TFAWS Interdisciplinary Paper Session

Thermal Analysis of the Advanced Modular Power Systems (AMPS) Power Electronic Modules

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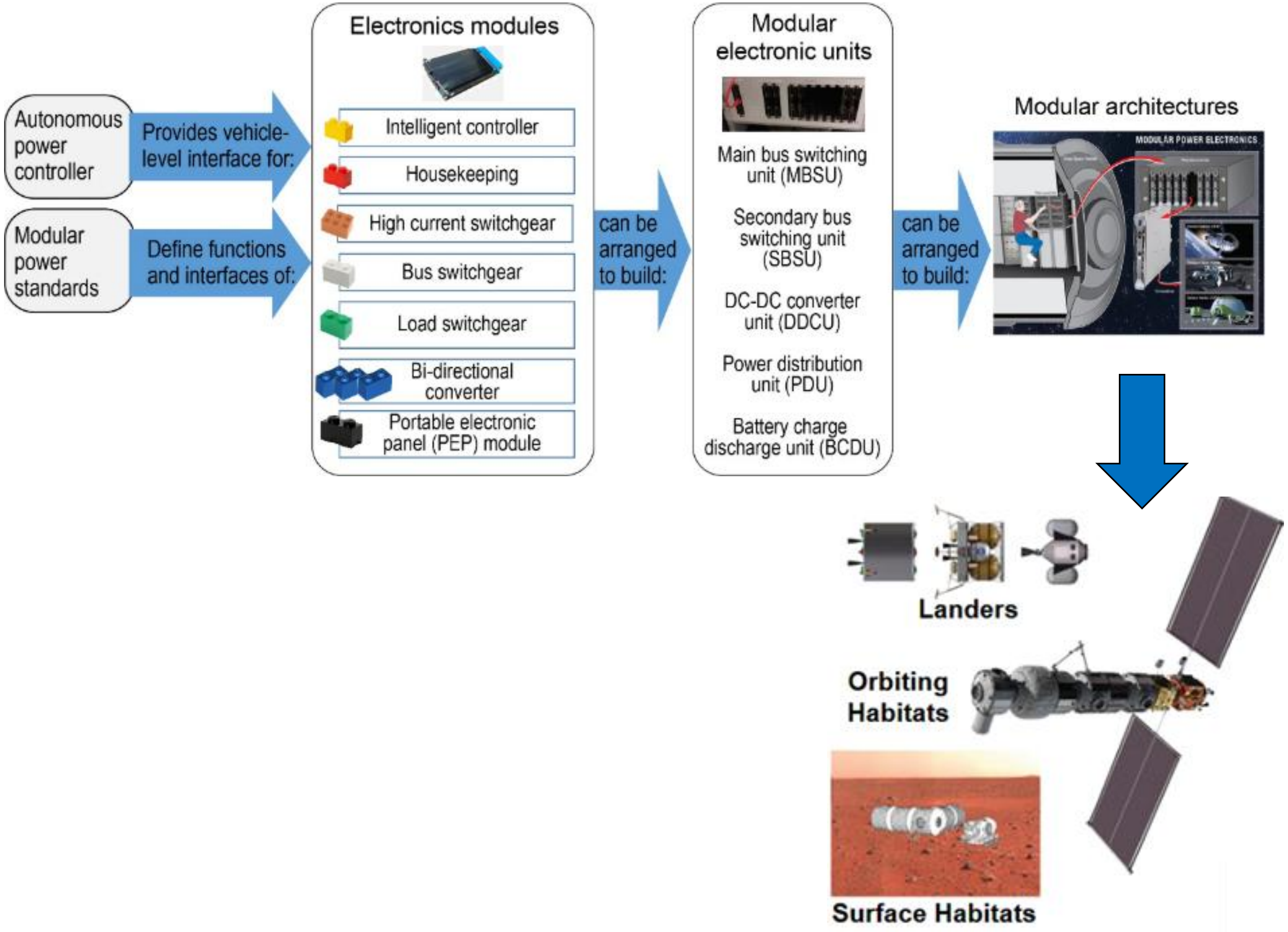
Outline

- Background
- Modules & Assembly
- Modeling Method
- Results
- Next Steps

Background: Advanced Modular Power Systems (AMPS)

- Development of space electronic modules that can:
  - Combine with standardized interfaces and chassis
  - Provide commonality across a variety of applications across space missions
  - Increase reliability and reduce the number of parts
- Contribute to the development and maturation of the Modular Electronic Standard for Space Power Systems (MESSPS)



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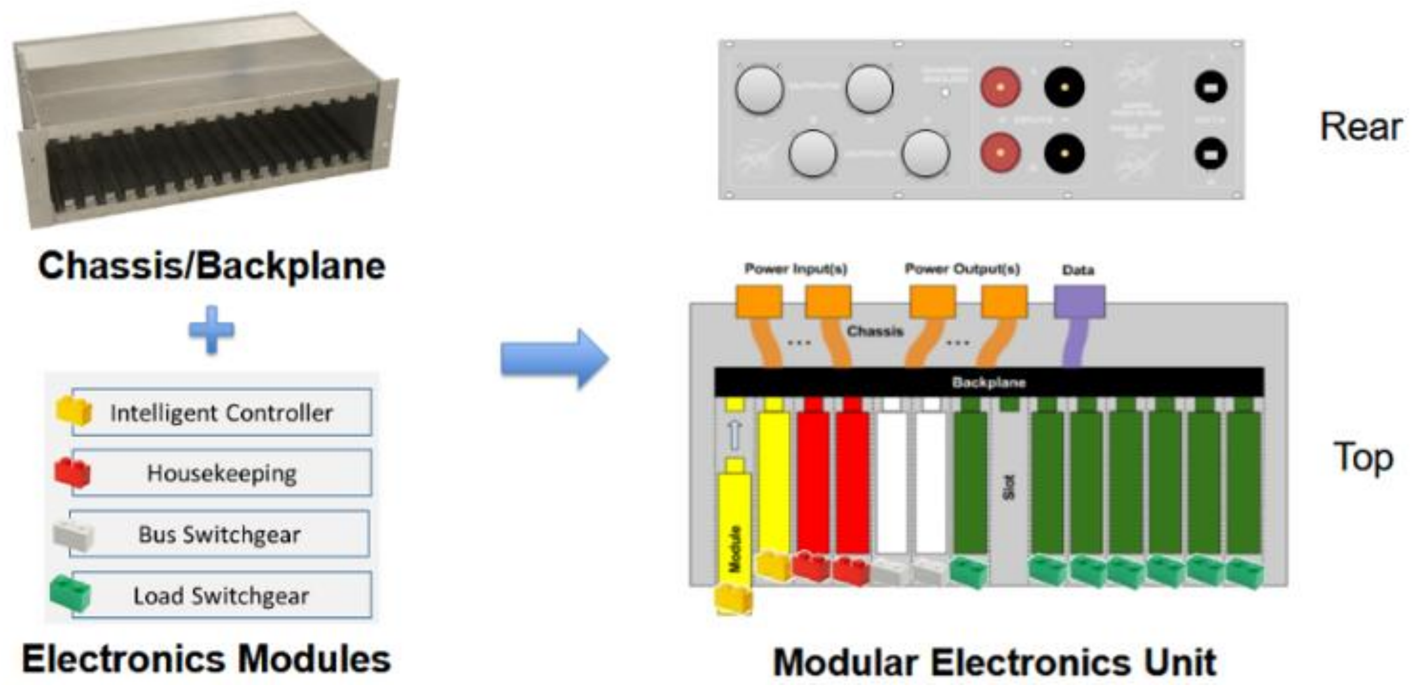
Background: Advanced Modular Power Systems (AMPS)

- Designing unique electronics modules
  - Combination of modules create MEUs
  - Main bus switching, battery charge/discharge/ power distribution
- Thermal challenges must be addressed:
  - Components are power dense
  - PCB layers are full of insulation
  - Path to heat rejection is torturous: Conduction only due to space applications



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AMPS: Current Path

- Seven different designs are currently being developed by AMPS
  - In-house designs to serve as <u>government-reference designs</u>
  - <u>Not final flight designs:</u> we would like to learn the strengths and weaknesses of these designs
  - Industrial-grade components utilized
- Goal: Generate & test prototypes to elevate to TRL 6
  - Evaluate designs and recommend changes
  - Subject modules to Vibe, Shock, EMI and TVAC testing
  - Application: Habitable, Lunar and Martian environments.

Module Category	Description	Modules
Utility	Provides supporting functions	Controller Module (CTLM) Housekeeping Power Module(HKPM)
Switchgear	Provides remote control and fault protection	Load Switchgear Module (LSGM) Bus Switchgear Module (BSGM) High Current Switchgear Module (HCSM).
Converter Modules	Provides voltage conversion and regulation	Portable Equipment Power Module (PEPM) Bidirectional Converter Module (BDCM)

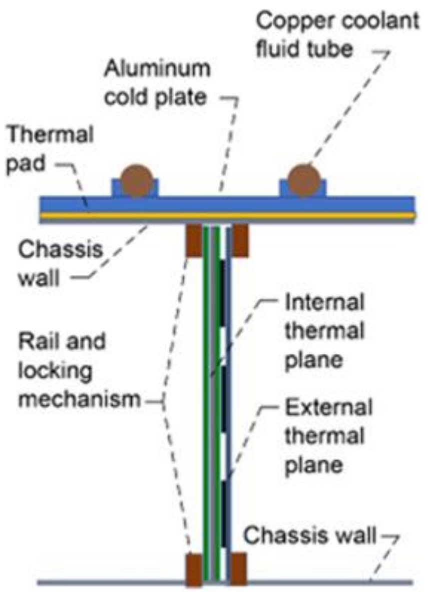
All limits and testing profiles are for prototype evaluation and <u>may not reflect final AMPS requirements</u>

Ref: 3

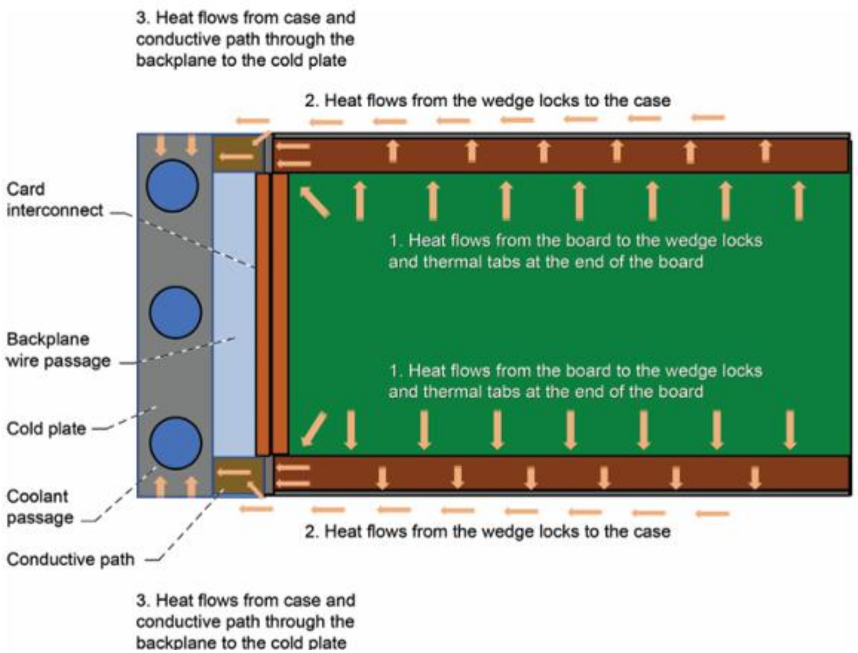
Module Thermal Design Techniques

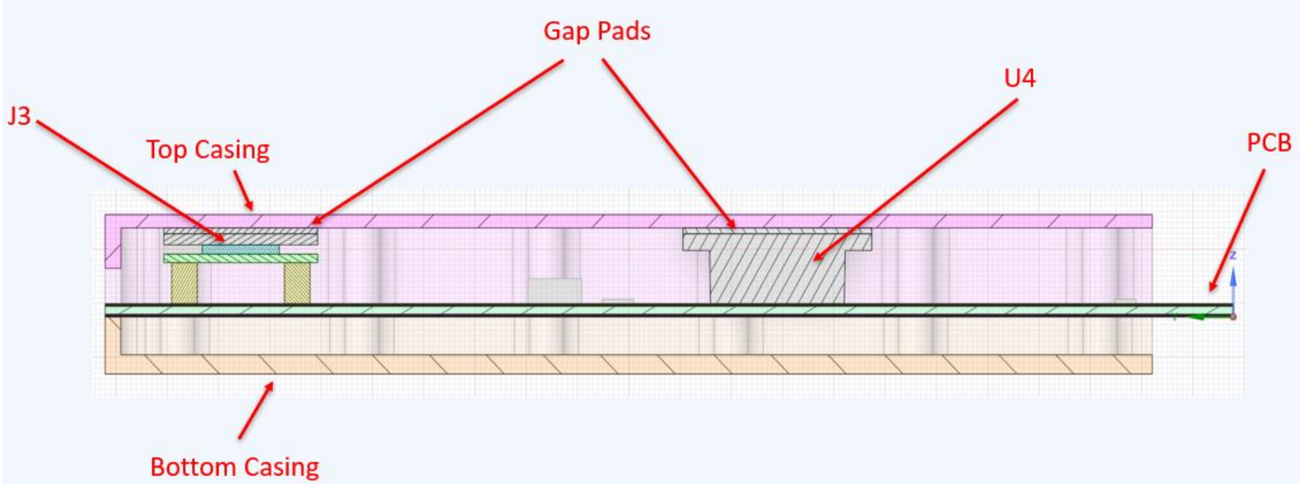
- Methods for improving thermal design:
  - Reduce the heat load (more efficient components)
  - Reroute the traces (generate a "thermal highway")
  - Add thermal vias (cut through the insulation)
  - Improve how heat is acquired and moved
- Boss-extrusion method
  - Heat transfer directly to the module case
  - Compliant gap pad interface
  - Thermal gap pad: TFLEX SF600

