TFAWS Passive Thermal Paper Session

Design Considerations For Characterizing Thermal Contact Conductance In Spacecraft Interfaces

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Presented By
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Greenbelt, MD

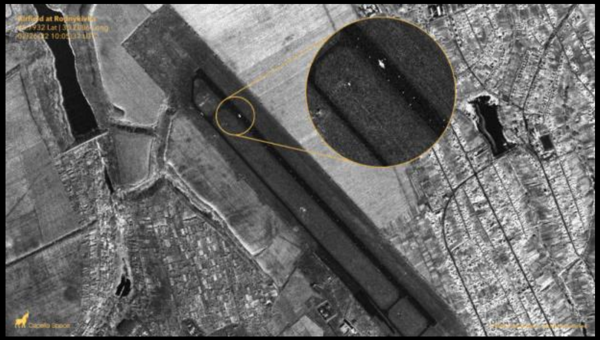
There's a revolution happening in space

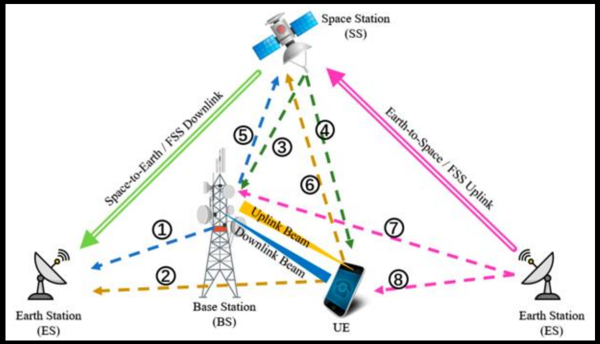
Satellites play an increasingly pivotal role in today's digital society

- More functionality
- Smaller footprints
- Faster time to launch
- More HEAT

To optimize performance, resilience, assembly, and manufacturing speed and costs, engineers require ***predictable performance*** from the elements that make up their systems

When it comes to thermal design, this has never been the case.



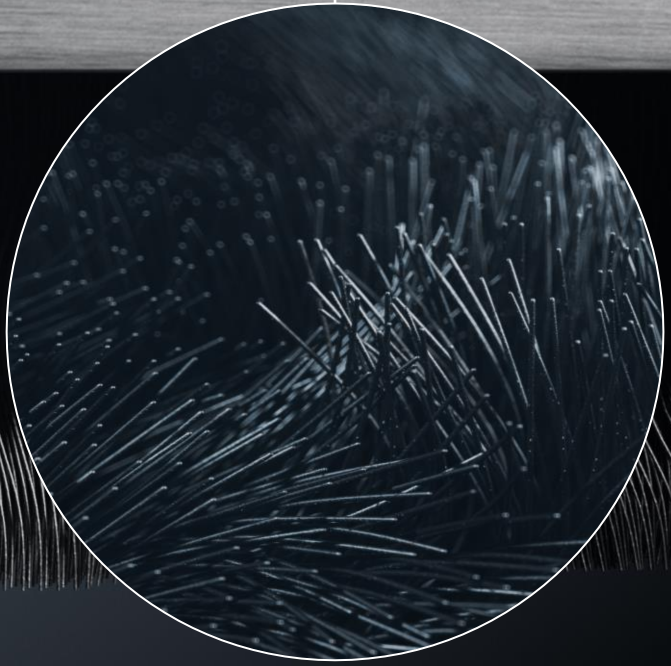


Source: ESA'S ANNUAL SPACE ENVIRONMENT REPORT

Carbice® Nanotube Technology

- **TRL9 maturity**
- **Space heritage since 2018**

Patent-protected and from recycled materials, Carbice® Nanotubes are vertically aligned carbon nanotube forests grown on and covalently bonded to both sides of an aluminum foil backbone.



Properties optimized with over 15 years of process expertise.

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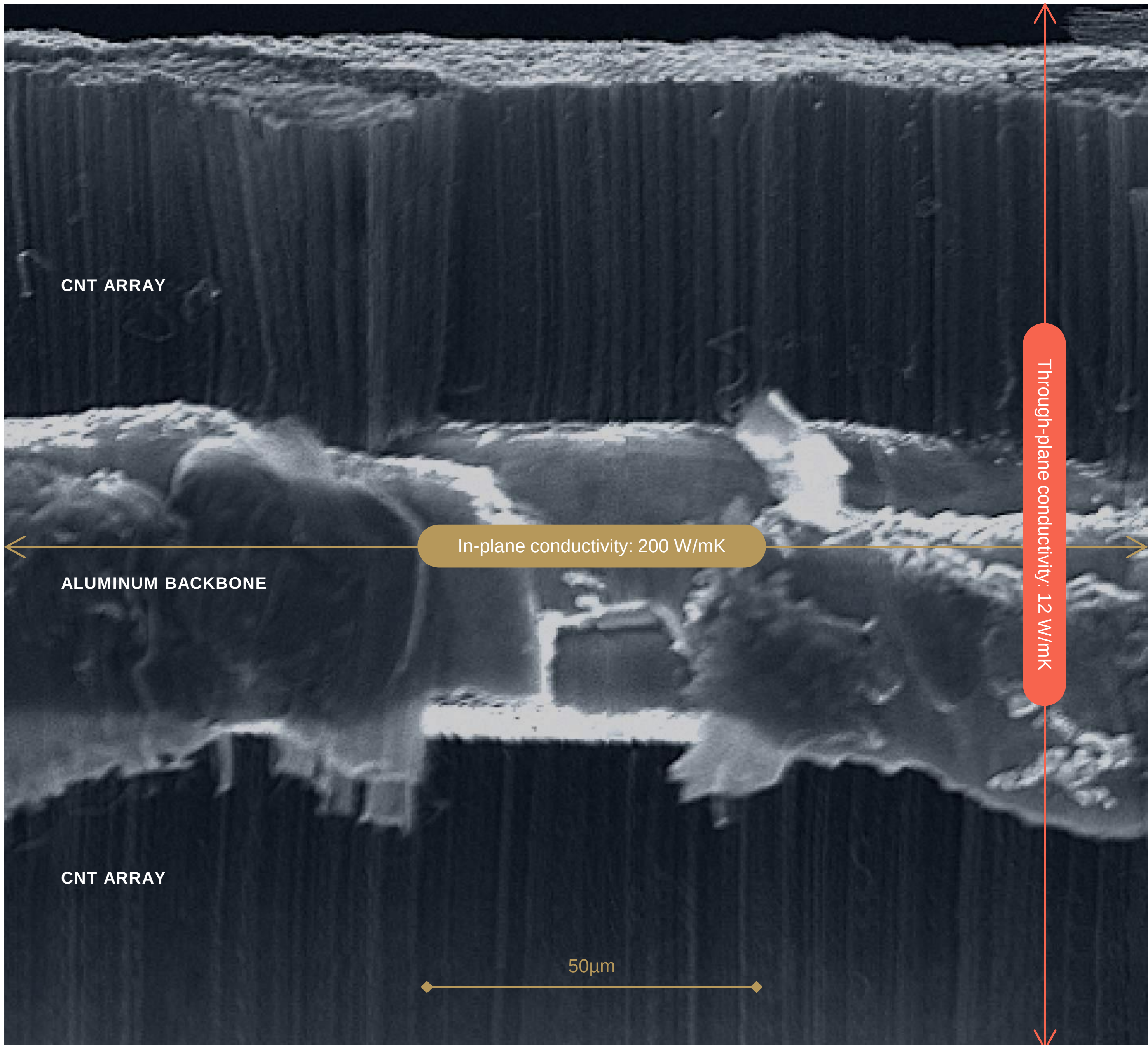
36 patents and growing

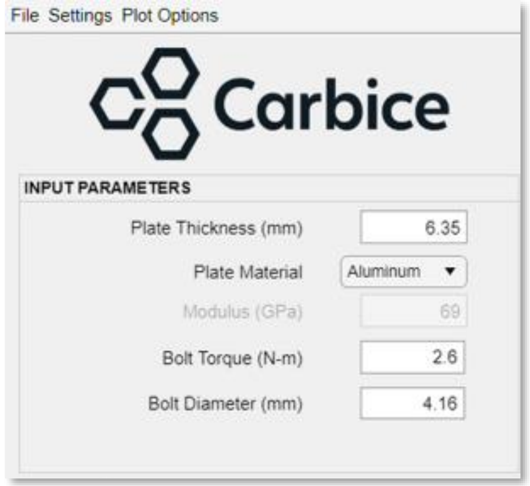
Thermal (IP-protected)	• Best Conductivity • Lowest Resistance • Transfers heat in all directions
Chemical Properties (IP-protected)	• Non-reactive and non-corrosive • Can withstand temperatures up to 660℃ • Hydrophobic. Even ice won't form on Carbice Pads
Mechanical Properties (IP-protected)	• CNTs are the strongest materials in terms of tensile strength and elasticity • Carbice CNTs are soft and flexible under radial pressure • Reversable dampening of shock and vibration
Electrical Properties (IP-protected)	• CNTs are inherently conductive • Carbice Pads can be either conductive or non-conductive with the addition of proven, customizable surfacing
Radiation Properties (IP-protected)	• Proven black absorber/emitter and electronics EMI frequency shield • Can block cosmic radiation particles

