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# Thermal Performance of CNT and CNT/Petal Thermal Interface Materials

Stephen L. Hodson<sup>1,2</sup>, Quentin E. Sneed<sup>1,3</sup>, Timothy S. Fisher<sup>2</sup>, Thomas W. Grasser<sup>1</sup>, and Robert A. Sayer<sup>1</sup>

<sup>1</sup>Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185

<sup>2</sup>Purdue University, 1205 West State Street, West Lafayette, IN 47907

<sup>3</sup>Howard University, 2400 6<sup>th</sup> Street NW, Washington, DC 20059

# Motivation

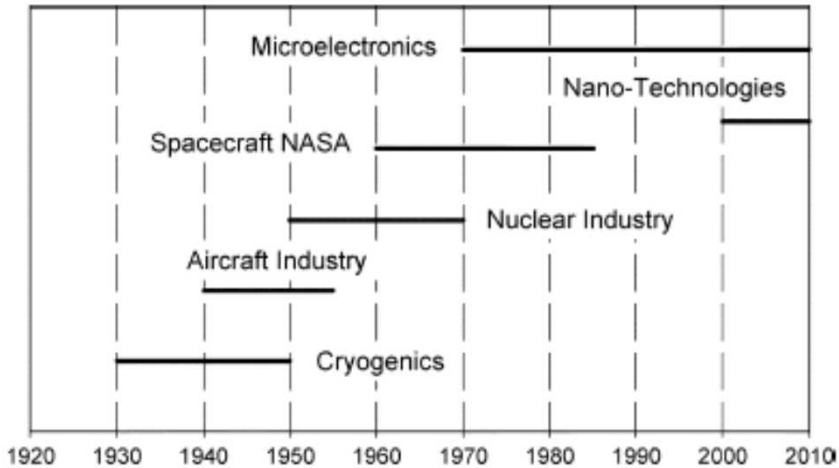


Fig. 1. Time line for thermal contact resistance research.

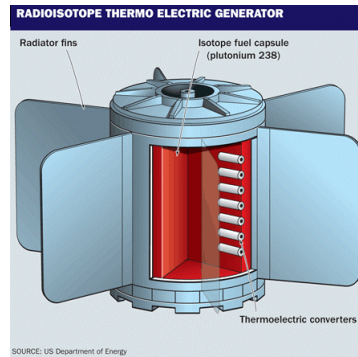
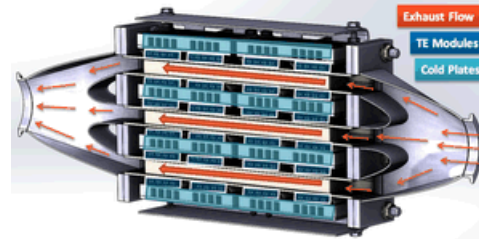
Yovanovich, IEEE Trans. Comp. Pack. Tech., 28(2), 182-286, 2005



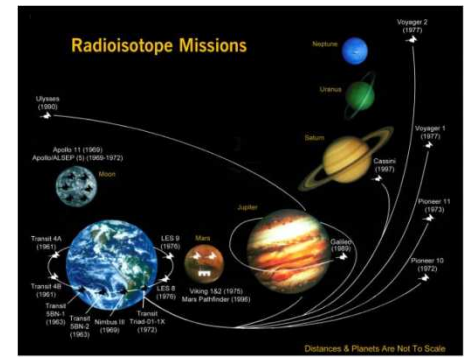
Intel.com

Operating Temperatures: >1300 K  
Operating Pressures: 0 – 10 MPa

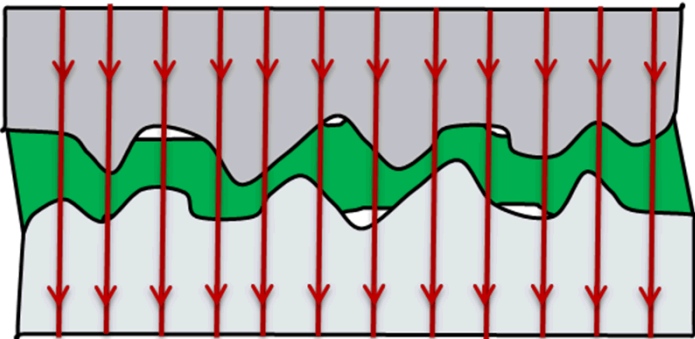
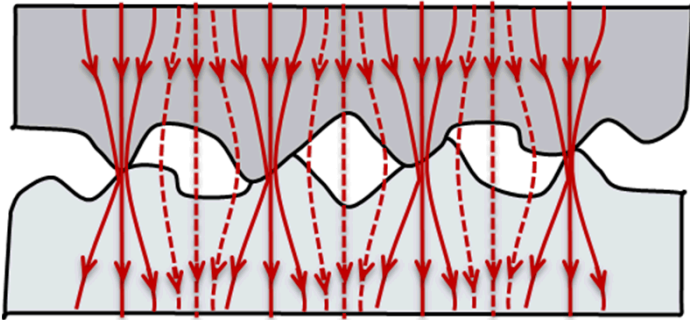
[www.greencarcongress.com](http://www.greencarcongress.com)



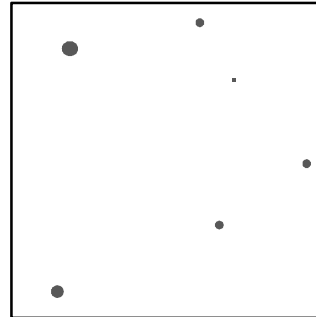
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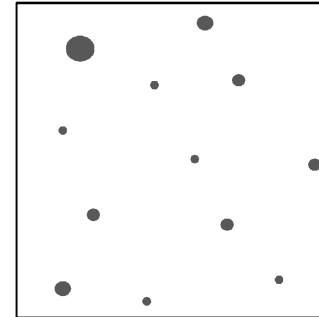
# Introduction



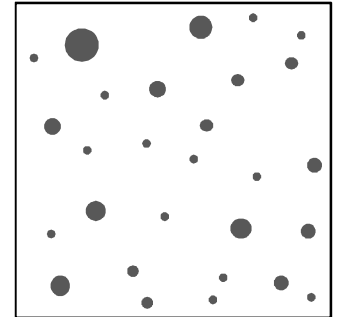
Low pressure



Moderate pressure



High pressure

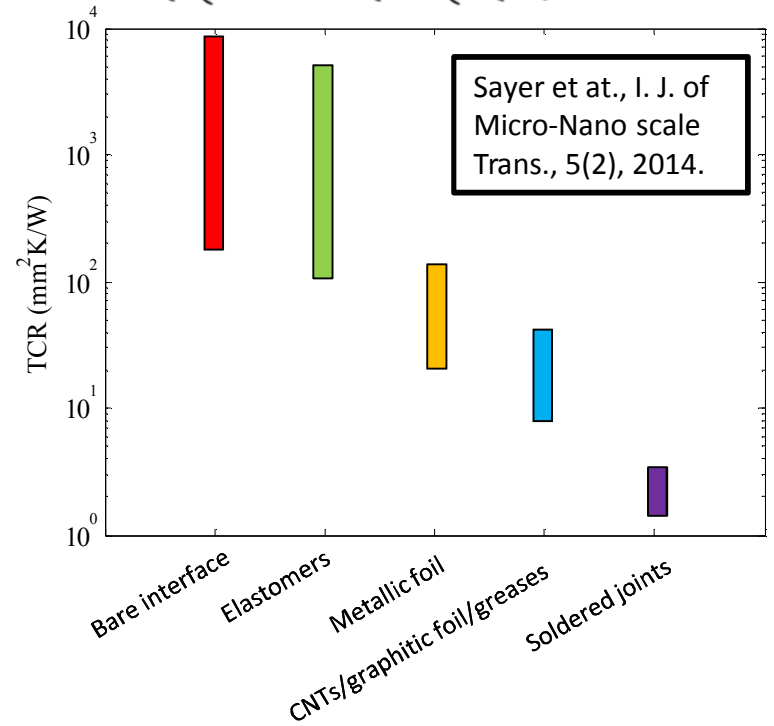
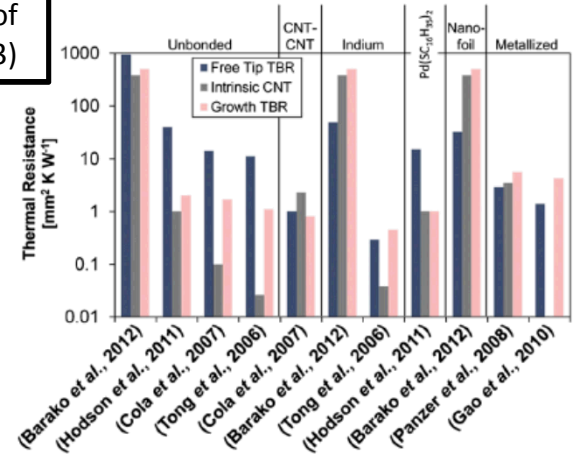
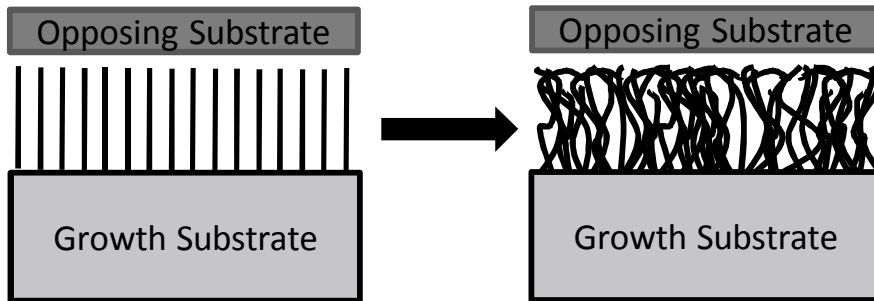
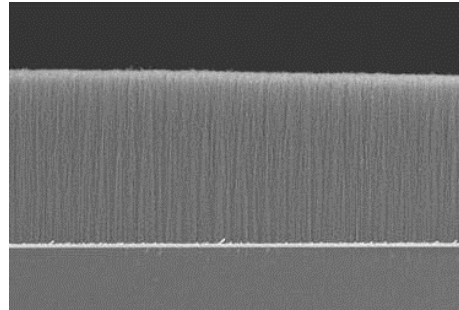
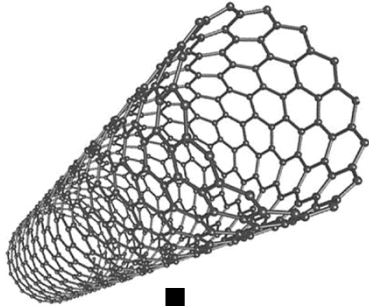


