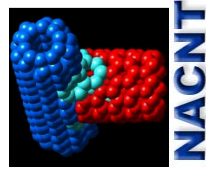


# Could Nano-Structured Materials Enable the Improved Pressure Vessels for Deep Atmospheric Probes?

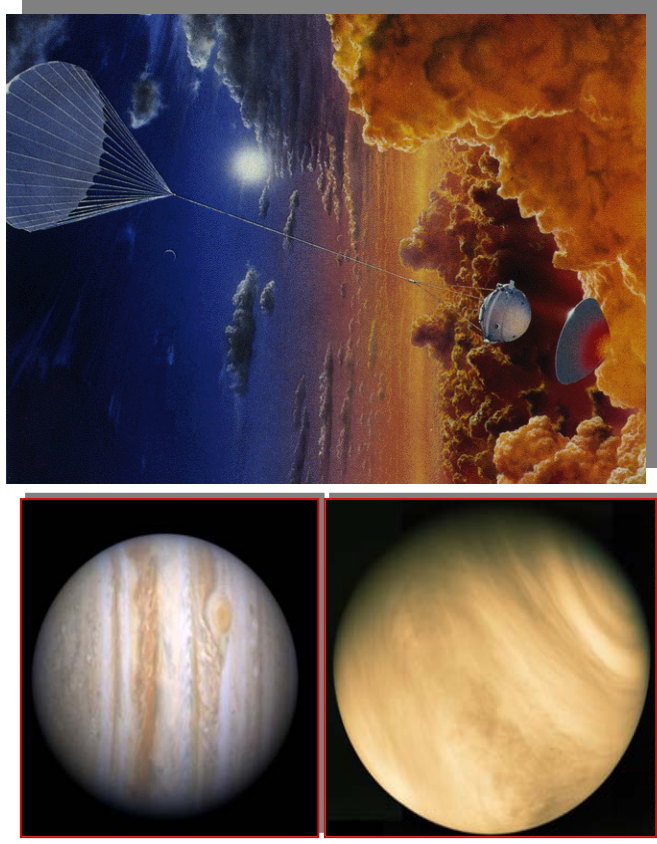


**D. Srivastava<sup>1</sup>, A. Fuentes<sup>2</sup>, B. Bienstock<sup>3</sup>, and J. O. Arnold<sup>1</sup>**

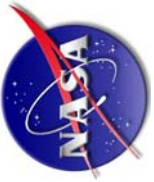
<sup>1</sup>NASA Ames Center for Nanotechnology (NACNT)/JARC

<sup>2</sup>University of Texas, Pan American, Summer Visiting Fellow at NACNT

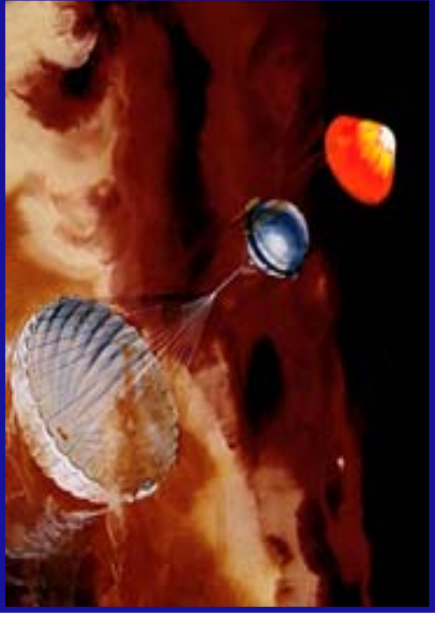
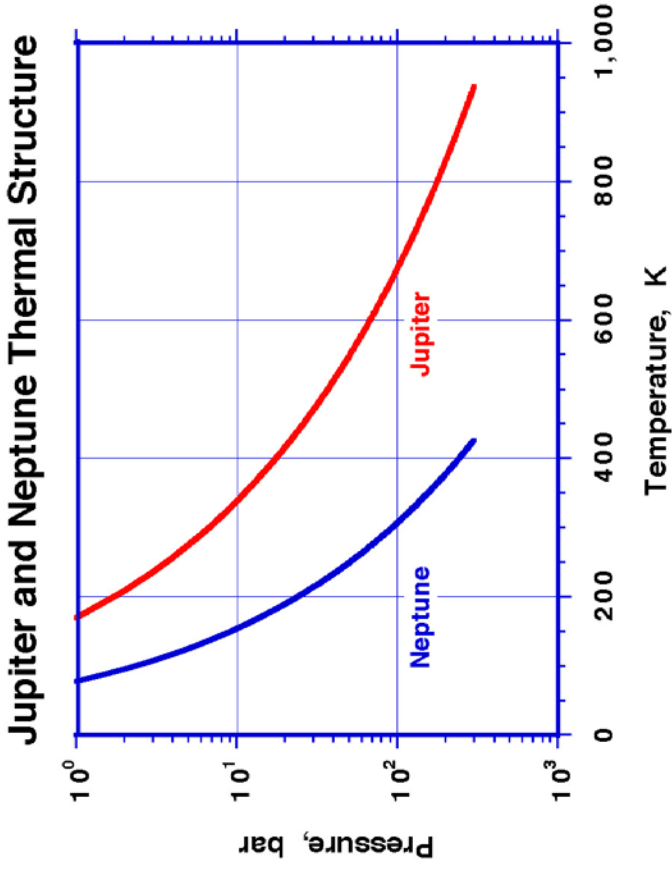
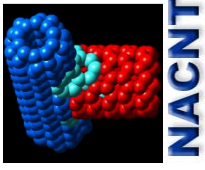
<sup>3</sup>The Boeing Corporation, El Segundo Office, CA



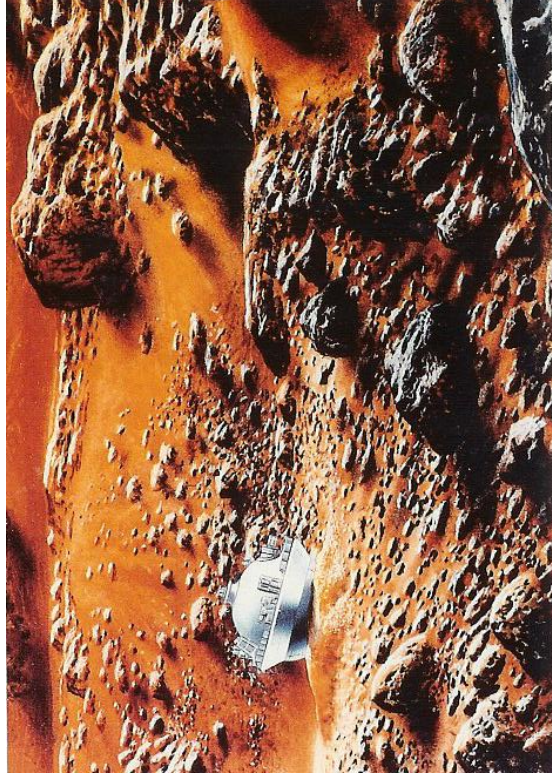
2<sup>nd</sup> International Planetary Probe Workshop, Aug 23-27, 2004,



