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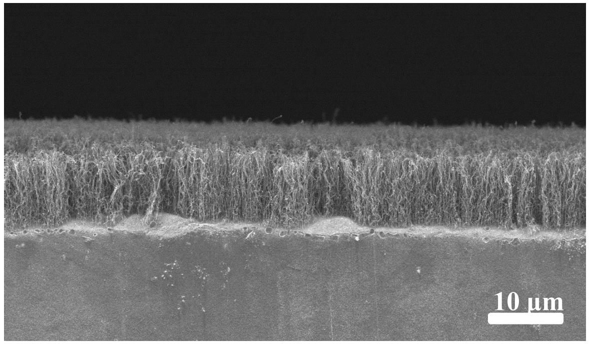

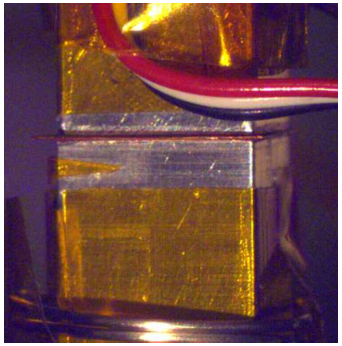

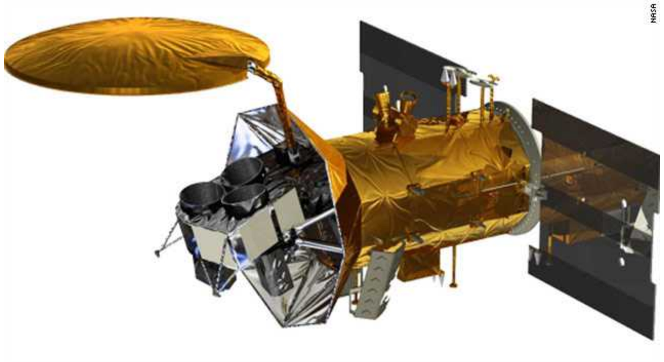

Thermal Contact Resistance of Gamma-Irradiated Metallic Foil and Carbon Nanotube Thermal Interface Materials

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Satellite Life Cycle

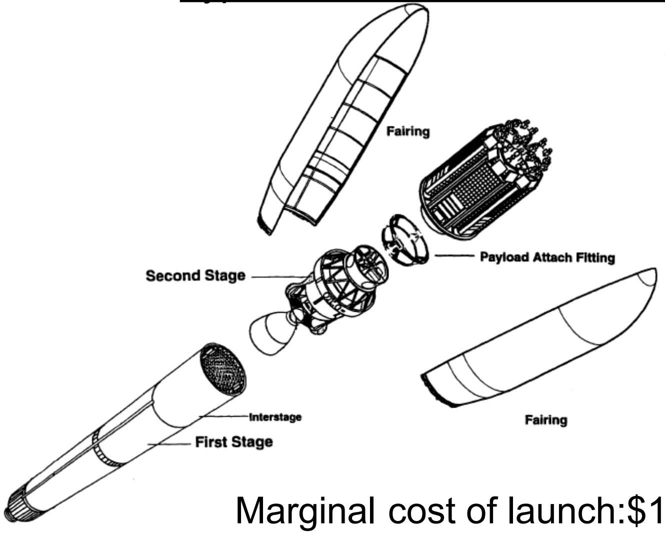
- Design and build (several years)
- Launch (several minutes)
- **Performance of mission (several years)**
- End of mission

Electronic components dissipate heat (Q=IV)

- Protected from overheating
- Heat can only be removed via conduction or radiation

Satellite build in a clean room [Source: NASA]