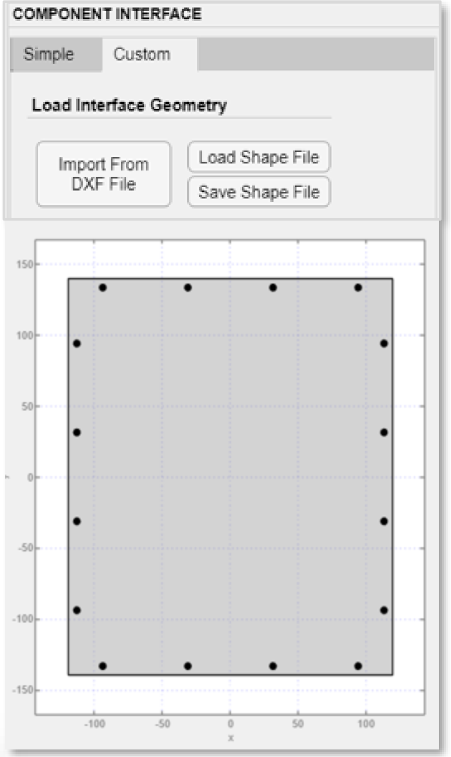


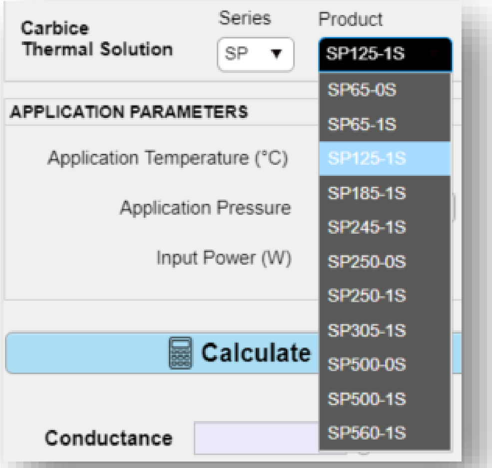
Reliable CNT mechanics enables high-fidelity digital interface design

Carbice® SIM is a suite of predictive modeling tools for fast and accurate analysis of thermal and structural performance of Carbice Space Pad in real interfaces.

- Thermal design is one of the only parts of the build process that relies on trial and error
- Mechanical-thermal co-design minimizes inefficiencies and ***creates the possibility for new optimization***
- Understanding real world thermal performance early in the design cycle ***saves testing time and money***.

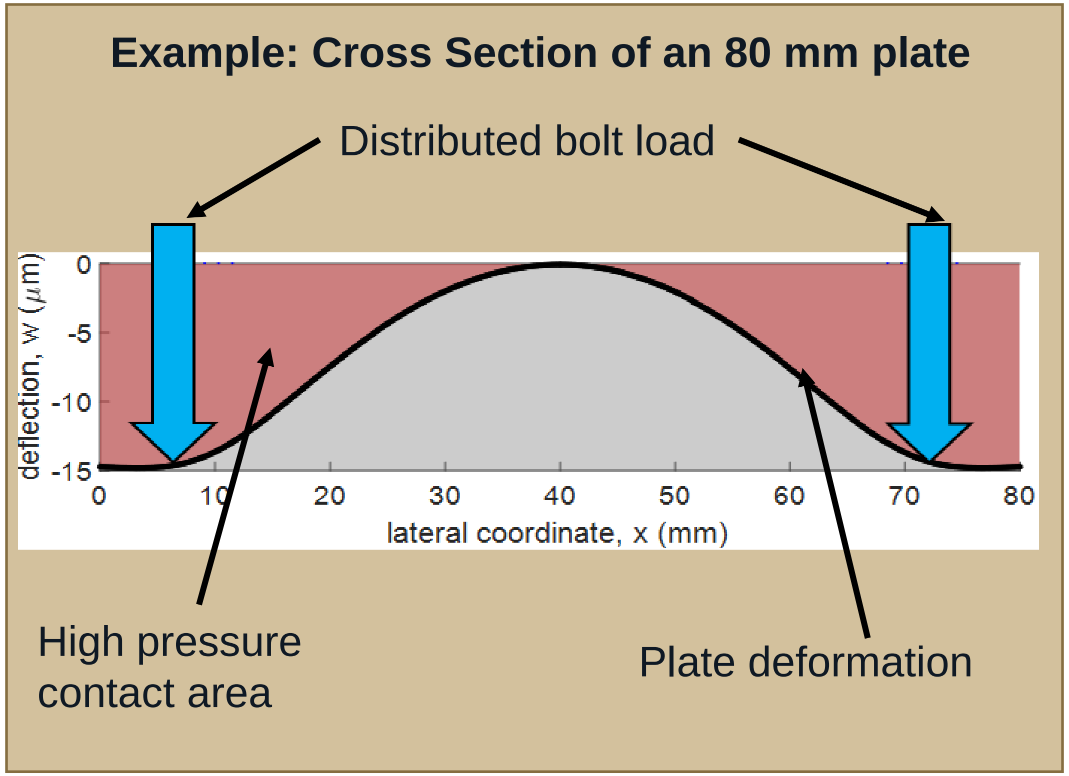




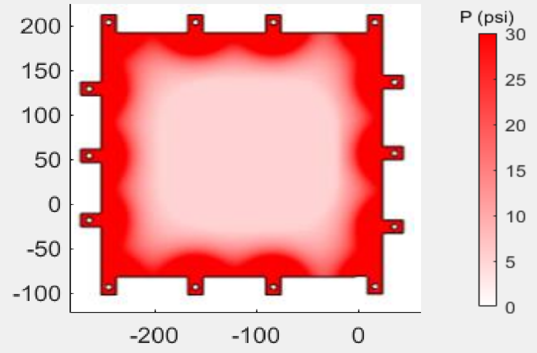


We utilize several Computational Models developed in-house

Deflection-contact predictions



Example of Gasket Pressure Distribution



Modeling Approach

- *Apply* distributed loads to interface at bolt/washer locations
- *Solve* the mechanical structural problem for the resulting plate/ box deflection
- *Identify* overlap between plate deflection and gasket to determine high pressure contact area and contact pressure distribution in interface
- Use interface pressure distribution, combined with pressure-conductance relationships for Carbice Space Pad to determine conductance distribution across interface
- *Solve* for temperature distribution in box/plate to incorporate spreading effects and power non-uniformity

High-fidelity thermal conductance prediction

Carbice® SIM simulation vs. Real interface measurements for small and large interfaces

Low Noise Amplifier

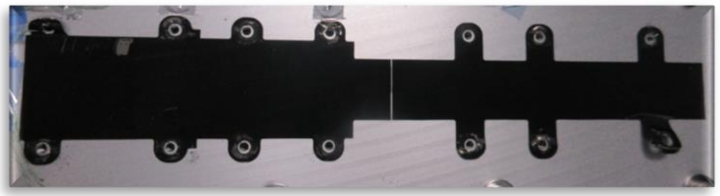
Simulated	1300	W/m^2-°C
Measured	1260	W/m^2-°C

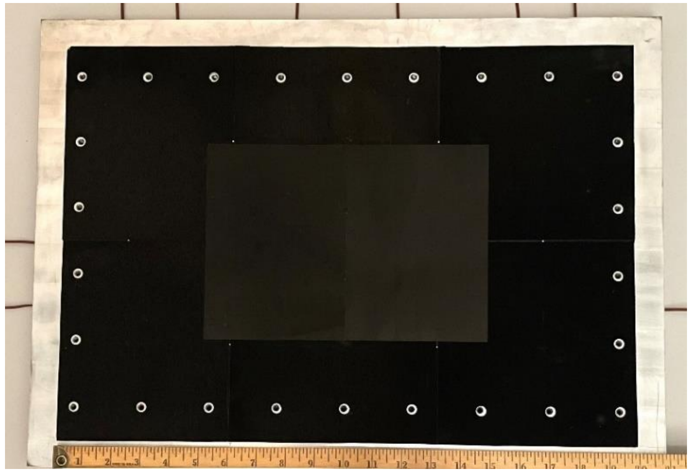
Traveling Wave Tube

Simulated	10,600	W/m^2-°C
Measured	10,300	W/m^2-°C

Large Electronics Panel

Simulated	2600	W/m^2-°C
Measured	2400	W/m^2-°C





Predictions are typically accurate to within ±10%

Predictable interface mechanics enables digital design transformations

Optimize the design iteration process rapidly and efficiently

Just starting the design process:
interface properties and thermal requirements not known.