# High Temperature/Pressure in Key X-Environments

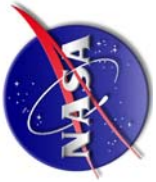


Pressure - Temperature Atmospheric Profiles Provided<sup>2</sup> by Rich Young, NASA Ames Research Center

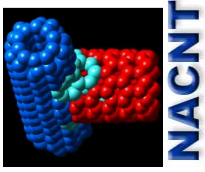


Artists Concept of Pioneer-Venus Small "Day" Probe on Venus' Surface. T= 740 K, P=96 bars Sealed Vessel with Xenon at 102 Kpa (15 psia).

Operated<sup>3</sup> for 68 minutes on Venus' surface - December, 1978



## The Case for Use of Nano-Structured Materials Pressure Vessel Design



- Pressure vessel structure is a mass driver for probe
- Reduction in structure mass can be used for science

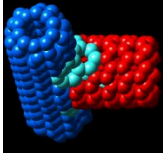
Probe	Pressure Vessel Mass (kg)	Total* Probe Mass (kg)	Pressure Vessel Structure Mass Fraction (%)
Pioneer Venus Large Probe	62	193	32
Pioneer Venus Small Probe	18	61	30

\* Excludes deceleration module mass

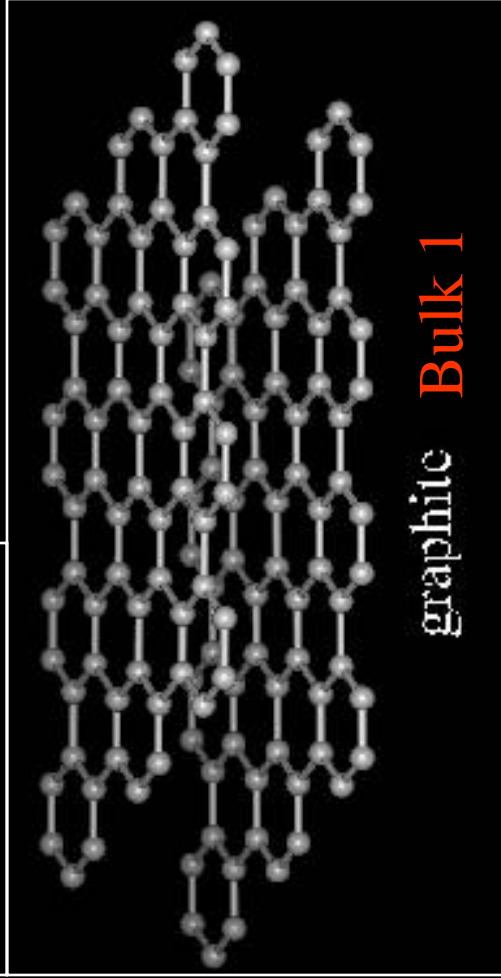
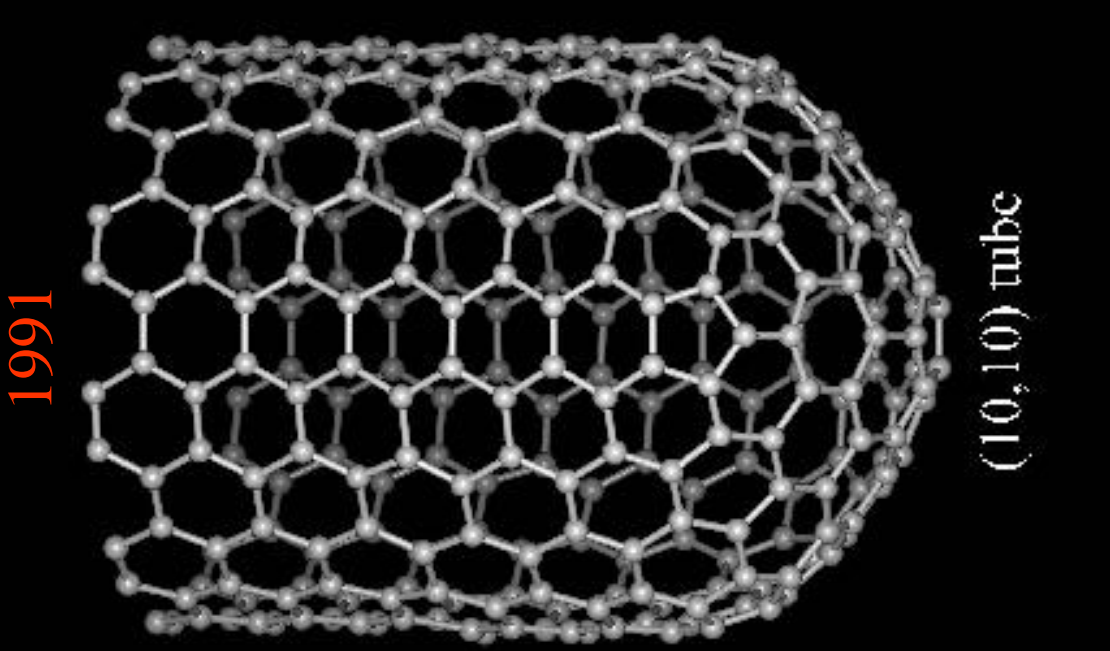
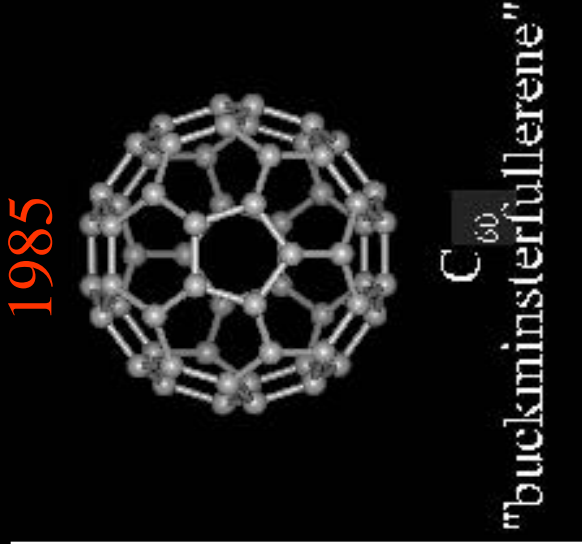
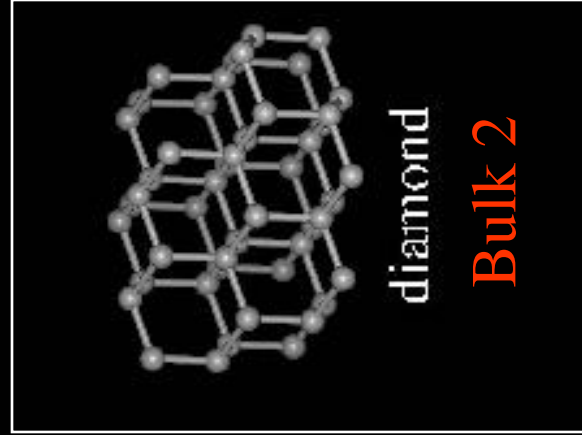


