ENABLING TECHNOLOGIES FOR AEROSPACE MISSIONS – The Case for Nanotubes

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FEL Users/Laser Processing Consortium Meeting
Jefferson Lab
March 11, 2004

Long Term Goals

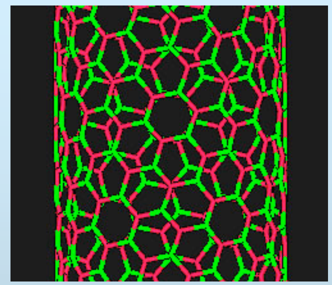
- Create a virtual presence throughout our solar system and probe deeper into the mysteries of the universe and life on Earth and beyond
- Conduct human and robotic missions to planets and other bodies in our solar system to enable human expansion
- Provide safe and affordable space access, orbital transfer and interplanetary transportation capabilities to enable research, human exploration and commercial development of space
- Develop cutting edge aeronautics and space systems technologies to support highway in the sky, smart aircraft and revolutionary space vehicles

Revolutionary Vehicles-Technologies

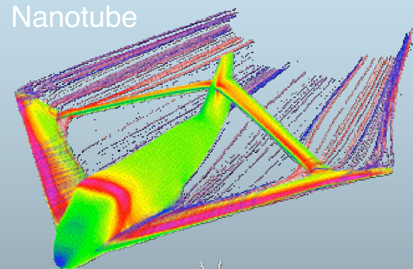
Today's Challenges:

- Develop light, strong, and structurally efficient air vehicles.
- Improved aerodynamic efficiency.
- Design fuel-efficient, low-emission propulsion systems.
- Develop safe, fault-tolerant vehicle systems.

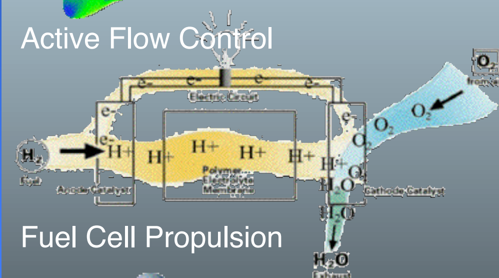
Technology Solutions:



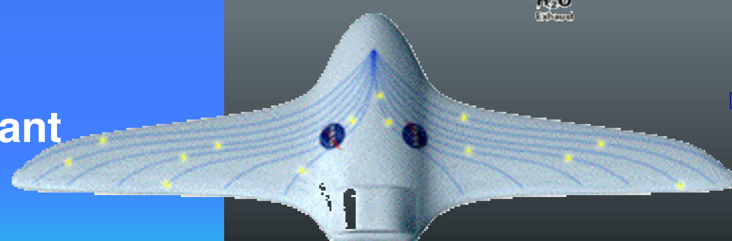
Nanotube



Active Flow Control



Fuel Cell Propulsion



Adaptive Control

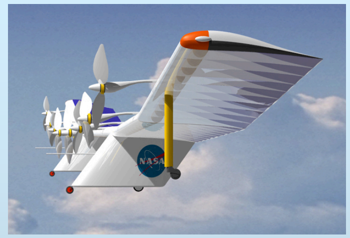
- Nanostructures: 20 times stronger than steel alloys at 1/6 the weight
- Active flow control
- Distributed propulsion
- Electric propulsion, advanced fuel cells, high-efficiency electric motors
- Integrated advanced control systems and information technology
- Central "nervous system" and adaptive vehicle control

Revolutionary Vehicles–Capabilities

Today's Challenges:

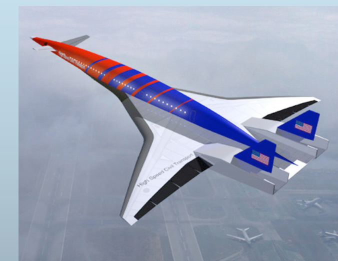
- **Long-duration and large, long-haul transportation**
- **High-speed commercial transportation**
- **Quiet and efficient runway-independent aircraft**
- **Autonomous operations capability**

Future Possibilities:

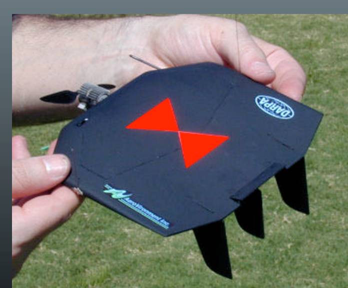


- Months aloft at high-altitudes and long distances

- Quiet, efficient, affordable supersonic flight



- Extremely short takeoff and landing–doorstep-to-doorstep



- Intelligent flight controls, micro-vehicles to transports

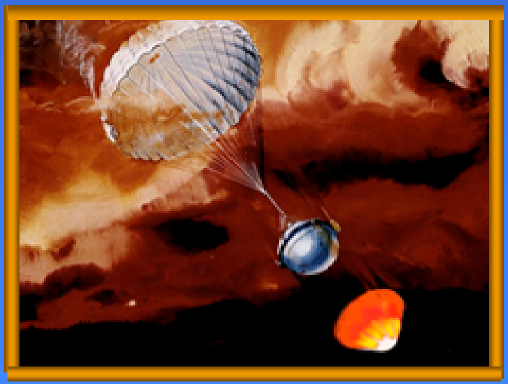
Space Vehicles-Technologies

Manned Missions

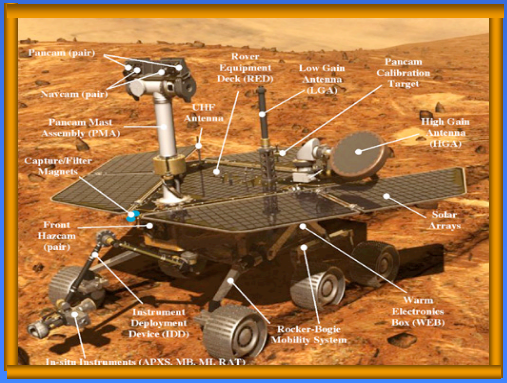
Apollo

Space Shuttle

Unmanned Missions



Galileo



Spirit & Opportunity

Revolutionary Systems-Capabilities

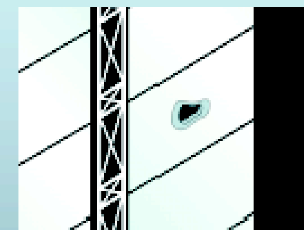
Today's Challenges:

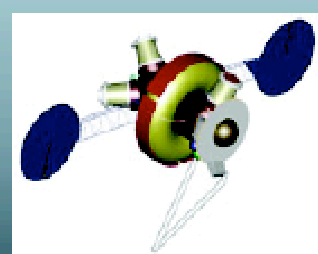
- **Low cost access to space**
- **Radiation resistance**
- **Resilience and long term durability**
- **Advance power and propulsion technologies**
- **Autonomous operations capability**

Future Possibilities:

