National Aeronautics and Space Administration

Ultra-flexible thermal bus for use in the Astro-H Adiabatic Demagnetization Refrigerator

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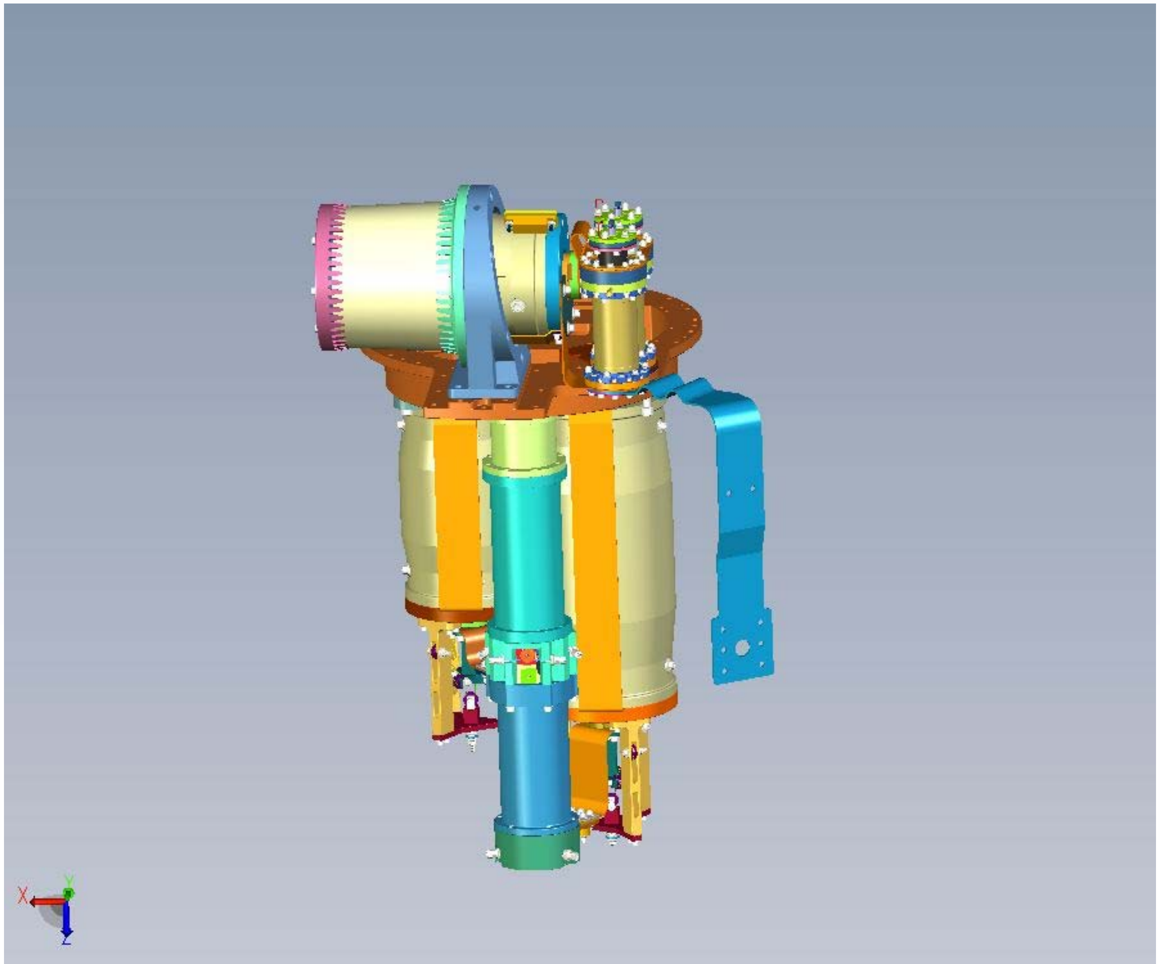
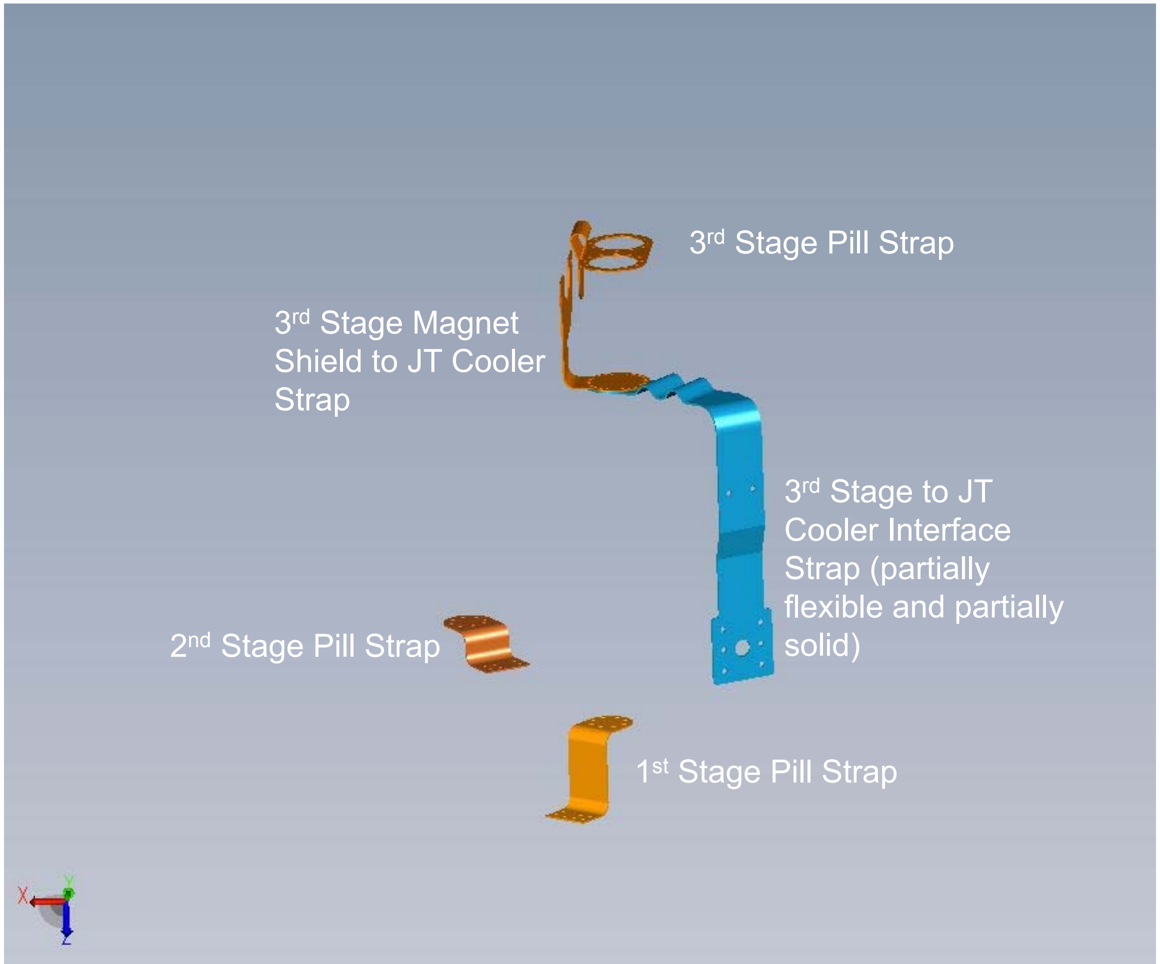
Astro-H 3-Stage ADR



