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

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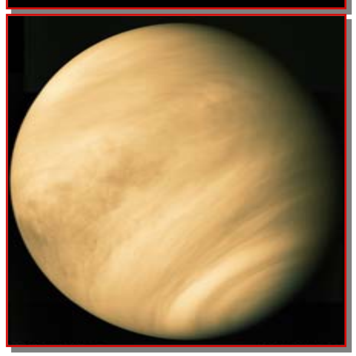
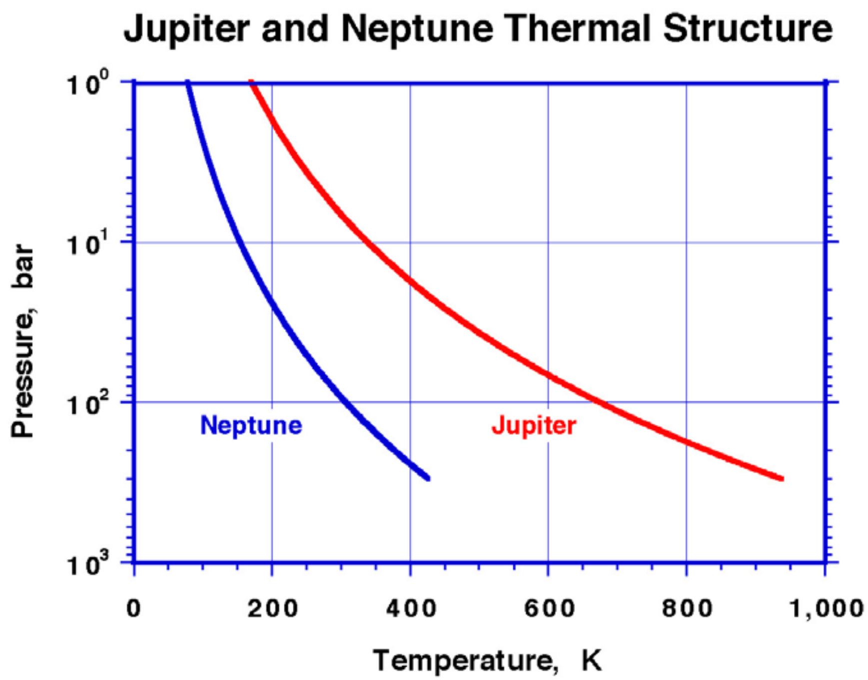
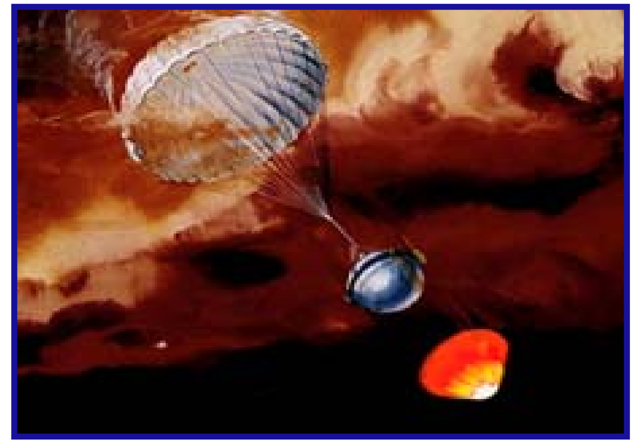


Ames Research Center

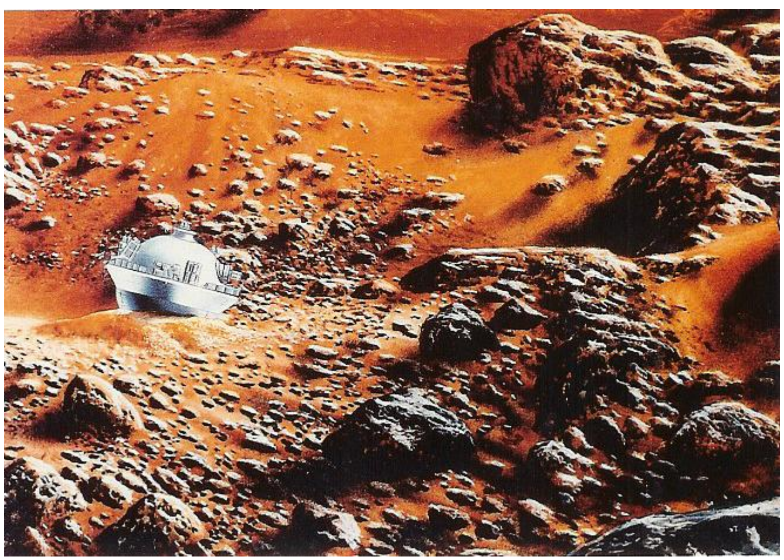
2nd International Planetary Probe Workshop, Aug 23-27, 2004,

High Temperature/Pressure in Key X-Environments





Pressure - Temperature Atmospheric ProfilesProvided[2] 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[3] for 68 minutes on Venus' surface - December, 1978