Slot View



Card View





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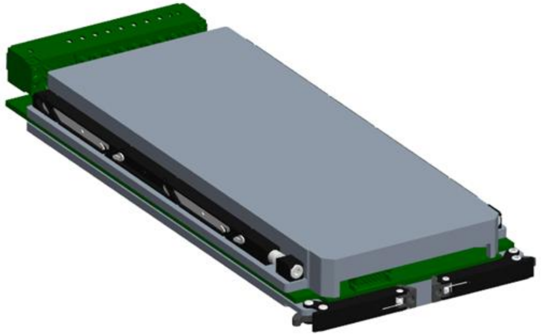
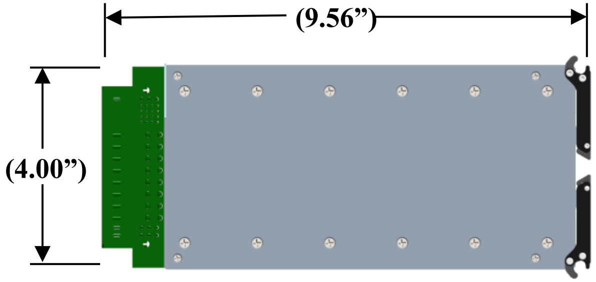
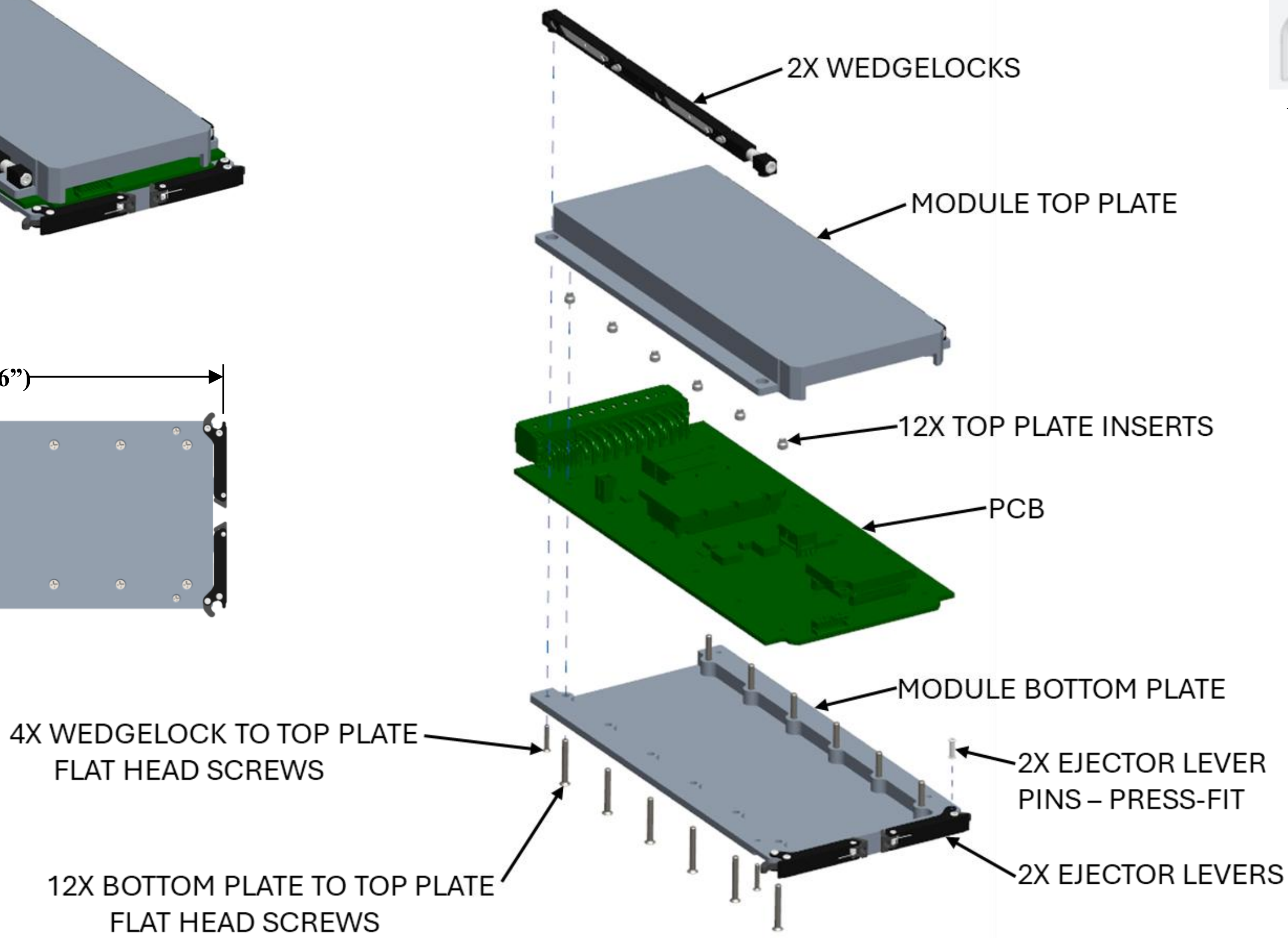
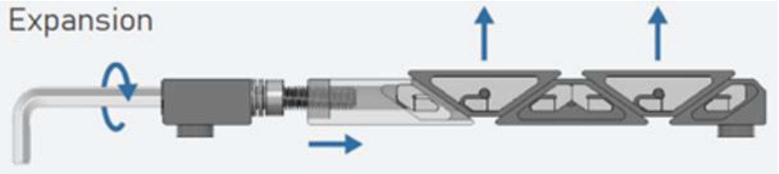
Module Breakdown









Wavetherm SW5-70-270-250-332-EN-30D-B075-BV

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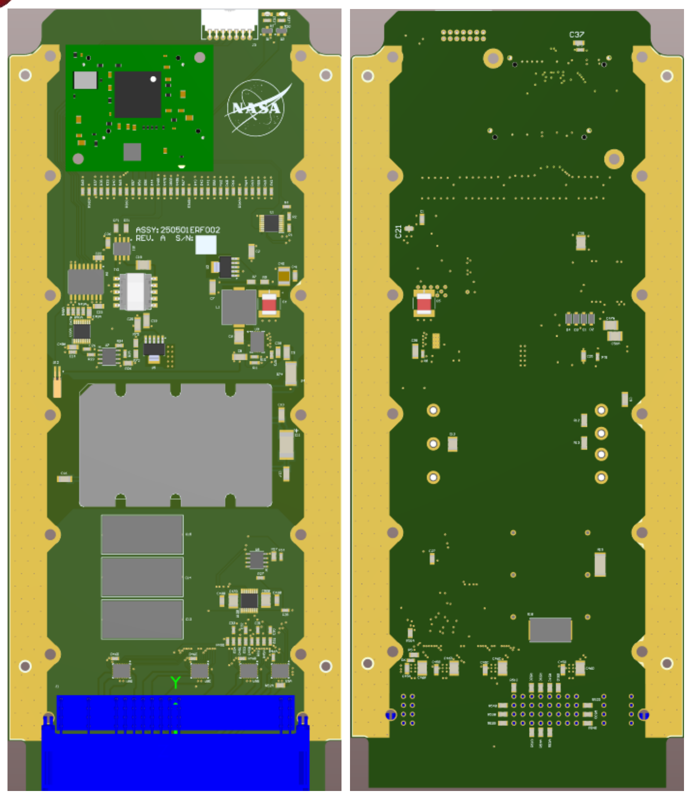
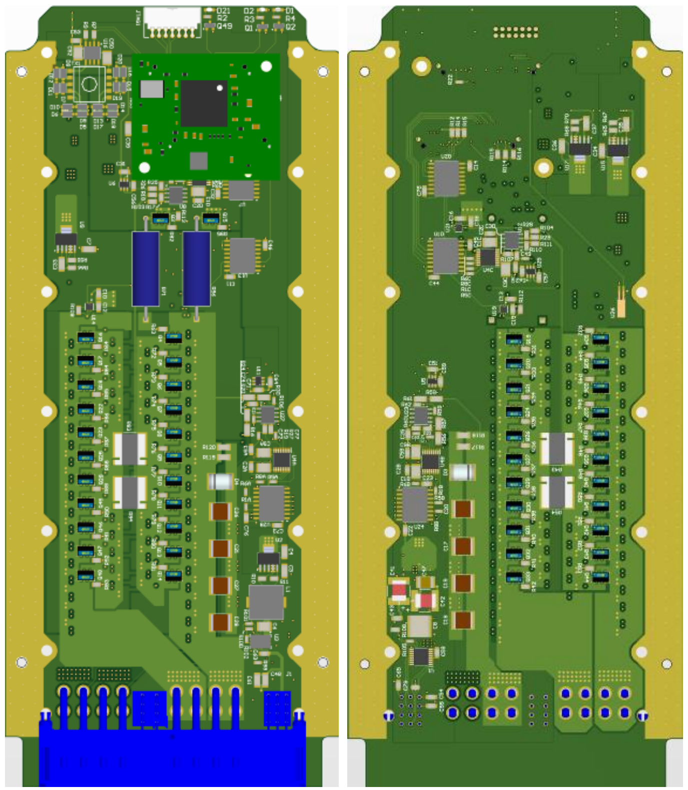
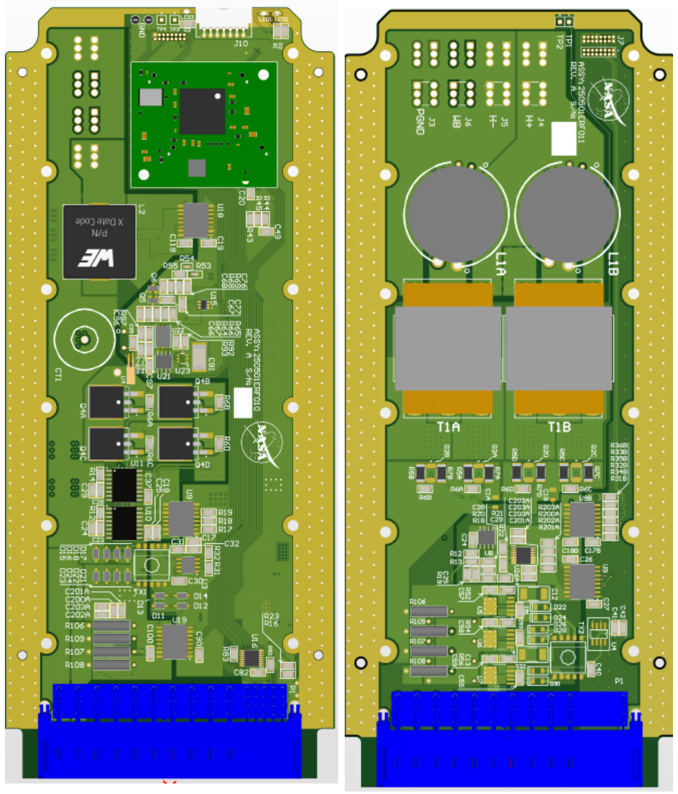
Modules: Focus On Three



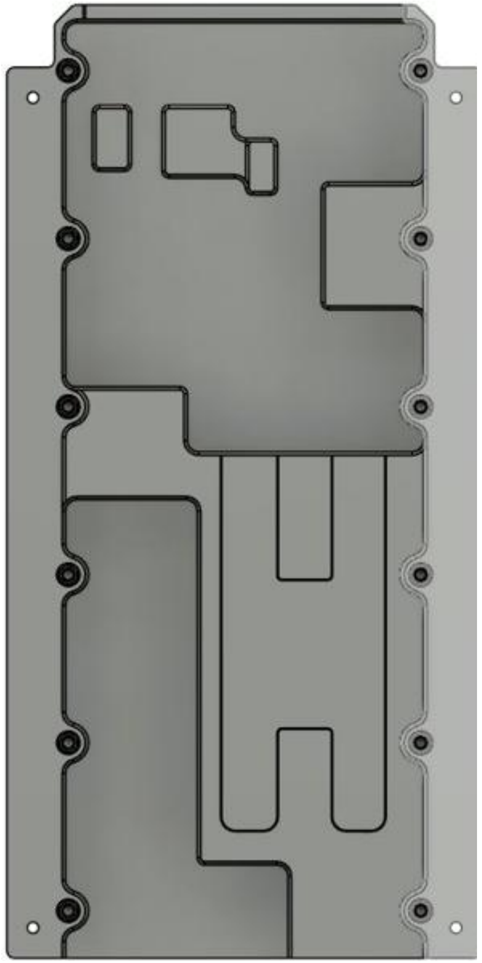




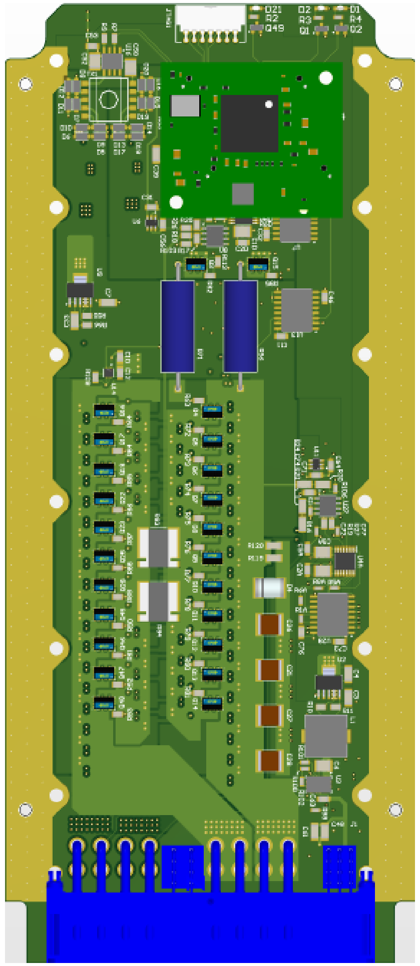
Housekeeping Module (HKPM)	Bus Switchgear Module (BSGM)	Bi-directional Converter Module (BDCM)
General Module	High component load and trace heat generation (high current draw)	High component load and a tri-module (2 distinct PCBs)