Flexible Thermal Straps within the ADR



3rd Stage Pill Strap

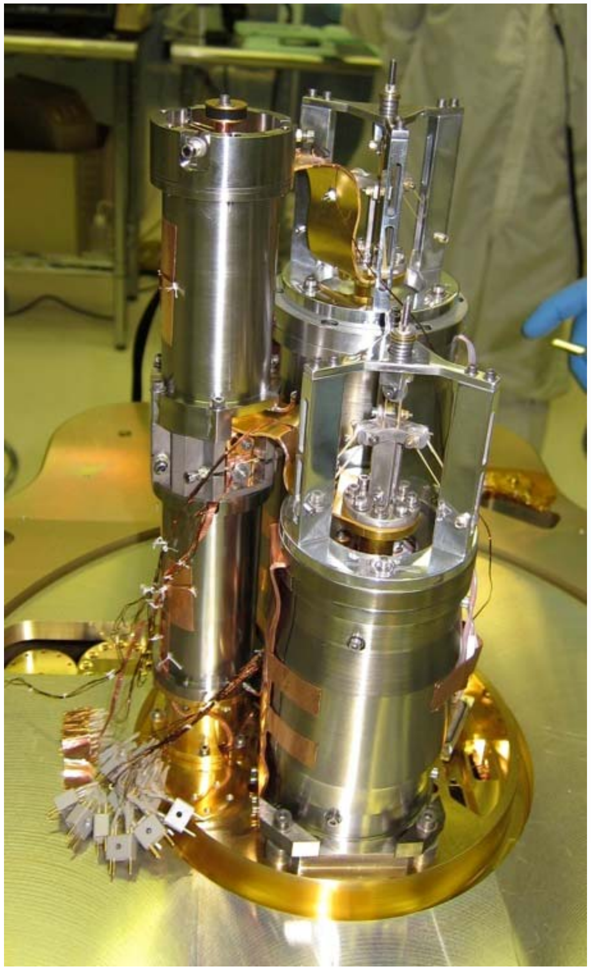
3rd Stage Magnet Shield to JT Cooler Strap

