EFFICIENT THERMALLY CONDUCTIVE STRAP DESIGN FOR CRYOGENIC PROPELLANT TANK SUPPORTS AND PLUMBING

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ABSTRACT

After evaluating NASA space architecture goals, the Office of Chief Technologist identified the need for developing enabling technology for long term loiters in space with cryogenic fluids. One such technology is structural heat interception. In this prototype, heat interception at the tank support strut was accomplished using a thermally conductive link to the broad area cooled shield. The design methodology for both locating the heat intercept and predicting the reduction in boil-off heat leak is discussed in detail. Results from the chosen design are presented. It was found that contact resistance resulting from different mechanical attachment techniques played a significant role in the form and functionality of a successful design.

Efficient thermally conductive strap design for cryogenic propellant supports and plumbing

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Presented By
J.P. Elchert

Thermal & Fluids Analysis Workshop
TFAWS 2012
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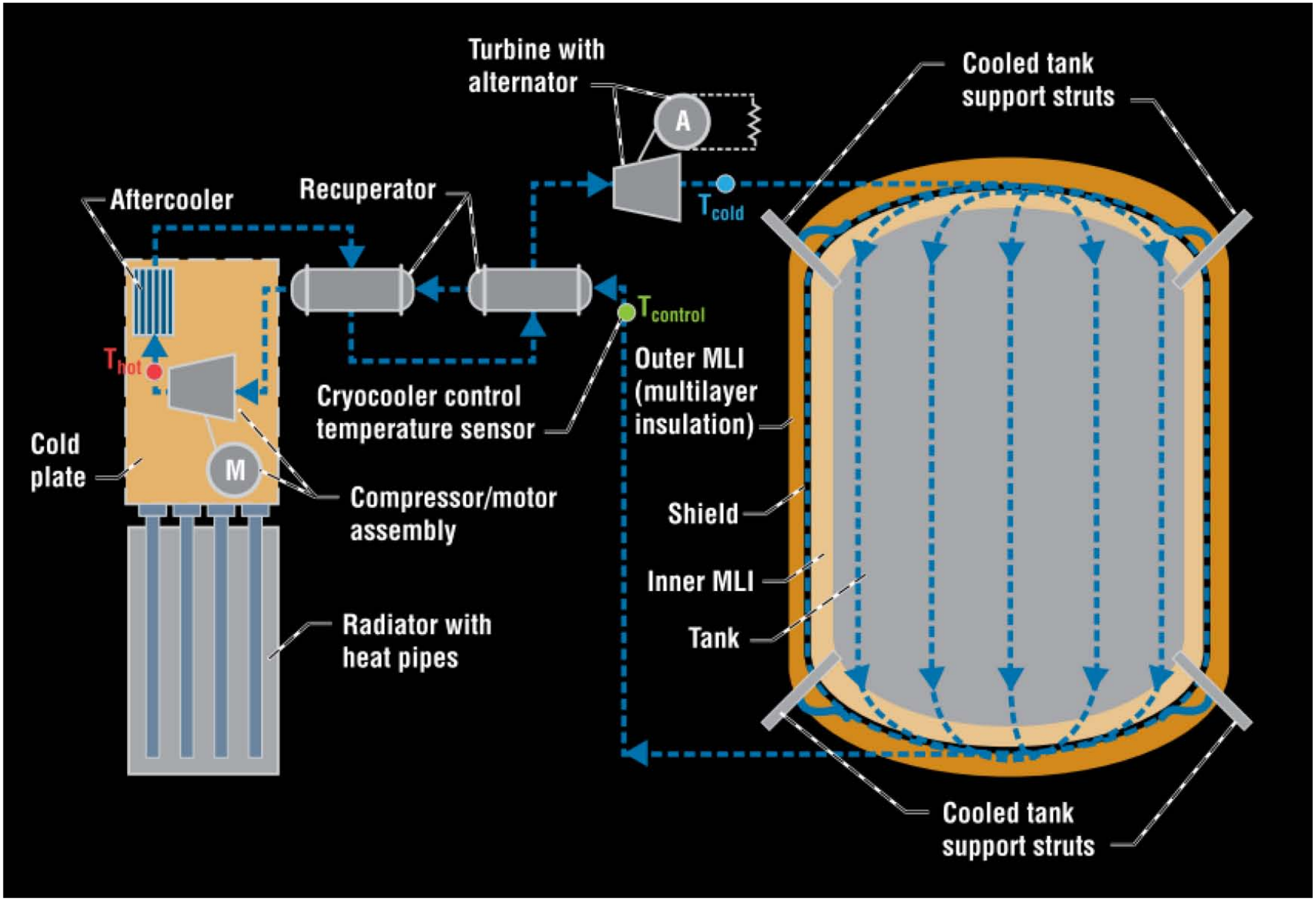
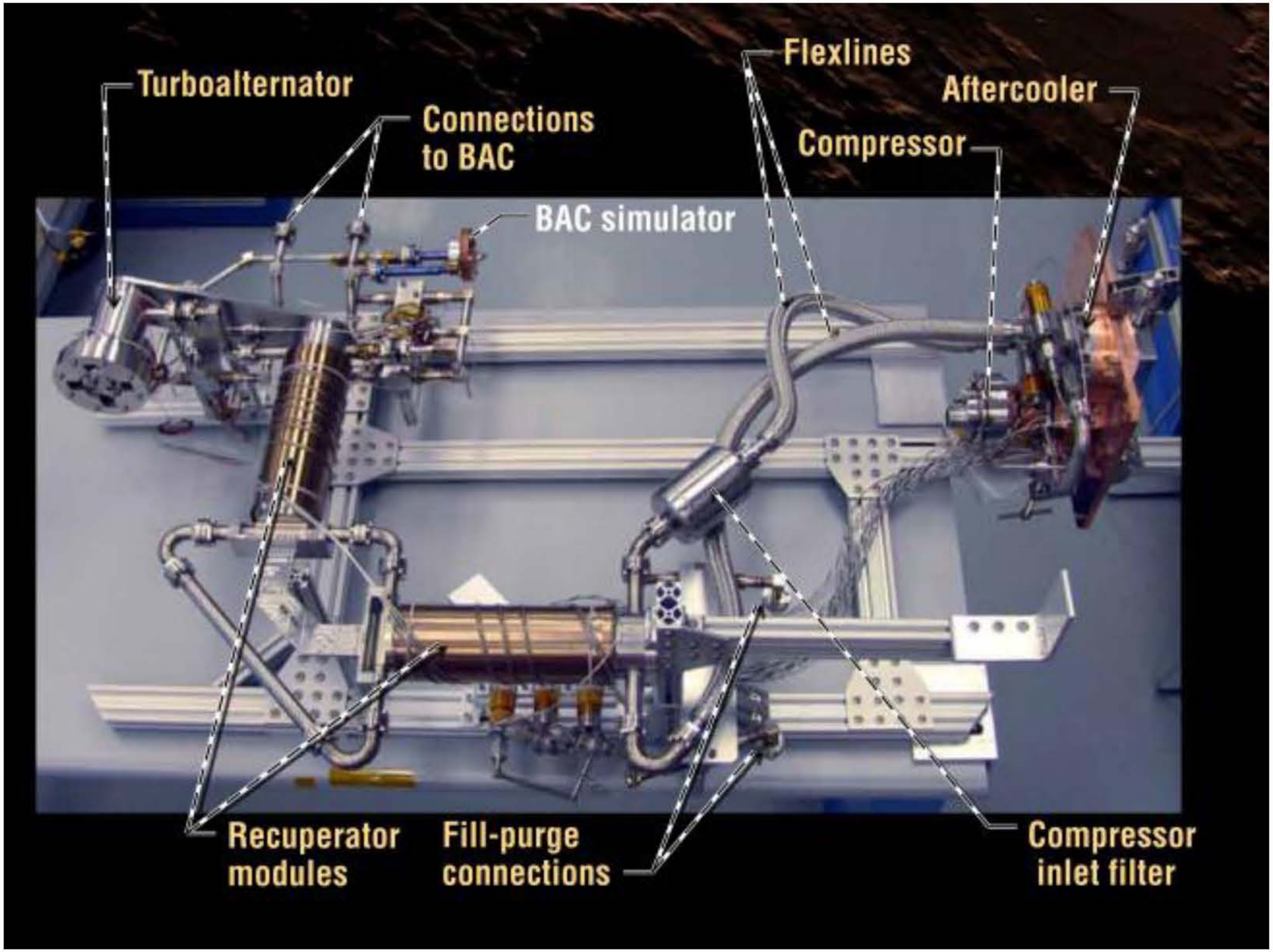
Jet Propulsion Laboratory
Pasadena, CA

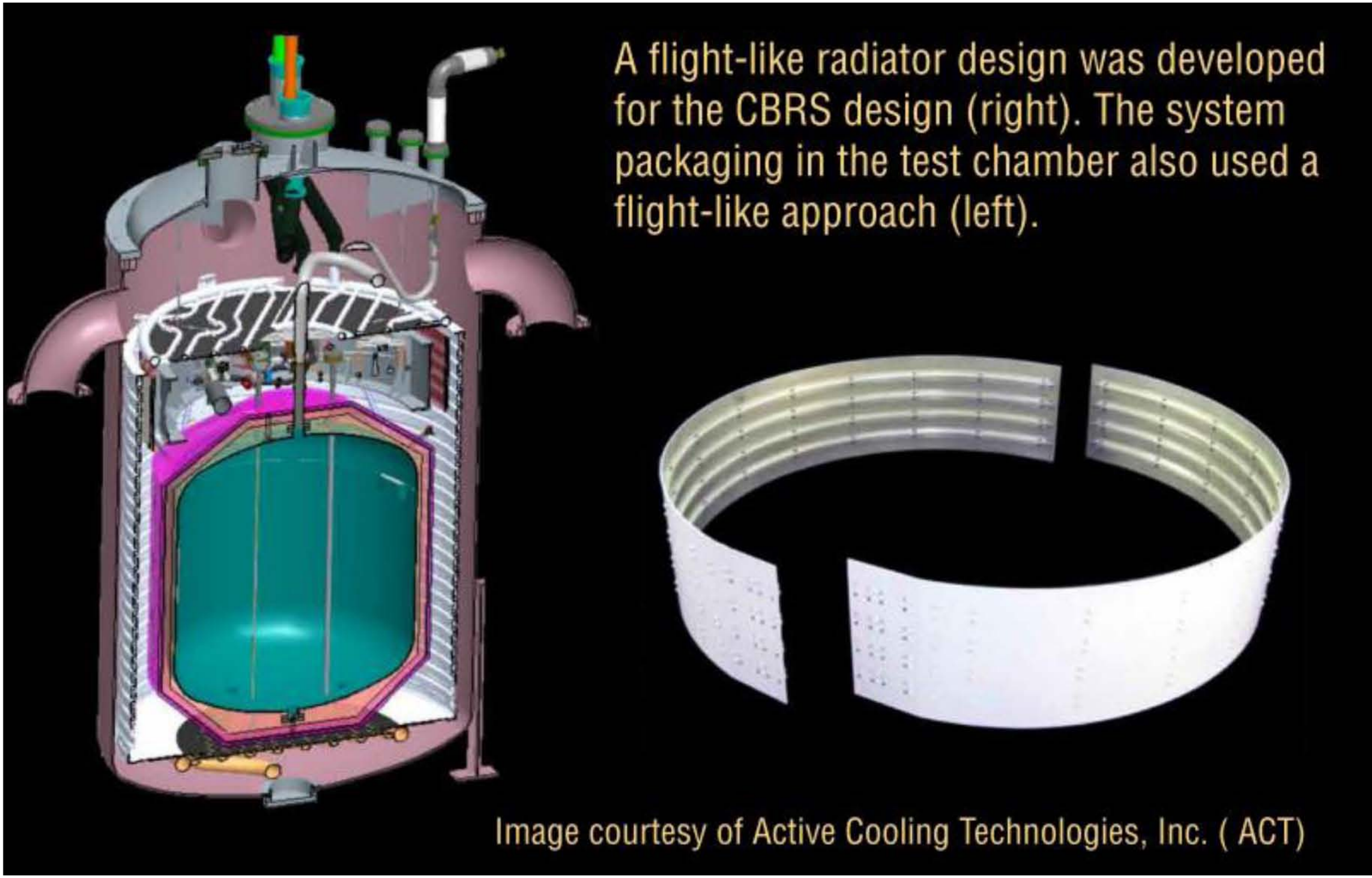
Cryogenic boil off reduction system test



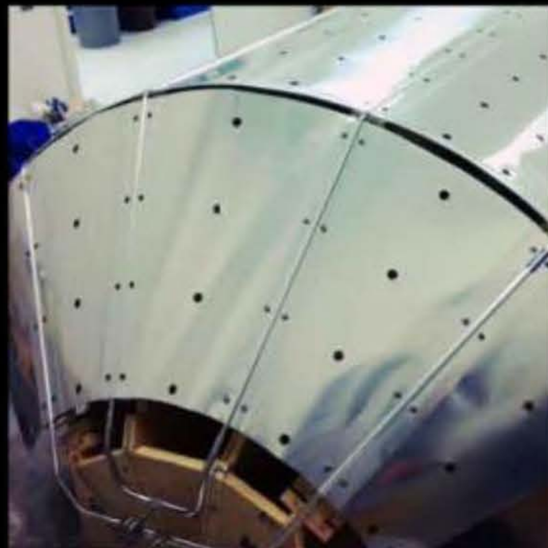
Utilizing a reverse turbo Brayton cycle cryocooler (Creare, Inc.)