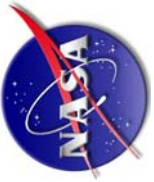


# Carbon based Nanomaterials

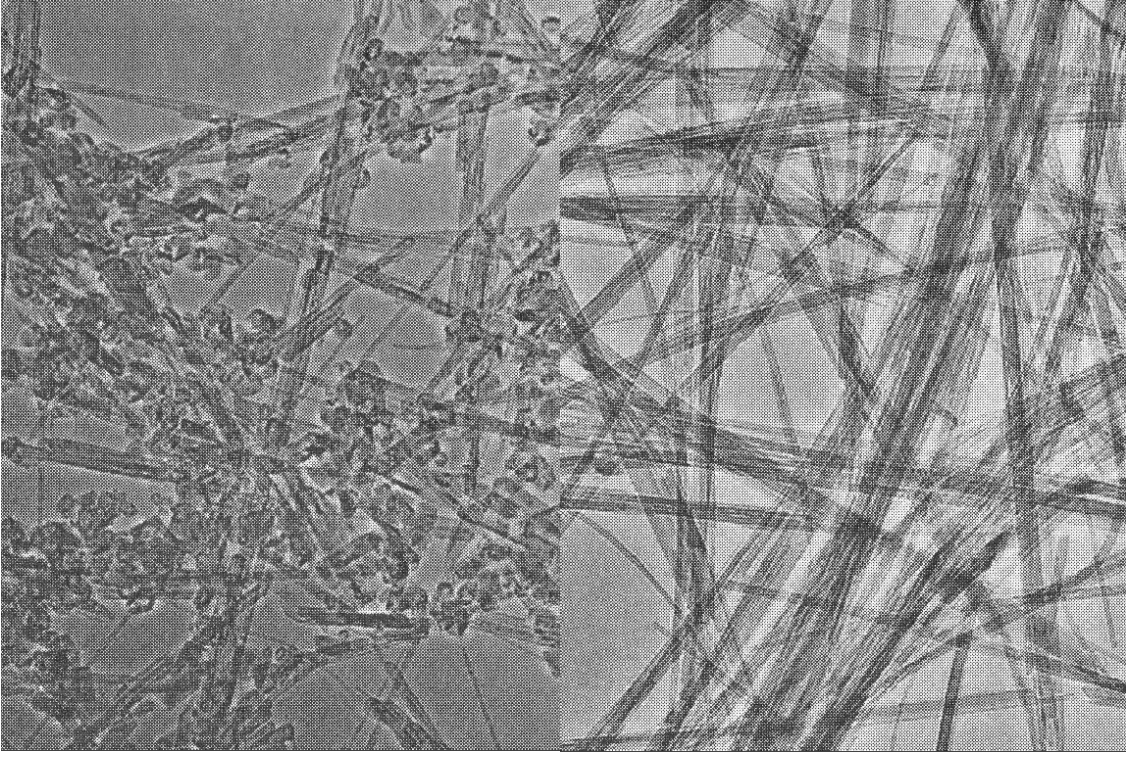
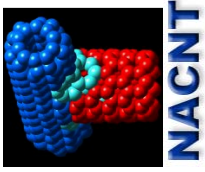


NACNT





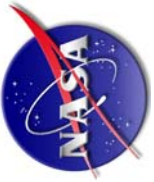
# Nanotube production & purification



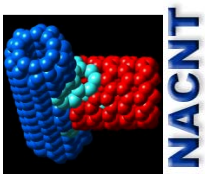
Micrographs illustrating purification  
of multiwalled nanotube sample

**MWNTs**  
**D = 2.5 – 30 nm**

Ebbesen et al.,  
Nature 367, 519 (1994)

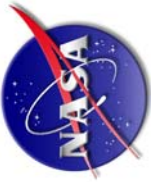


## Nanomechanics of Carbon Nanotubes

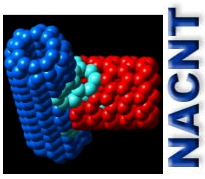


- *Elastic* properties:  $E = \sim 1.2 \text{ TPa}$   
( $E = k/a$ )
- *Plastic/Fracture* properties: compression & tension  
yield strain  $\geq 15 - 20\%$  (?)
  - Strain rate?
  - Defects?
  - Mechanisms?
  - Applications?
- *Superstrong Material*:  $\sigma_Y = 750 - 1000 \text{ GPa!}$ 
  - Diamond (50 GPa), WC (6 GPa), Steel (0.5-2 GPa)



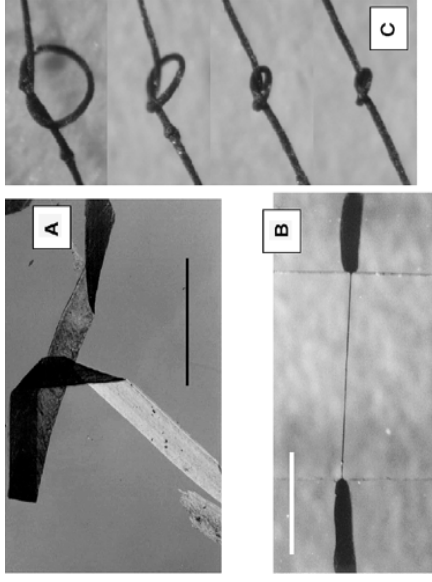
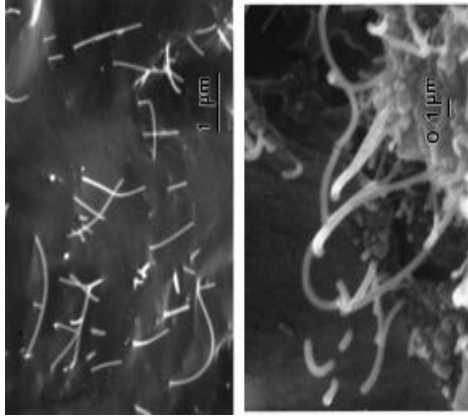