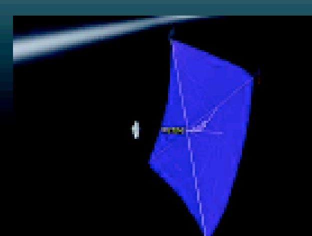
- Reusable launch vehicles

- Resilient, self-repairing structures





- Modular, multifunctional structures



- Intelligent flight controls

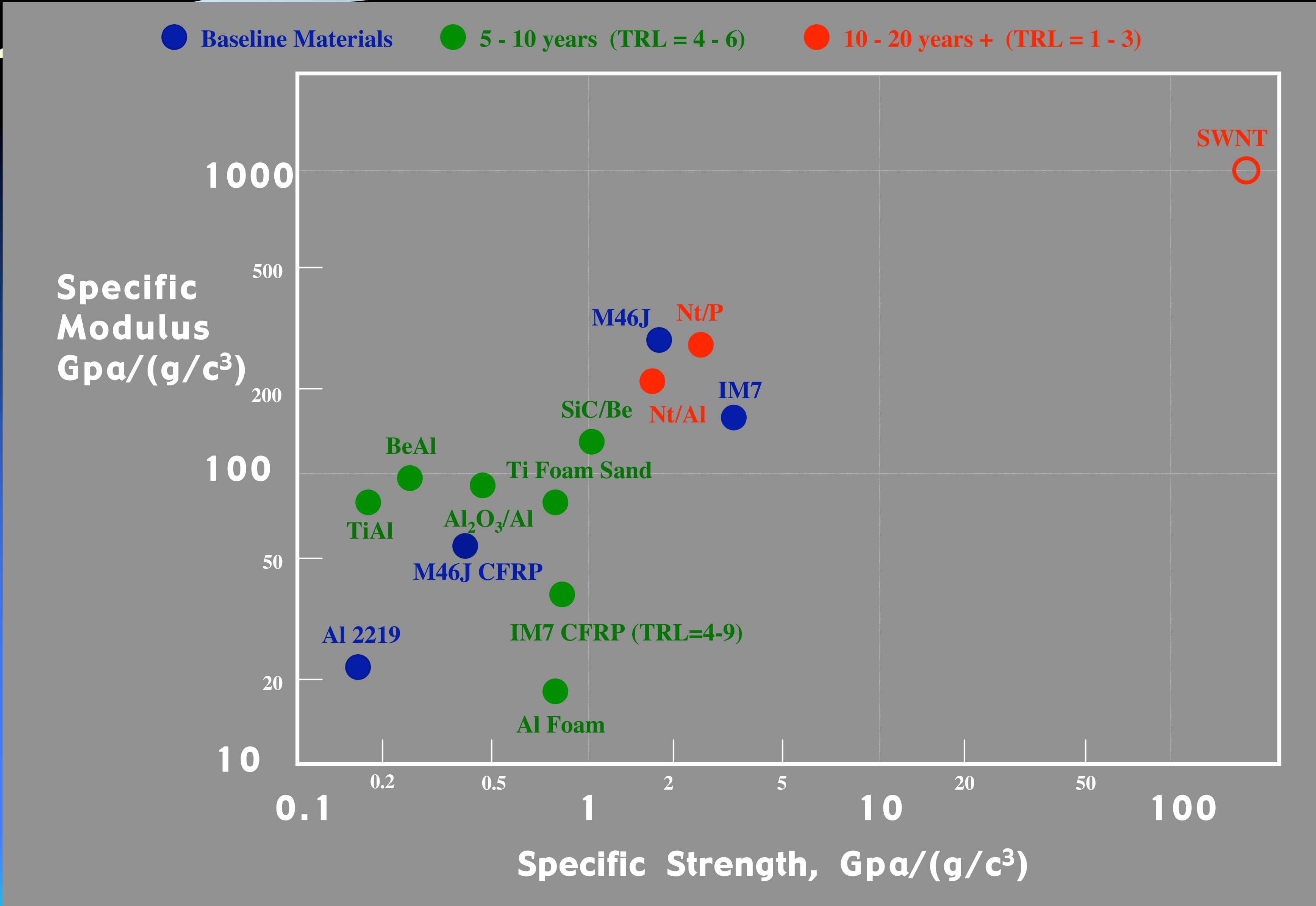
Critical Technologies Required to Achieve Goals

- Vehicle primary and secondary structures
- Radiation protection
- Propulsion and power systems
- Fuel storage
- Electronics and devices
- Sensors and science instruments
- Medical diagnostics and treatment

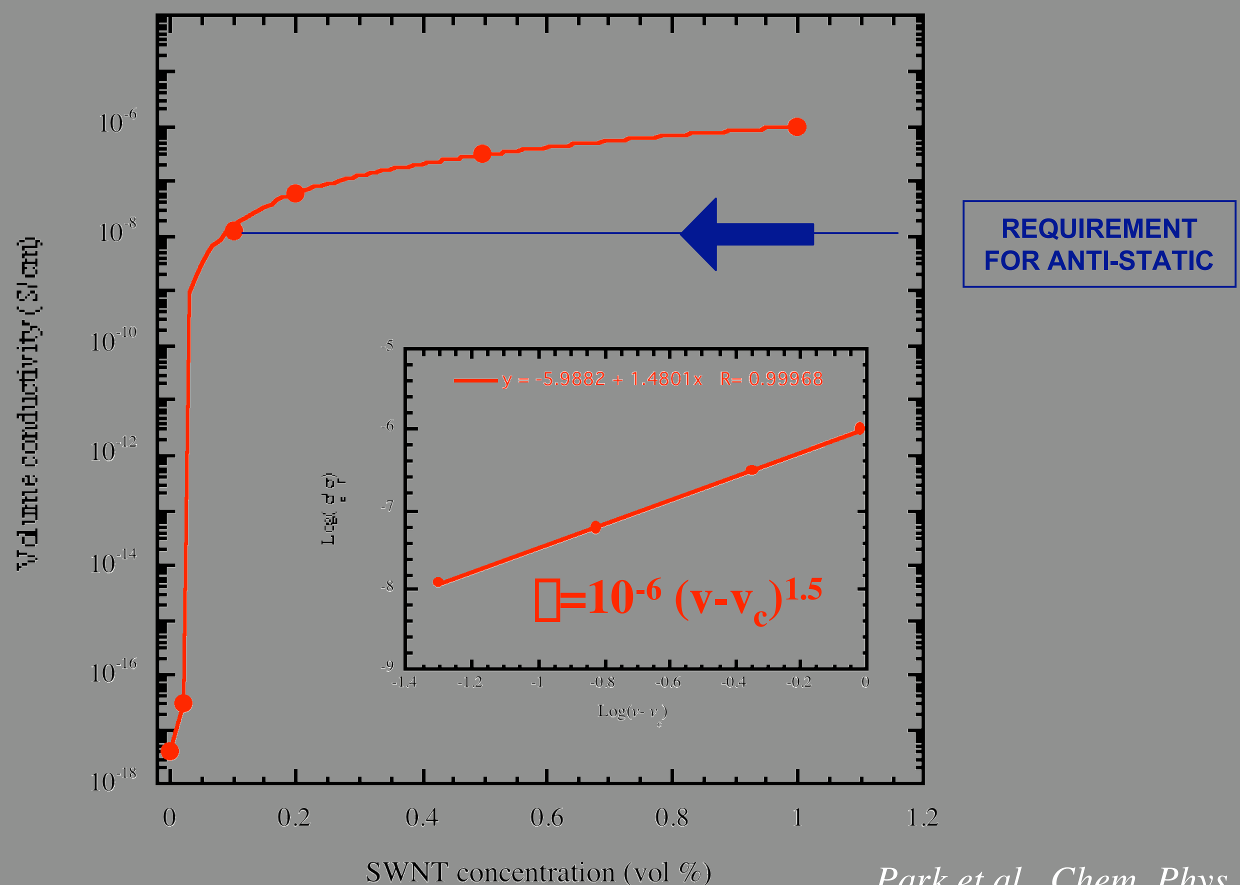
Comparison of Material Properties

Property	Aluminum 2219-T87	IM7 Carbon Fiber	Carbon Nanotubes (CNT)
Density, g/cm^3	2.83	1.78	1.36
Tensile Strength, GPa	0.46	5.5	> 30
Tensile Modulus, GPa	73	300	1030
Elongation, %	10	1.8	15
Thermal Conductivity, W/m/K	121	50	2000
Electrical Conductivity, S/m	$\sim 6 \times 10^5$	$\sim 6 \times 10^4$	1×10^9