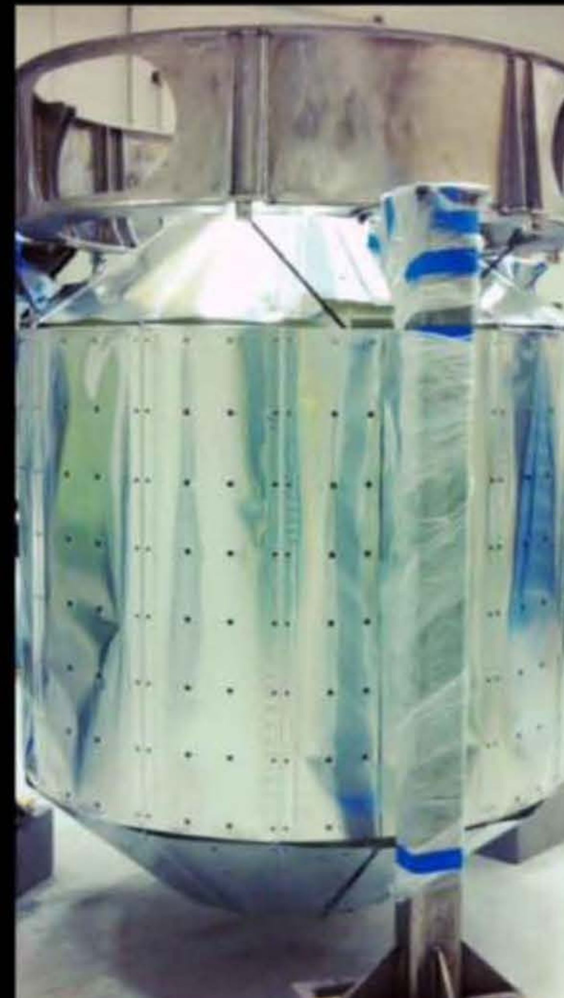
Vacuum apparatus and radiator



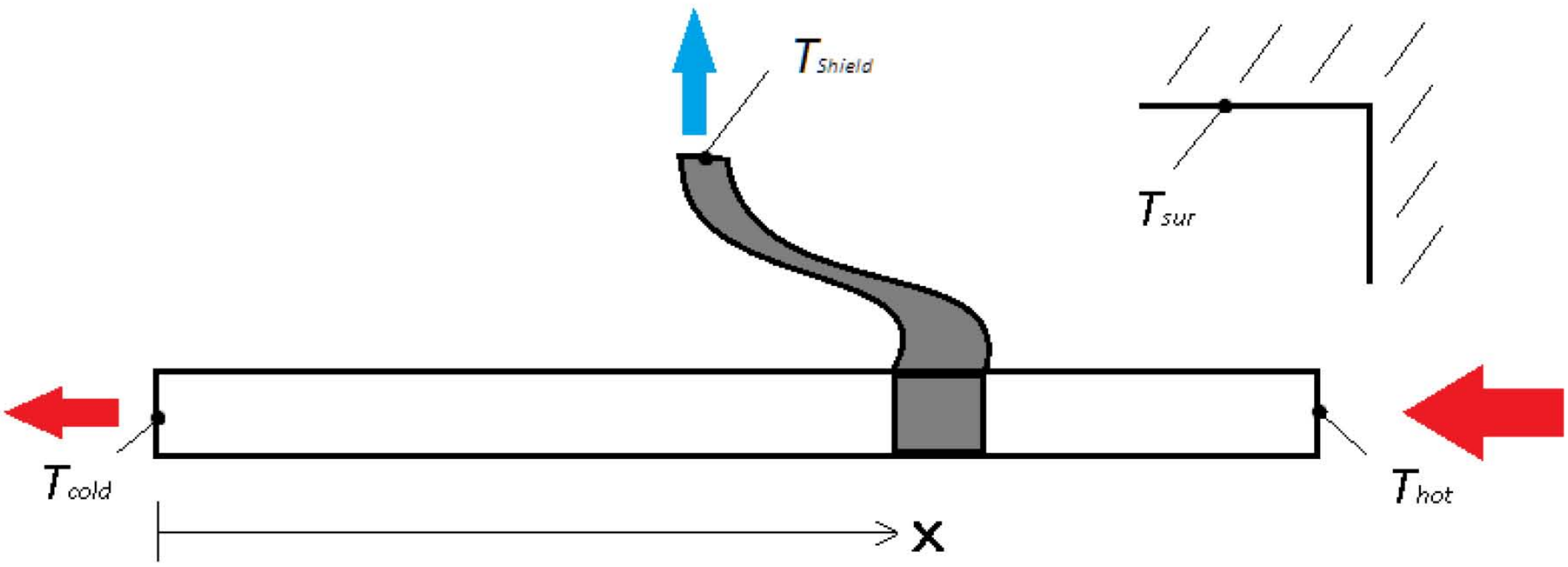
Broad area cooled shield



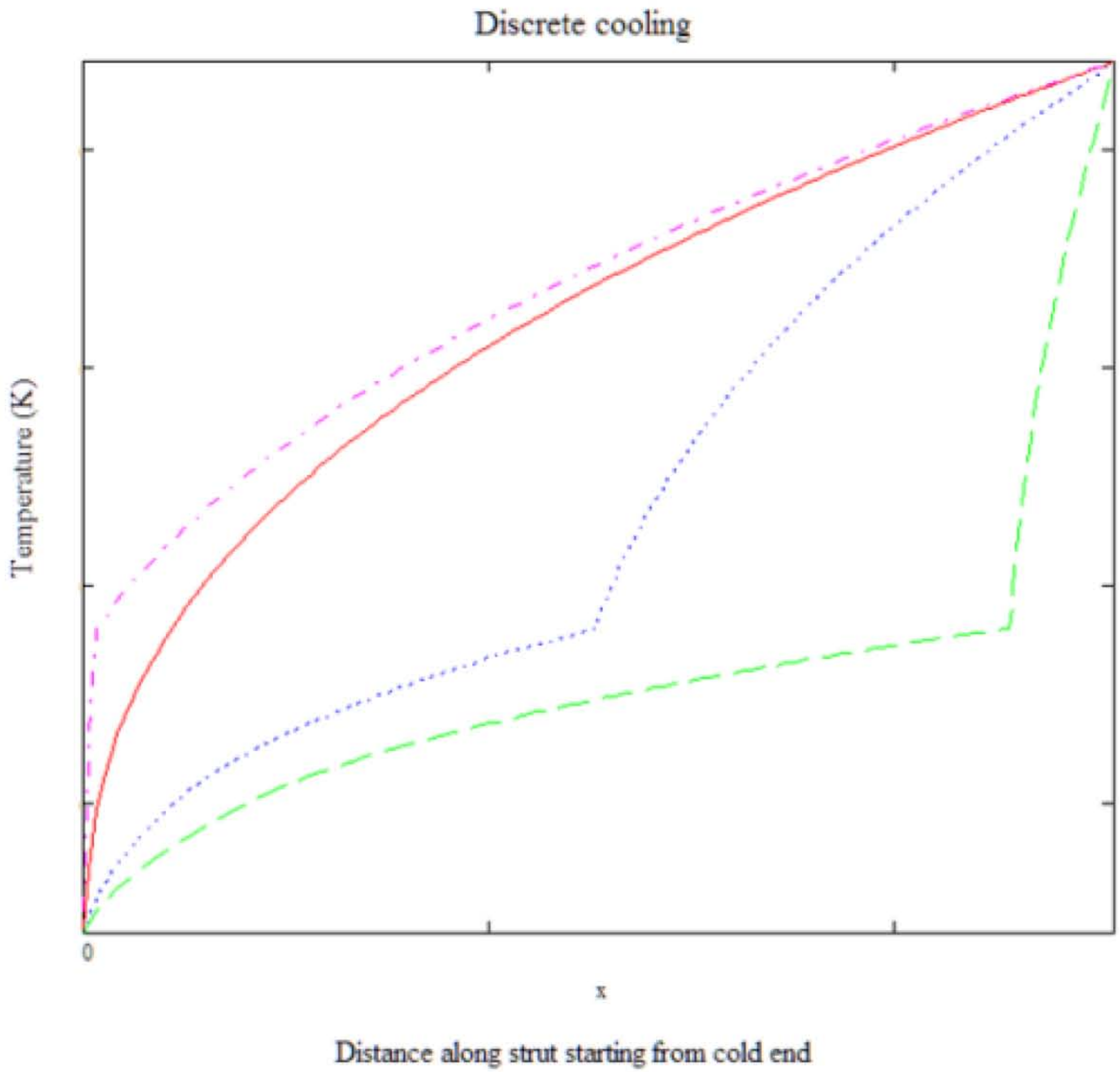
The CBRS design uses the pictured broad area cooling shield to intercept heat radiating into the tank. Heat conducted into the tank through penetrations, like the titanium strut shown below, is also intercepted.



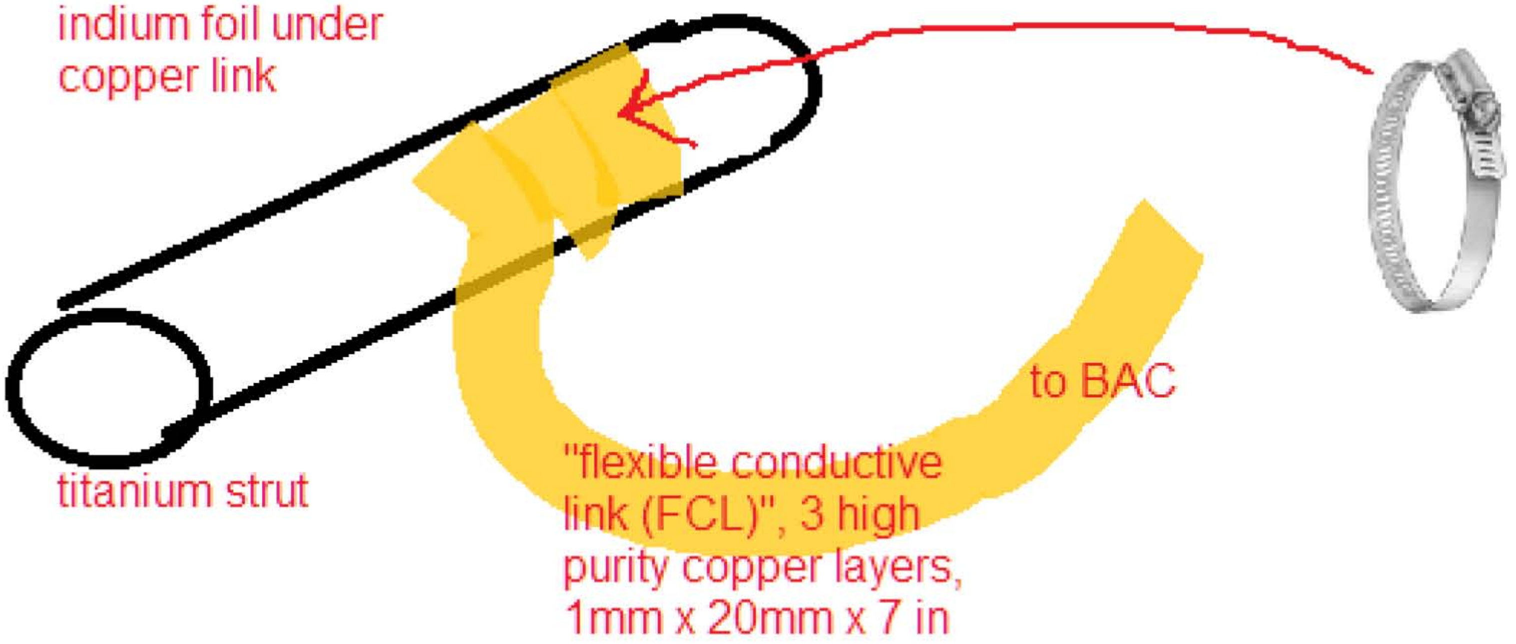
Piggybacking off the cooled shield



Ideal temperature profiles



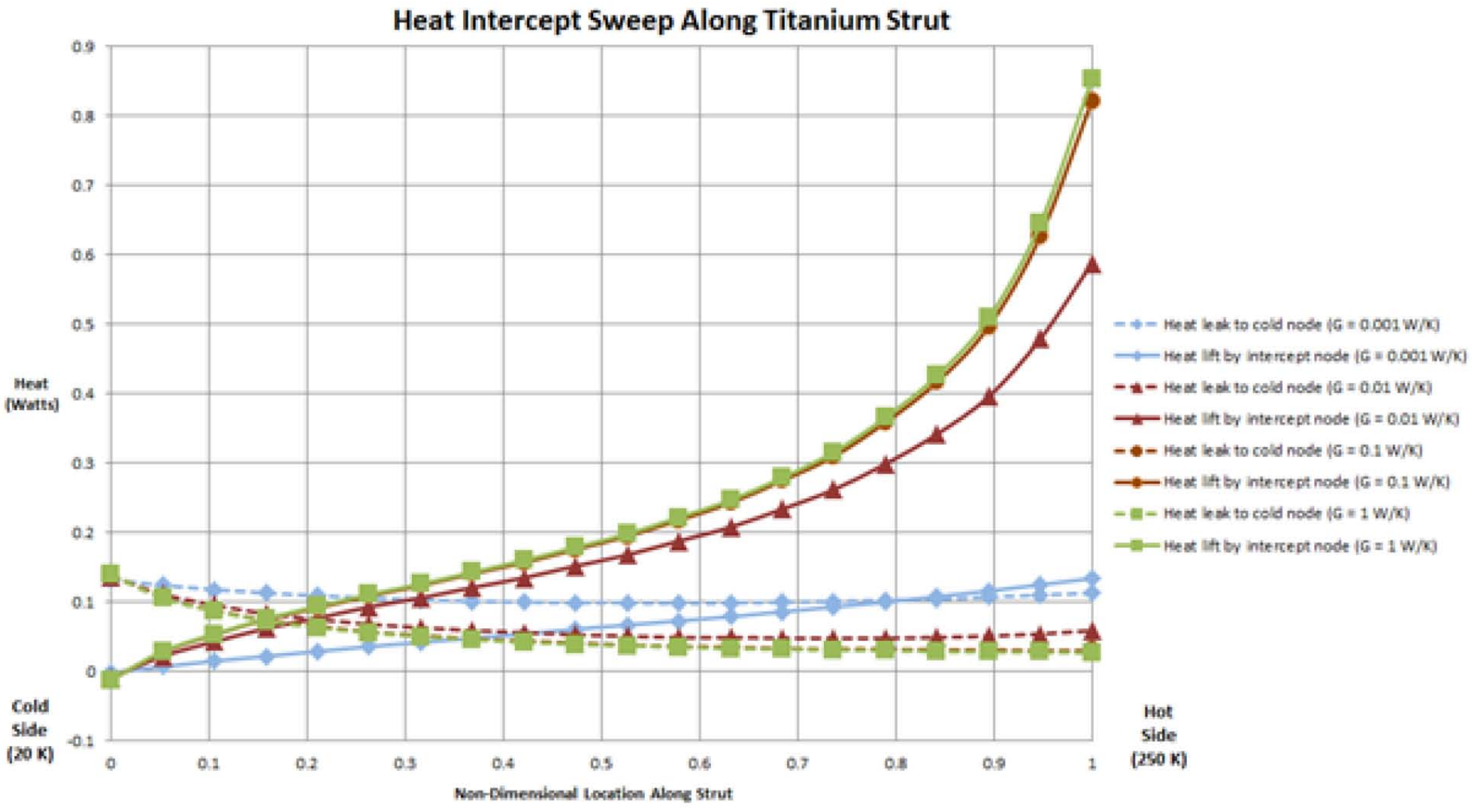
Initial conceptual sketch



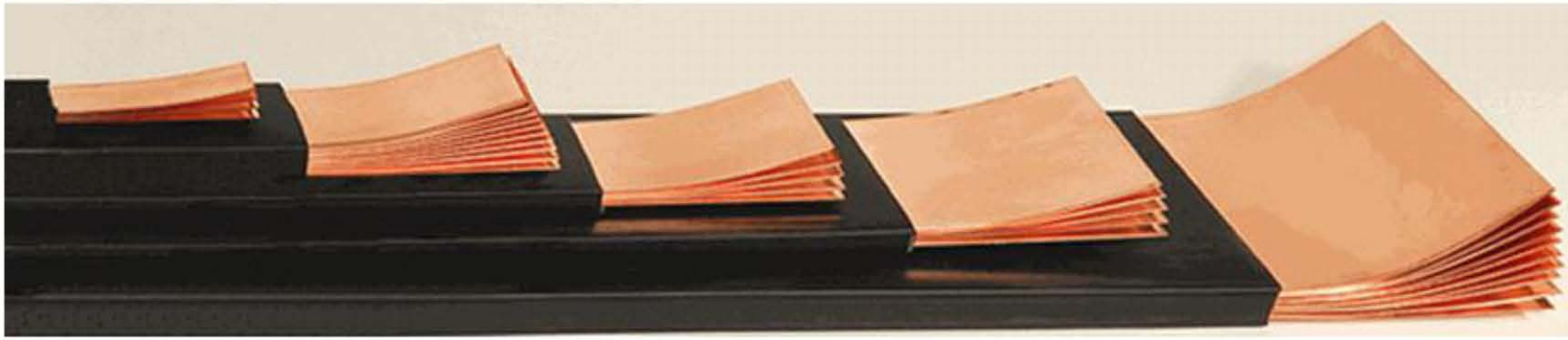
Four steps

1. Sizing with `ideal' model
2. Detailed design
3. Validate with most detailed model
4. Troubleshoot and redesign

Step 1: Sizing the thermal link



Semi-flexible ETP copper bus bar for prototype



Flexible Insulated Busbar

Storm copper components, Co.
http://store.electrical-insulators-and-copper-ground-bars.com/flexible-insulated-busbar.html