# CNT-composites: Example (Polymer)



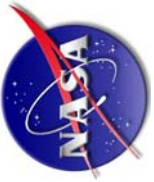
SEM images of polymer (polyvinylalcohol) ribbon contained CNT fibers & knotted CNT fibers

SEM images of epoxy-CNT composite

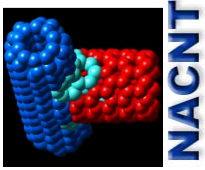


(L.S.Schadler et.al., Appl. Phys. Lett. V73 P3842, 1998)

(B. Vigolo et.al., Science, V290 P1331, 2000)



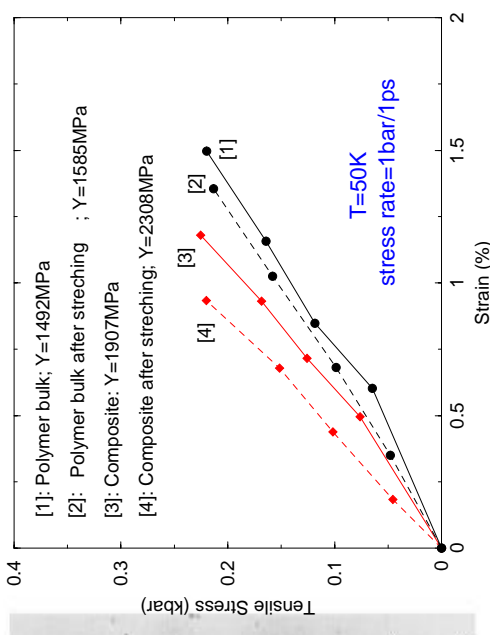
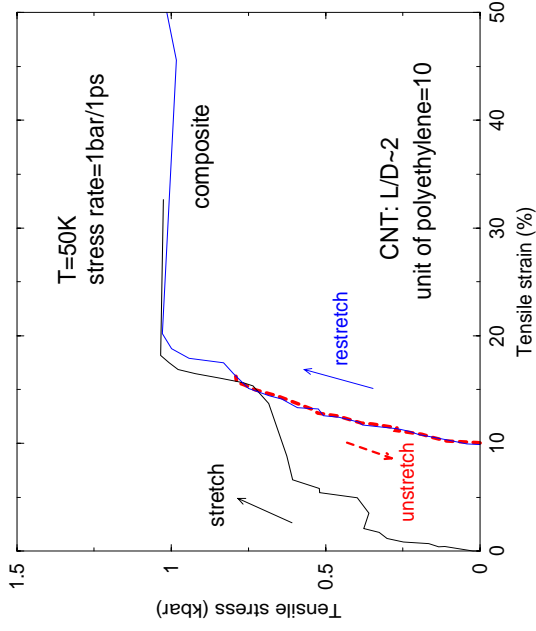
Effect of Loading sequence on Composite with 8% by volume



## Simulations of CNT-Polyethylene Composites

Work hardening of composite with stretching

TEM images of alignment of CNTs in a polymer matrix by stretching

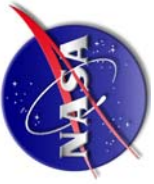


-Young's modulus of CNT composites 30% higher than polymer matrix

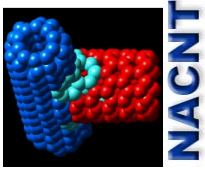
-Stretching treatments enhance  $Y$  by 50% (L/D~2,  $N_p=10$ )

D. Srivastava, C. Wei and K. Cho, Appl. Mech. Rev. (2003)





## Models for Particulate Reinforced Composites



Mittal et.al., NASA Technical Report, 1996

Micromechanics Models for for Particulate Reinforced Composites

$$\rho_{pc} = V_f \rho_f + (1 - V_f) \rho_m$$

Density of composite

$$E_{pc} = \frac{V_f^{0.67} E_m}{1 - V_f^{0.33} \left(1 - \frac{E_m}{E_f}\right)} \quad \text{where } (1 - V_f^{0.67}) E_m$$

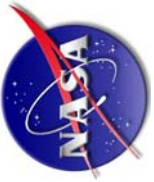
Elastic Modulus of Composite

$$K_{pc} = \frac{V_f^{0.67} K_m}{1 - V_f^{0.33} \left(1 - \frac{K_m}{K_f}\right)} + (1 - V_f^{0.67}) K_m$$

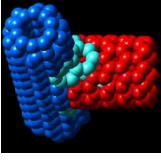
Thermal Conductivity of Composite

Where  $V_f$  is volume fraction

**Assumption:** Ideal Interface – perfect bonding at the interface



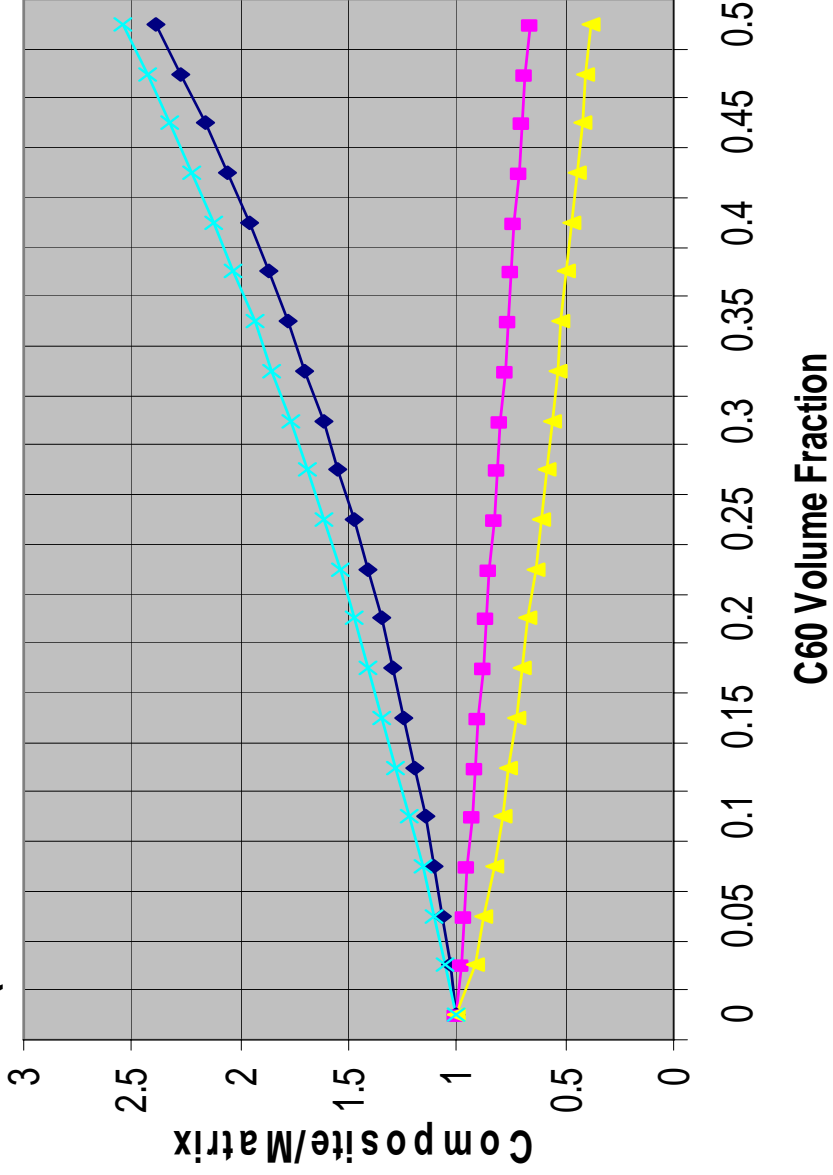
# Fullerene/Ti Composite for High Strength-Insulating Layer