Properties of Materials for Vehicle Structure

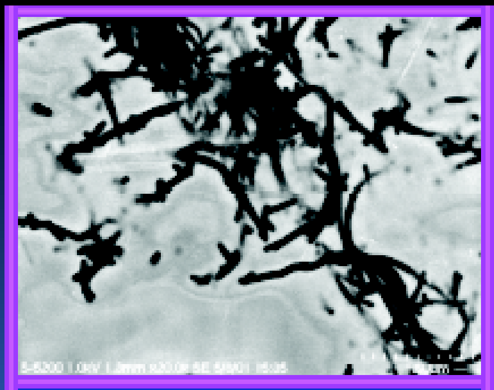


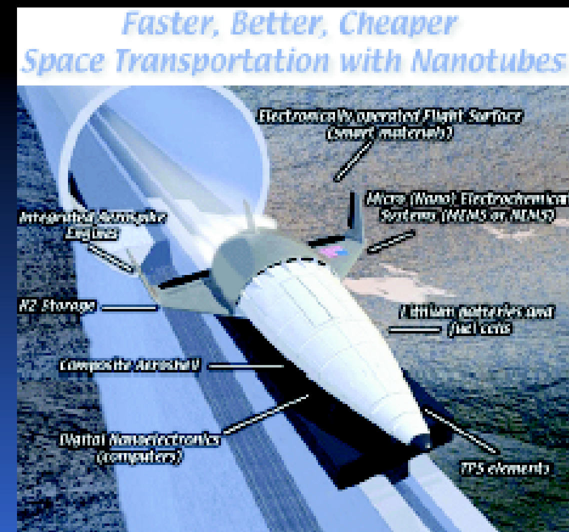
High Electrical Conductivity for Effective Electrostatic Charge Dissipation

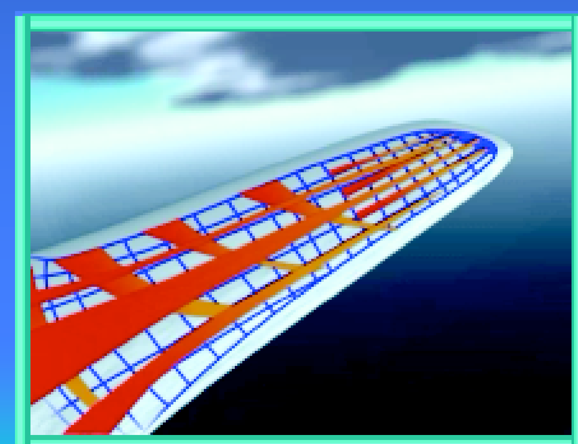


Park et al., Chem. Phys. Lett., accepted

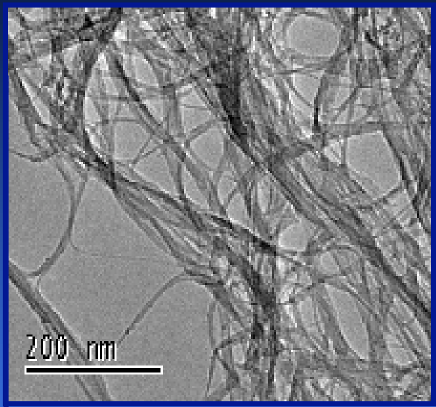
Multifunctionality as a Route to Structural Weight Reduction





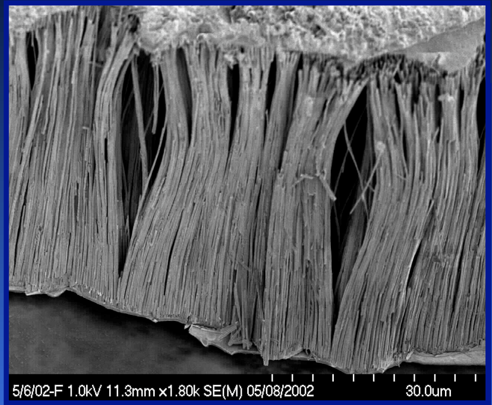


Emerging Materials Technologies for Propulsion and Power Applications



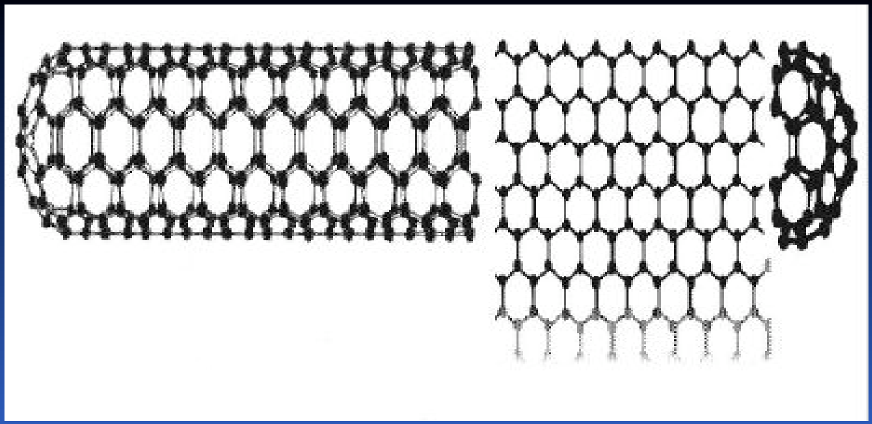
Carbon Nanotube Polymers

Boron Nitride Nanotube Alloys



Silicon Carbide Nanotube Ceramics

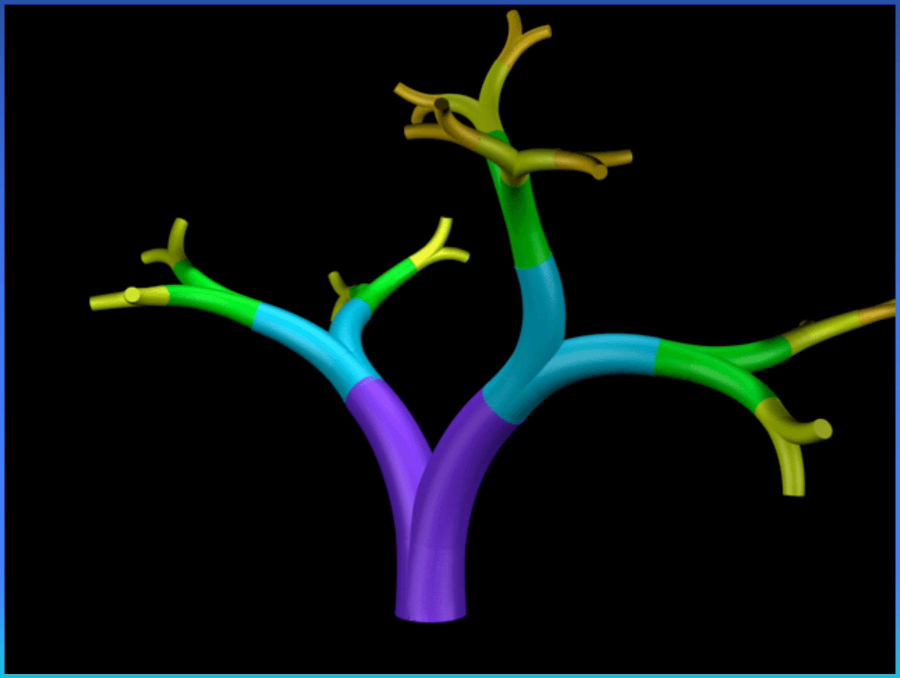
Single-Walled Carbon Nanotubes For Chemical Sensors