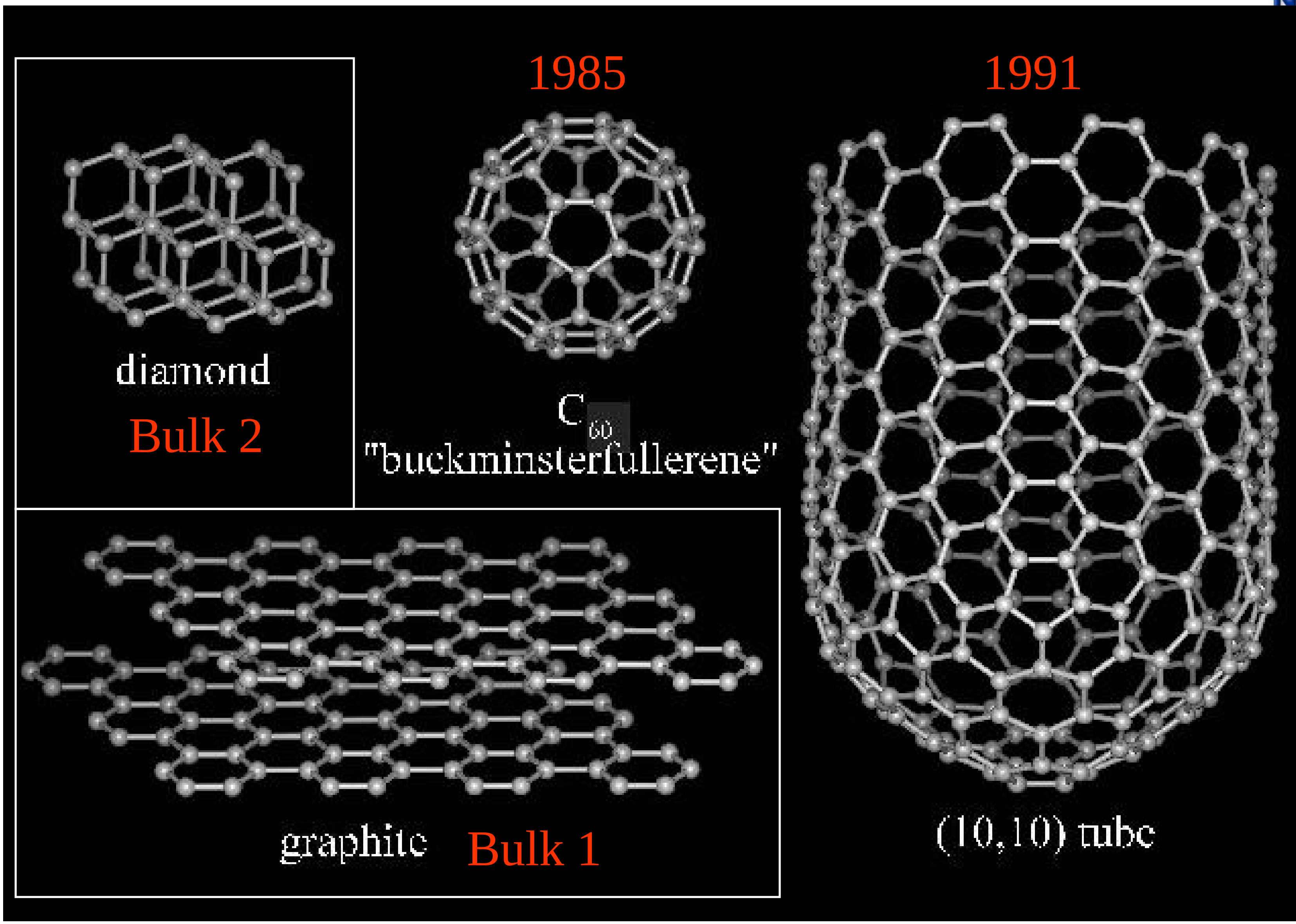
The Case for Use of Nano-Structured Materials
Pressure Vessel Design