Pressure

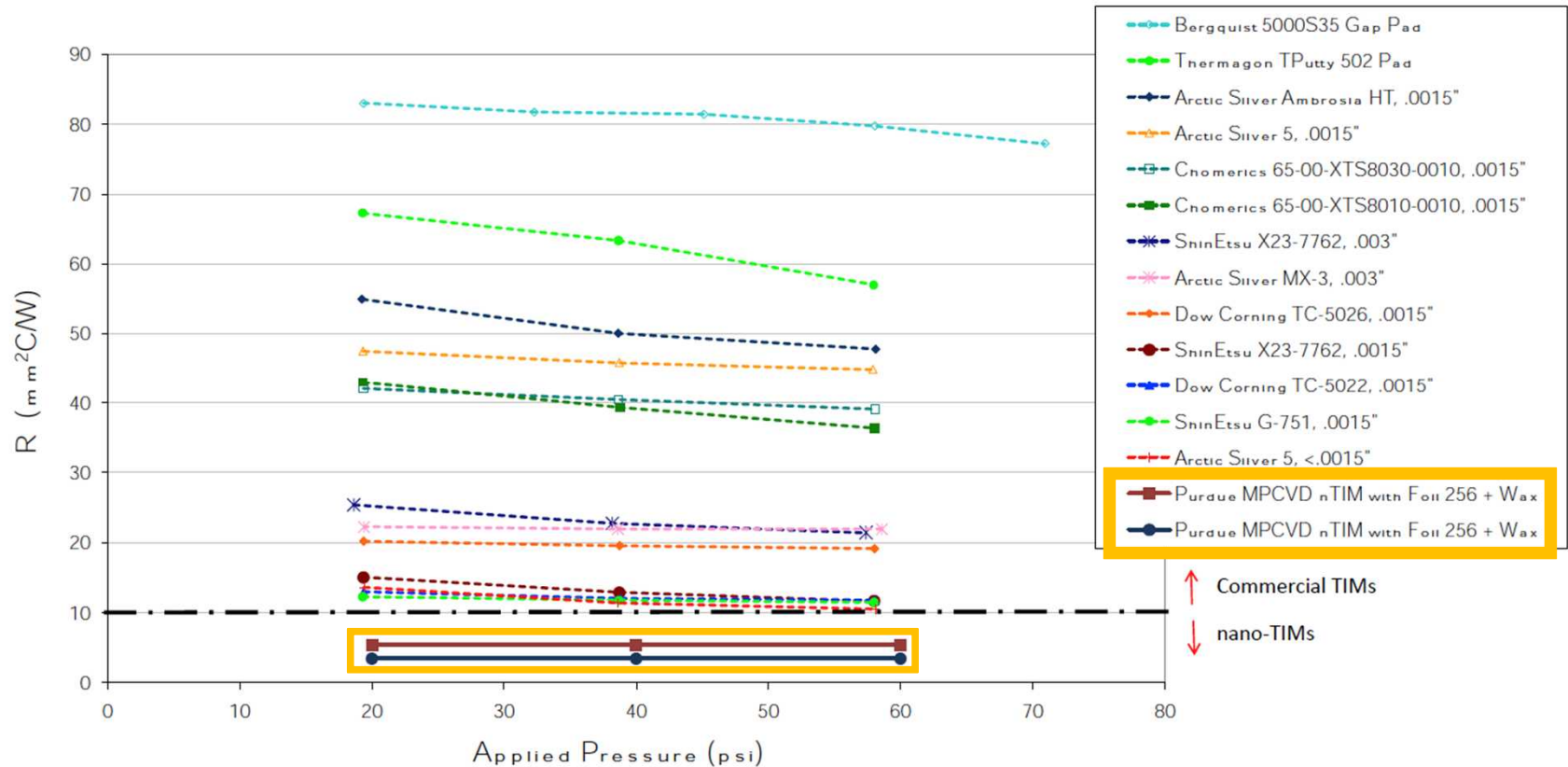
# Carbon Nanotube Thermal Interface Materials (CNT TIMs)

Marconnet et al., Rev. of Mod. Phys., 85(3), 2013

worldofnanoscience.weebly.com

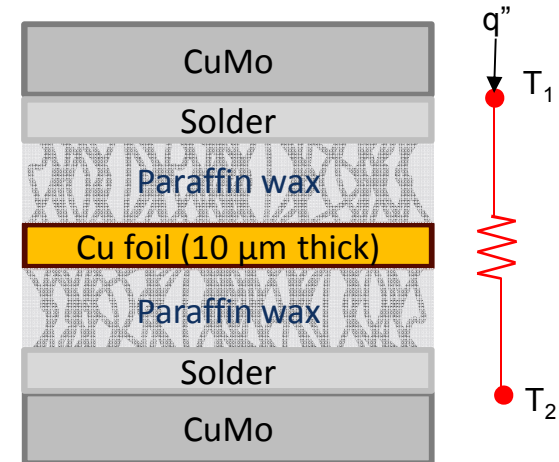
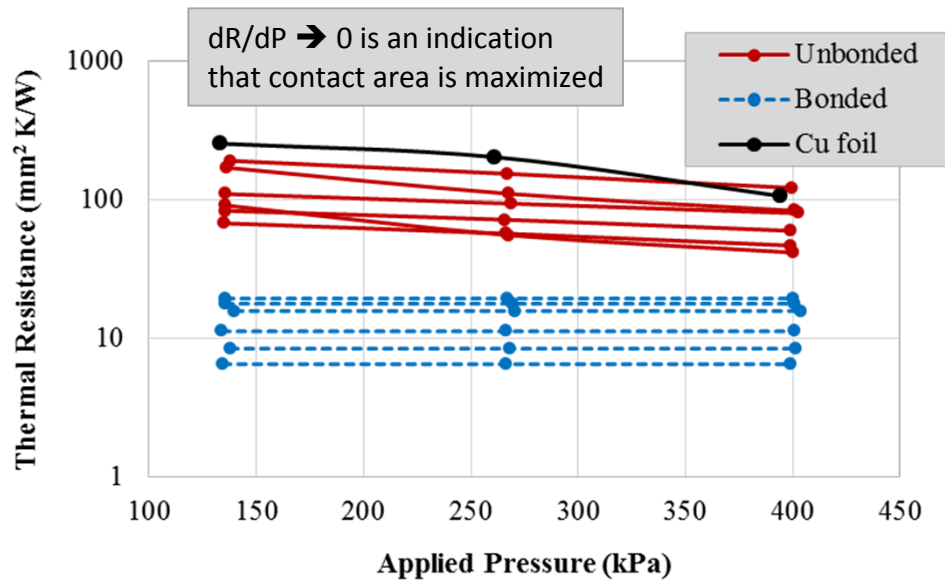


# Thermal Performance of CNT TIMs



Wasniewski et al., J. Electronic Pack., 134(2), 2012.

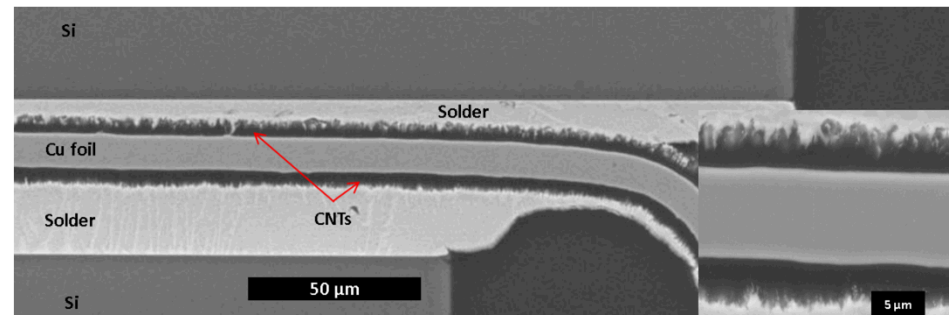
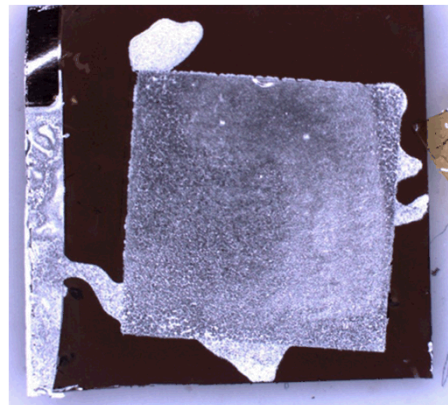
# Solder Bonding & Wax Infiltration



Solder Foils

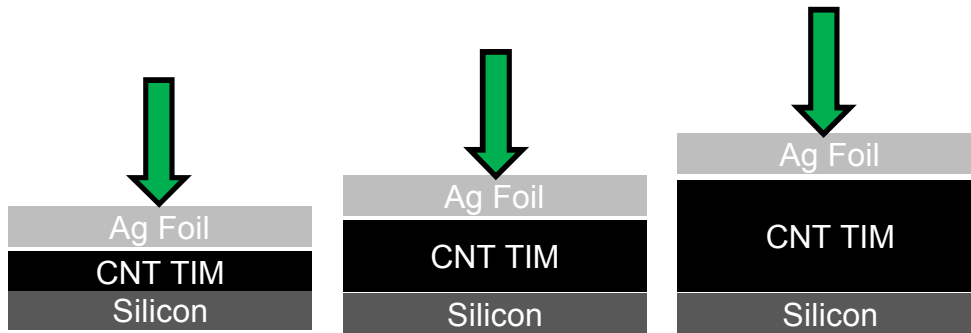
Indalloy Sn63  
 Indalloy 121  
 Indalloy 256

