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Aerospace Engineering Department

Jet Propulsion Laboratory
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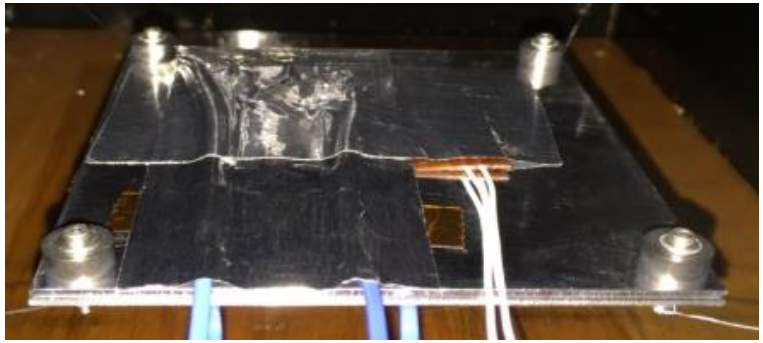
Design and Testing of a Low Cost Shape Memory Alloy (SMA) Heat Switch for CubeSats



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March 28th, 2017

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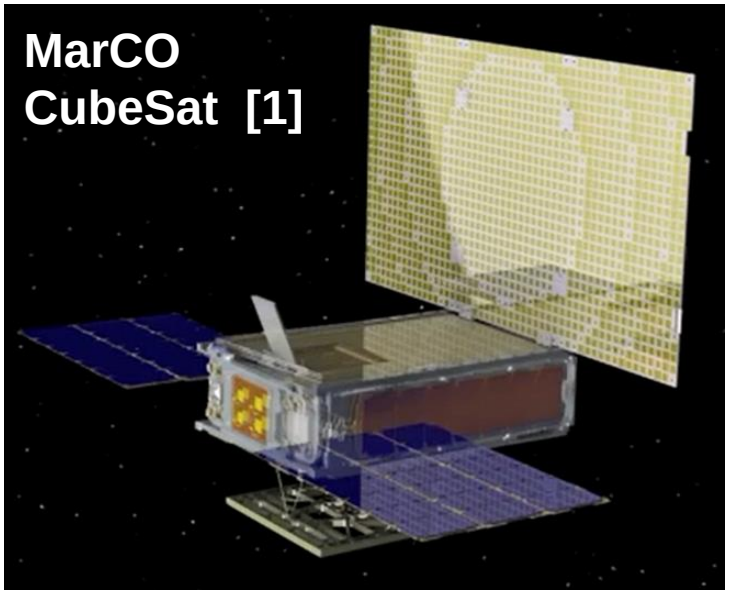
Outline

- Introduction
- Design
- Analysis
- Test Set Up
- Test Results
- Lessons Learned
- Design Improvements
- Future Work
- Conclusions

Introduction

- Until recently, CubeSats and NanoSats have relied solely upon heaters and thermal coatings to achieve thermal control.

- Deployable solar panels are changing CubeSat thermal dissipations:
  - More Power Available
  - Larger Power Dissipation Ratio



- CubeSats are starting to be used on interplanetary missions:
  - MarCO is accompanying Insight Spacecraft to Mars in 2018 [1]
  - **Missions beyond Mars will likely require a thermal turn down device.**

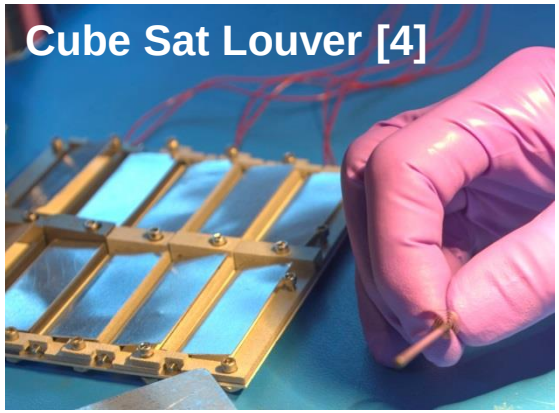
Current Turn Down Technology

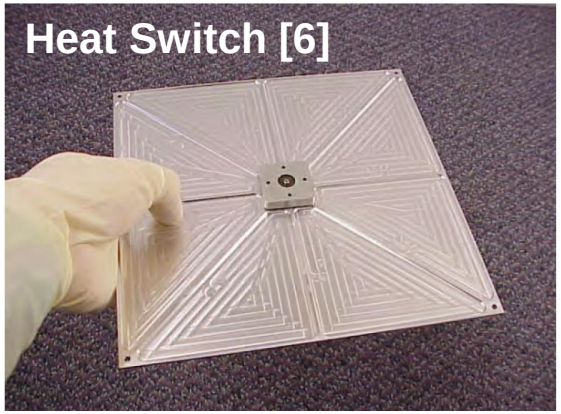
- Louvers
  - Typically use bimetallic springs and low ε vanes and yield turn down ratio of ~ 7:1 [2]
  - Recently adapted for CubeSats by GSFC [3, 4]
  - Planned for use on Dellingr CubeSat [4]

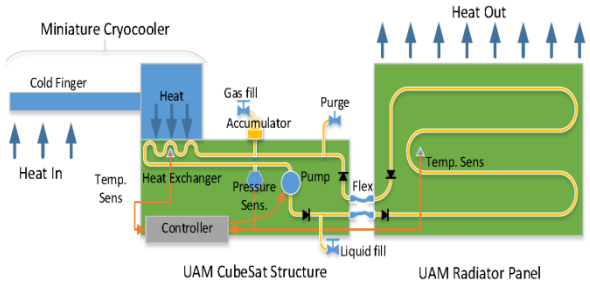
- Thermal Switches
  - Typically use paraffin wax phase change to provide a turn down ratio of up to 100:1 [2]
  - Heat Switch Radiators have been developed with a turn down ratio of 20:1 [5]

- Fluid Loops
  - Valves or pump modulation used for turn down
  - Ongoing work though NASA/University Partnerships [7, 8]

- **Primary challenge for turn down technology in CubeSats is cost and volume constraints!**

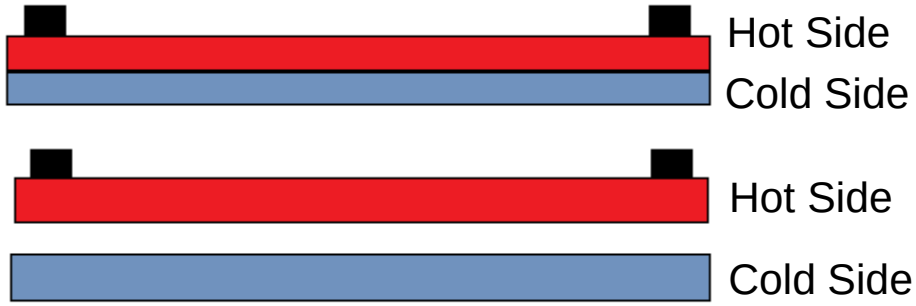


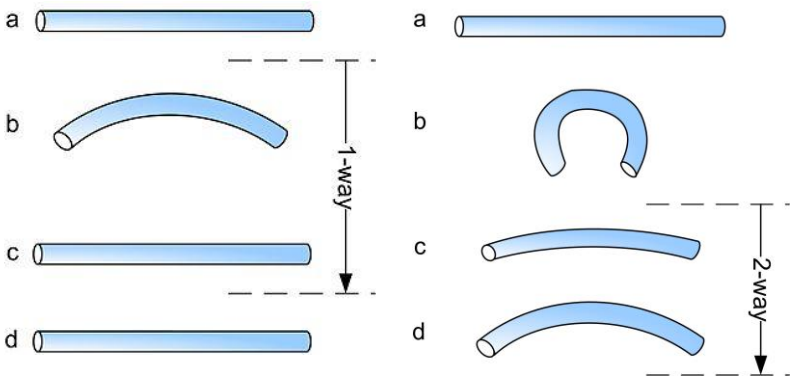




CryoCubeSat Concept [7]

