412th Test Wing

War-Winning Capabilities … On Time, On Cost

U.S. AIR FORCE

Digital Model Thermal Engineering Validation

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- Receiver Simulation Tool
- KC-46 ARASQ
- 419th Bombers B-52H

Overview

- Need for Digital Models for Thermal Analyses
- Problem Statement
- LRU Overview
- Thermal Chamber Testing
- Analysis Breakdown
- Blended Approach of FEA & Hand Calculation
- Successes, Benefits, & Future Work

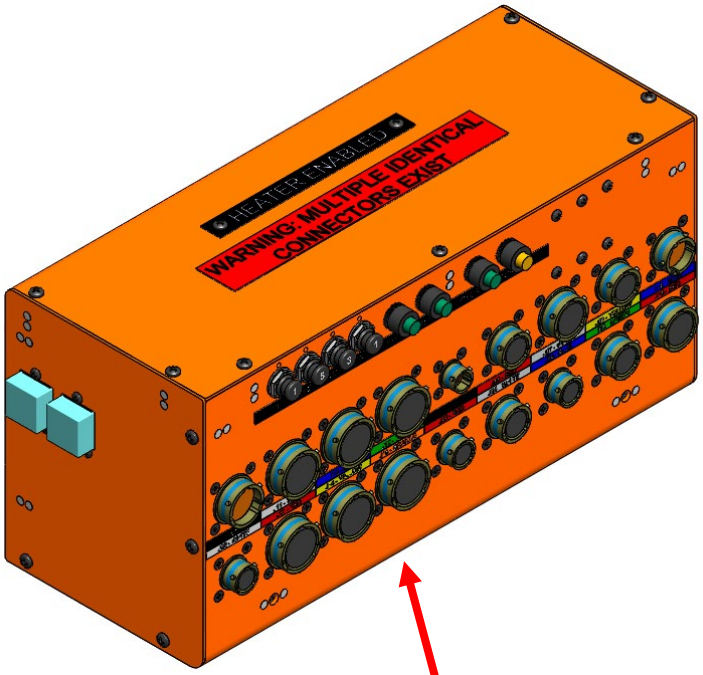
Need for Digital Models for Thermal Analyses

- More Line Replaceable Units (LRUs) are being fabricated with newer, updated technology as instrumentation requirements scope increase.
- Data Acquisition Systems (DAS) require to be maintained within an operating temperature range to complete missions.
- These DAS can generate enough heat in certain environments to increase temperature past its operating limits.
- Current methods include to test the LRU after it is fabricated to determine the operating temperature.

Problem Statement

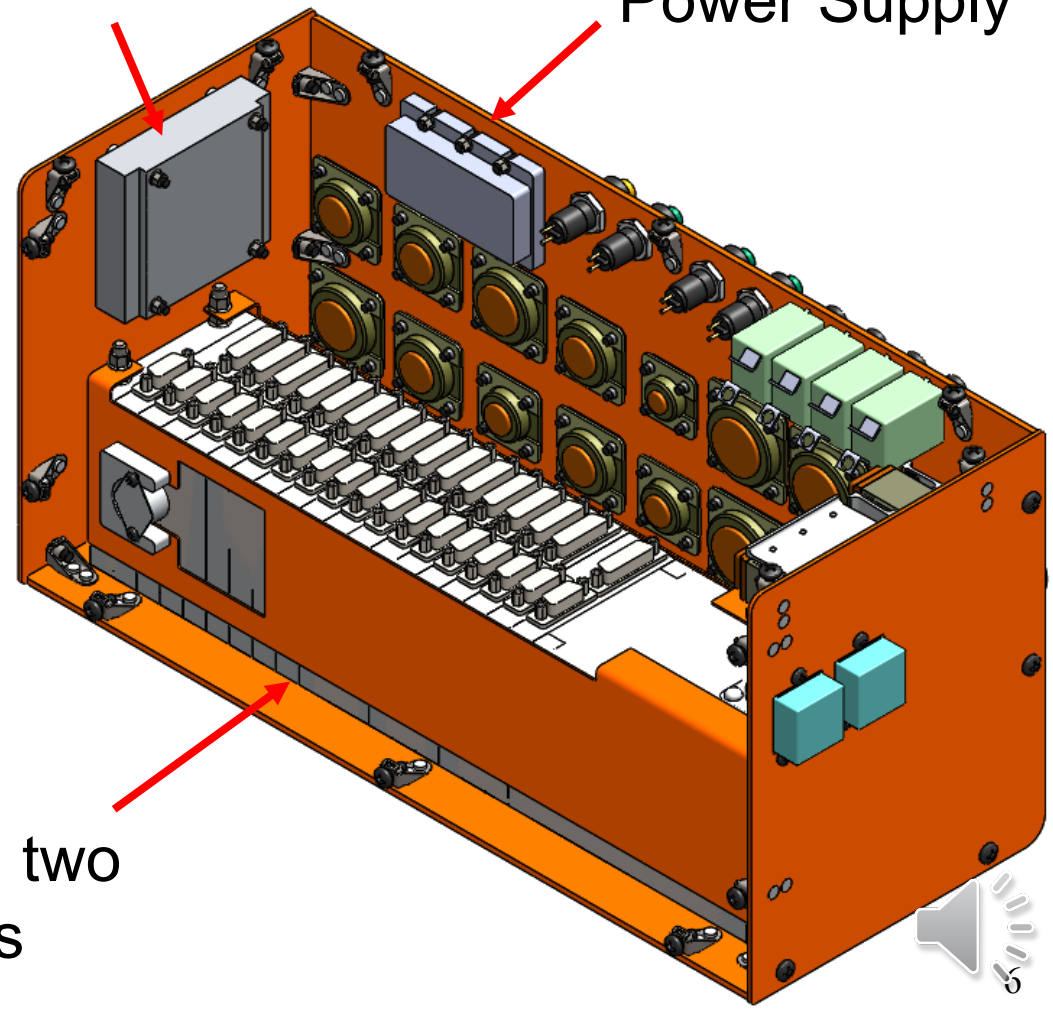
- Given the total power input and overall efficiency (heat generated), the LRU material properties and dimensions, find the final steady-state operating temperature of components in the LRU at certain ambient temperatures.