Step 2: Detailed sizing via trial and error

I'll choose 400 W/m-K for the ELI copper that's 99.9% pure (see STCH vol. 2 for a graph of thermal conductivity as a function of T for different copper alloys. They show 99.95% ETP, but that's okay, it can be estimated based on the trends of decreasing copper content curves.

$$k_{FCL} := 4\frac{W}{cm \cdot K} = 400 \cdot \frac{W}{m \cdot K}$$

Shortest distance between the two attachment points

$$L_{req} := 6.25in$$

Shape efficiency $\eta_s := 0.7$

Heat transfer length of the FCL $L_{FCL} := \frac{L_{req}}{\eta_s} = 8.929 \cdot in$

End piece efficiency (how well the foils are attached to the end piece) choose 1.0 if welded, and down to 0.3 for other attachment methods $\eta_E := 1.0$

Foil thickness $t := 1mm$

Number of foils $N_{foils} := 3$

Width of foils $W_{FCL} := 20mm = 0.787 \cdot in$

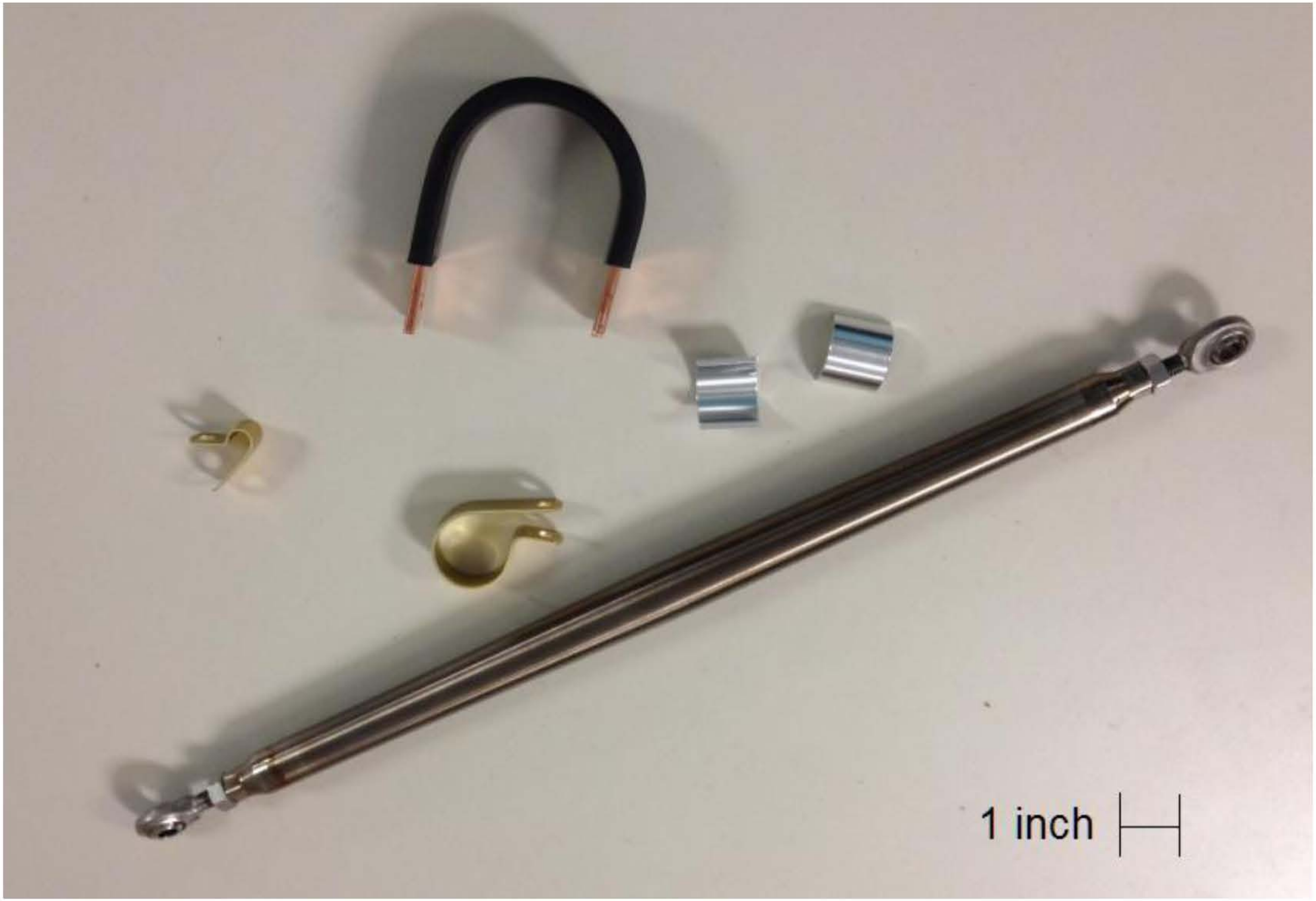
Heat transfer cross sectional area $A_{FCL} := W_{FCL} \cdot (N_{foils} \cdot t) = 60 \cdot mm^2$

Actual cross sectional area (for packaging concerns only; this number is irrelevant to heat transfer) $\eta_P := 0.95$ $A_{actual} := \frac{A_{FCL}}{\eta_P} = 63.158 \cdot mm^2$

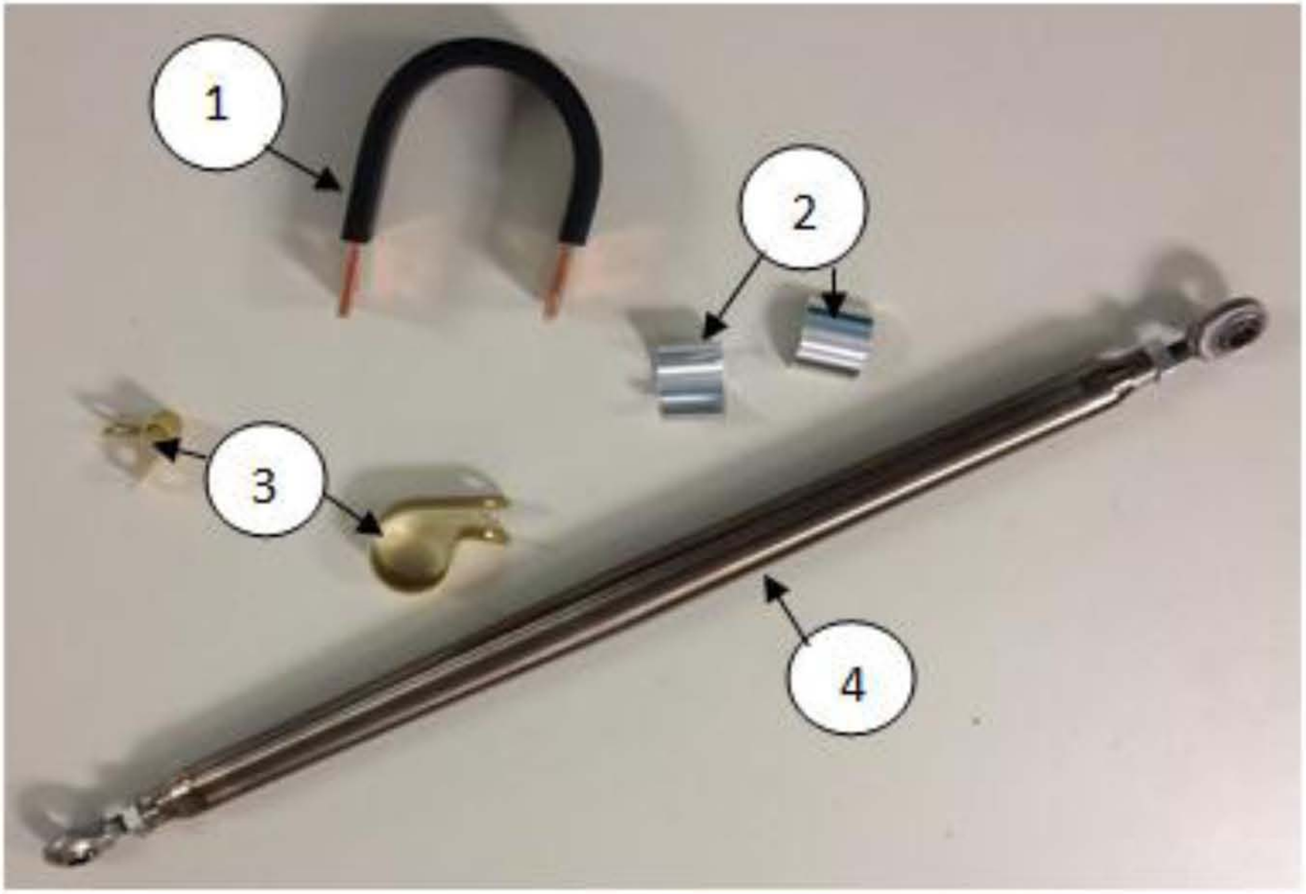
Pure conduction conductance $G_{FCL} := \frac{k_{FCL} \cdot A_{FCL}}{L_{FCL}} = 0.106 \cdot \frac{W}{K}$

- one dimensional, steady state, constant properties, no heat generation model
- utilizing a few flexible thermal link specific parameters and estimates (shape efficiency, for example)
- More information on this approach can be found in the Spacecraft Control Thermal Handbook, Volume 1.