Typical launch vehicle and satellite



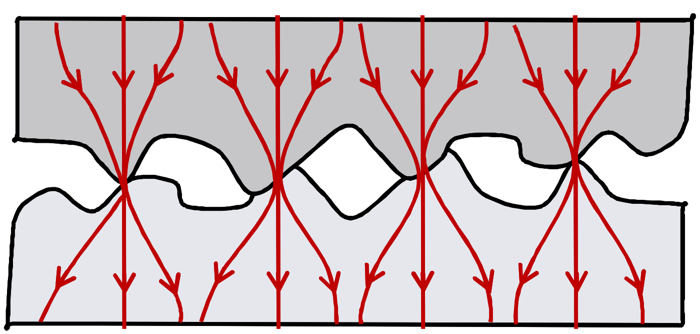
Marginal cost of launch:$10,000/lb

Thermal Contact Resistance

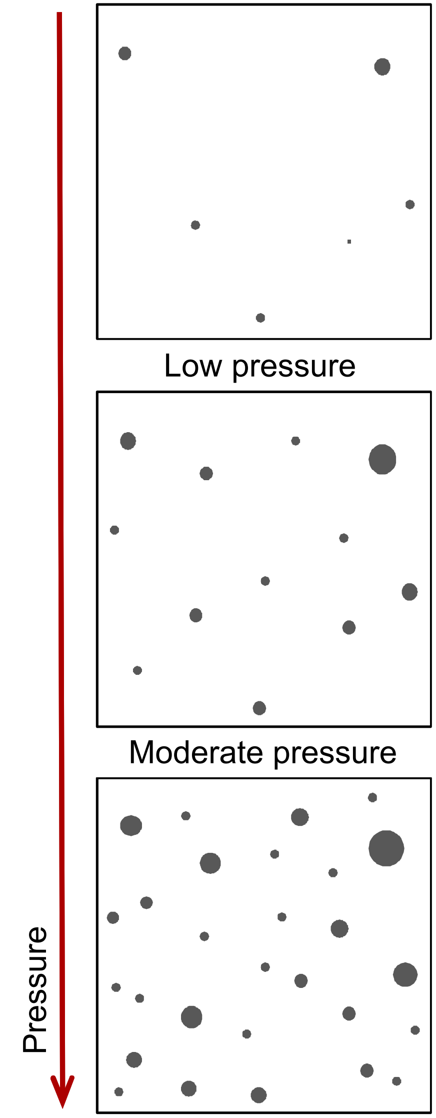
- For interfaces in contact, the real area of contact is typically 2 to 6 orders of magnitude less than the apparent area of contact $\frac{A_r}{A} = \frac{P}{H}$
- In vacuum, thermal contact resistance (TCR) of a Gaussian surface is given by

$$R = 0.88\frac{\sigma}{km}\left(\frac{H}{P}\right)^{0.94} = aP^b$$

- For systems with multiple interfaces, TCR can consume a significant part of the thermal budget

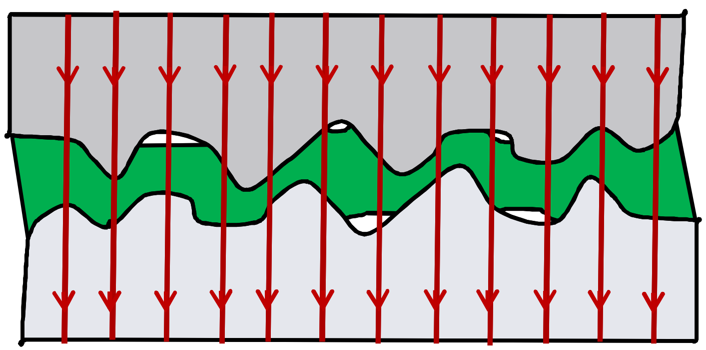


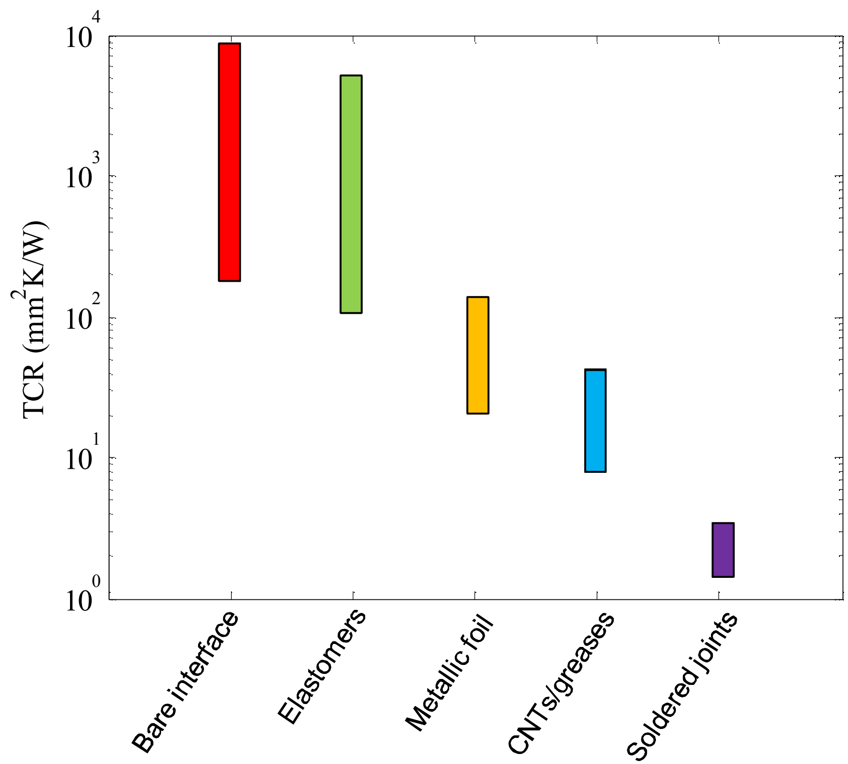
A	Apparent contact area
A_r	Real contact area
a,b	Constants
H	Hardness
k	Thermal conductivity
m	Asperity slope
P	Contact pressure
R	Contact resistance
σ	Surface roughness