3rd Stage to JT Cooler Interface Strap (partially flexible and partially solid)

2nd Stage Pill Strap

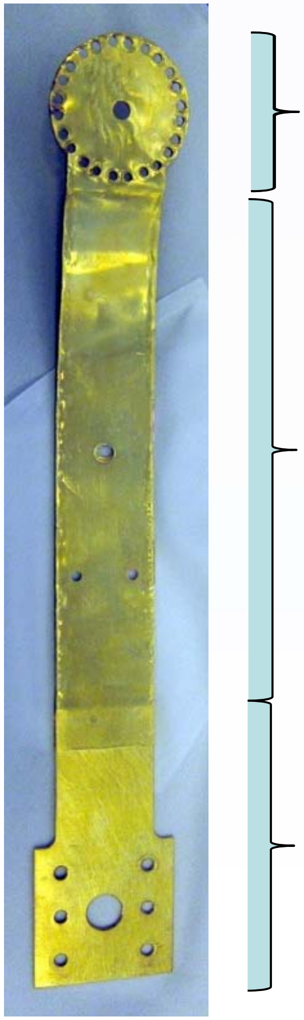
1st Stage Pill Strap

Motivation for Flexible Straps



- Paramagnetic salt pills suspended using Kevlar
- Copper thermal straps connect pills to heat switches
- Desirable to have high-conductivity straps without imparting a side load to the Kevlar suspension
- Flexible straps satisfy all requirements

Diffusion Bonding of Copper Foils



Solid section from bonding

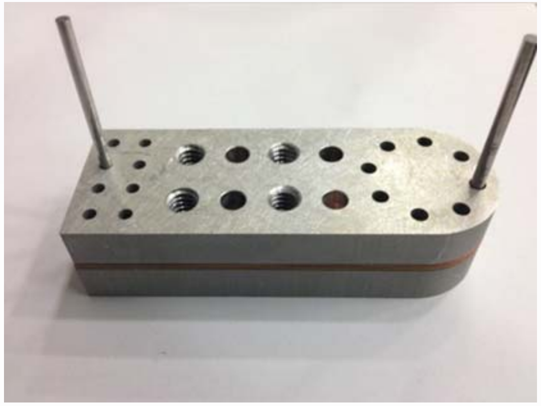
Unbonded Flexible Region (individual foils)

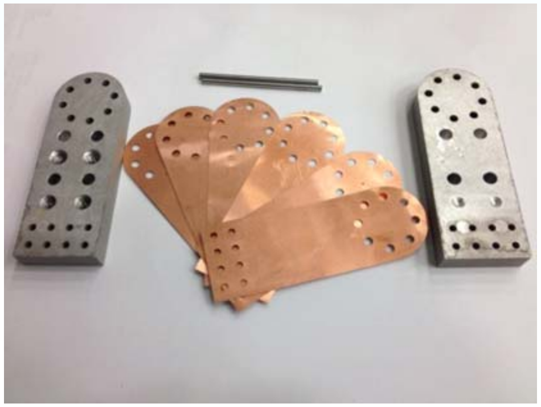
Overlap region (bonded)

Solid Region

- Cut thin foils of high-purity copper into shape of thermal strap (include features such as bolt holes)
- Stack them together
- Clamp end points together using moderate pressure (a few MPa)
- Place stacked foils and clamps into furnace
- Anneal for a few hours at 800 °C
- Remove clamps from bonded strap
- Gold plate completed thermal strap

Precision Cutting of the Foils





- Cut strips of high-purity copper foil larger than necessary for strap geometry
- Stack foils and clamp between two aluminum plates
- Electro-discharge machine (EDM) foils and fixture to shape
- Add features such as screw or retaining holes by interpolating a pilot hole with EDM (does not leave a burr)