Module Breakdown – Boss + Gap Pads

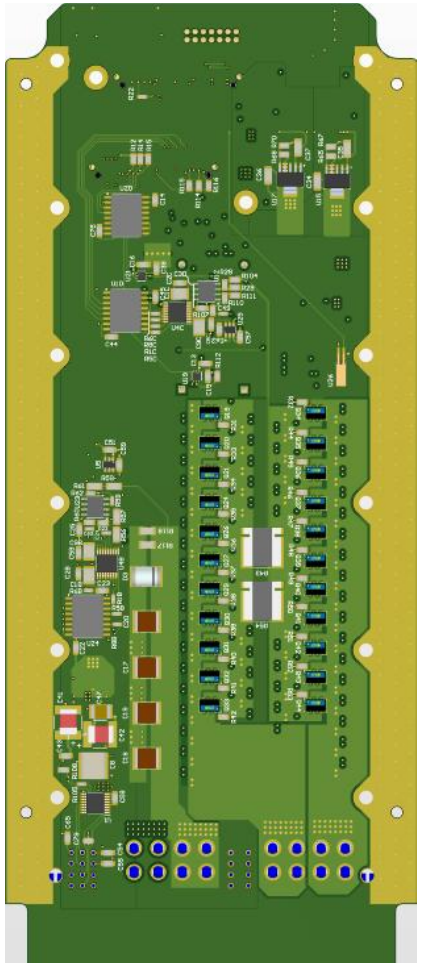
Top - Case



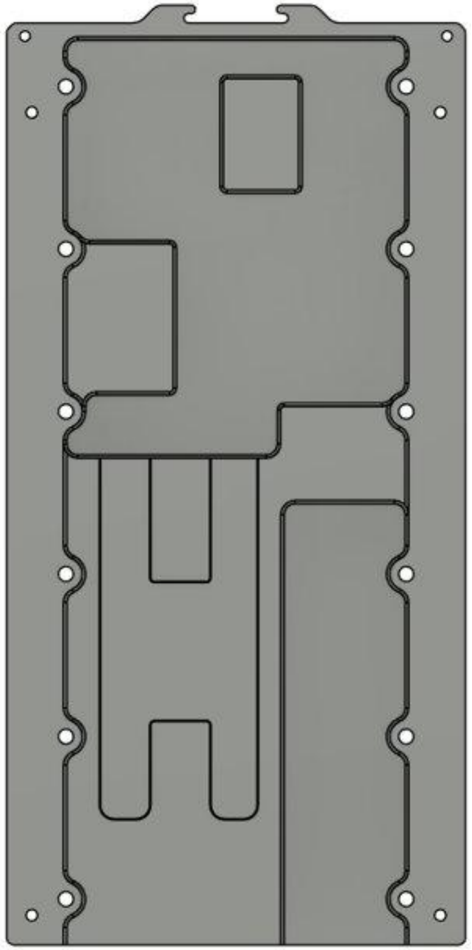
Top - PCB



Bottom - PCB



Bottom - Case

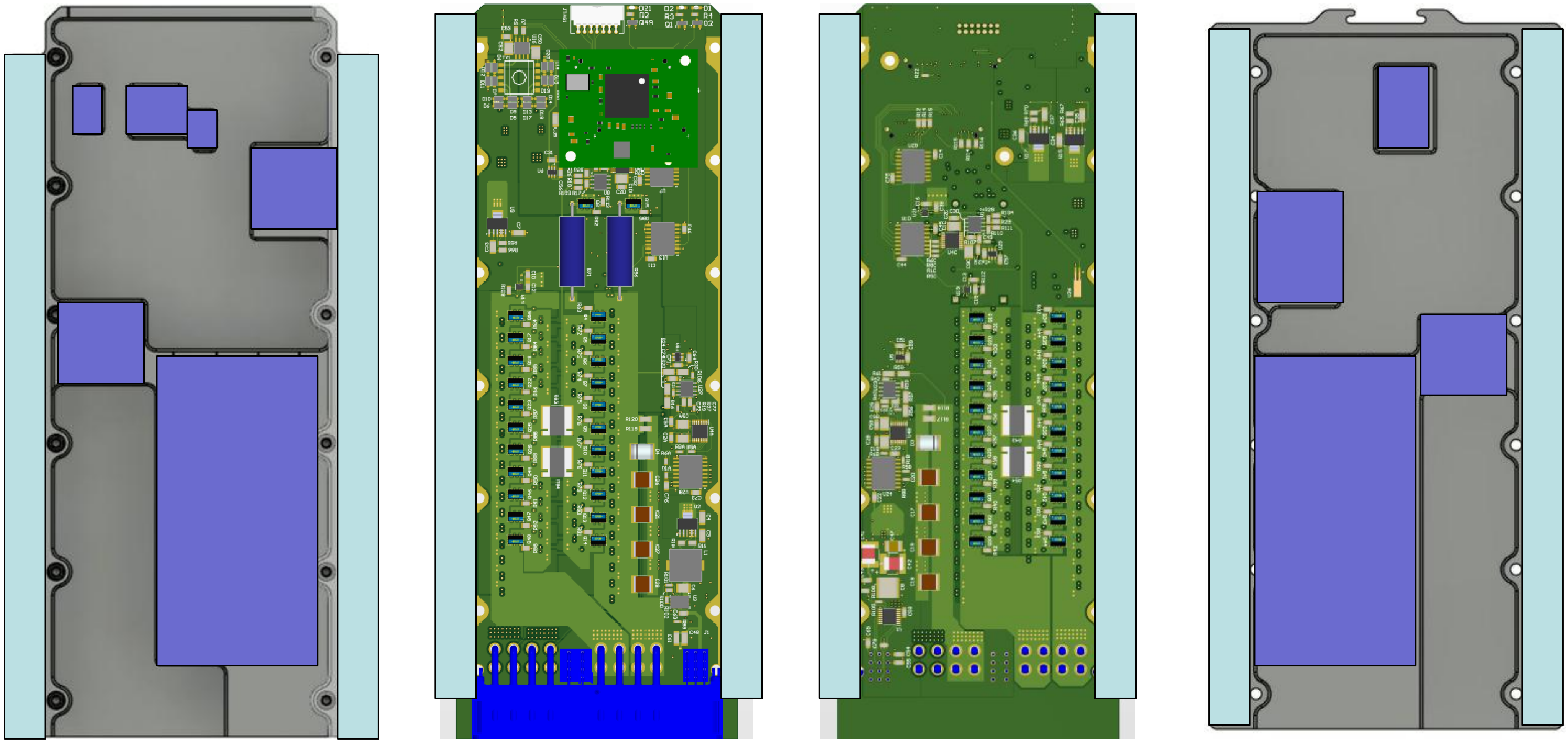


BSGM

**Flip the cases onto the PCB

Module Breakdown – Boss + Gap Pads

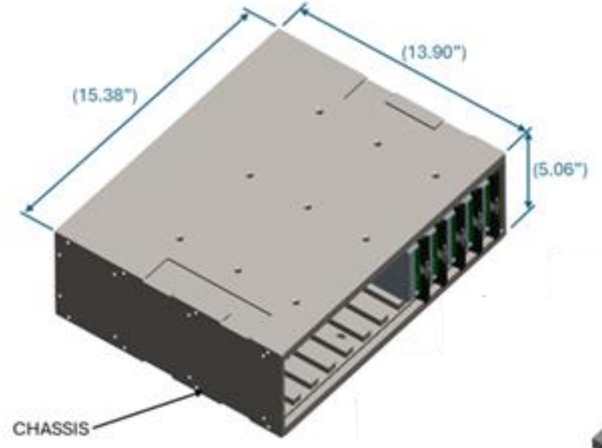
Top - Case | Top - PCB | Bottom - PCB | Bottom - Case



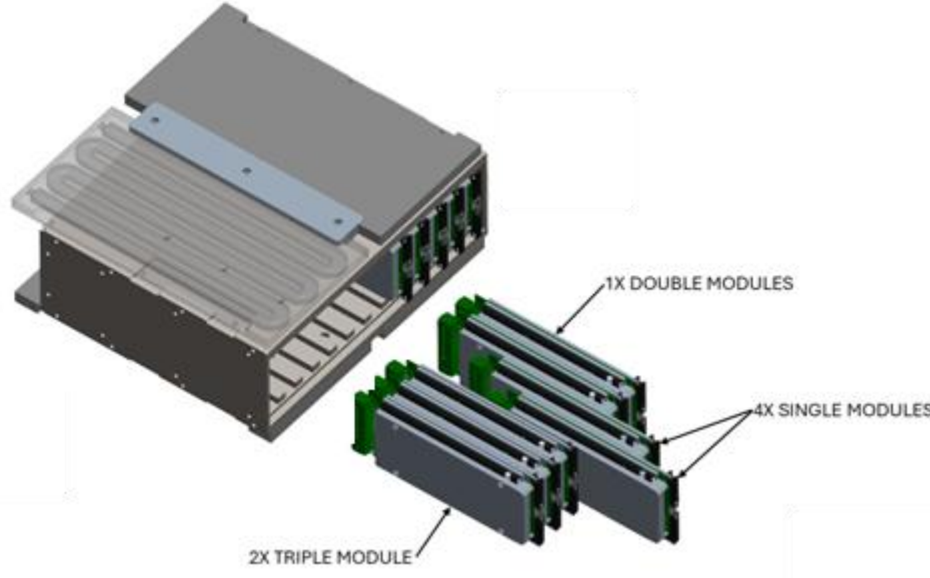
Tgon-800 | TFlex SF600

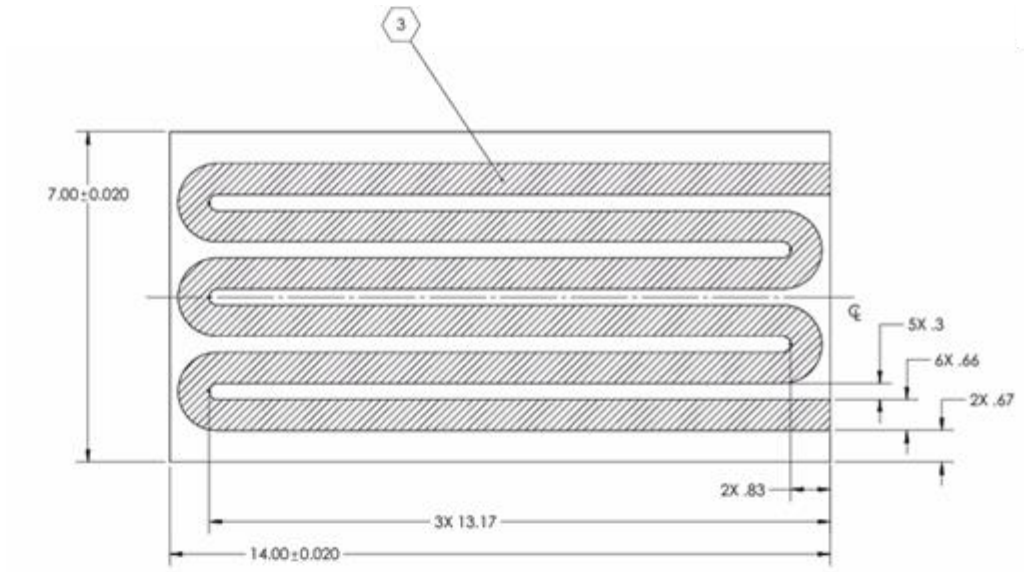
Assembly

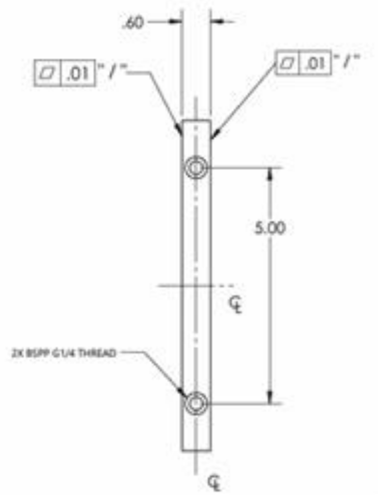
- Chassis:
  - Aluminum with 12 slots
  - Common backplane
- Cold Plates:
  - 2 connected in parallel
  - Wakefield Thermal: 131569



The authors would like to acknowledge Thomas Luginbuhl and Paul Newman for the CAD Pictures







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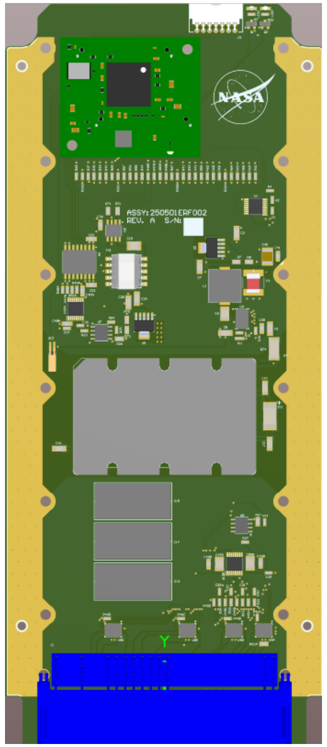
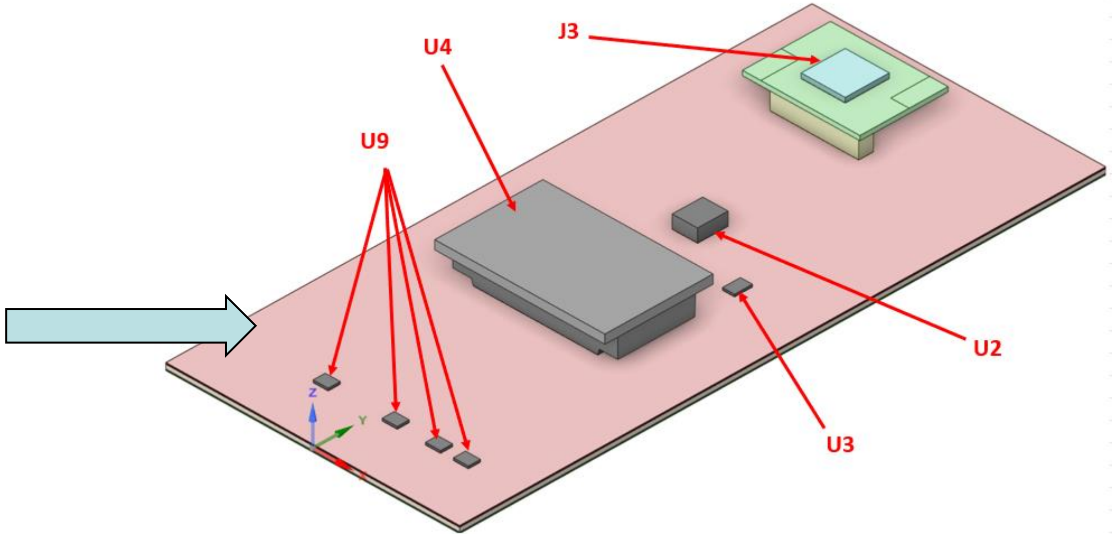
METHODOLOGY

Modeling Method

- Ansys Tool Suite
  - ANSYS Sherlock
    - Generate MCAD with components (or use CAD tool of choice)
  - ANSYS Space Claim/Discovery
    - Defeature and remove components
  - ANSYS Mechanical
    - Analysis & Trace modeling





- Components are modeled as primitives with heat generation
  - Data sheets are used to generate two-resistor models

Evaluation Parameters

- Limits
  - Base: Specification/Data Sheets
  - Electrical derating: EEE-INST-002

- Thermal Margin: SMC-S-0016
  - Uncorrelated models: 11℃ margin

Black: Specification/Data Sheet Limits

Red: Derated Limits per EEE-INST-002

HKPM Components Of Interest

Component Designation	Part Number	Heat Load (W)	Min Temp (℃)	Max Temp (℃)
U2	TPS7A4501DCQR	1.00	-40	125 (93.75)
U3	LM73605-Q1	0.25	-40	150 (110)
U4	V110C12C100BL	9.44	-40	100 (80)
J3	LFD2NX-40-7BG256A	1.00	-40	125 (85)
U9 A-D	TPS274160B	0.45	-40	150 (110)

BSGM Components Of Interest

Parameter	Value
MOSFET Part Number	EPC2307
Number of MOSFET	44
Total MOSFET Load	5.808 W
Total Trace Load	1.900 W
Min Temp	-55 ℃
Max Temp	150 ℃ (120℃)

BDCM Components of Interest

BDCM 1

Component Designation	Part Number	Number	Total Heat Load (W)	Min Temp (℃)	Max Temp(℃)
R106 - 109	RWR80SR100FRB12	4	2.5	-55	250 (125)
Q4 A-B	IXFA80N25X3	4	12 W	-55	150 (110)
U2	TPS7A4501DCQR	2	0.5	-40	125 (93.75)

