



Applied Nanotechnology for Human Space Exploration

Leonard L. Yowell
NASA Johnson Space Center

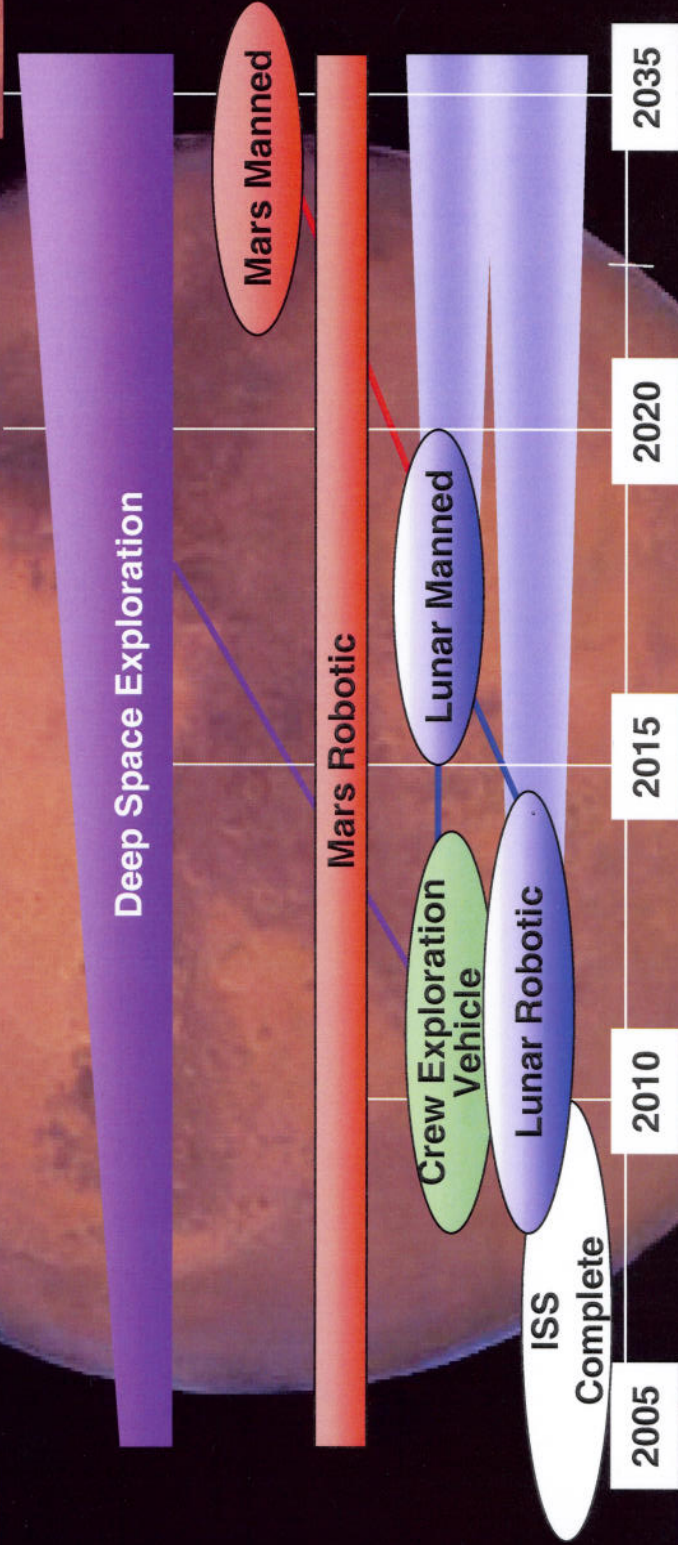
February 20th, 2007

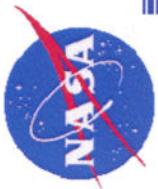
E-Mail: leonard.yowell-1@nasa.gov

Phone: 281-483-2811



NASA's Strategic Vision





Exploration Architecture



Launch Vehicles



Lunar / Interplanetary Transfer



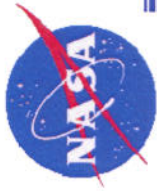
Crew Exploration Vehicle (CEV)
ISS Operations



Lunar Surface Operations



Planetary Operations
(Human/Robotic)



Future Exploration Mission Requirements Cannot Be Met with Conventional Materials

Vehicles and Habitats

- Reduced mass and volume
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multi-functionality
- Improved durability
- Environmental resistance
(dust, atmosphere, radiation)



EVA Suits

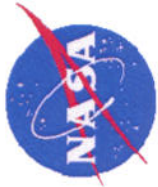
- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance



Satellites and Rovers

- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

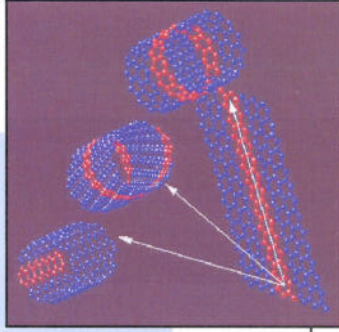




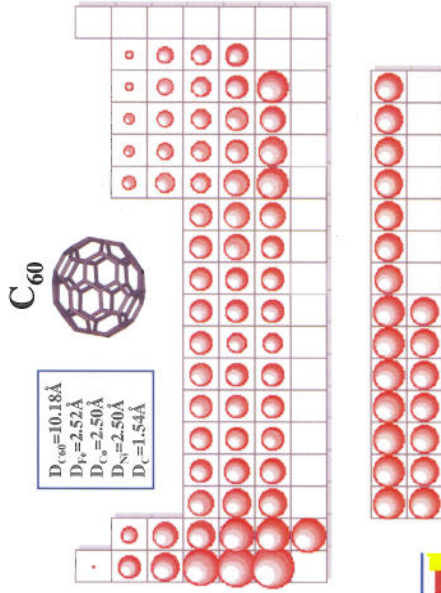
Nanomaterials: Single Wall Carbon Nanotubes

Unique Properties

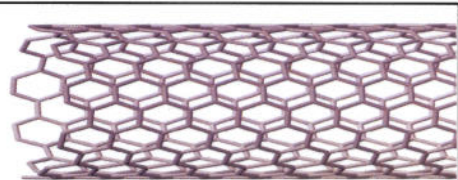
- Exceptional strength
- Interesting electrical properties (metallic, semi-conducting, semi-metal)
- High thermal conductivity
- Large aspect ratios
- Large surface areas