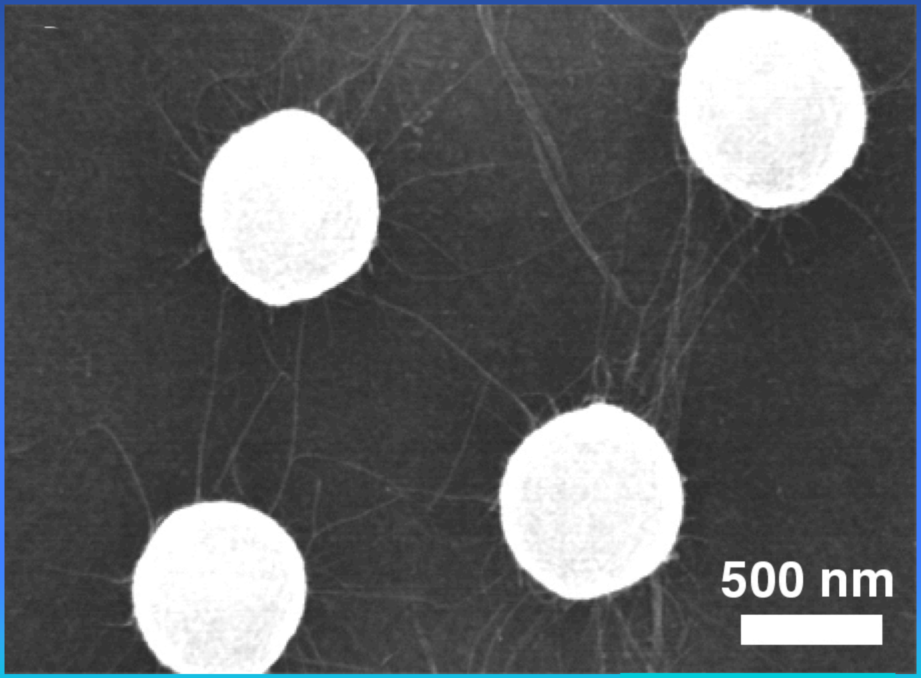


- Every atom in a single-walled nanotube (SWNT) is on the surface and exposed to environment
- Charge transfer or small changes in the charge-environment of a nanotube can cause drastic changes to its electrical properties

Nanotube Based Computing

- Four-level CNT dendritic neural tree with 14 symmetric Y-junctions
- Branching and switching of signals at each junction similar to what happens in biological neural network
- Neural tree can be trained to perform complex switching and computing functions
- Not restricted to only electronic signals; possible to use acoustic, chemical or thermal signals

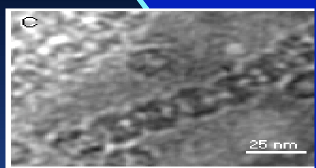


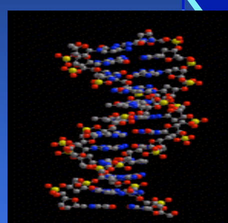


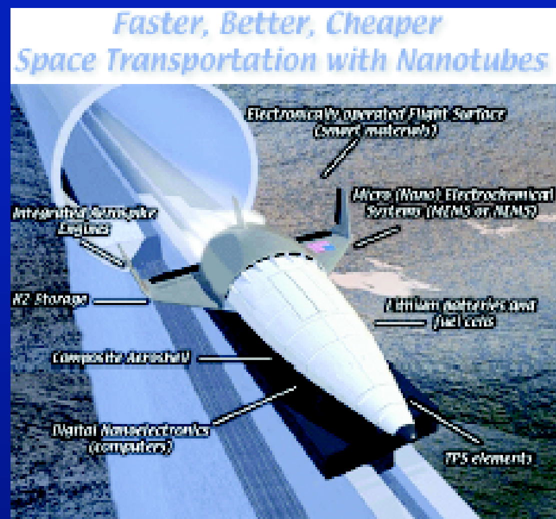
Technology Fusion

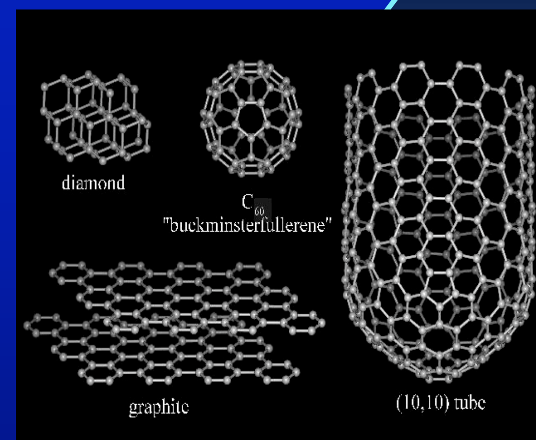
BiOtechnology

NanOtechnology

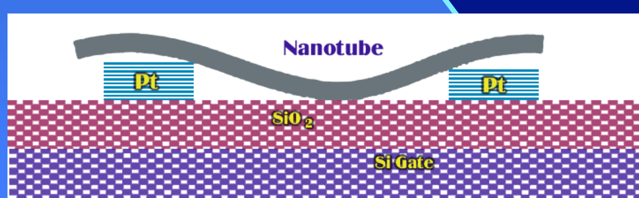








Carbon Nanotubes



Nanoelectronics

InfOtechnology

Role of CNTs

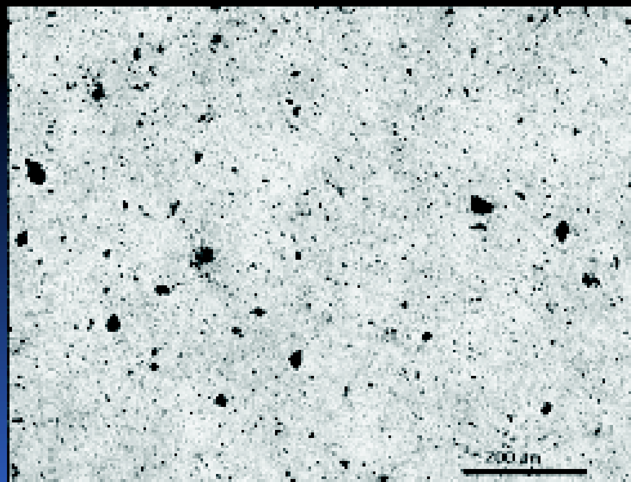
- Enable radical design changes
  - Permit combination of properties not previously possible
  - Affords multifunctionality for increased efficiency