LRU Overview



Thermal Reference Junction

Power Supply



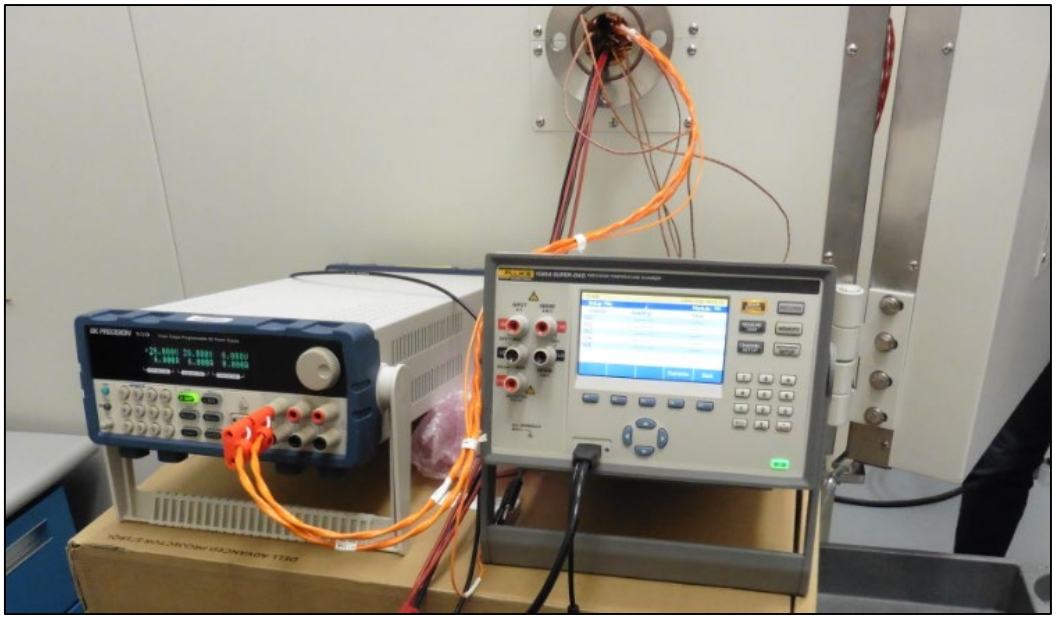
Connectors, LEDs, Circuit Breakers

DAS equipped with two thermostat switches

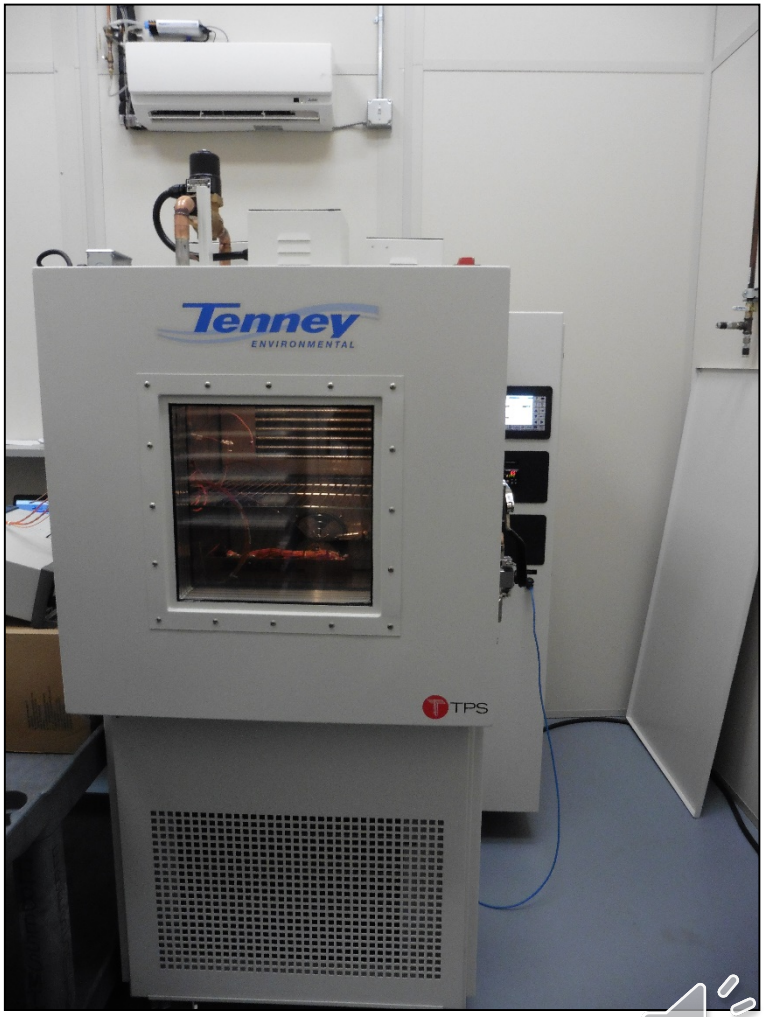
Thermal Chamber Testing

Power Supply (left)

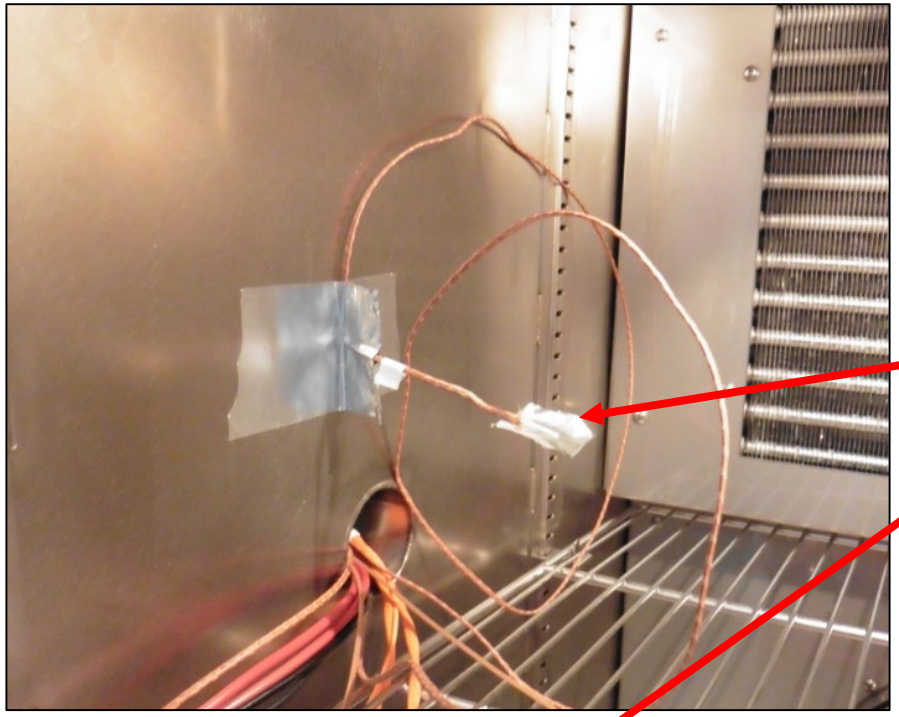
Fluke Precision Temp Scanner (right)