Thermal Interface Materials

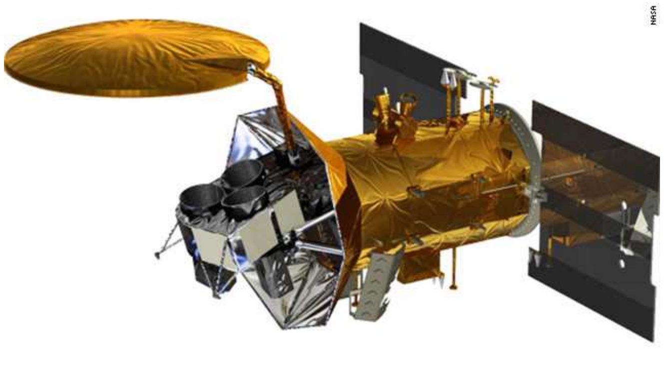
- Thermal interface materials (TIMs) provide a means of decreasing TCR by filling the gaps between asperity contacts
  - Thermal greases
  - Metallic foils
  - Carbon nanotube (CNT) materials
  - Elastomeric materials





Satellite Systems

- Special considerations are required for TIMs used in satellites
  - Low outgassing (NASA standards)
  - Lightweight
- Space systems are exposed to a wide array of radiation sources
  - UV
  - X-ray
  - Charged particles
  - γ-ray



NASA Aquarius satellite [2]

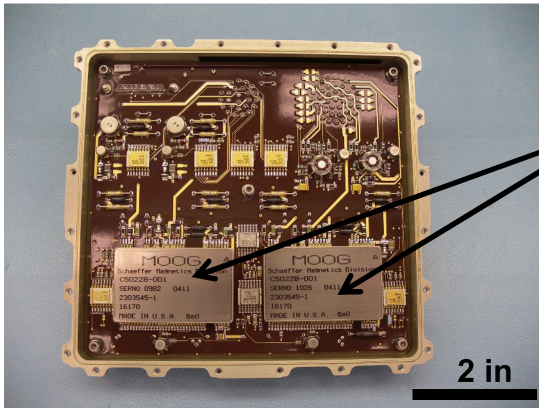
UV, X-ray, Charged particles: Absorbed and reflected by outer materials

γ-ray:
Experience little attenuation
Easily reach and pass through all components
Doses as high as 10 Mrad /yr [3]
Interactions with TIMs are important

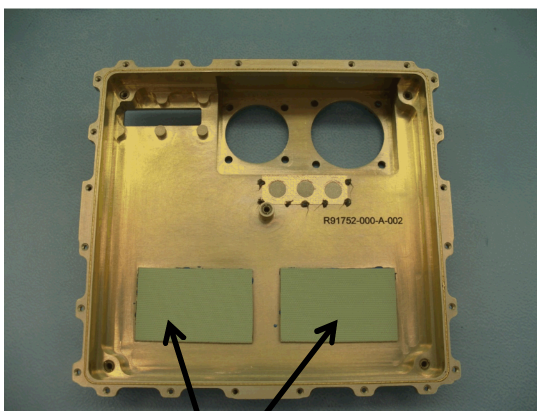
[2] CNN Wire Staff, NASA launches satellite for critical mapping mission, June 10, 2011.
[3] R. Akau et al., 2012, Nexus Test Report for Thermal and Mechanical Study of Silver-Teflon Tape for Space Applications, SNL, Albuquerque.

