1	110	110		85	79.7	
Delfino	TMS320C28346ZFEQ	1	1989.6	1989.6		125	85.9	
1.2V Regulator	TPS62400DRCT	1	22.5	22.5	13%	85*	78.6	Derated Ambient Temp
1.8V Supply	TPS72118DBVT	1	38.45	38.45	33%	85*	79	Max dissipation 154mW
EEPROM	AT24C512C-SSHD-T	1	9.9	9.9		85	78.9	
Ethernet TxRx	DP83640TVVX/NOPB	1	330	330		95	78.6	
Opto Coupler	AFBR-59F1Z	1	247.5	247.5		85	76.6	
Total			3307.6585	3432.46				

High Power Heat Sink Thermal Analysis

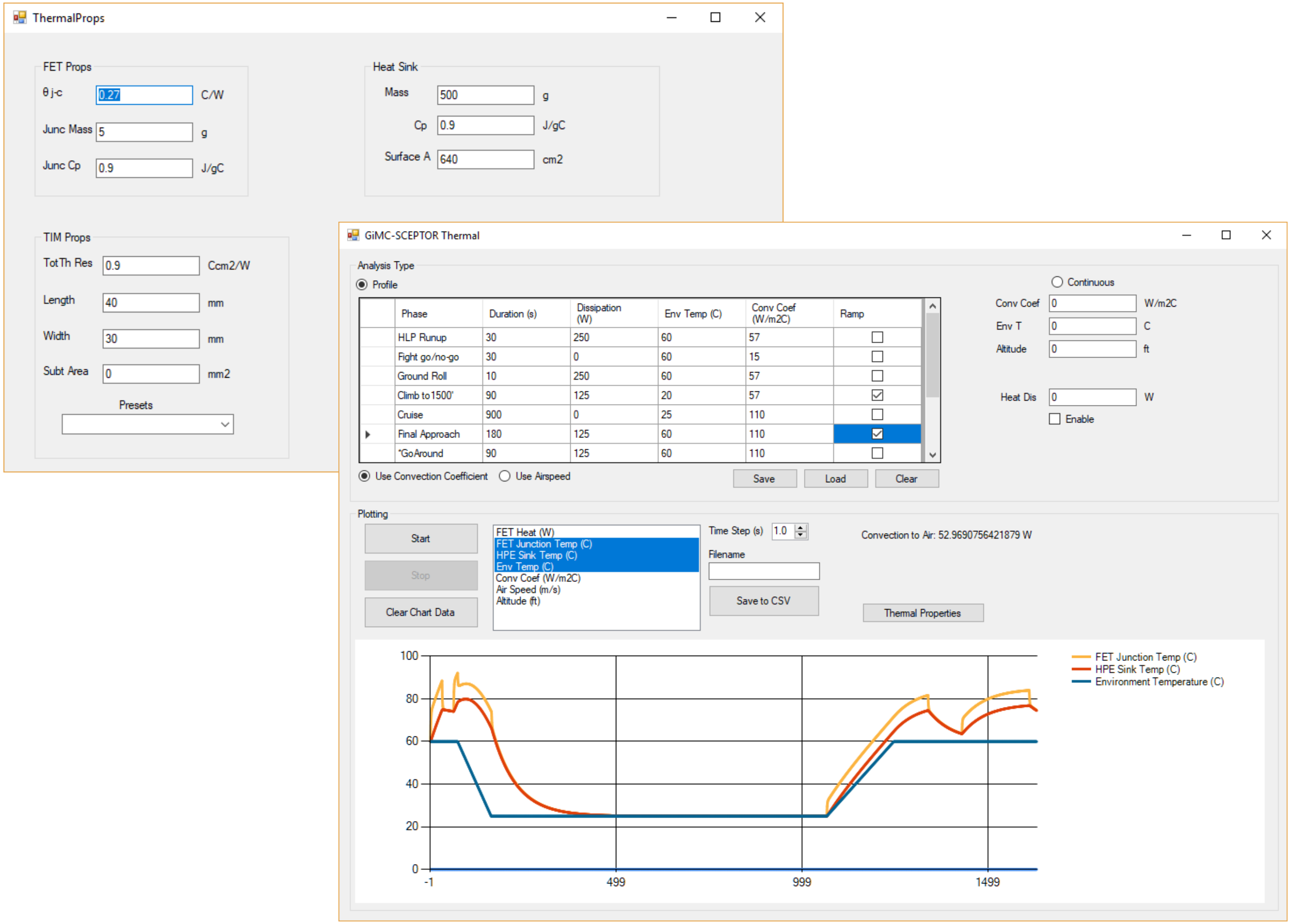
- Analysis assumptions
  - FETs
    - θ_{jc}= 0.27 C/W
    - Junction mass = 5g
    - Junction c_p= 0.9 J/g*C
  - Heat Sink
    - Mass = 380g
    - C_p= 0.9 J/g*C
    - Surface Area = 640 cm^2
  - Environment
    - 20s/90s Transient
      - Temperature = 60C
      - Convection Coefficient = 50 W/m^2C
    - Flight Profile
      - Worst case flight maximums