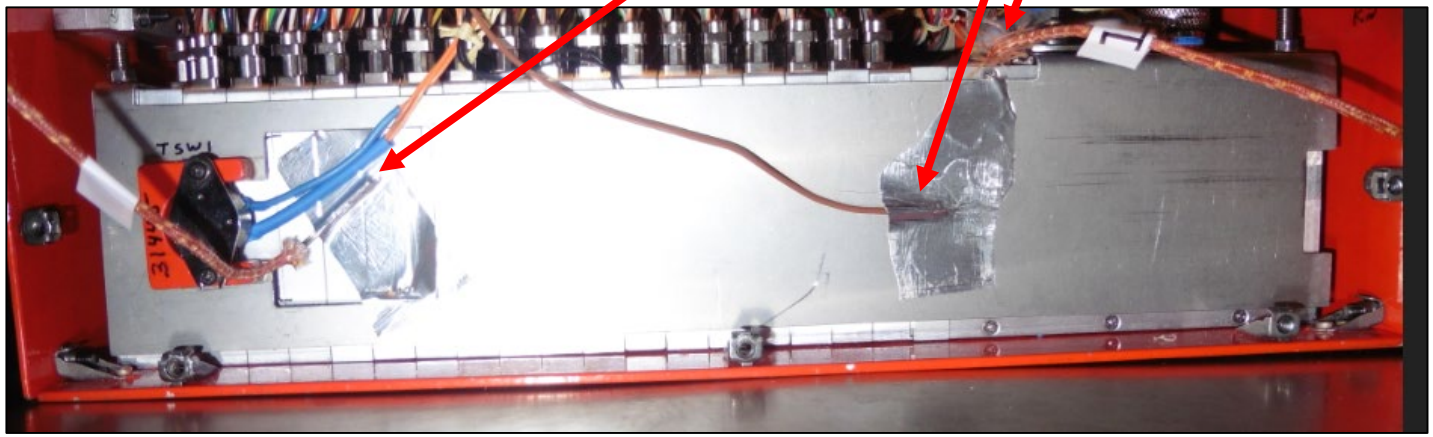
Tenney Environmental Chamber



Thermal Chamber Testing



Thermocouples



Analysis Breakdown

Conduction

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \quad \text{(W)}$$ 1-D

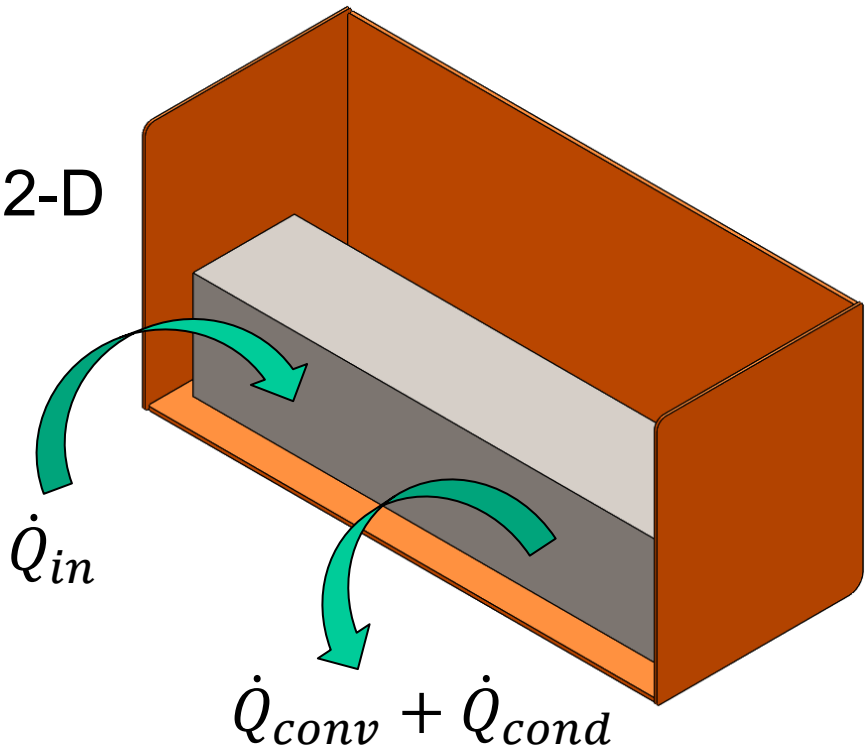
$$\frac{T_{m-1,n} - 2T_{m,n} + T_{m+1,n}}{\Delta x^2} + \frac{T_{m,n-1} - 2T_{m,n} + T_{m,n+1}}{\Delta y^2} + \frac{\dot{e}_{m,n}}{k} = 0$$ 2-D

Convection

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \quad \text{(W)}$$

$$\text{Nu} = \frac{hL_c}{k} = C(\text{Gr}_L\,\text{Pr})^n = C\,\text{Ra}_L^n$$

$$\text{Ra}_L = \text{Gr}_L\,\text{Pr} = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}\text{Pr}$$

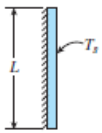
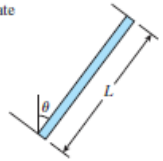
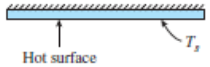
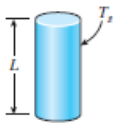
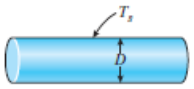
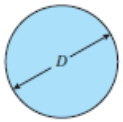


- Reference – Cengle, Yunus. *Heat and Mass Transfer: Fundamentals and Applications*.

Analysis Breakdown

TABLE 9–1

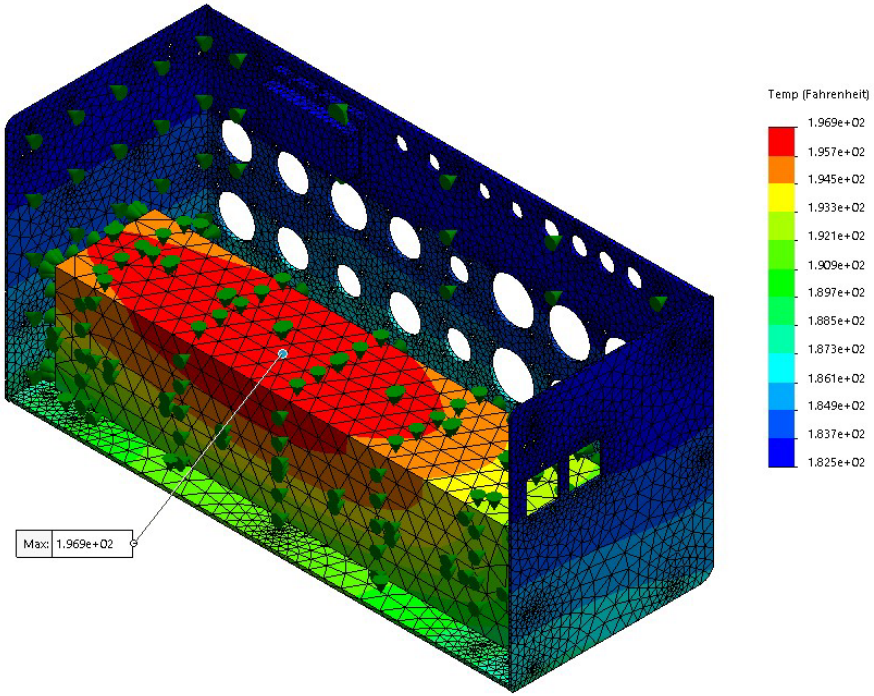
Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu
Vertical plate 	L	10^4–10^9 10^{10}–10^{13} Entire range	$\mathrm{Nu} = 0.59\mathrm{Ra}_L^{1/4}$ (9–19) $\mathrm{Nu} = 0.1\mathrm{Ra}_L^{1/3}$ (9–20) $\mathrm{Nu} = \left\{0.825 + \frac{0.387\mathrm{Ra}_L^{1/6}}{[1 + (0.492/\mathrm{Pr})^{9/16}]^{8/27}}\right\}^2$ (9–21) (complex but more accurate)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g\cos\theta$ for $0 < \theta < 60°$
Horizontal plate (Surface area A and perimeter p) (a) Upper surface of a hot plate (or lower surface of a cold plate) (b) Lower surface of a hot plate (or upper surface of a cold plate) 	A_s/p	10^4–10^7 10^7–10^{11} 10^5–10^{11}	$\mathrm{Nu} = 0.59\mathrm{Ra}_L^{1/4}$ (9–22) $\mathrm{Nu} = 0.1\mathrm{Ra}_L^{1/3}$ (9–23) $\mathrm{Nu} = 0.27\mathrm{Ra}_L^{1/4}$ (9–24)
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{\mathrm{Gr}_L^{1/4}}$
Horizontal cylinder 	D	$\mathrm{Ra}_D \leq 10^{12}$	$\mathrm{Nu} = \left\{0.6 + \frac{0.387\mathrm{Ra}_D^{1/6}}{[1 + (0.559/\mathrm{Pr})^{9/16}]^{8/27}}\right\}^2$ (9–25)
Sphere 	D	$\mathrm{Ra}_D \leq 10^{11}$ ($\mathrm{Pr} \geq 0.7$)	$\mathrm{Nu} = 2 + \frac{0.589\mathrm{Ra}_D^{1/4}}{[1 + (0.469/\mathrm{Pr})^{9/16}]^{4/9}}$ (9–26)