TIMS in Satellite Systems

Control electronics box assembly

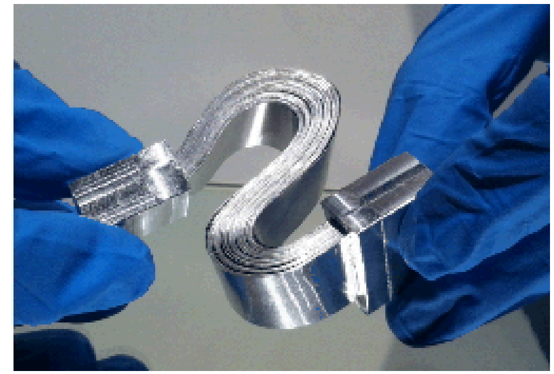


Power converters
4 W dissipated

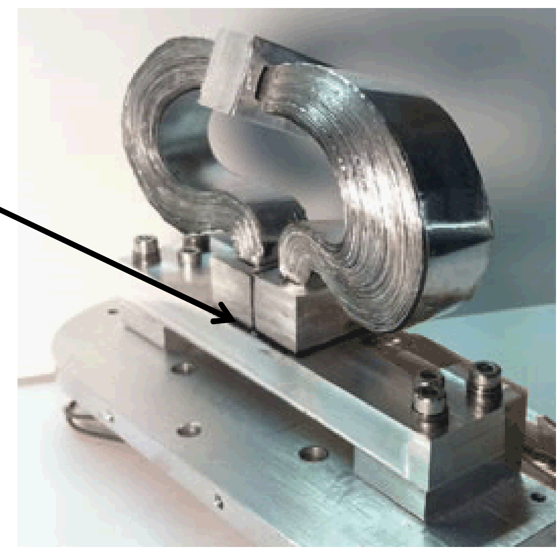


Elastomeric TIMs

Thermal straps



CNT TIMs
(or metal foil)

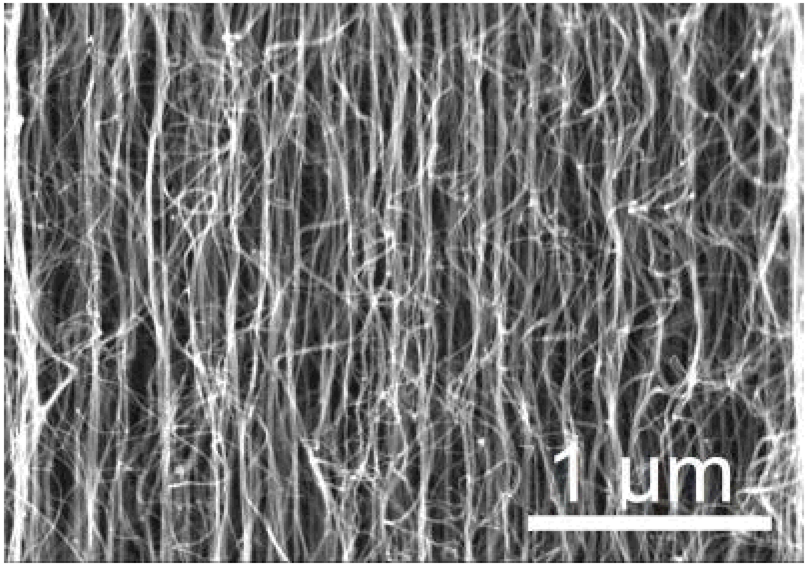


www.thermotive.com

Materials

- 4 metallic foils were chosen due to their common use as well as their contrasting material properties
- CNTs were grown on a Cu foil substrate with a tri-layer catalyst
  - 30 nm Ti
  - 10 nm Al
  - 5 nm Fe
- Microwave plasma chemical vapor deposition (MPCVD) was used to grow CNTs
  - N_2 anneal
  - 2.5 minute growth
    - 800°C
    - 300 W
    - 10 Torr
    - 50 sccm H_2, 10 sccm CH_4
- CNTs
  - 10 µm in length
  - 20 – 50 nm in diameter

Metal	Thermal conductivity (W/mK)	Young's modulus (GPa)	Vickers hardness (MPa)
Copper/CNT	0.5-5	1	-
Aluminum	237	70	167
Copper	401	120	369
Nickel	91	200	638
Tin	67	50	80