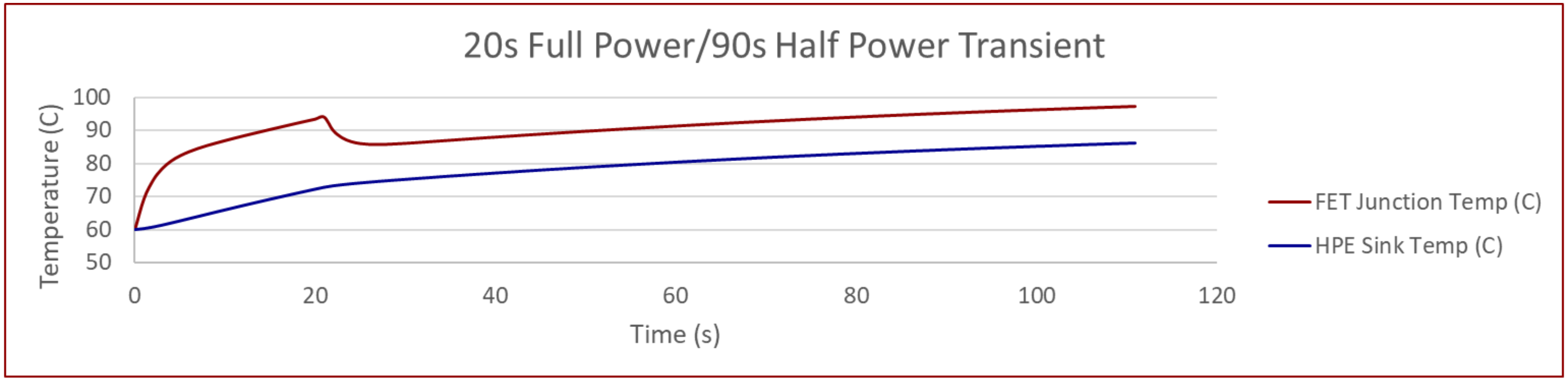
Phase	Duration (Seconds)	High Lift Controller Input Power (kW) 97.0% Efficiency 1 Motor	12 Motors
Taxi from NASA	600	-	-
TO Checklist	120	-	-
Cruise Runup	30	-	-
HLP Runup	30	11.4	136.7
Flight go/no-go	30	-	-
Ground roll	10	11.4	136.7
Climb to 1500'	90	5.7	68.4
Cruise Climb	540	-	-
Cruise	300	-	-
Descent to 1500'	450	-	-
Final approach	180	5.7	68.4
Go Around to 1500'	90	5.7	68.4
Approach pattern	90	-	-
Final approach	180	5.7	68.4
Rollout and turnoff	60	-	-
Taxi to NASA	600	-	-
Total (s, kWh, Wh)	3400	1.0	11.8