Range of Ra	Nu
10^4–10^9	$\mathrm{Nu} = 0.59\mathrm{Ra}_L^{1/4}$
10^{10}–10^{13}	$\mathrm{Nu} = 0.1\mathrm{Ra}_L^{1/3}$

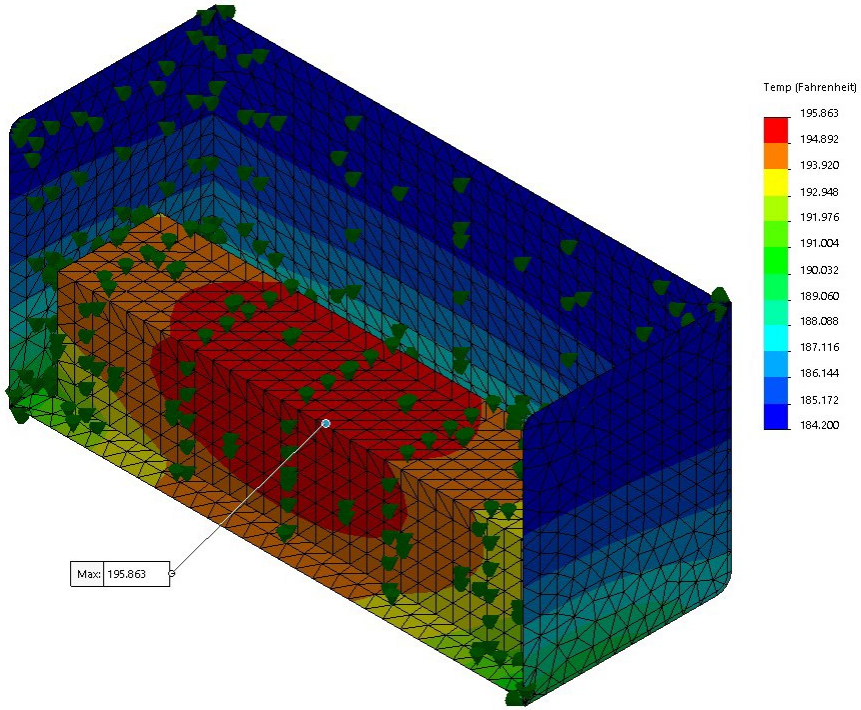
$$\mathrm{Nu} = C\,\mathrm{Ra}_L^n$$

Blended Approach of FEA and Hand Calculation



SolidWorks Simulation

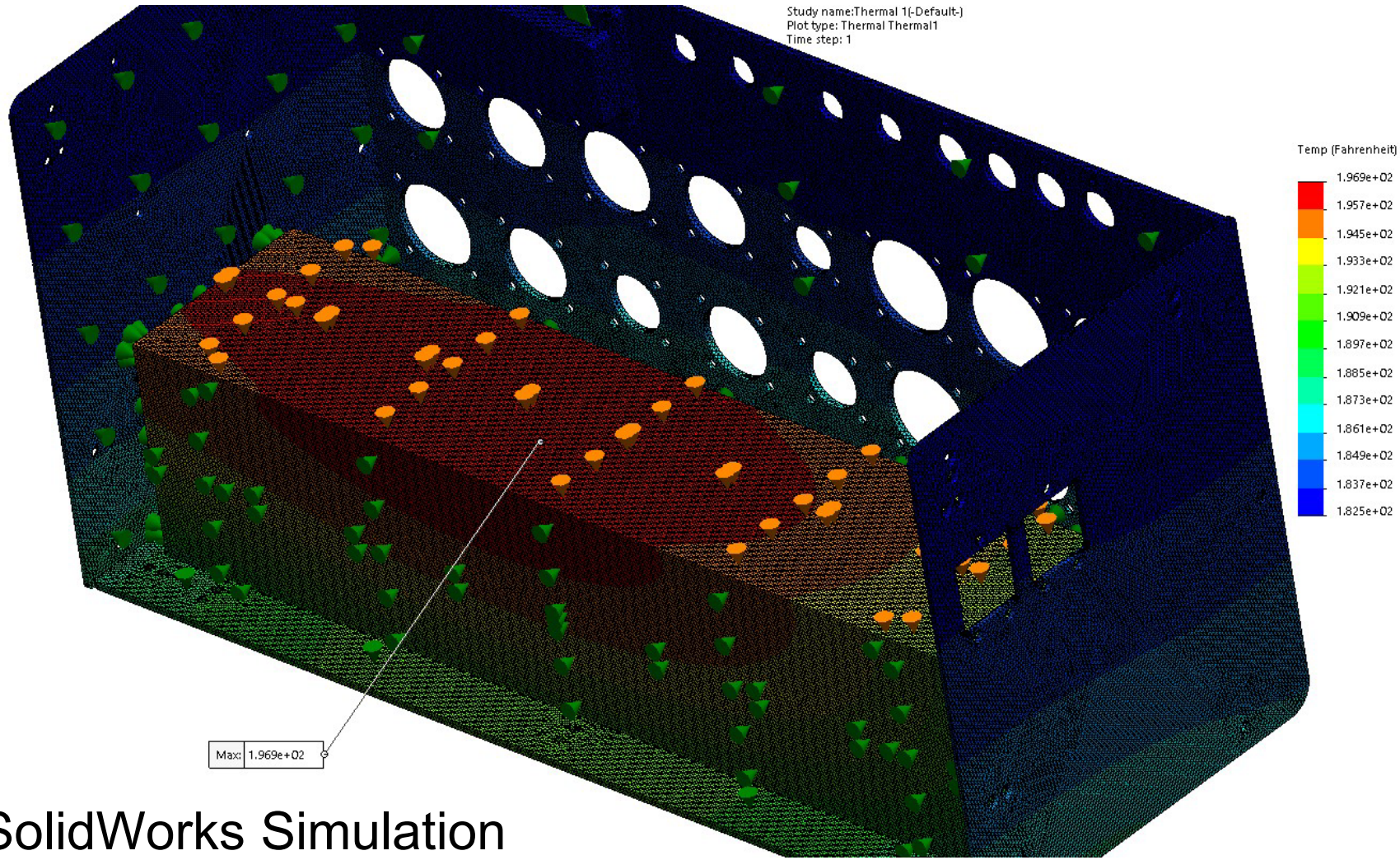
Tri-elements, curvature-based mesh