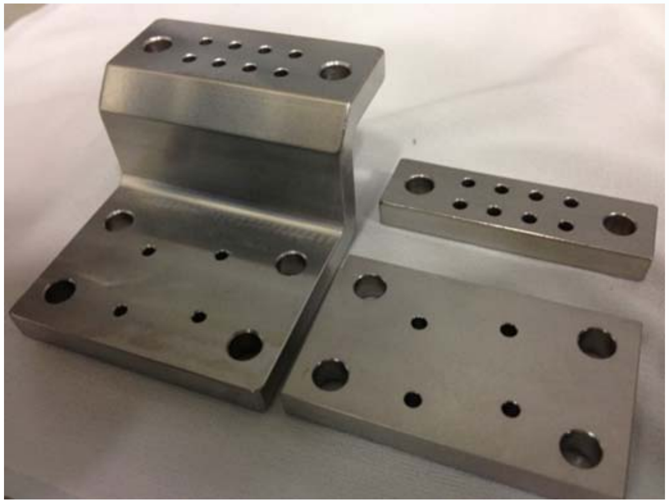
Cleaning Foils Prior to Bonding

Remove oxide layer using mild acid (20% HCl or Kester Copper-Nu)

Lift-off oxides and other surface contaminants using deionized water

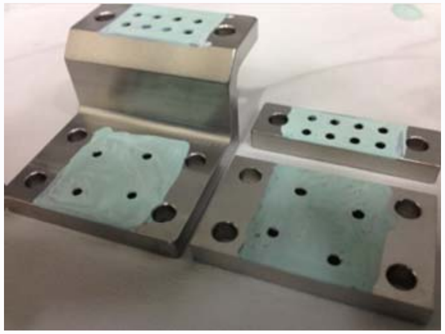
Dry using IPA bath.

Bonding Fixture

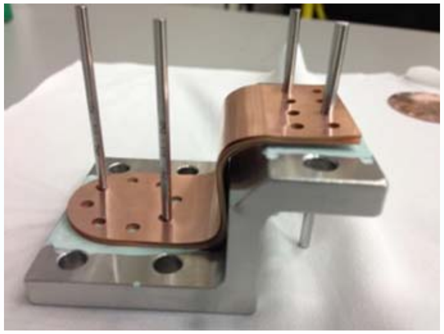


- Typically Made from 304 Stainless Steel
- Dictates the shape of the completed strap
- Provides a means to apply the clamping force necessary for bonding

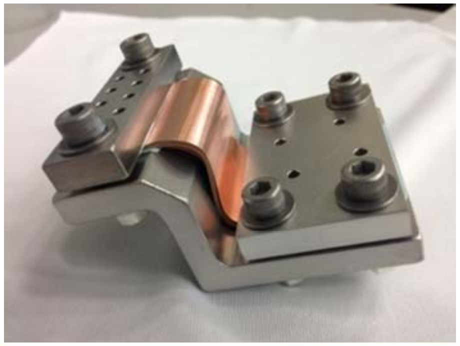
Assembly on Fixture



Coat fixture with Titanium Dioxide (release agent)