Initial interface design:
some parameters known, e.g.
- Interface area, shape
- Bolt pattern, loads
- Heat loads

Final/ Late-state component design:
well defined interface, fasteners, and thermal loads and requirements.

Concept Study → **Preliminary Design** → **Final Design**

Early Design Guide

Carbice SIM

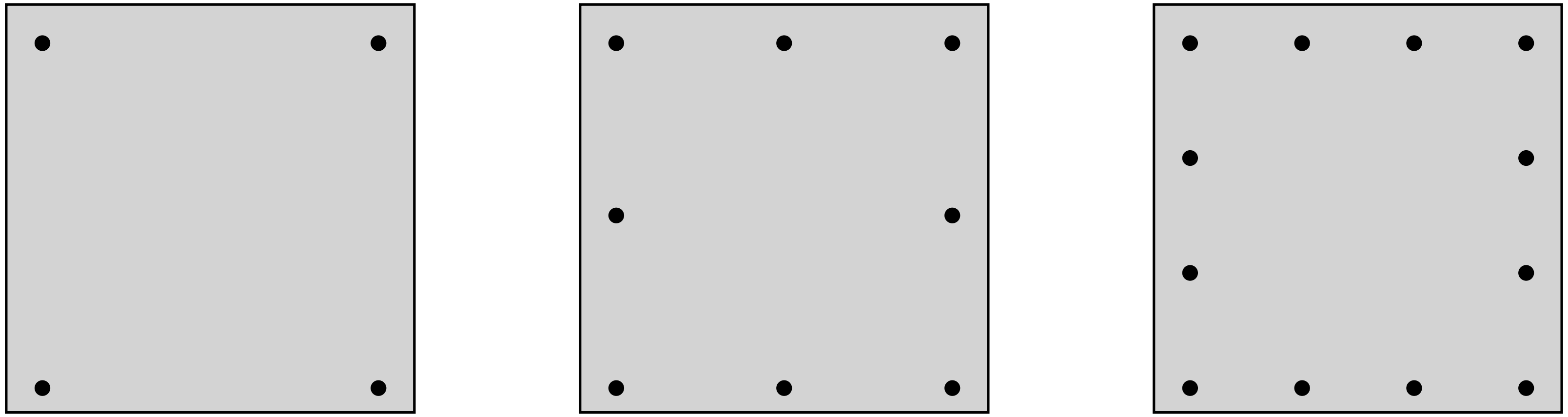
Order of magnitude estimate of conductance and inform how your system will work.

Engage with us early in the design process to optimize your overall system design.
- Reduce box size, weight
- Save on assembly time
- Increase component density

Eliminate Surprises!
Get an accurate conductance estimate to save time on assembly integration & test.

Optimize fasteners to meet your needs

Few Fasteners or Low Pressure → **Many Fasteners or High Pressure**



~50 psi average pressure	**~100 psi** average pressure	**~150 psi** average pressure

2000	W/m²-°C
350	BTU/hr-ft²-°F

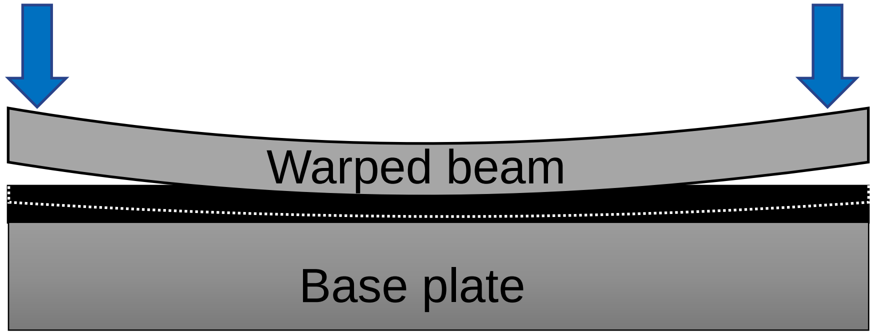
4700	W/m²-°C
825	BTU/hr-ft²-°F

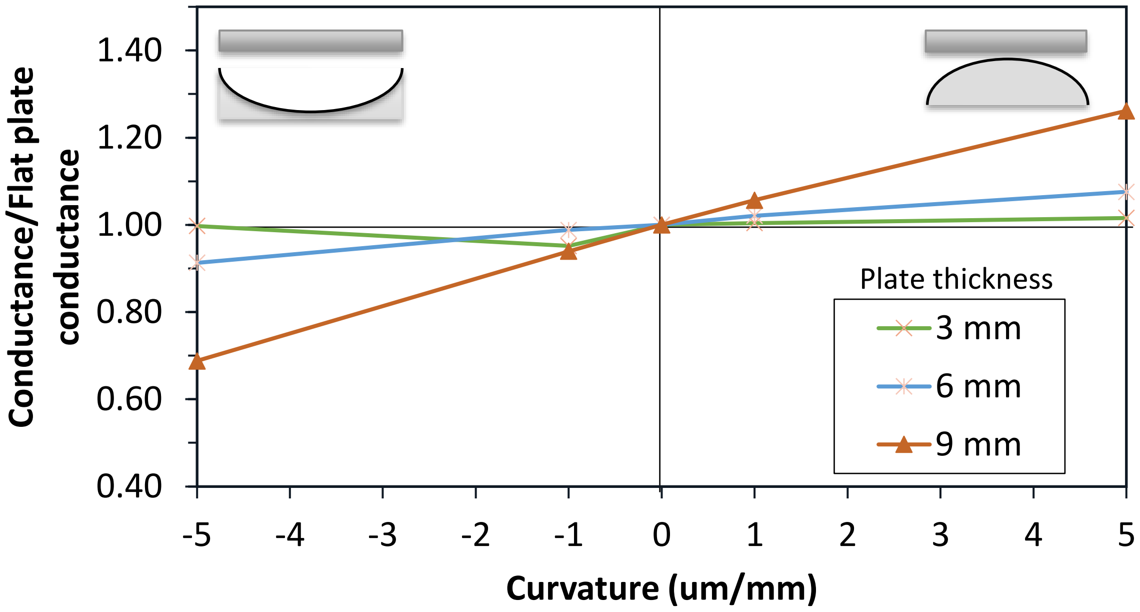
8800	W/m²-°C
1550	BTU/hr-ft²-°F

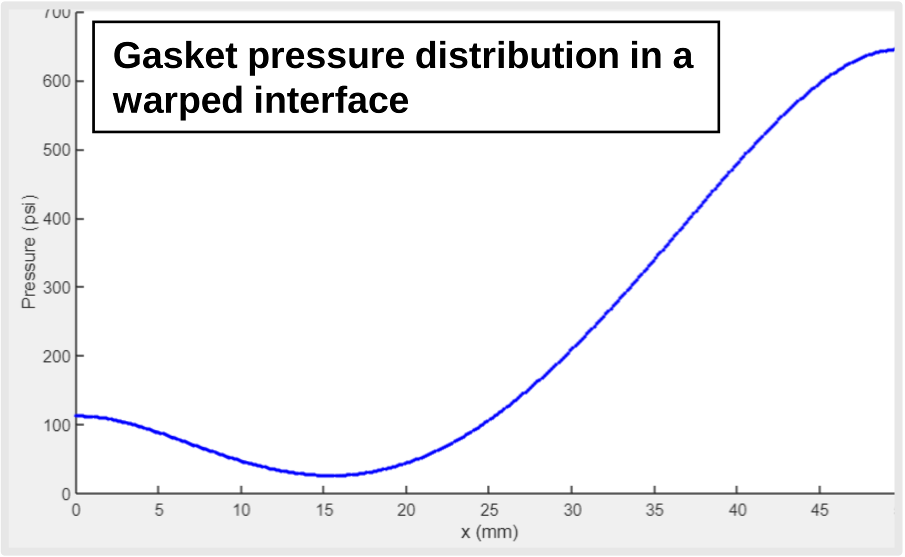
Results shown for SP125x-1S in 18x18 cm^2 (50in^2) plate, with #8-32 fasteners.