- 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

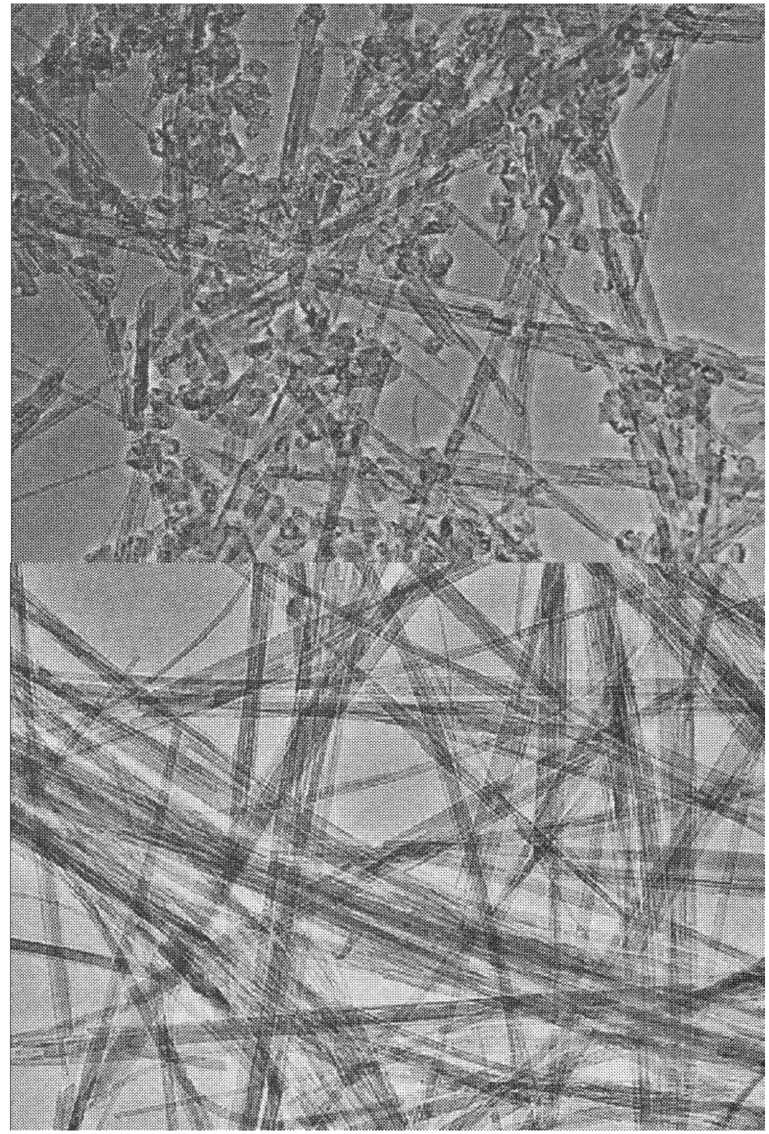
Carbon based Nanomaterials



http://cnst.rice.edu/images/allotropes.jpg

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: $E = \sim 1.2$ TPa

  $(E = k/a)$

- *Plastic/Fracture* properties: compression & tension

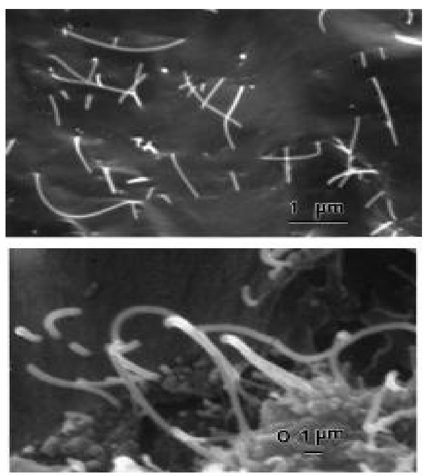
  yield strain $\geq$ 15 - 20% (?)

  - Strain rate?
  - Defects?
  - Mechanisms?
  - Applications?

- *Superstrong Material:* $\sigma_Y = 750 - 1000$ GPa!
  - Diamond (50 GPa), WC (6 GPa), Steel (0.5-2 GPa)

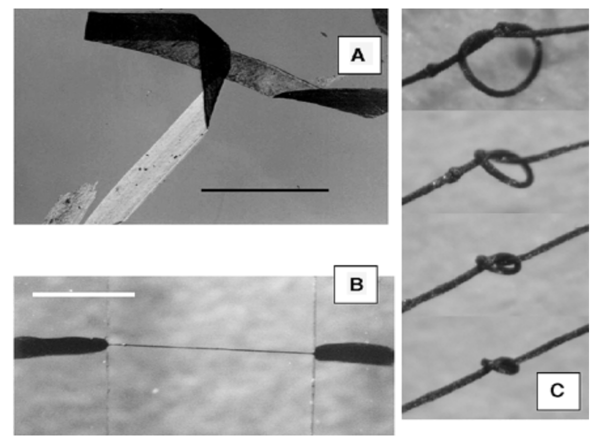
CNT-composites: Example (Polymer)

SEM images of epoxy-CNT composite



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

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



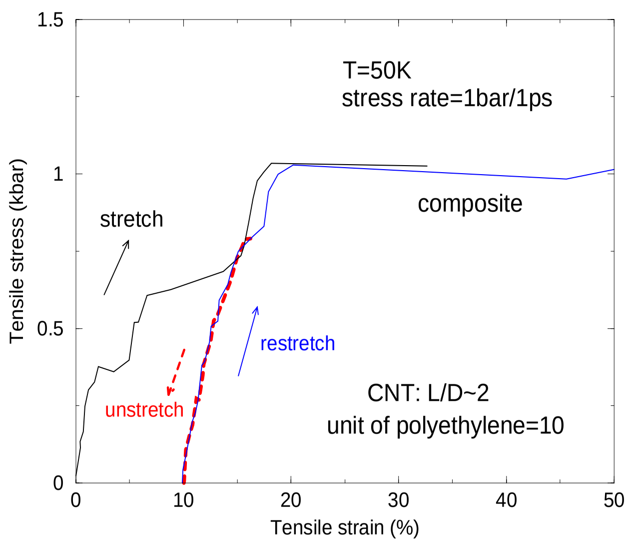
(B. Vigolo et.al., Science, V290 P1331, 2000)

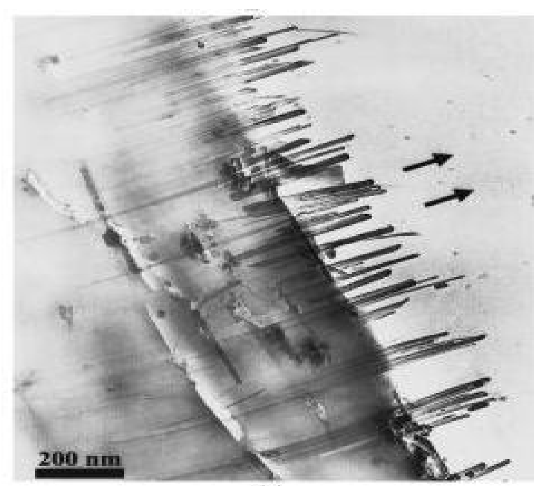
Effect of Loading sequence on Composite with 8% by volume