Concept

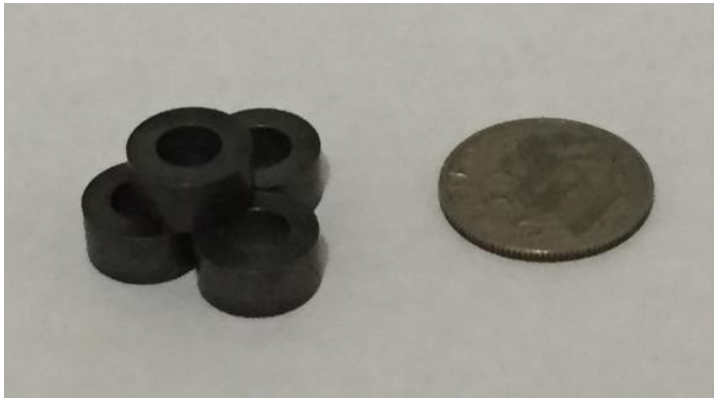


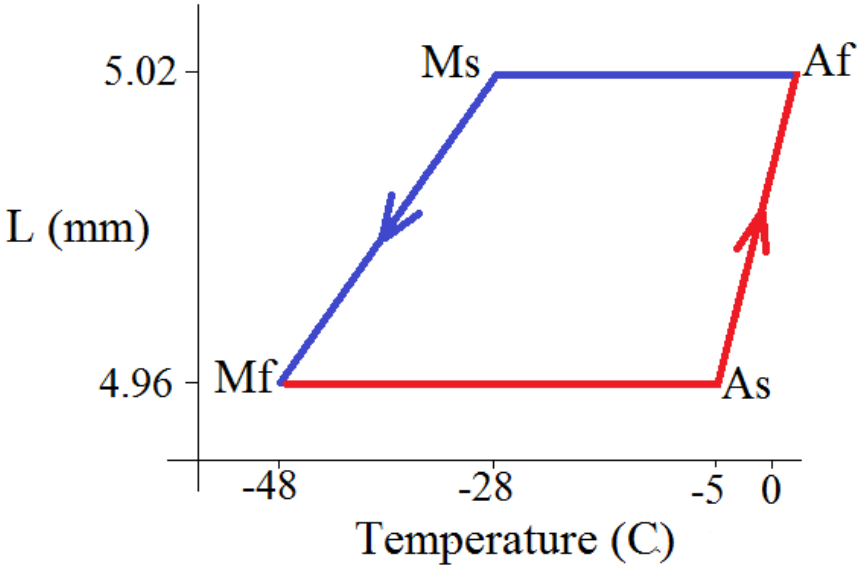


1 Way vs. 2 Way SMAs [9]

- <u>Heat Switch has two modes:</u>
  - Hot (ON): Plates are in contact through bolts
  - Cold (OFF): Plates will be separated from one another
- <u>Shape Memory Alloys (SMA)</u>
  - Crystalline structure can change between Martensite (Cold) and Austentite (Hot)
  - “Remembers” original shape and deforms once heated and/or cooled
  - One Way vs. Two Way

SMA Washer Selection

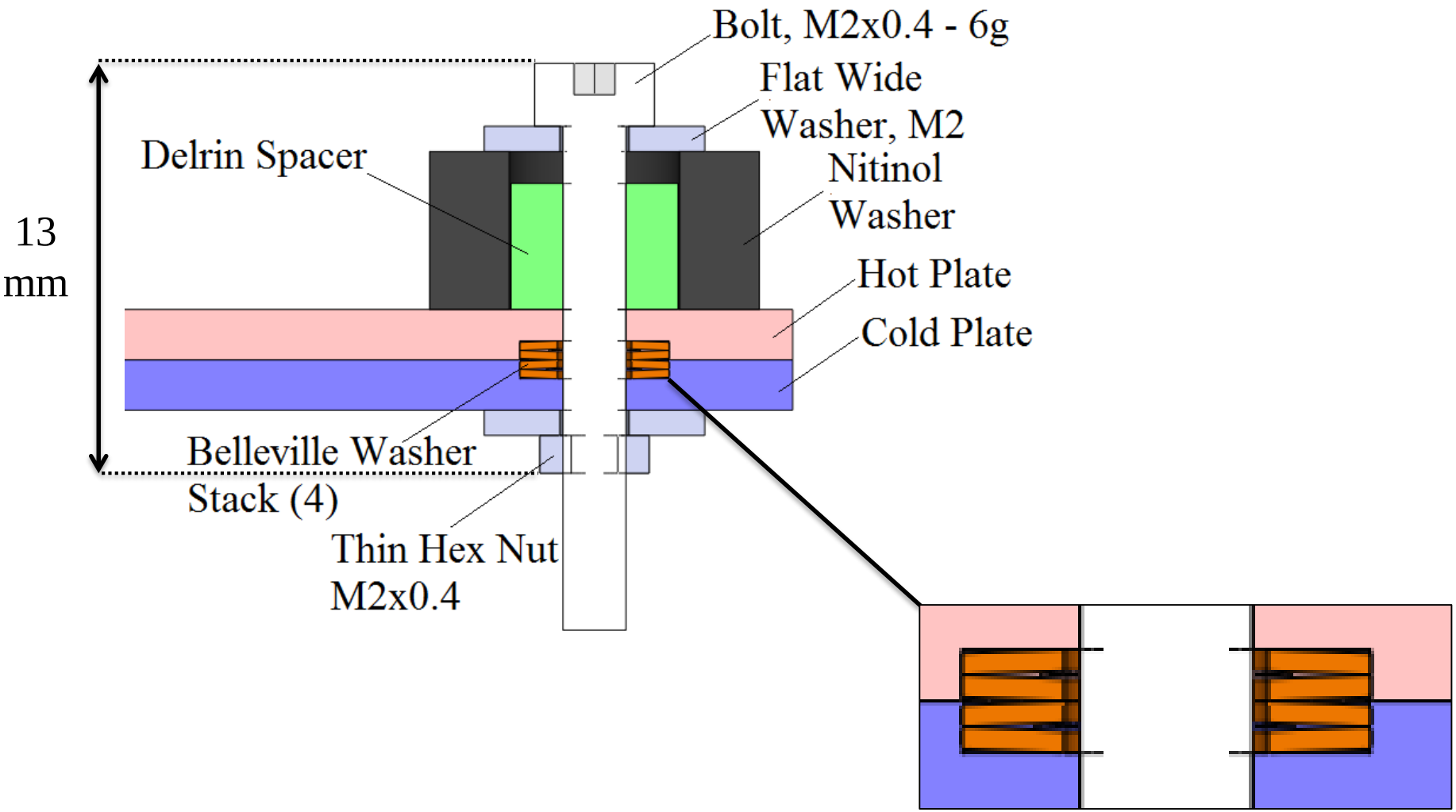




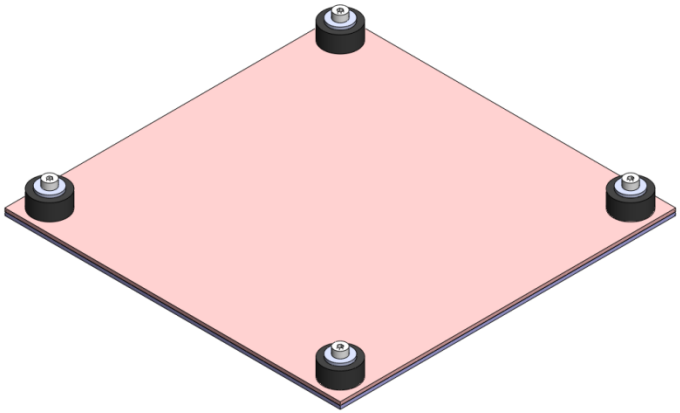
- <u>Criteria for Selecting SMA Washer:</u>
  - Temperature Range
  - Elongation (% strain)
  - Two – Way
  - Cost
  - Lead Time

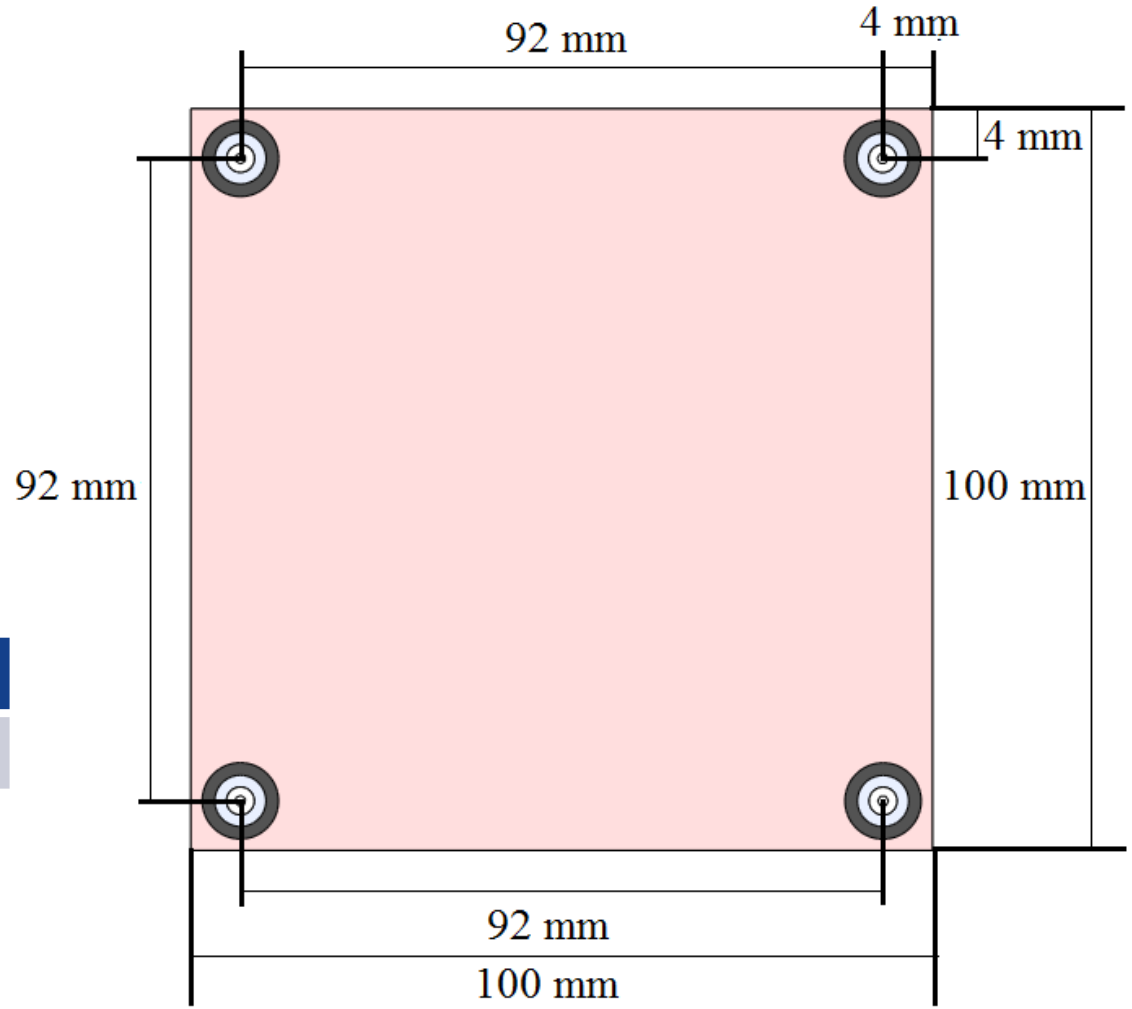
- <u>Selected Washer:</u>
  - Intrinsic Devices – Nitinol (Alloy D)
  - $\varepsilon = 1.25\ \%$
  - Operable Temp Range
    - -196 °C to 200 °C