BDCM 2

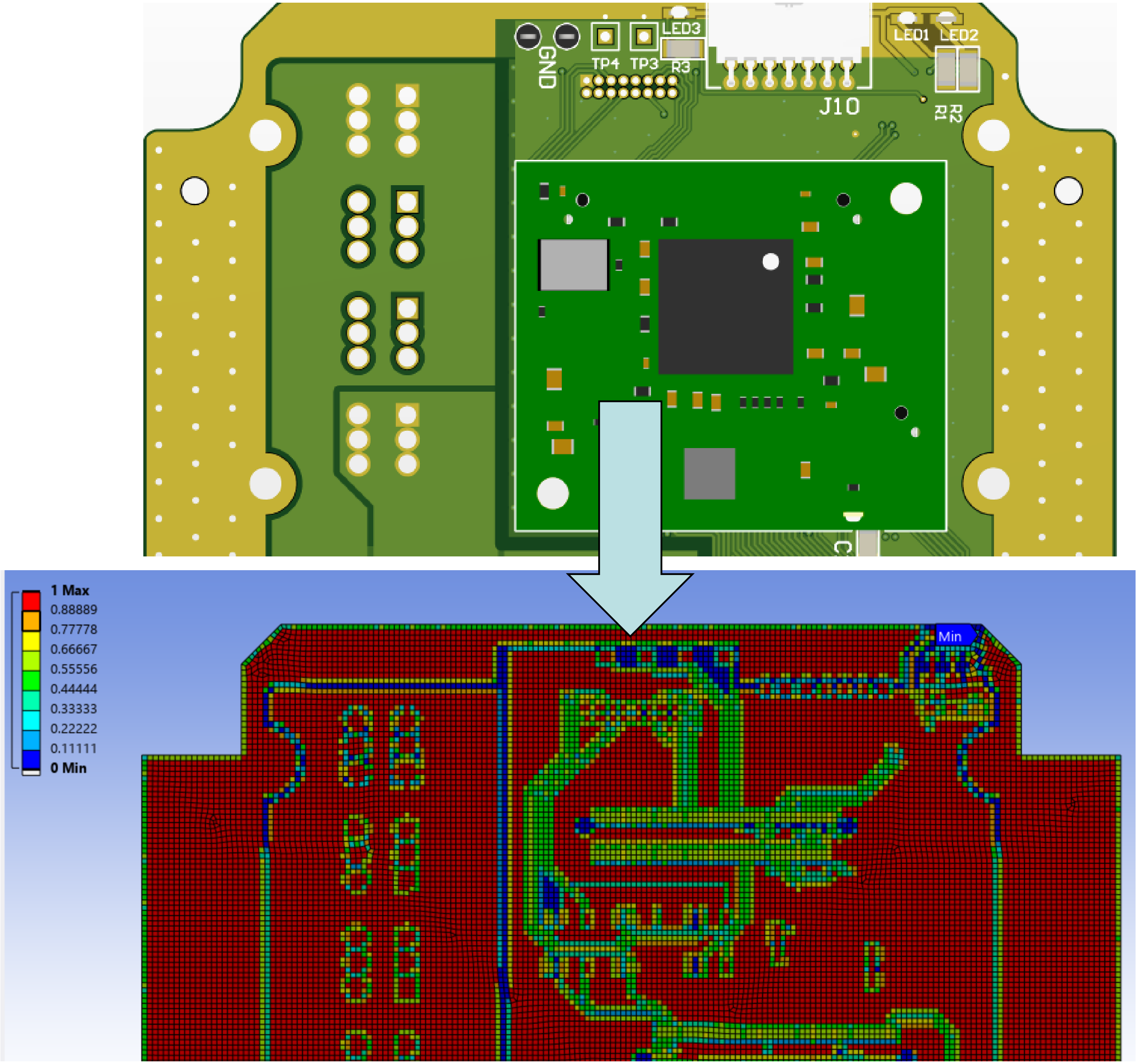
Component Designation	Part Number	Number	Total Heat Load (W)	Min Temp (℃)	Max Temp(℃)
R14-17, R106-109	RWR80SR100FRB12	8	5	-55	250 (125)
Q4A-B	IXFx80N25X3	4	12	-55	150 (110)
D34 A-B	ER5J-TP	4	1	-55	150 (110)
D56 A-B	1.5SMB30A	4	1	-65	150 (110)
D78 A-B	5.0SMDJ100A	4	2	-55	150 (110)
T1 A-B	P.N.501694	2	6	-40	130 (110)
L1 A-B	Custom	2	2	N/A	N/A

PCB Modeling

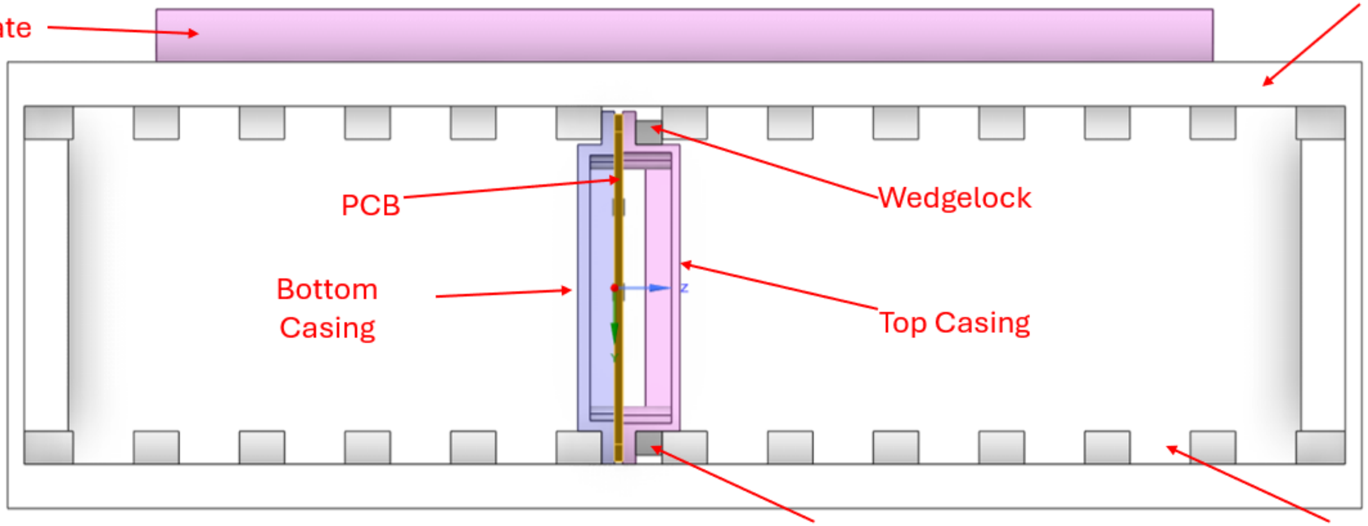
- Homogenous
  - A single solid represents the entire PCB
  - Average material properties are employed (rule of mixtures)

- Trace mapping
  - Resolve the PCB layers
  - Traces and thermal vias are represented via material assignment
  - ANSYS uses the ODB++ files to replace mesh elements with the appropriate trace material property

- Mesh sensitivity studies were conducted for each



Evaluation Scenario

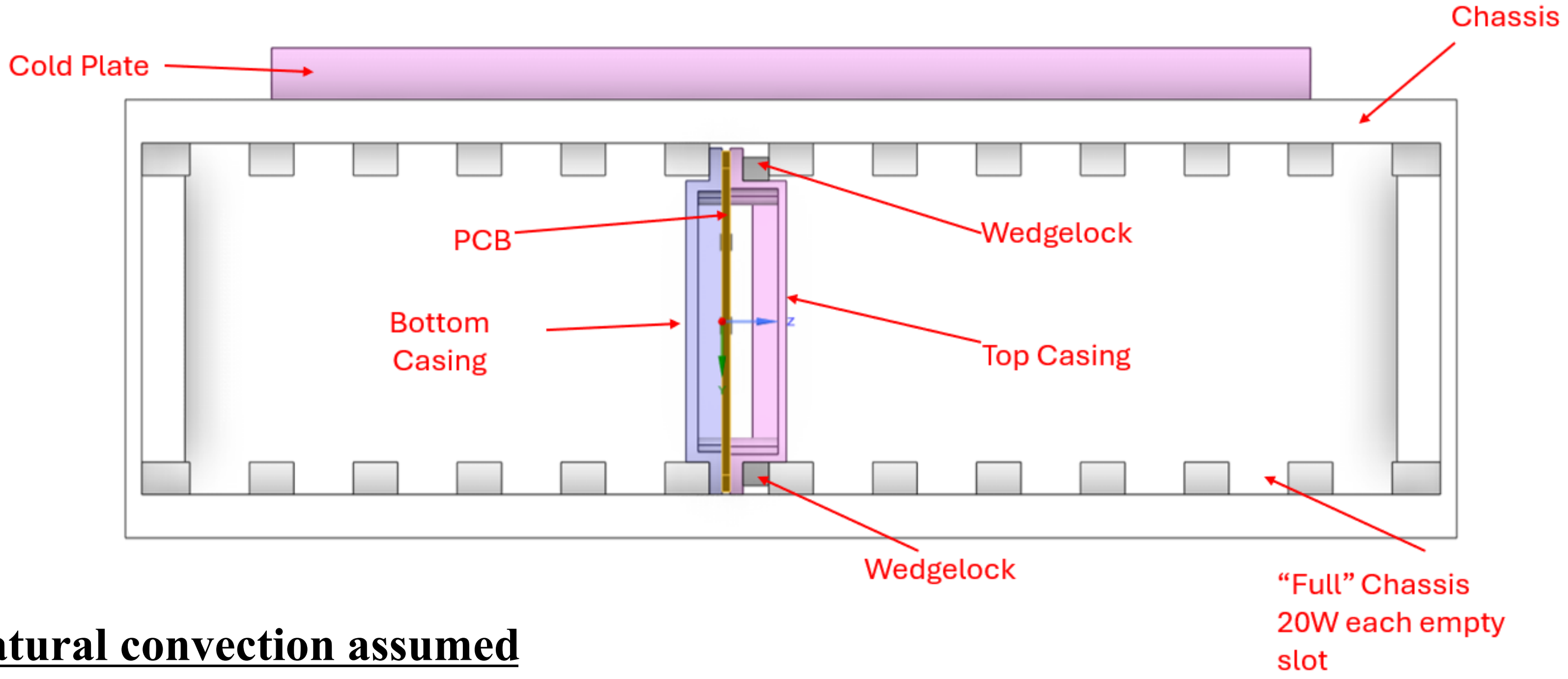


<u>No radiation or natural convection assumed</u>

- Coolant: Relatherm S-2 Silicone Heat Transfer Fluid
- Flow rate: $0.15\ GPM \leq \dot{V} \leq 2.00\ GPM$
  - $265 \frac{W}{m^2 - K} \leq \bar{h} \leq 2150 \frac{W}{m^2 - K}$
- Temperature Range: $-40℃ \leq T_{fluid} \leq 70\ ℃$
  - To represent a range of environments

- Worst Case:
  - Full contact on the bottom teeth
  - Partial contact at the top teeth
  - Hot: 70 ℃, 0.15 GPM (265 $\frac{W}{m^2-K}$)
  - Cold: -40 ℃, 2.00 GPM (2150 $\frac{W}{m^2-K}$)

Evaluation Scenario



<u>No radiation or natural convection assumed</u>

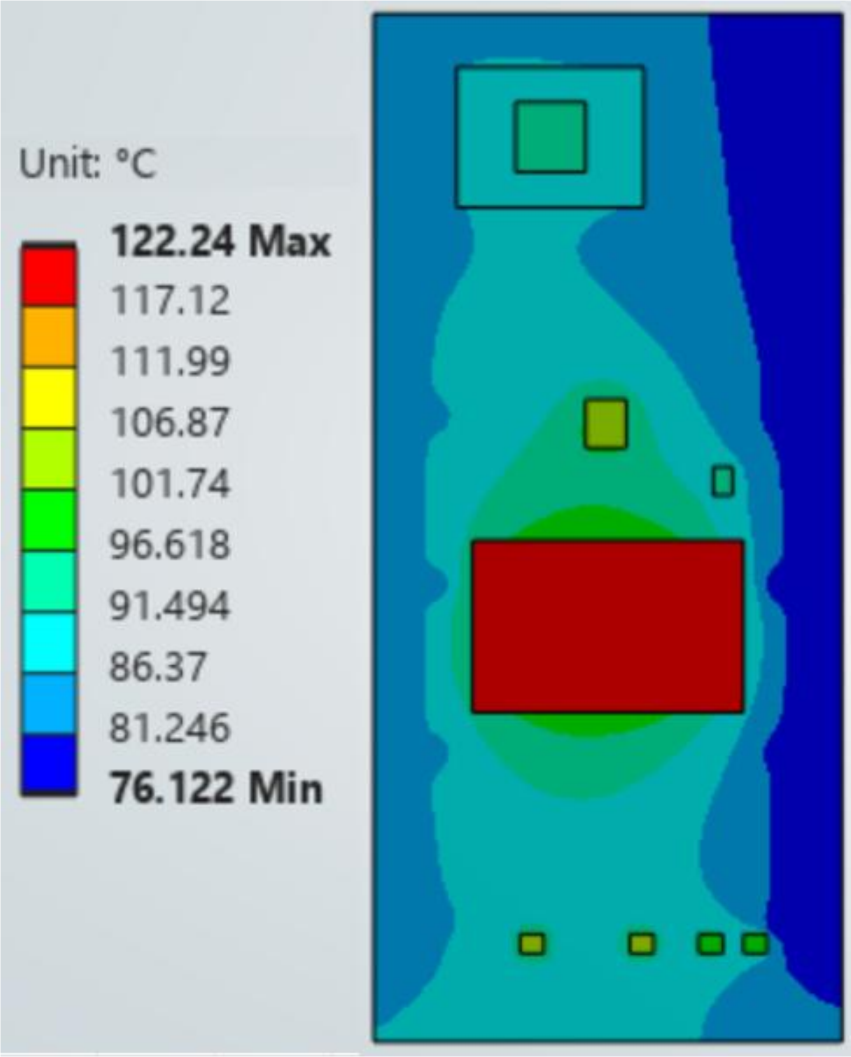
- Analysis: HKPM & BSGM
  - Single module in the chassis
    - Modules with nominal and worst-case 20W heat load
    - With (HKPM & BSGM) and without Boss-extrusions (HKPM only)
  - Full Chassis
    - Evaluated modules will run at nominal heat loads
    - Evaluated modules will use Boss-extrusions
    - Other slots will have 20 W simulated worst-case heat loads

- Analysis: BDCM
  - Single & Full Chassis
    - Evaluated modules will run at nominal heat loads
    - Evaluated modules with use Boss-extrusions
    - Trace-mapped (for PCB of interest) and homogenous models used
    - Full: Other slots will have 20 W simulated worst-case heat loads