SolidWorks Simulation

Combination of Shell-elements and Tri-elements, standard mesh

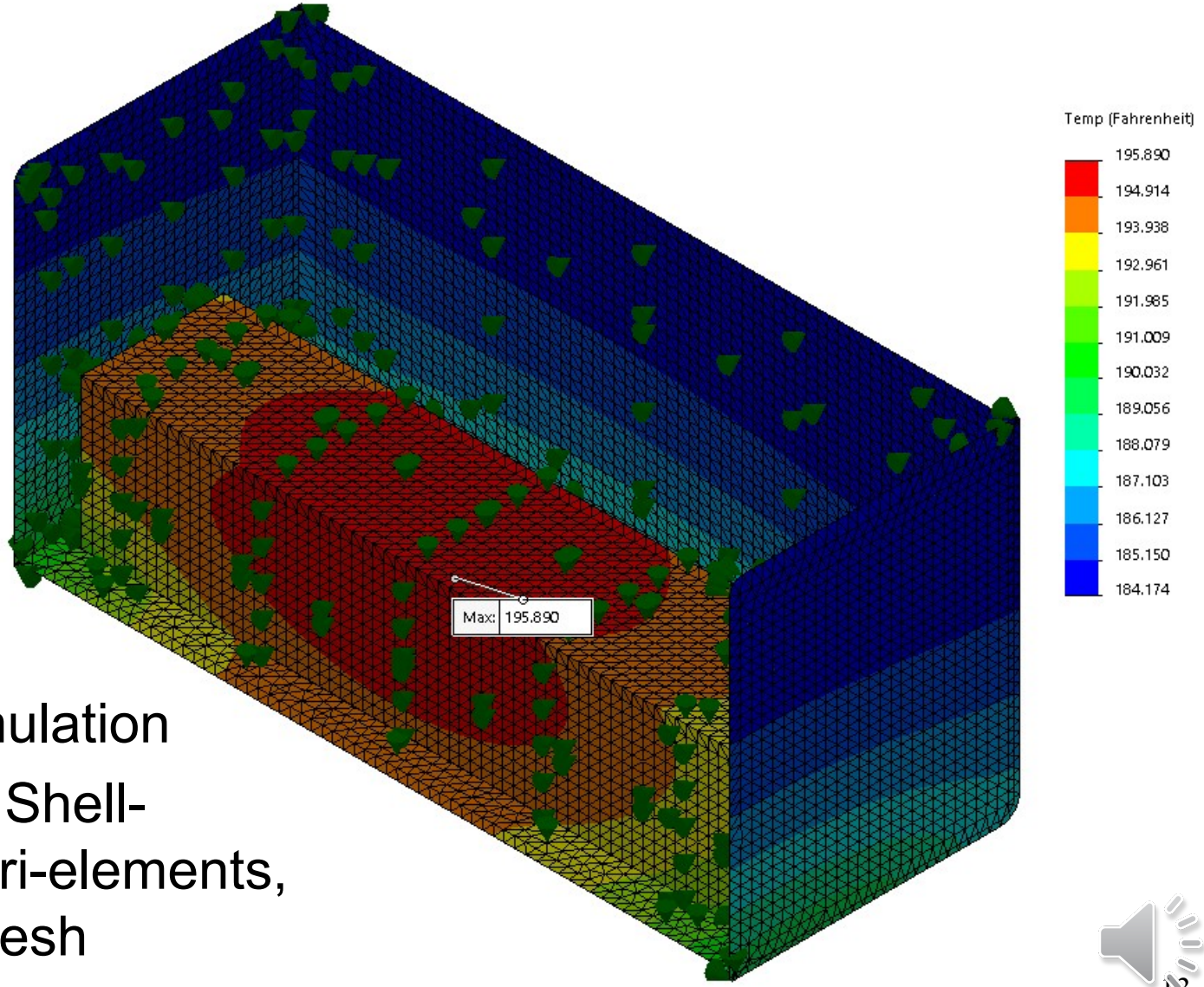
Blended Approach of FEA and Hand Calculation



SolidWorks Simulation

Tri-elements, curvature-based fine mesh

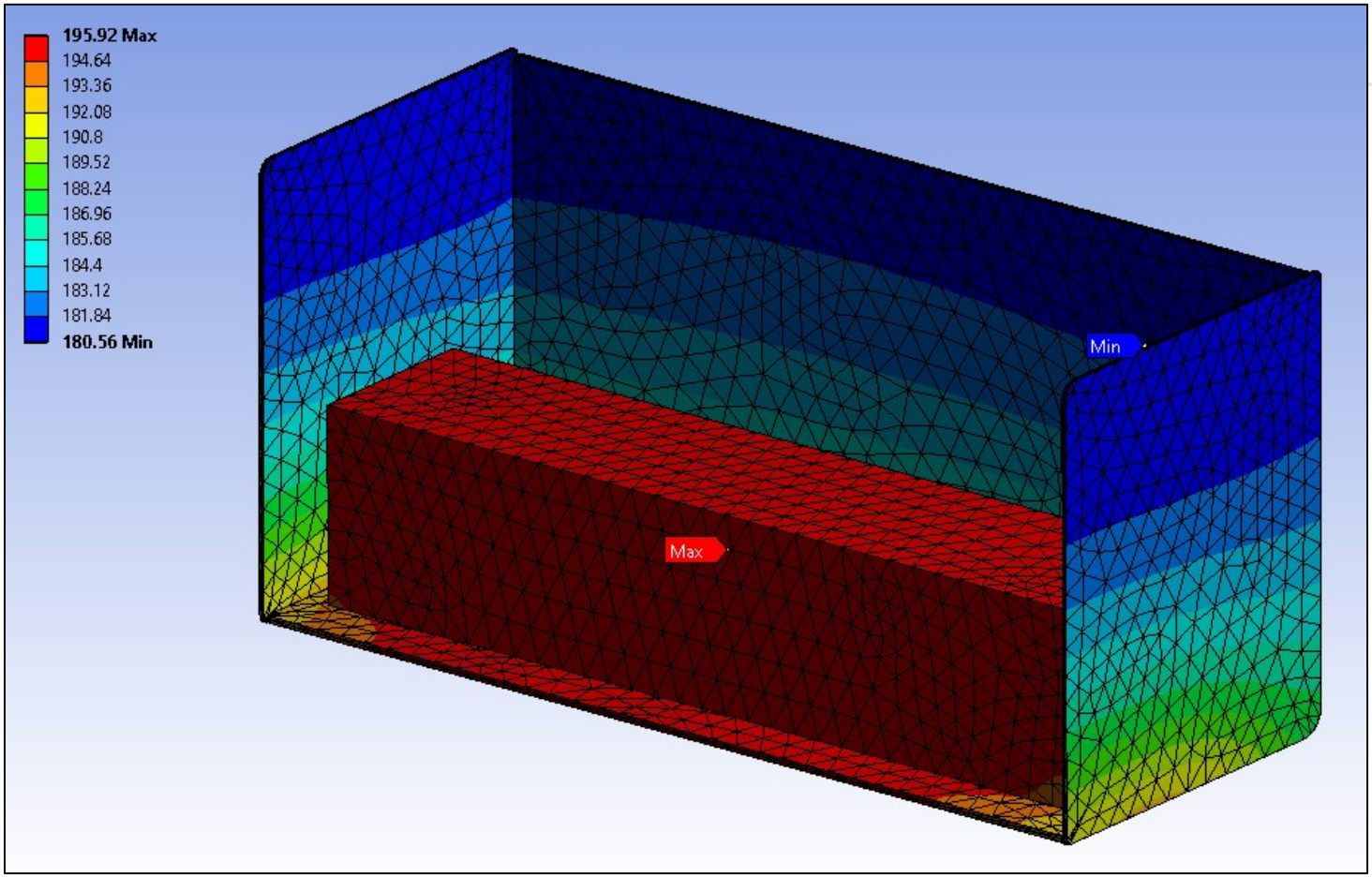
Blended Approach of FEA and Hand Calculation