Heat Switch Cross Section



Heat Switch Cross Section





Mass	Volume
0.107 kg	1.76×10^{-5} m^3

Parts List

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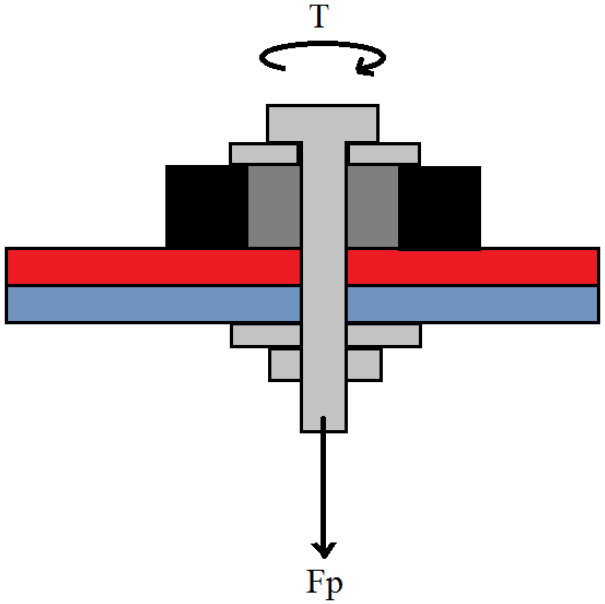
Part	Description	Quantity	Cost
Flat Wide Washer	316 Stainless Steel, M2	100	$4.17
Belleville Washer	Series 300 Stainless Steel, M2	24	$26.44
Thin Nut	316 Stainless Steel, M2x0.4	25	$3.04
Aluminum Plate	2024-T3	2	$30.90
SMA Washers	Nitinol, 2-way SMA	4	$600
Bolt	316 Stainless, M2x0.4-6g, length: 16 mm	50	$9.77
Spacers	Delrin® Acetal Resin, M2	40	$36.00
		Total Cost:	**$710.32**

Stress Analysis

- Bolt Torque = 176 N-mm
- Bolt Preload = 440 N
  - P = T/cD = (176 N-mm)/(0.2*2mm) = $\mathbf{440\ N}$

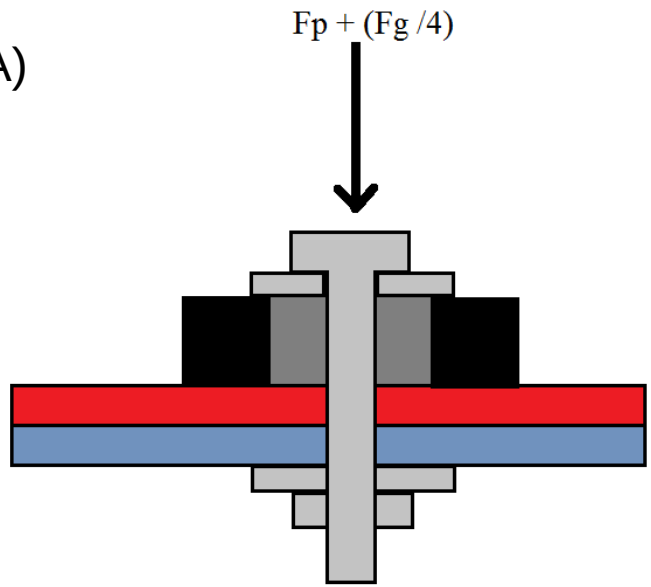


- σ_{T-Bolt} = P/A_{bolt} = $\mathbf{140.1\ MPa}$
  - **29.1 % of Allowable**
- $\sigma_{B-SMA} = P/A_{SMA} = \mathbf{6.96\ MPa}$
  - **1.58 % of Allowable**
- $\varepsilon_{Bolt} = \sigma_{T-bolt}/E_{316-SS}$ = $\mathbf{0.0007374}$
  - $\Delta l = l * \varepsilon$ = 0.0000133m = $\mathbf{13.3\ \mu m}$
- $\Delta l_{SMA} = l_{SMA} * \varepsilon$ = $\mathbf{63.2\ \mu m}$
  - **Change in length of SMA 5 times greater than that of bolts guarantees gap in OFF position**

Stress Analysis

- 200g force applied to the assembly:
  - $\boldsymbol{F_g} = 200 * 9.81\ \frac{m}{s^2} * 0.1067\ kg = \mathbf{210}\ \boldsymbol{N}$
  - $\boldsymbol{F_{bolt}} = F_{preload} + \frac{F_g}{4} = \mathbf{492.5}\ \boldsymbol{N}$

A)



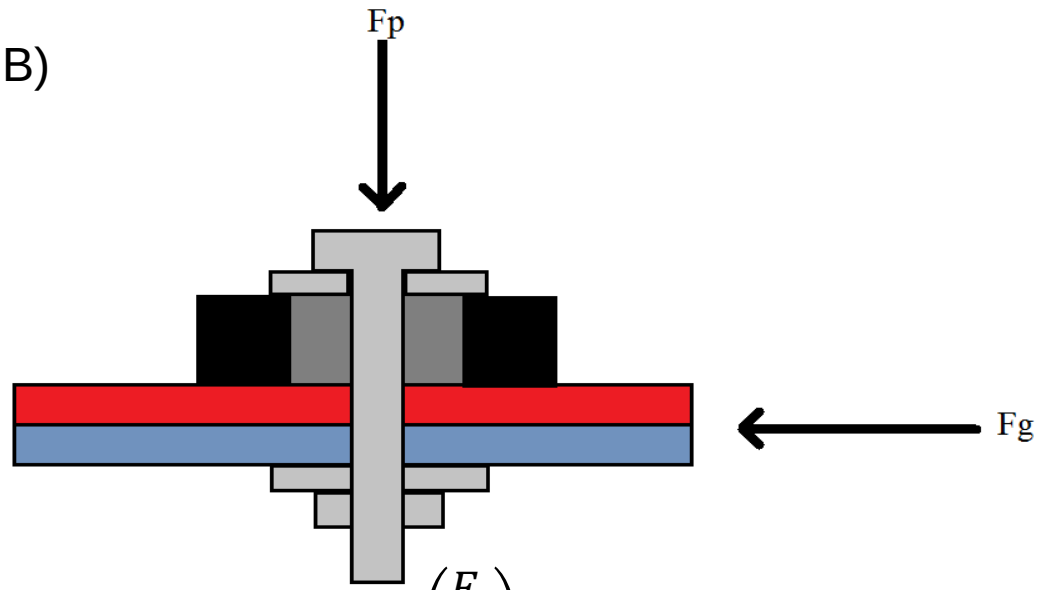
σ_{T-Bolt} = P/A_{bolt} = $\mathbf{156.8}\ \boldsymbol{MPa}$

32.5% of Allowable

$\sigma_{B-SMA} = P/A_{SMA} = \mathbf{7.79}\ \boldsymbol{MPa}$

1.76 % of Allowable

B)



$\tau_{bolt} = \left(\frac{F_g}{4}\right)/A_{bolt} = \mathbf{16.8}\ \boldsymbol{MPa}$

