Thermally-conductive Metallic Coatings and Applications for Heat Removal on In-space Cryogenic Vehicles

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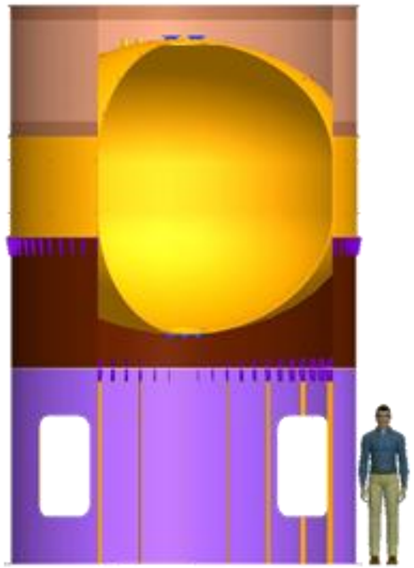
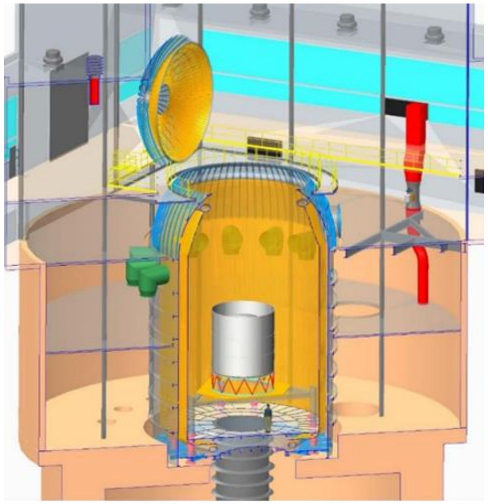
Background and evolvable Cryogenics (eCryo)

- NASA Glenn's evolvable Cryogenics (eCryo) project aiming to demonstrate applicability of structural cooling utilizing boil-off vapor on a large flight-like liquid hydrogen cryogenic stage.
- Most cryogenic upper stages experiences significant heat leak – counteracted by carrying excess propellant to accommodate boil-off loses.
- Future exploration missions will require cryogenic propellant resource utilization to increase from hours to days.
- The vapor heat interception system will be integrated with upper-stage representative MLI on the test tank and will be tested thermally in the Spacecraft Propulsion Research Facility at NASA's Plum Brook Station.
- Vapor cooling goal performance parameter calls for a 15% reduction in overall tank boil-off rate while also minimizing added weight.