Curvature and Flatness Tolerances

✓ Carbice® SIM can give predictable conductance for Curved, Wavy, or Warped interfaces







Characterization and Validation of Interface Thermal Performance

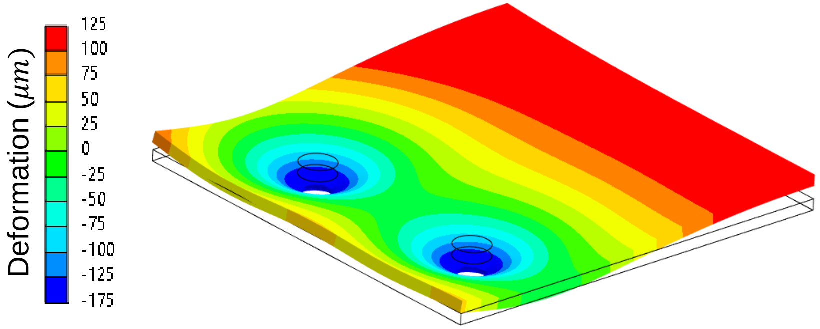
Machining, instrumenting, and powering full fidelity Thermal Test Vehicles (TTVs) is often impractical:

When implementing compressible gaskets, capturing the important *spatial and structural physics* of the component under test is critical for capturing performance

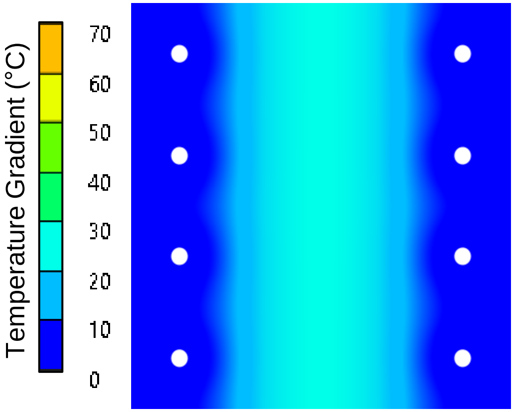
<u>Critical parameters include</u>

- Contact pressure distribution
- Power maps and power density
- Representing 2D and 3D heat flow pathways

Plate deflection



Thermal map



Structural Guidelines for Designing a Thermal Test Vehicle

Design with Structure in Mind

- Satellite boxes and other thermal interfaces are tested in Thermal Vacuum (TVAC) to assess thermal behavior. Usually a Thermal Test Vehicle (TTV) is machined for TVAC testing.
  - The structure of a TTV is often overlooked in thermal testing. Rigidity affects the deformation and compression of a thermal gasket.

- Sidewalls, bolt tabs, structural ribs, and other structurally nonuniform features are important when considering TTV appropriate for thermal interface testing.
  - Thin-plate models often severely underpredict conductance of complex boxes, leading to poor translation of TVAC into real assembly.

Flexural rigidity affects plate deformation. For a thin plate:

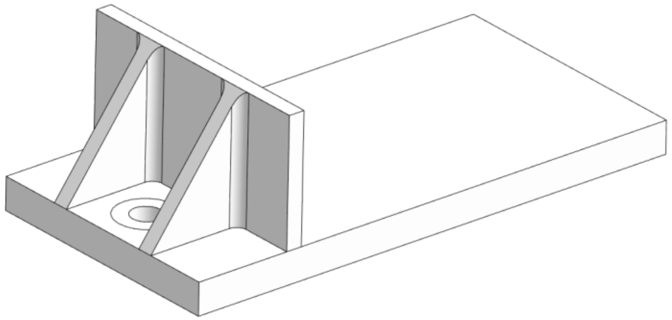
$$D = \frac{Et^3}{12(1-\nu^2)}$$

E: Young's modulus
t: plate thickness
ν: Poisson's ratio

Defeature Strategically – Sidewalls

- Often, there is a need to defeature components in models or TTV:
  - Distribute proprietary components, build a less complex TTV for testing, FEA simulations with less computational burden, reduced order models/calculations.

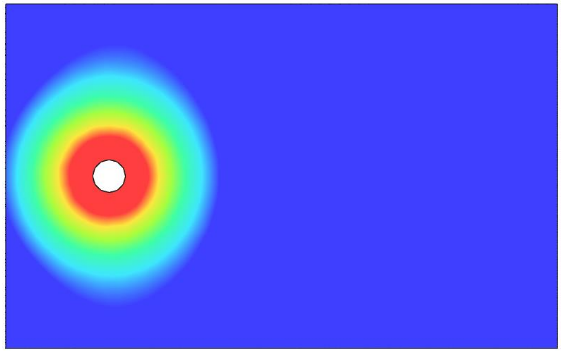
- Sidewalls, ribs, and bolt tabs:
  - Recommend 1” sidewalls to represent box
  - Some structural linkage between walls and bolts tabs should be present



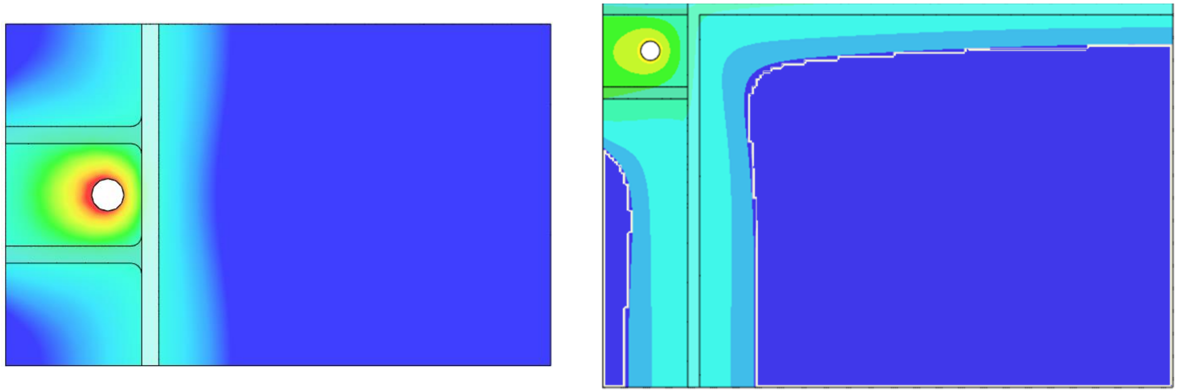
Section of a box
¼” Al base with 1/8” walls
2.5” width per bolt
8” length
2700 N per bolt

FEA predictions of gasket contact pressure

Simple plate, without walls



Contact pressure of boxes with walls



Conductance is ***30 % lower*** if walls are ignored!

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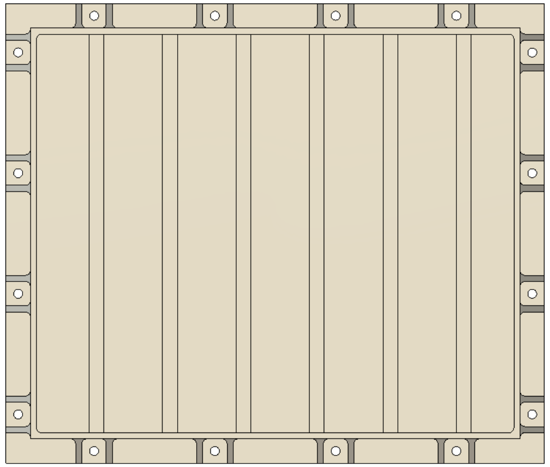
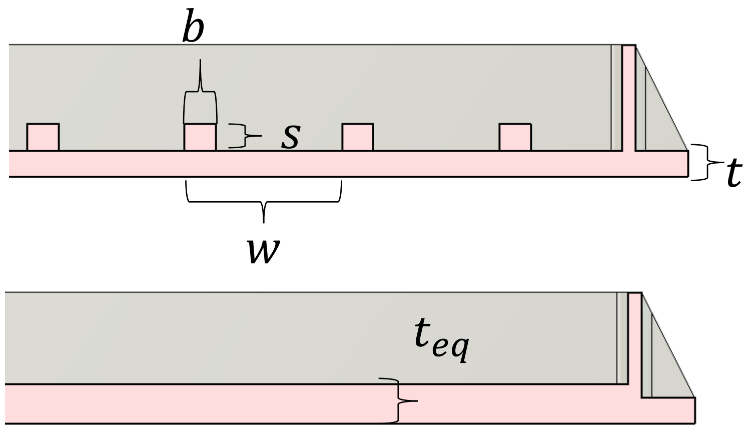
Defeature Strategically – Ribs

- Ribs enhance structural rigidity and help gasket contact:
- TTV design should incorporate this rigidity to avoid underpredicting contact
- Equivalent Plate Method: equate the total rigidity of ribs + base to find the equivalent uniform-thickness for TTV





Assuming plate and ribs are all the same material (E, ν).