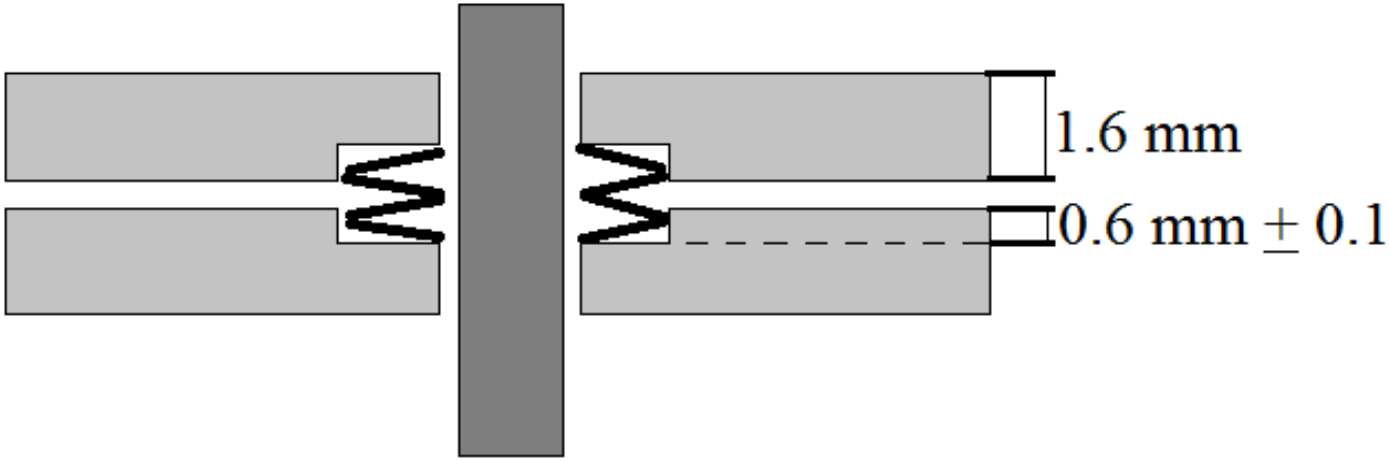
5.81% of Allowable

$4 * \mu * F_p > F_g\ (\boldsymbol{No\ Slip})$

580.8 N > 210 N ✓

Tolerance Analysis

- Use 4 Belleville Washers in Series:



- With a tolerance of 0.6 mm ± 0.1:
  - Gap size will be 1.0 to 1.4 mm
- Lower bound allowable washer stack height is 1.0 mm
  - Maximum loaded Belleville washer thickness = 0.25 mm
  - 4 x 0.25 mm = 1.0 mm
  - **Aluminum plates will contact before spring stack is bottomed out**
- Upper bound allowable washer stack height is 1.4 mm
  - Minimum unloaded Belleville washer thickness = 0.38 mm
  - 4 x 0.38 mm = 1.52 mm
  - **Guaranteed gap of > 0.12 mm gap when spring stack is fully expanded**

Thermal Analysis

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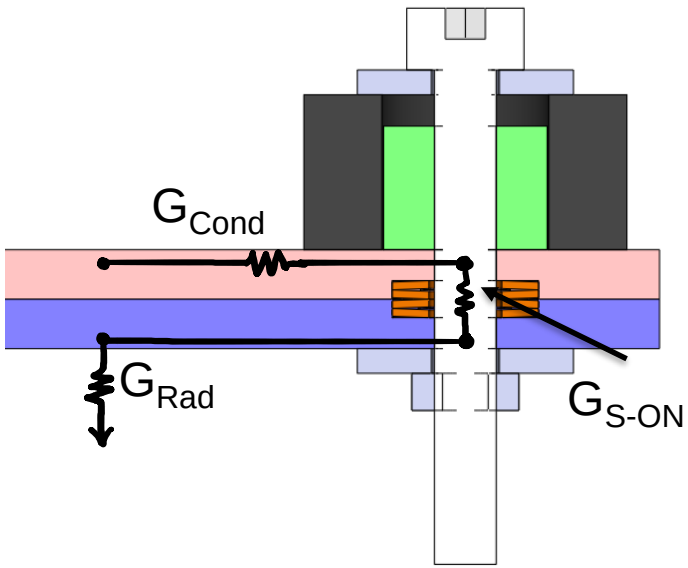
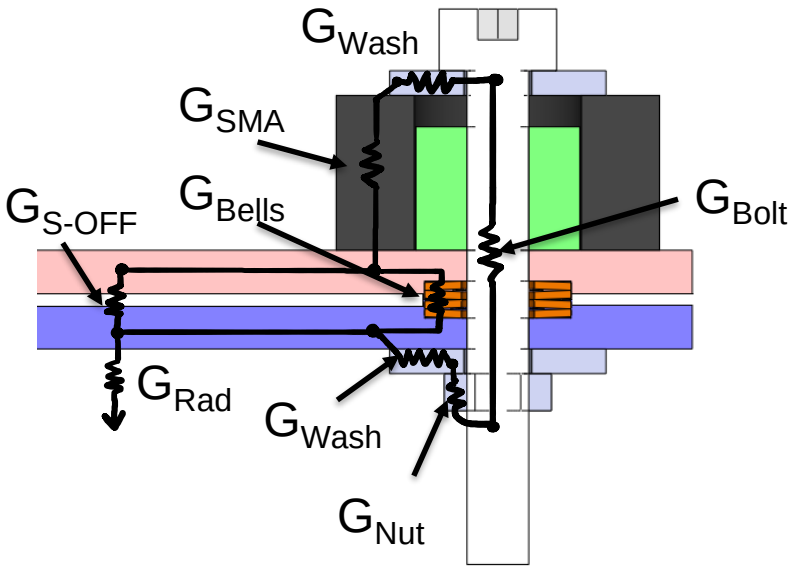
	WCH Minimum Conductance	WCC Maximum Conductance
G_{Switch}	G_{S-ON}	$G_{BoltAssembly} + G_{S-OFF} + G_{Bells}$
$G_{Assembly}$	$(G_{Rad}^{-1} + G_{S-ON}^{-1} + G_{Cond}^{-1})^{-1}$	$\left(\left(G_{BoltAssembly} + G_{S-OFF} + G_{Bells}\right)^{-1} + G_{Rad}^{-1}\right)^{-1}$





Thermal Analysis

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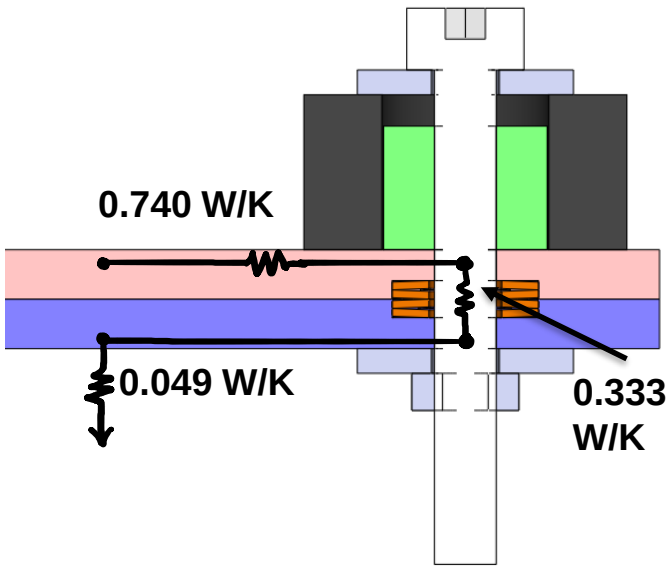
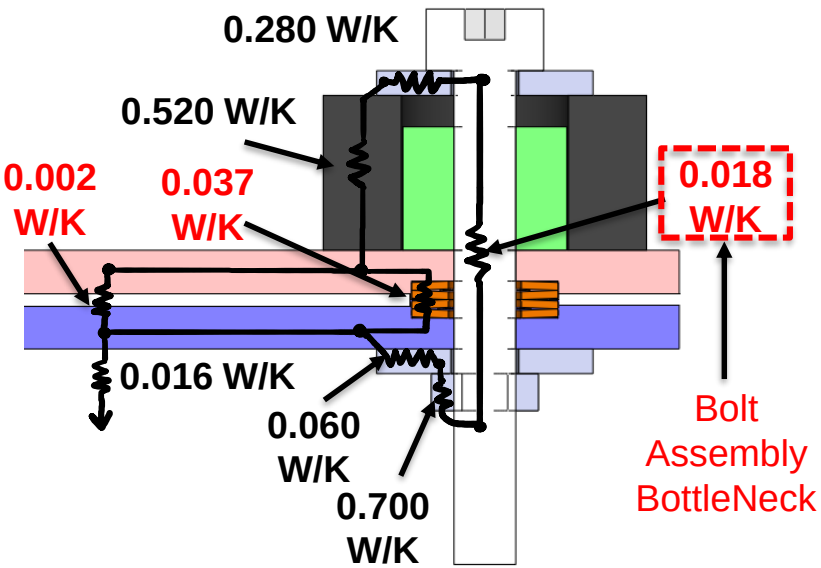
	WCH Minimum Conductance	WCC Maximum Conductance
G_{Switch}	0.333 W/K	0.053 W/K
$G_{Assembly}$	0.041 W/K	0.012 W/K