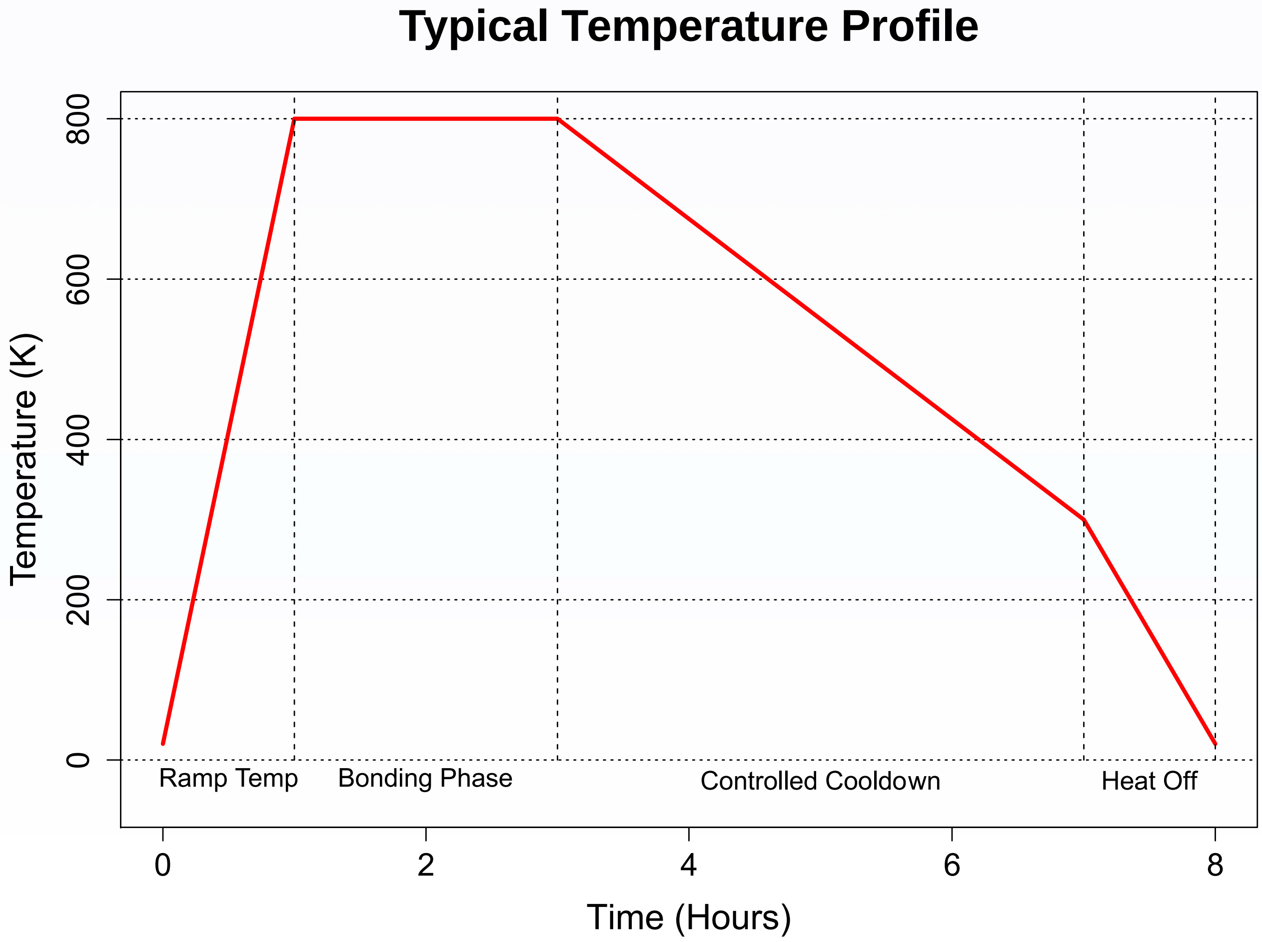


Use guide pins to form the foil shape and align features

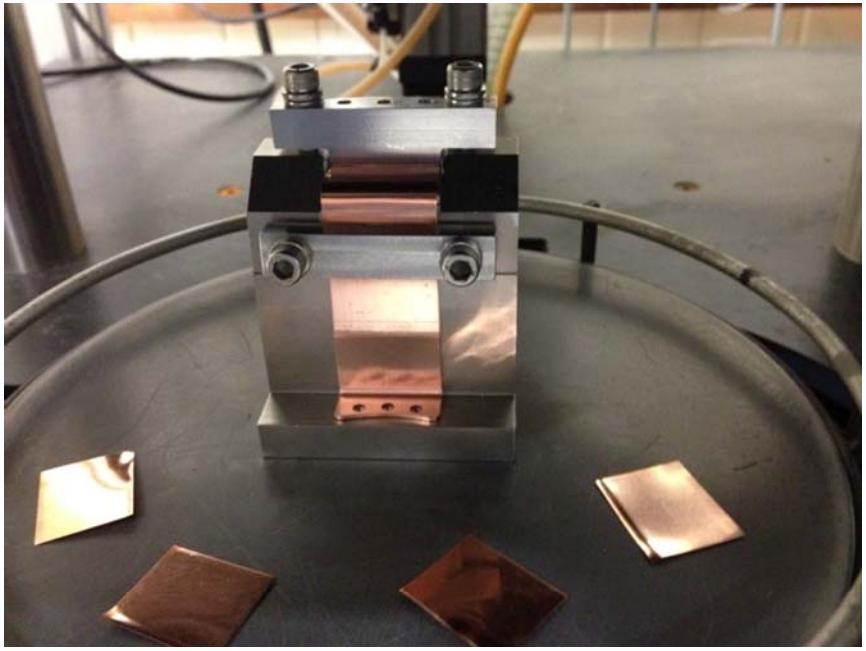


Torque hardware to achieve ~3 MPa pressure

Bonding / Anneal in Vacuum Furnace

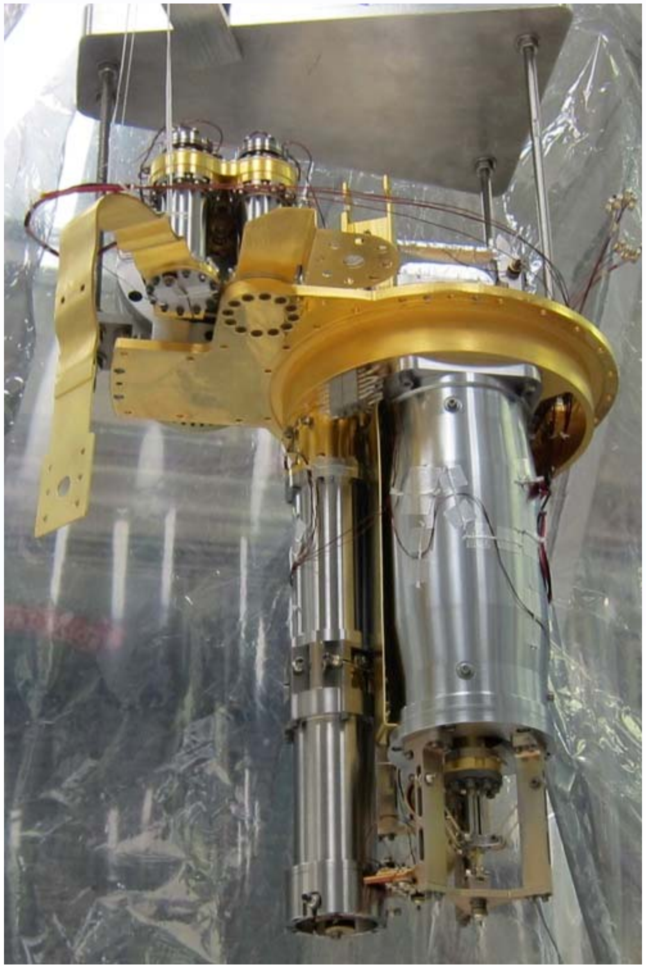


Final Steps



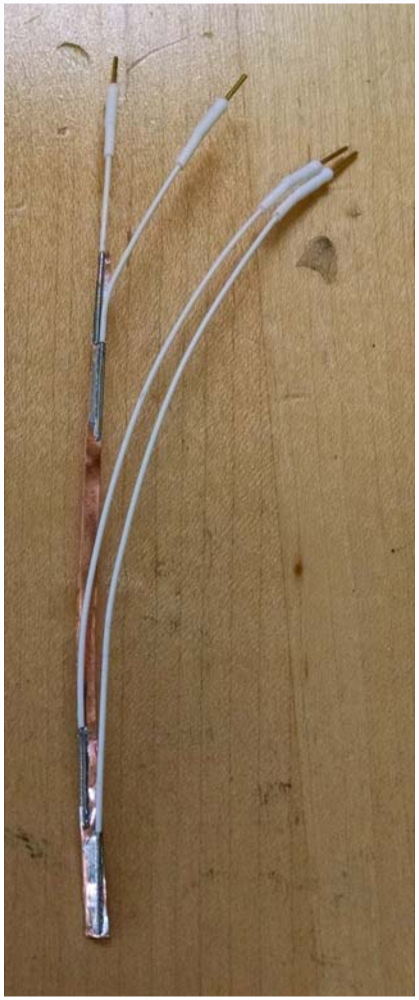
- Remove bonded strap from fixture
- Clean residual release agent
- Measure residual resistance ratio of complete strap (optional)
- Gold plate entire strap

Role of Magnetic Impurities in Raw Material



- Ferromagnetic impurities substantially decrease thermal conductivity
  - Unpaired electrons in impurity create a magnetic dipole moment
  - Long-range effect
  - Few PPM is enough to see effect
  - Iron common in copper
  - Chromium and Nickel may be present also
- Best to choose 6N (99.9999%) pure copper or verify there is a low ferromagnetic impurity content

Verify copper purity



Measure the residual resistance ratio of the copper foils:

$$RRR == R_{RT} / R_{4K} = \rho_{RT} / \rho_{4K}$$

- Electrical measurement easier than thermal one
- Compare various samples without precise measurements of sample geometry
- Need thin, long sample with 4-point resistance setup