Mod 4 HLP Flight Profile from AFRC

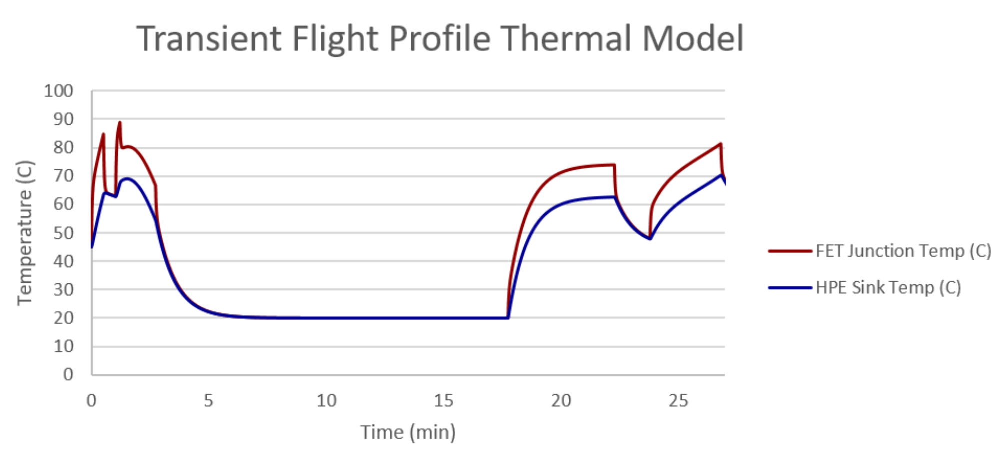
C# Model GUI


ThermalProps
FET Props
θ j-c 0.27 C/W
Junc Mass 5 g
Junc Cp 0.9 J/gC
Heat Sink
Mass 500 g
Cp 0.9 J/gC
Surface A 640 cm2
TIM Props
Tot Th Res 0.9 Ccm2/W
Length 40 mm
Width 30 mm
Subt Area 0 mm2
Presets
GiMC-SCEPTOR Thermal
Analysis Type
Profile
Continuous
Phase | Duration (s) | Dissipation (W) | Env Temp (C) | Conv Coef (W/m2C) | Ramp
HLP Runup | 30 | 250 | 60 | 57
Fight go/no-go | 30 | 0 | 60 | 15
Ground Roll | 10 | 250 | 60 | 57
Climb to 1500' | 90 | 125 | 20 | 57
Cruise | 900 | 0 | 25 | 110
Final Approach | 180 | 125 | 60 | 110
GoAround | 90 | 125 | 60 | 110
Conv Coef 0 W/m2C
Env T 0 C
Altitude 0 ft
Heat Dis 0 W
Enable
Use Convection Coefficient
Use Airspeed
Save
Load
Clear
Plotting
Start
Stop
Clear Chart Data
FET Heat (W)
FET Junction Temp (C)
HPE Sink Temp (C)
Env Temp (C)
Conv Coef (W/m2C)
Air Speed (m/s)
Altitude (ft)
Time Step (s) 1.0
Filename
Save to CSV
Convection to Air: 52.9690756421879 W
Thermal Properties
100
80
60
40
20
0
-1
499
999
1499
FET Junction Temp (C)
HPE Sink Temp (C)
Environment Temperature (C)