Size Comparison – C₆₀, Nanotubes, and Atoms



Single Wall Carbon Nanotube

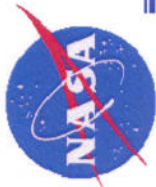


Possible Applications

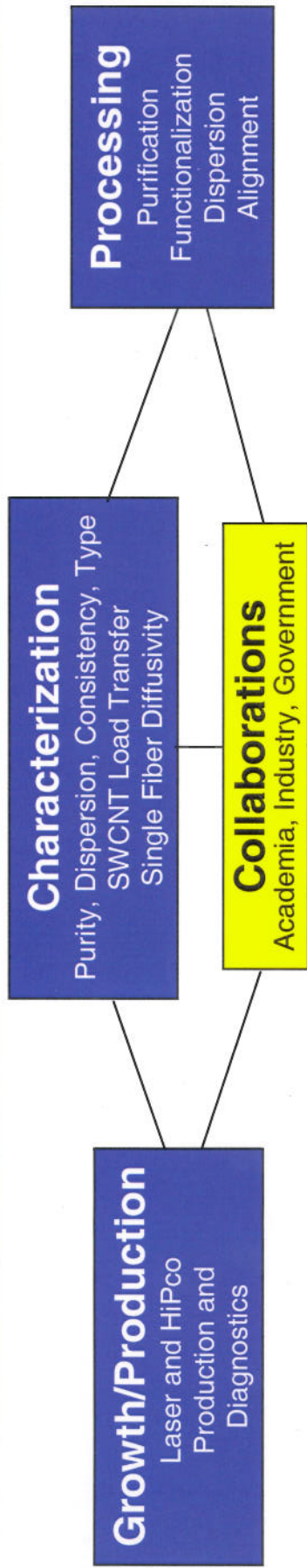
- High-strength, light-weight fibers and composites
- Nano-electronics, sensors, and field emission displays
- Radiation shielding and monitoring
- Fuel cells, energy storage, capacitors
- Biotechnology
- Advanced life support materials
- Electromagnetic shielding and electrostatic discharge materials
- Multifunctional materials
- Thermal management materials

Current Limitations

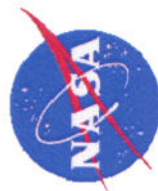
- High cost for bulk production
- Inability to produce high quality, pure, type specific SWCNTs
- Variations in material from batch to batch
- Growth mechanisms not thoroughly understood
- Characterization tools, techniques and protocols not well developed



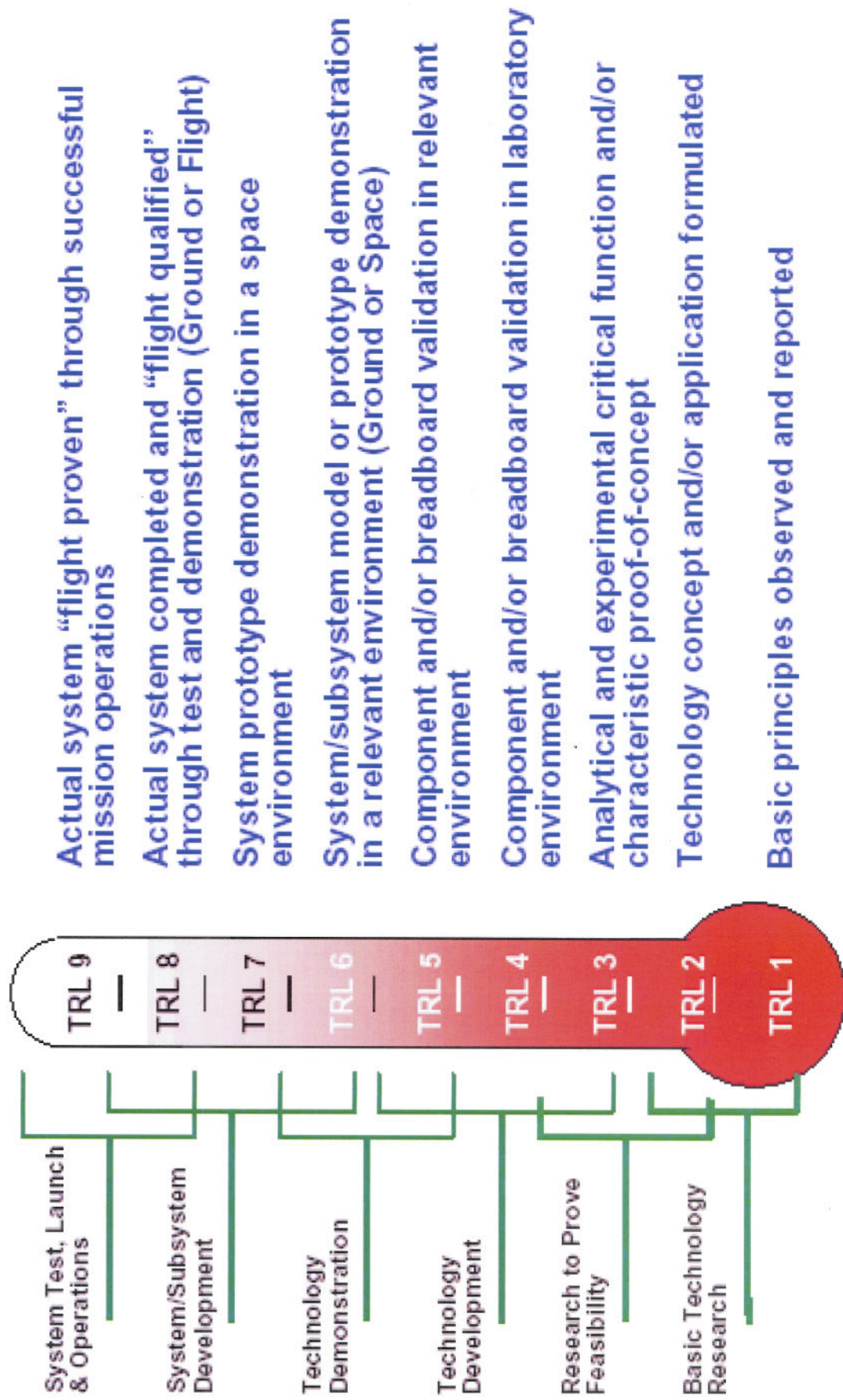
Applied Nanotechnology at JSC: Fundamentals to Applications

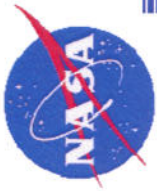


APPLICATIONS	PARTNERS					TRL				
	1	2	3	4	5	1	2	3	4	5
Supercapacitors	X	X	X	X		EP, GRC, Industry				
ESD / EMI Shielding	X	X	X			EV, OA, Rice, UTPA, UTD, Industry				
Regenerable CO ₂ Removal	X	X				EC, ARC, Rice, UTA Industry				
Proton Exchange Membrane – PEM - Fuel Cells	X	X				EP, GRC, Industry				
Water Disinfection & Recovery	X	X				EC, Industry				
Active / Passive Thermal Management Materials for Space	X	X				EC, Rice, Industry				
Multifunctional Materials: Thermal Radiation & Impact Protection (TRIPS)	X	X				ES3, ARC, Rice, Industry				
Nanotube-Based Structural Materials & Advanced Repair	X	X				EC, MA, ES3, Rice				
Radiation Dosimeter	X					NX, Rice, PV, Ames				



Technology Readiness Levels (TRL)





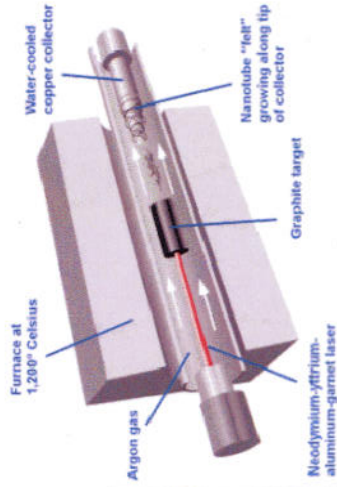
Growth, Modeling, Diagnostics, and Production

Objective: Ensure a reliable source of single wall carbon nanotubes with tailored properties (length, diameter, purity, chirality)