1. Thinner plate bending moment of area:

$$I_{plate} = \frac{wt^3}{12}$$

w: plate width (per rib)
t: nominal thickness

2. Moment of area of the ribs:

$$I_{rib} = \frac{bs^3}{12}$$

b: rib width
s: rib height (above the plate)

3. Equate the flexural rigidity of ribs + base

$$I_{equiv} \equiv I'_{plate} + I'_{rib} = \frac{wt_{eq}^3}{12}$$

t_{eq} : equivalent plate thickness
I'_{plate}: shifted to new centroid
I'_{rib}: shifted to new centroid

4. Solve for t_{eq}

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Ribs Enhance Structural Rigidity

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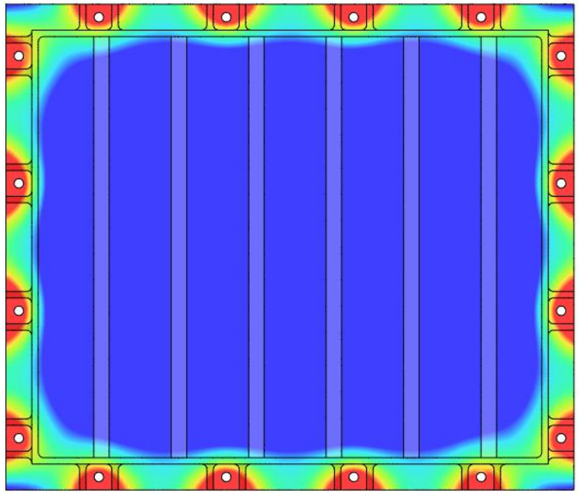
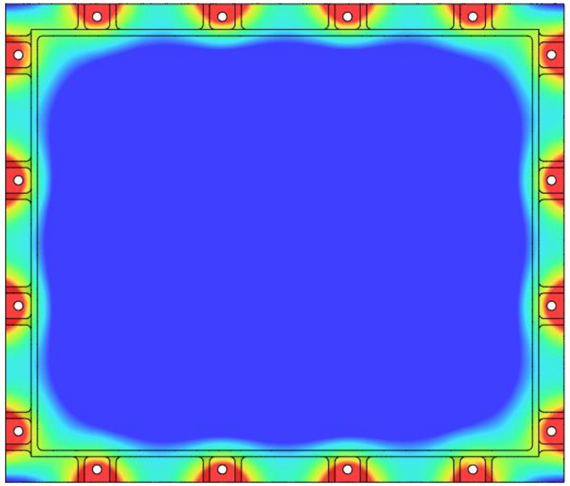
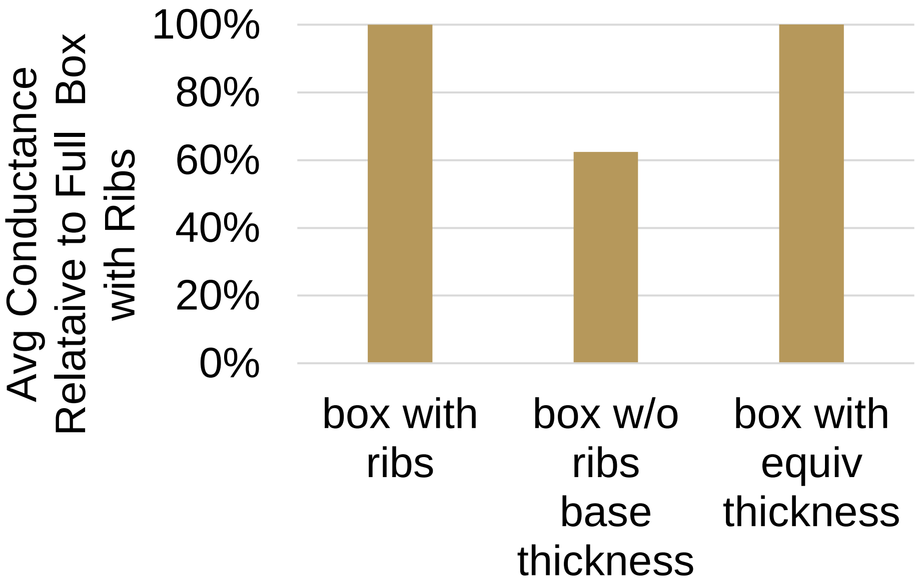
Full box with ribs



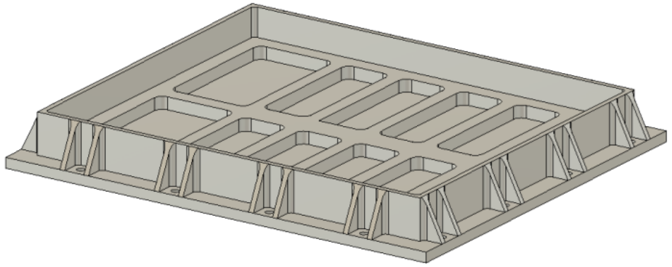
Box with uniform interior – Equivalent thickness method



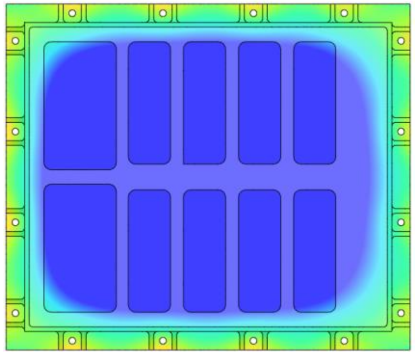


11" x 9" box
2700 N per bolt
SP125x-1S gasket

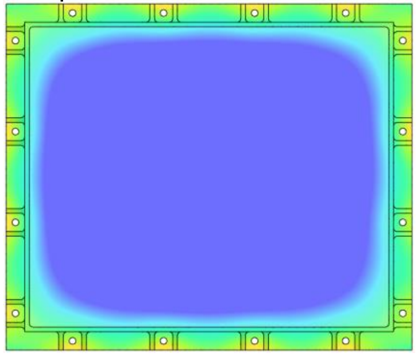
Also works to simplify more complex interior features



Full box with complex ribs



Equivalent thickness method



Evaluating 2D and 3D Heat Dissipation

Heat Spreading / Constriction Resistance

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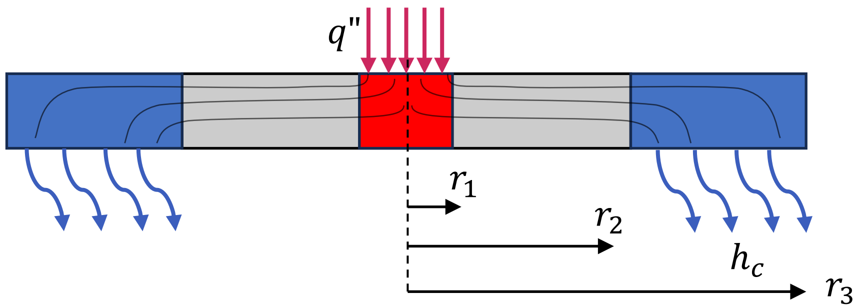
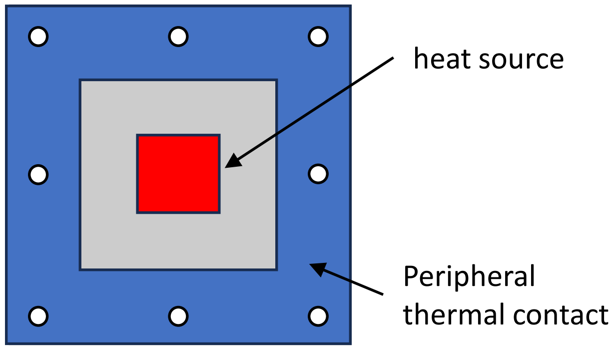
Concentrated heat and/or nonuniform conductance introduces spreading resistance

- Spreading from the heat source location, R_q
- Spreading laterally across the plate, R_{spr}
- Constriction into the conduction boundary, R_{con}





<u>Spreading / Constriction Correlation*</u>

$$R_{tot} = {}^{\Delta T}/_{q} = R_q + R_{spr} + R_{con}$$

Where ΔT is between the hot spot and the cold sink.

$$R_q: \begin{cases} R_q^{avg} = \frac{1}{8\pi kt} & \ll \text{avg. of hot spot} \\ R_q^{peak} = \frac{1}{4\pi kt} & \ll \text{peak of hot spot} \end{cases}$$