0.051 mm thick

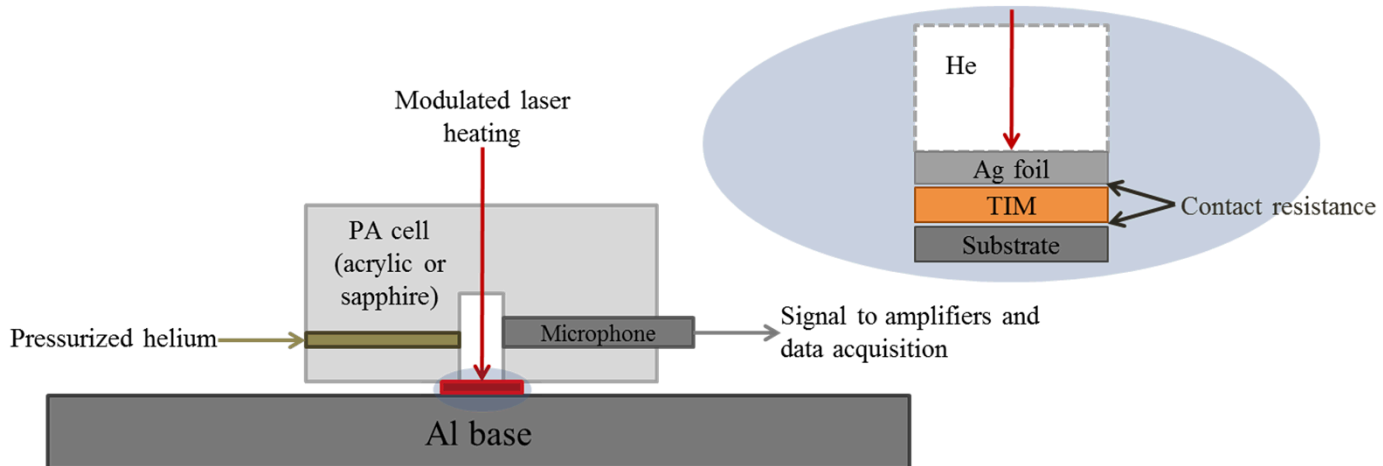
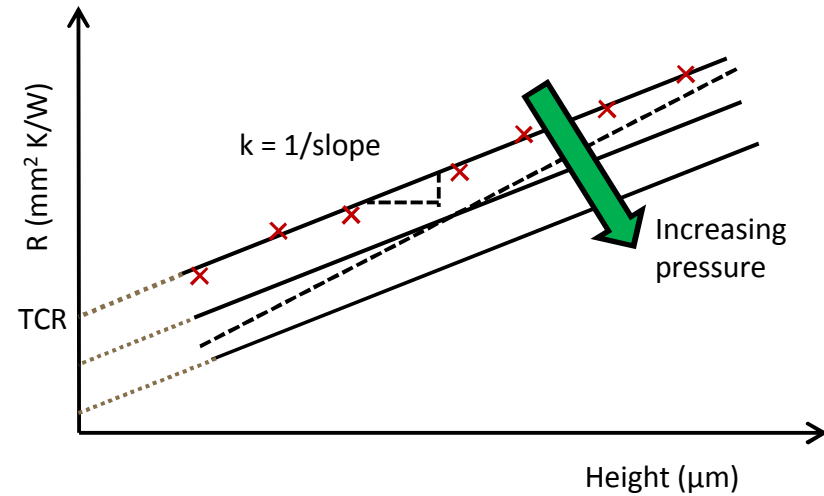


Wasniewski et al, J. Electronic Pack., 134(2), 2012.

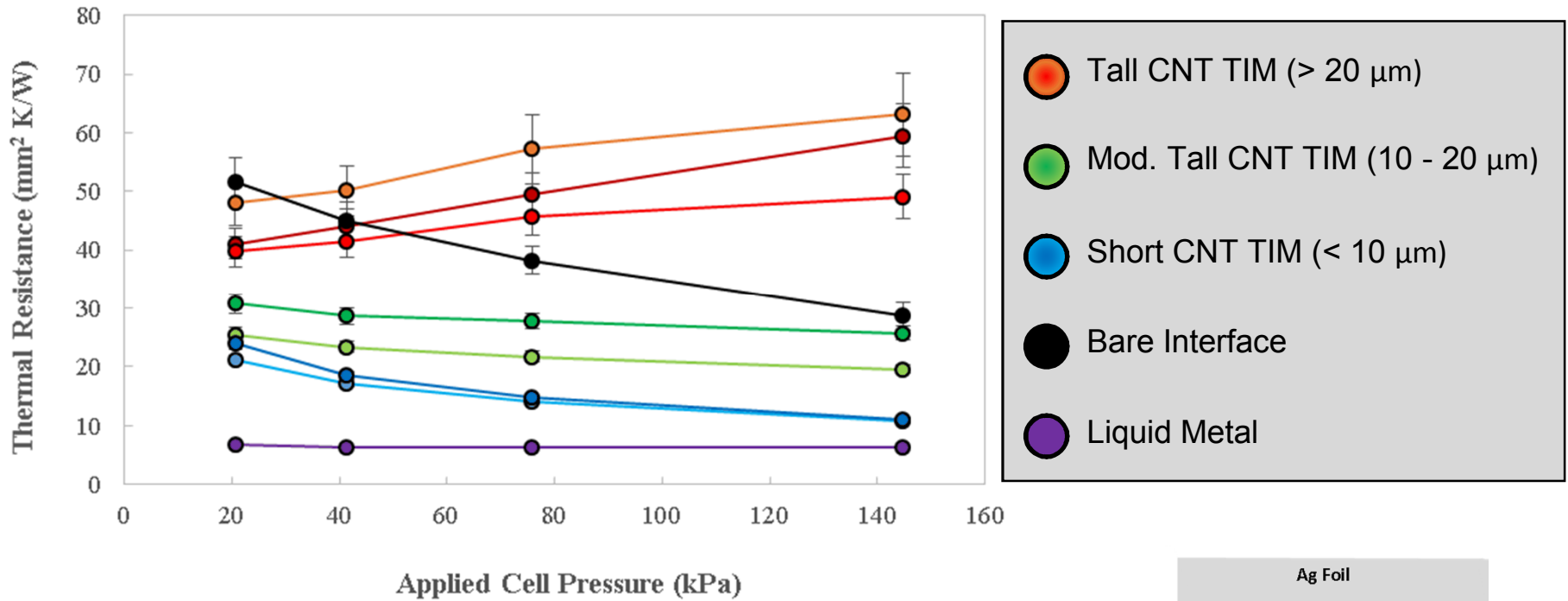
# Thermomechanical Performance CNT TIMs



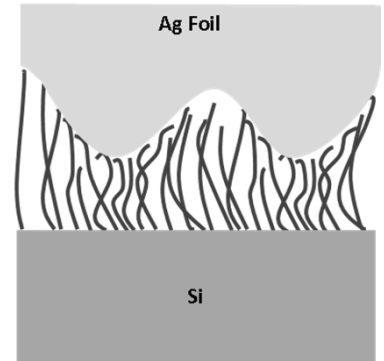
$$R_{meas}(P) = R_{bulk} + R_{contact} = \frac{\bar{h}_{urf}}{k_{eff}} + R_{Ag\ foil-CNT\ TIM} + R_{CNT\ TIM-Ag\ foil}$$



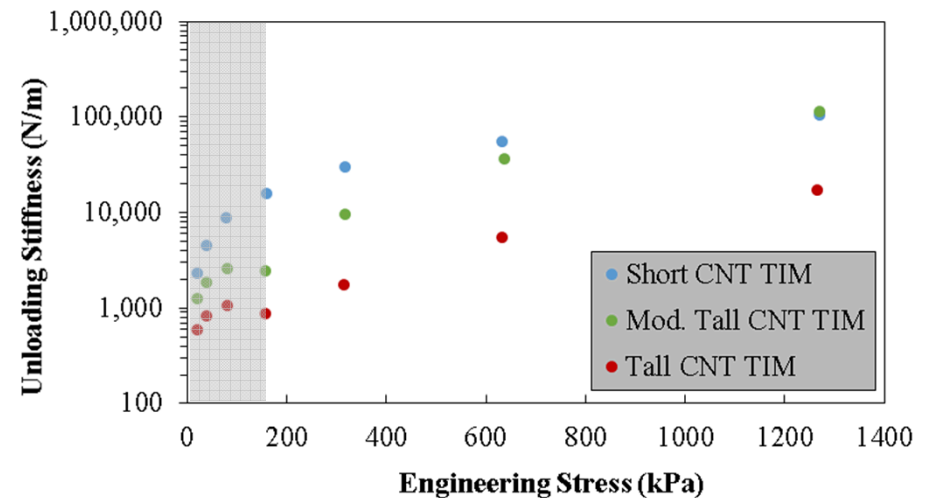
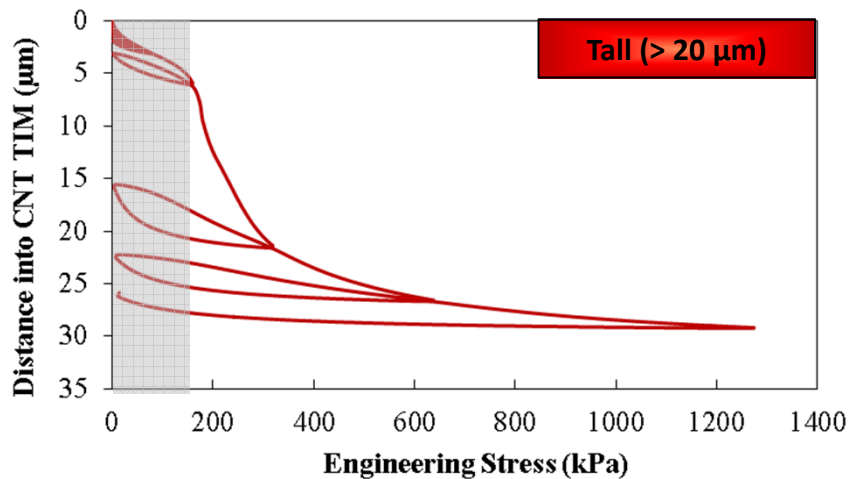
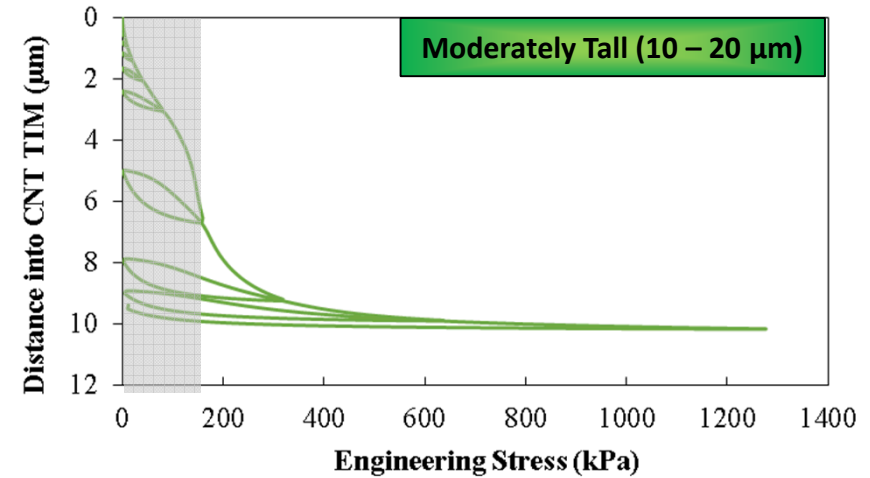
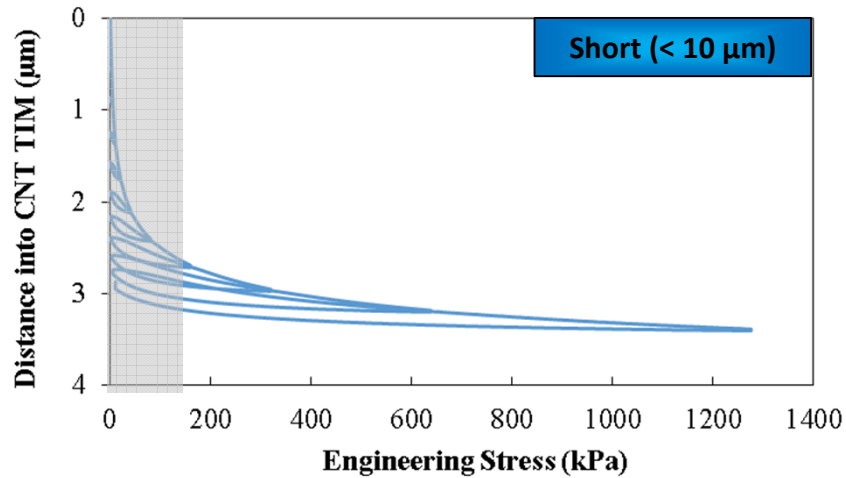
# Raw Data