Results



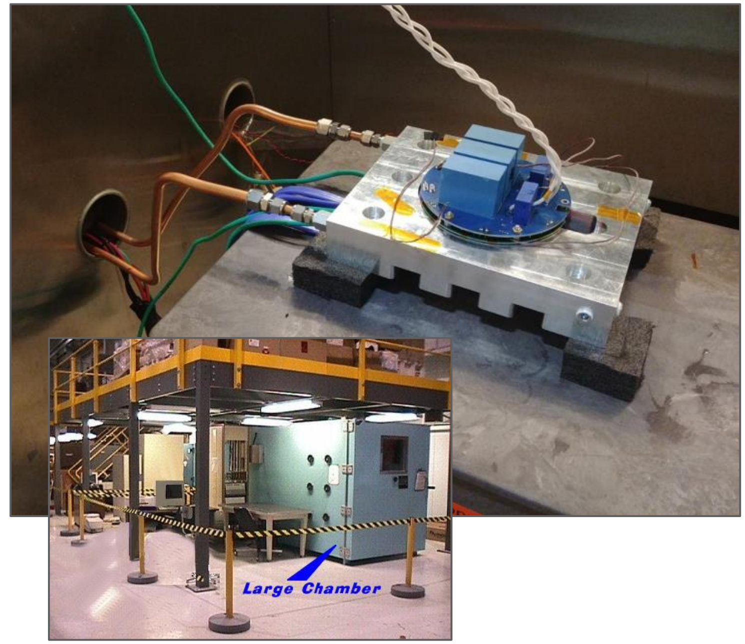
Phase	Duration (s)	Dissipation (W)	Env Temp (C)	Conv Coef (W/m2C)
HLP Runup	30	250	45	57
Fight go/no-go	30	0	45	15
Ground Roll	10	250	45	57
Climb to 1500'	90	125	25	57
Cruise	900	0	25	110
Final Approach	180	125	45	110
*Go Around	90	125	45	110
Approach Pattern	90	0	45	110
Final Approach	180	125	45	110
Ground	20	0	45	57

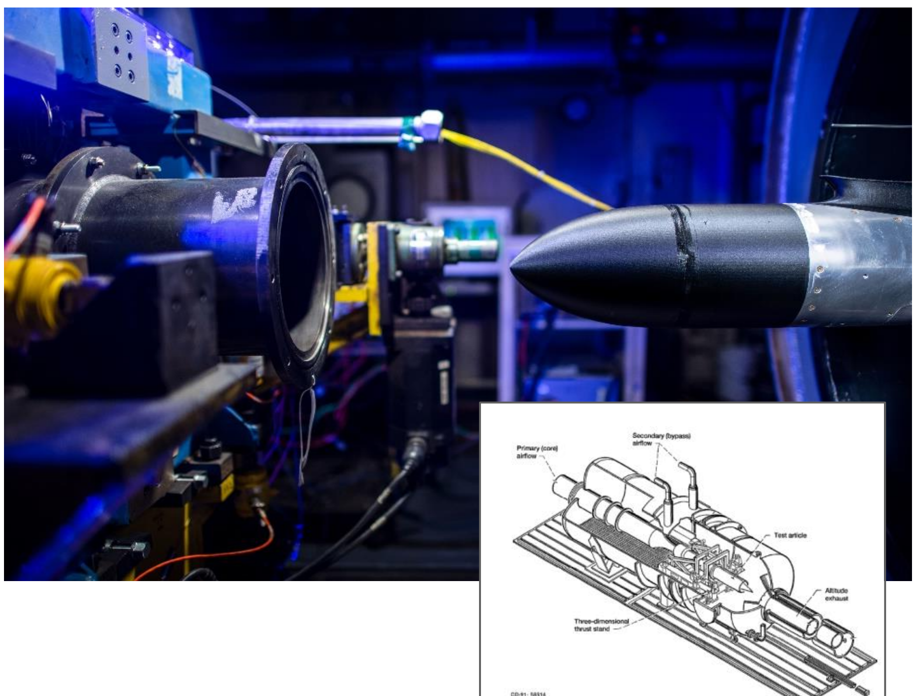


Transient results with heat sink mass, thermal resistance, temperature, and convection modeled at profile power

Testing

- Steady State Thermal Extremes
  - Sea level Thermal Chamber
  - -40C to +60C Extremes
  - Functional & Workmanship Testing
  - Water cooled test heat sink