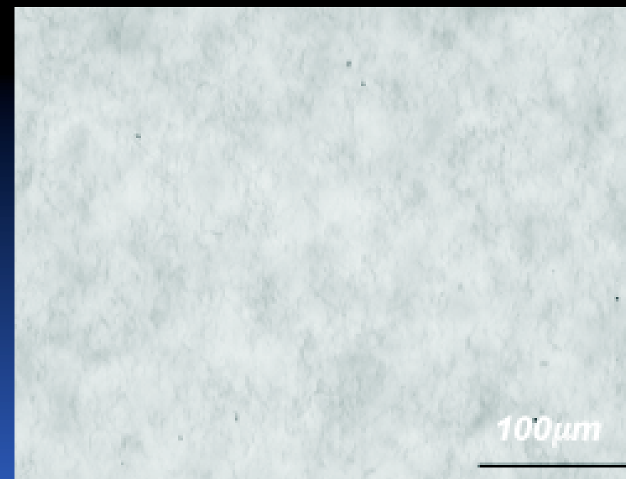
Challenges

- Translating excellent combination of CNT properties on the nanoscale to structural properties on the macroscale
  - Inconsistent quality of carbon nanotube supply
  - Dispersion of carbon nanotubes
  - Characterization of carbon nanotube nanocomposites
  - Scaling down processing equipment to work around low CNT supply

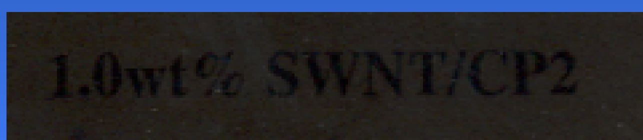
Effect of CNT Dispersability

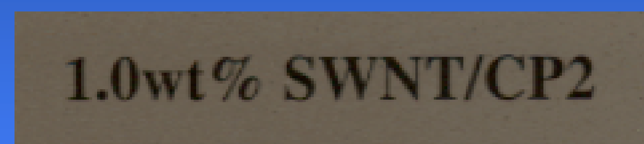
Poor pre-dispersion | ***Good dispersion (optically dispersed)***