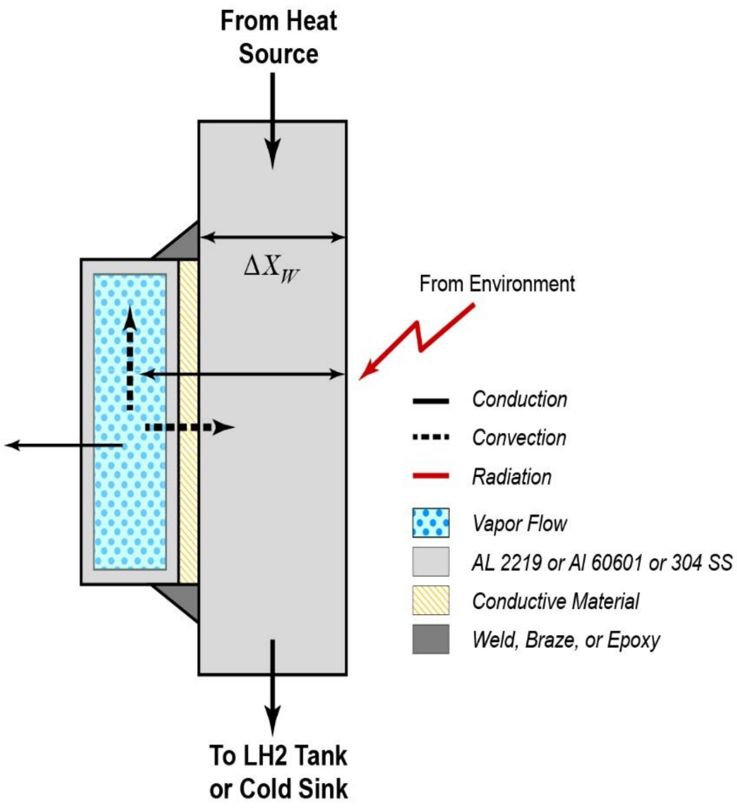
eCryo Test Assembly





Need for Conductive Materials

- **For large in-space cryogenic upper stages, the required thermal conductance for suitable axial heat removal from a forward skirt by vapor cooling may not be achievable by simple methods of attaching fluid channels to the inner or outer surface of the forward skirt wall.**
- **Without significant coordination and modification to the basic structural design, novel and complex attachment mechanisms with high thermal conductance are required.**
  - Preferable methods would allow for addition of the cooling system to existing structure with minimal impact to the structure.
  - Methodologies must be utilized in order to enhance heat transfer from the fluid to the skirt surface.
  - The preferred method to increase the thermal performance of the system is to apply metallic or other thermally conductive material coatings to the inner surface area of the fluid channel where the tubing is attached the skirt wall.