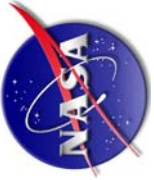
NACNT

## Composite Spherical Shell -Ti+C60

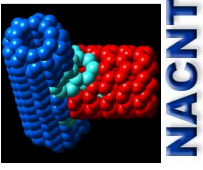
( $E_f=860$  GPa,  $E_m=116$  GPa,  $K_f=0.25$  W/m-k,  $K_m=17$  W/m-k,  $df=1.745$  g/cc, and  $dm=4.5$  g/cc)



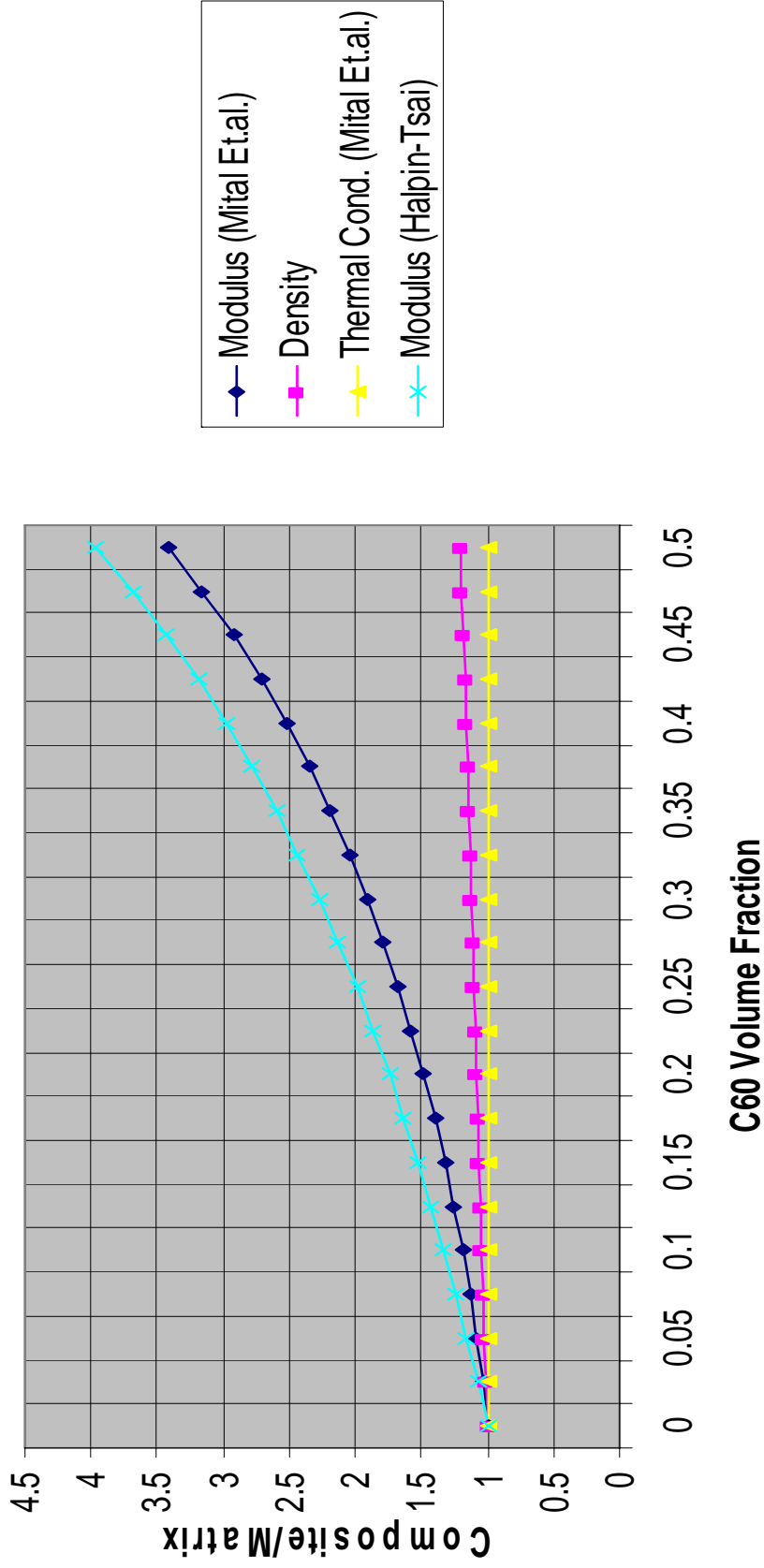
Legend:  
- Modulus (Mital Et.al.)  
- Density  
- Thermal Cond. (Mital Et.al.)  
- Modulus (Hapin-Tsai)



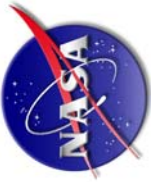
# Fullerene/Epoxy Composite for High Strength-Insulating Layer



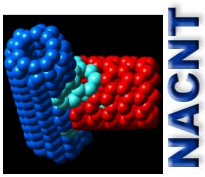
**Composite Spherical Shell -ABS+C60** ( $E_f=860$  GPa,  $E_m=1.8$  GPa,  $K_f=0.25$  W/m-k,  $K_m=0.25$  W/m-k,  $d_f=1.745$  g/cc, and  $d_m=1.05$  g/cc)