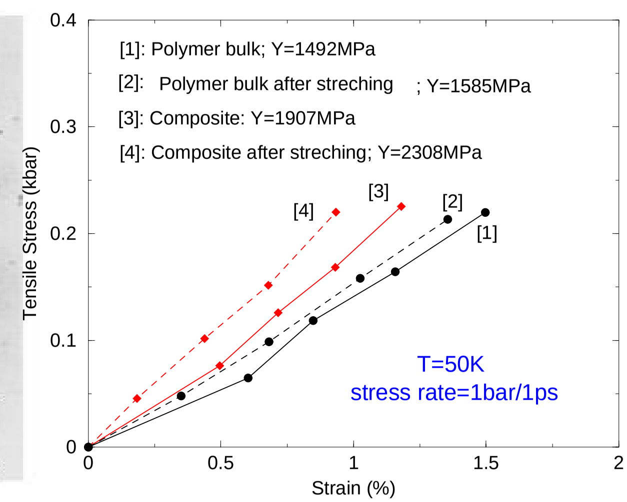
Simulations of CNT-Polyethylene Composites

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, Np=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

$$E_{pc} = \frac{V_f^{0.67} E_m}{1 - V_f^{0.33}(1 - \frac{E_m}{E_f})} + (1 - V_f^{0.67})E_m$$

Elastic Modulus of Composite

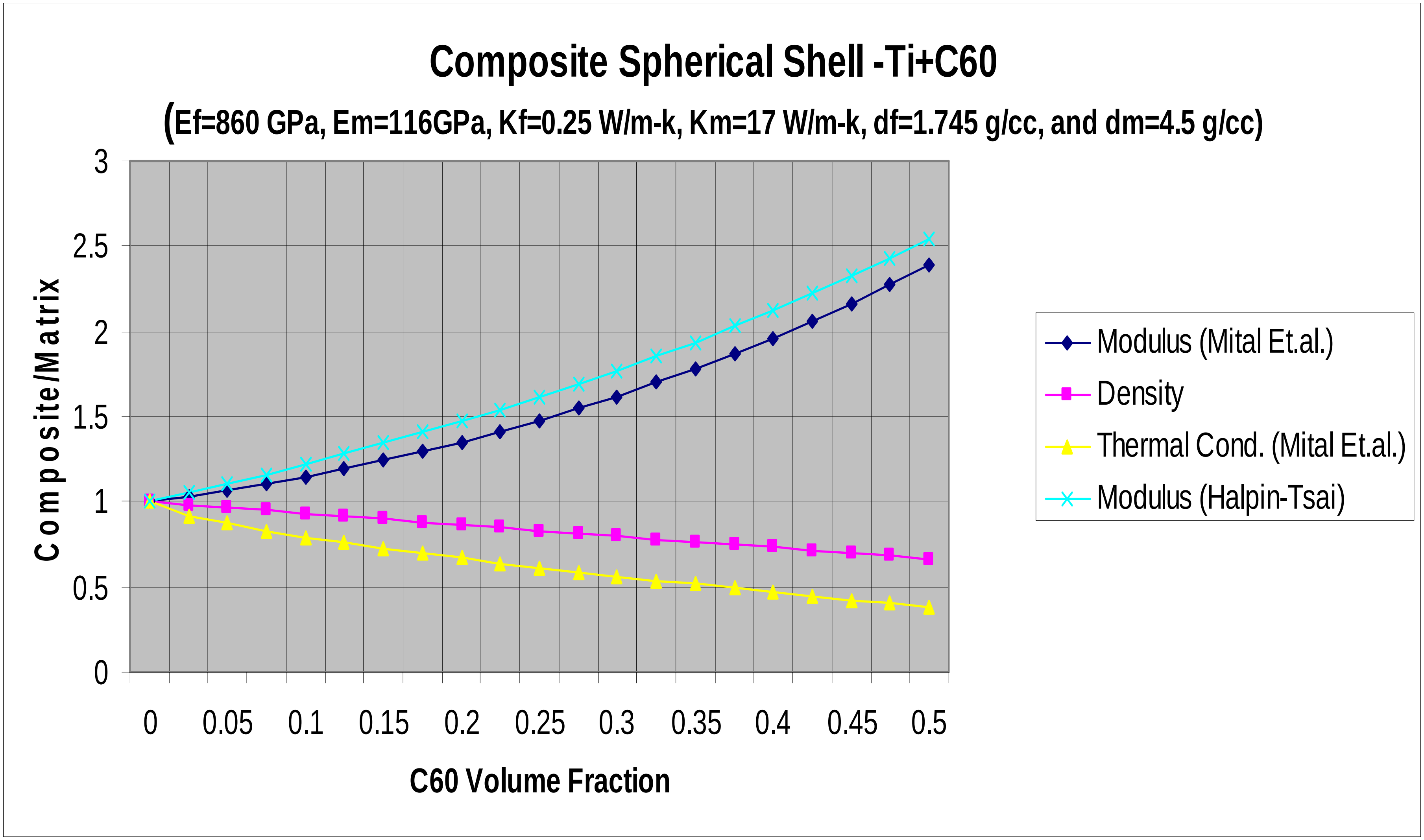
$$K_{pc} = \frac{V_f^{0.67} K_m}{1 - V_f^{0.33}(1 - \frac{K_m}{K_f})} + (1 - V_f^{0.67})K_m$$