Laser Ablation

Graphite $\xrightarrow[\text{argon}]{\text{Co, Ni Catalysts } 4000\text{-}5000 \text{ K}}$ fullerenes + SWCNT + impurities

- Batch process
- ~1g/day
- Large diameters (~1.4nm)



High Pressure CO (HiPCO)

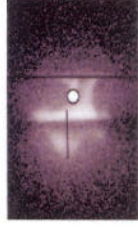
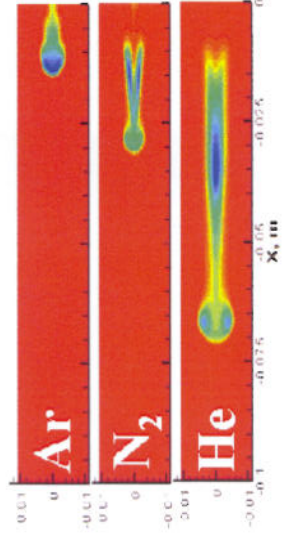
CO + CO $\xrightarrow[10\text{-}40 \text{ atm}]{\text{Fe, Ni Catalysts } 900\text{-}1200\text{C}}$ CO₂ + SWCNT + impurities

- Continuous process
- 10-100's g/day
- Small diameters (0.9nm)
- Company spin-off (CNI)

Rice Univ. & NASA \rightarrow Carbon Nanotechnologies, Inc.



Modeling, Diagnostics, and Parametric Studies





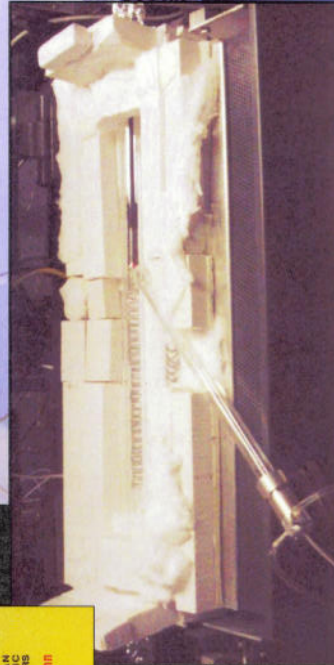
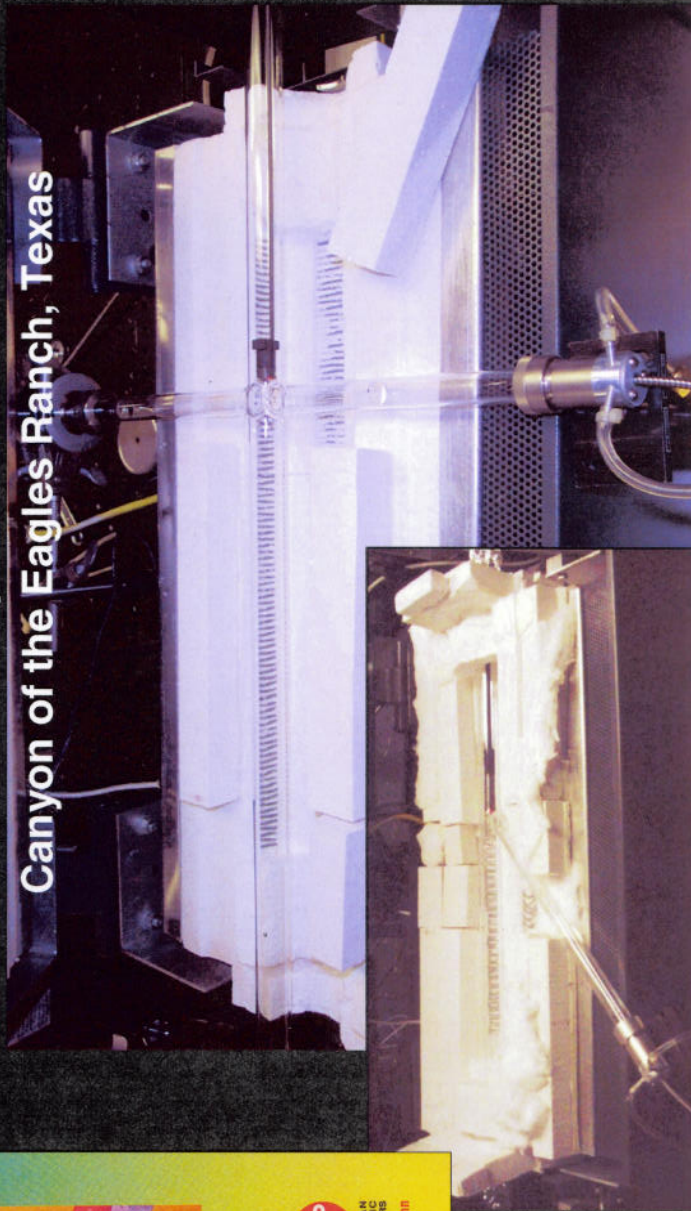
Growth, Modeling, Diagnostics and Production



NASA / Rice University

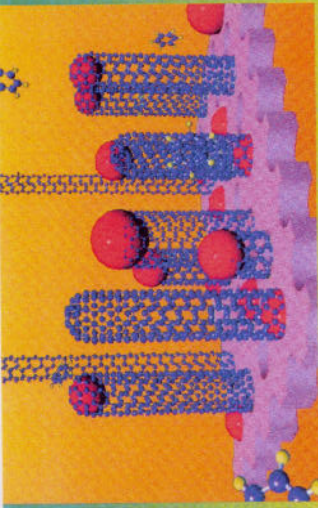
3rd Single-Wall Nanotube Growth Mechanisms Workshop
April 2007