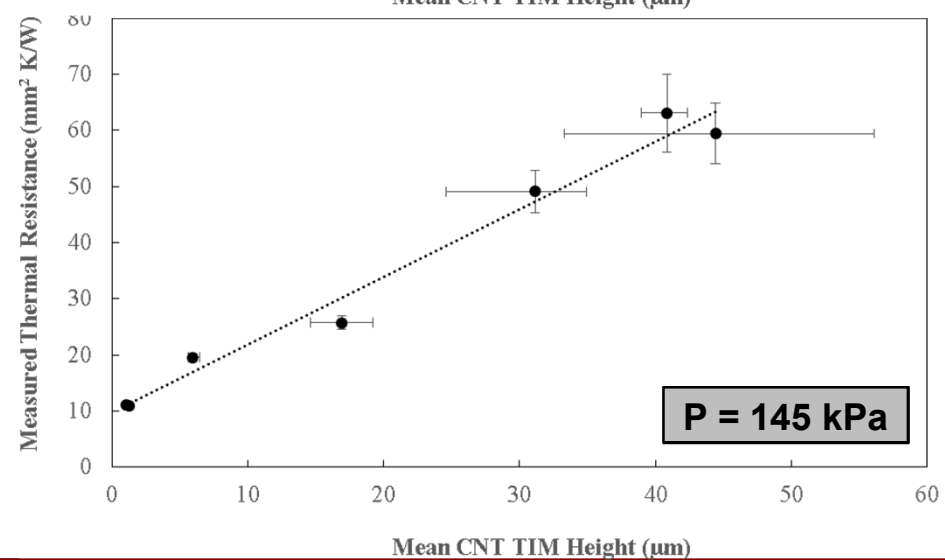
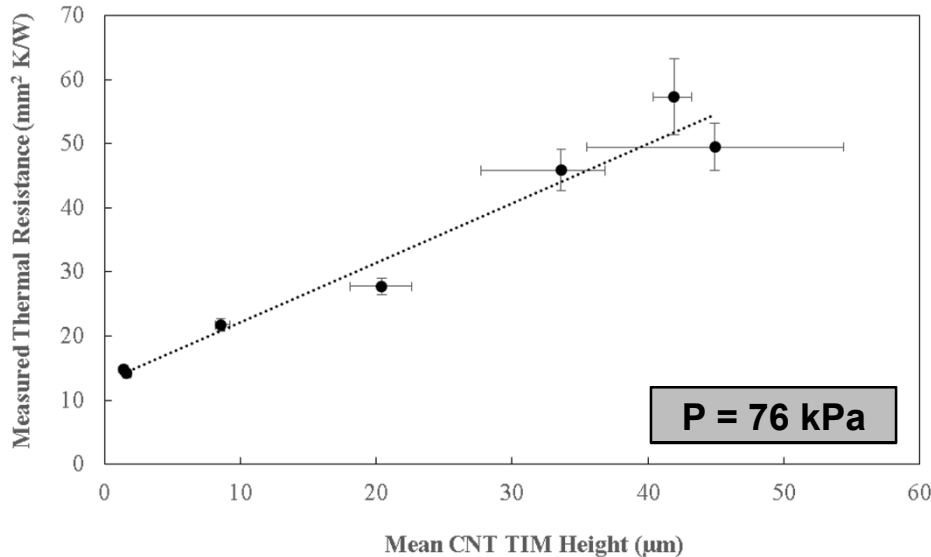
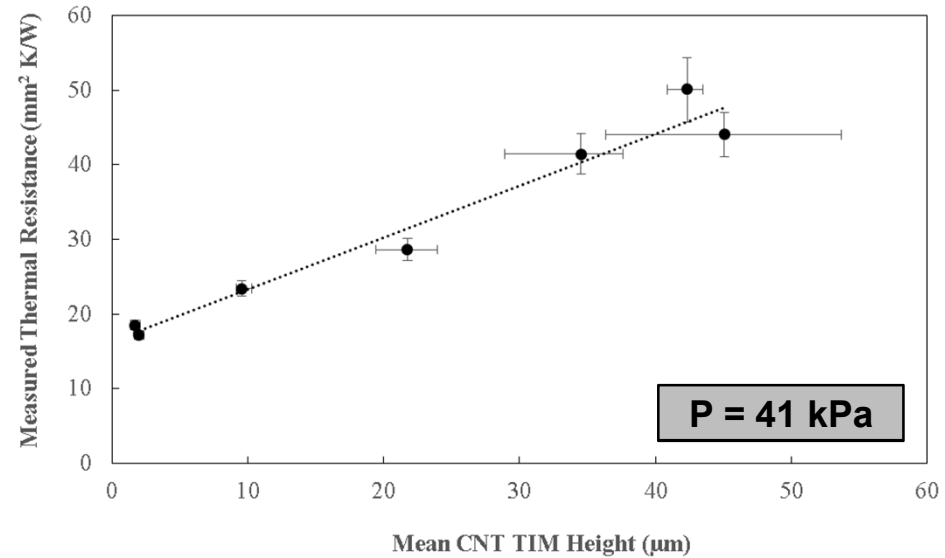
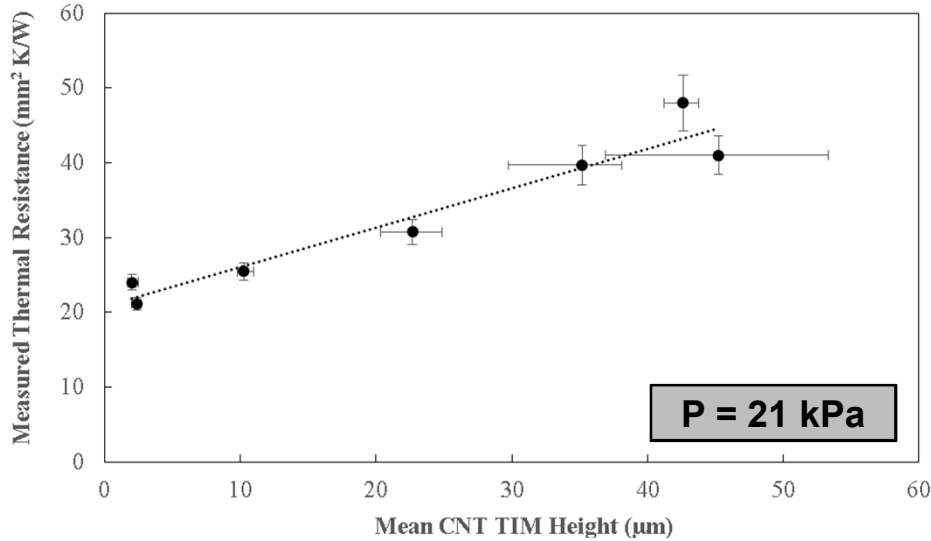
$$R_{meas}(P) = R_{bulk} + R_{contact} = \frac{\bar{h}_{turf}}{k_{eff}} + R_{Ag\ foil-CNT\ TIM} + R_{CNT\ TIM-Ag\ foil}$$