Thermal Conductivity of Composite

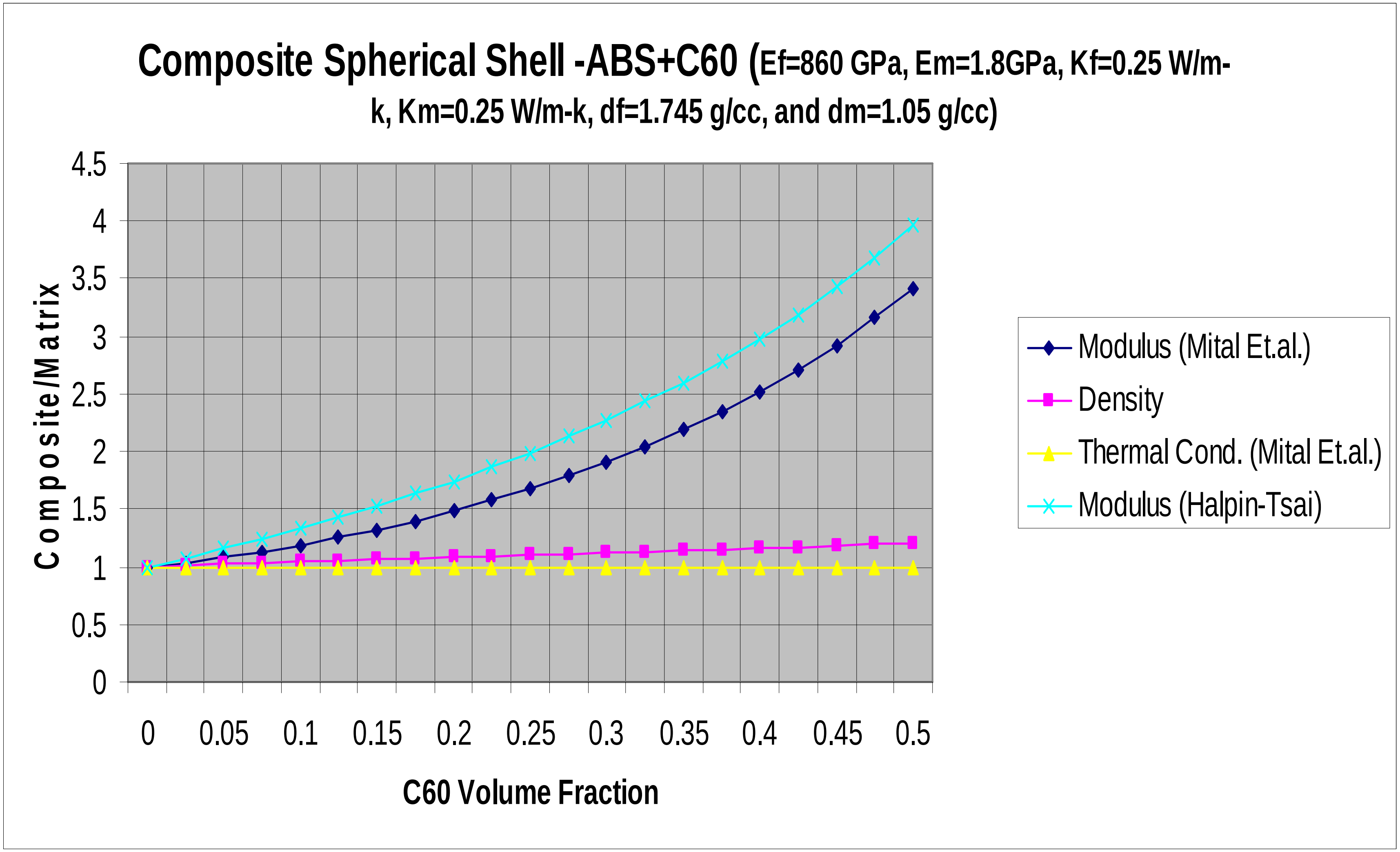
Where V_f is volume fraction

Assumption: Ideal Interface – perfect bonding at the interface

Fullerene/Ti Composite for High Strength-Insulating Layer



Fullerene/Epoxy Composite for High Strength-Insulating Layer



Models for Continuous Fiber Reinforced Composites

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

Halpin-Tsai Equations

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

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

with ξ = 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 $$l_c = \frac{\sigma_f d}{\tau_c}$$