Canyon of the Eagles Ranch, Texas



Volume 4 Number 4
April 2004

Journal of
Nanoscience and Nanotechnology

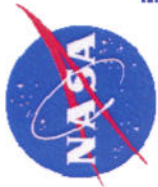


A Special Issue on
Single-Walled Carbon Nanotubes Growth Mechanisms

GUEST EDITORS
Carl D. Scott and Sivaram Arepalli

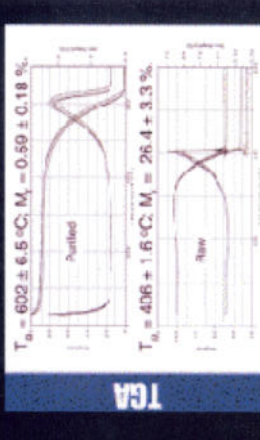
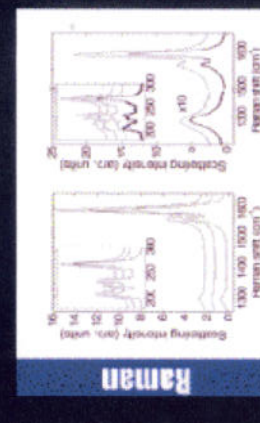
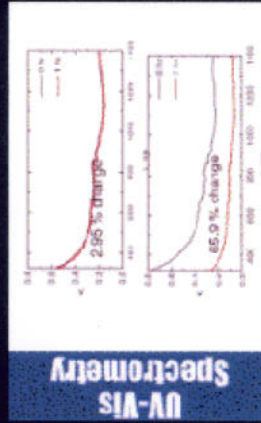
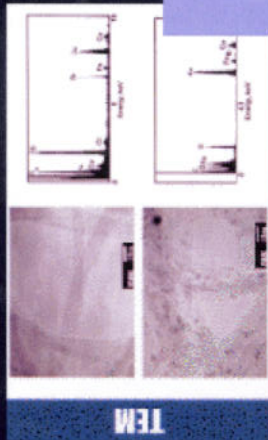
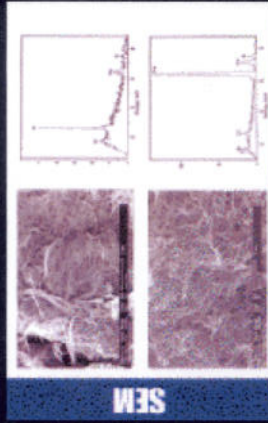
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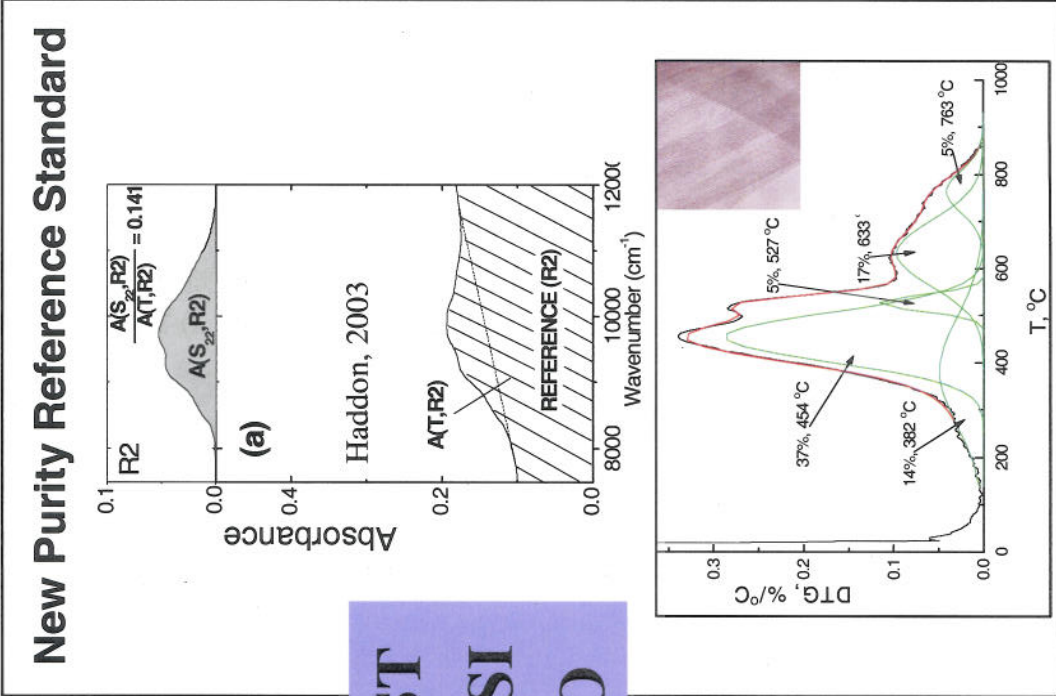


Characterization: Purity, Dispersion & Consistency

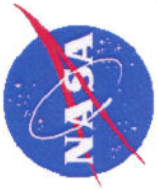
Standard Nanotube Characterization Protocol



NIST
ANSI
ISO

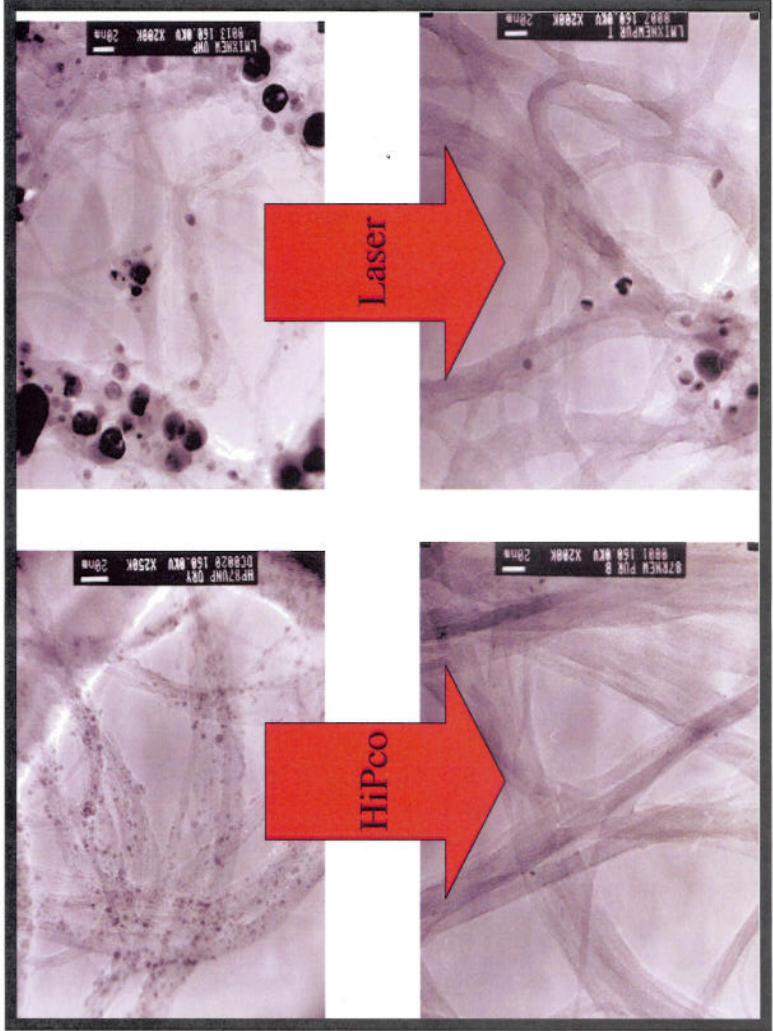
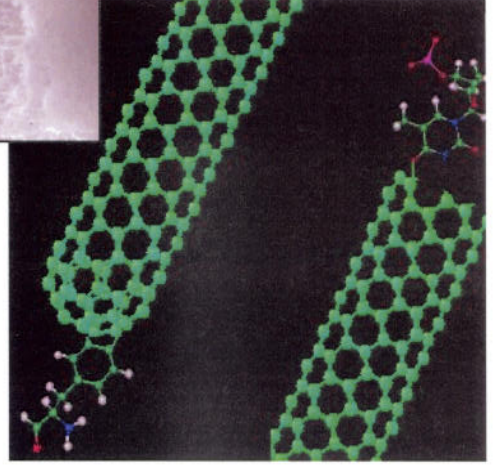
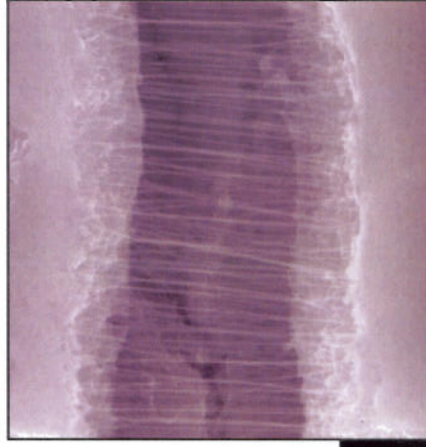
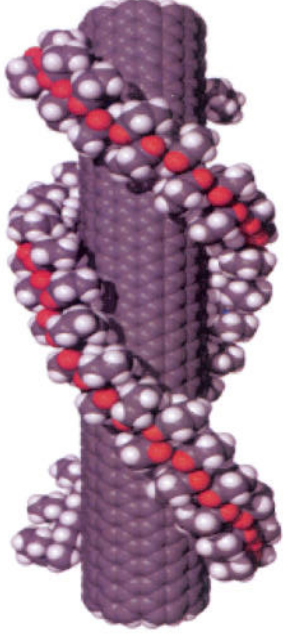