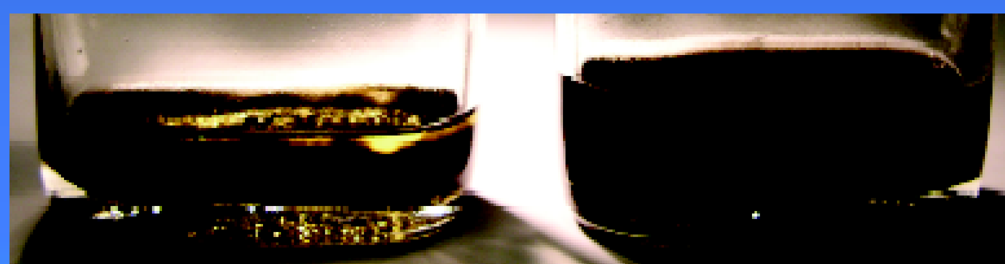




Direct mixing | ***In situ polymerization under sonication***



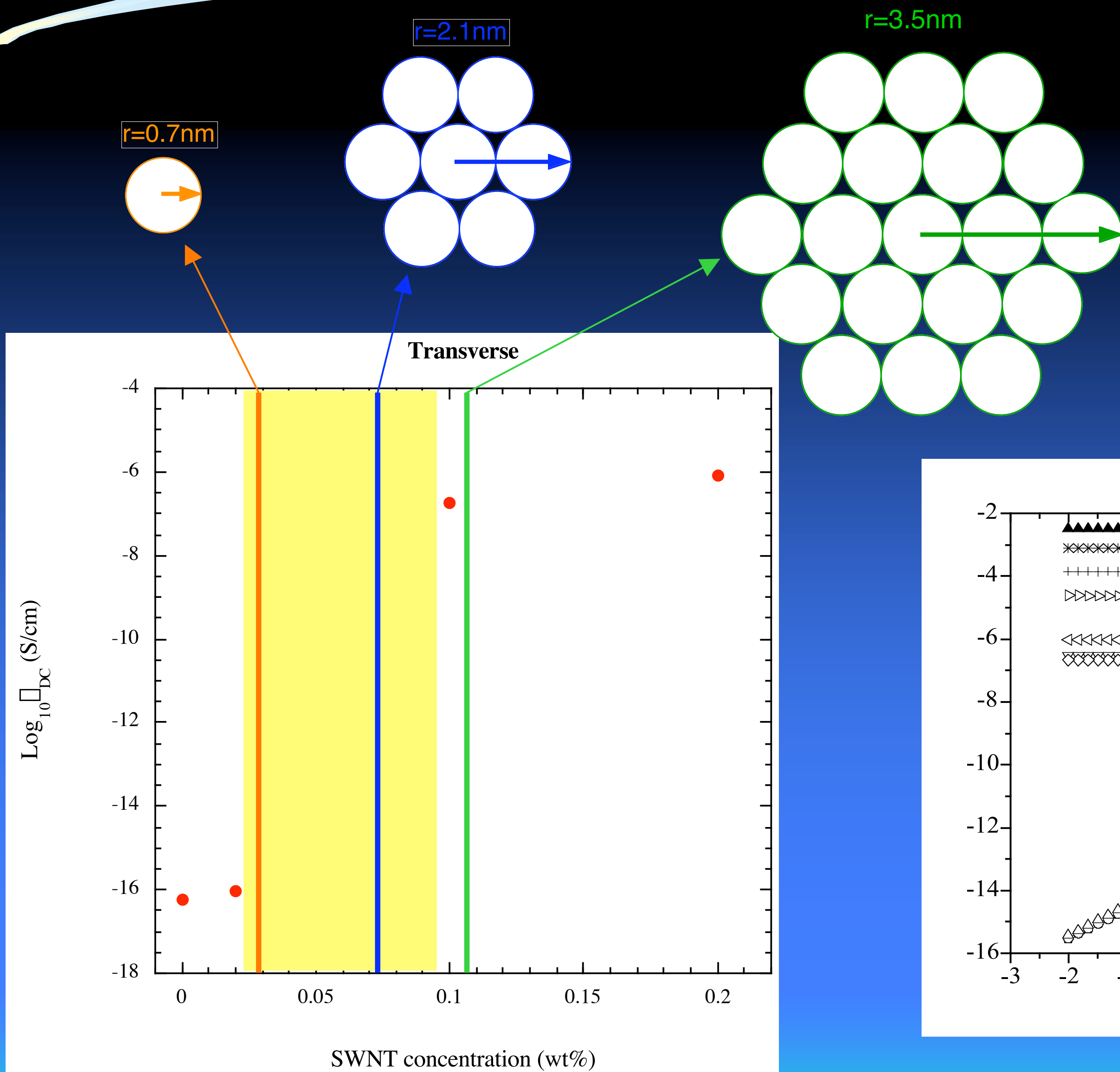


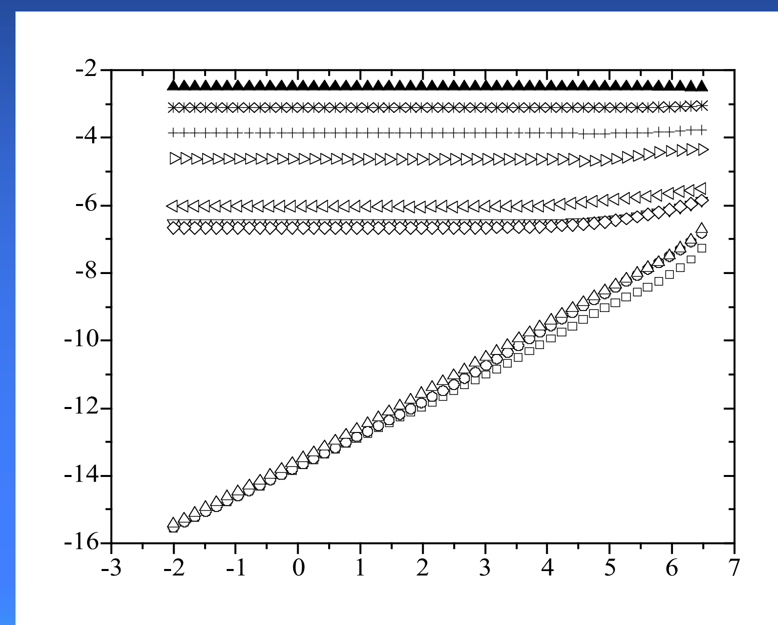


0.05%SWNT-CP2
Kinetically stable
After 2 years

0.05%SWNT-(b-CN)APB/ODPA
Thermodynamically stable
After 2 years

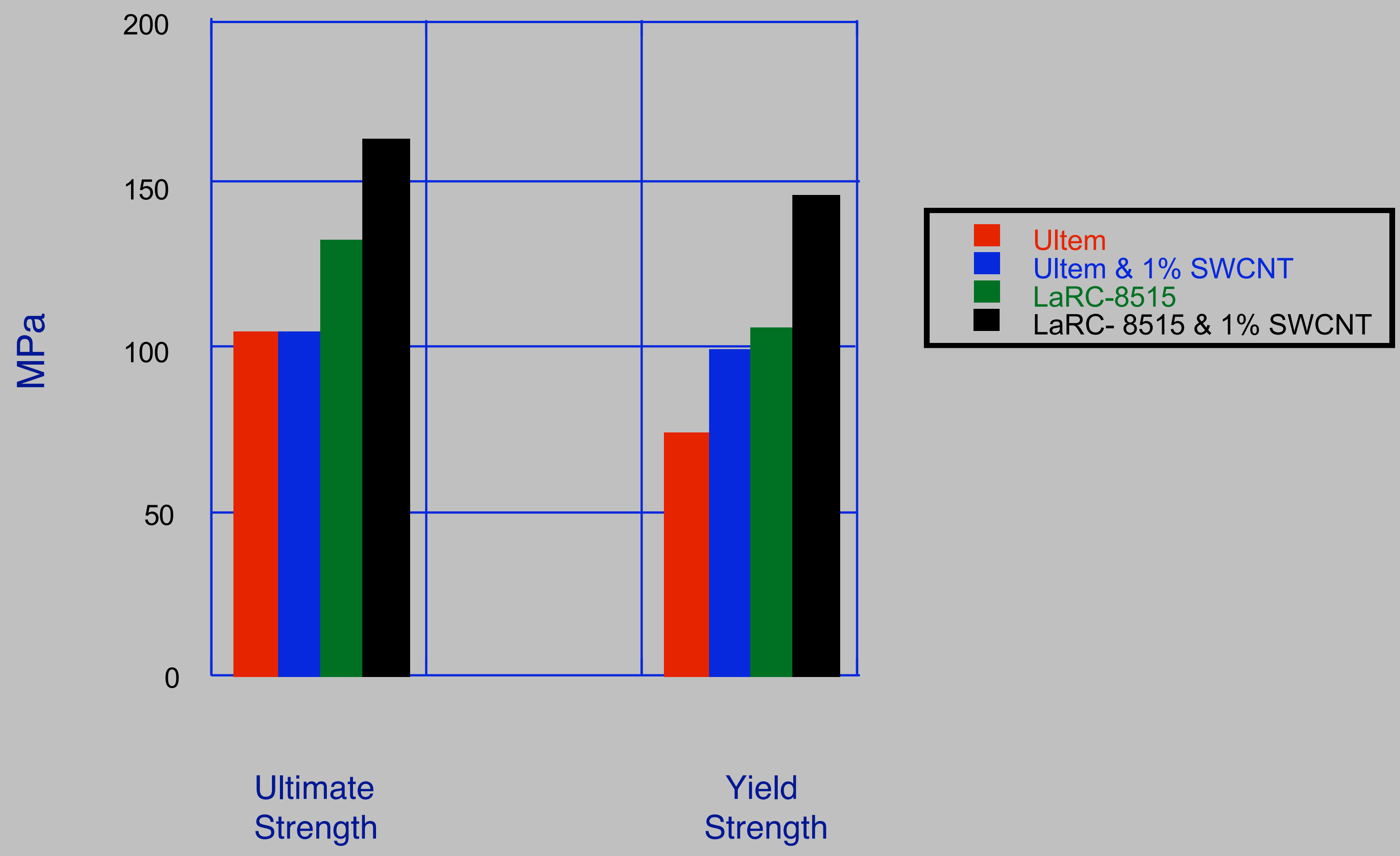
Dispersion Efficiency





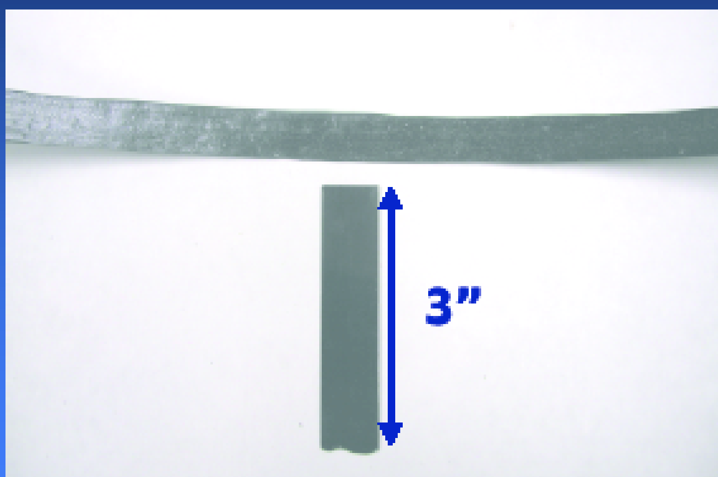
Ounaies et al., *Composites Sci. and Technol.* ASAP (2003)

Effect of CNT Reinforcement on Nanocomposite Fiber Strength



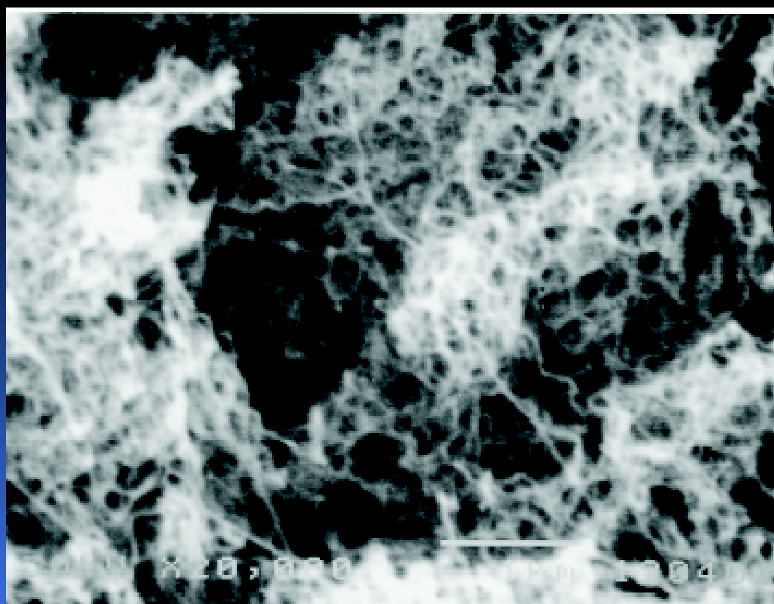
Fabrication of CNT Laminates and Composites