Note: WCC conductance will be reduced due to thermal contact resistance

Heat Switch Assembly

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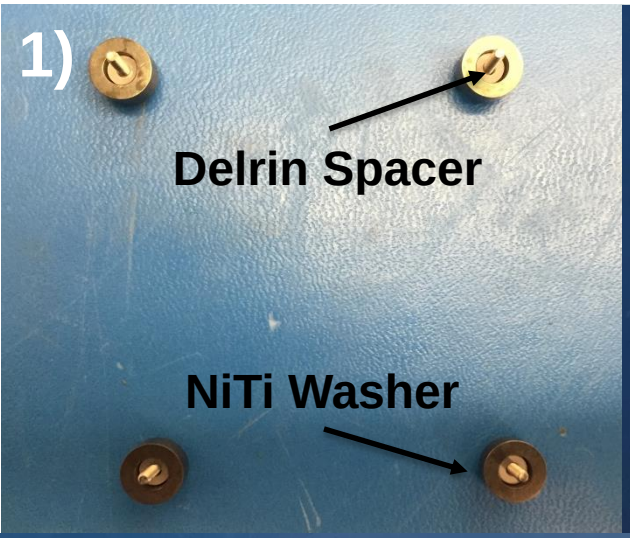

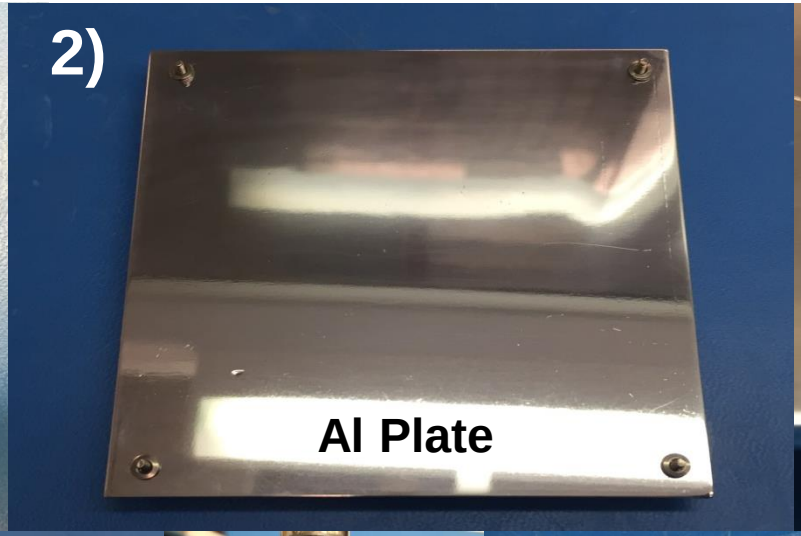

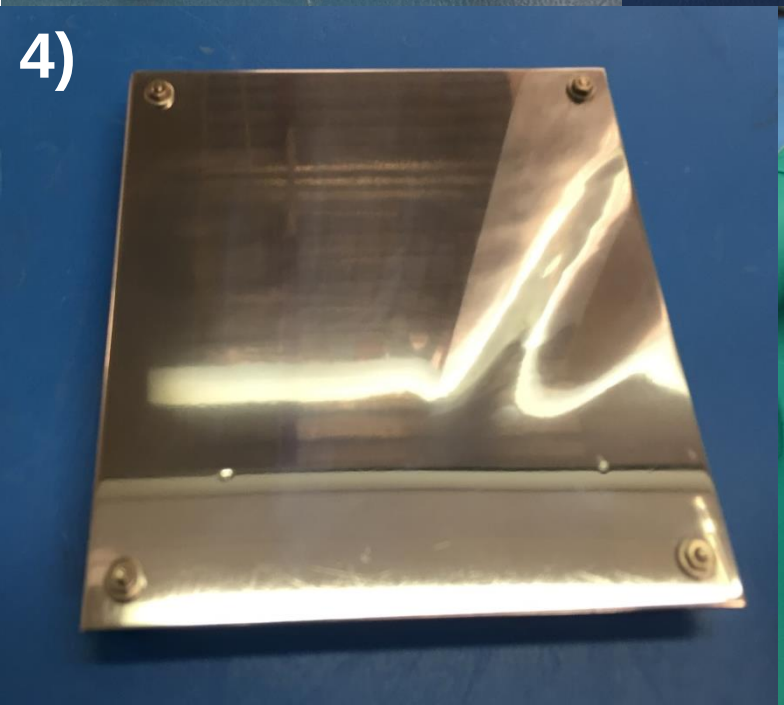

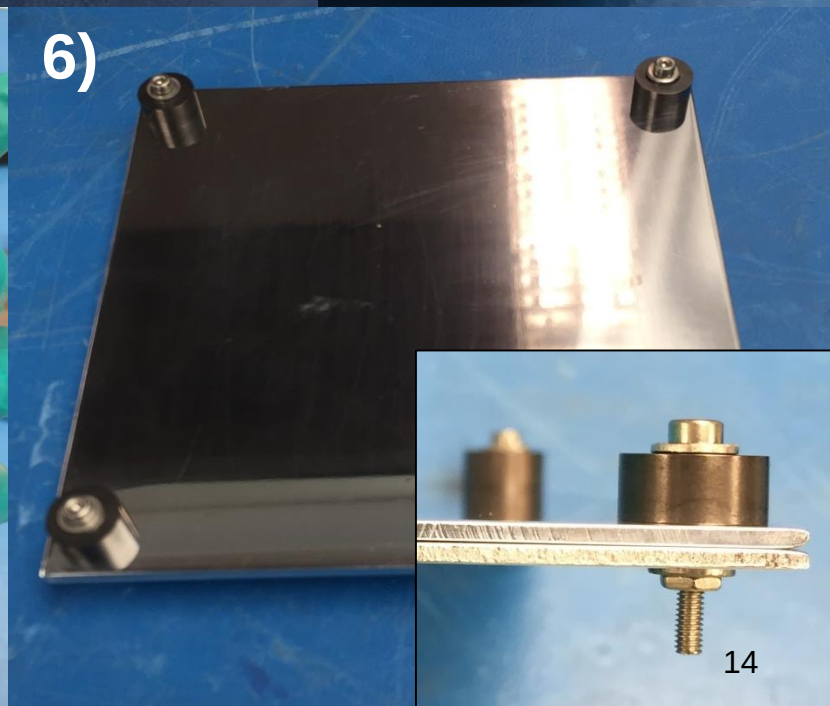

Test Set Up

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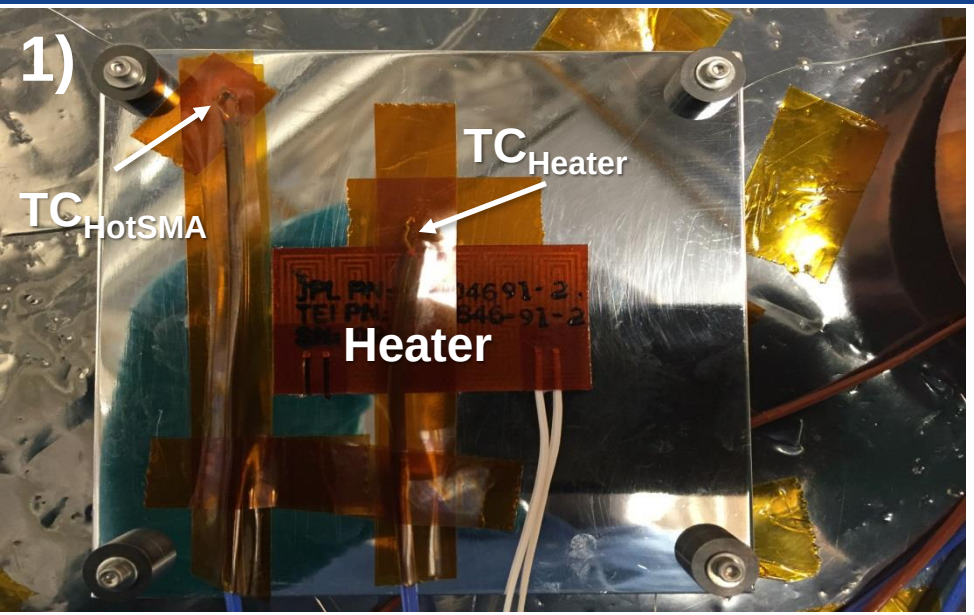
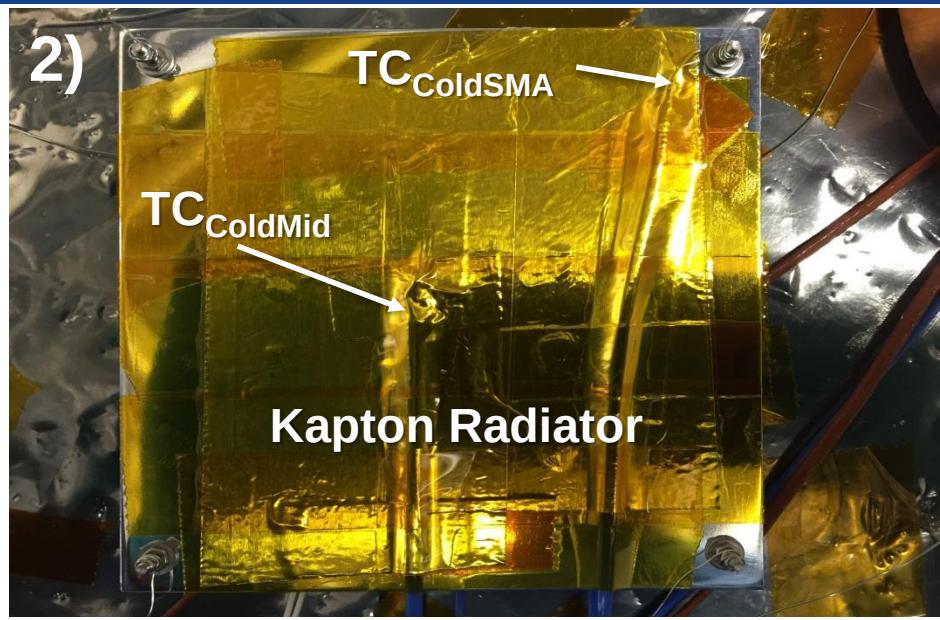
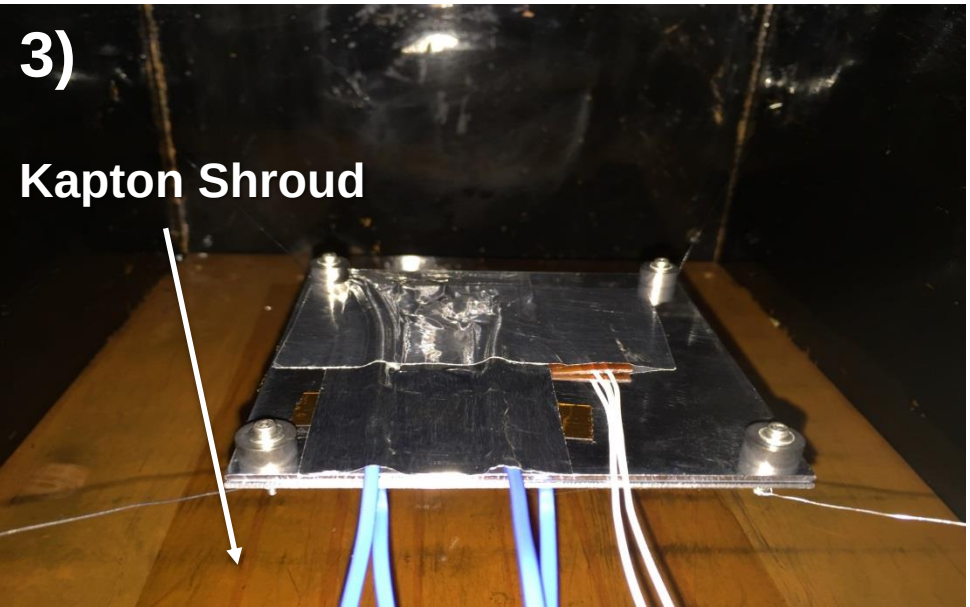
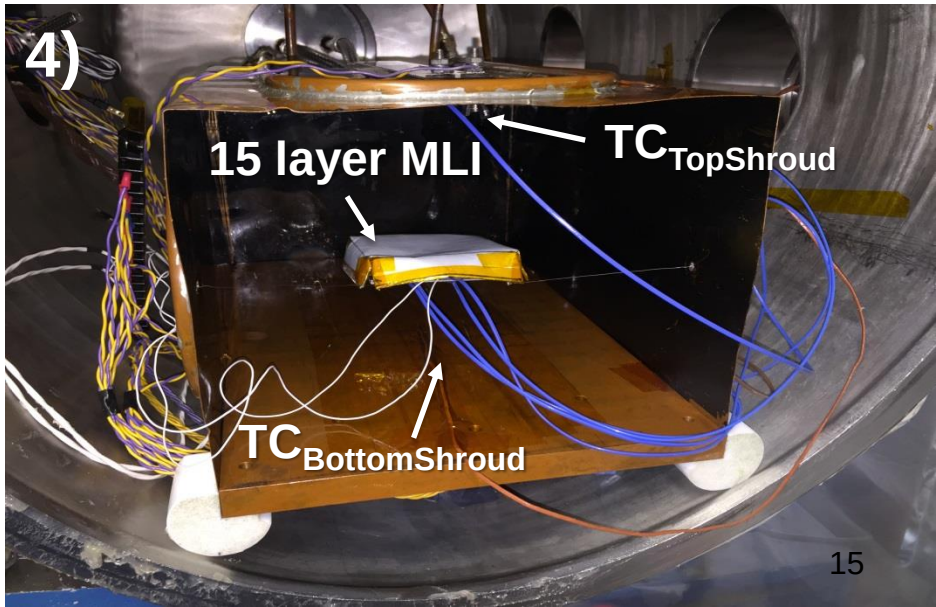