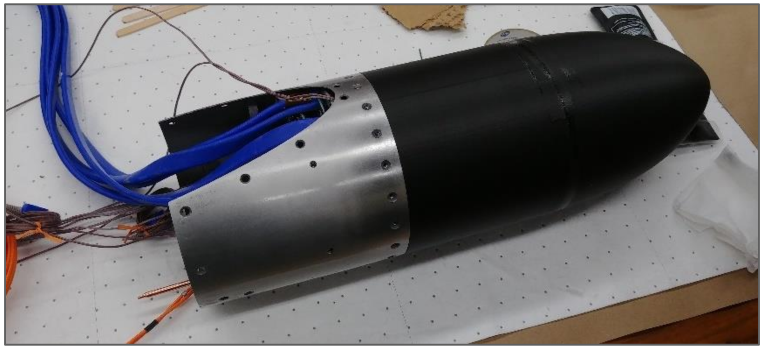


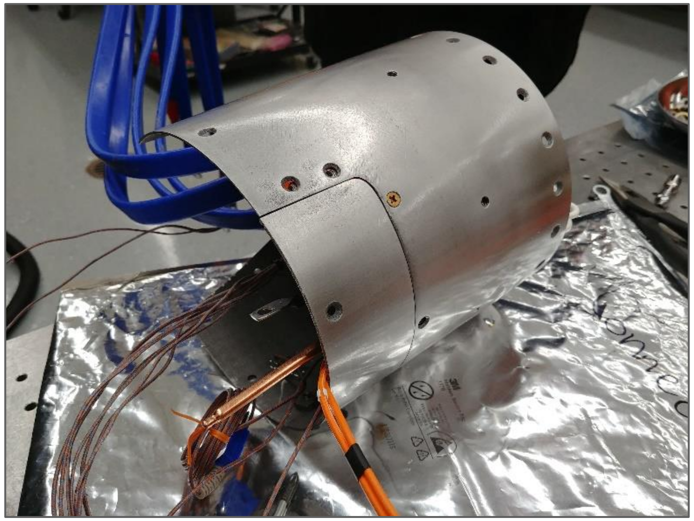


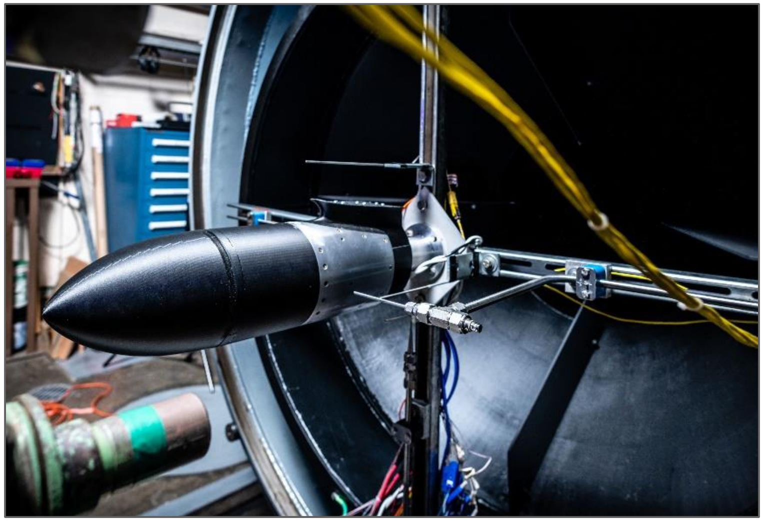
- Transient Wind Tunnel Testing
  - Sea level & Altitude (15kft) Testing
  - Flight Heat Sink performance and Model Validation
  - Functional testing at worst case conditions