RESULTS

HKPM FEA Results: PCB Modeling Comparison

Homogenous



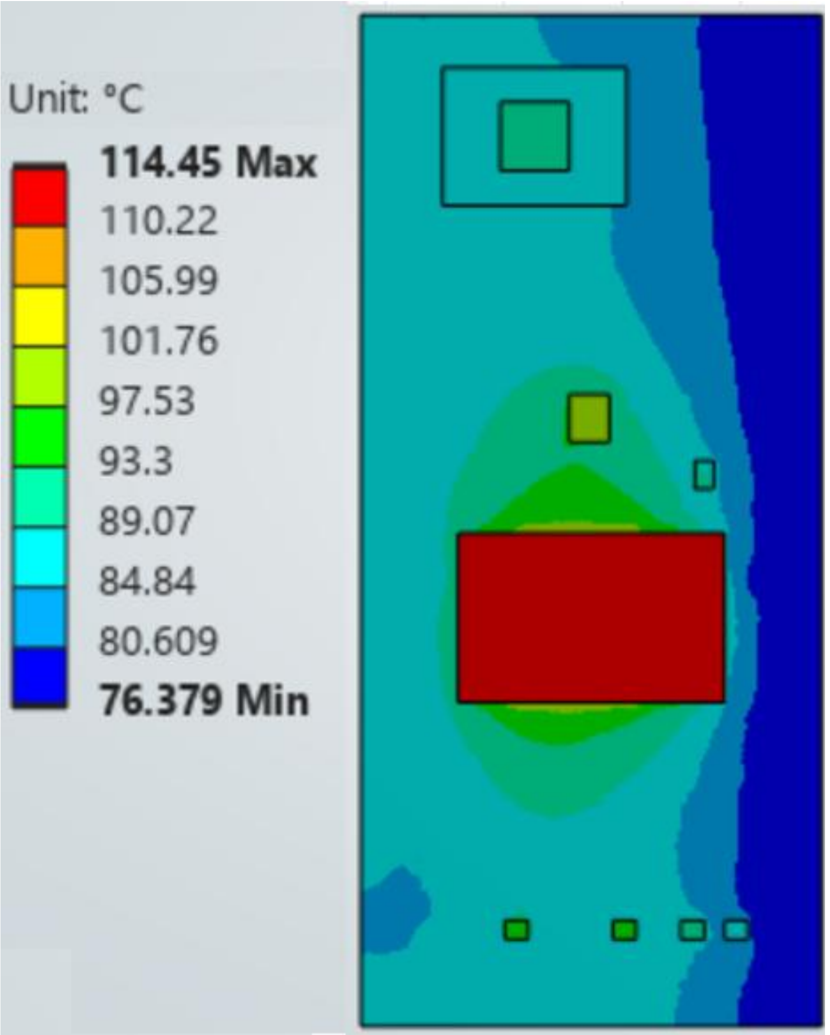
No Boss-extrusions

70 ℃

0.15 GPM

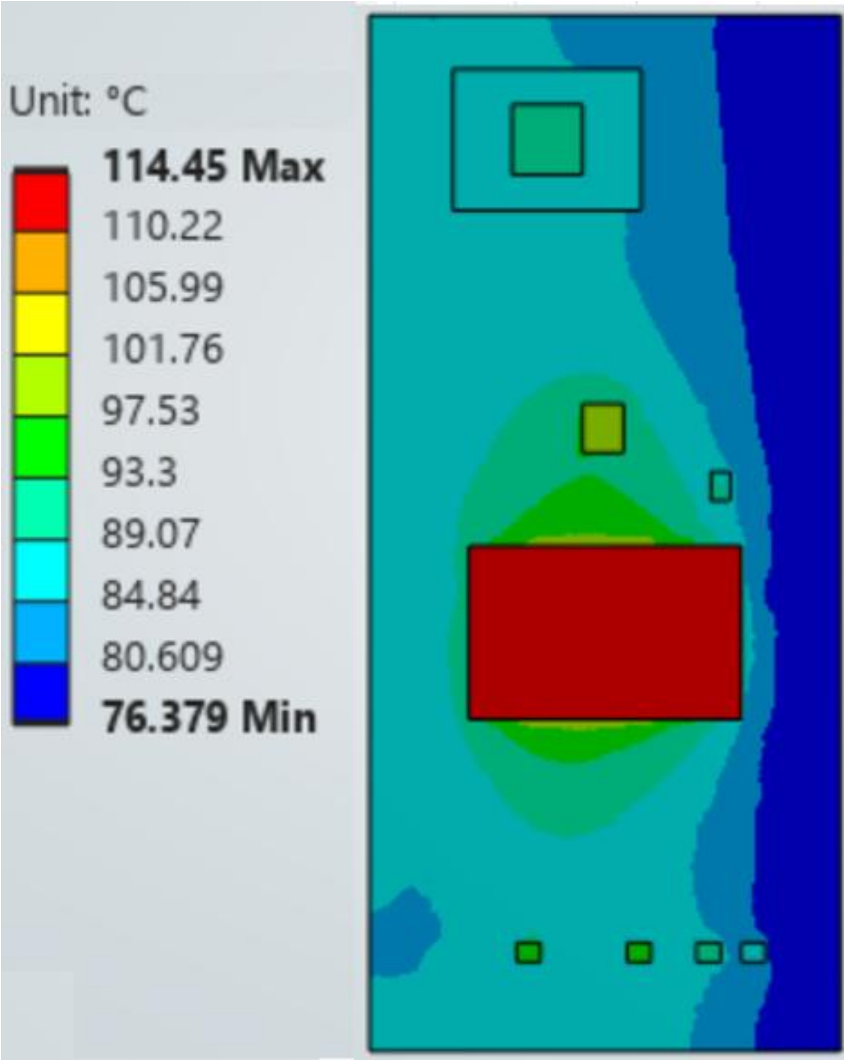
$$265\ \frac{W}{m^2 - K}$$

Trace-Mapped



HKPM FEA Results: Effect of Boss-extrusions

No Boss



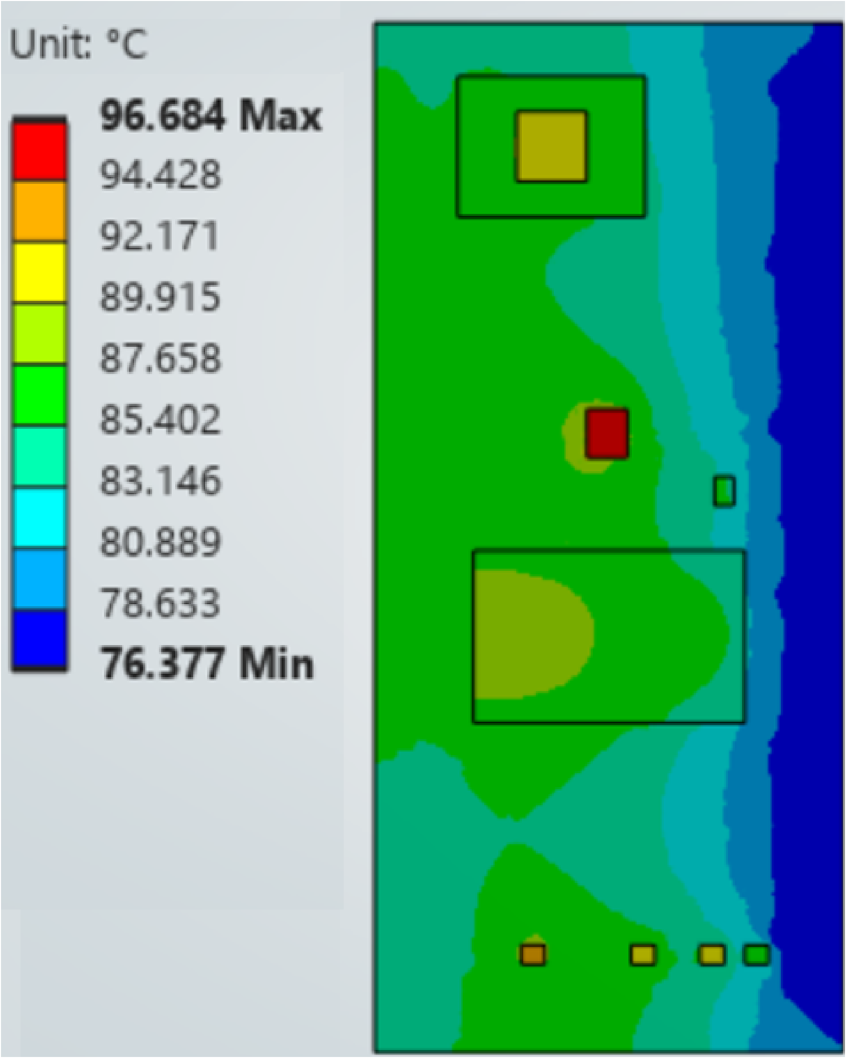
Trace Mapped

70 °C

0.15 GPM

$$265\ \frac{W}{m^2 - K}$$

With Boss



HKPM: Full Chassis Results

11 ℃ Margin added to all results

Trace Mapped PCB w/ Boss-extrusions

HKPM Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
U2	107.7	-27.6
U3	96.5	-39.4
U4	100.9	-33.7
U9 A-D	104	-30.8
J3	101.7	-33.3

Highlighted values violate component temperature limit.

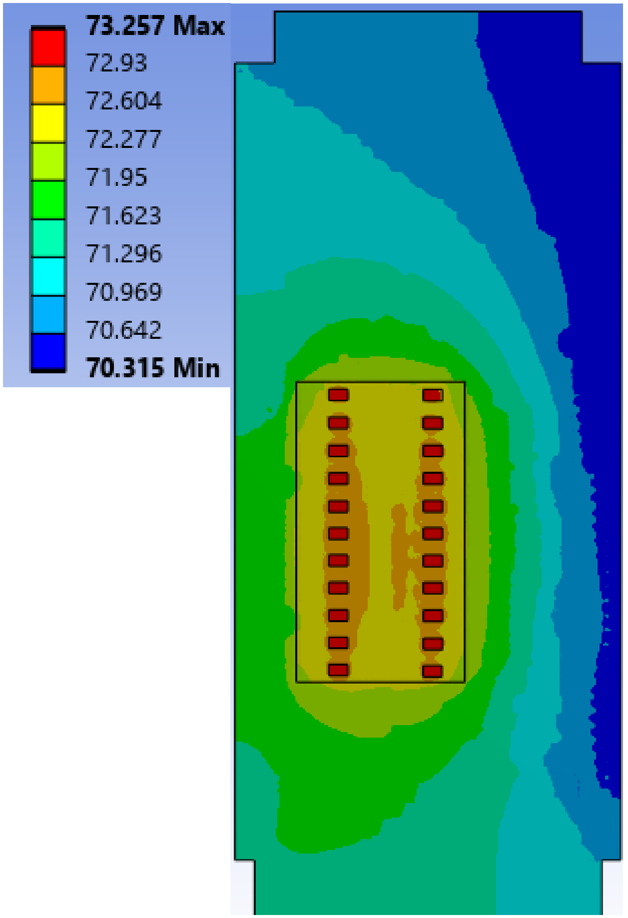
Black: Specification/Data Sheet Limits

Red: Derated Limits per EEE-INST-002

Component Designation	Part Number	Heat Load (W)	Min Temp (℃)	Max Temp (℃)
U2	TPS7A4501DCQR	1.00	-40	125 (93.75)
U3	LM73605-Q1	0.25	-40	150 (110)
U4	V110C12C100BL	9.44	-40	100 (80)
J3	LFD2NX-40-7BG256A	1.00	-40	125 (85)
U9 A-D	TPS274160B	0.45	-40	150 (110)