First iteration hardware

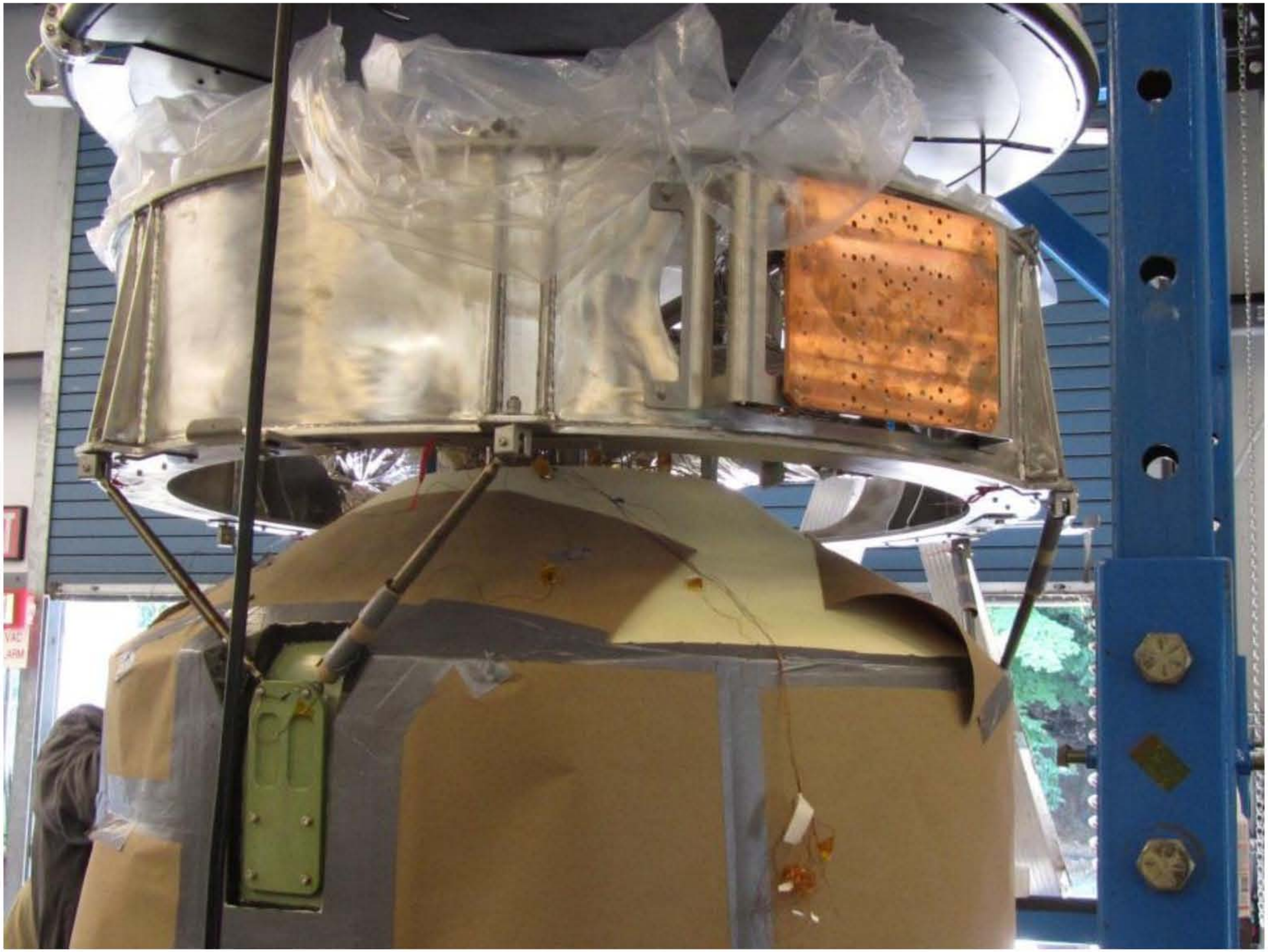


First iteration hardware

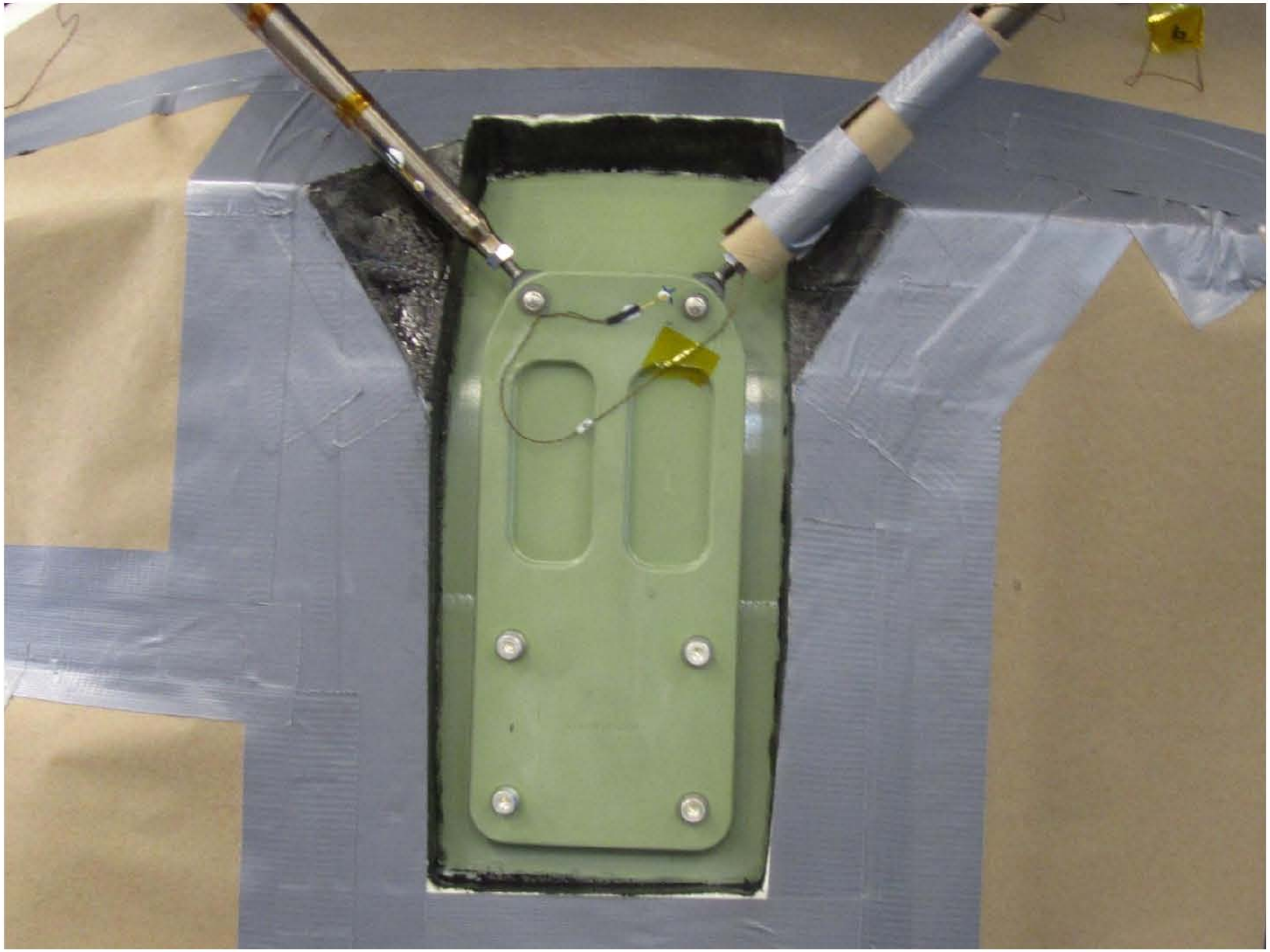


1. Thermal link
2. Indium Foil
3. Original Collars
4. Titanium Strut

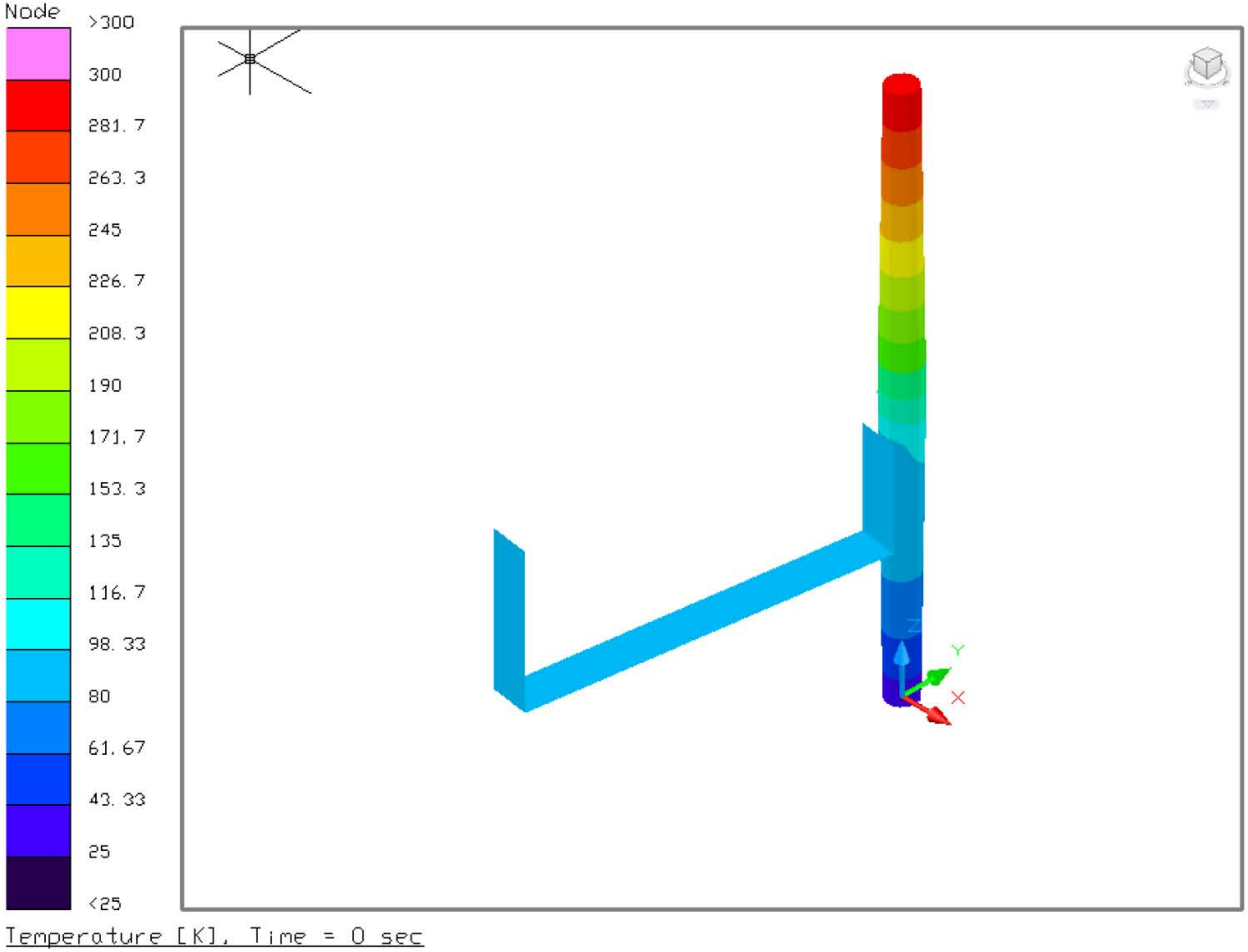
Prototype pictures



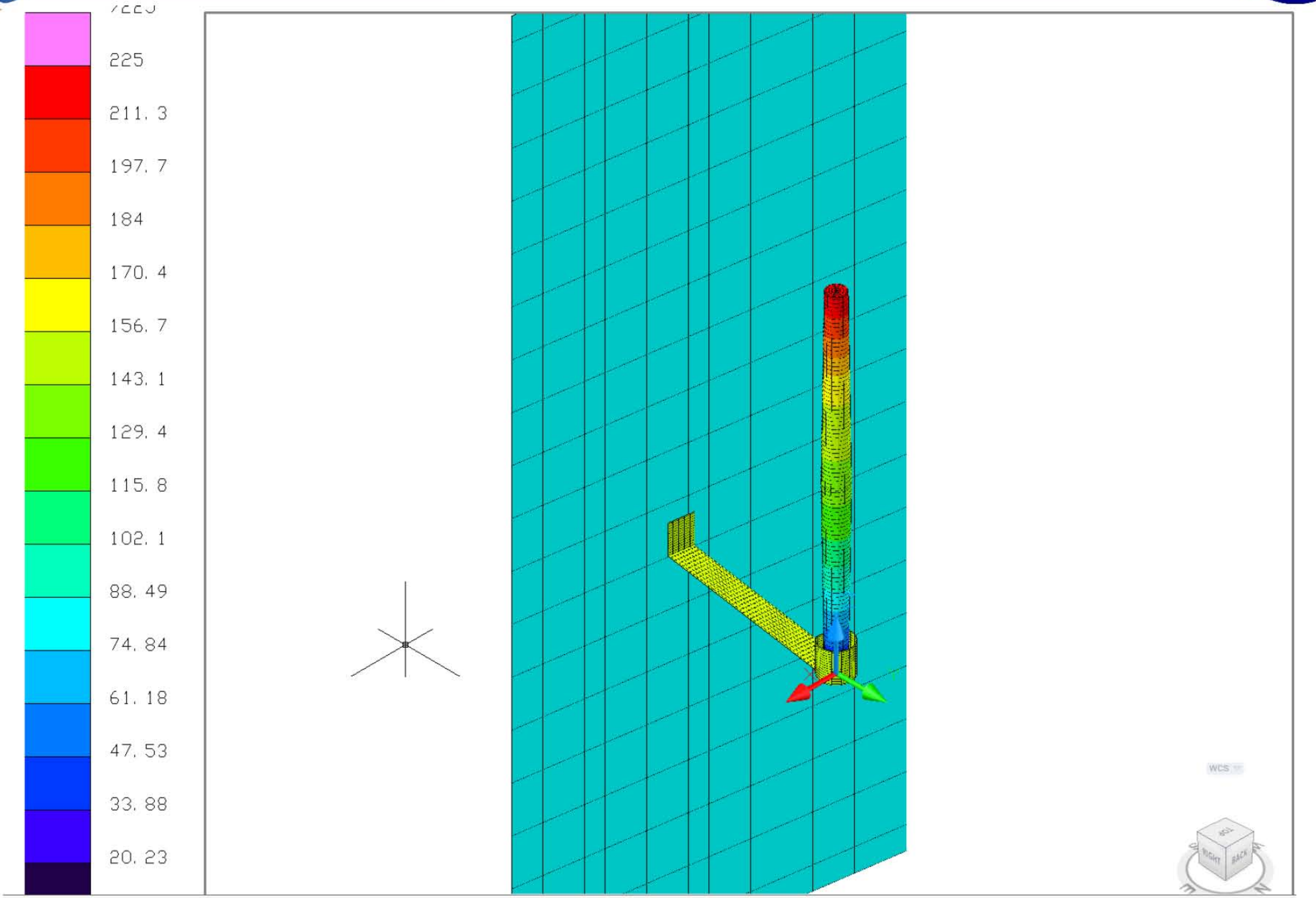
Prototype pictures