## Models for Continuous Fiber Reinforced Composites



IC Finegan et. al., Composite Science and Tech (2003)

### Halpin-Tsai Equations

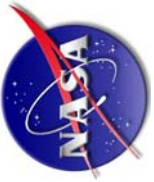
$$\frac{E}{E_m} = \frac{1 + \xi\eta V_f}{1 - \eta V_f}$$

$$\text{where } \eta = \frac{(E_f / E_m) - 1}{(E_f / E_m) + \xi}$$

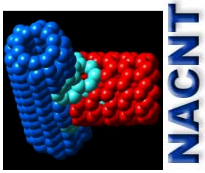
where  $\xi$  is a measure of fiber reinforcement depends on fiber geometry, packing geometry, and loading conditions at the interface

with  $\xi = 2l/d$  for longitudinal modes and  $= 2$  for transverse modes

For limiting cases, the measure of fiber reinforcement could be 0 (series model) or infinity (parallel model).



## Tensile Strength for Discontinuous Fiber Composites



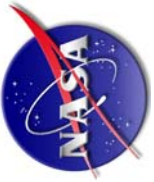
Critical length for discontinuous composite 
$$l_c = \frac{\sigma_f d}{\tau_c}$$

where  $\tau_c$  is the shear strength of the bond at the interface

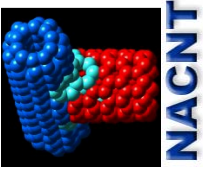
and  $\sigma_f$  is the tensile strength

$$TS_{comp} = TS_f V_f \left( 1 - \frac{l_c}{2l} \right) + TS_m (1 - V_f) \quad \text{for } l > l_c$$

$$TS_{comp} = \left( \frac{l\tau_c}{d} \right) V_f + TS_m (1 - V_f) \quad \text{for } l < l_c$$



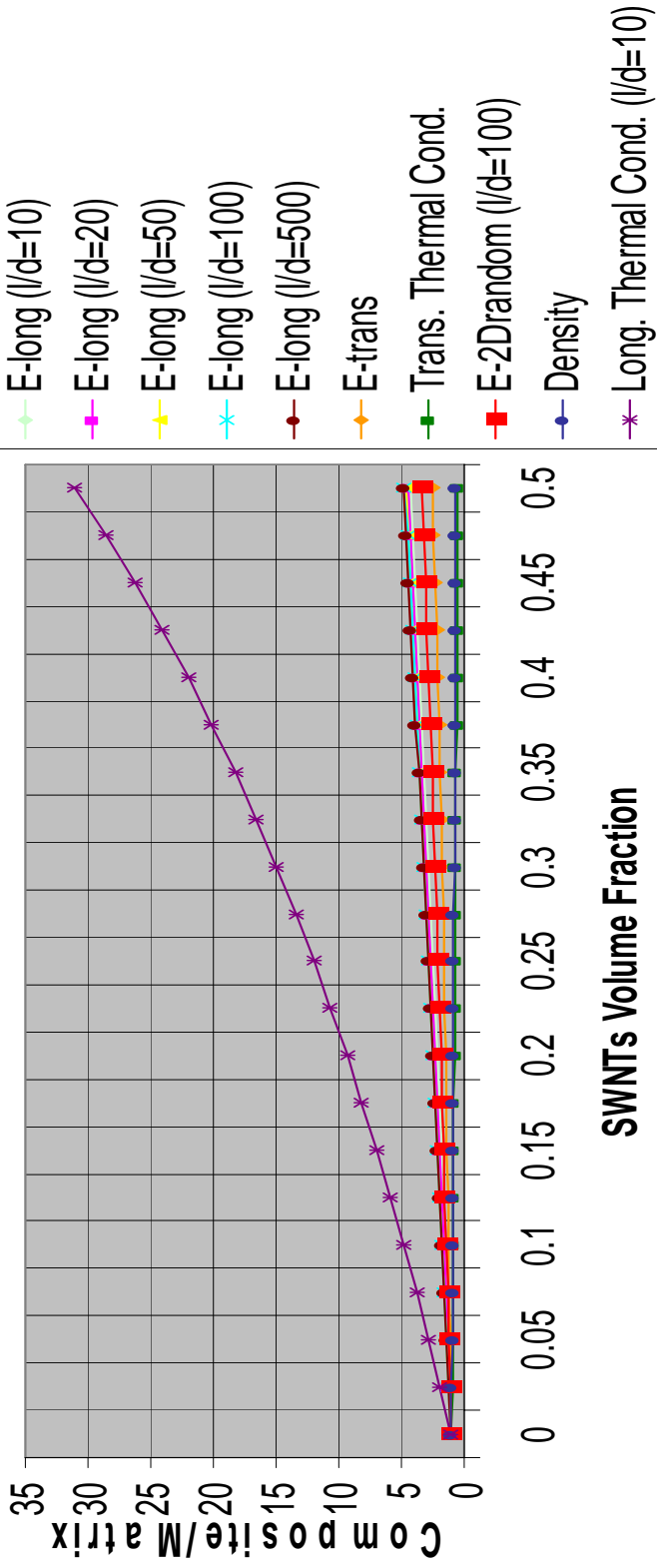
# Ti + SWNT Composites: Thermal/Mechanical



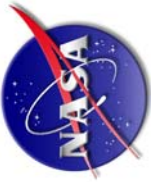
## Composite Spherical Shell - Ti+SWNTs

Based on Halpin-Tsai Equations

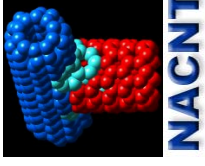
(Elong=1000 GPa, Fftrans=860, Em=116GPa, Kfl=2000 W/m-k, Kft=0.25 W/m-k, Km=17 W/m-k, df=1.745 g/cc, and dm=4.5 g/cc)