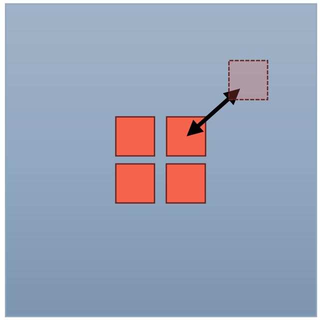
$$R_{spr} = \frac{1}{2\pi kt} \ln\left(\frac{r_2}{r_1}\right)$$

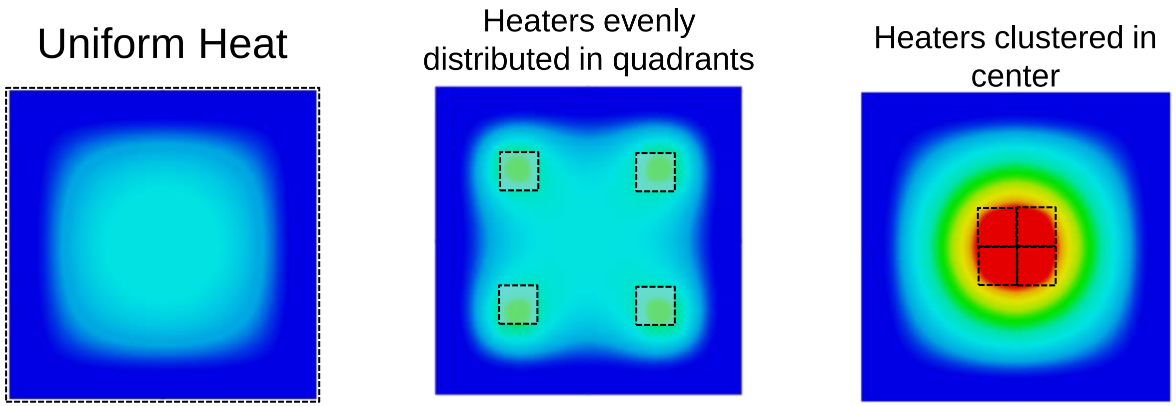
$$R_{con} = \frac{1}{2\pi r_2 kt\alpha}\left(\frac{K_1(\alpha r_3)I_0(\alpha r_2)+I_1(\alpha r_3)K_0(\alpha r_2)}{I_1(\alpha r_3)K_1(\alpha r_2)-I_1(\alpha r_2)K_1(\alpha r_3)}\right) \sim \frac{1}{2\pi r_2\sqrt{kth_c}}\left(\frac{K_0(\alpha r_2)}{K_1(\alpha r_2)}\right)$$

$$\text{where } \alpha \equiv \left(\frac{h_c}{kt}\right)^{\frac{1}{2}}$$

** Fan Wang, "Dynamic load capacity of power processing units for electrical power supply", 2009*
** Johannes, Adam, "The Printed Circuit Board as a Heat sink", 2009*

Emulate Uniform Heating in TTV: Guidelines for Heater and Thermocouple Placement

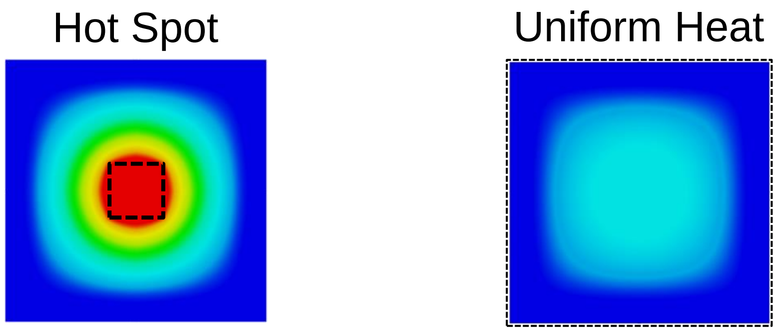




Thermocouples and heater proximity

- Place thermocouples at least an extra ½ diameter away from any heaters
- Avoid clustering heaters near center
- Uniform heat can be emulated if heaters are evenly spaced in quadrants of the plate

Correlate Uniform Heat to Hot Spots

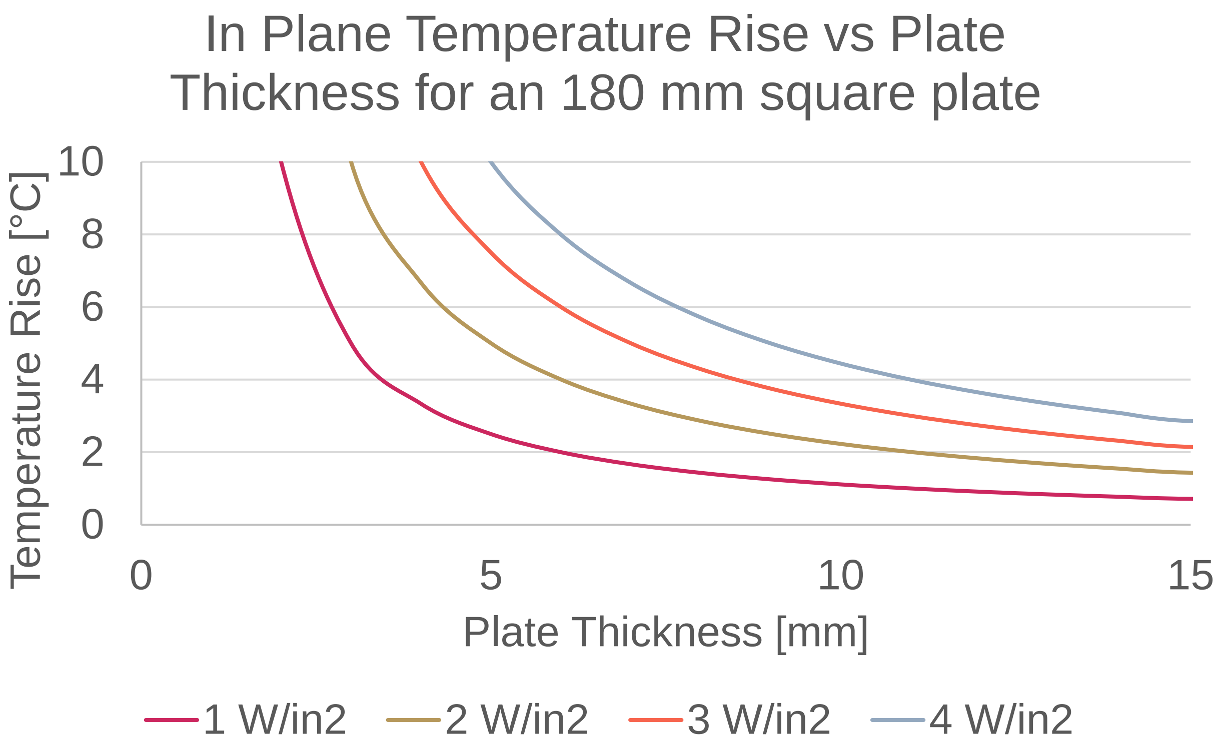


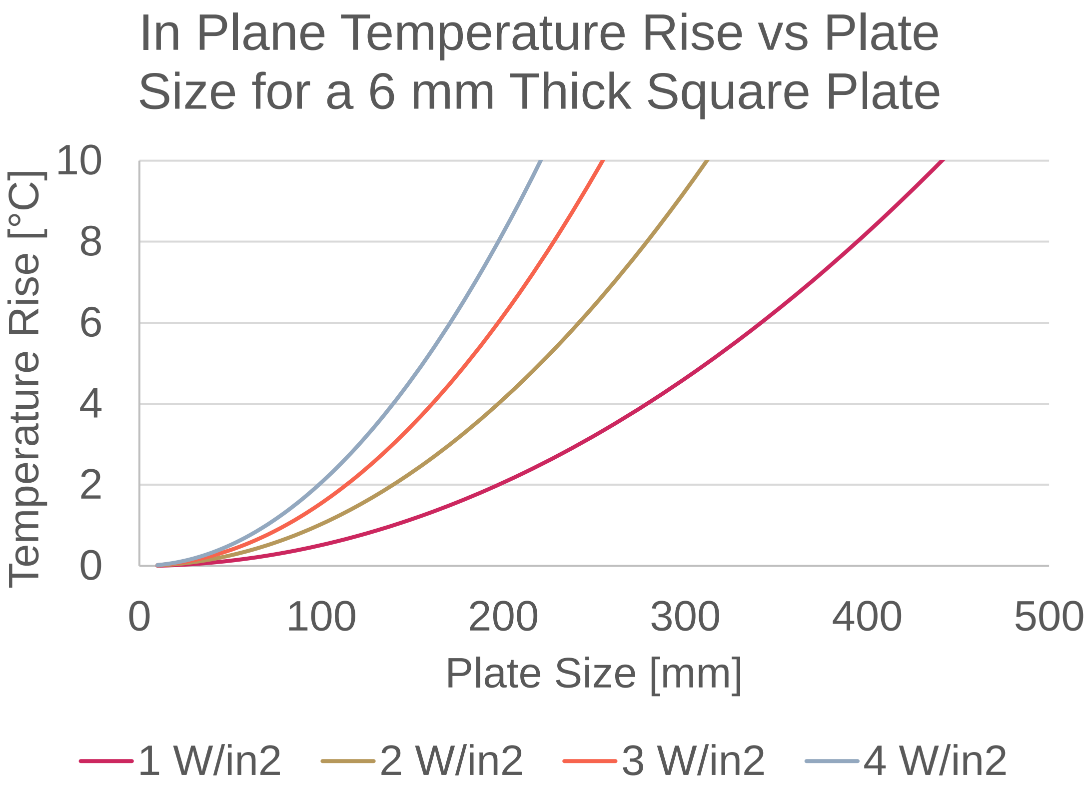
- Spreading Correlation can be used to quickly approximate temperatures for concentrated heat flux, given uniform heat flux data/prediction and vice versa.