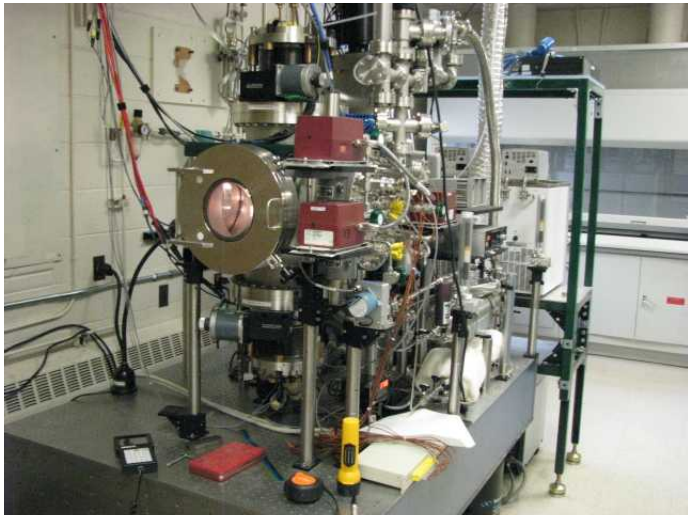
Radiation Dosing

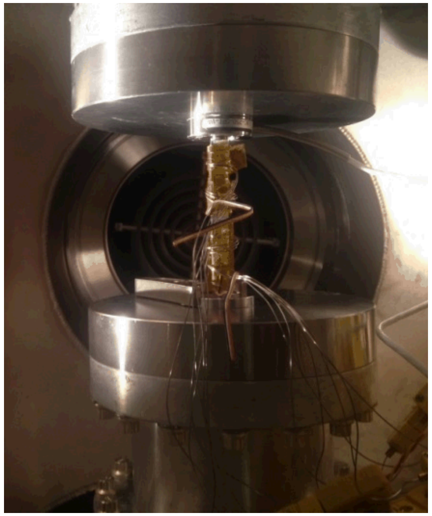
- Accelerated radiation aging was conducted in a ^{60}Co gamma cell
  - 250 rad/sec
  - Total doses of 50 Mrad
  - Dose chosen to be consistent with previous studies of TIMs [4-6]
  - Representative dose of a 5 to 10 year mission life

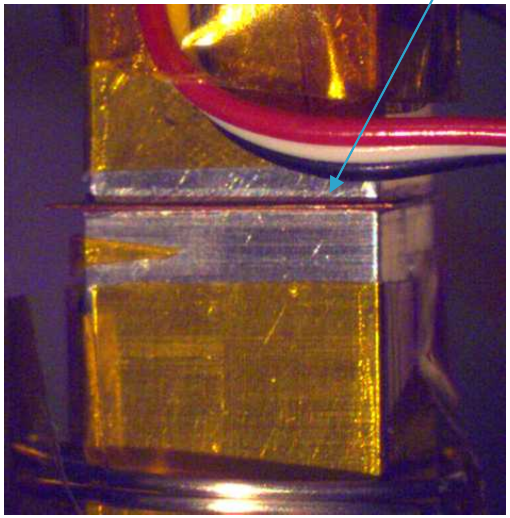
[4] R. Sayer et al., 2013, ASME Summer Heat Transfer Conference, HT2013-17408
[5] S. Hodson et al., 2013, ASME IMECE, IMECE2013-62773
[6] R. Sayer et al., 2014, Vibration Institute Training Conference

1-D Steady State Experimental System