Laminate

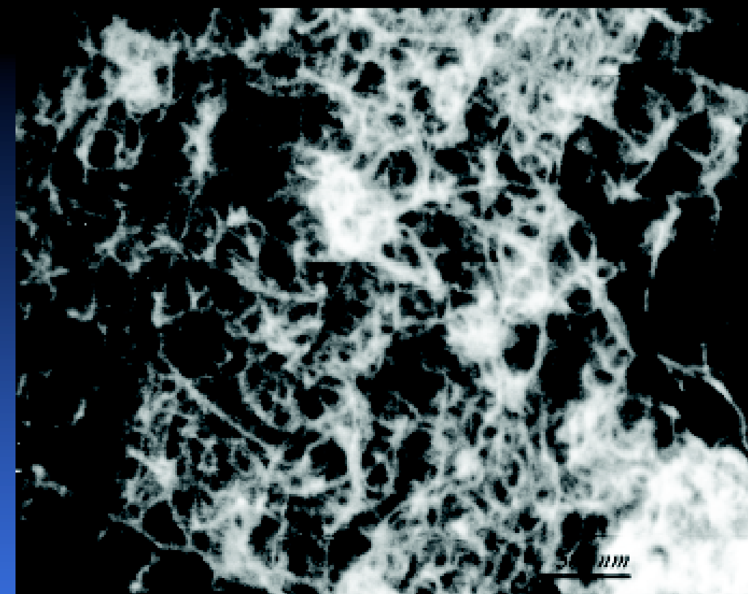


Composite

Both NiCo and NiY Work in FEL System



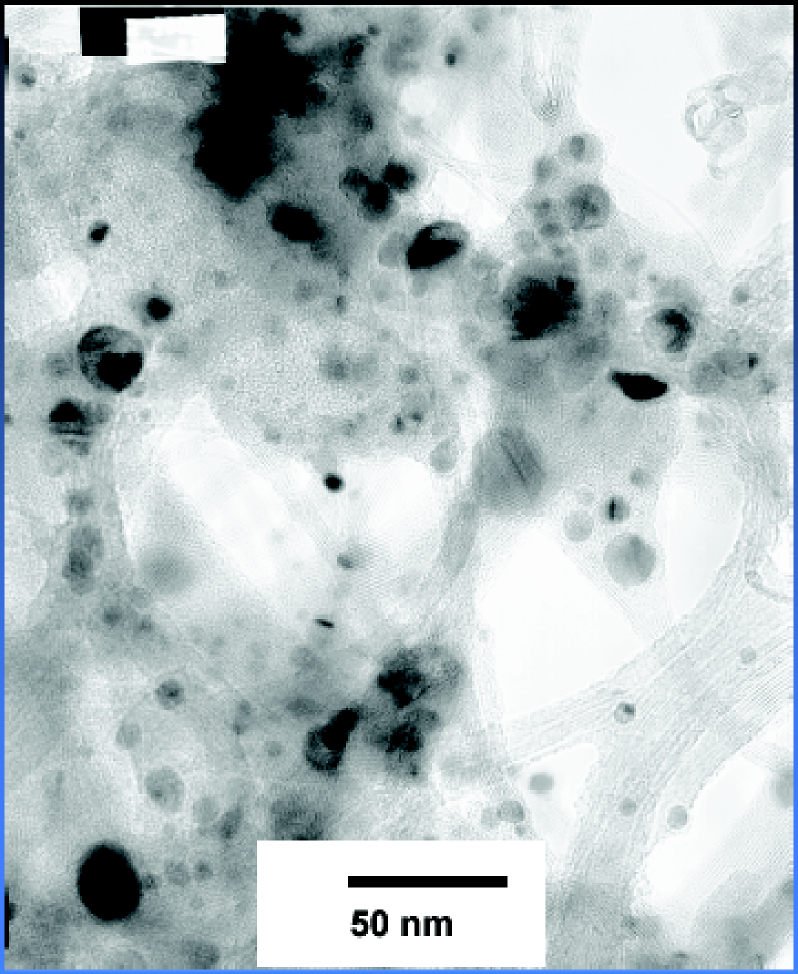
NiY (1:4 at. %) catalyst



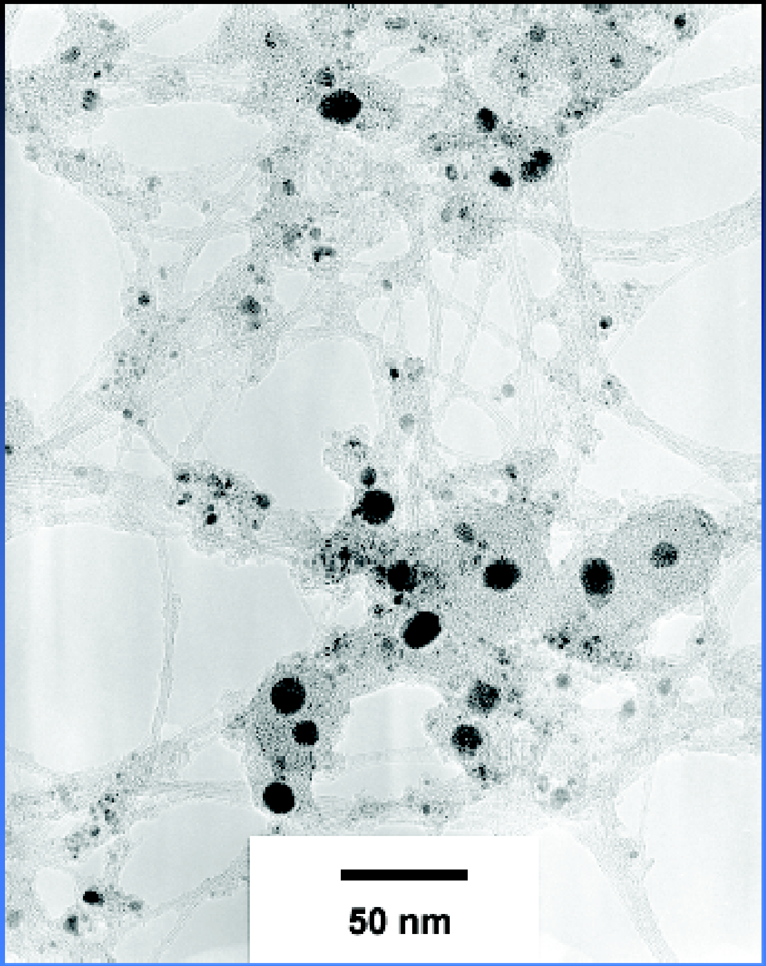
NiCo (0.5:0.5 at. %) catalyst

- Unusual for both types of catalyst to work in same system
- Both show relatively small, randomly oriented bundles
  - Bundle diameter for NiY are 4 – 10 nm
  - Bundle diameter for NiCo are 4 – 18 nm