Test Procedure

1. Place assembled article in the TVAC with steel wires and connect all TC's and Power Supply to Heater.

2. Close TVAC Chamber.

3. Bring chamber pressure < 1×10^{-3} torr, so that all pressure values are in the 10^{-4} torr range.

4. Turn on cooling lines for shroud to bring to -70 °C.

5. Once Shroud reaches -70 °C turn on power for heater.

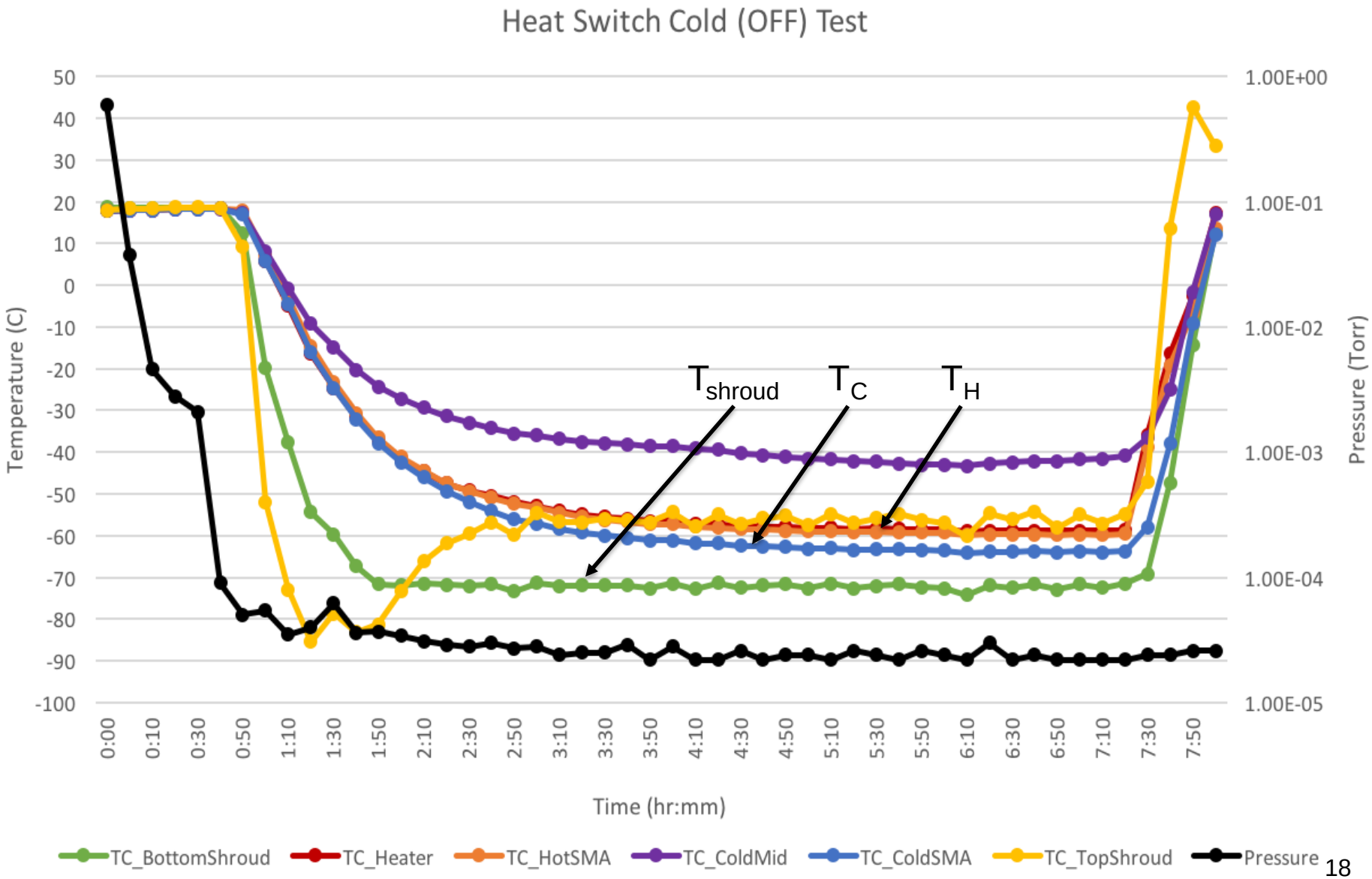
6. Wait until test article TCs reach steady state with a criteria of 0.2 °C/hr for a 1 hour duration.