- e.g., assume $R_{uniform}$ is already known. Compute the extra resistance from constricting the heat source from r_{uni} to r_{hot}.

$$R_{hot} - R_{uniform} \sim \frac{1}{2\pi k t} \ln\left(\frac{r_{uni}}{r_{hot}}\right)$$

When is constriction and spreading important?





$$R_{peak-average} = \frac{1}{8\pi kt}$$

- Large Boxes
- Thin Plates
- High Power Densities

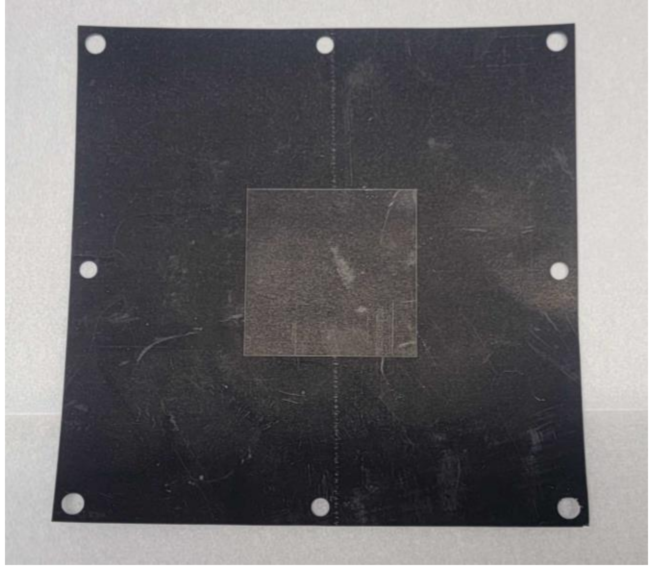
Analysis for 125 um thick gasket
Spreading Resistance Is decreased by:

- Increasing gasket thickness
- Targeting contact through gasket structuring

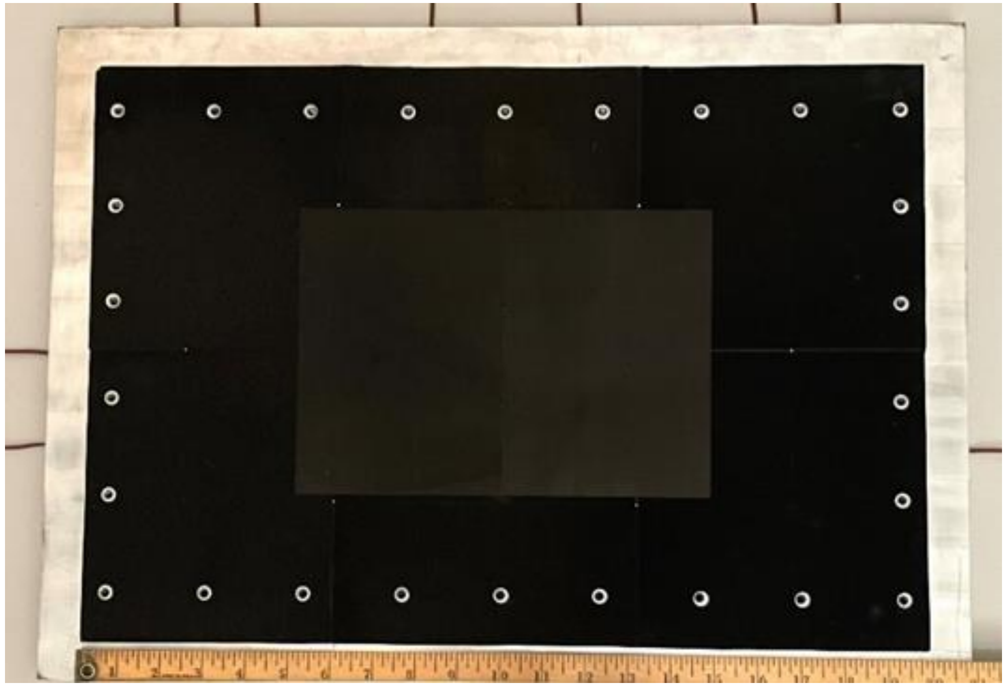
Carbice SIM-Stack: Interface Structuring to target Hot Spots

Structural-Thermal Modeling, combined with Carbice's unique ability to layer our gaskets with no thermal penalty enables efficient solution design for systems with hotspots, very large spans, or for targeted contact with heat pipes etc.

Comes as a single gasket, which is ready to apply to interface without any further effort from the customer



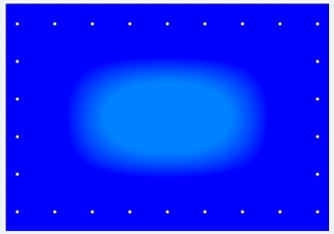
7" x 7"



20" x 14"

U.S. Patent Application No. 17/492,349 *"STEPPED GASKETS FOR THERMAL INTERFACES AND METHODS OF MAKING AND USING THEREOF"*

Targeted Thermal Contact for Hot Spots in Large Interfaces



SP305x-1S,
100 W uniform heat

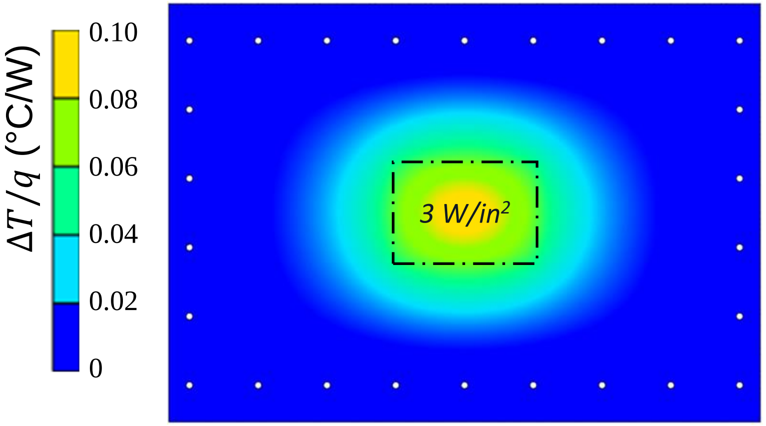
Carbice works in large area interfaces

- For 100 W uniform heat, SP305x-1S gives average temperature rise of <0.3 °C.

Plate:
- *dimensions: 20” x 14”*
- *Thickness: 0.4”*

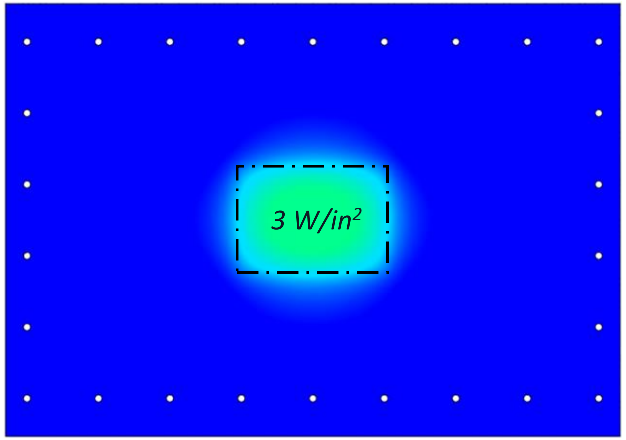
Heat Loads:
- *3 W/in² hot spot (5” x 3.5”)*

SP305x-1S (single layer)



Hot Spot region
$\Delta\bar{T}$ = 3.6 °C

Two-layer structured gasket:
SP305 + targeted SP305 layer



Hot Spot region
$\Delta\bar{T}$ = 1.9 °C

Carbice© SIM structural-thermal modeling enables predictive design for targeted heat dissipation.