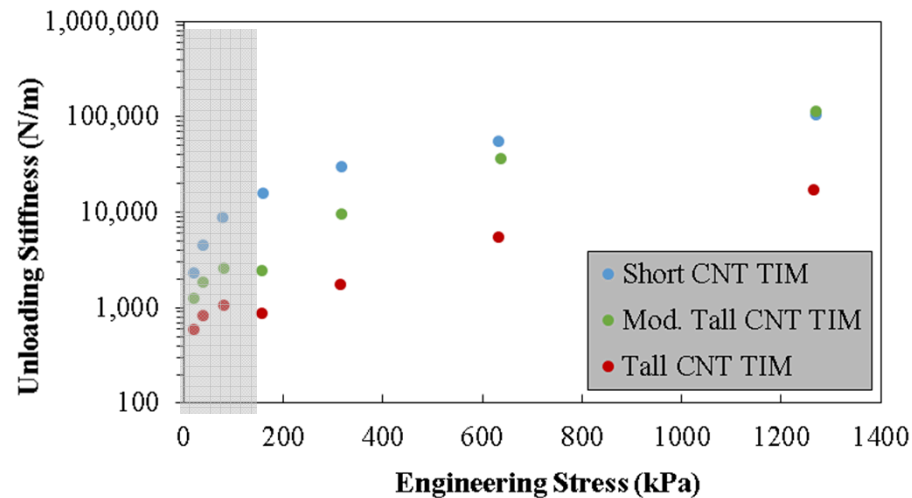
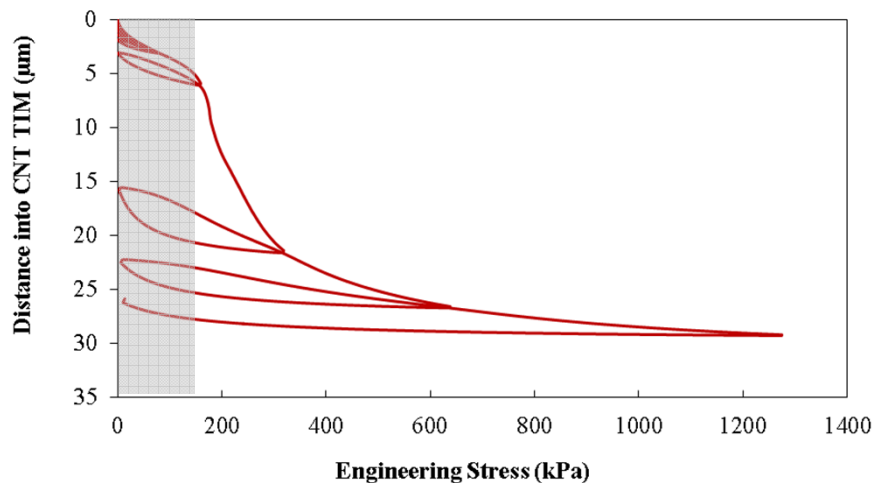
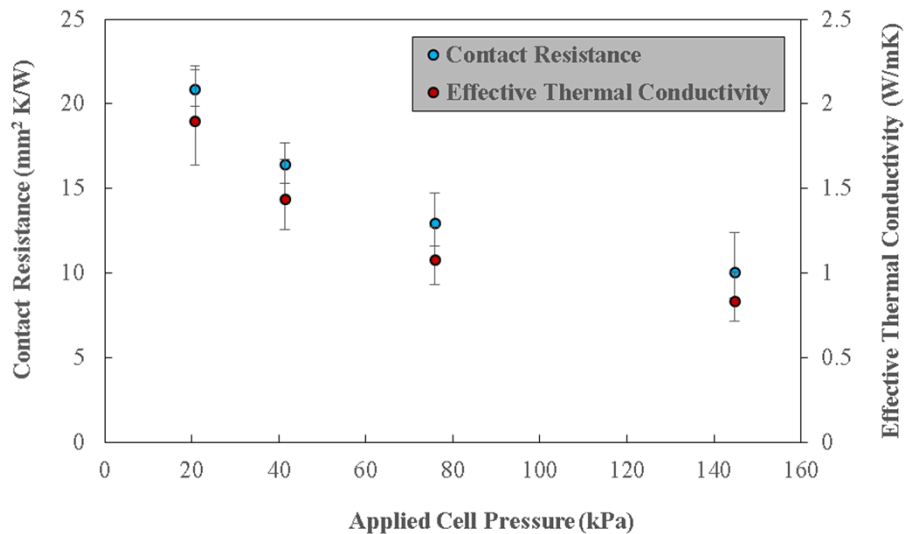
# Nanoindentation Measurements



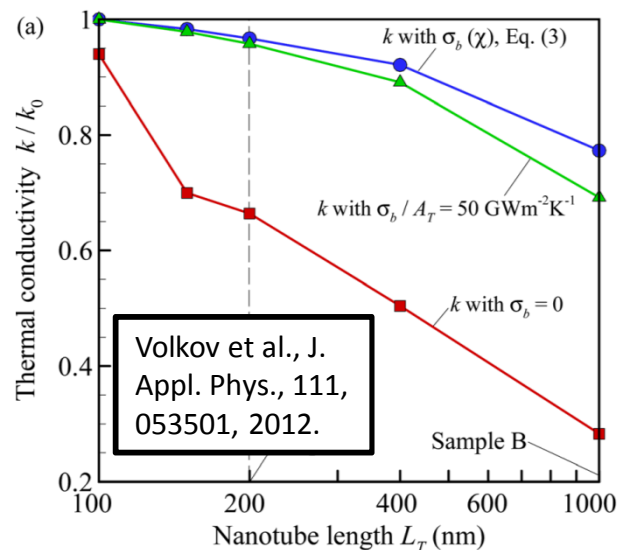
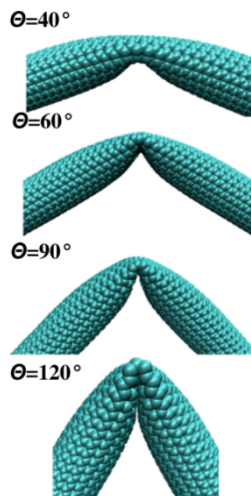
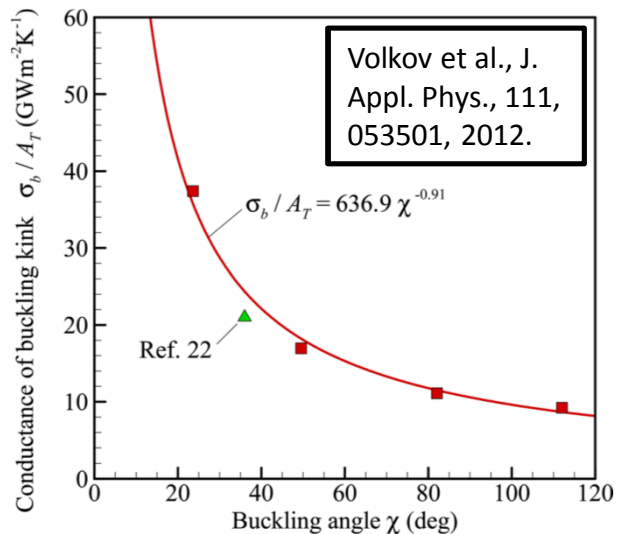
# Extract Effective Thermal Conductivity ( $k_{\text{eff}}$ ) and Thermal Contact Resistance (TCR)



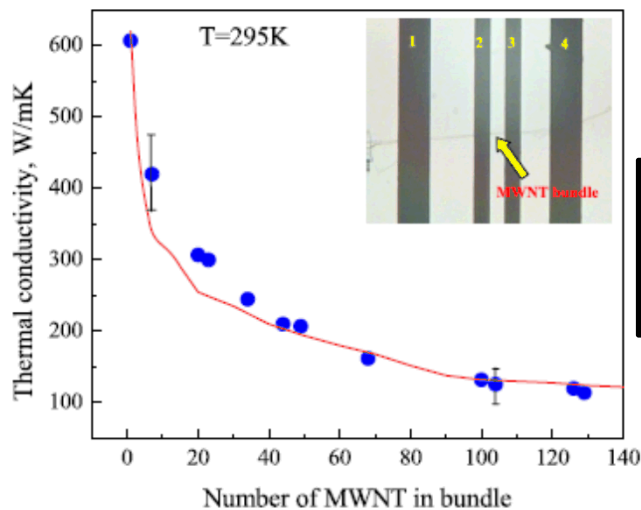
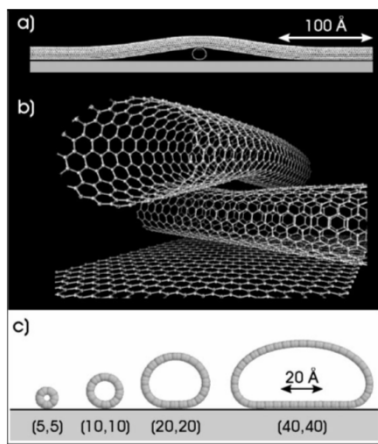
# $k_{\text{eff}}$ and TCR



# Supporting Literature

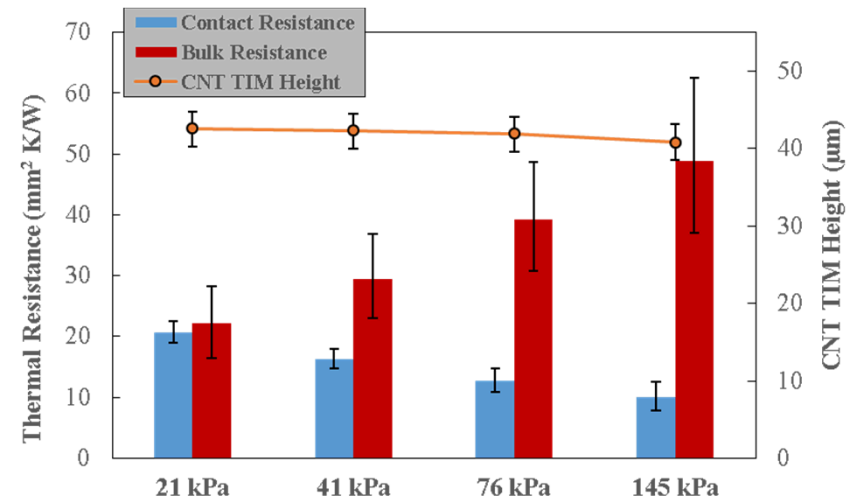
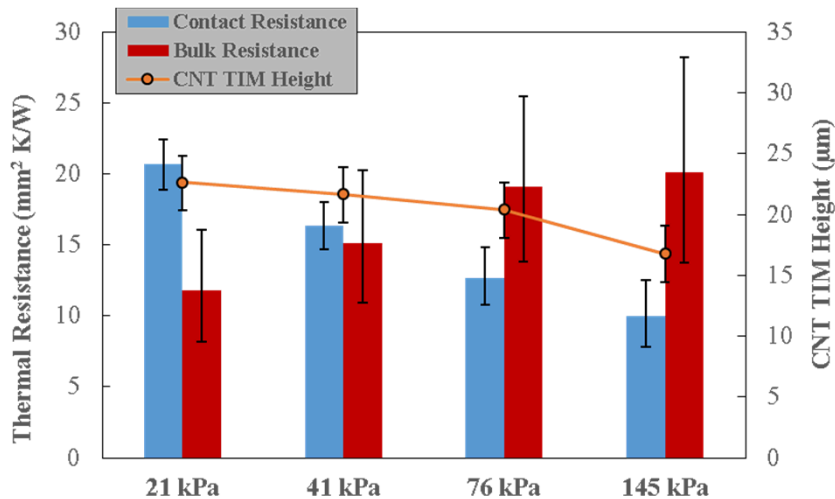
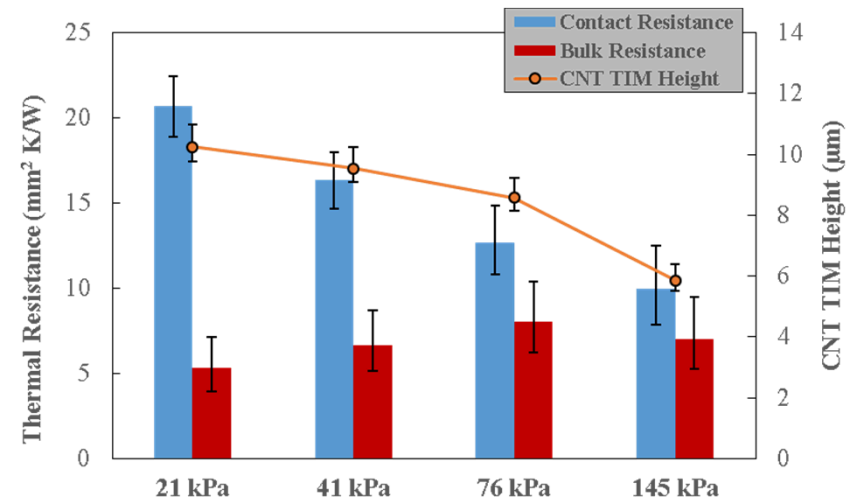
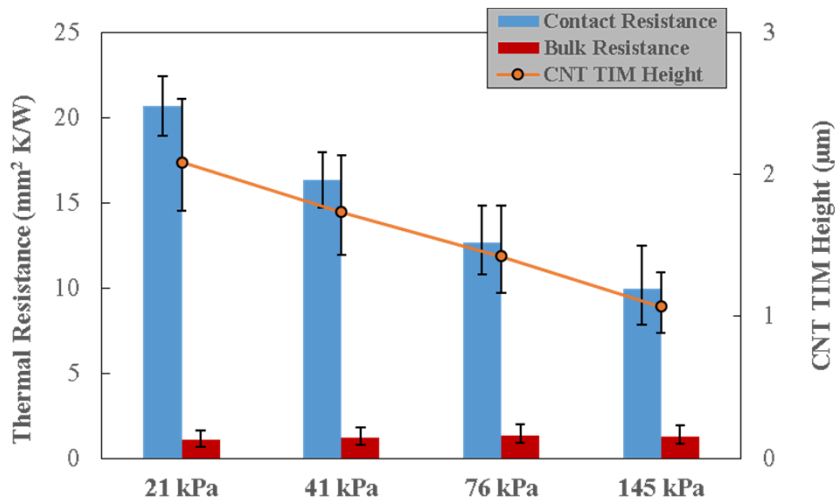