SolidWorks Simulation

Combination of Shell-elements and Tri-elements, standard fine mesh

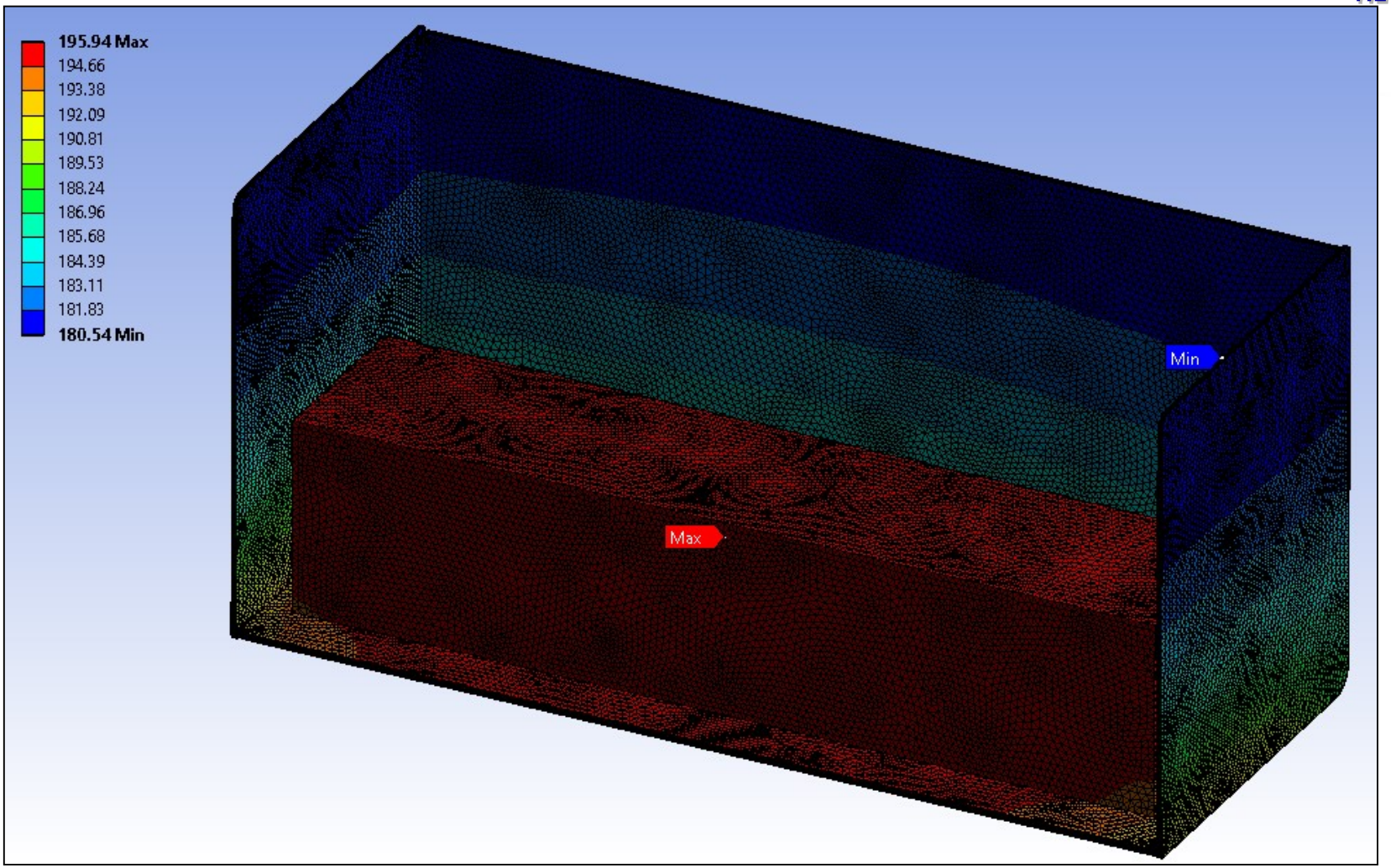
Blended Approach of FEA and Hand Calculation



ANSYS Mechanical

Tri-elements, curvature-based mesh

Blended Approach of FEA and Hand Calculation



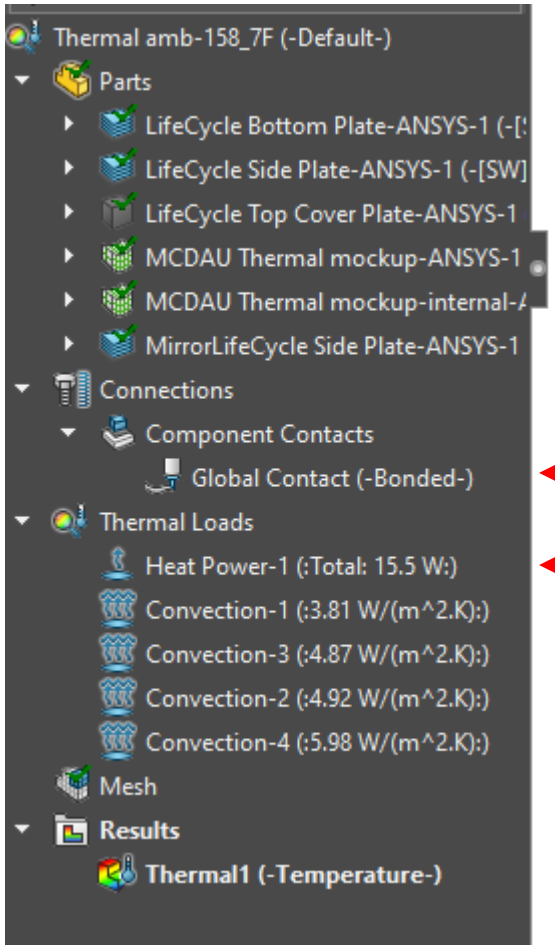
ANSYS Mechanical

Tri-elements, curvature-based fine mesh

Blended Approach of FEA and Hand Calculation

- The results from each model at different sized mesh are within +/- 1% max temperature from each other.
- The model with least amount of elements and fastest solving speed was chosen as the base model for the analysis.
  - SolidWorks Simulation, Tri & Shell element, standard mesh