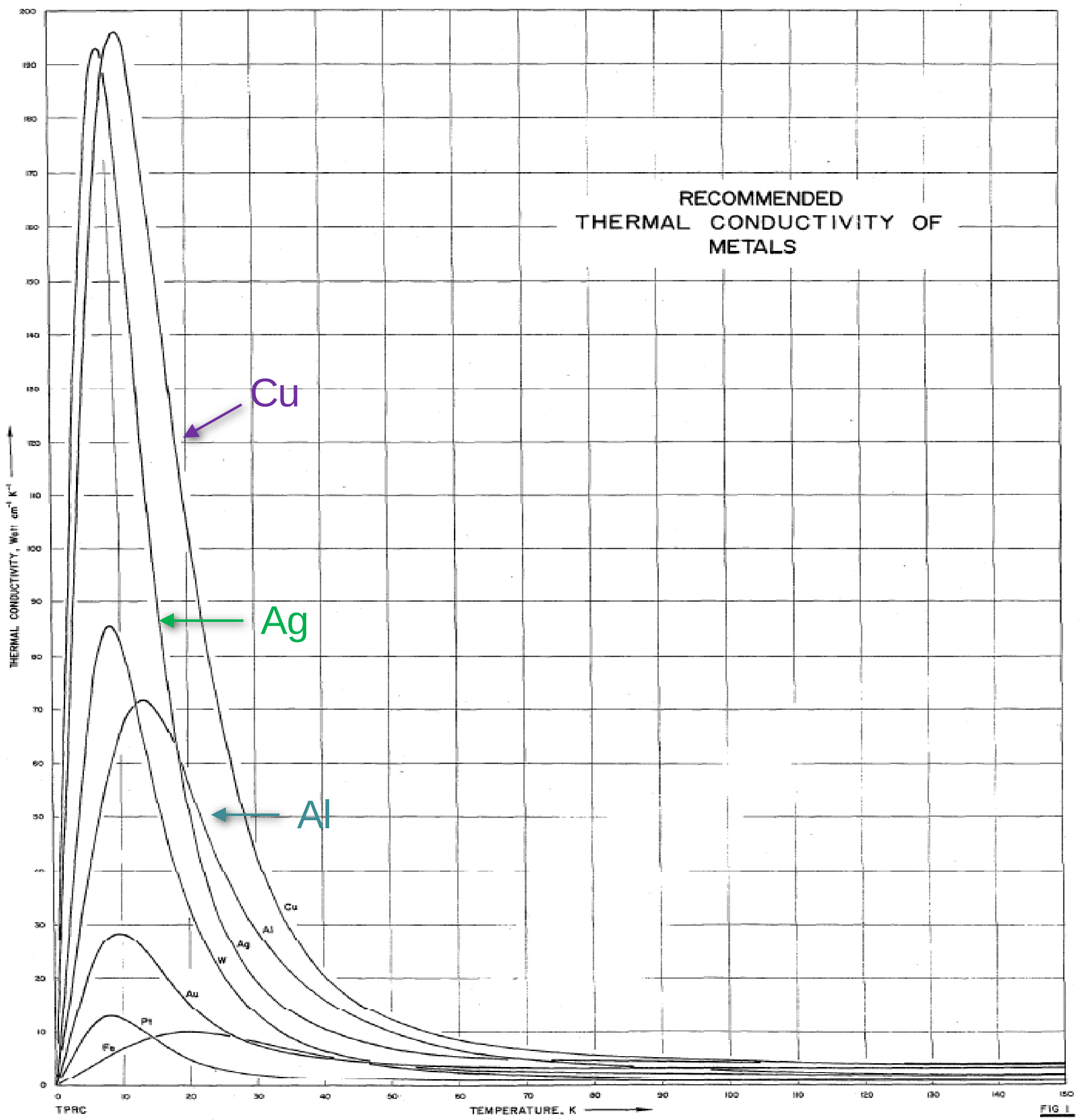


Conductance Testing Rationale

- **Preliminary analysis performed to determine needed contact resistance to meet vapor cooling performance goal.**
  - Determined may not meet goals with typical mechanical attachment methods (bolting).
- **Identified a need to qualitatively evaluate effectiveness of thin film conductive coatings on channel materials in order to determine benefit to meeting vapor cooling performance goals.**
- **Test rig designed at NASA Glenn Research Center to provide thermal contact resistance testing between small sample coupons.**
- **Tests determined qualitative contact conductance between various test samples.**
  – Materials ranked in order of temperature drop, (i.e. the lowest delta T corresponding to the best thermal conductance)
- **Absolute conductance values were not measured due to the difficulty in properly calibrating the test rig.**

Conductive Metallic Candidates

- Data on pure metal conductance suggests that relatively soft coatings of copper or aluminum will provide adequate conductance enhancement.
  - Data from 1960s National Standard Reference Data Series
  - Information on applications very limited



Conductance Test Samples

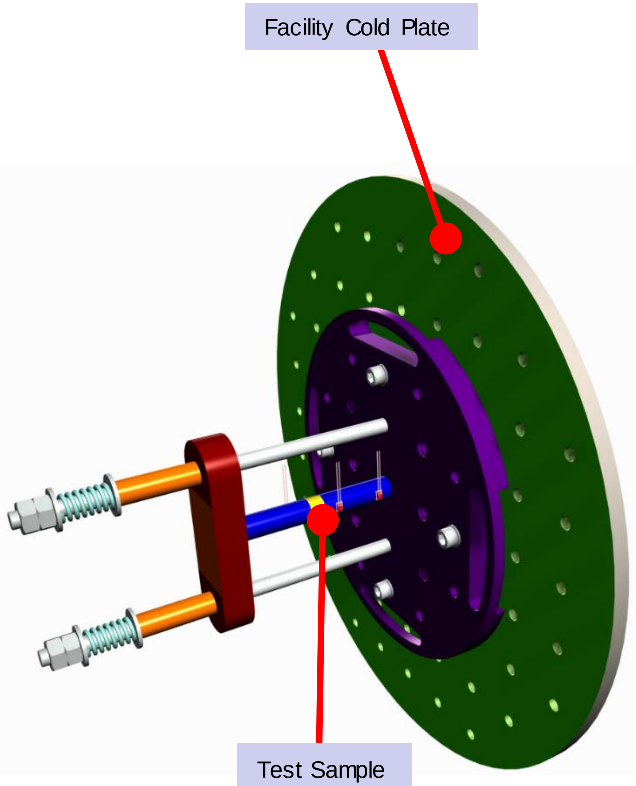
- Small discs (Al 6061, 0.39” x 0.13”) coated with conductive materials by electron beam deposition @ GRC
  - Practical handling size – allowed for significant heat flux and temperature differential
- Coatings ranged from 0.5 – 2 nm (5 – 20 A)
  - Verified with microscopy
- Samples were etched to a mirror finish in order to ensure low surface roughness and eliminate the need for post-processing.
- Tests performed at 3 contact pressures
- Prioritized testing matrix to ensure data needed received for test article application
- Coated sample in contact with test fixture of the same material to mimic skirt-channel contact