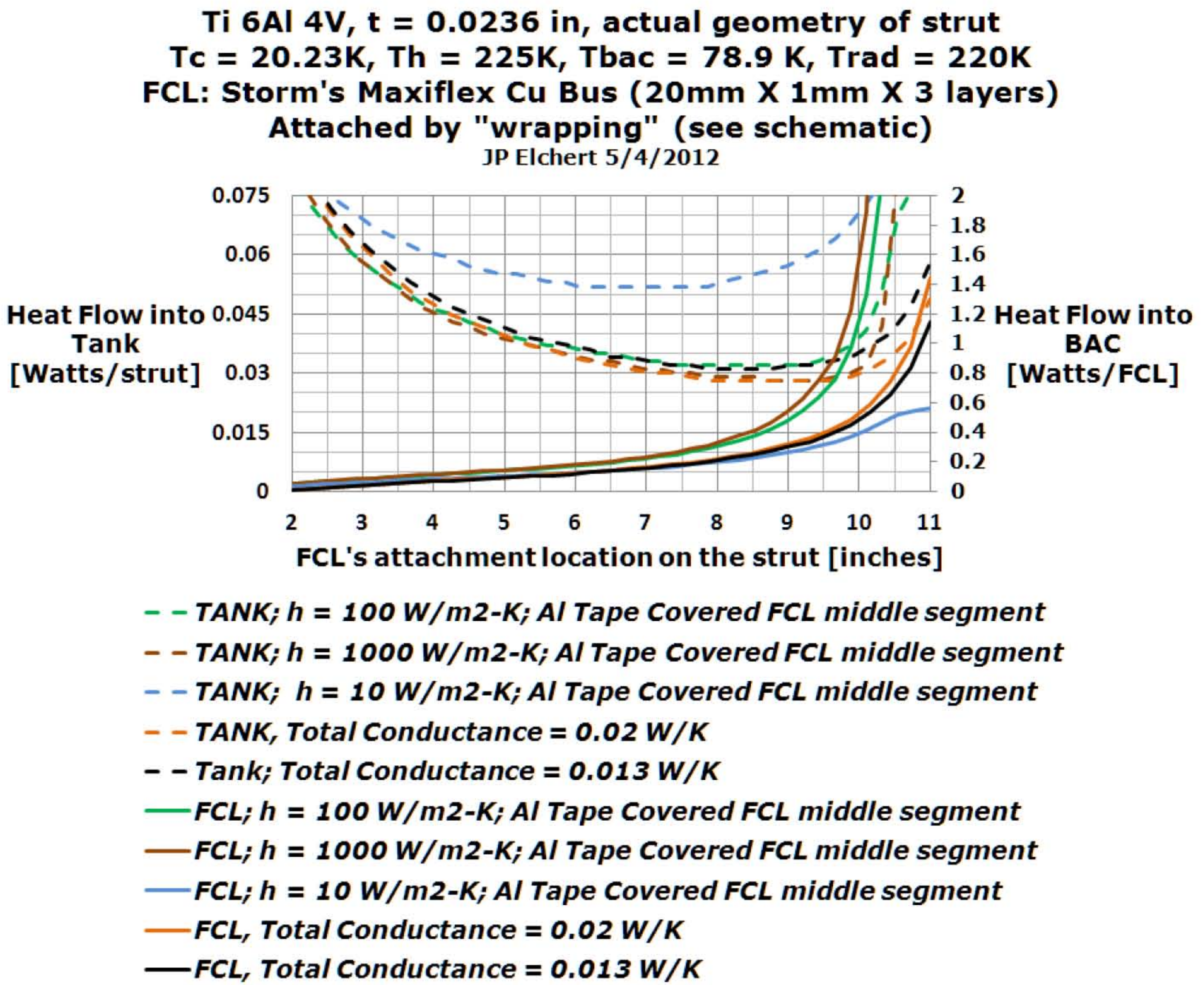
Step 3) Validation



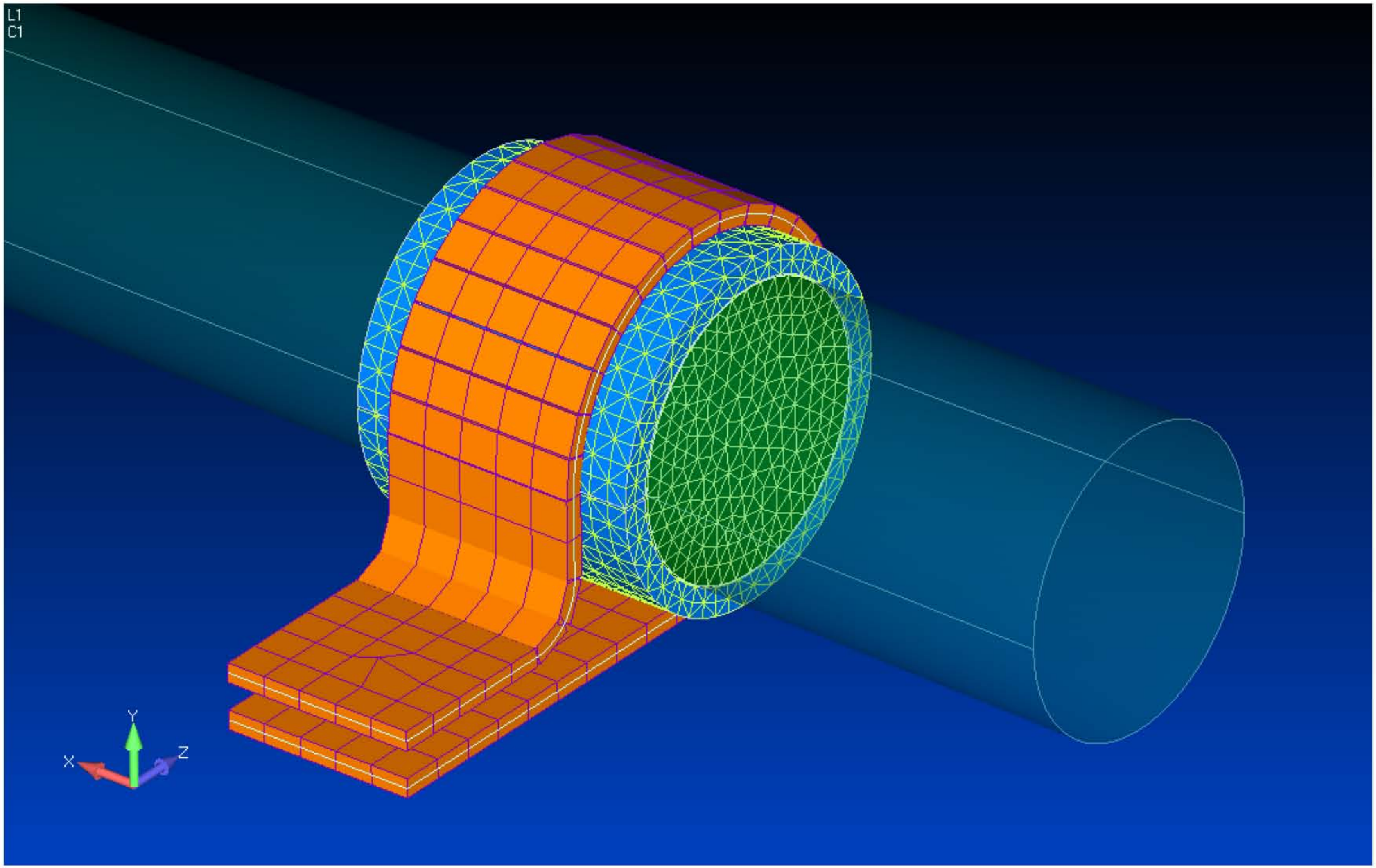
Step 3) Validation



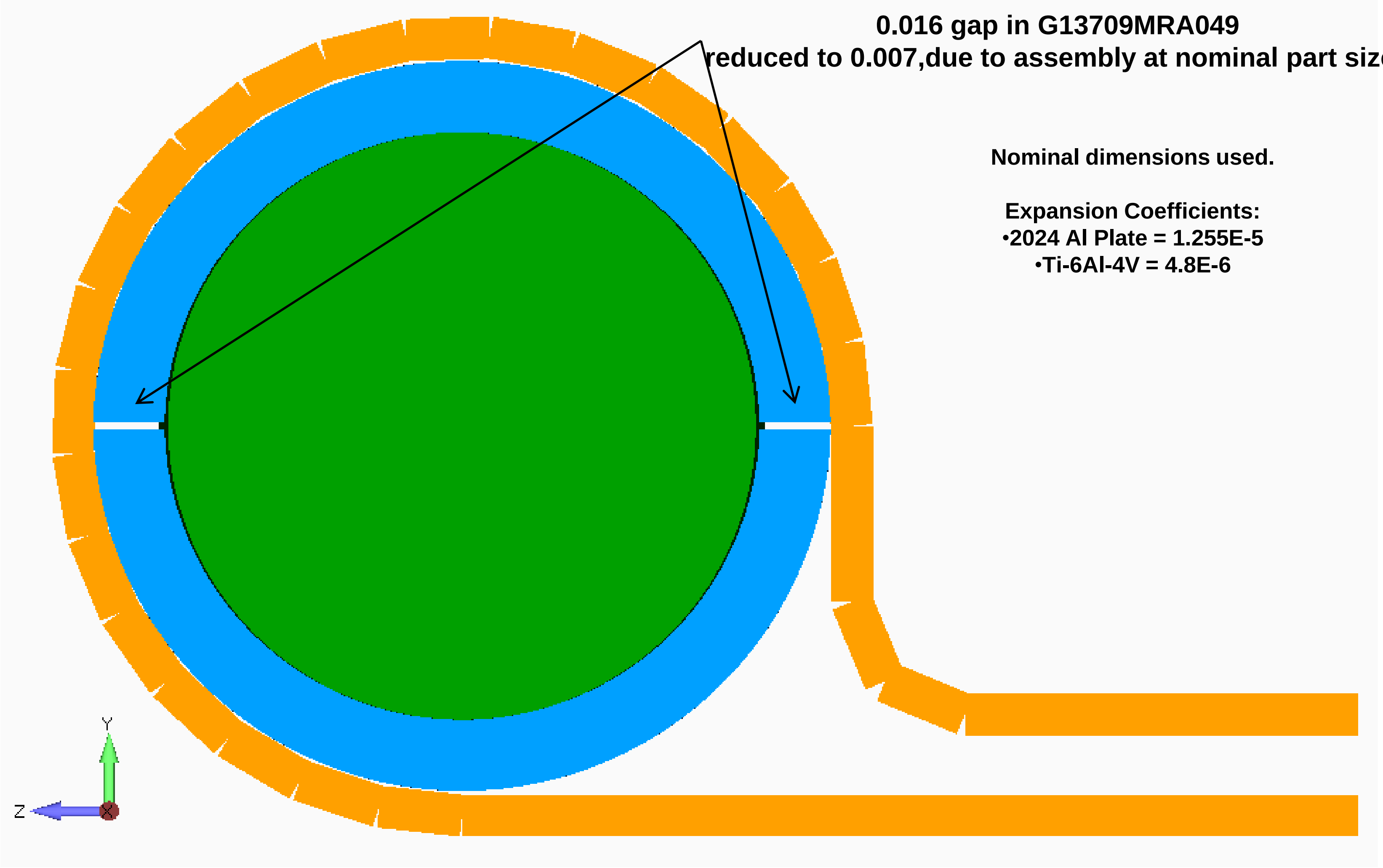
Step 3) Validation



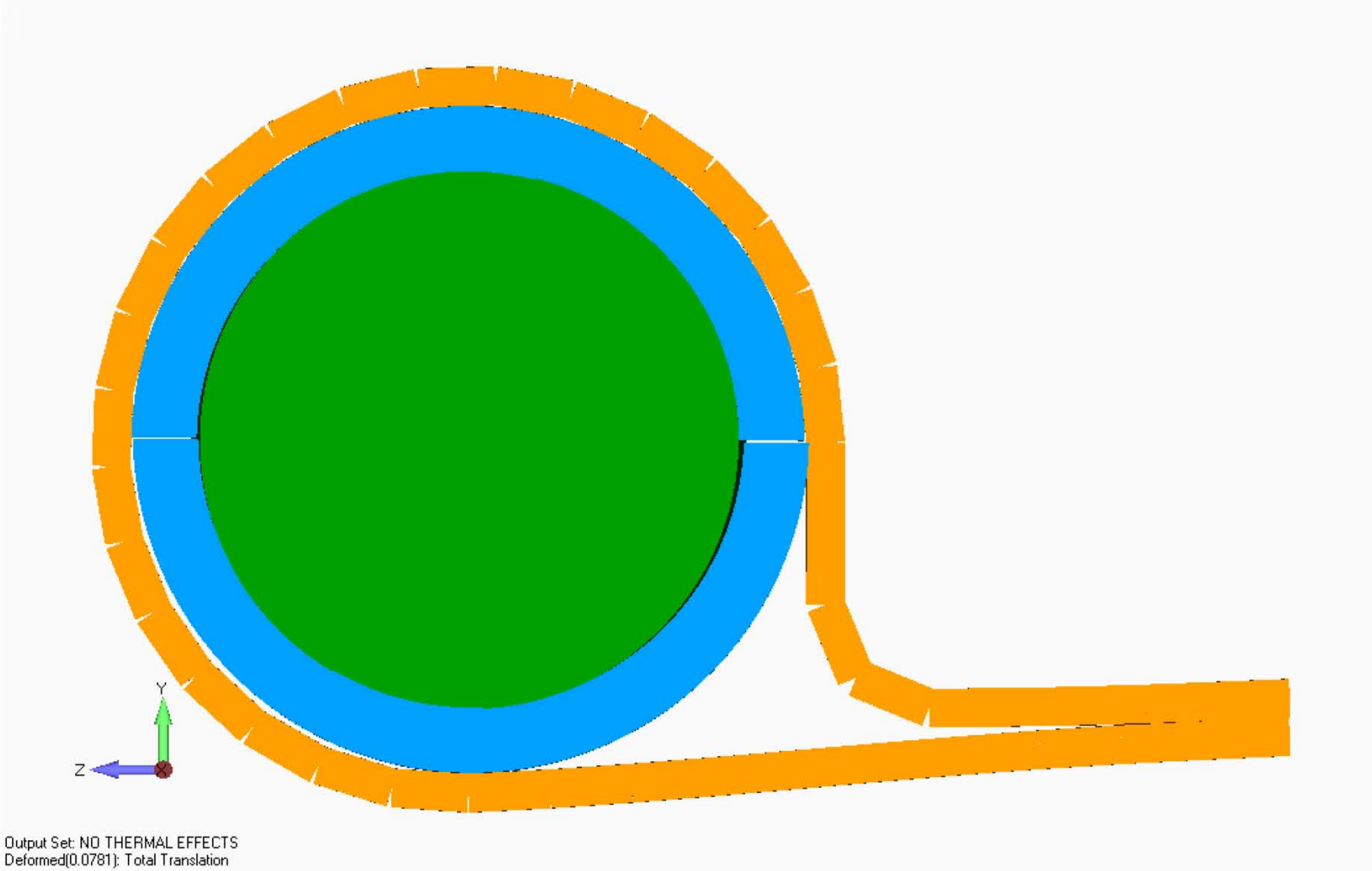
Contact resistance concerns (Gebby results)



Model prior to loading (credit Gebby)