Arepalli, et al., Carbon, 2004



Processing

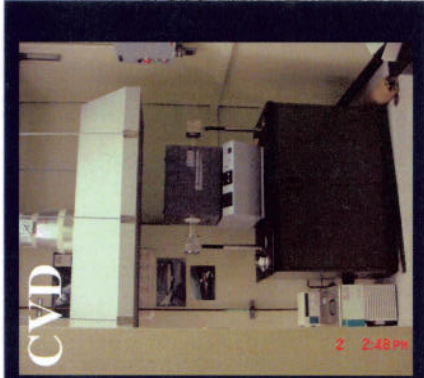
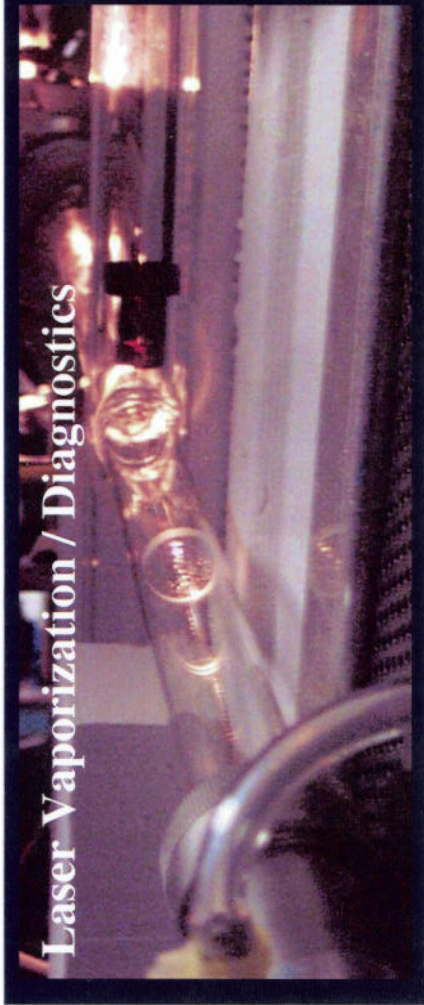
- * Dispersion
- * Purification
- * Functionalization
- * Alignment
- * Surface Area





Nanoelectronics: Enabling Technologies

Nano-Fabrication

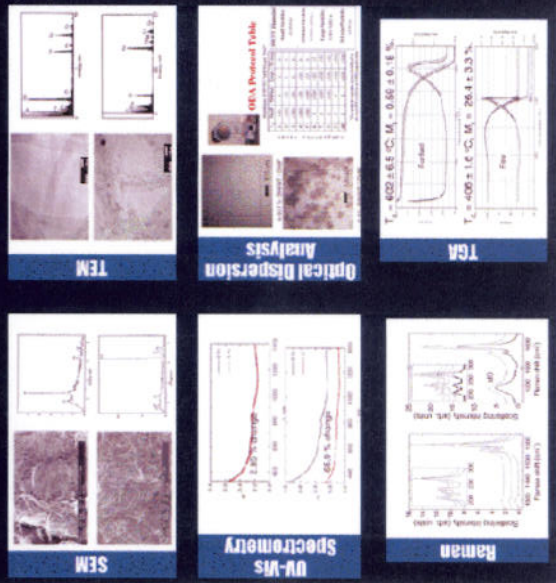


(10,10) Armchair Tube

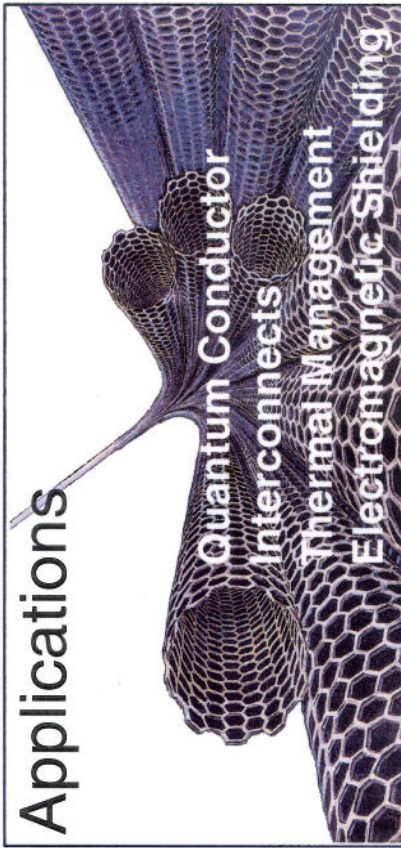


Nano-Characterization

Standard Nanotube Characterization Protocol

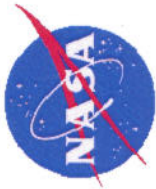


Type-Specific Nanotube Synthesis



Chirality Assessment





Applications for Human Space Exploration

Multi-functional /

Structural Materials

- Primary structure (airframe)
- Inflatables

Advanced Life Support

- Regenerable CO₂ Removal
- Water recovery

Power / Energy Storage

Materials

- Proton Exchange Membrane (PEM) Fuel Cells
- Supercapacitors / batteries

Thermal Protection and Management

- Ablators and ceramic nanofibers
- TPS repair materials
- Passive / active thermal management (spacesuit fabric, avionics)