Material	# of samples
Copper (Cu) – Thick (2 nm)	2
Copper (Cu) – Thin (0.5 nm)	2
Aluminum (Al) (1 nm)	2
Silver (Ag) (1 nm)	2

Electron Beam Deposition

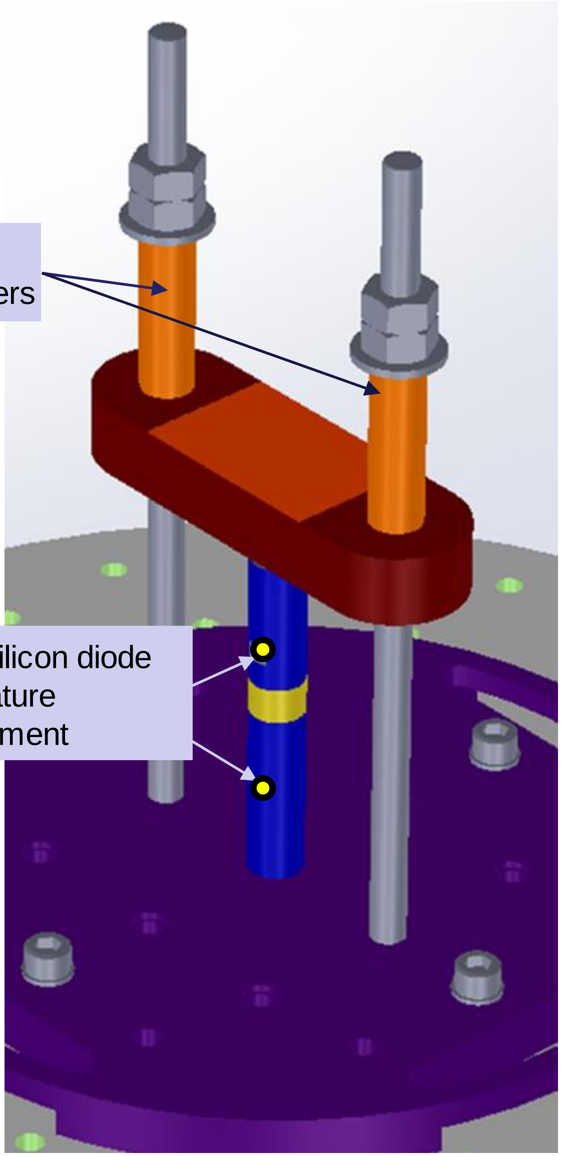
- Mostly metals – Al, Ag, Pt, and Cu
- 9 kV operation
- Tungsten filament with magnetic field directed into a crucible of target material
- 10^{-6} to 10^{-7} Torr scale
- Quartz Crystal Microbalance (QCM) for in-situ thickness measurement
- Coating generally under lower stress thus allowing for thicker coatings – Angstroms to 5 microns or so is possible