Wind Tunnel Test Unit Build

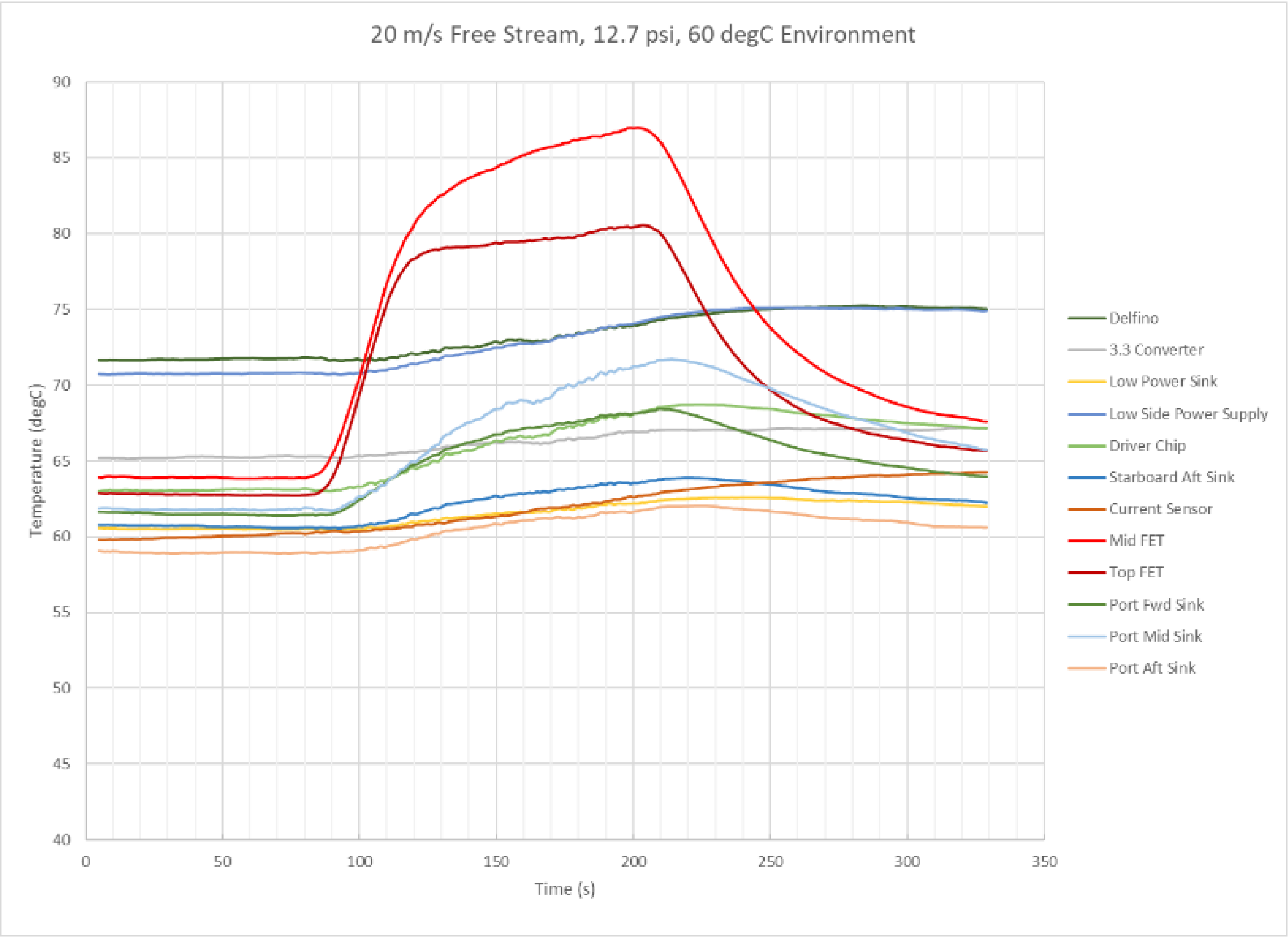
- Additively manufactured aluminum heat sink
- 3D printed forward Nacelle and Motor Section analog







Testing Results (Transient)