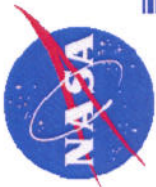
Electromagnetic / Radiation

Shielding and Monitoring

- ESD/EMI coatings
- Radiation monitoring

Nano-Biotechnology

- Health monitoring (assays)
- Countermeasures

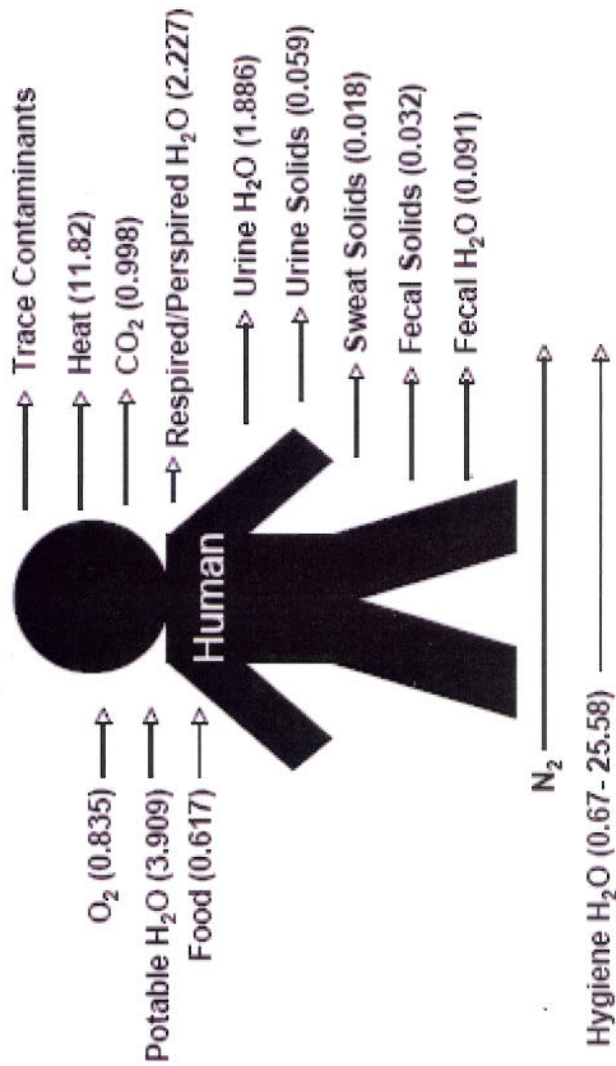


Exploration Life Support

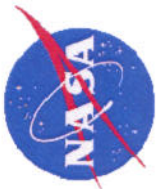
CHALLENGE:

Supply the daily needs of humans for long duration missions

- Air Revitalization
- Food Management
- Solid Waste Management
- Thermal Control
- Water Reclamation



Human consumable and throughput values
in kg/crewmember/day Klaus et al, 2005



Exploration Life Support: Atmosphere Revitalization System

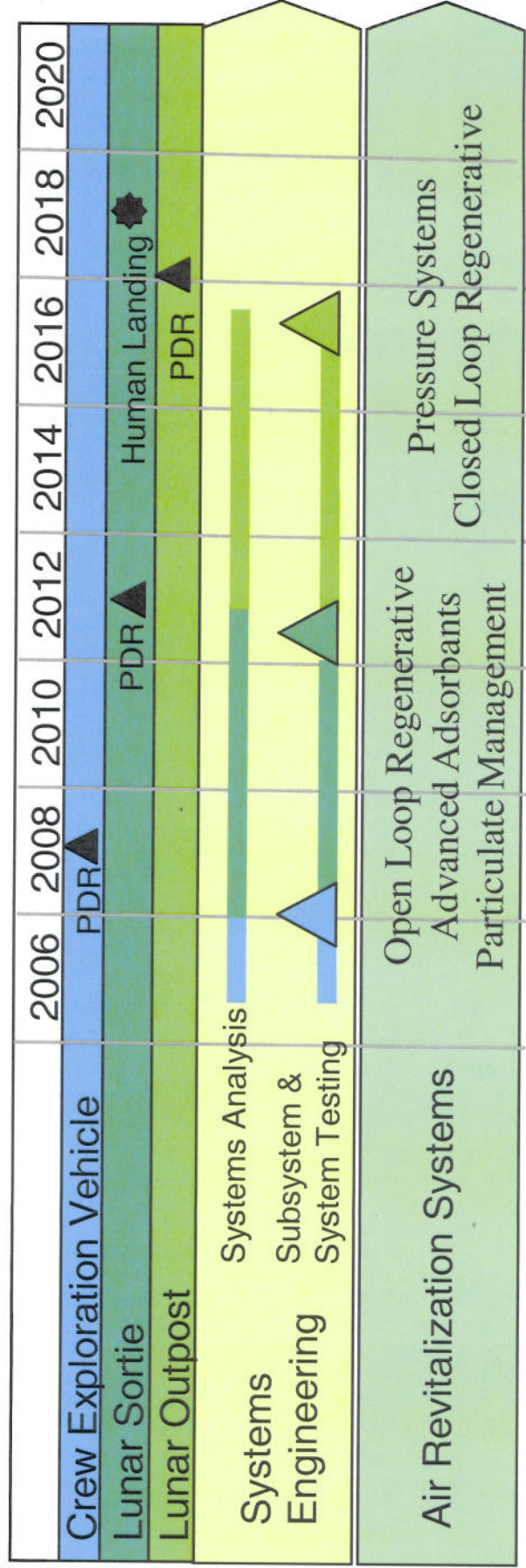
MISSION:

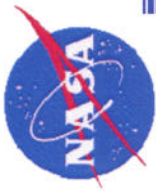
- Vehicle cabin atmospheric pressure & quality
- Atmospheric gas storage, supply and distribution
- Carbon dioxide partial pressure control
- Trace contaminant & particulate control
- Resource recovery, storage and distribution
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety



LiOH Canisters

Experimental
Regenerable System





Advanced Life Support: Regenerable CO₂ Removal

CHALLENGE:

- Long duration space flight requires a regenerable system for air revitalization
- NASA need: lower mass, higher performance, reduced volume

SOLUTION:

- Carbon Nanotubes: superior surface area & thermal conductivity
- Functionalized with CO₂ scrubbing chemistry – less volatile
- Suitable for both EVA and vehicle applications
- Applicability to smokestack applications on Earth

COLLABORATION:

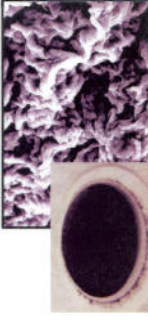
- Rice University: Nanotube functionalization
- UTA: Primary amine chemistry
- JSC (EC): Requirements for space systems
- NASA Ames: Nanomaterials for trace contaminant control system & CO₂ Sensors
- Energy industry participation interest



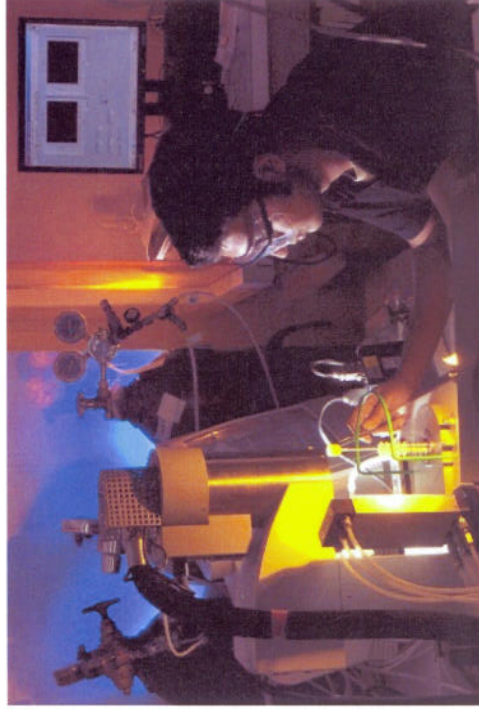
Current RCRS materials:
Zeolites and amine-coated polymer beads.