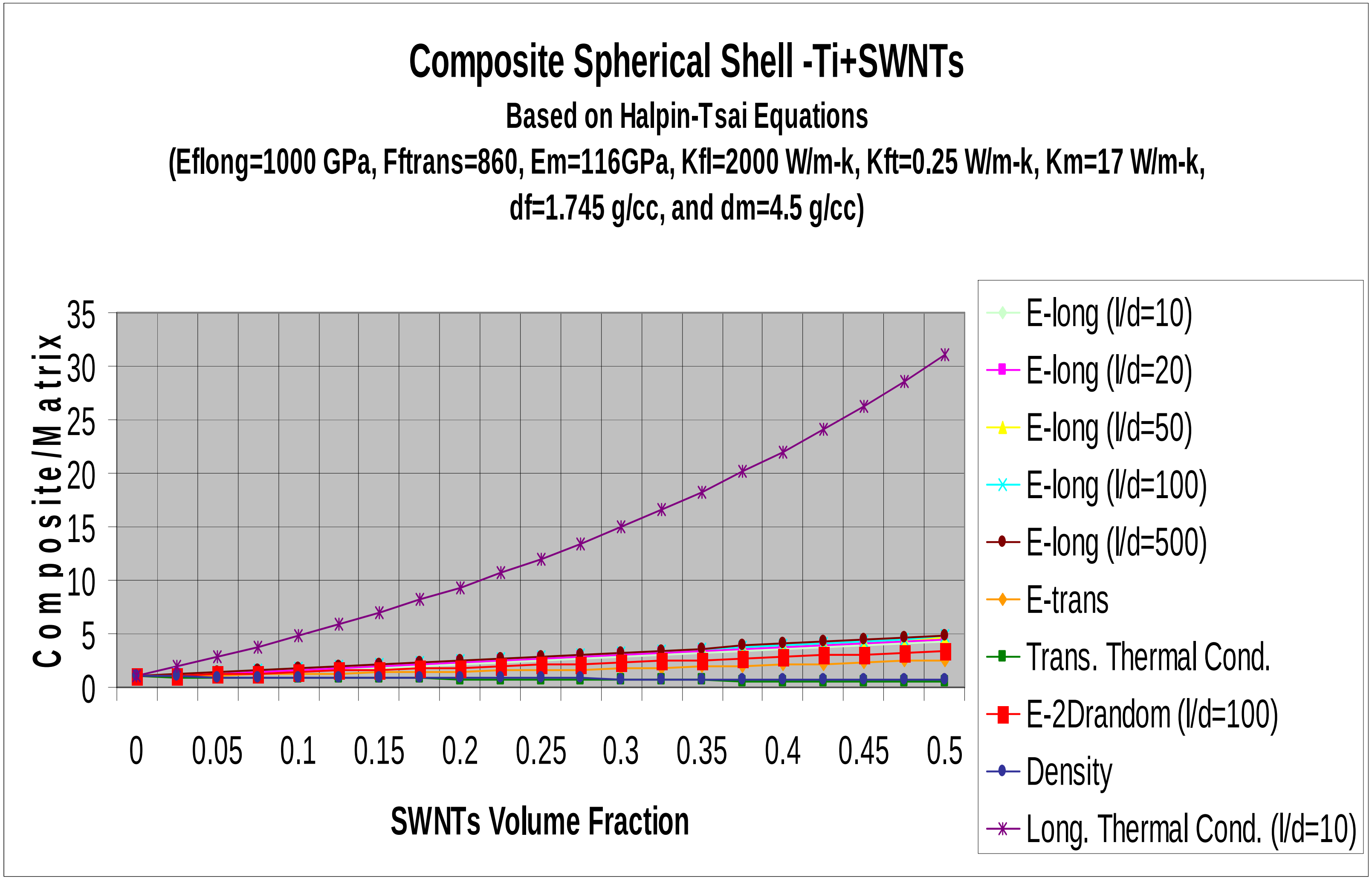
where τ_c Is the shear strength of the bond at the interface

and σ_f is the tensile strength

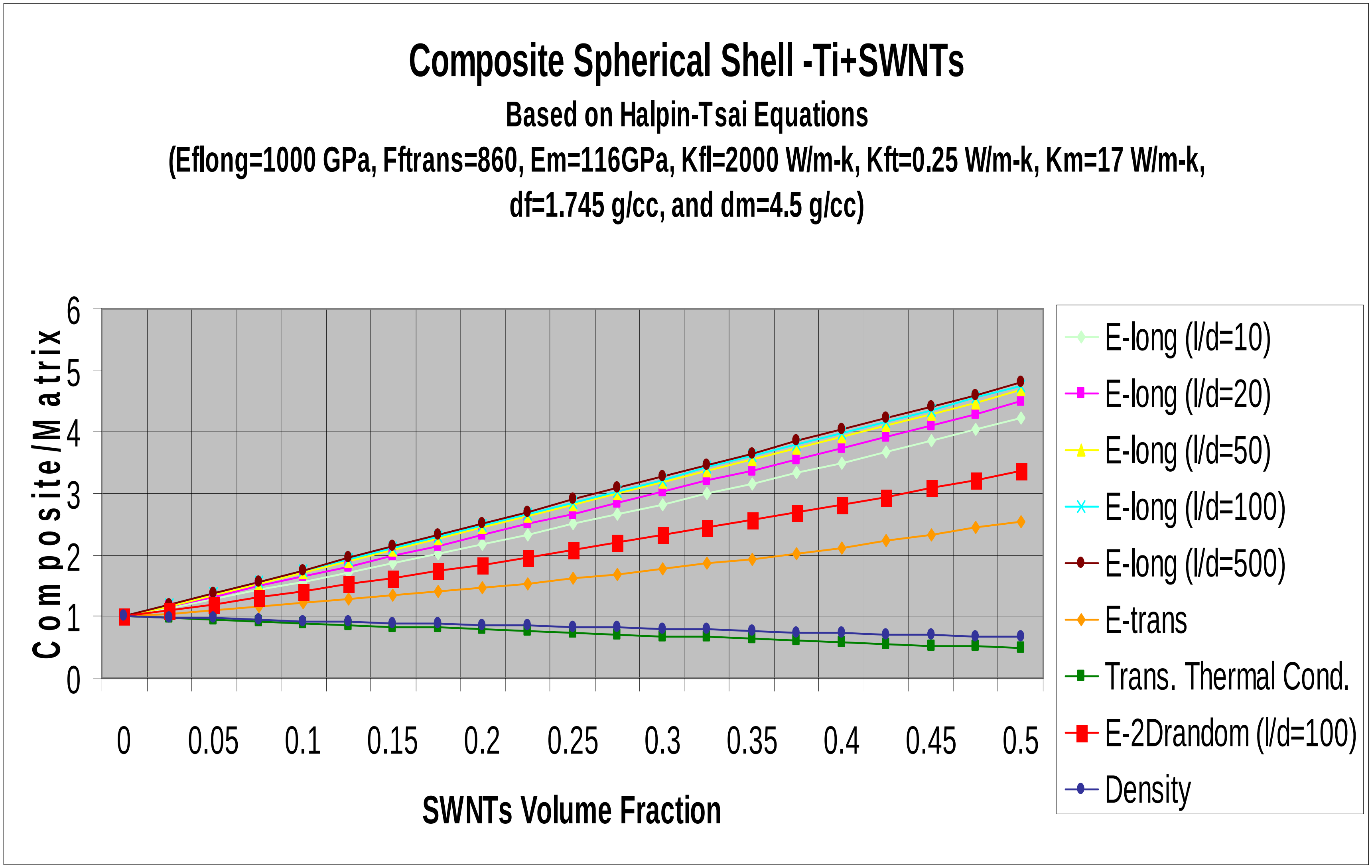
$$TS_{comp} = TS_f V_f \left(1 - \frac{l_c}{2l}\right) + TS_m (1 - V_f) \quad \text{for} \quad l > l_c$$