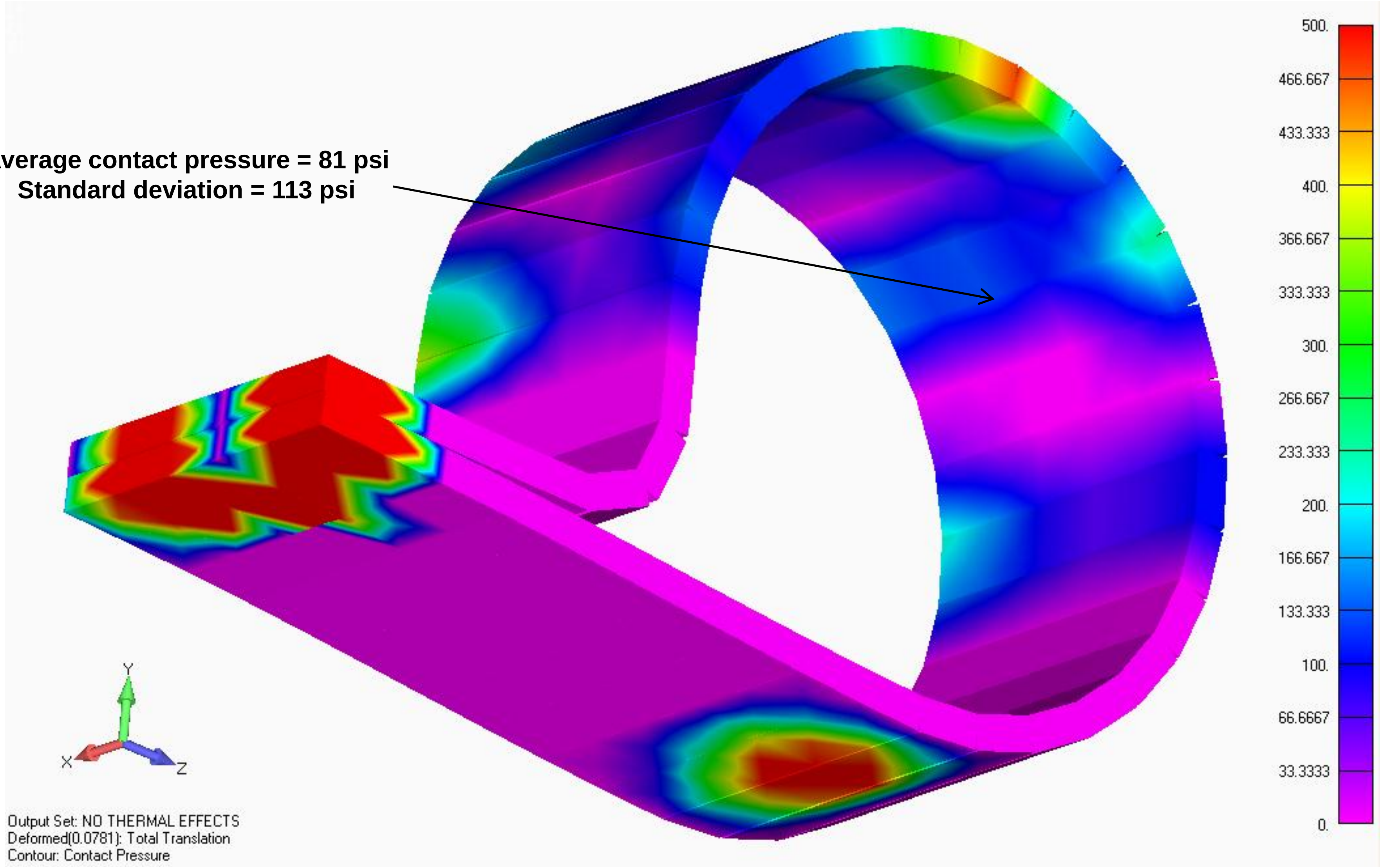


Deformed displacement, neglecting CTE

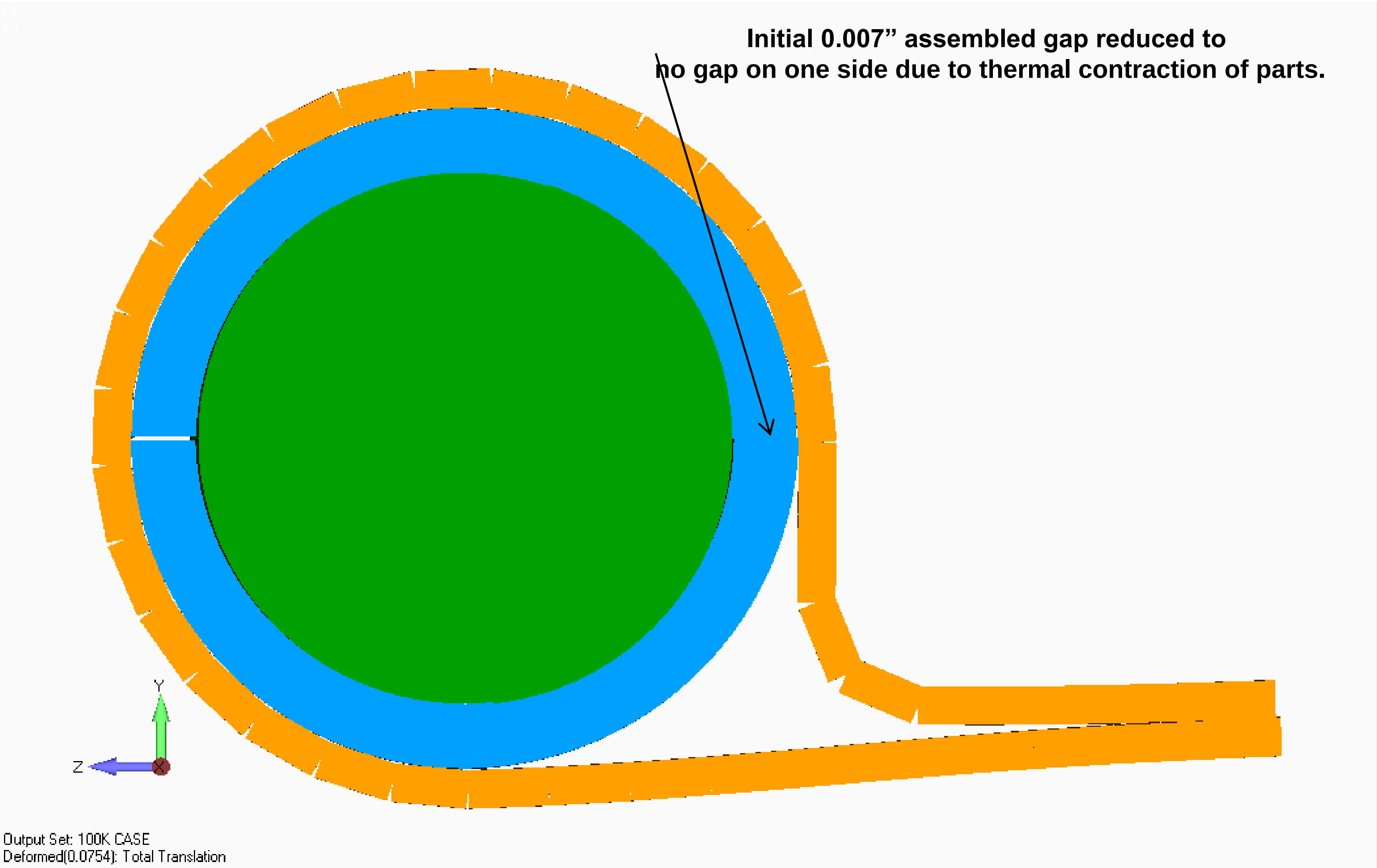


Contact Pressure (psi)

Average contact pressure = 81 psi
Standard deviation = 113 psi



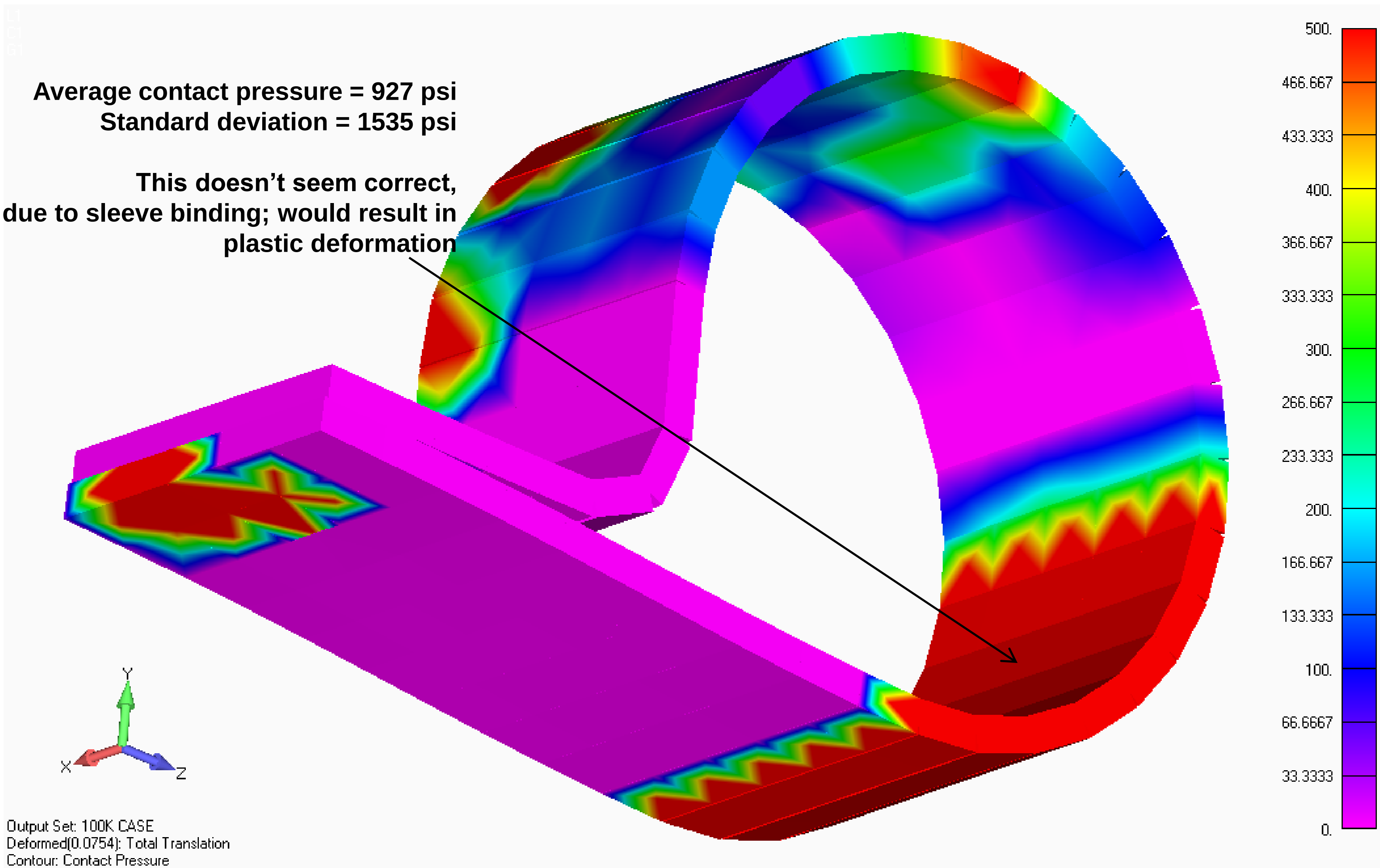
Deformed total displacement, cooled to 100K