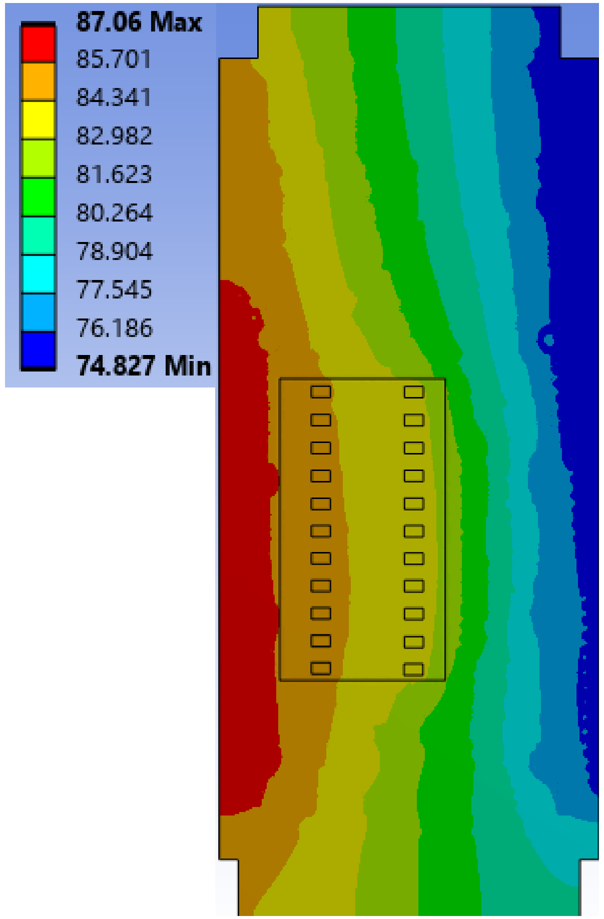
BSGM: FEA Results

Worst Hot



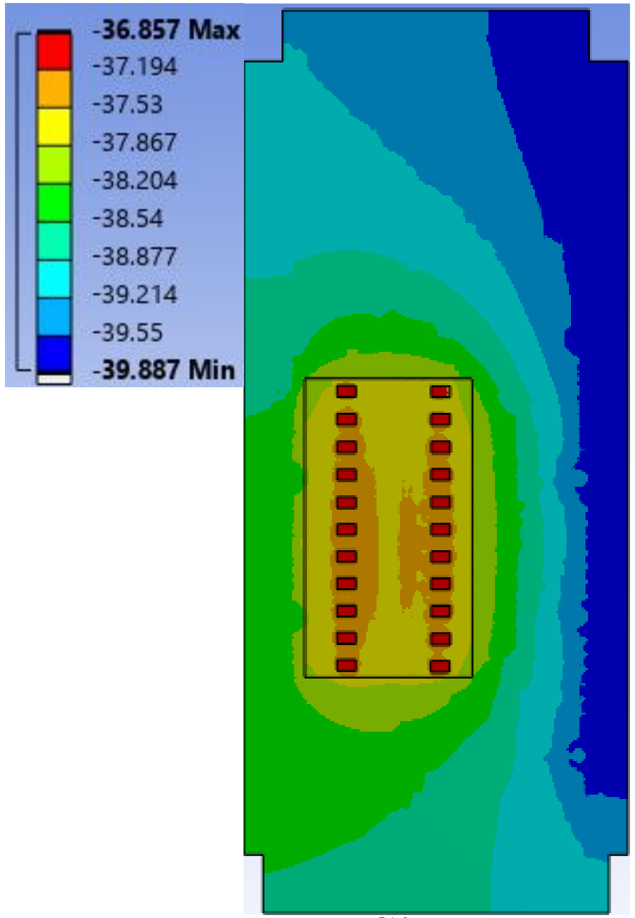
Single Module

Worst Hot



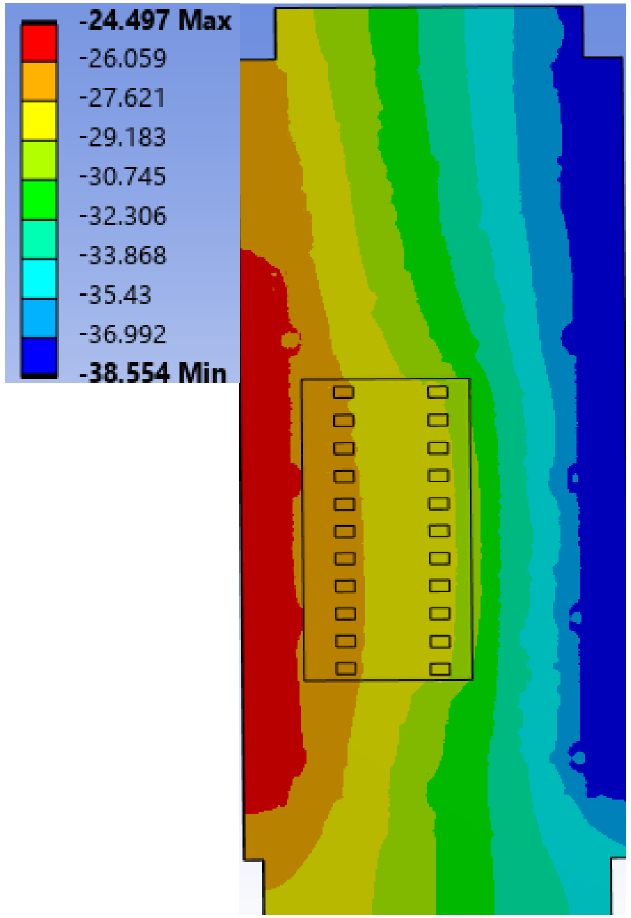
Full Chassis

Worst Cold



Single Module

Worst Cold



Full Chassis

*Nominal Loads Implemented

BSGM MOSFET Temperatures: Tabulated Results

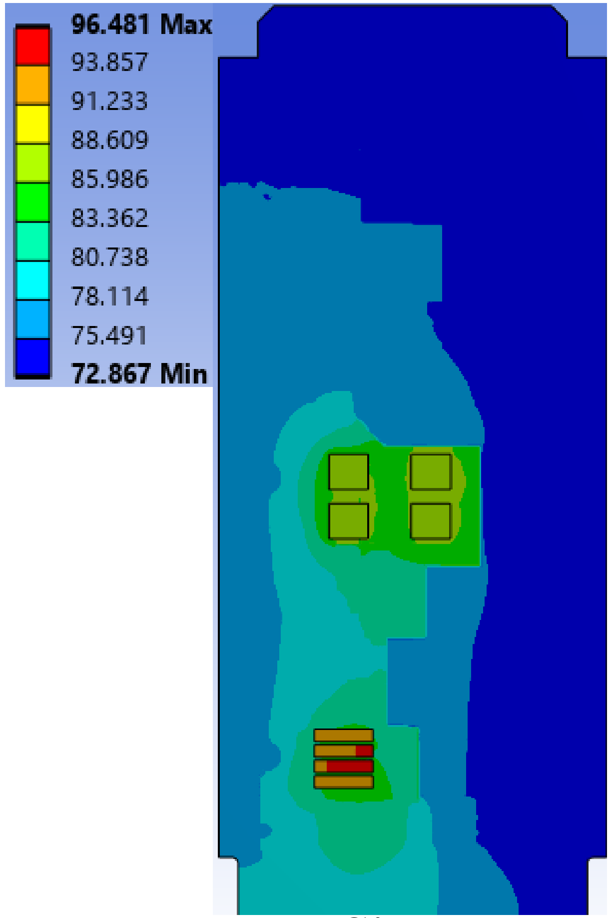
<u>11 ℃ Margin added to all results</u>

Scenario	Trace Heat Load (W)	Total Module Load (W)	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
Single Module	1.90	7.71	84.25	-48.49
Single Module	14.19	20.00	92.22	-41.80
Full Chassis	1.90	7.71	96.27	-40.51
Full Chassis	14.19	20.00	104.08	-34.08

- All cases had $\dot{Q}_{MOSFET} = 5.808\ W$
- Full Chassis: Empty Slots Have 20 W Load
- T_{max} = 150 ℃ (120 ℃)
- T_{min} = -55 ℃

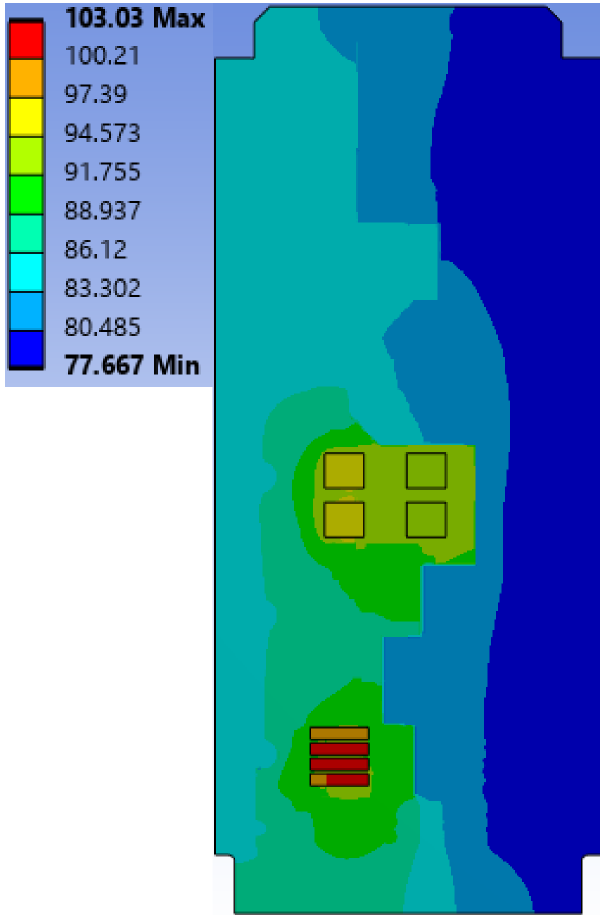
BDCM 1: FEA Results

Worst Hot



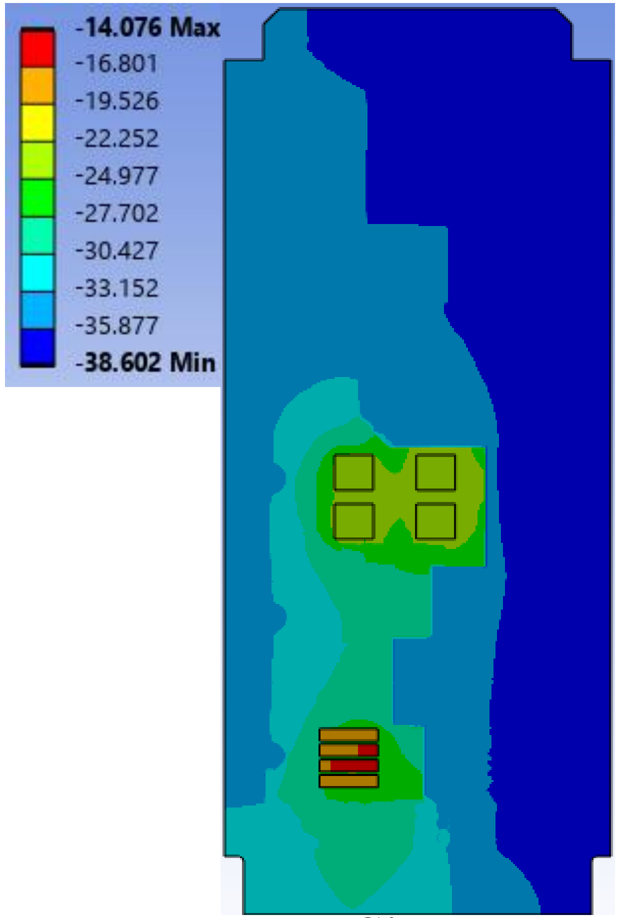
Single Module

Worst Hot



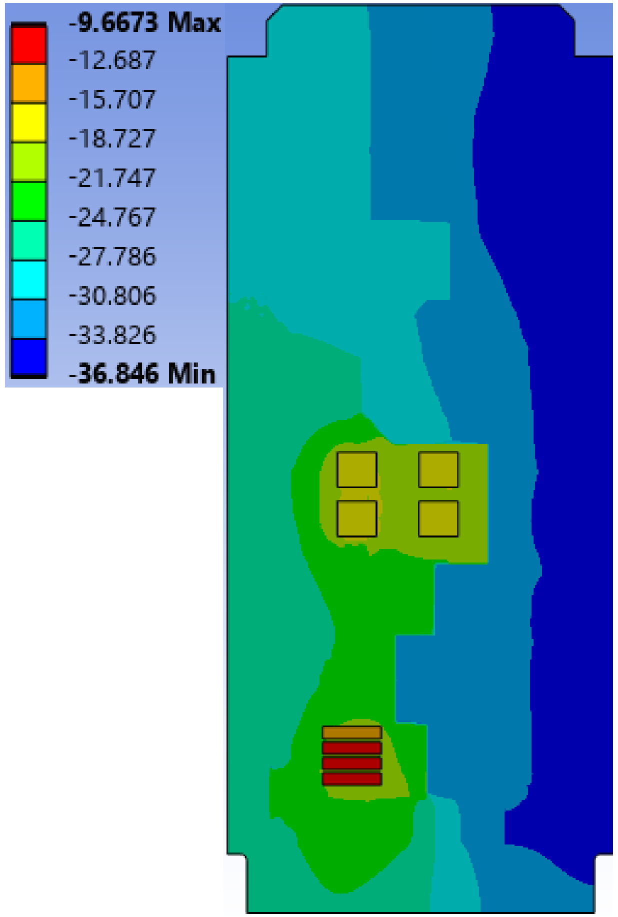
Full Chassis

Worst Cold



Single Module

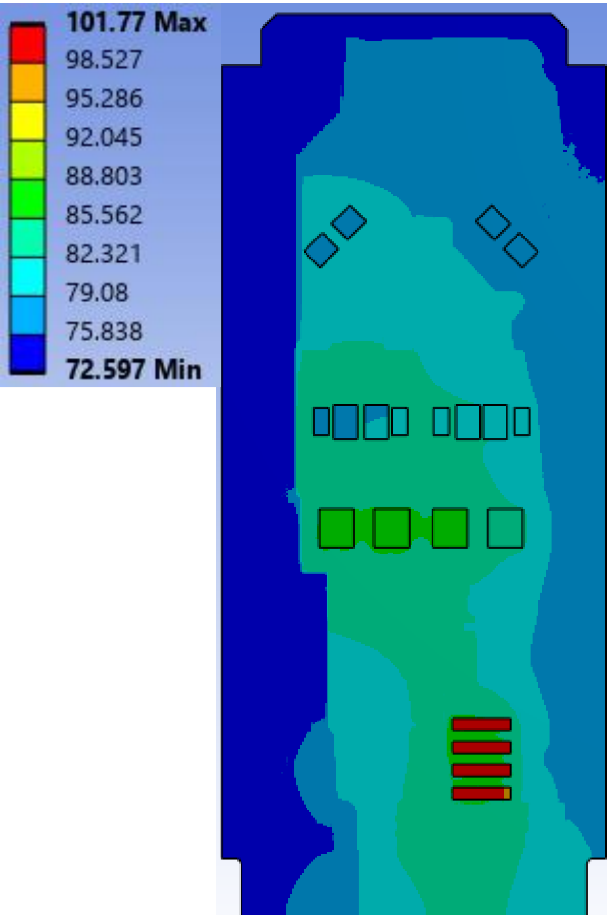
Worst Cold



Full Chassis

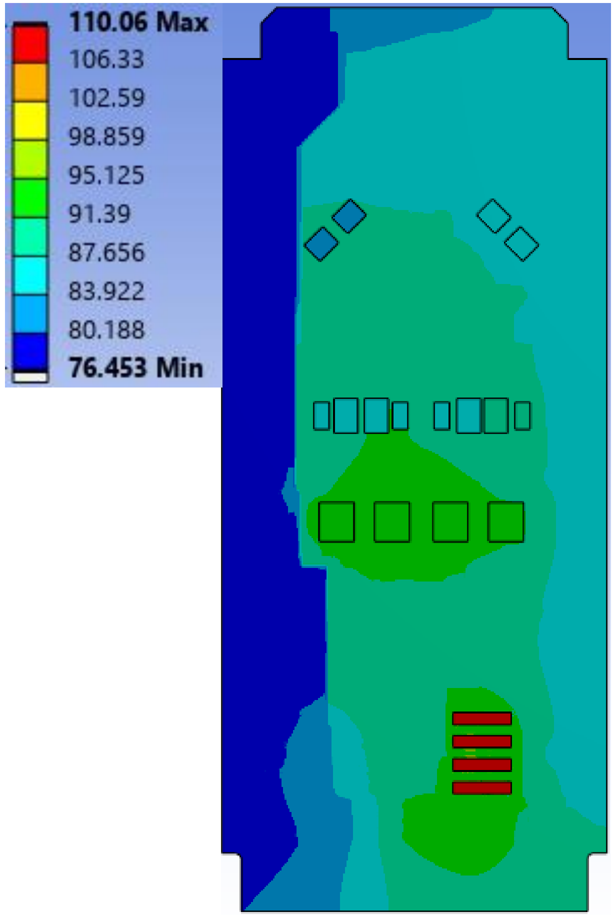
BDCM 2: FEA Results

Worst Hot



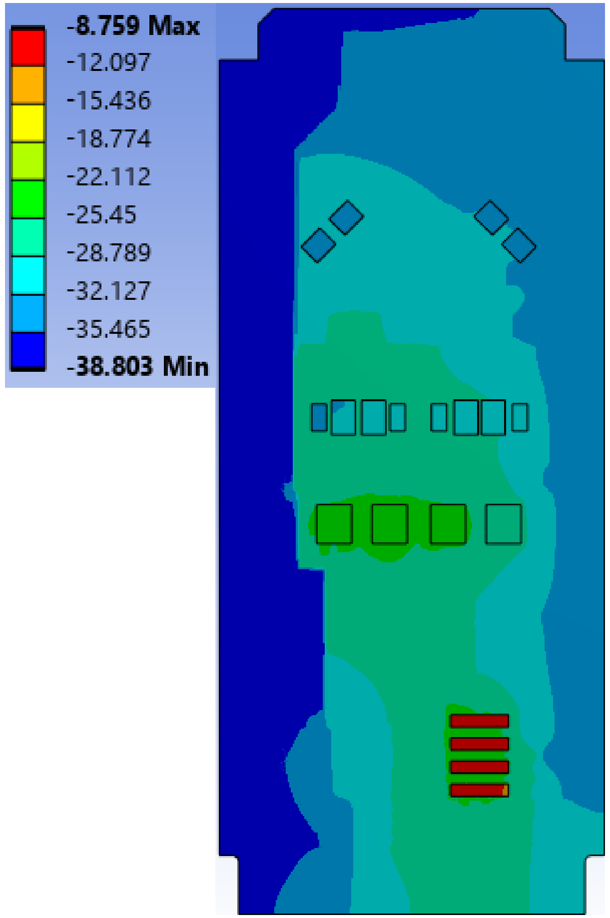
Single Module

Worst Hot



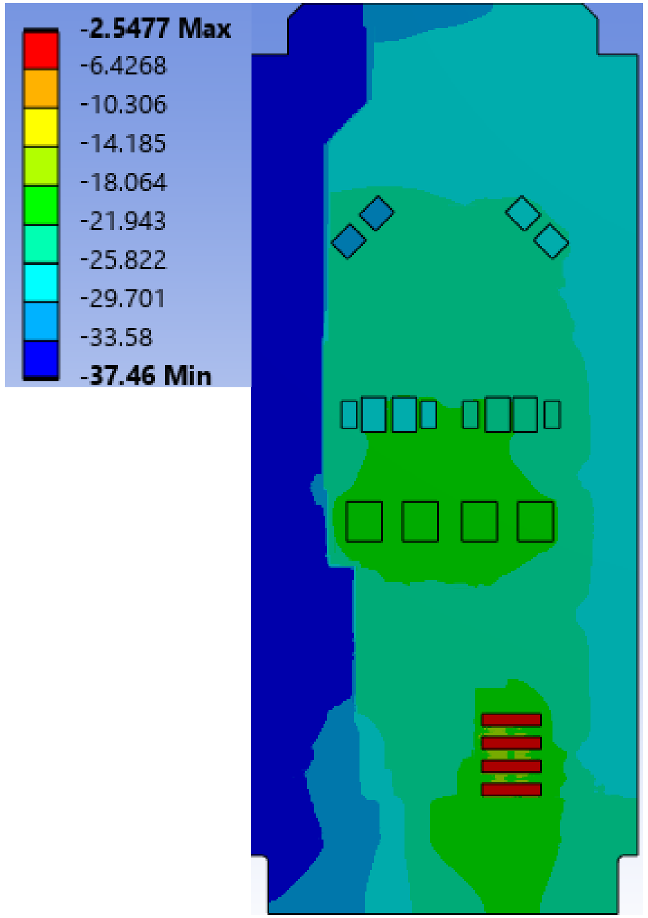
Full Chassis

Worst Cold



Single Module

Worst Cold



Full Chassis

All temperatures are in °C

****Resistors didn't have bosses**

BDCM 1: Full Chassis Results

<u>11 ℃ Margin added to all results</u>

BIDI Top Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
Q4 A-D	106.40	-29.69
Resistors*	114.03	-26.77
U2	95.05	-42.52**

***Resistors did not have a boss-extrusion in the models**
**** Temp. violation is a result of added margin past the sink temperature.**
Highlighted values violate component temperature limit.