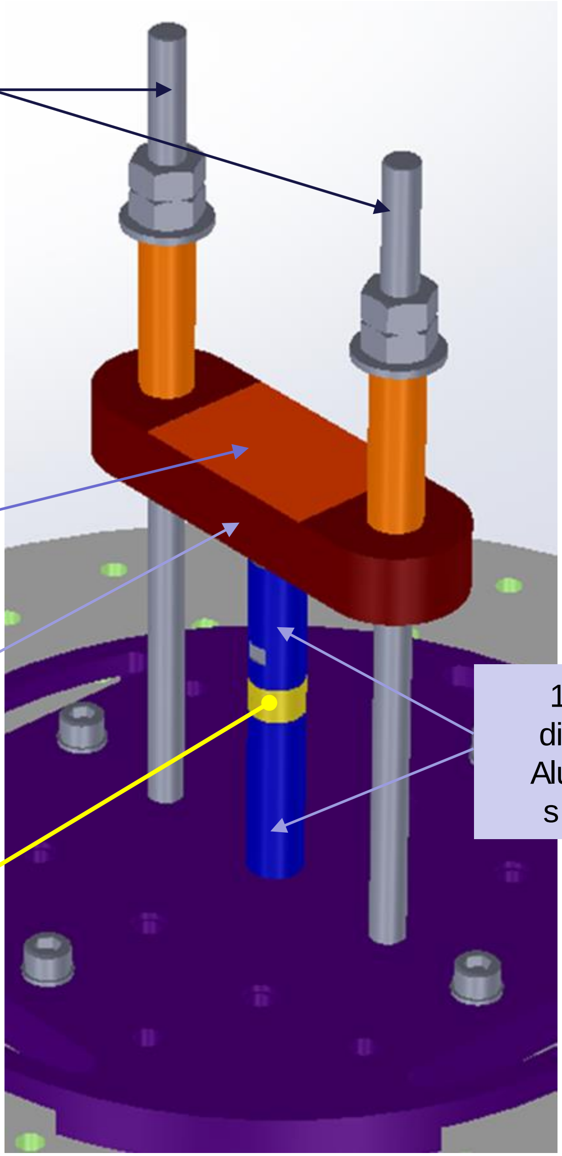
Test Fixture and Configuration



- Tests performed at the Space Dynamics Laboratory at Utah State University
- Test Fixture
  - Stainless steel threaded rods that straddle test sample are double-nutted - Provided compression to test article.
  - Aluminum hot plate, with heater bonded, provided rigidity and conducts heat to aluminum "flux meters"
  - Silicon diode temperature differential measurement
  - Invar 36 provided CTE compensation
- Test fixture attached to cryocooler cold head in vacuum chamber, with cryocooler set at 40 K
- Assembly allowed to stabilize for approximately 48 hours from start of cool-down before heater power applied
- Collected data at zero heater power, 0.75W, and 1.5W
  - Maximum amount of heat lift that could be applied while maintaining a minimal amount of power on the control heater – maintained stable cold-head temperature
- Uncoated samples were fully investigated at three torque values, three separate times to provide a rough idea of test-to-test variation. The sample was removed from the test rig between each test to ensure that all factors that might influence the variation were investigated.
- Coated samples were tested at one or two torque values
  - Goal was to compare results to fully quantified uncoated samples