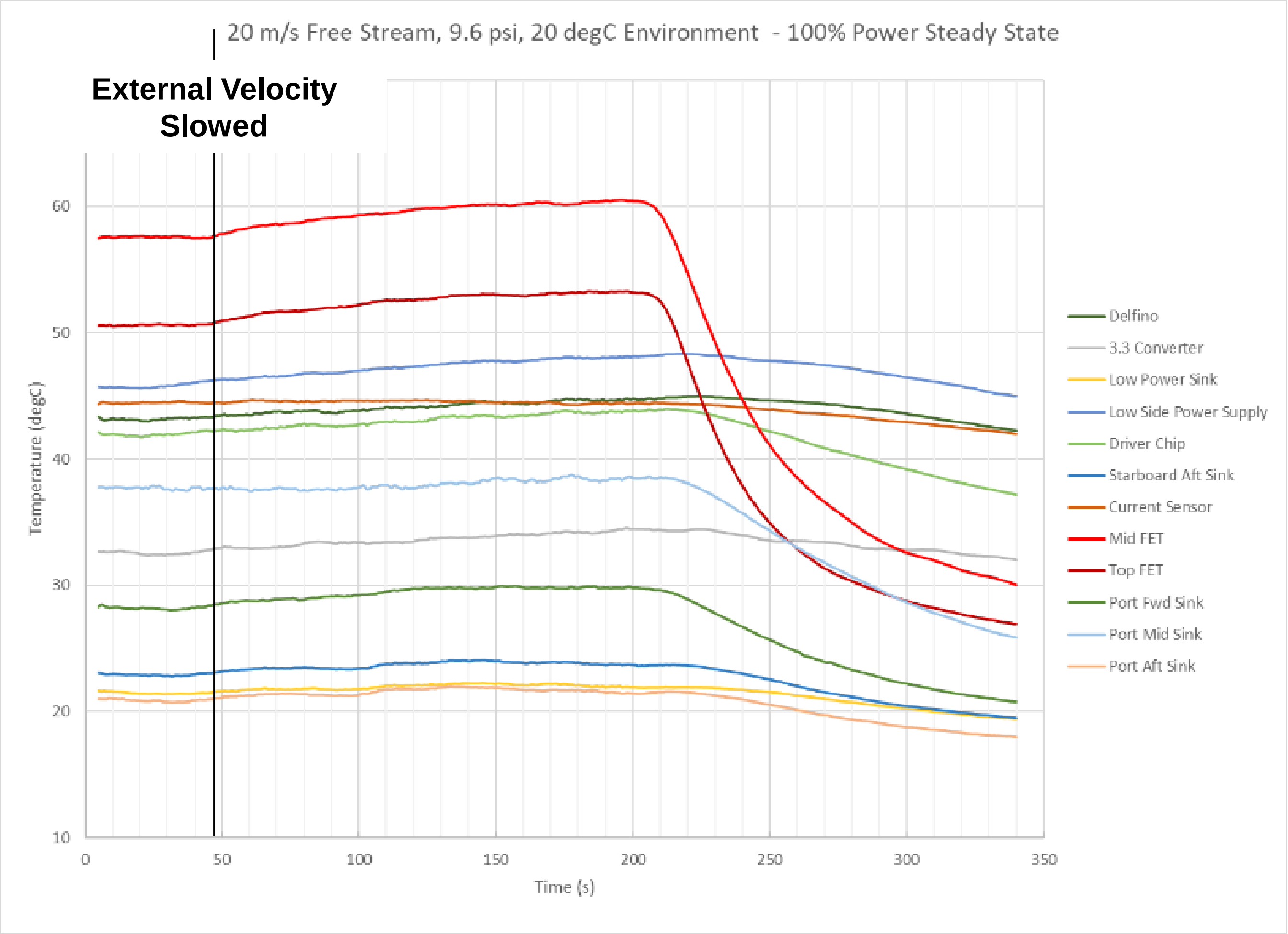
Transient Test Case 4

- 20s 100% power
- 90s 50% power
- Environment
  - 20m/s
  - 12.7 psi (4000 ft)
  - 60 degC

Testing Results (Steady State)

<u>Steady State Test Case 2</u>

- Continuation from previous test
- 100% power
- Environment
  - 20m/s
  - 9.6 psi (11300 ft)
  - 20 degC



Conclusions / Wrap-Up

- Developed models for heat transfer characterization and transient modeling of passive 'OML' cooled power electronics

- Designed, built, and tested well-integrated multidiscipline motor controller package for X57

- Completed design successfully met all operational and environmental requirements at worst case conditions