7. Turn Off heaters and bring chamber back to room temperature.

Test Matrix

Run	Description	Heater Power (W)	Voltage (V)	Shroud Temperature (°C)	Chamber Pressure (Torr)
1	Hot Case	4.5	13.4	-70	$1\ x\ 10^{-4}$
2	Cold Case	0.1	2.0	-70	$1\ x\ 10^{-4}$

Cold Case Test Data



Hot Case Test Data

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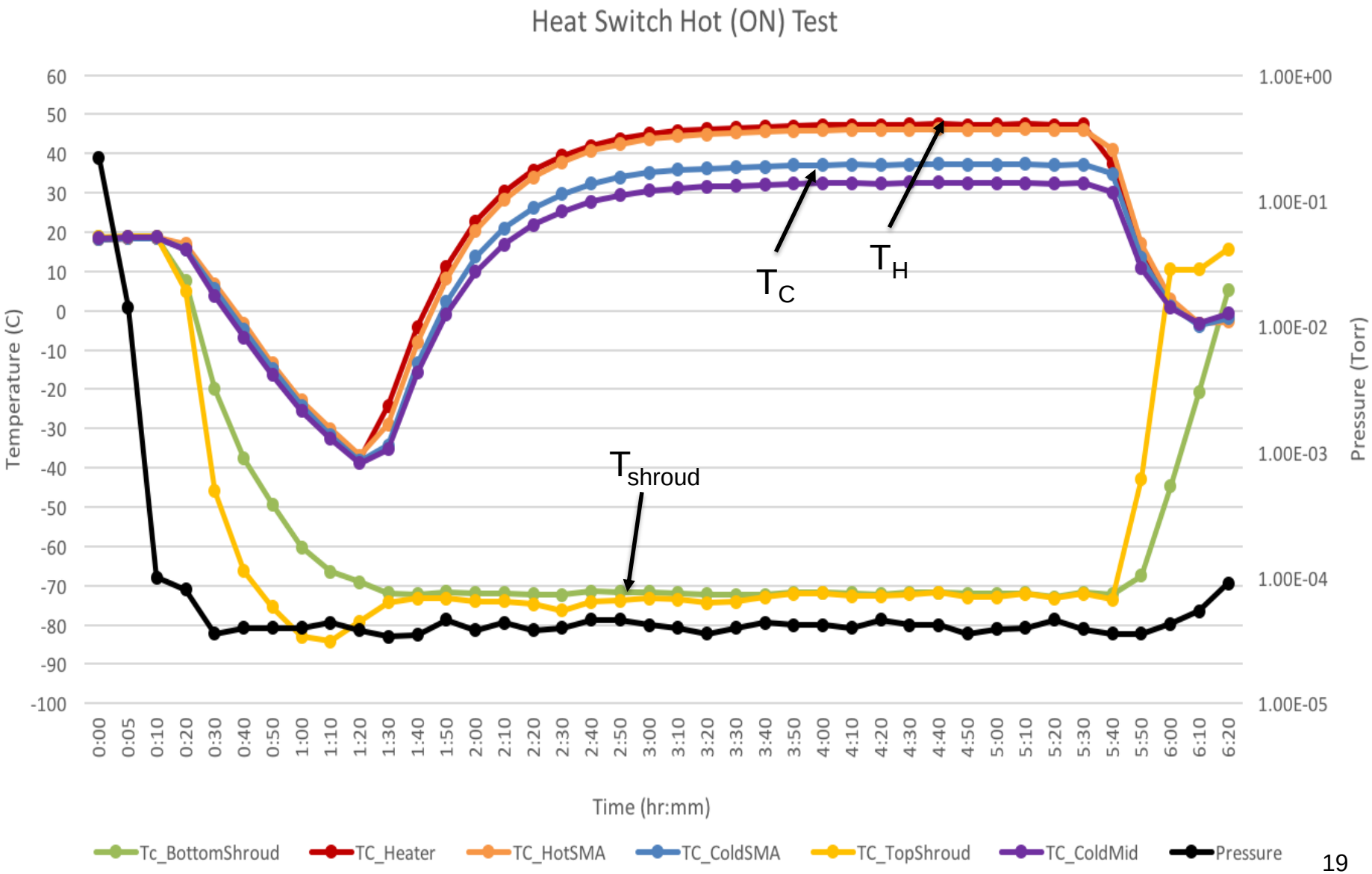
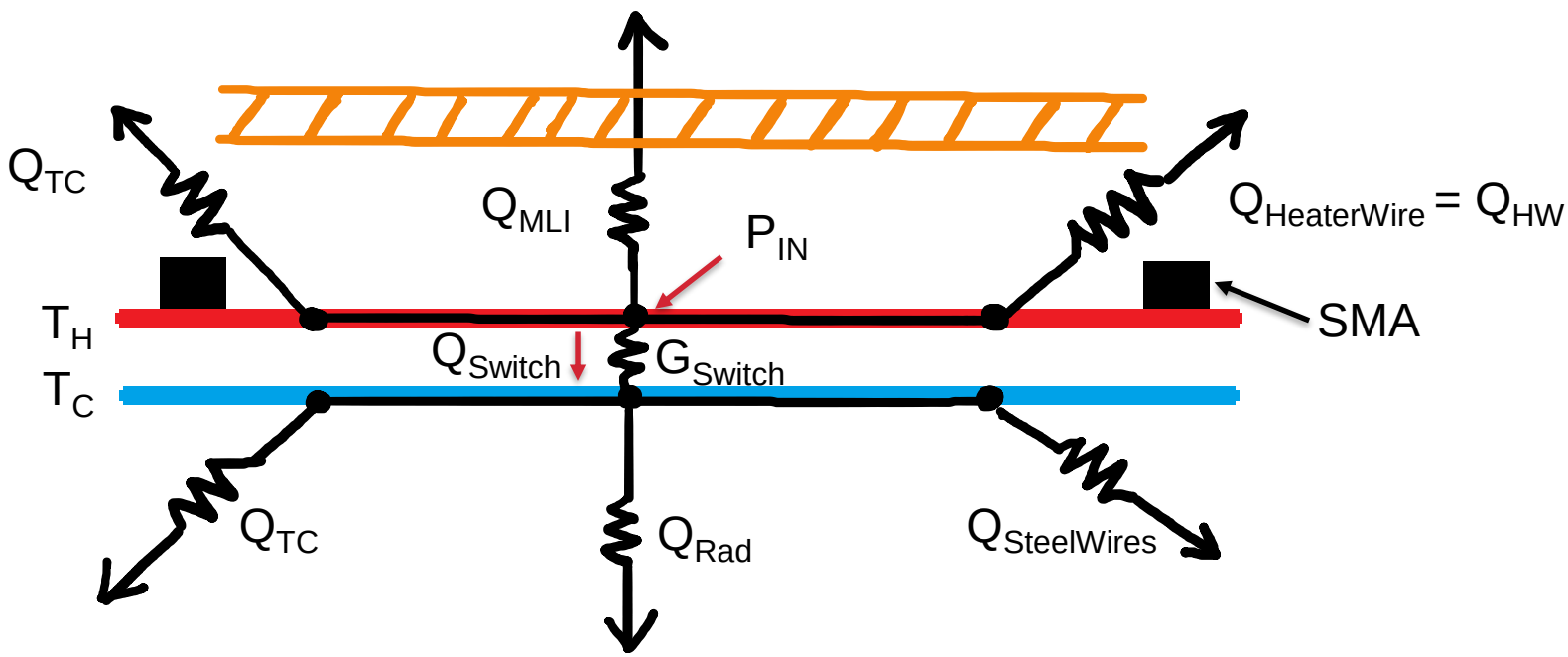


Test Method and Uncertainty

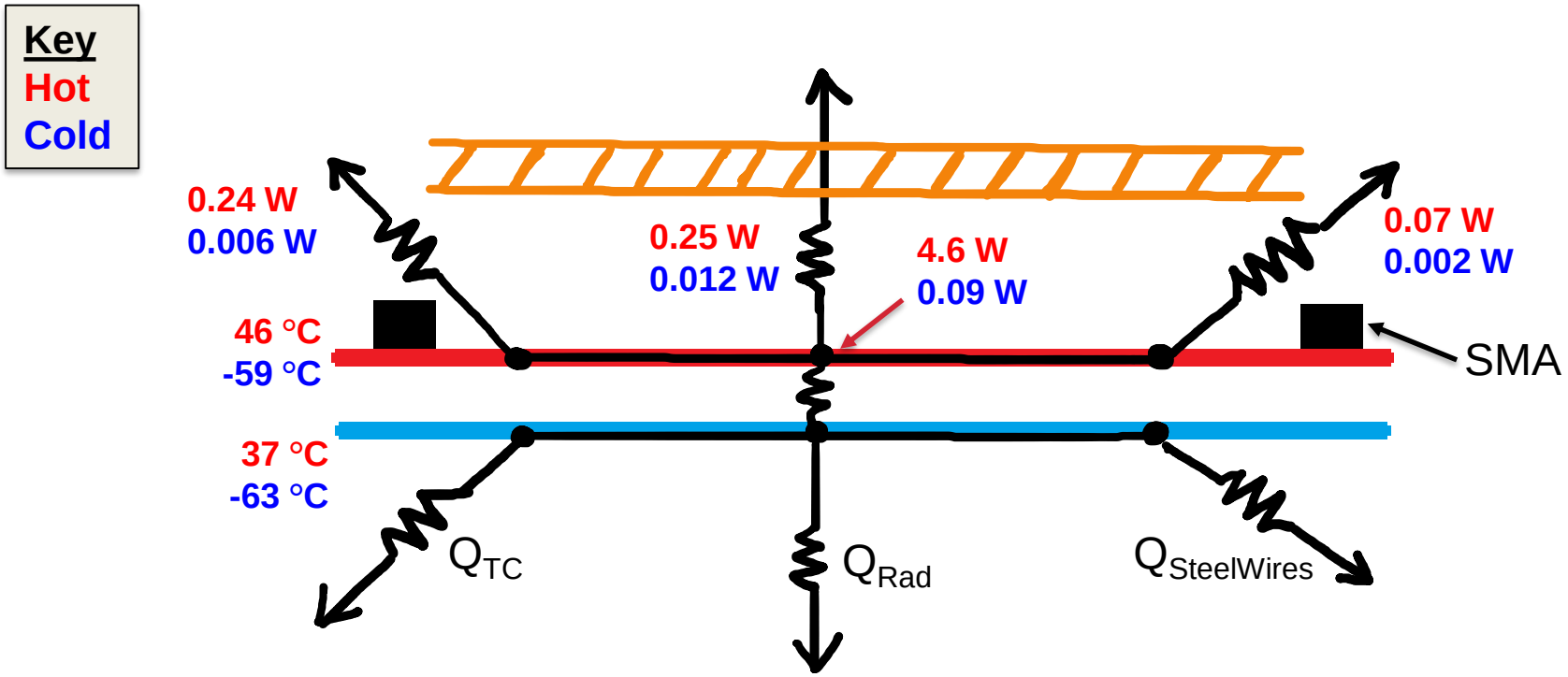
- **Relevant Equations:**
  - $Q_{MLI} = A\varepsilon^{*}\sigma\left(T_H^4 - T_{Shroud}^4\right)$
  - $Q_{RAD} = A\varepsilon\sigma\left(T_C^4 - T_{Shroud}^4\right)$
  - $Q_{Switch} = G_{Switch}(T_H - T_C)$
  - $P_{IN} = Q_{Switch} + Q_{MLI}$