3 W/in² central, concentrated heat
- Spreading resistance of hot spot dominates for large plates
- Targeting the heat source with a second layer of SP305x reduces hot spot temperature 50 %

**Carbice© SIM Predictions*

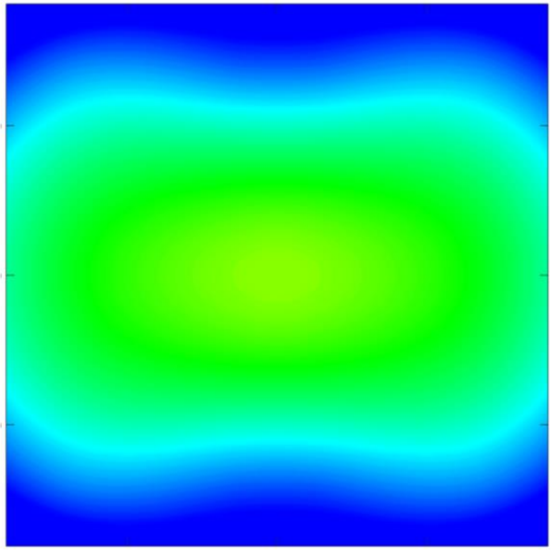
Case Study:
SP65-1S + SP65-1S in large interface with centralized heating

Plate:
- *dimensions: 7” x 7”*
- *Thickness: 1/4”*

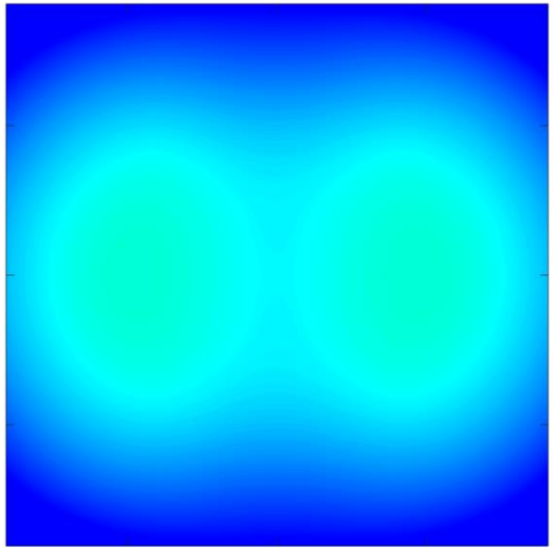
Heat Loads:
- *467 W*

Vacuum

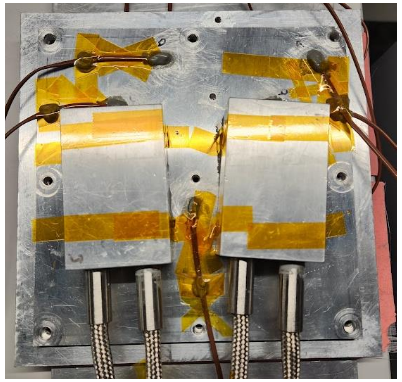
SP65-1S (single layer)



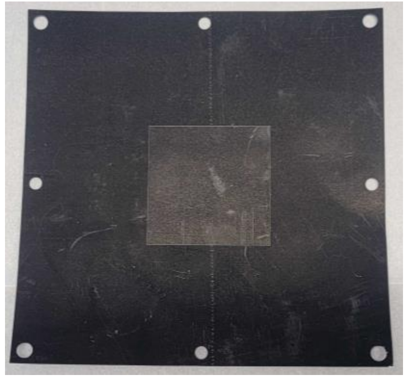
Two-layer structured gasket:
SP125x + targeted SP65 layer



TVAC plate test setup



Two-layer SP125/SP65



- Targeting the heat source with a second layer of SP65-1S reduces *center* peak temperature by 20 °C

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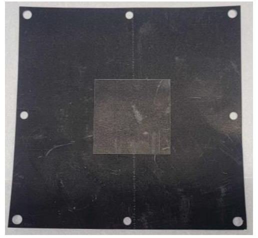
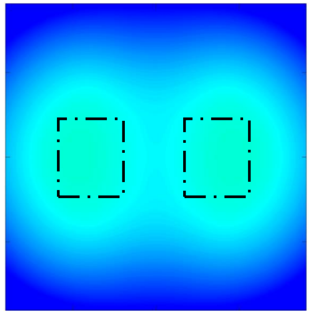
Predictability of Carbice® SIM vs. TVAC Data

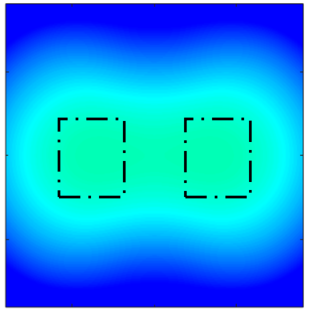
<u>*Case Study 1:*</u>
Plate: *7” x 7”*
Heat Loads: *467 W, two hot spots*

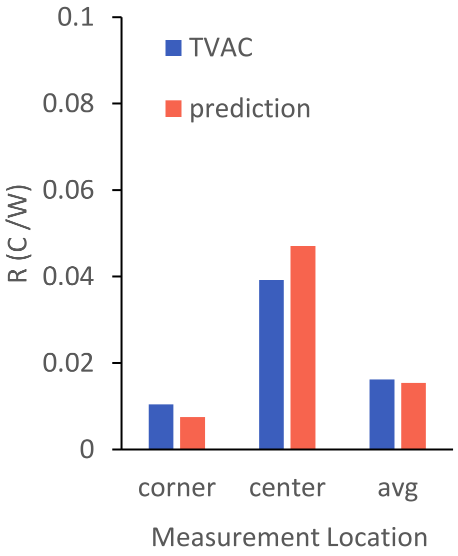


TVAC Data

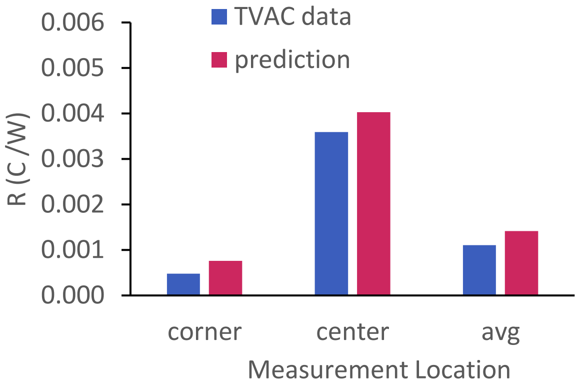


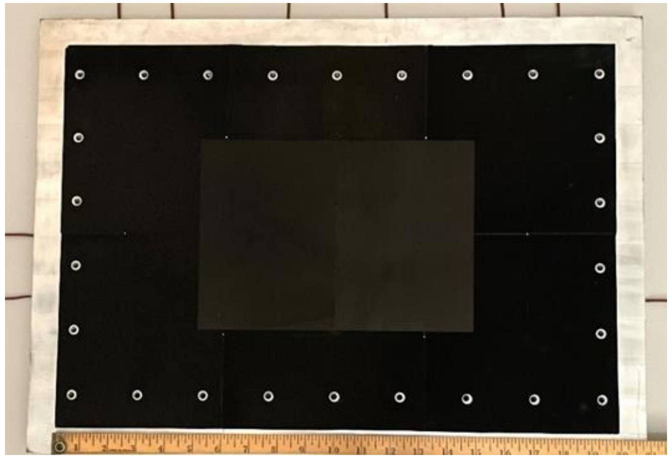
Simulation





<u>*Case Study 2:*</u>
Plate: *20” x 14”*
Heat Loads: *1500 W, several hot spots*





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Carbice Pads Manufactured at scale NOW in our AS9100D certified production facility in Atlanta, GA

- 23,000 sq ft facility and machinery in place
  - Current capacity = 3 Million in^2 of Carbice Pad per year
  - Ramping to 100 Million in^2 of Carbice Pad per year without additional tooling.
- Protected by deep IP moat
- Carbice® Pads are shipping to paying customers in SPACE, POWER and DATA markets today
- Carbice transforms the carbon footprint of building things

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Customers, local dignitaries and government officials at the Grand Opening of our new facility in Aug 2022.

Carbice **Achieve more.**

Craig Green, PhD
CTO
craig.green@carbice.com