- Minimum chamber pressure: 3×10^{-4} Pa
  - Capabilities in N_2, Ar, He, air and other gas environments up to 85 kPa
- Maximum interface pressure: 70 MPa
- Temperature range: 0 to 80 ℃
- 2 aluminum heat flux meters (HFMs)
  - 38 mm length, 8 mm x 8 mm square cross-section
- 12 thermocouples (6 per HFM)







Heat Flux Meters

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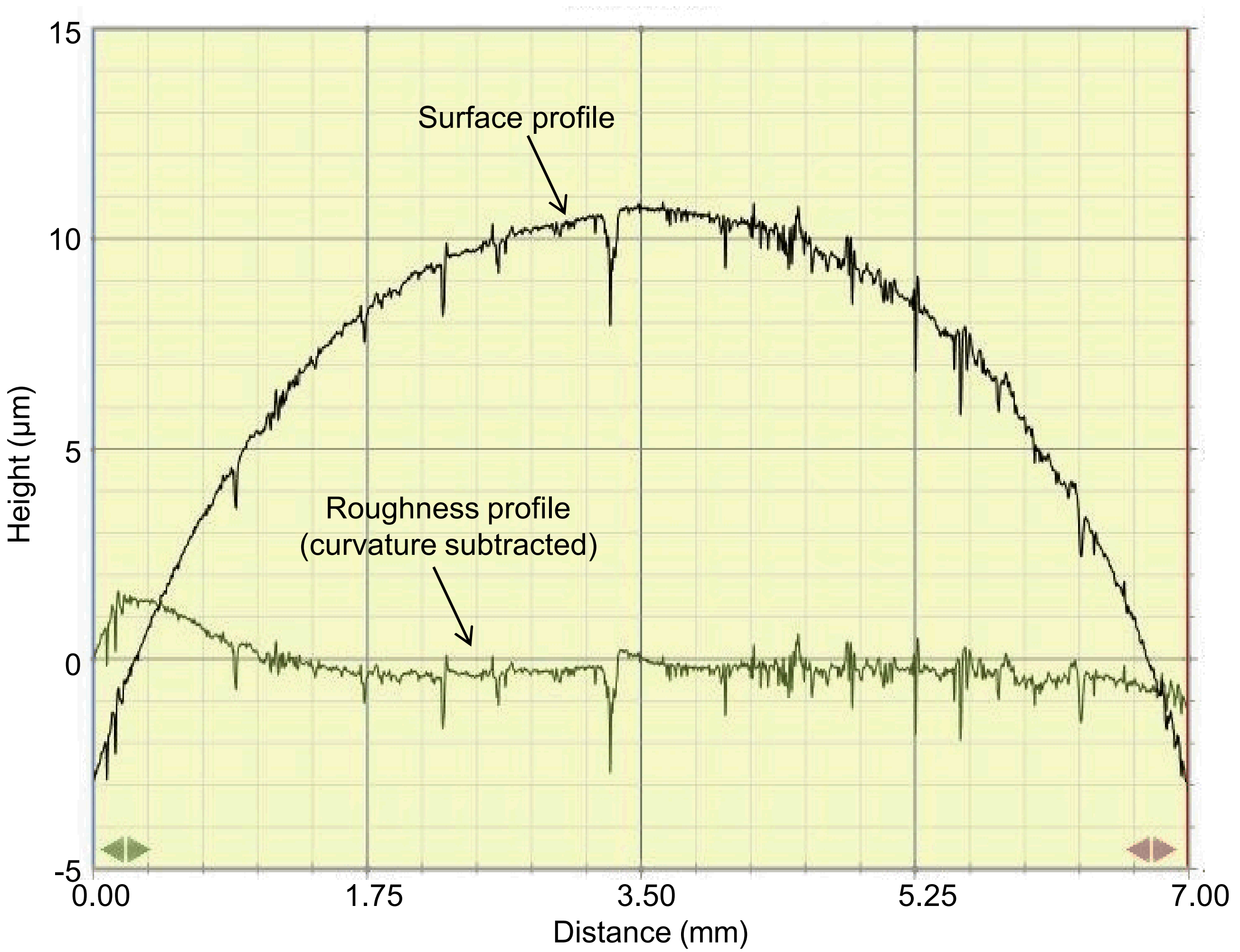
- Due to the large curvature of the HFMs, contact area is difficult to determine
- Results are given in units of overall thermal resistance (K/W) rather than area normalized contact resistance (mm^2K/W)