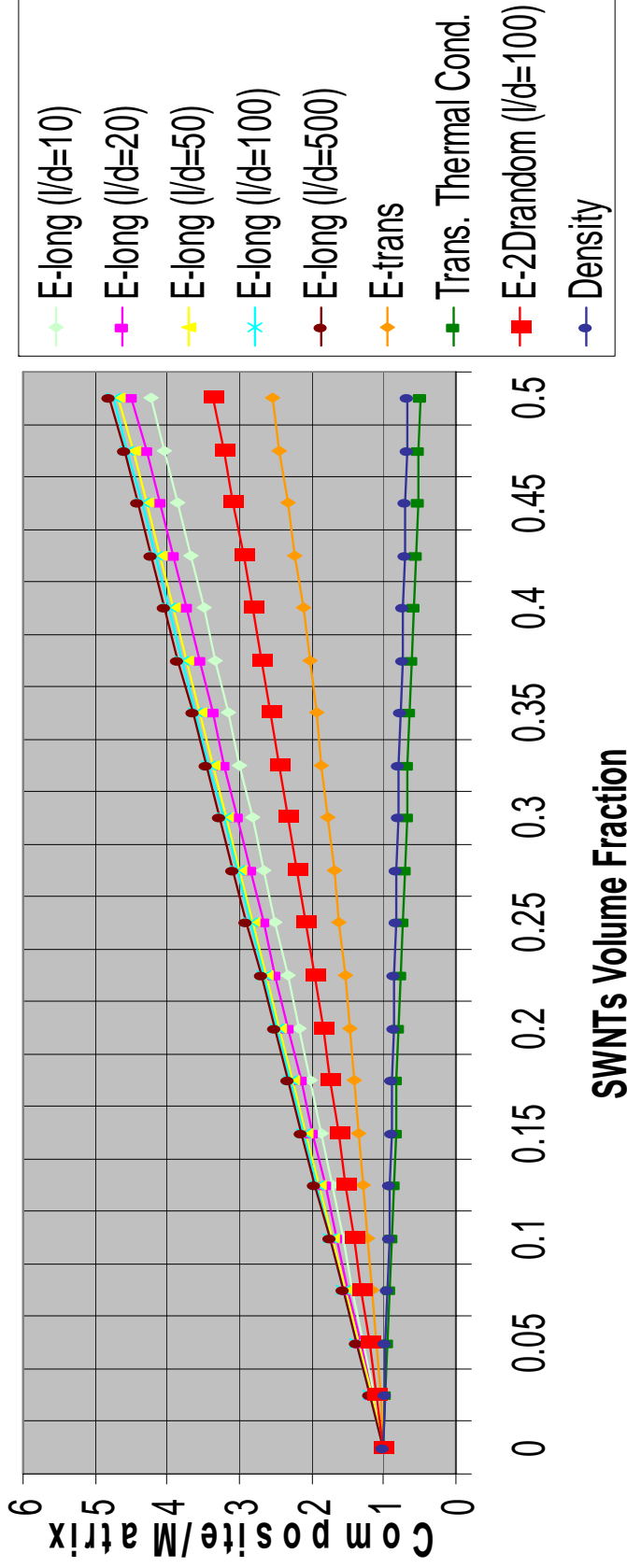
# Ti + SWNT Composites: Thermal/Mechanical

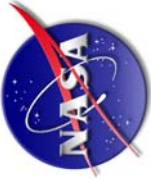


## Composite Spherical Shell - Ti+SWNTs

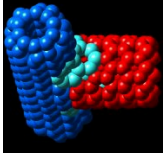
Based on Halpin-Tsai Equations

(Elong=1000 GPa, Ffrans=860, Em=116GPa, Kfl=2000 W/m-k, Kft=0.25 W/m-k, Km=17 W/m-k, df=1.745 g/cc, and dm=4.5 g/cc)



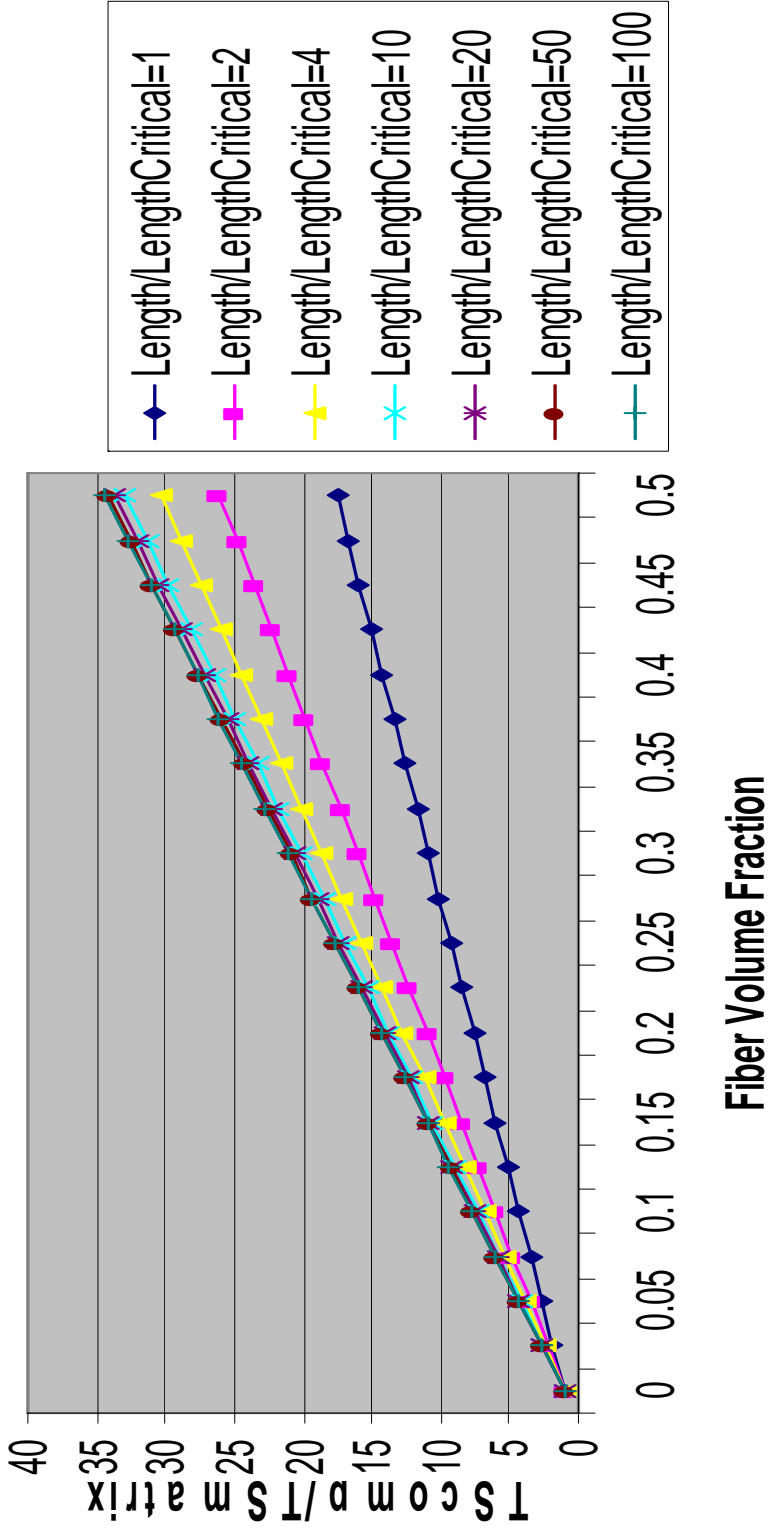


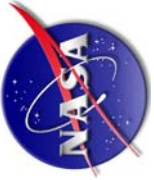
# Ti + SWNT Composites: Tensile Strength