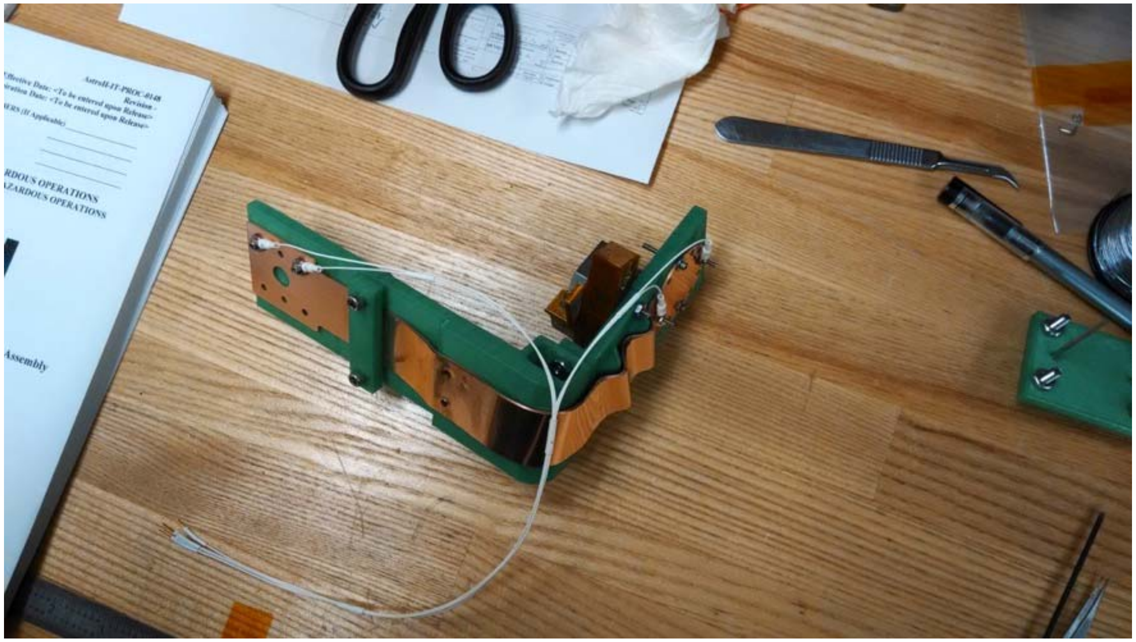
RRR ≤ 300 ➔ OK copper (OFHC)
RRR ≥ 1000 ➔ Highly annealed 6N (99.9999% pure) copper
or lower purity copper with low ferromagnetic
impurity levels

Example: 4N copper gives poor conductivity in thermal strap
Estimation of RRR from conductivity ≈ 200
Noted there is 3 PPM of iron in this material
Independent electrical measurement of RRR = 188

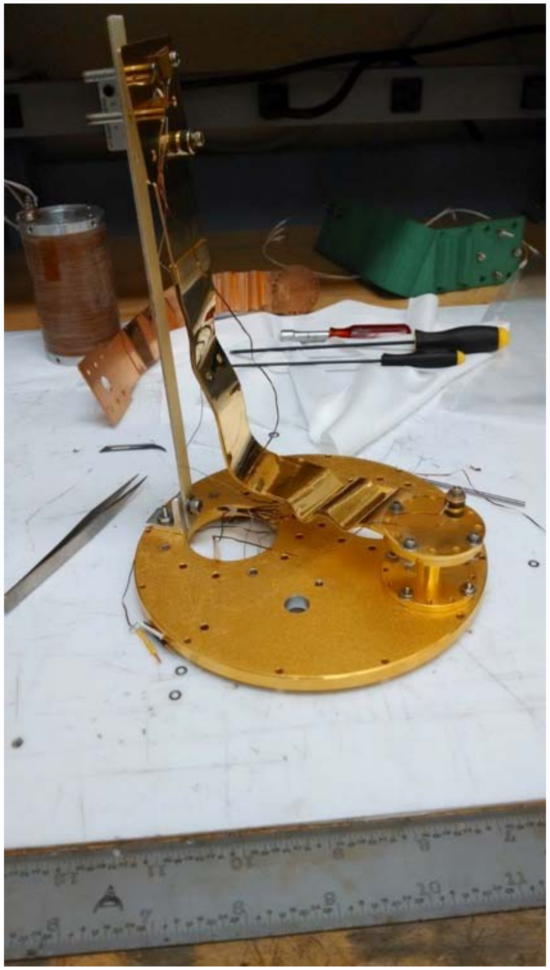
Verify strap hasn’t changed during bonding

Measure the RRR after diffusion bonding strap to verify possible contaminants in furnace haven’t diffused into strap at high temperature

- Difficult for good copper (low Ω at low T)