Avouris et al., Appl. Surf. Sci., 141, 201-9, 1999.



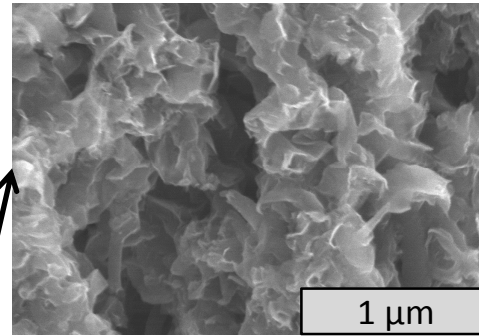
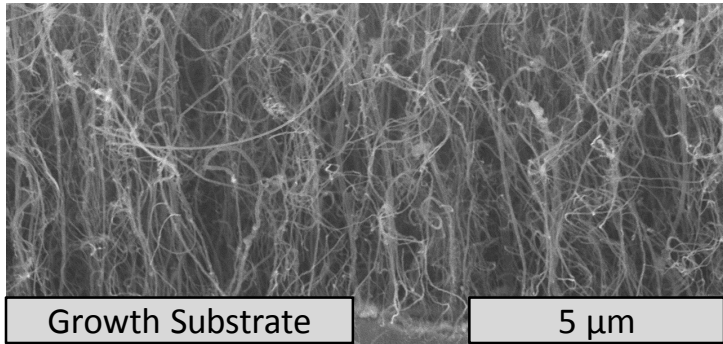
Aliev et al., Nanotechnology, 21, 053709, 2010.

# Bulk and Contact Resistance Contributions

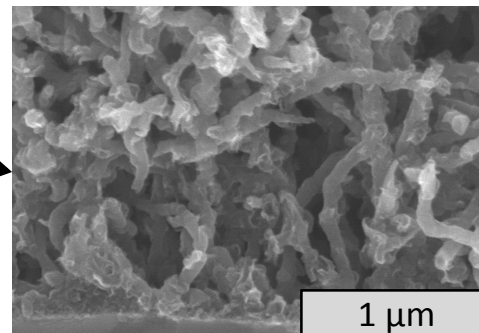
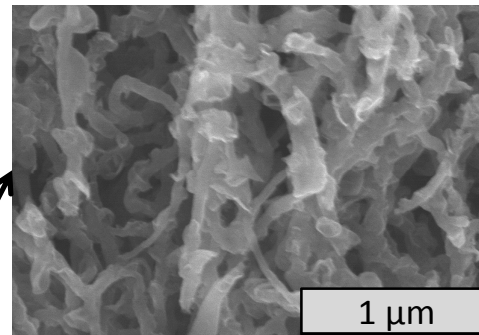
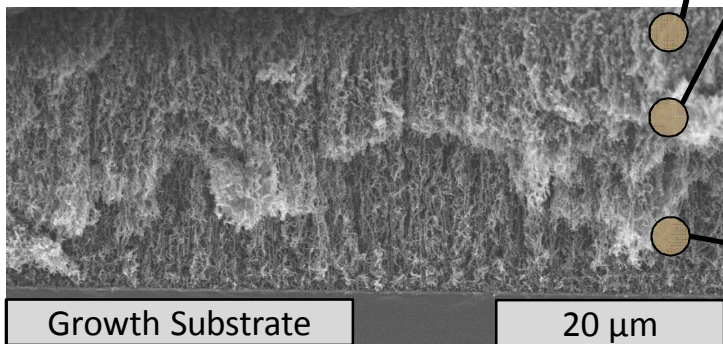


# CNT and CNT/Petal TIMs

CNT TIM



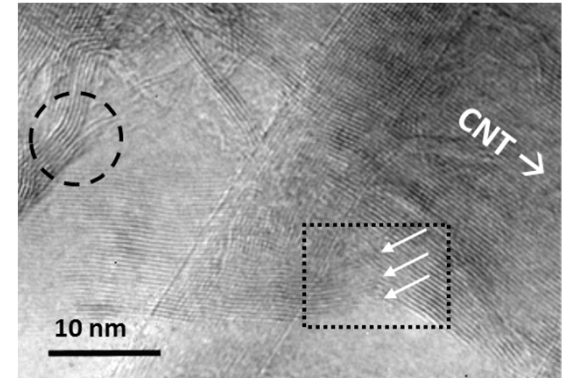
CNT/Petal TIM



Raman

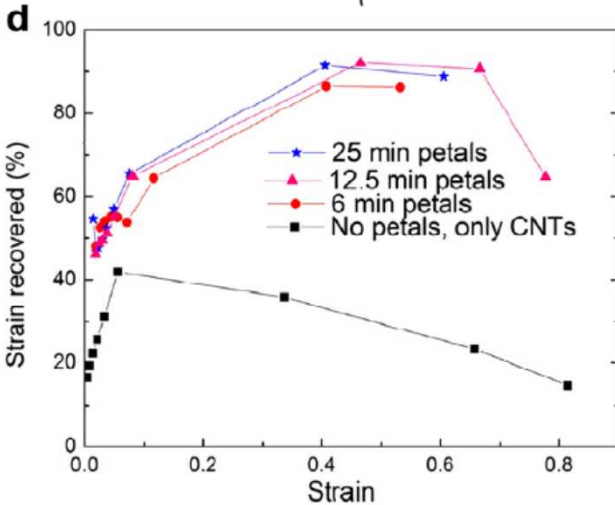
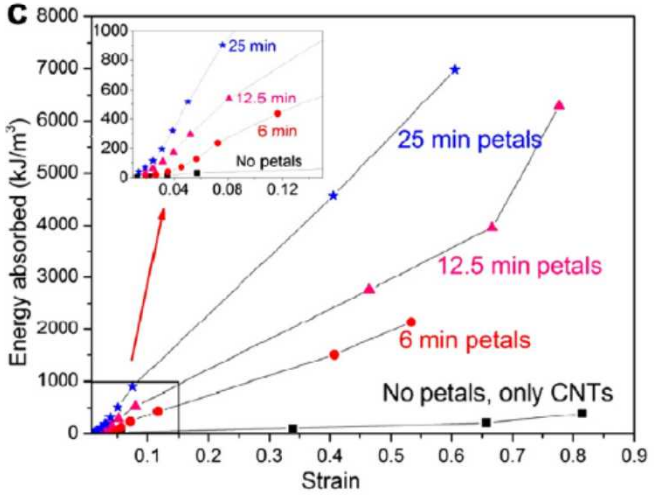
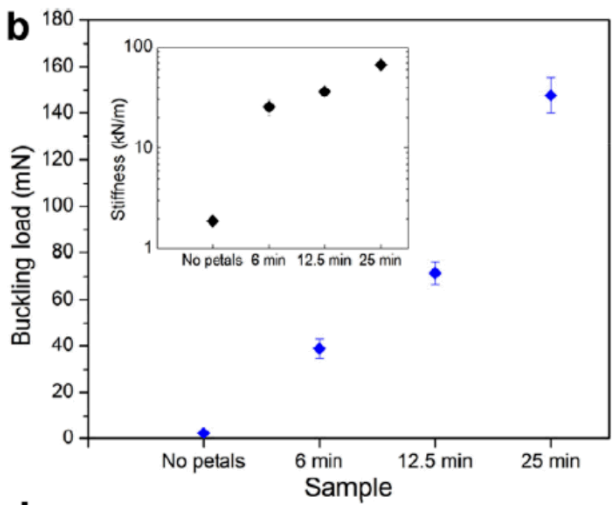
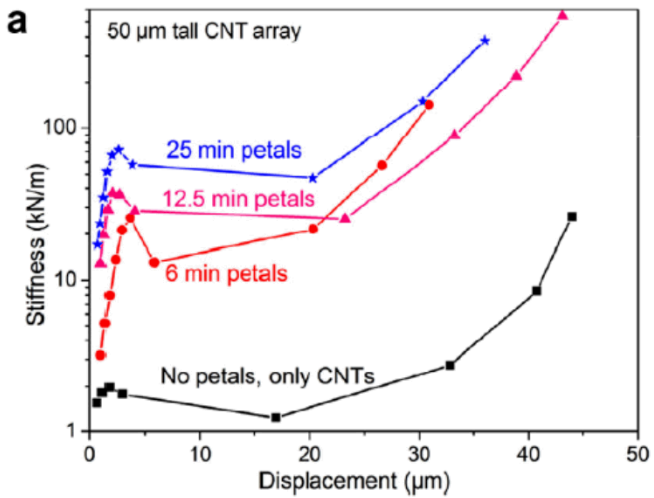
Material	D band ( $\text{cm}^{-1}$ )	G band ( $\text{cm}^{-1}$ )	I(D)/I(G) ratio
CNT	~1350	~1585	~0.8-1.6
Graphene	~1350	~1585	~0-0.2
CNT	~1340	1590	1.43
CNT-graphene	~1340	1590	0.41