TEM comparison, Nd:YAG (JSC) vs FEL Synthesized Raw Material

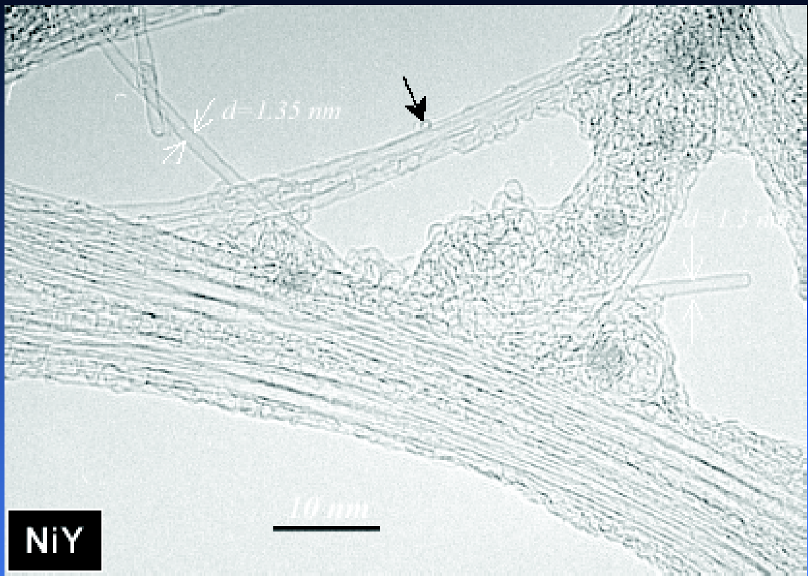


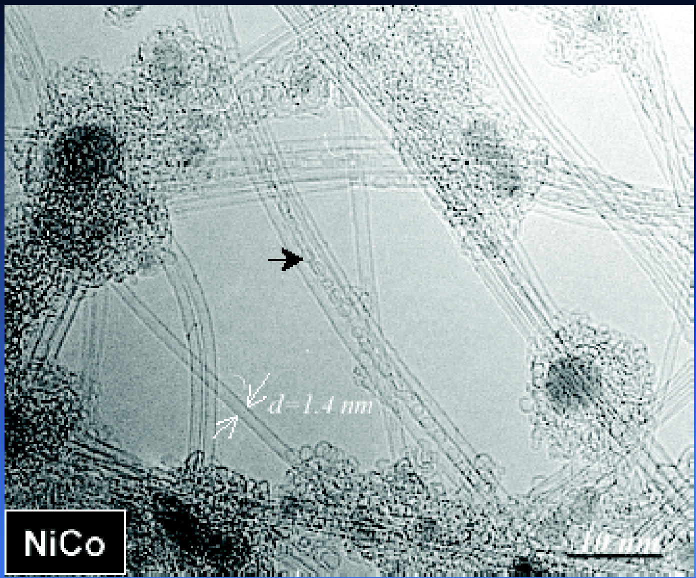
Nd:YAG laser



FEL

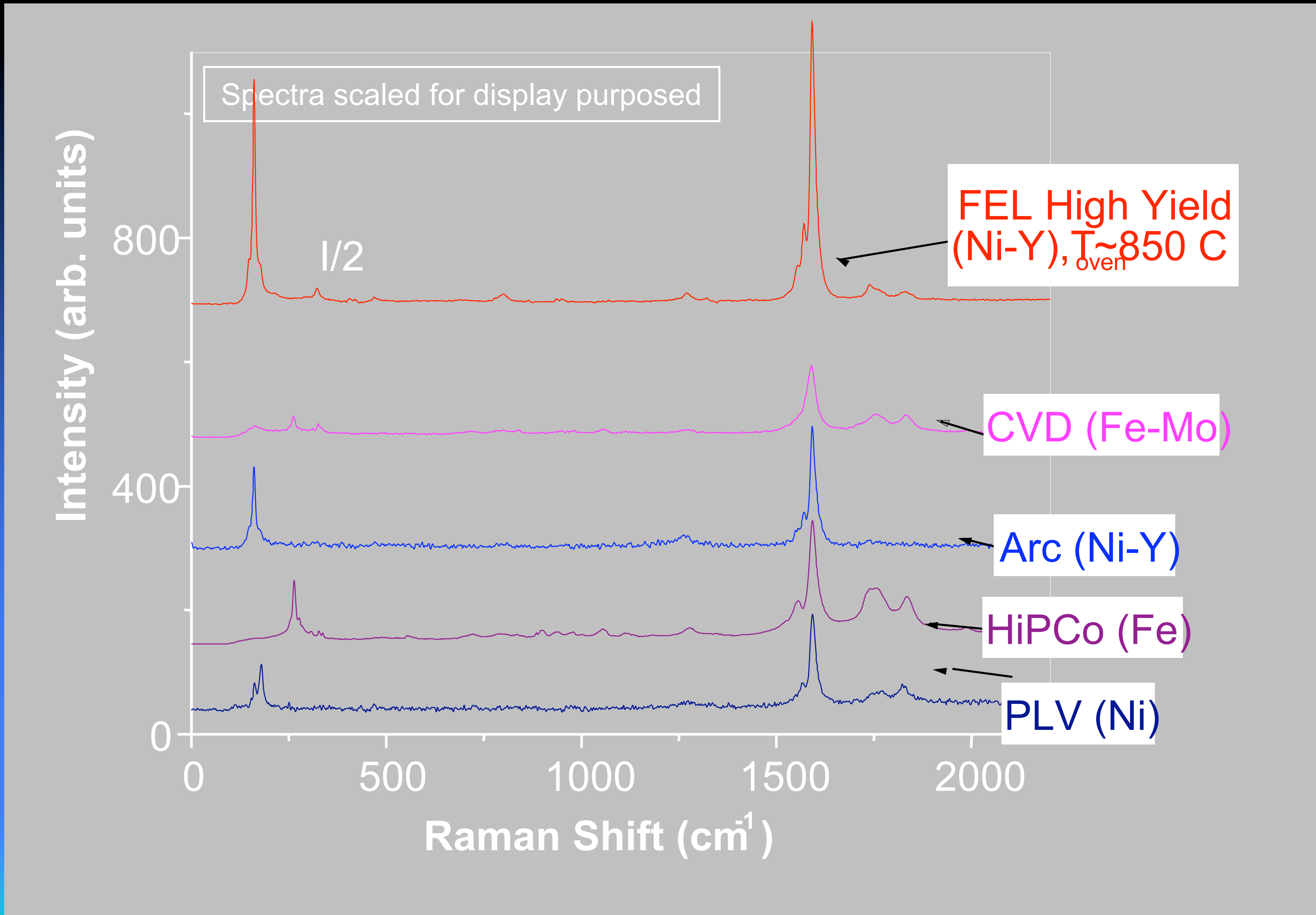
HRTEM Shows Bundles, Individual Tubes, & Peapods





- No double-wall or multi-wall tubes were observed
- Individual tubes and small bundles are seen
- Fullerenic carbon shells are observed outside and inside the nanotubes (peapods)

Raman Spectroscopy of FEL tubes vs other Synthesis Techniques



FEL CNTs Enable NASA Missions

- World record production rate for laser synthesis
  - from mg/hr rates, to g/hr rates
- Analysis shows superior material – Control is key
  - higher purity
  - fewer defects
  - longer bundles of smaller diameter
- First material delivered to users
  - favorable properties for matrix reinforcement
  - good dispersion in films