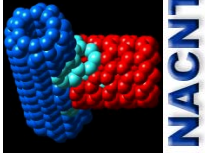
NACNT

## Longitudinal Tensile Strength (TS) of Nanotube-Titanium Composite for $L > L_c$ ( $TS_f = 15\text{GPa}$ and $TS_m = 220\text{MPa}$ )

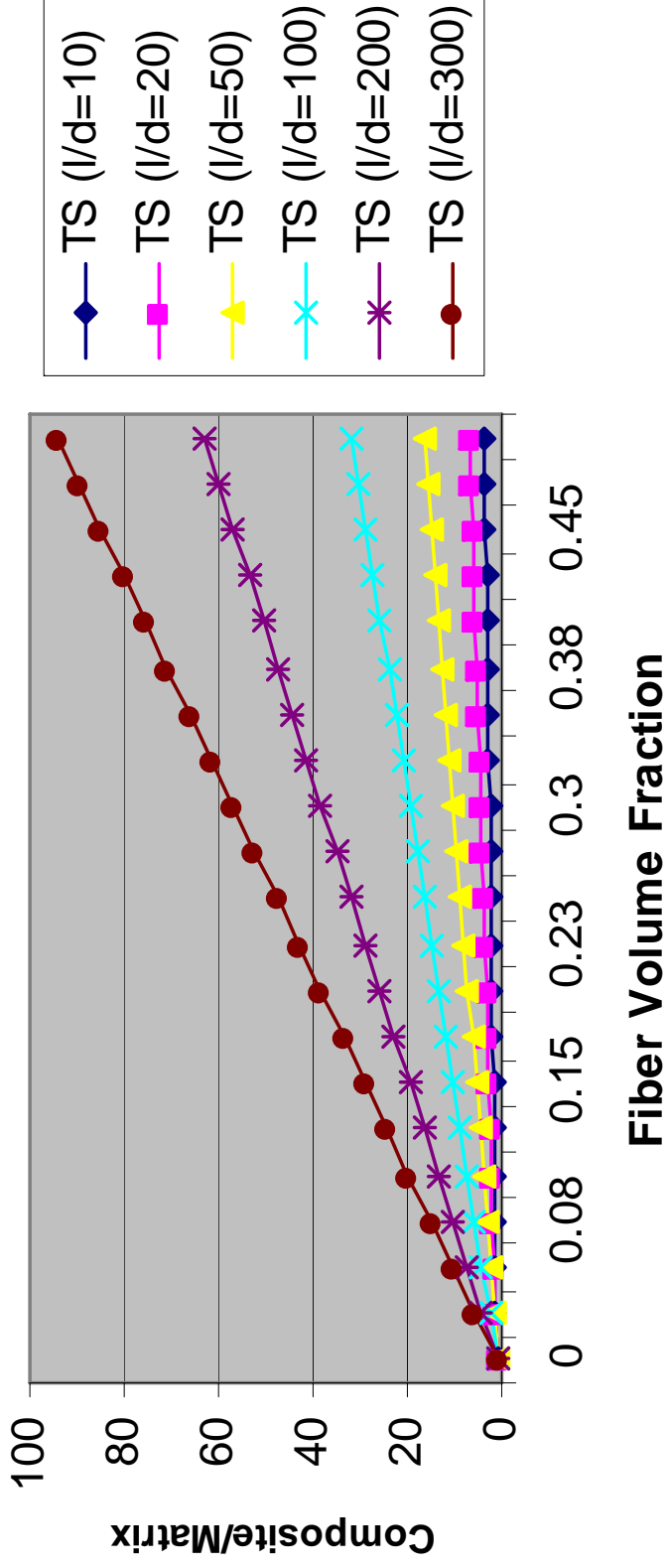




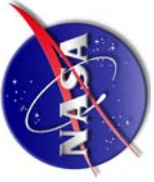
# Ti + SWNT Composites: Tensile Strength



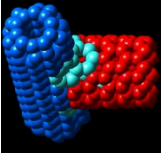
**Tensile Strength (TS) of Nanotube-Polymer Composite. Results for Polymer with TS of 80 MPa and Bond Shear Strength of 50 MPa ( $L < L_c$ )**





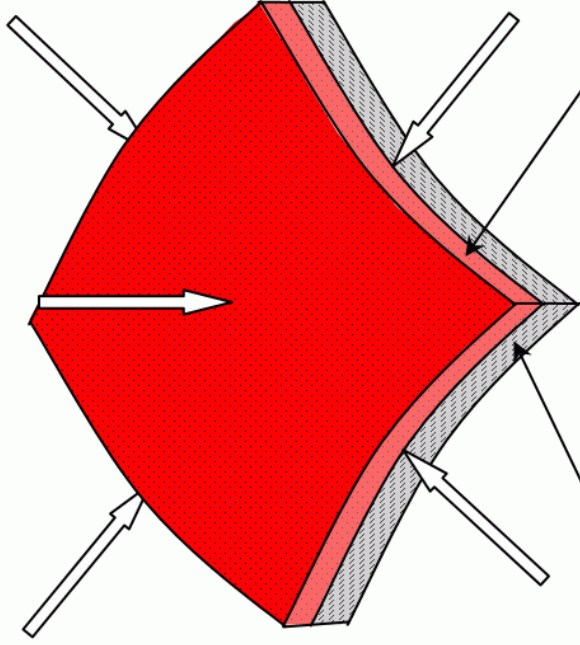


# Nano-structured Shell for Pressure Vessels



NACNT

## Nano-enabled Spherical Shell Compressional Loading and Temperature



Composite  
Thermal Layer  
Ti + Fullerenes

Composite Structural  
Layer Ti + Carbon  
Nanotubes

- 0.35 Fullerene / 0.65 Ti Composite  
Modulus (+100%)  
Density (-25%)  
Th Cond. (-50%)
- 0.35 CNT / 0.65 Ti Composite  
Modulus (+250%)  
Density (-25%)  
Th Cond (L) (x 15-20)  
Th Cond (T) (x 0.75)  
Tensile S (X 20 L > Lc)  
Tensile S (X 40 L < Lc)

- These are upper-limits for stiffness and thermal conductivity estimates:  
**Assumption:** micro-mechanical models with mostly perfect interfaces