HRTEM



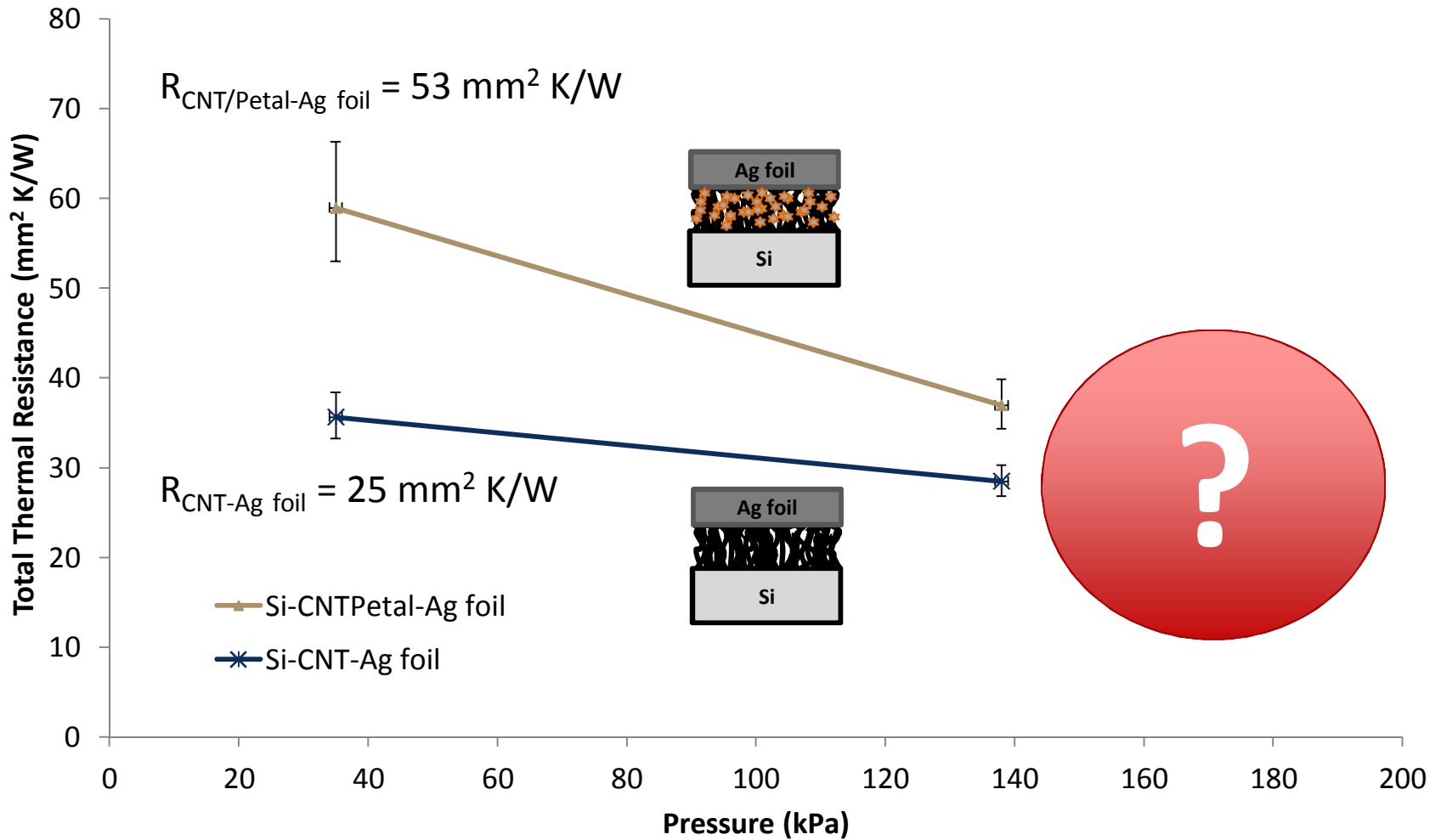
Density:  $220 \text{ kg/m}^3$   
Thermal conductivity:  $5 \text{ W/m K}$

# CNT/Petal Mechanical Deformation



Kumar et al., Carbon, 84, 236-5, 2015.

# CNTs versus CNT/Petals

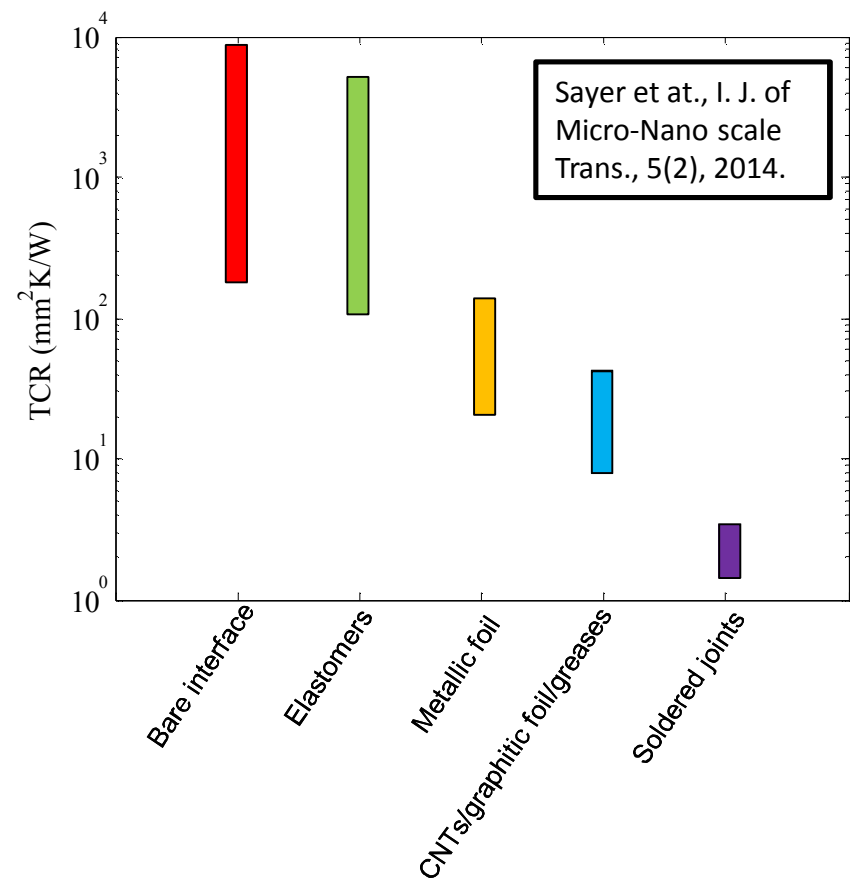
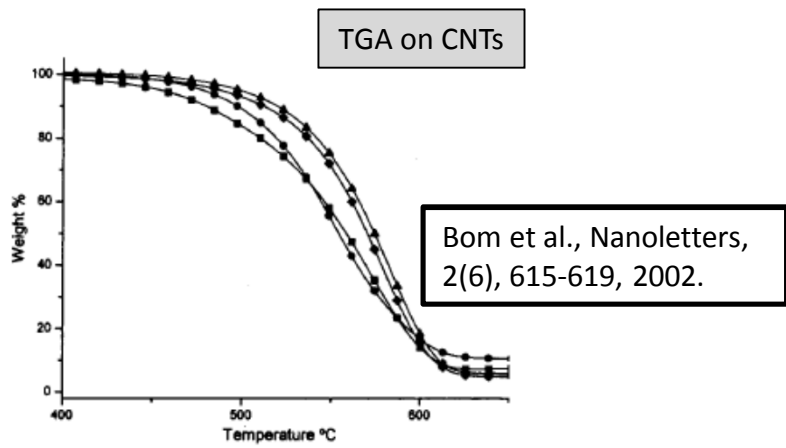


# TIMs at Elevated Temperatures

- Thermal interface materials (TIMs) provide a means of decreasing TCR by filling the gaps between asperity contacts

- Thermal greases
- Elastomeric materials
- Solders

- Metallic foils
- Graphitic foils
- Carbon nanotube (CNT) materials

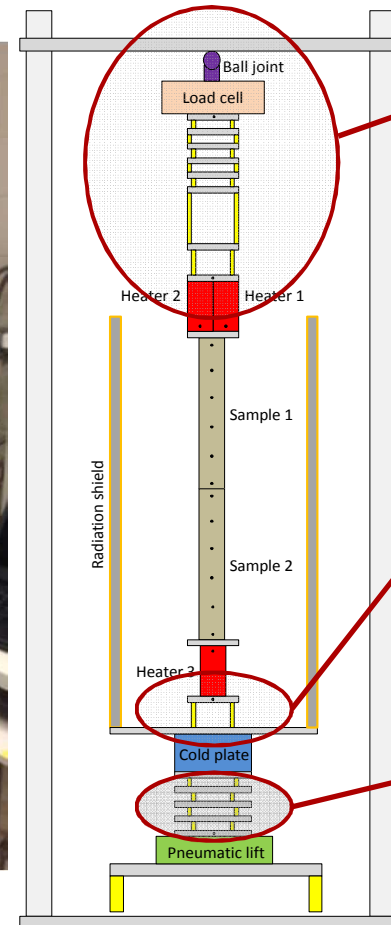


# 1D Steady State Experimental System

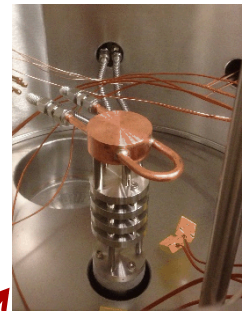
- ASTM D470-06 standard
- Key features
  - Housed in vacuum chamber to eliminate convective losses (10  $\mu$ Torr)
  - Au electroplated shield mitigates radiative losses
  - 14 thermocouples (7 per HFM) plus additional for monitoring other locations of the system
  - Maximum interface temperature of 900 K
  - Maximum interface pressure for  $\frac{1}{2}$ " diameter heat flux meters (HFMs): 8 MPa
  - *In situ* adjustable interface pressure