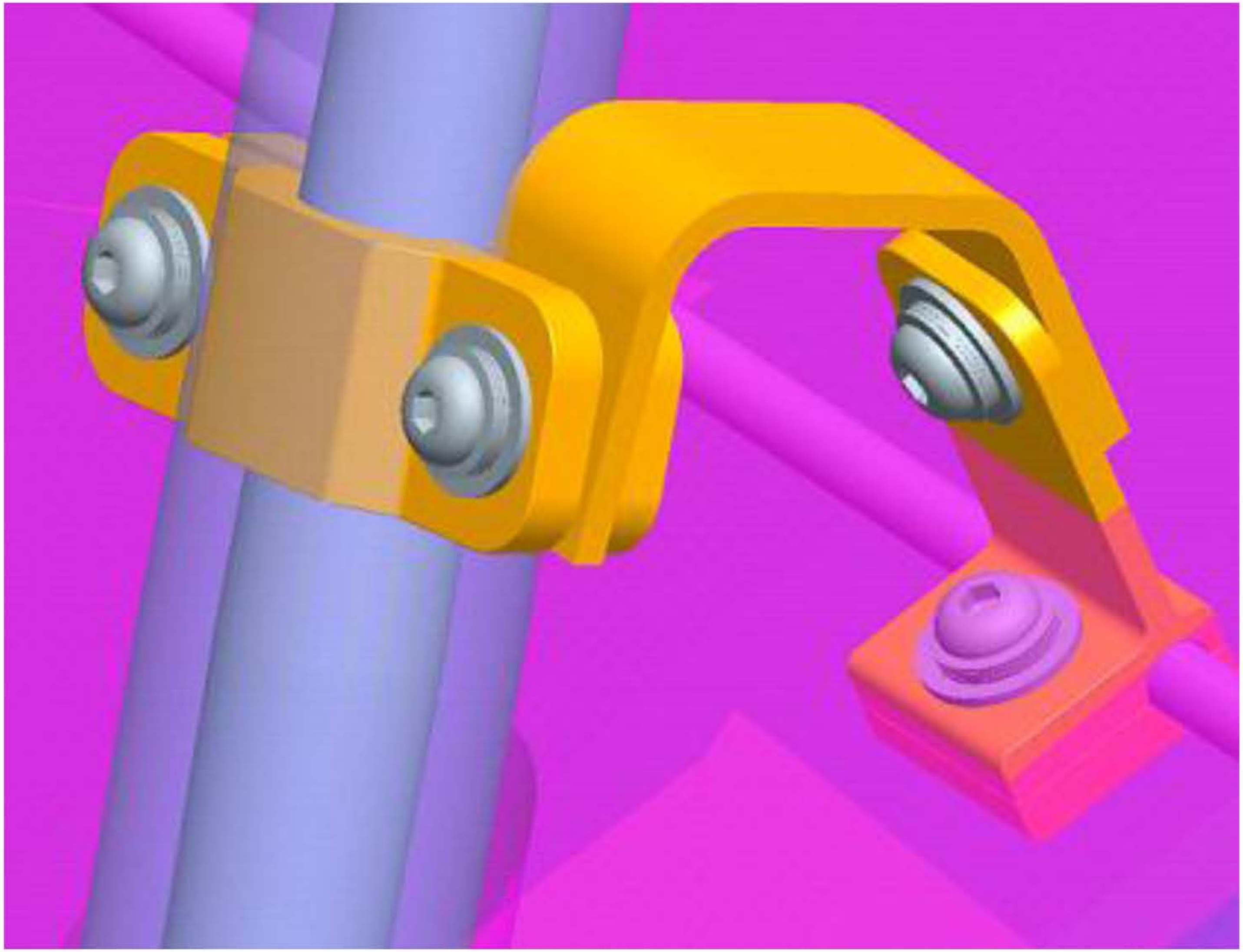
Contact pressure (psi), cooled to 100K

Average contact pressure = 927 psi
Standard deviation = 1535 psi

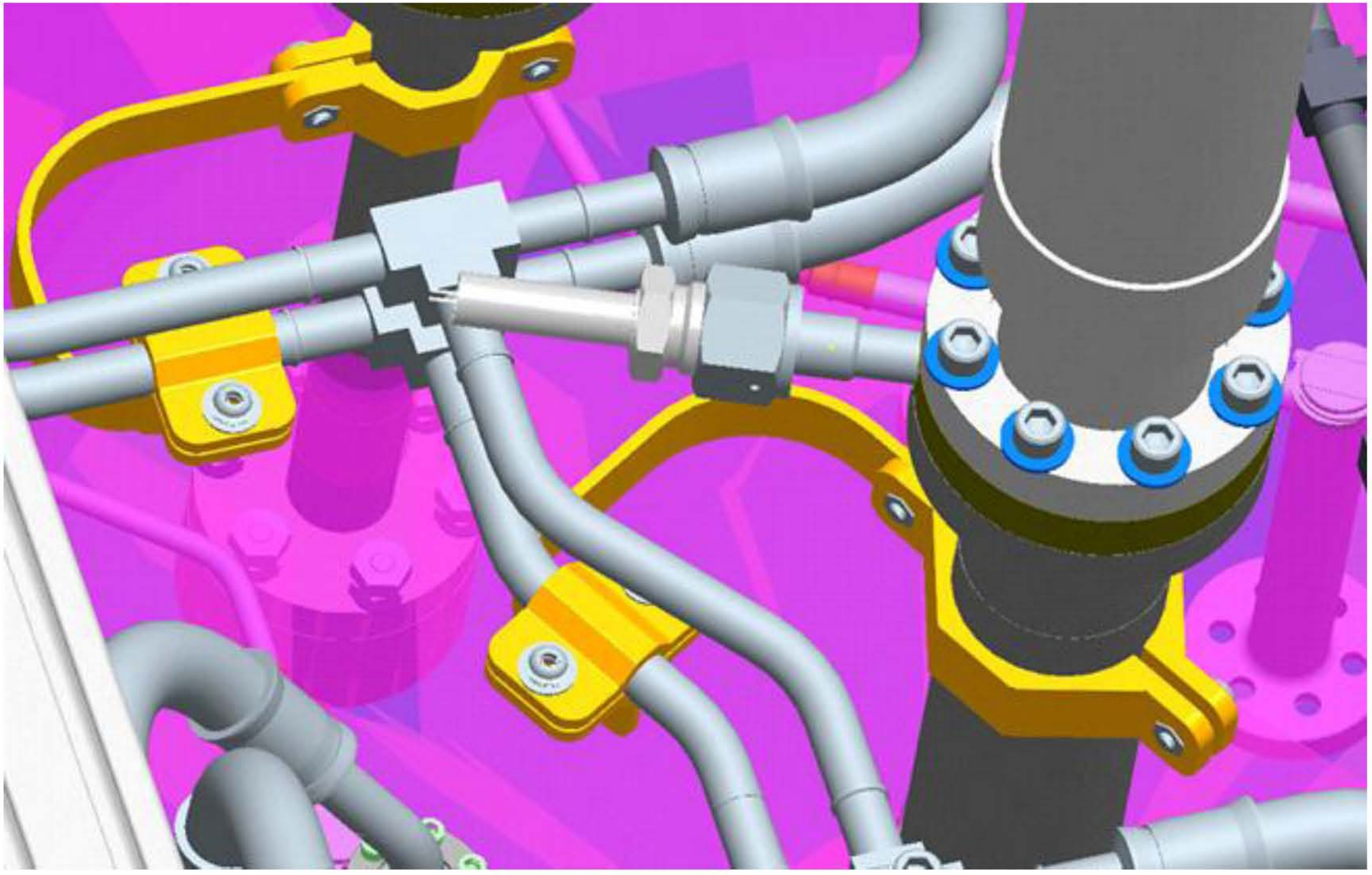
This doesn't seem correct, due to sleeve binding; would result in plastic deformation



Step 4) Redesign



Total conductance ~0.05 W/K



Thermal Desktop Model: Summary of Results (Kashani results)

T shroud (K)	T sup ring (K)	Sup ring Heat (W)	T reject (K)	Strap cnd (W/K)	Mass flow (g/s)	T shield/ cooler(K)	Q cooler (W)	P input (W)
220	249	28.52	N/A	N/A	N/A	N/A	N/A	N/A
220	249	28.52	220	0.013	N/A	199	N/A	N/A
220	250	28.52	275	1	2.0	77.2	11	277
220	248	28.52	275	0.013	2.0	77.2	11	277
220	248	28.52	275	0.03	2.0	77.2	11	277

Heat Leak to Tank (W)					Heat Removed by ATC System (W)			
MLI	**Struts**	**Stand-offs**	**Vent**	**Total**	**MLI**	**Struts**	**Manifold**	**Total**
1.1590	0.6315	N/A	0.5441	2.3346	N/A	N/A	N/A	N/A
1.1491	0.6052	0.1818	0.6654	2.6015	N/A	N/A	N/A	N/A
0.2483	0.1347	0.0607	0.2237	0.6674	6.0659	1.8704	1.6293	9.5656
0.2477	0.1991	0.0606	0.3178	0.8252	6.0692	1.6446	1.239	8.9528
0.2480	0.1638	0.0606	0.2234	0.6958	6.0676	1.7702	1.6326	9.4704

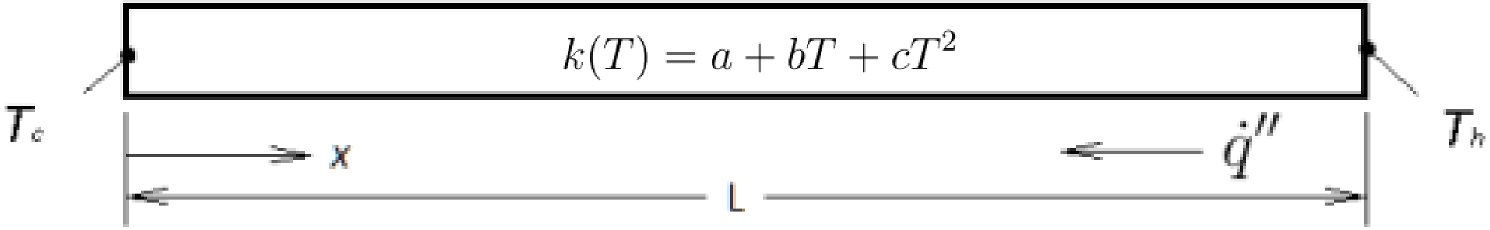
Reduction in heat leak

- Reduction in strut heat leak of roughly 70%
- Temperature gradient across thermal link of roughly 10K; temperature gradient drives the design less than conductance
- Fin efficiency still above 90%
- Using bus bar for the prototype was economical; a true flexible foil copper thermal link with state of the art end pieces would perform better (eliminates some contact resistances)

Extra: Intro. to general strut heat transfer

- Boundary conditions
- Conduction
- Radiation
- Insulation

Textbook conduction



$$\dot{q}'' = -k\frac{\mathrm{d}T}{\mathrm{d}x}$$

$$T(0) = T_c \quad \Rightarrow \quad \theta(T(0)) = \theta(T_c)$$
$$T(L) = T_h \quad \Rightarrow \quad \theta(T(L)) = \theta(T_h)$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(k\frac{\mathrm{d}T}{\mathrm{d}x}\right) = 0 \quad \& \quad \theta(T) \equiv \int_0^T -k(T)\,\mathrm{d}T \quad \Rightarrow \quad \frac{\mathrm{d}^2\theta}{\mathrm{d}x^2} = 0$$

$$aT + \frac{b}{2}T^2 + \frac{c}{3}T^3 = \frac{\theta(T_h) - \theta(T_c)}{L}x + \theta(T_c)$$

Fox and Scurlock's Boil off experiment

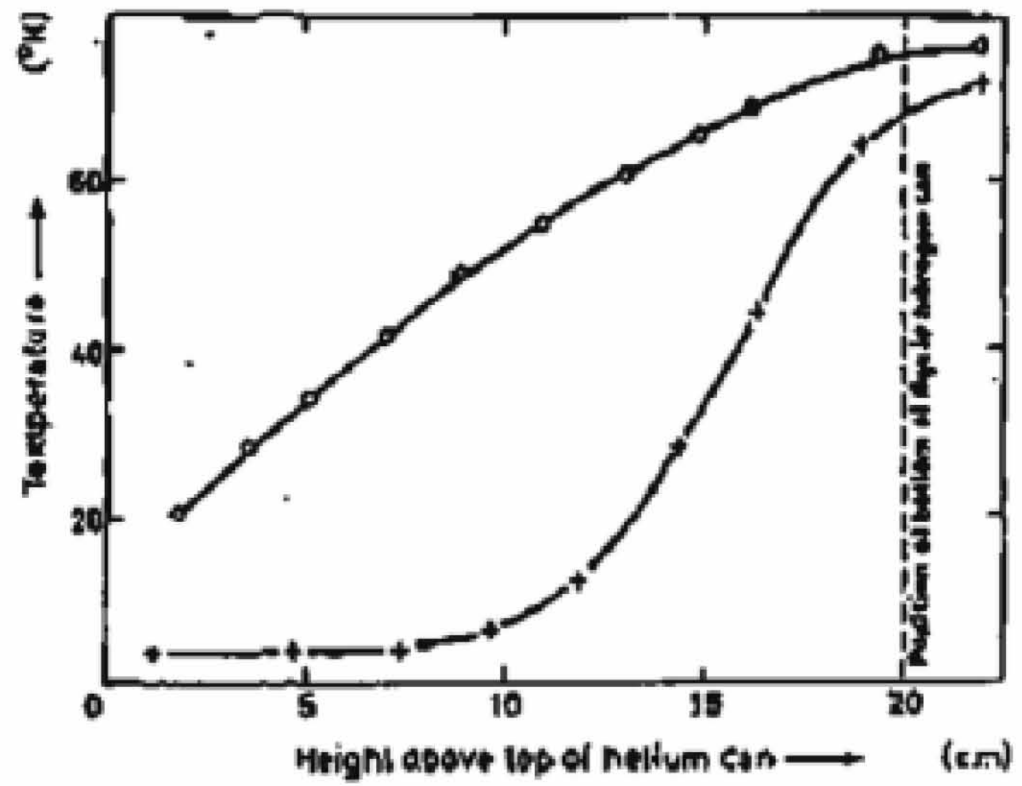
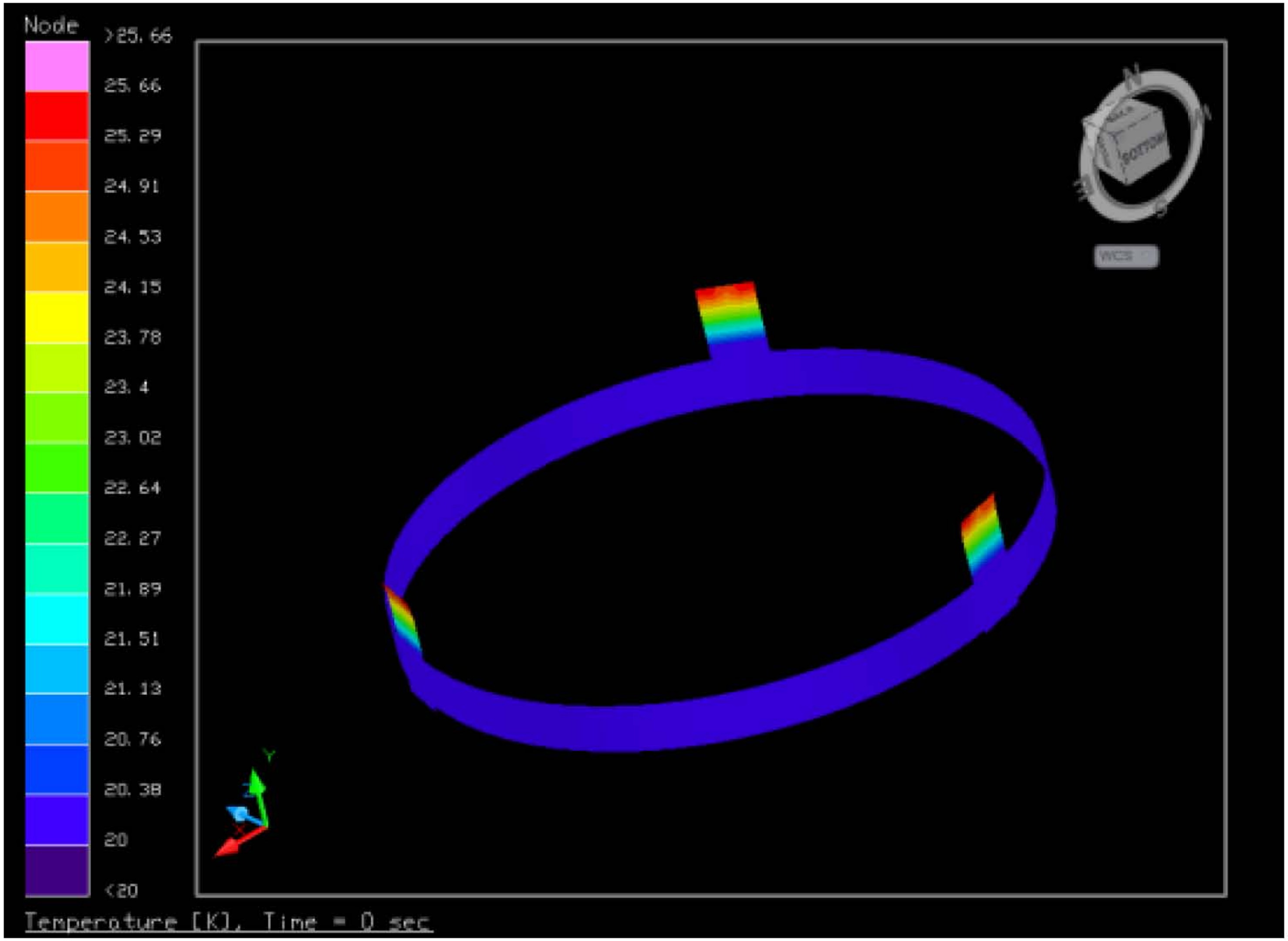
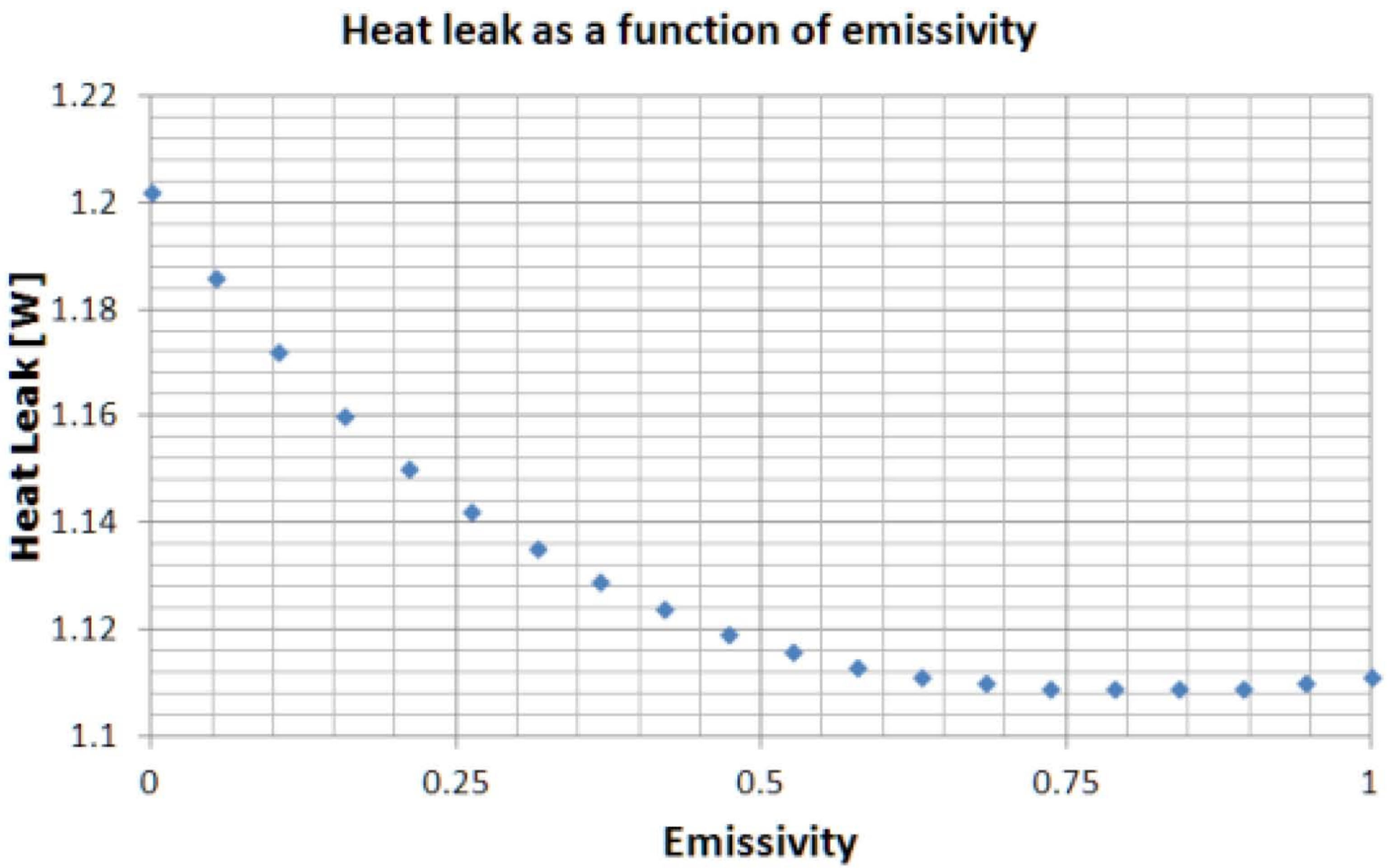