Test Fixture



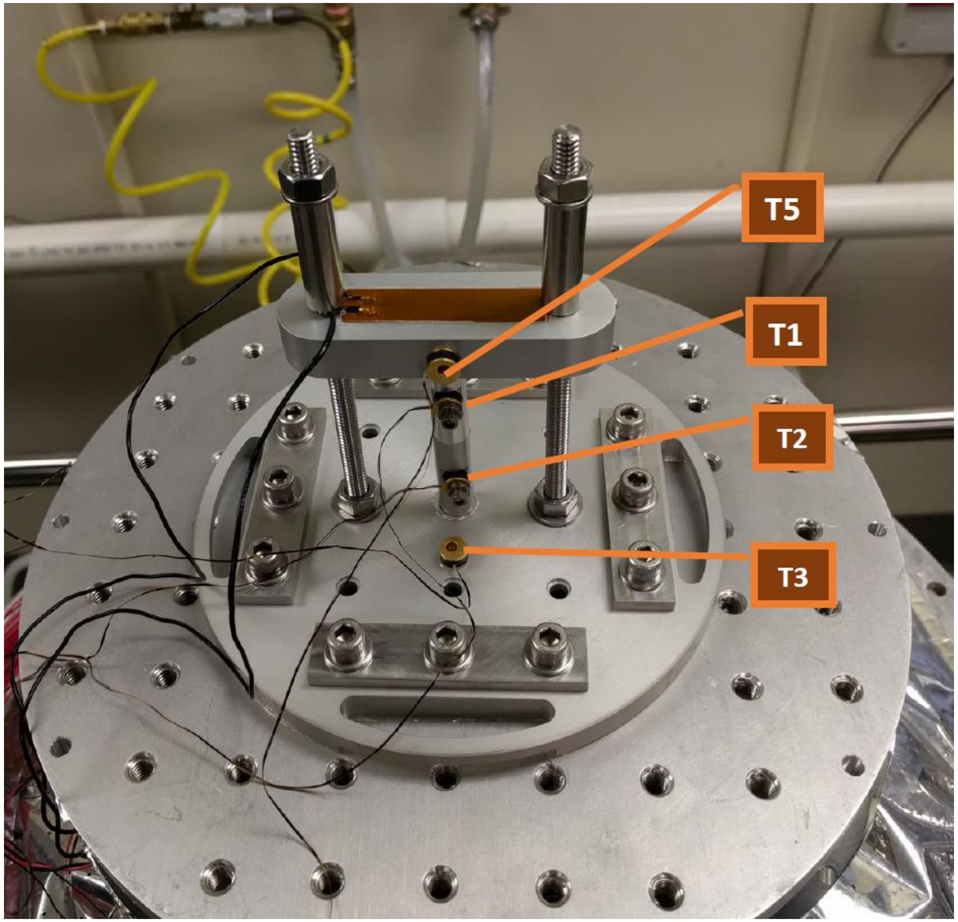


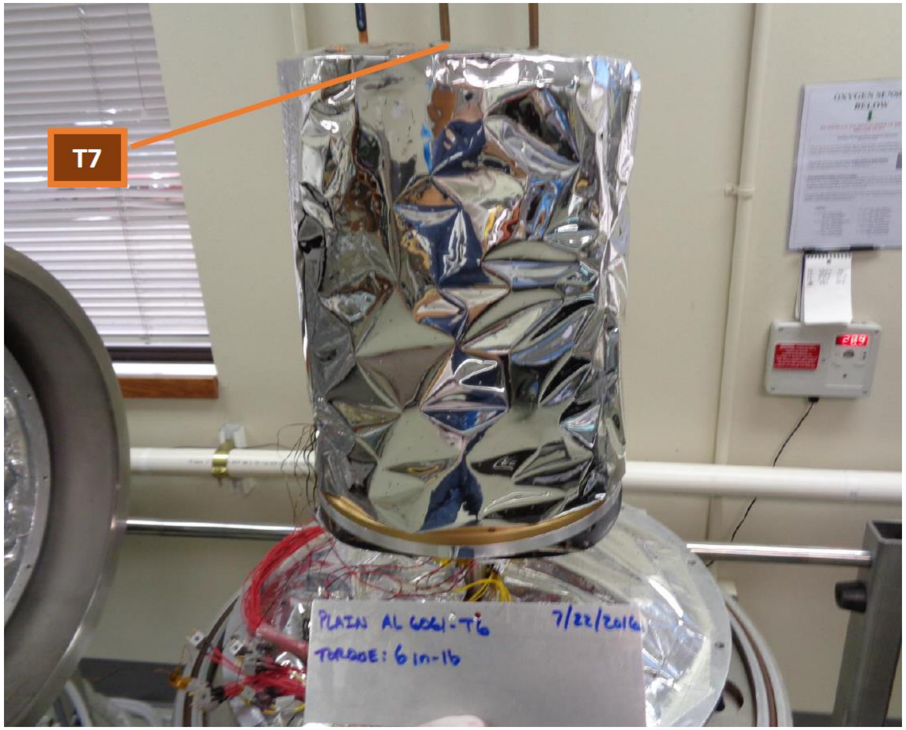
Test Matrix

Applied Torque	Contact Pressure (psi)	Test Samples				
		1. Uncoated Al6061	2. Copper (Cu) - Thick	3. Copper (Cu) - Thin	4. Silver	5. Aluminum
3 in-lb	1015	3	1	1	1	-
6 in-lb	2030	3	-	-	-	1
9 in-lb	3045	2	1	1	1	-
# of Samples		**6**			**Total Tests**	**35**