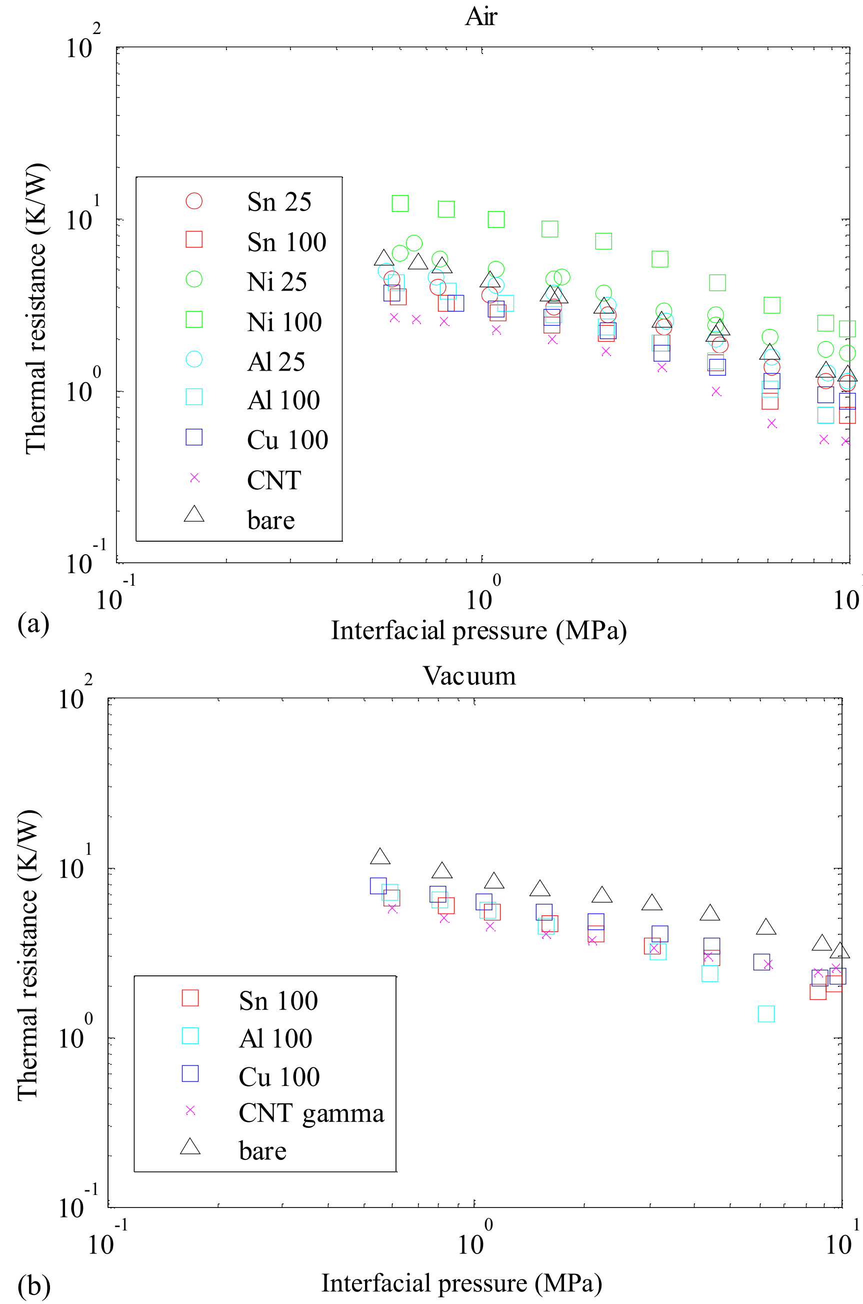


Results

- 9 different samples were tested in both air and vacuum environments

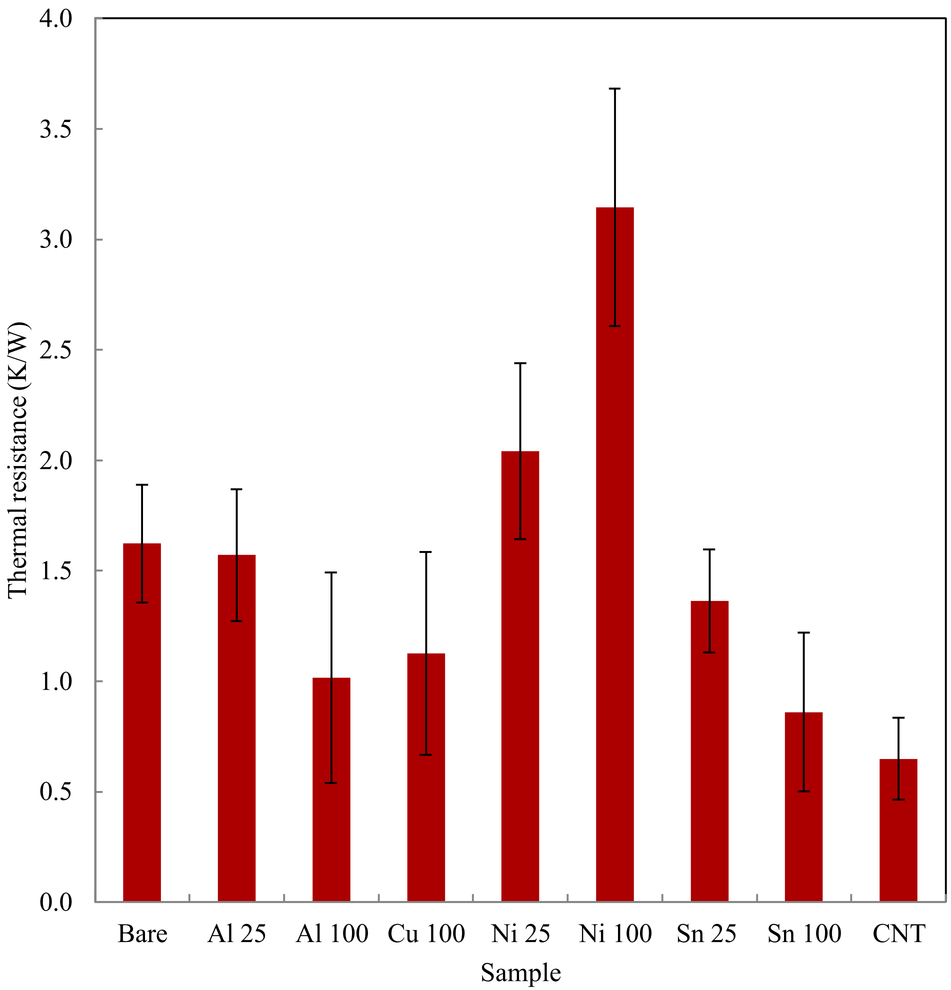
Sample	Material	Thickness (µm)
1	Al	25
2	Al	100
3	Cu	100
4	Ni	25
5	Ni	100
6	Sn	25
7	Sn	100
8	Cu/CNT	~120
9	bare	--

- Interface pressures between 0.5 – 10 MPa
- Interface temperature ~ 330 K
- Al, Cu, Sn, and Cu/CNT materials improved contact resistance