- **Methods to Calculate G**
  - $G_{switch,\,max} = P_{IN}/(T_H - T_C)$
  - $G_{switch,\,min} = \frac{(P_{IN} - Q_{MLI} - Q_{TC} - Q_{HW})}{(T_H - T_C)}$
  - $G_{assembly,\,max} = P_{IN}/(T_H - T_{Shroud})$
  - $G_{assembly,\,min} = \frac{(P_{IN} - Q_{MLI} - Q_{TC} - Q_{HW})}{(T_H - T_{Shroud})}$



Test Results

	Cold Case T_{avg} = -61 °C	Hot Case T_{avg} = 41.5 °C	Turndown Ratio
G_{SWITCH}	0.019 to 0.022 W/K	0.460 to 0.520 W/K	23 to 25 : 1
G_{ASSEM}	0.006 to 0.008 W/K	0.034 to 0.039 W/K	5.2 to 5.8 : 1



Lessons Learned

- TVAC testing takes a long time!
  - Even with an article this small and simple in nature, multiple days are required for each part of the assembly and testing process.
    - Day 1: Assembly of Test Article
    - Day 2: Set Up Test Article in TVAC
    - Day 3: Cold Test
    - Day 4: Hot Test

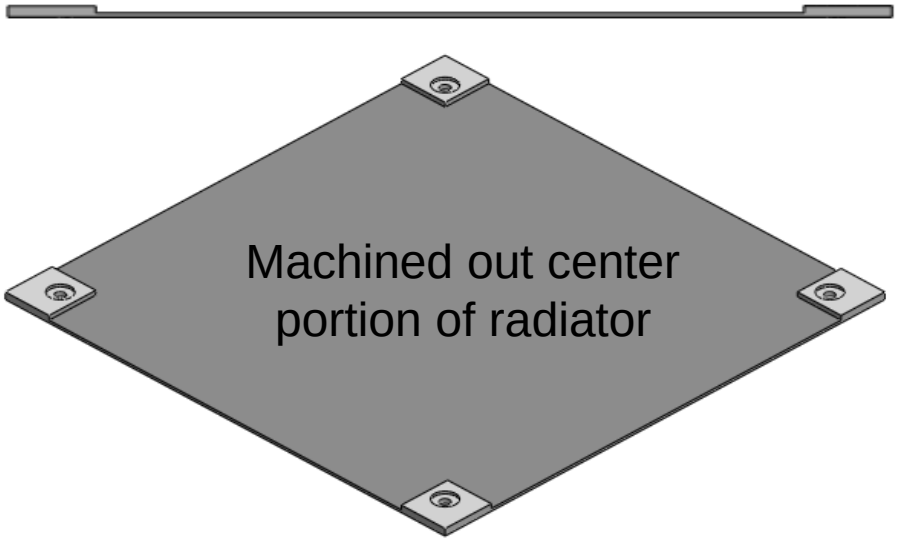
- Better Understanding of Radiation and Conductive Heat Transfer Concepts and applications to design.

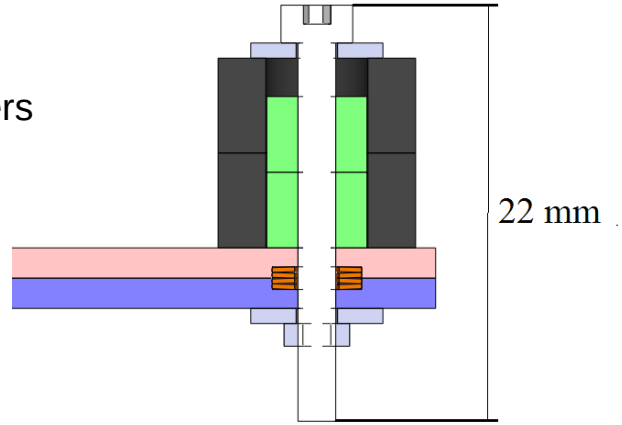
- Time + Budget + Wants = Compromise

- Broaden Knowledge Spectrum in Aerospace Testing Requirements and Types

Design Improvements

- Machine out center portion of radiator
  - Ensures the two plates only contact near SMA region.
  - Ensures the two plates never contact in center region.
- Larger Area Radiator
  - Improve the $G_{assembly}$ cold to hot ratio
- Titanium Bolts and Belleville Washers
  - Reduced cold side heat leaks
- Low Profile Flanged Nuts and Bolts
  - Reduce the total stack height
- Thicker Radiator Plate
  - More Mass, Improved radiator efficiency
- Additional Belleville Washers
  - More Volume, Reduced cold side conductance
- Helical springs or wave washers instead of Belleville washers
  - Less heat leak, Less separation force
- White Painted Radiator
  - Improved radiator efficiency
- Use two NiTi washers
  - More Volume, Increased Cold Side Gap



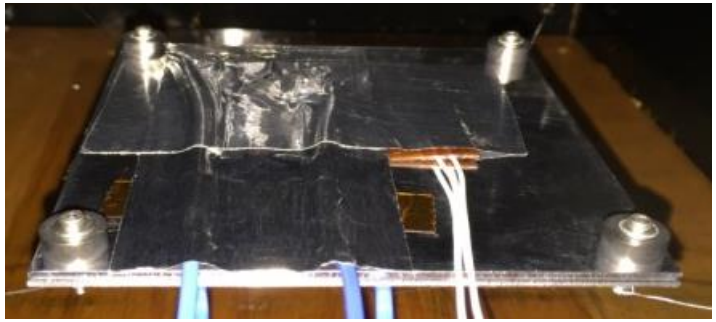
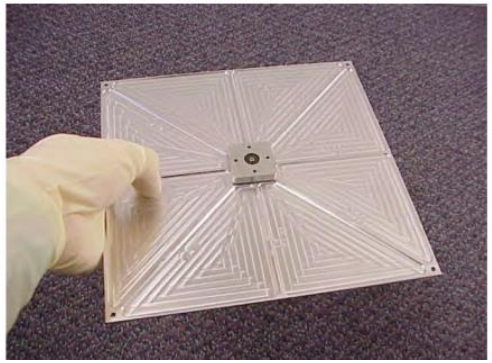


Two NiTi Washers

Future Work

- Build and Test Heat Switch with Design Improvements
- Test at intermediate temperatures
  - Develop understanding of heat switch's hysteresis
- Run the heat switch through multiple hot and cold cycles
  - Understand any longer term effects of cycling
- Qualification Testing:
  - Vibration Testing
  - Shock Testing

Comparison to State of the Art

	SMA Heat Switch	Paraffin Heat Switch [2, 6]
		
Heat Switch Conductance Ratio	~ 24:1	~ 100:1
Overall Assembly Power Turn Down Ratio	~ 5.5:1	~ 20:1
Cost	~ $1,000	~ $100,000
Assembly Height	3 to 13 mm	2 to 17 mm

Conclusions

- Successful design, fabrication, and testing of a SMA actuated heat switch was performed in a 12 week period.
- The tested heat switch had a ON/OFF conductance ratio of ~ 24:1.
  - ~ 5.5 :1 for the heat switch radiator assembly.
- The heat switch can be built without any specialized equipment or skills, at a cost of < $1000.
- **This heat switch shows promise for missions which require a low cost, moderate performance heat switch.**

Acknowledgements

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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Questions?