Test Chamber

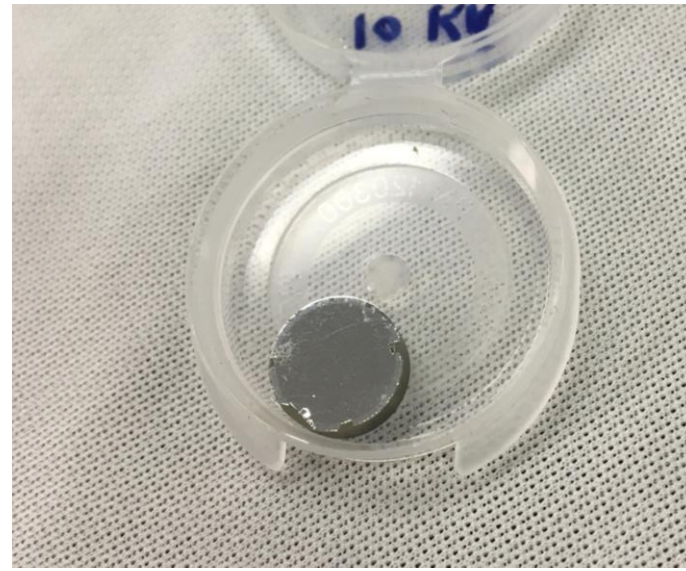
Test Fixture Set-up



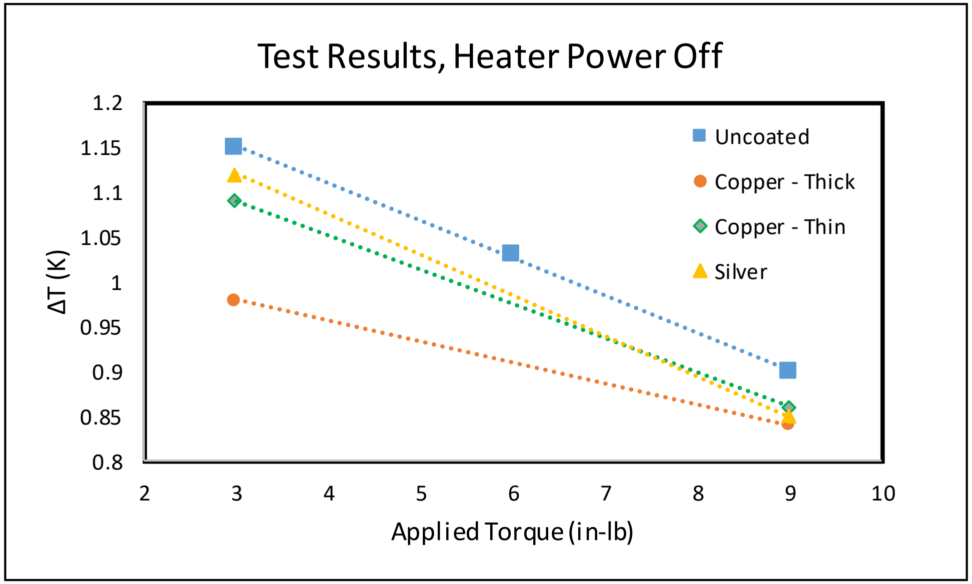


Testing Results and Conclusions

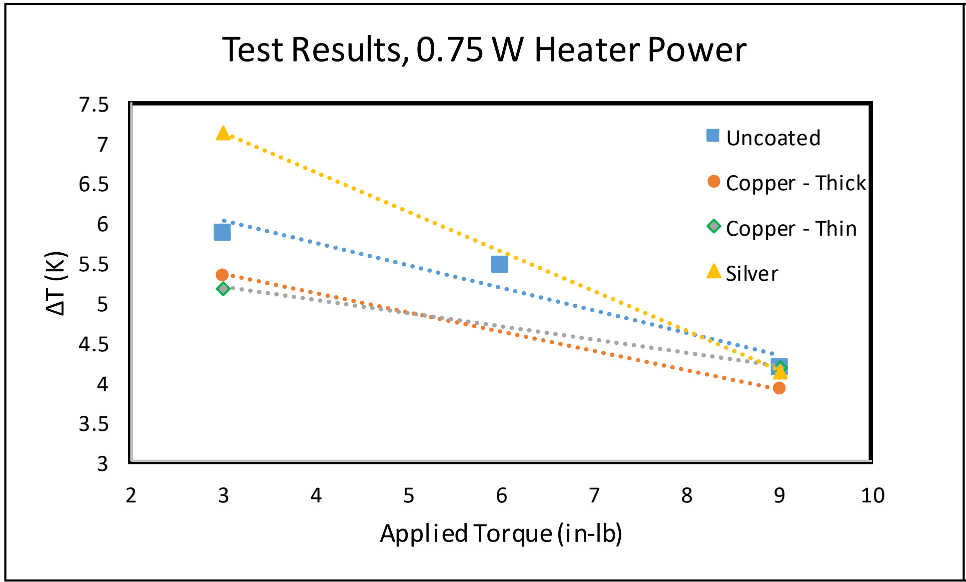
- **Aluminum sample coatings did not adhere well to surface – unable to test**
  - Hypothesizing due to contamination
  - Test was unable to be completed on Al-coated samples
- **Based on data received, highly conductive coatings can reduce ΔT (and subsequent contact resistance) across the sample**
  - More information is needed on conductivity coatings like silver
- **Thicker coatings appear to achieve higher contact resistance reduction – more testing is needed**
- **Impact of coatings is lower with higher contact pressures**
- **Only 10 – 15% increase in heat transfer**



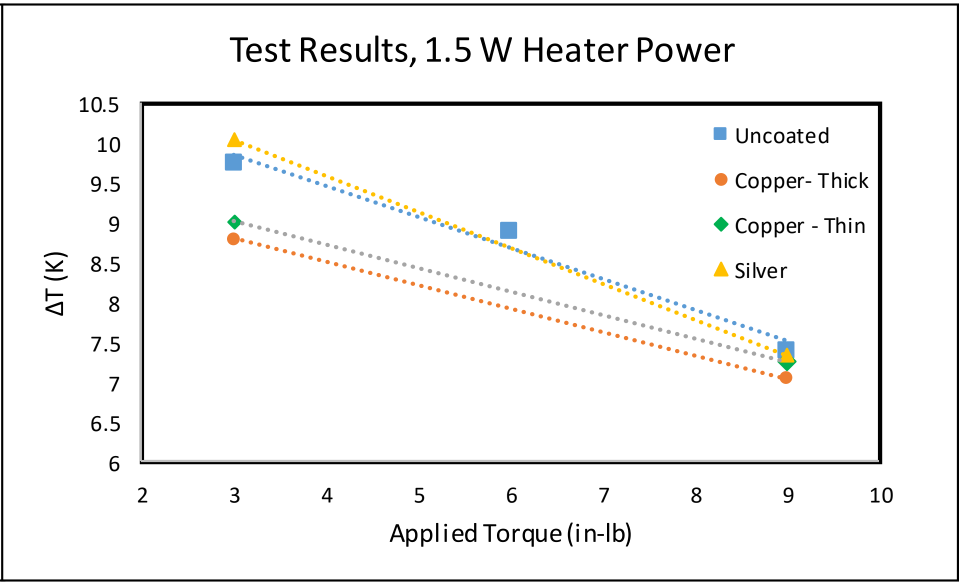
Results



Test Results, Heater Power Off
ΔT (K)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
2
3
4
5
6
7
8
9
10
Applied Torque (in-lb)
Uncoated
Copper - Thick
Copper - Thin
Silver



Test Results, 0.75 W Heater Power
ΔT (K)
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2
3
4
5
6
7
8
9
10
Applied Torque (in-lb)
Uncoated
Copper - Thick
Copper - Thin
Silver



Test Results, 1.5 W Heater Power
ΔT (K)
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
2
3
4
5
6
7
8
9
10
Applied Torque (in-lb)
Uncoated
Copper- Thick
Copper - Thin
Silver

Forward Work

- Hardness testing in order to understand relationship to surface hardness
- Repeat testing with calibrated test rig to obtain actual conductance data
- Application of coating on small-scale vapor cooling test
- Apply results to in-house vapor cooling model to predict applications for large-scale systems