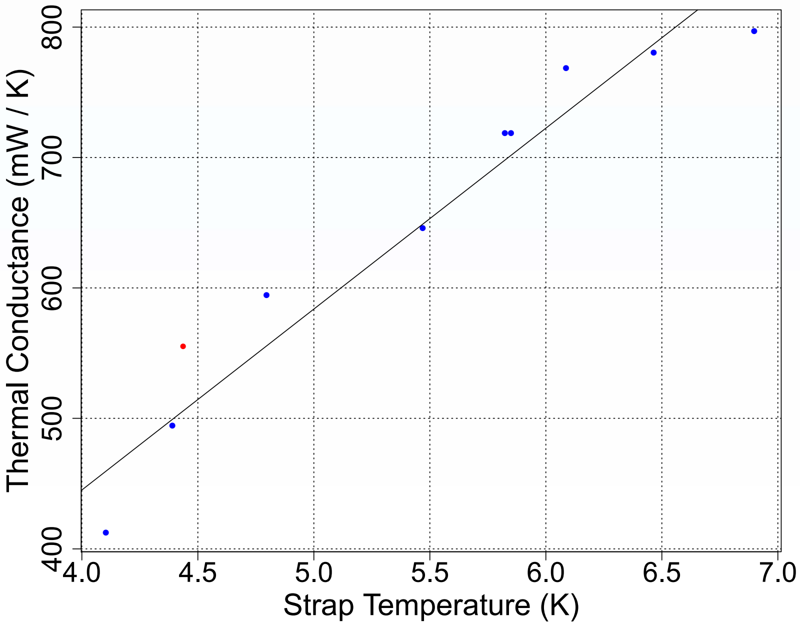


Measure Conductance of Actual Strap



Measure thermal conductance of completed strap

- More difficult than electrical measurement
- No ambiguity in interpreting data
- Heat on the “free” end, thermometer on both ends: $\kappa = \text{Heat}_{\text{input}} * L / A / \Delta T$



Note on Gold Plating

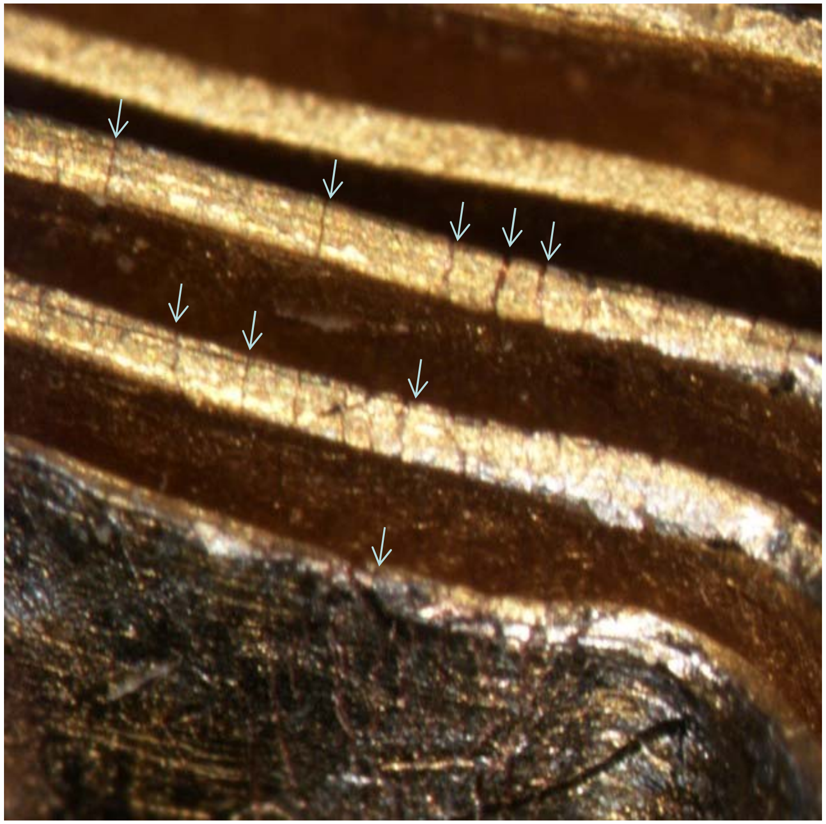


Photo courtesy of Len Wang, NASA/GSFC, Code 541

- Gold plating enhances the conductance at interface boundaries
- Gold plating of copper usually involves an electroless nickel (Ni-15%P) underlay followed by a thin coating of gold
- Electroless nickel is brittle and prone to crack on flexible parts
- Crack may propagate into copper base material
- Best to use either electrolytic nickel as underlay or forego completely and use thicker gold plating (~ 0.005 mm)