Blended Approach of FEA and Hand Calculation



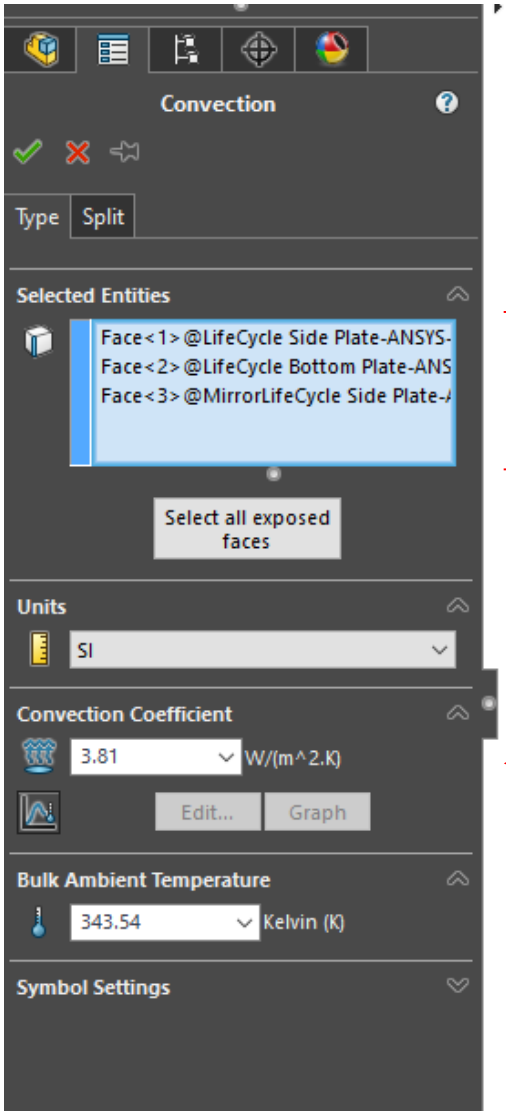
Define parts and material composition

Assuming Globally Bonded Contact

Given Heat Generated

Convection thermal loading

Blended Approach of FEA and Hand Calculation

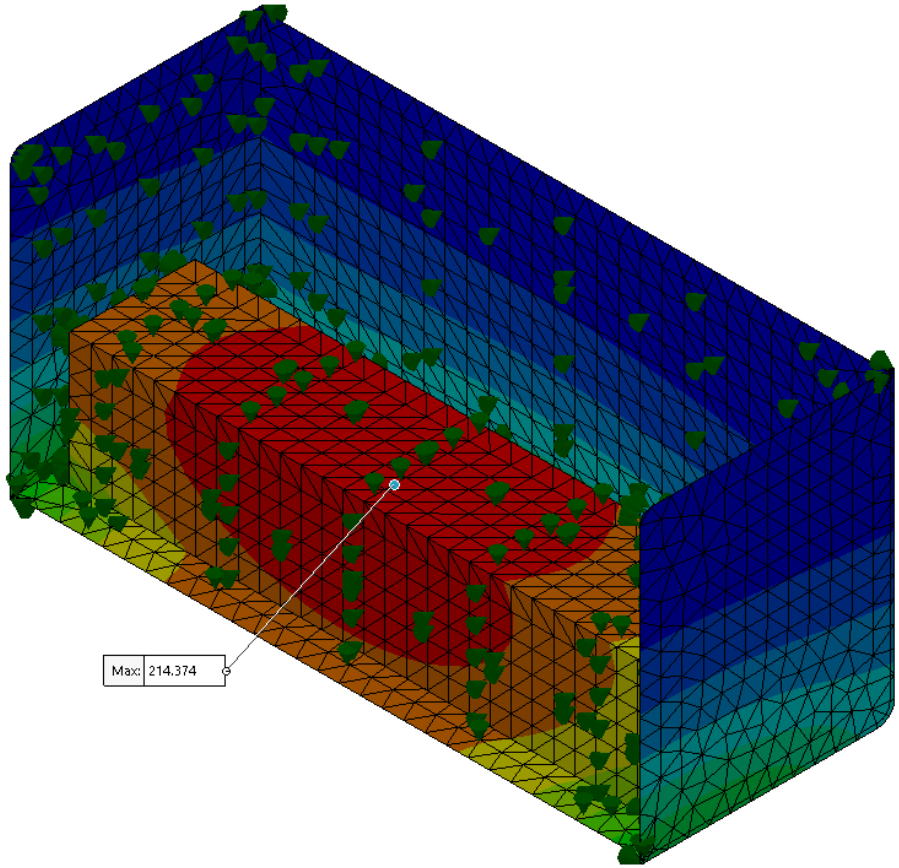


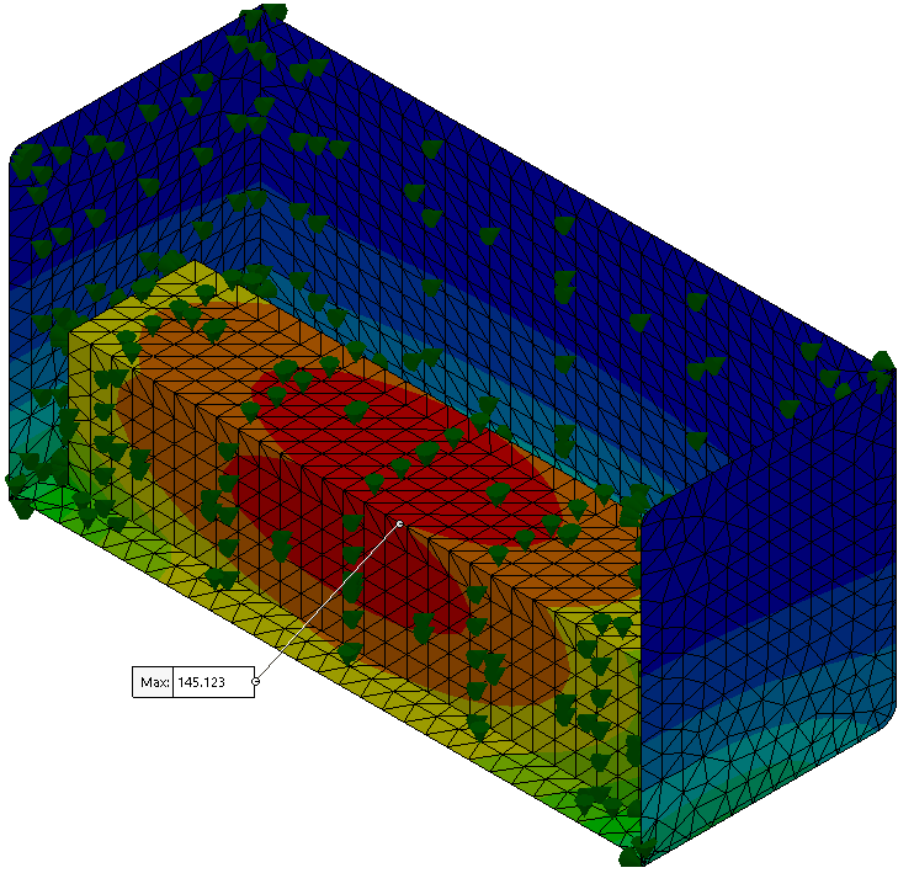
Applicable faces subjected to convection