Figure 1. Temperature profiles in open tube + and closed tube ○

A gradient exists through the attachment brackets



`Optimum' uniform emissivity



Emissivity of inner coating of tube

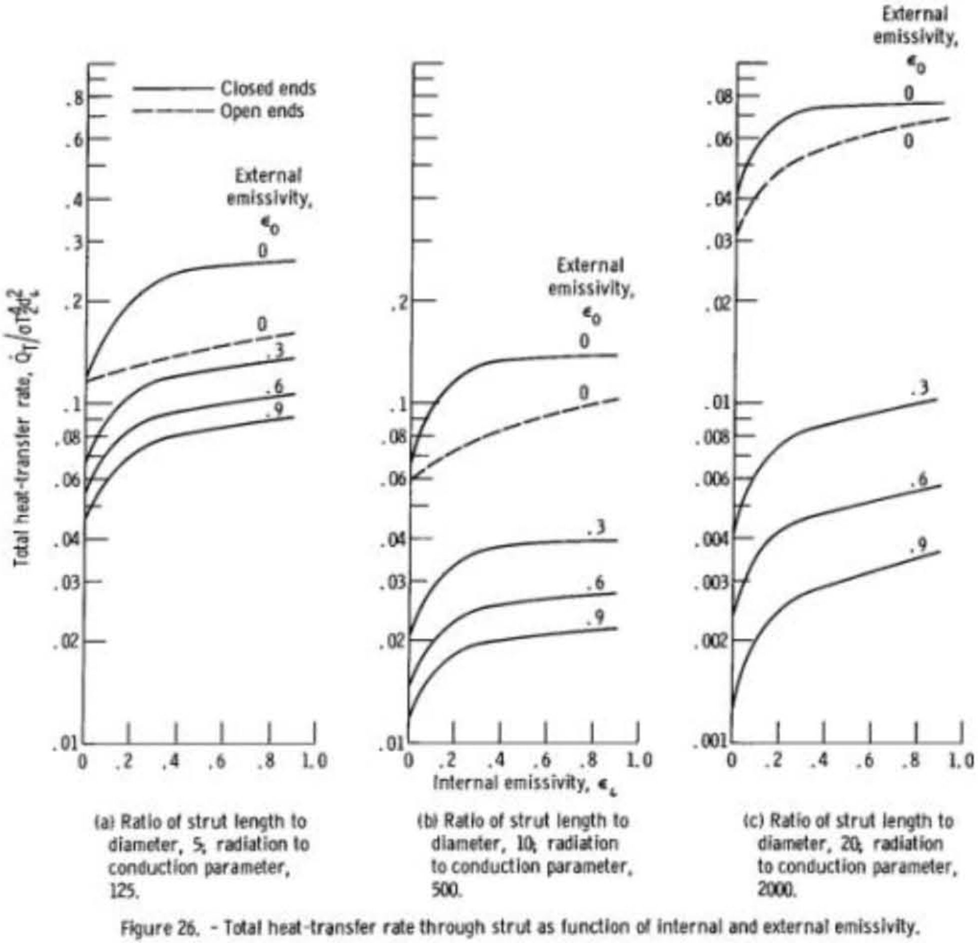
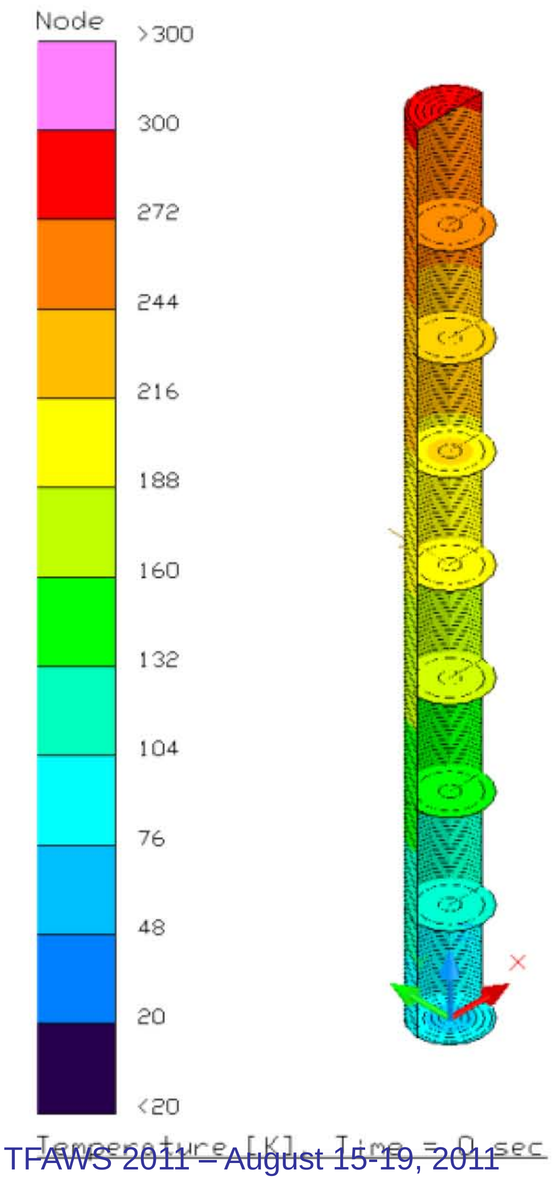


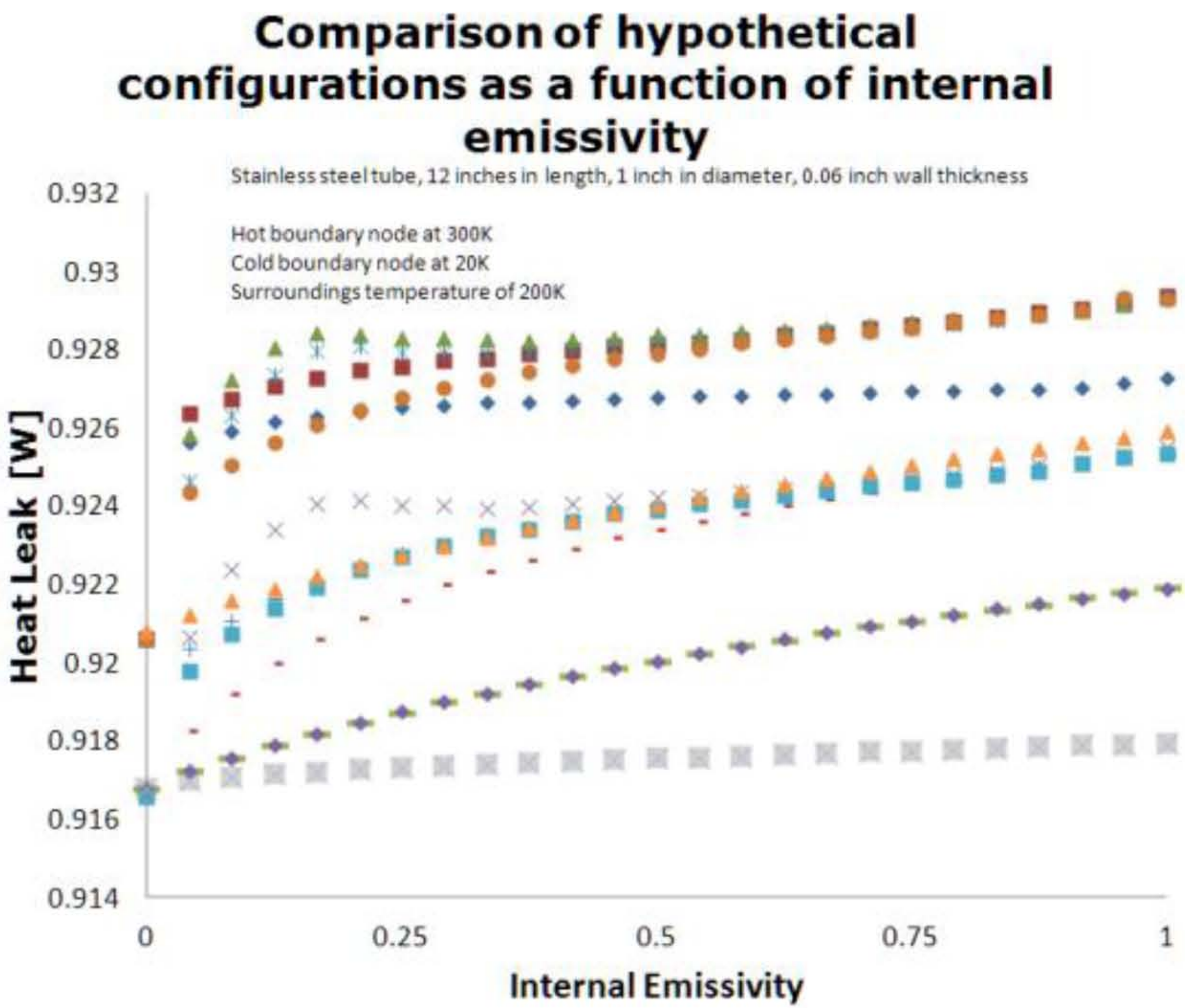
Figure 8: In their analysis, the external, large, isothermal surroundings temperature was taken to be 0K.

Boyle, Robert J. and Richard H. Knoll, "Thermal analysis of shadow shields and structural members in a vacuum." D-4876, NASA Lewis Research Center, 1968

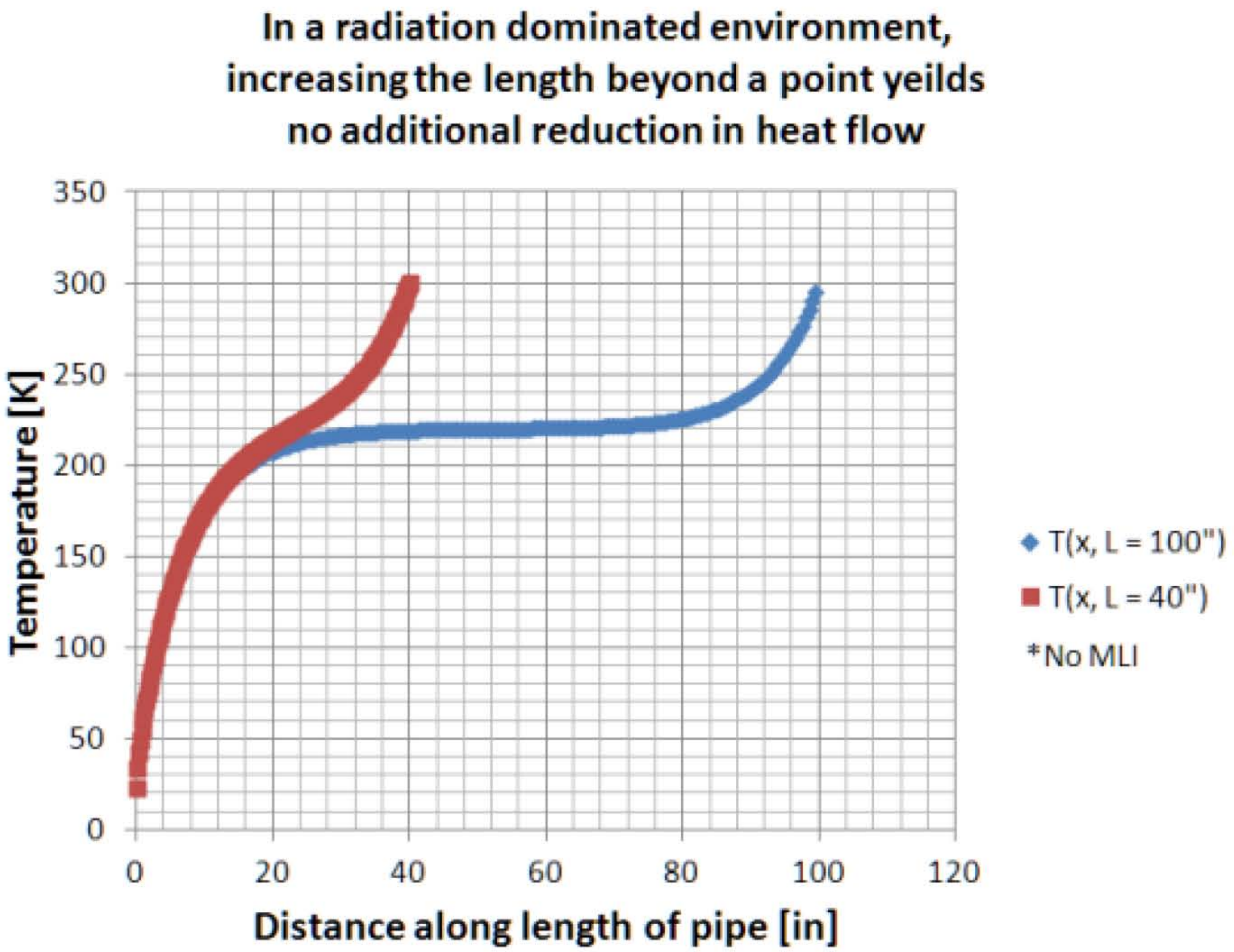
Extending Boyle and Knoll’s work



Extending Boyle and Knoll's work



Critical length / fin problem



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