Component Designation	Part Number	Number	Total Heat Load (W)	Min Temp (℃)	Max Temp(℃)
R106 - 109	RWR80SR100FRB12	4	2.5	-55	250 (125)
Q4 A-B	IXFA80N25X3	4	12 W	-55	150 (110)
U2	TPS7A4501DCQR	2	0.5	-40	125 (93.75)

BDCM 2: Full Chassis Results

11 °C Margin added to all results

BIDI Top Component	Hot Spot Temperature (°C), Case: Worst-Hot	Cold Spot Temperature (°C), Case: Worst-Cold
D34 A-B	100.79	-42.50
D56 A-B	104.69	-40.35
D78 A-B	105.02	-39.52
Q4 A-D	103.92	-31.59
Resistors*	121.06	-23.33
T1 A-B	104.74	-43.40**

*Resistors did not have a boss to them in the models.

** Temp. violation is a result of added margin past the sink temperature.

Highlighted values violate component temperature limit.

Component Designation	Part Number	Number	Total Heat Load (W)	Min Temp (°C)	Max Temp(°C)
R14-17, R106-109	RWR80SR100FRB12	8	5	-55	250 (125)
Q4A-B	IXFx80N25X3	4	12	-55	150 (110)
D34 A-B	ER5J-TP	4	1	-55	150 (110)
D56 A-B	1.5SMB30A	4	1	-65	150 (110)
D78 A-B	5.0SMDJ100A	4	2	-55	150 (110)
T1 A-B	P.N.501694	2	6	-40	130 (110)
L1 A-B	Custom	2	2	N/A	N/A

Results Summary

- Housekeeping Power Module (HKPM)
  - Use trace mapping for PCB models
  - Use boss-extrusions to effectively remove heat
  - Violating limits: U2, U4, J3
  - Inter-module heating should be considered in future designs
- Bus Switchgear Module (BSGM)
  - Not violating limits despite having high loads in component and traces
- Bi-directional Converter Module (BDCM)
  - Not violating limits

Next Steps

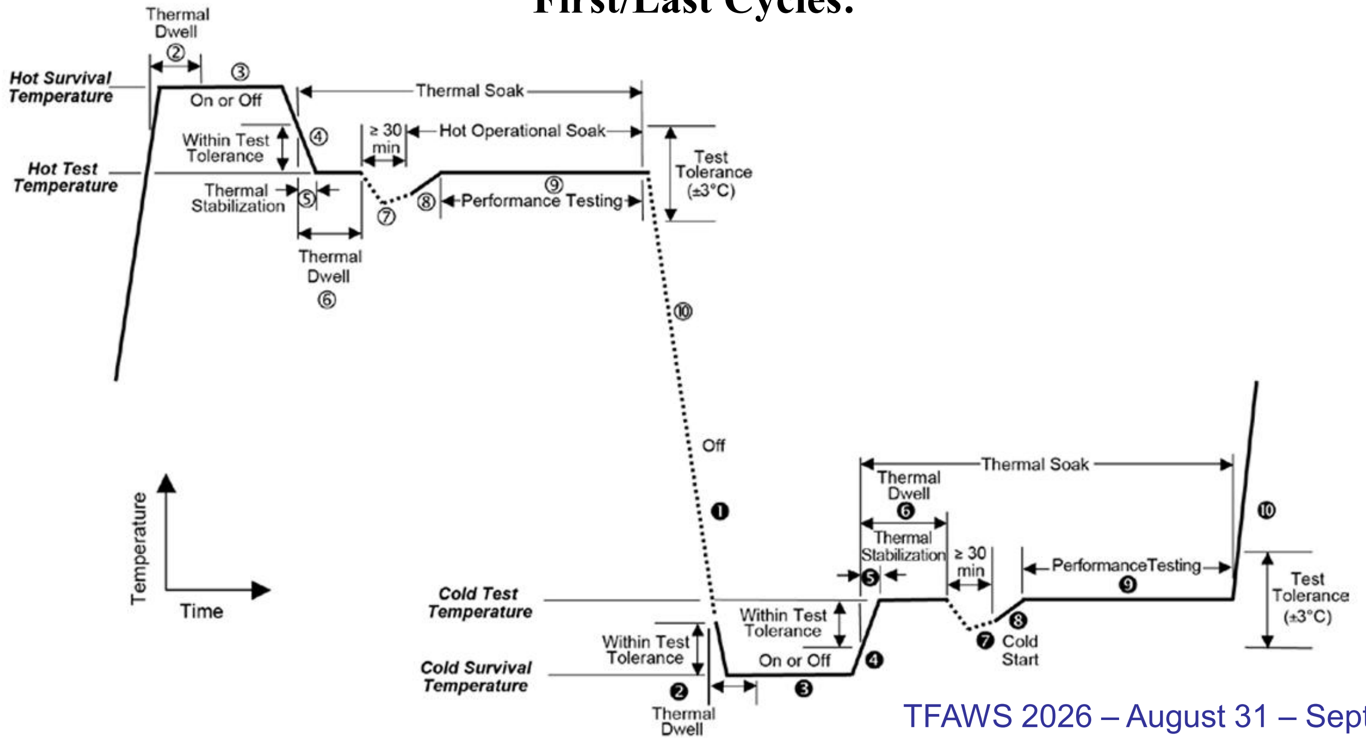
- Complete testing and extract data
  - Location: NASA Glenn Research Center
  - TVAC: VF-18
  - Vibe, Shock, EMI

- Continue design and analysis of next set of modules

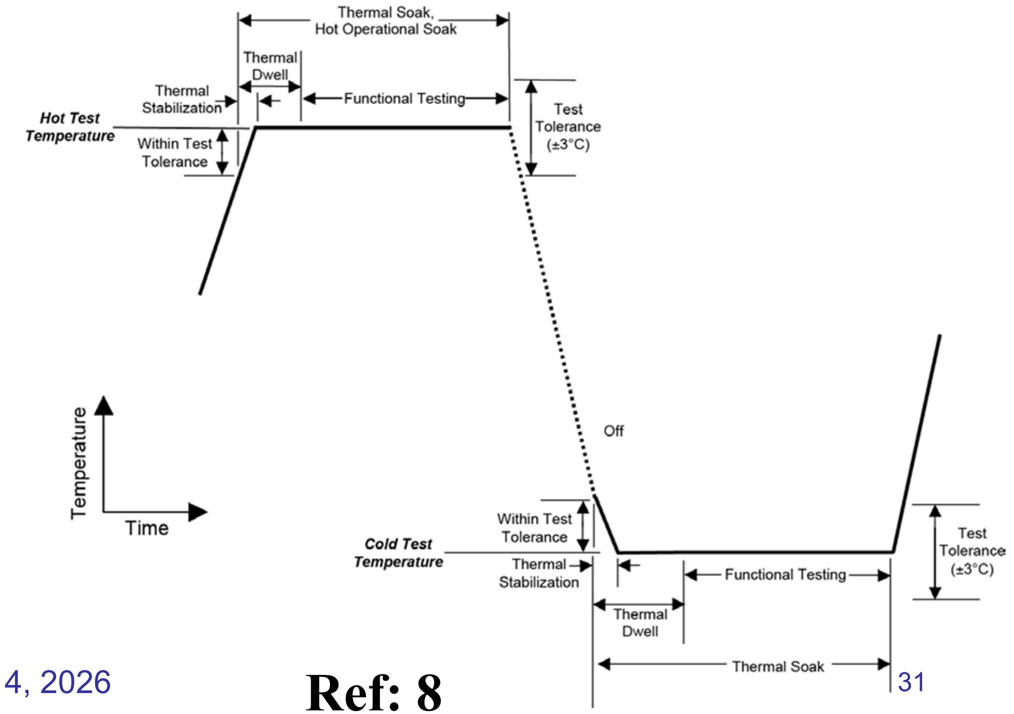
TVAC Plans

- Thermal-vacuum test: Take components to their physical thermal limits (max/min temps) as well as operational thermal limits as predicted by thermal modeling.
- The objective of TVAC is to stress components, bonds, solders, TIMs, etc. to age the connections, degrade the components, and characterize true thermal performance of the design.
- Must total at least 4 thermal cycles (hot/cold=1 cycle).
  - First + last cycles: system is off; take system to max/min survival temps.
  - Intermediate cycles: system is running; take system to max/min operating temps as predicted by previous modeling.

First/Last Cycles:



Intermediate Cycles:



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[2] A. Colozza, B. Burson, K. Bozak and B. Gardner, "Advanced Modular Power System Fully Populated Electronics Enclosure Thermal Testing," National Aeronautics and Space Administration (NASA), Cleveland, 2020. https://ntrs.nasa.gov/citations/20205000060

[3] B. G. Gardner, "Modular Standards for Space Power Systems," in International Aerospace Congress 2019, Washington, D.C., 2019. https://ntrs.nasa.gov/citations/20190032519

[4] K. Bozak, Y. De Jesus-Arce, J. Soeder, B. Gardner, J. Csank and K. Boomer, "Advanced Modular Power Systems (AMPS) Project 101," National Aeronautics and Space Administration, Cleveland, 2020. https://ntrs.nasa.gov/citations/20205004169

[5] A. J. Colozza and B. G. Gardner, "Advanced Modular Power System Electronics Enclosure Thermal Testing," National Aeronautics and Space Administration, Cleveland, 2019. https://ntrs.nasa.gov/citations/20190025222

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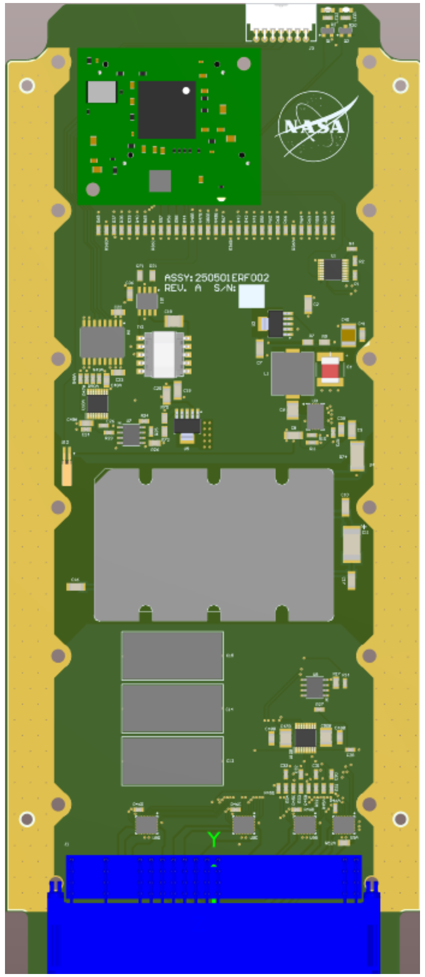
[7] Wakefield Thermal, “Friction Stir Welded Cold Plates Data Sheet,” [Online]. Available: https://wakefieldthermal.com/content/data_sheets/FSW-Cold-Plates_Wakefield-Thermal.pdf [Accessed 3 August 2026].

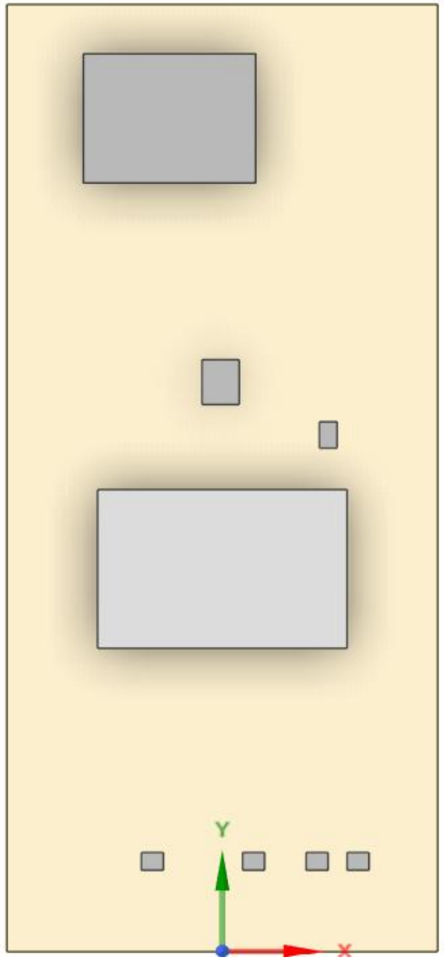
[8] Air Force Space Command, “Space and Missile Systems Center Standard. Test Requirements For Launch, Upper-Stage and Space Vehicles,” Air Force Space Command, 2014.