Kurt J. Lesker Vacuum System



Top assembly



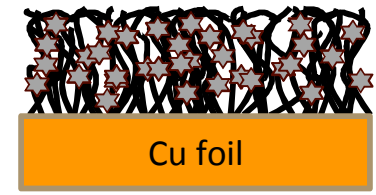
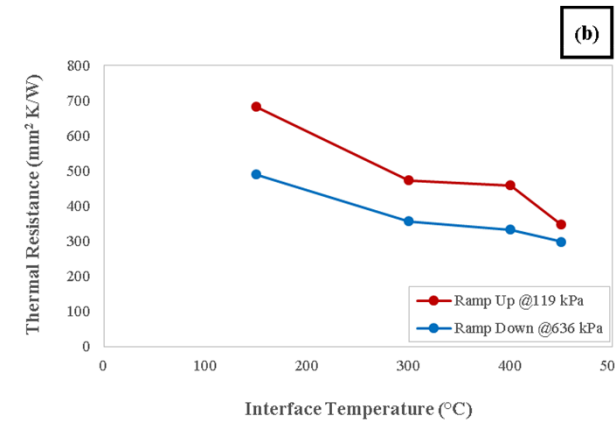
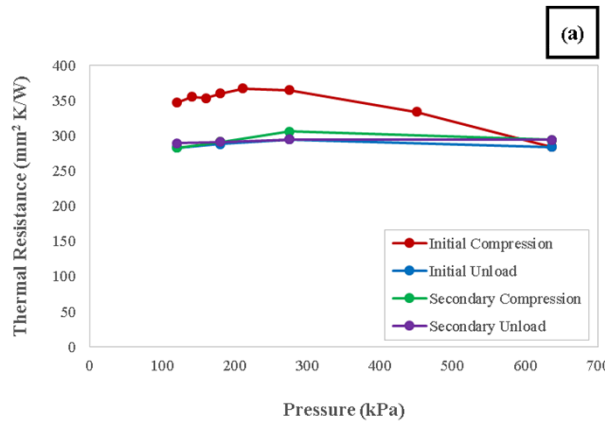
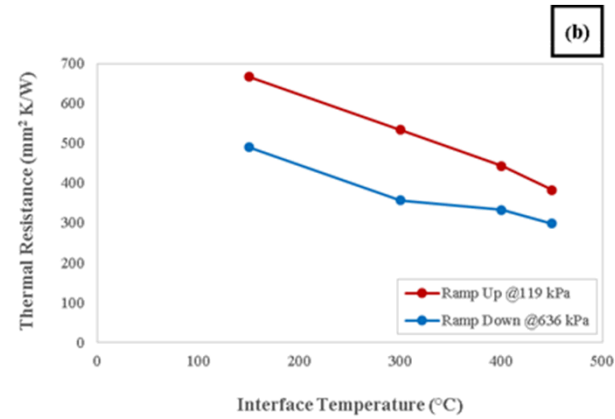
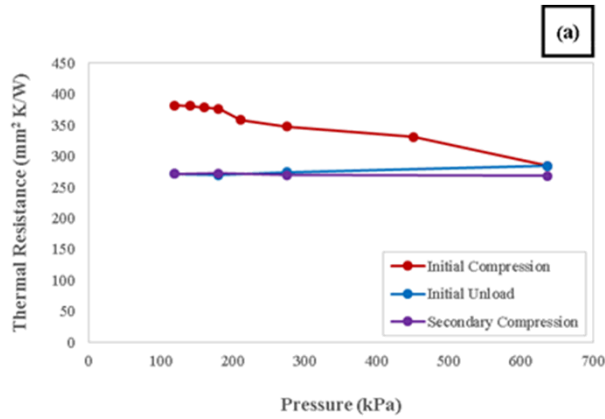
Bottom assembly



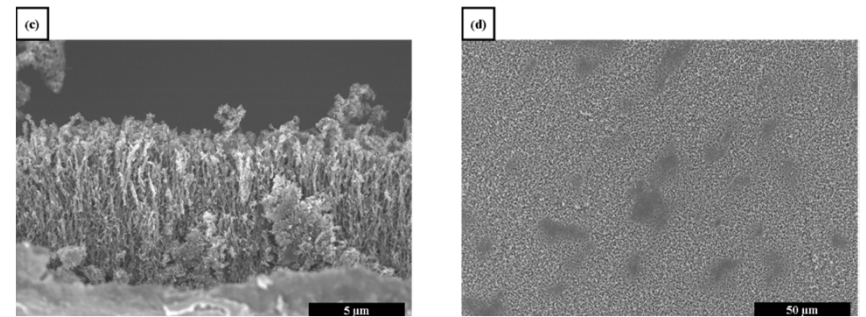
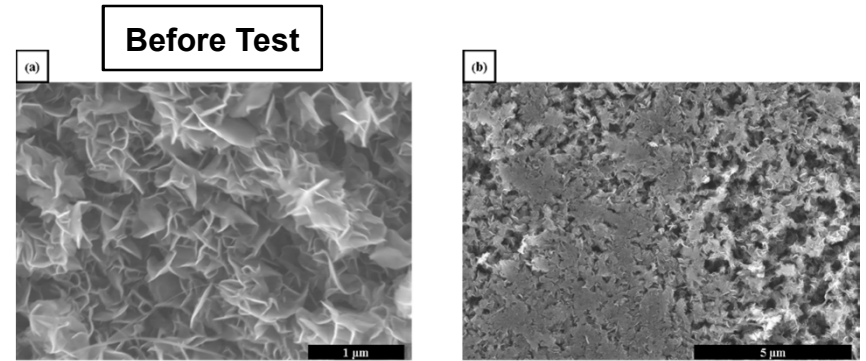
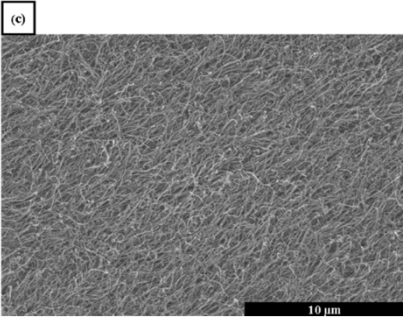
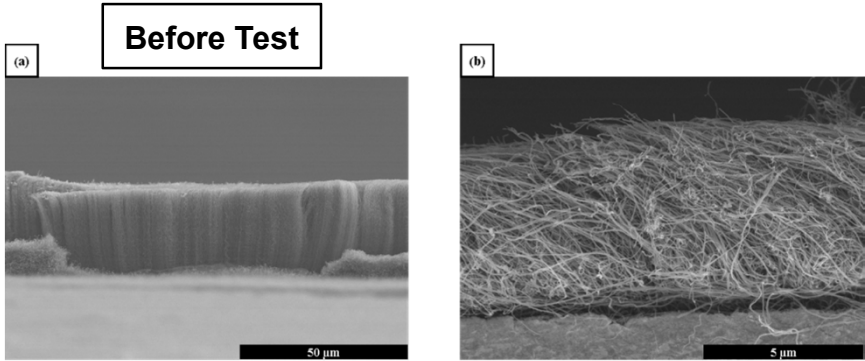
Custom pneumatic actuator

# CNT and CNT/Petal TIM Comparison Sandia National Laboratories

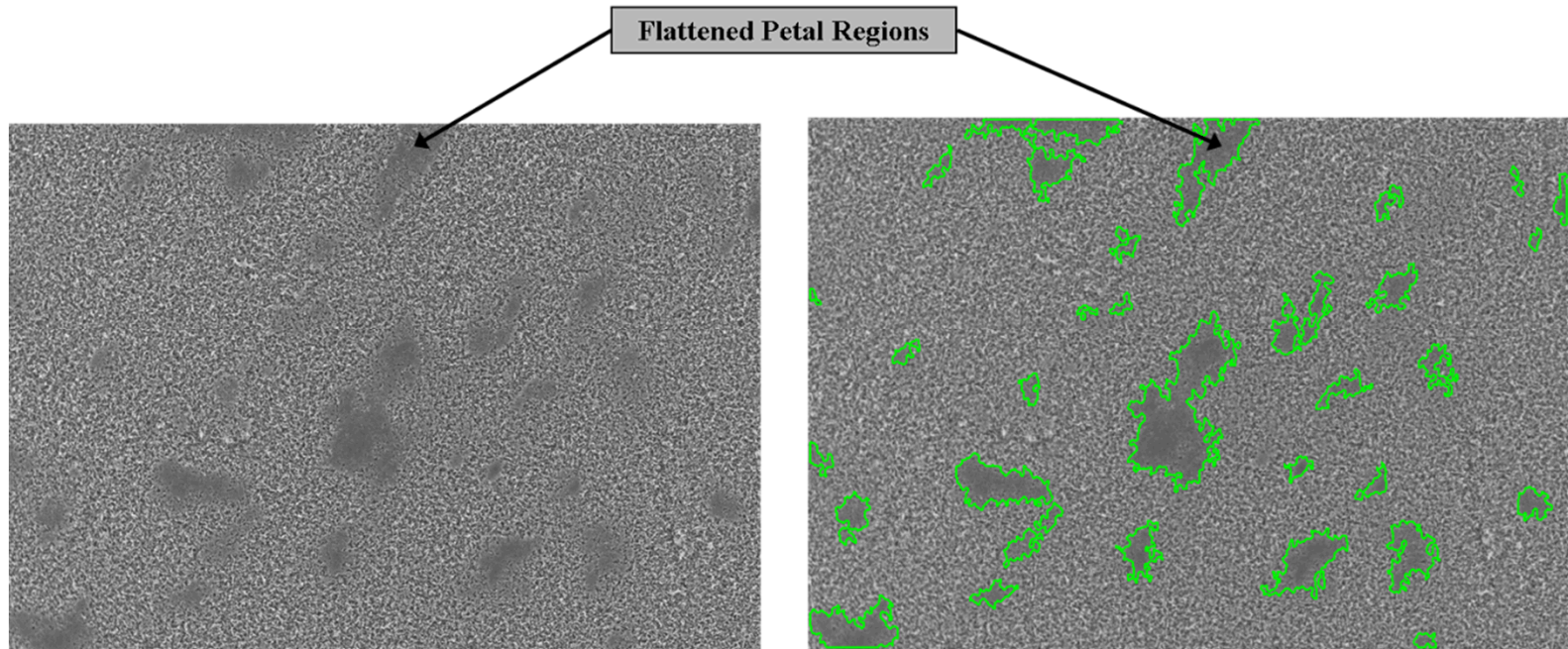
**Test Sequence: Ramp up to 450°C at lowest pressure, perform mechanical cycles, then ramp down to 150°C at highest pressure**



# Forensic Observations



# Estimation of Contact Area for CNT/Petal TIM



**Contact area ratio  $\approx 10\%$**   
**Reduction in TR  $\approx 20\%$**

**This analysis does not account for contact in the z-direction**

# Concluding Remarks

- CNTs offer moderate thermal performance for low temperature applications
- Performance limited by varies factors
  - Contact area (number and size of CNT-to-substrate contacts)
  - Effective thermal conductivity (defects, CNT-to-CNT contacts)
  - Thermomechanical effects
- CNTs with graphitic petals opens a new avenue for CNT TIM engineers
  - Denser
  - Higher thermal conductivity
  - Stiffer mechanical response
  - Need to develop methods to flatten petals at interface with opposing substrate

# Backup Slides

# Estimation of CNT Height From NI