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

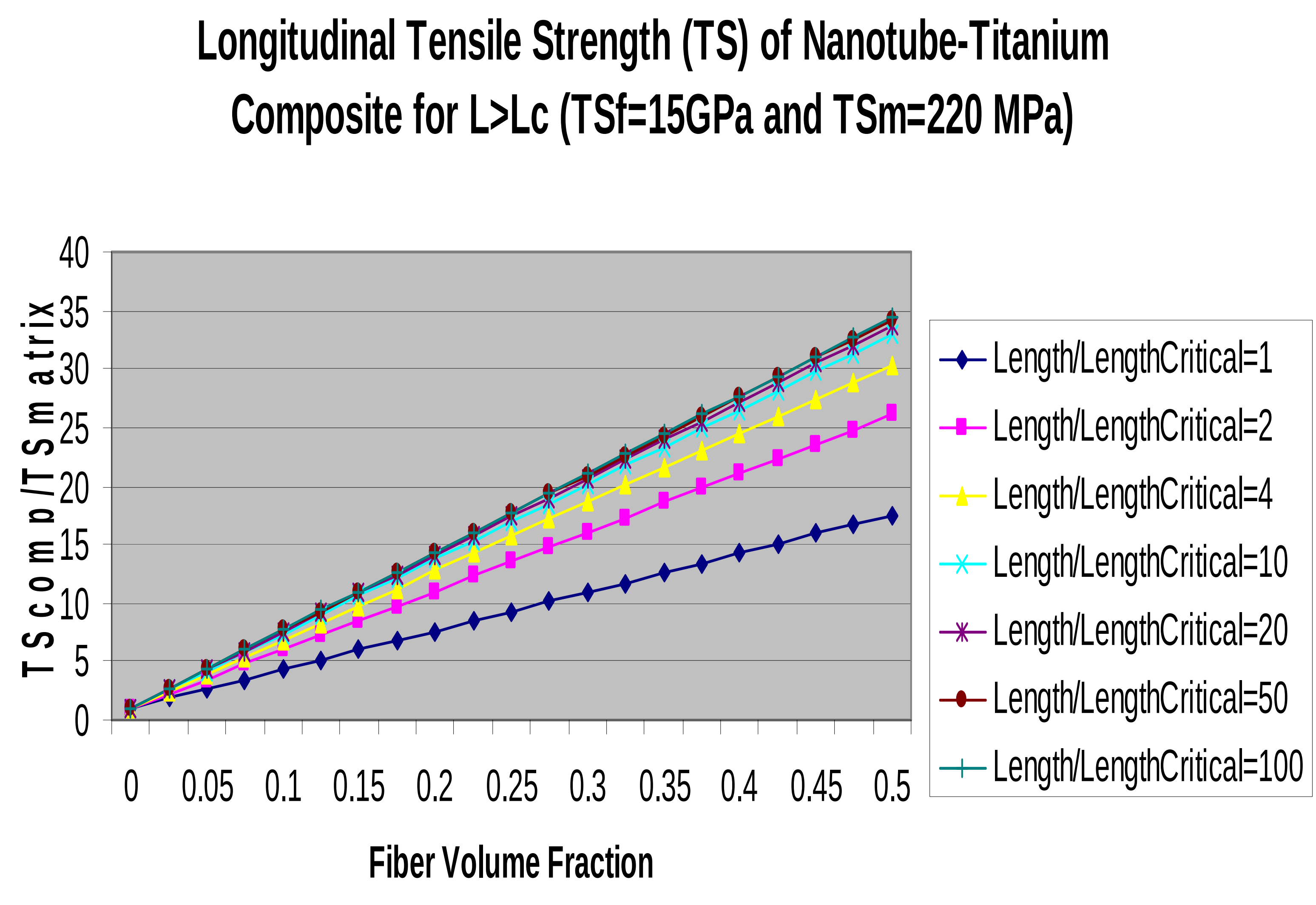
Ti + SWNT Composites: Thermal/Mechanical