To be replaced by



Single Wall Carbon Nanotube (SWCNT) Structure

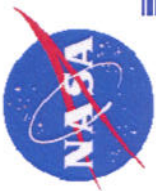


Micro-scale testing with thermo-gravimetric analysis



RICE

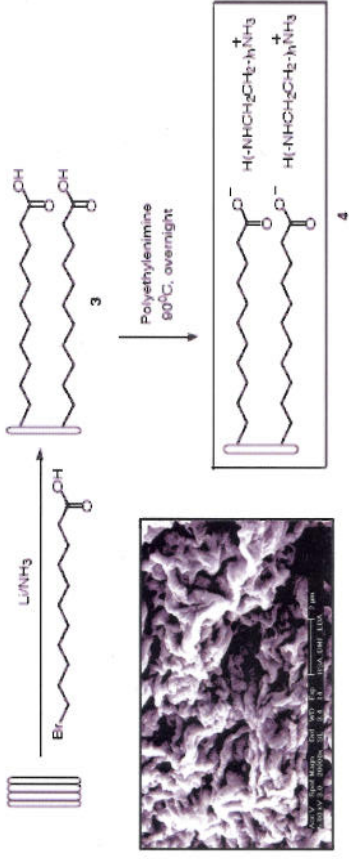




Exploration Life Support: Regenerable CO₂ Removal

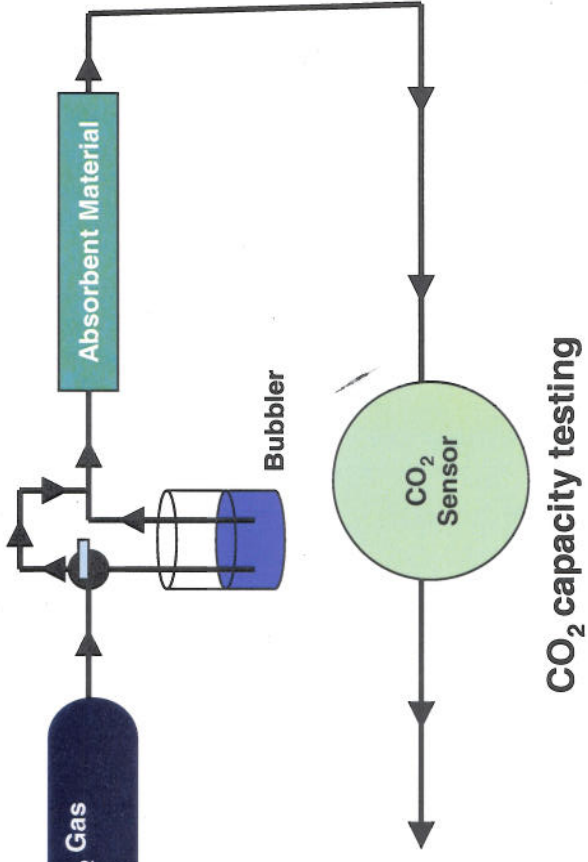
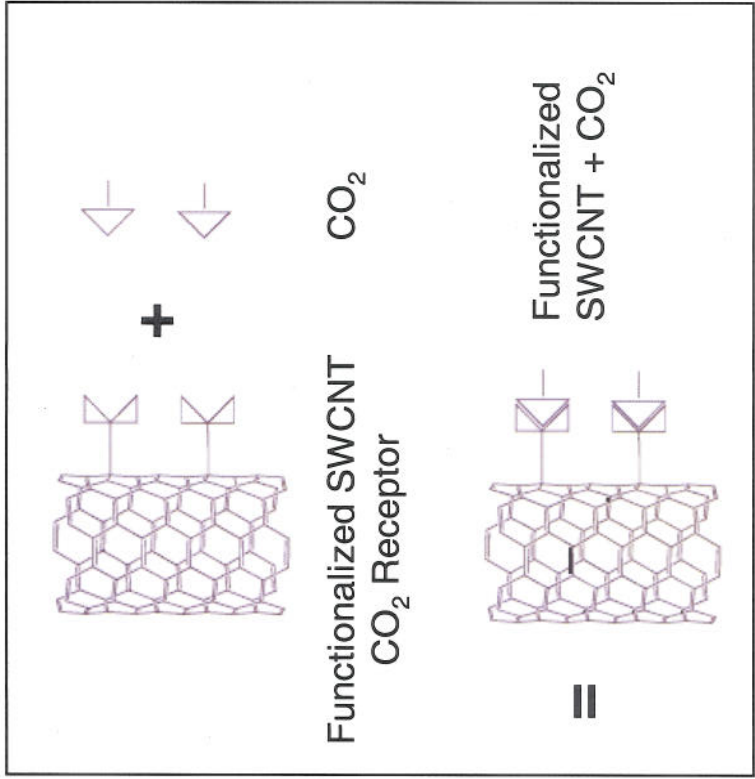
NanoMaterial Solution:

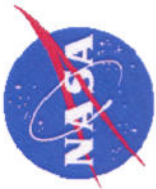
- Use SWCNT functionalized with CO₂/H₂O scavenging amines
- Amines require lower energy for regeneration than present molecular sieve
- Higher surface area reduces system size/ weight



Nanotube functionalization chemistry

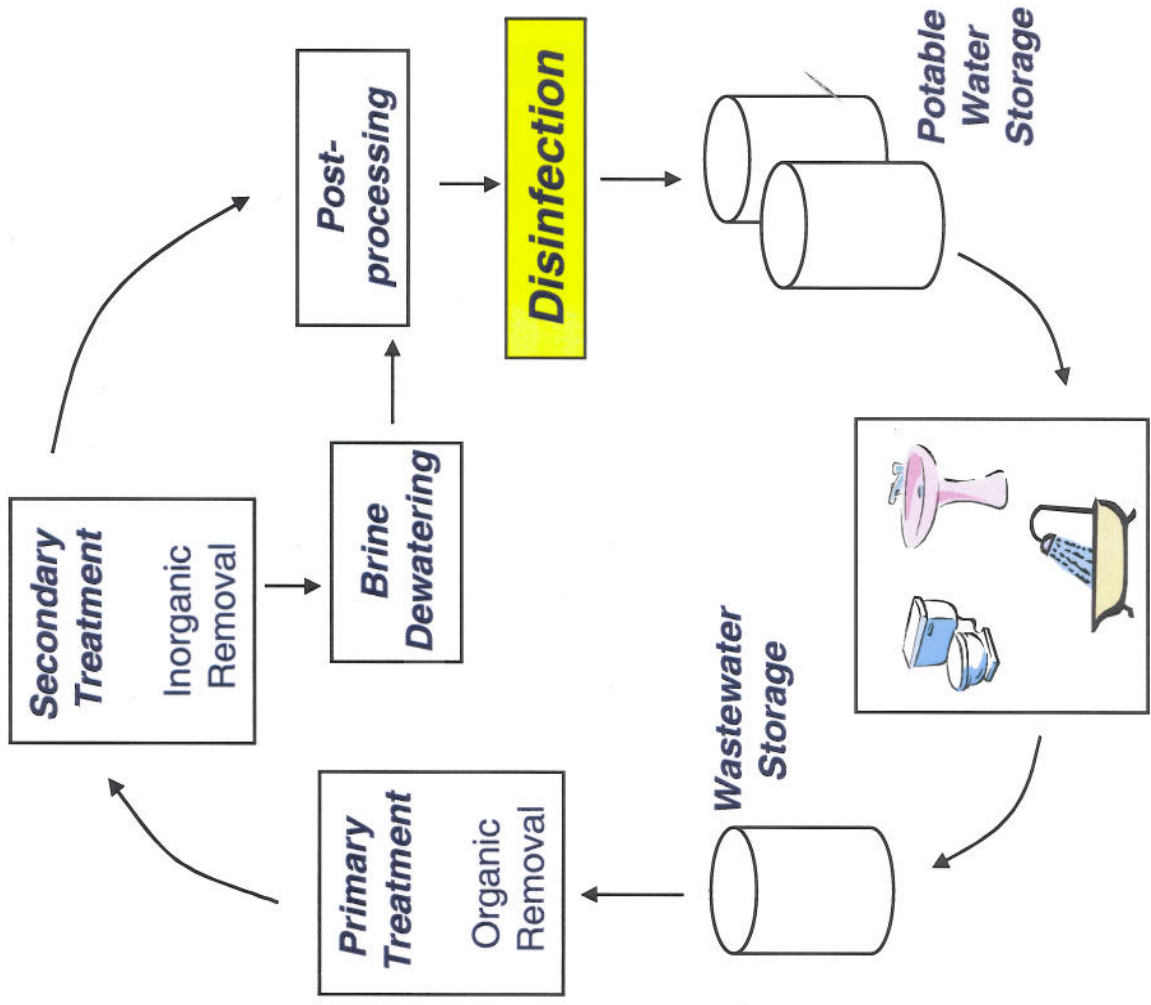
(Chattopadhyay et al, 2005)