BACKUP

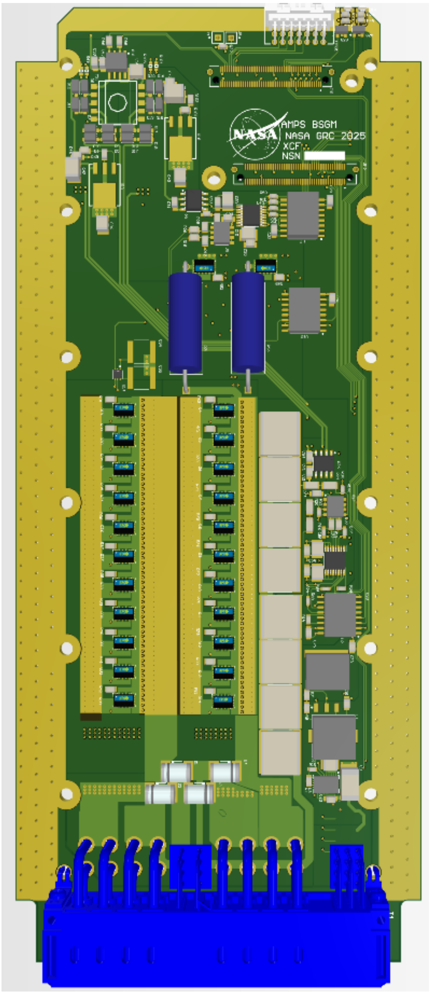
HKPM & BSGM Defeatured



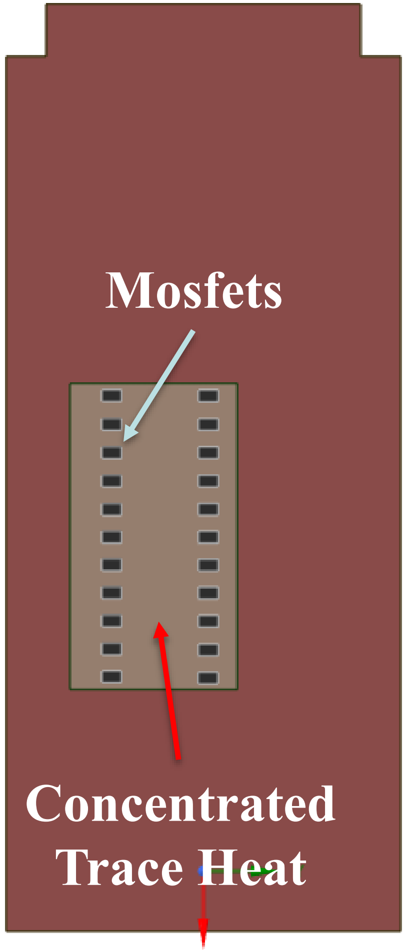
Housekeeping:
CAD Model



Housekeeping:
Defeatured



BSGM:
CAD Model

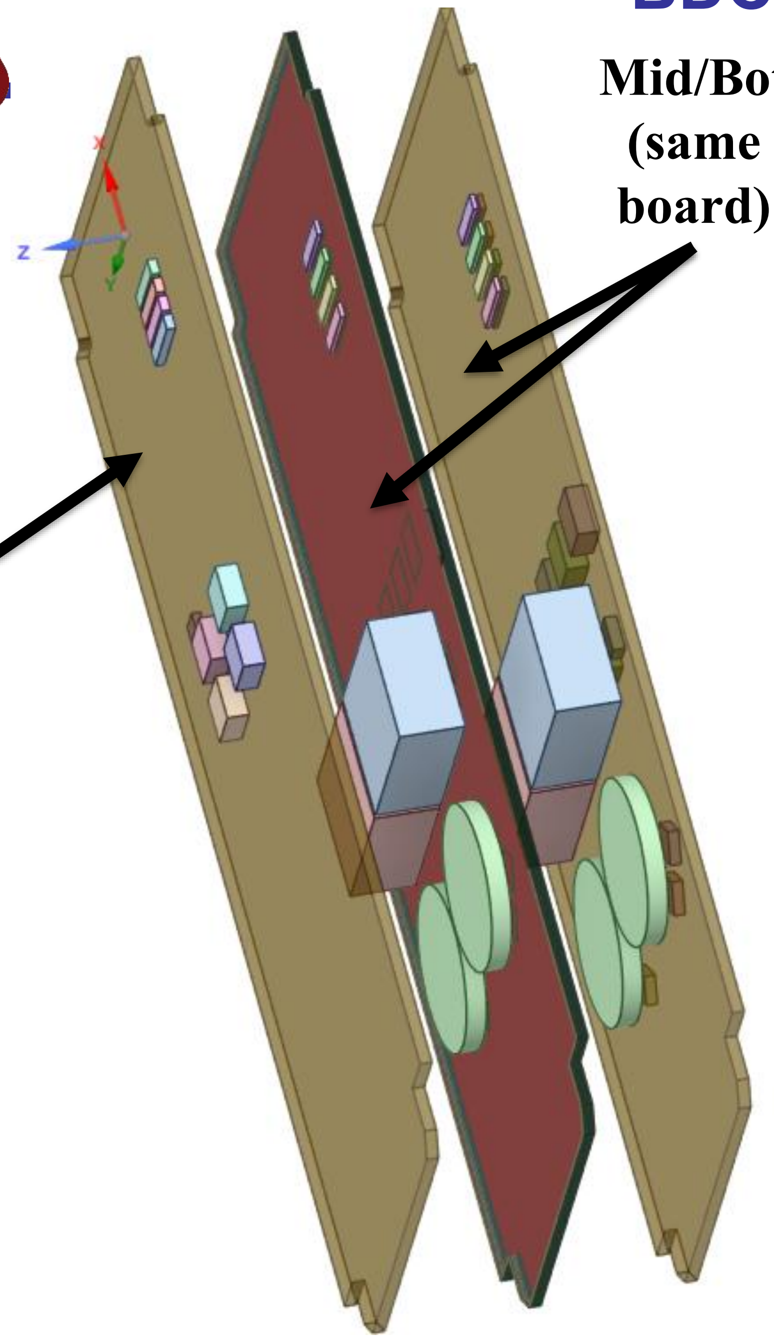


BSGM:
Defeatured

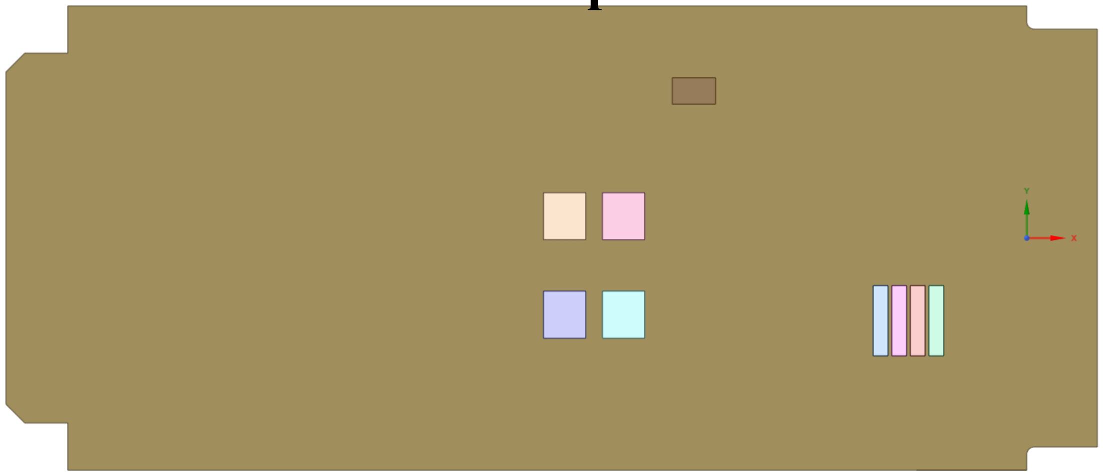
BDCM Boards - Defeatured

Mid/Bot (same board)

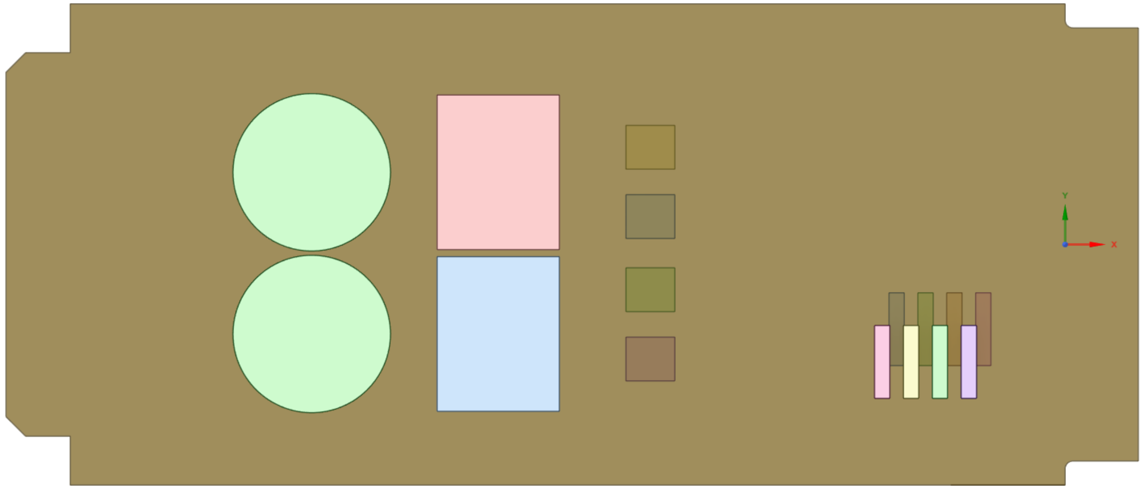
Top



Top

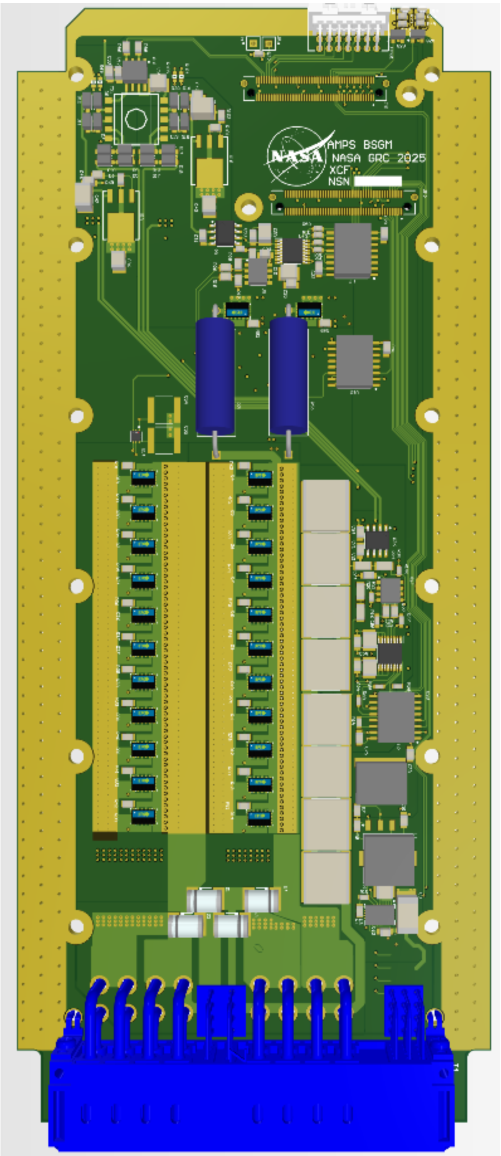


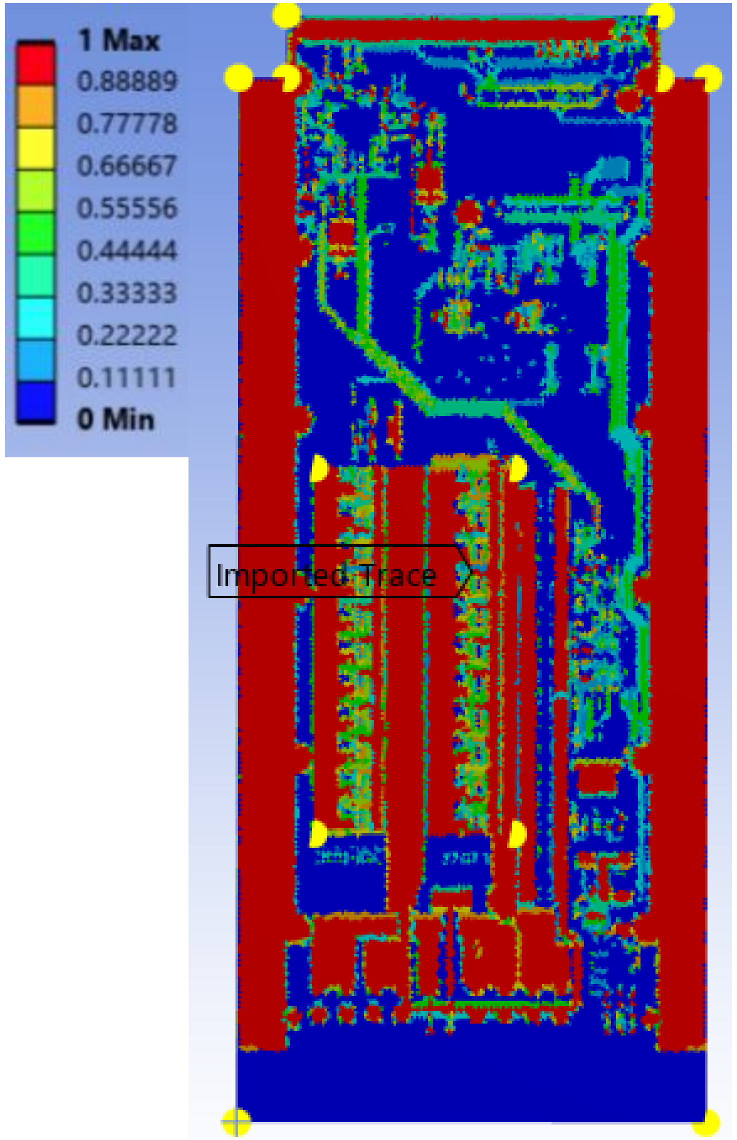
Mid/Bot



PCB Modeling: Trace Mapping

- Each layer of the PCB is modeled and meshed separately
- Each PCB is assigned FR-4 material properties
- Program assesses locations and replaces mesh elements with averages of copper and FR-4
- Thermal Vias and traces are modeled <u>on each layer</u>
  - More accurate than homogeneous modeling
  - Can get a better grasp of in-plane and through-plane heat transfer





HKPM: Full Chassis Results

11 ℃ Margin added to all results

Homogenous PCB w/ Boss

HKPM Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
U2	112.4	-22.9
U3	101.0	-34.8
U4	101.8	-32.7
U9 A-D	112.0	-22.9
J3	103.6	-31.5

Trace Mapped PCB w/ Boss

HKPM Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
U2	101.3	-31.8
U3	94.84	-41.1
U4	100.1	-34.7
U9 A-D	101.3	-33.6
J3	100.3	-34.8

BDCM 1: Single vs Full Chassis Results

11 ℃ Margin added to all results

BDCM 1 (Single)

BIDI Top Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
Q4 A-D	98.75	-34.69
Resistors*	107.13	-30.64
U2	89.55	-46.11

***Resistors did not have a boss to them in the models**

BDCM 1 (Full)

BIDI Top Component	Hot Spot Temperature (℃), Case: Worst-Hot	Cold Spot Temperature (℃), Case: Worst-Cold
Q4 A-D	106.40	-29.69
Resistors*	114.03	-26.77
U2	95.05	-42.52

BDCM 2: Single vs Full Chassis Results

11 °C Margin added to all results

BDCM 2 (Single)

BIDI Top Component	Hot Spot Temperature (°C), Case: Worst-Hot	Cold Spot Temperature (°C), Case: Worst-Cold
D34 A-B	92.88	-45.79
D56 A-B	97.19	-43.64
D78 A-B	97.40	-43.17
Q4 A-D	97.59	-37.64
Resistors*	112.77	-29.91
T1 A-B	96.99	-46.05

BDCM 2 (Full)

BIDI Top Component	Hot Spot Temperature (°C), Case: Worst-Hot	Cold Spot Temperature (°C), Case: Worst-Cold
D34 A-B	100.79	-42.50
D56 A-B	104.69	-40.35
D78 A-B	105.02	-39.52
Q4 A-D	103.92	-31.59
Resistors*	121.06	-23.33
T1 A-B	104.74	-43.40

***Resistors did not have a boss to them in the models**