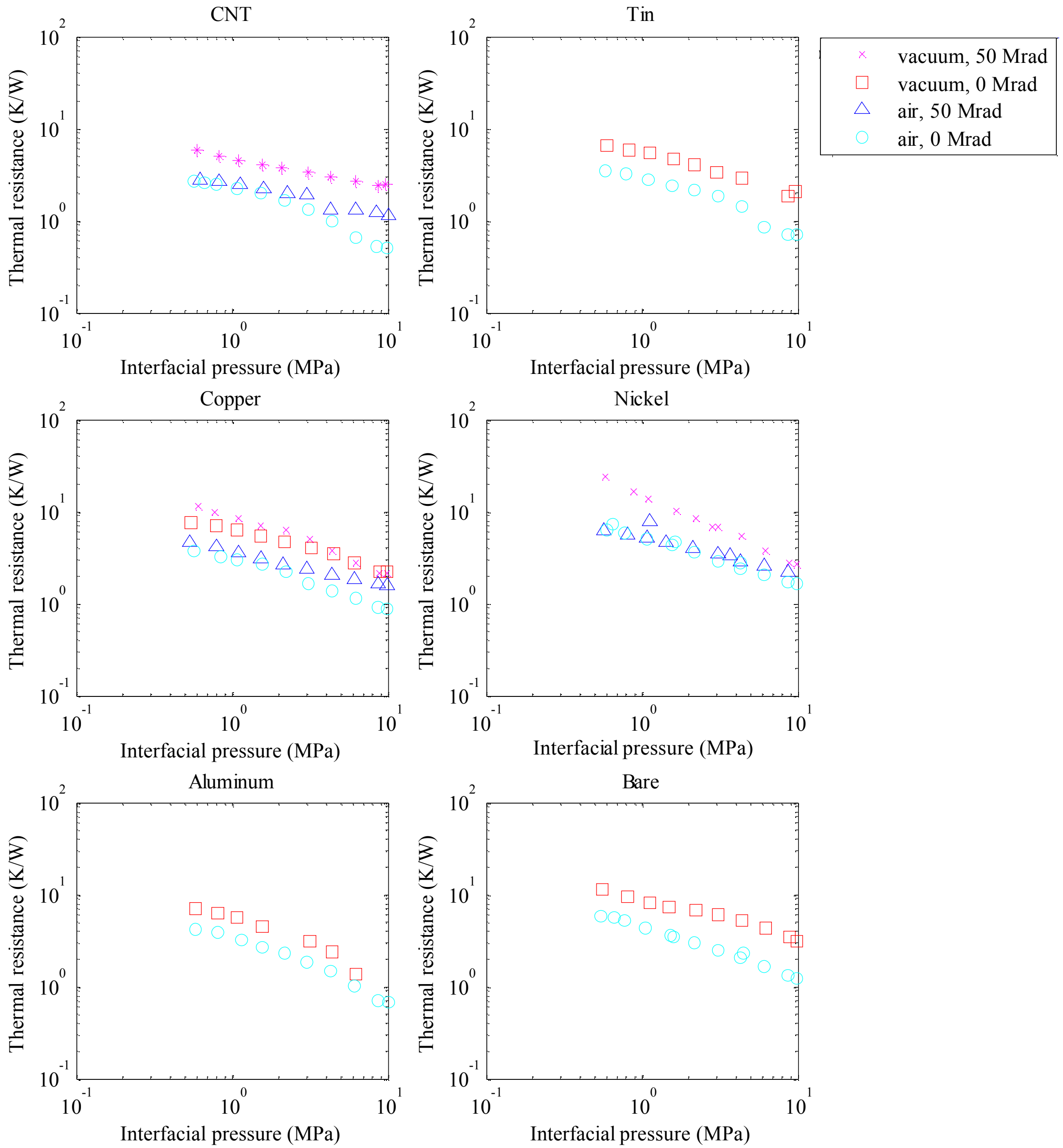
Thermal Resistance in Air at 6.2 MPa

- Thicker foils perform better than thinner foils for Al, Cu, Sn, and Cu/CNT.
  - Opposite for Ni foil
- Total thermal resistance
  - Hardness
    - Affects contact area
  - Thermal conductivity
  - Constriction resistance
  - Boundary resistance



Effects of Gamma Irradiation: 100 µm Thick Foils

- $TCR_{air} < TCR_{vac}$ due to conduction through air gaps
- Radiation hardening
  - Ni foil
  - Cu/CNT foil below 1 MPa
- Deformation of mechanically hardened Cu foil important above 1 MPa



Conclusions

- Mechanical and thermal stability are vital to satellite component performance and longevity
- Thermal interface materials must maintain their heat transport capabilities under gamma radiation exposure
- Exposure to gamma radiation can affect the performance of satellite components
- Radiation aged TIMs were thermally tested in a 1D reference bar setup
  - Ni and Cu/CNT foils exhibited radiation hardening
  - Cu/CNT foils outperform Al, Ni, and Sn foils
  - Foil thickness affects the contact resistance

Acknowledgement

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Loading Hysteresis