Convection Heat Transfer Coefficient, range from 2 – 25 W/(m^2 K) for gases

Given Ambient Temperature

Blended Approach of FEA and Hand Calculation





h = 2.0 W/(m^2 K)

Max temp = 214°F

h = 25 W/(m^2 K)

Max temp = 145°F

Blended Approach of FEA and Hand Calculation

- Begin refining the convection coefficient by using the plate midpoint temperature $T_{L/2}$ for T_s in the evaluation of the film temperature.
  - Used to get the thermal properties of air from a table.
- Using the equations for Nusselt Number, Grashof Number and so forth, determine h.
- Repeat this process for each face with different temperatures and orientation.
- Rerun the analysis for these new values of h, and repeat this process until the temperatures on the applied convection surfaces no longer change.

Successes, Benefits, and Future Work

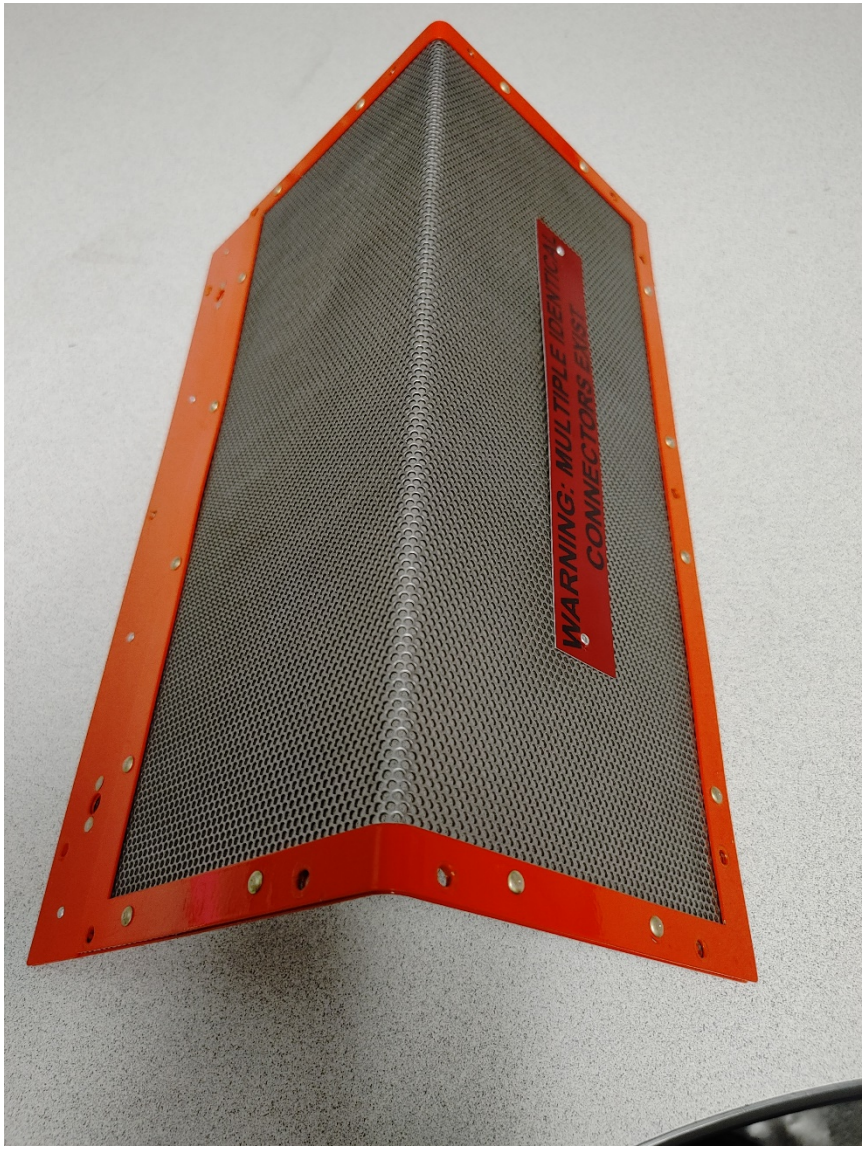
Ambient Temp (^{0}F)	Max Temp from Thermal Chamber Test (^{0}F)	Max Temp from Thermal Simulations (^{0}F)	Percentage Error %
159	195	196	0.5
135	168	170	1.2
73	112	107	4.5

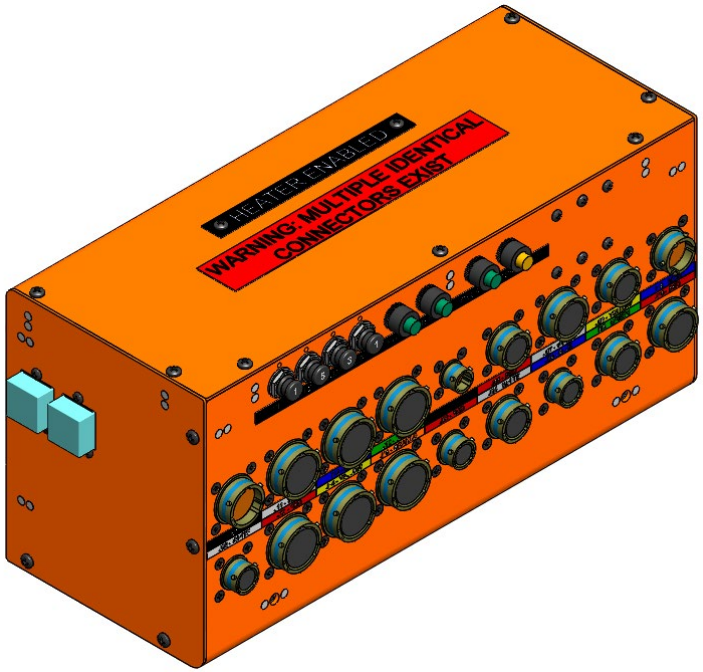
- With this current approach of FEA thermal analysis, we are able to determine if an LRU can be maintained within operating temperature limits with just natural convection, or if forced convection (i.e. a fan) will be required, <u>while LRU is in design phase</u>.

Successes, Benefits, and Future Work

- Run chamber tests on closed LRUs. Acquire data to validate a closed LRU mathematical model.
- Run chamber tests on LRUs with fans
- Increase the fidelity and viability of using FEA thermal analysis.

Successes, Benefits, and Future Work





QUESTIONS???