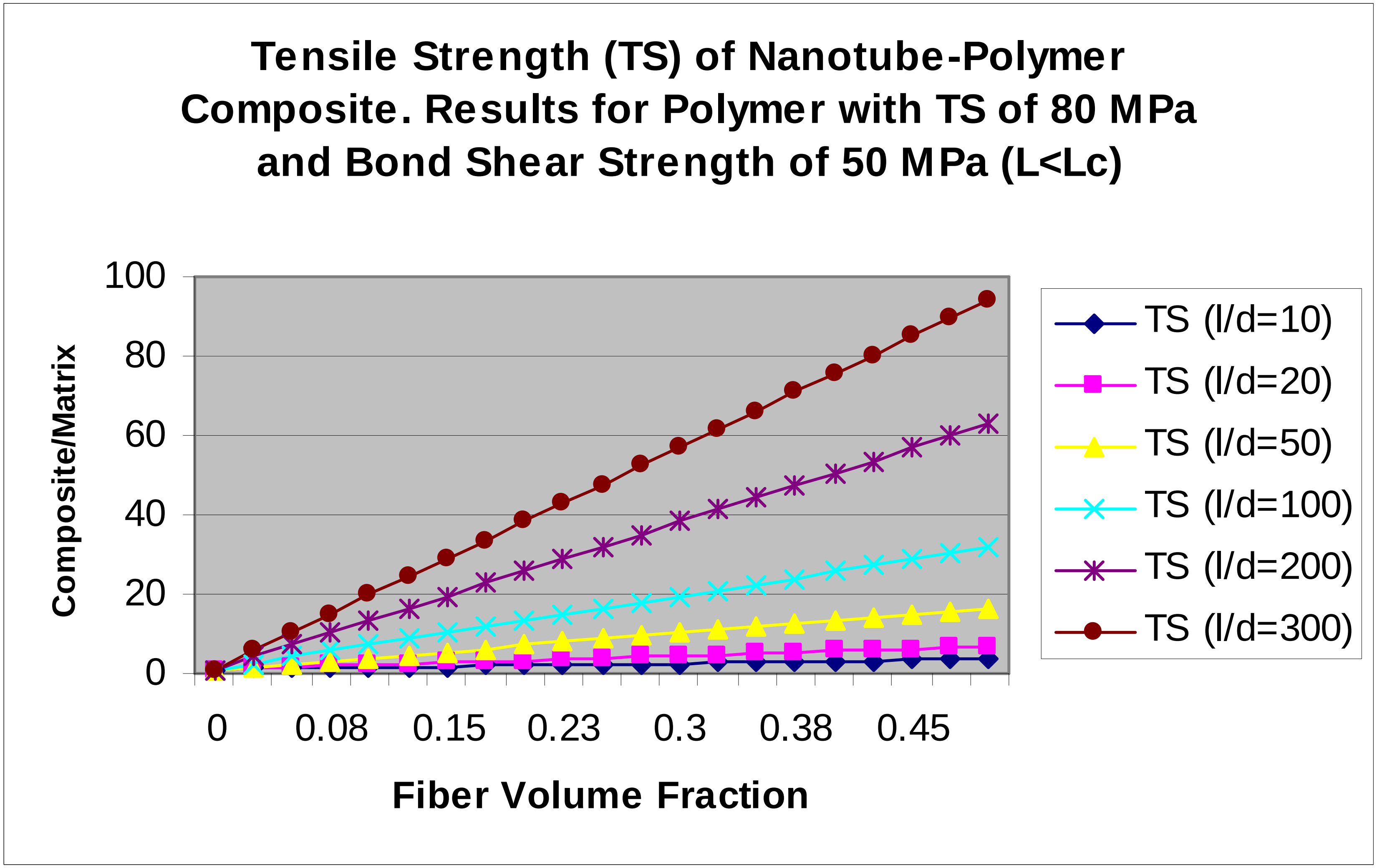
Ti + SWNT Composites: Thermal/Mechanical



Ti + SWNT Composites: Tensile Strength

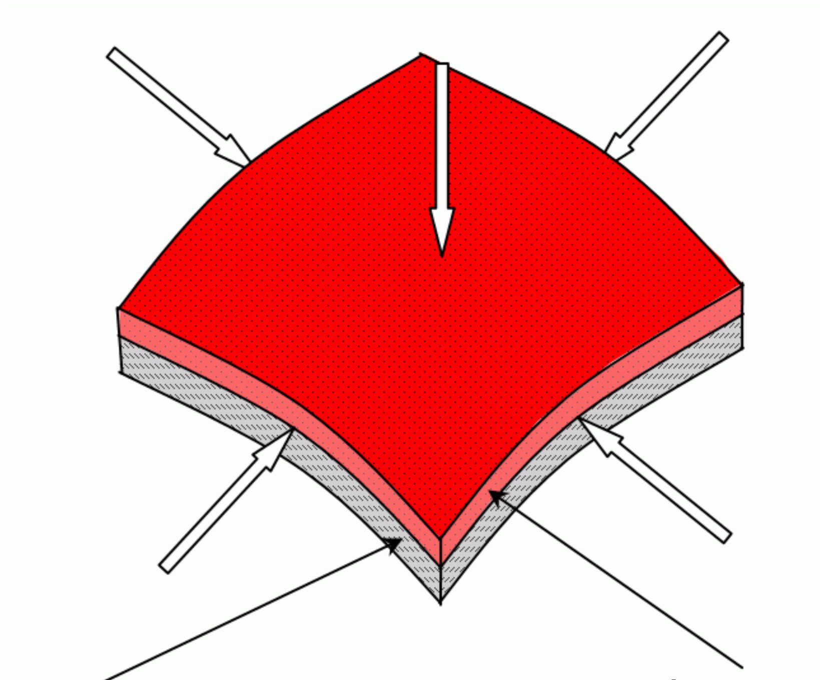


Ti + SWNT Composites: Tensile Strength



Nano-structured Shell for Pressure Vessels

Nano-enabled Spherical Shell Compressional Loading and Temperature



- 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