Exploration Life Support: Water Recovery

- Transport and storage of wastewater from human interfaces
- Primary processing: organic and nitrogenous contaminant reduction
- Secondary processing: inorganic contaminant reduction
- Brine dewatering: water removal from highly concentrated brine
- Post-processing and disinfection: polishing to meet potability standards
- Storage and transport of potable water prior to consumption





Advanced Life Support: Water Disinfection / Recovery

CHALLENGE:

- NASA requires renewable chemical-free systems to purify water in space
- Current solution: Iodine – toxic to astronauts and non-regenerable

SOLUTION:

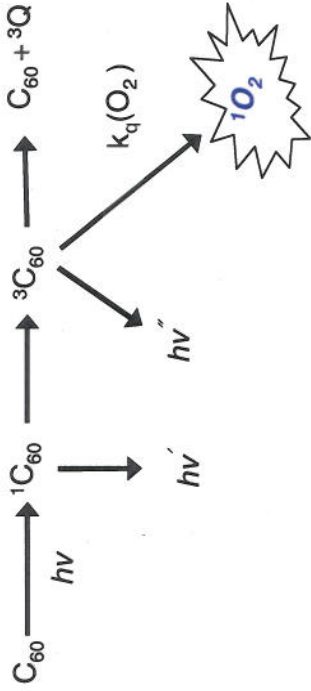
- C_{60} /fullerene enhances disinfection property of UV light
- Singlet oxygen production enhances the rate at which bacteria are killed
- Chemical-free system for closed loop water purification
- Commercial Potential - Portable water disinfection devices

COLLABORATION:

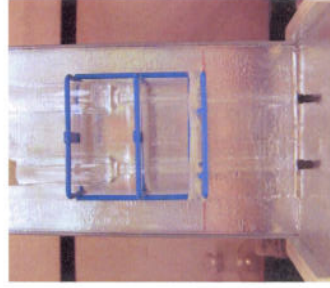
- NASA JSC Advanced Life Support (EC)
- Rice University: C_{60} deposition



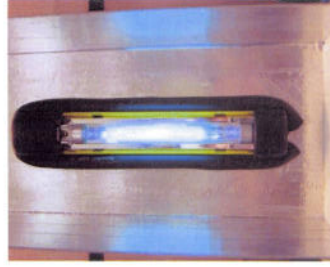
RICE



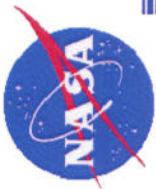
UV light energizes fullerenes. Upon relaxation, photons are emitted and the excited fullerenes interact with oxygen molecules in water to produce singlet oxygen. *Singlet oxygen kills bacteria.*



Water purifier cell



UV Light source



Power & Energy: Supercapacitors

CHALLENGE:

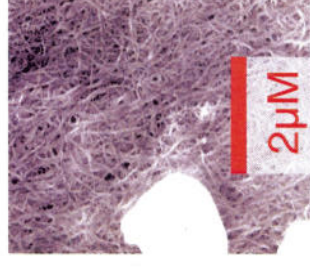
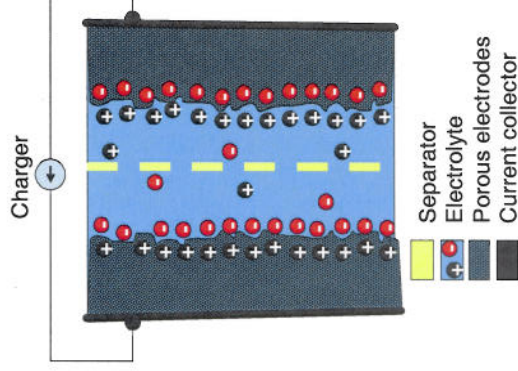
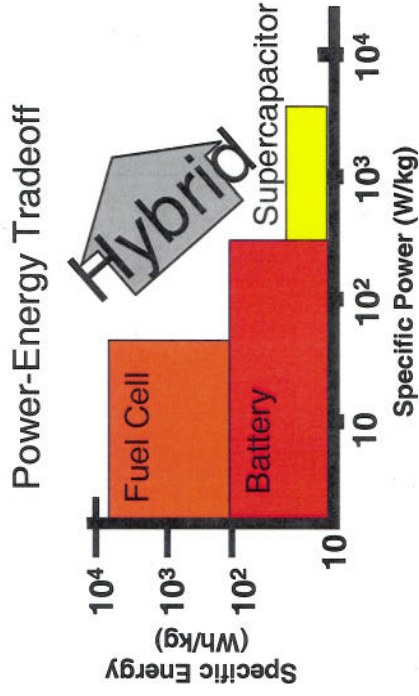
- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

SOLUTION:

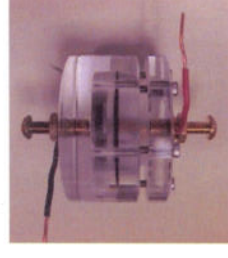
- Carbon nanotube surface area and nanoporosity superior to current materials for electrolyte ion support
- Carbon nanotube electrolyte supports: enhanced electrical and thermal conductivity
- Potential for enhanced performance and longer cycle life

COLLABORATION:

- NASA Glenn: Separator materials
- JSC (EP): Requirements
- Georgia Tech: Functionalized nanomaterials
- ReyTech Corp.: Improved fabrication & packaging

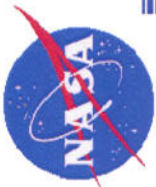


Nanotube electrolyte support



Supercapacitor test cell





Power & Energy: Fuel Cells

CHALLENGE:

- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

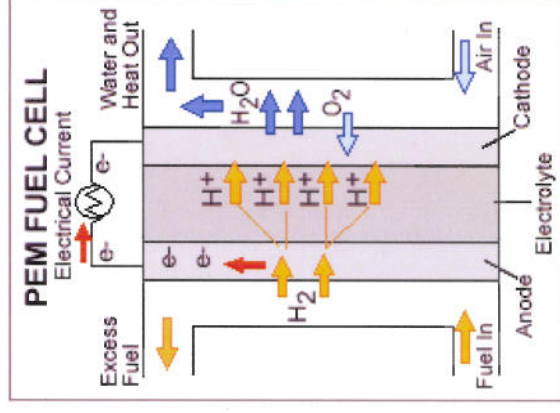
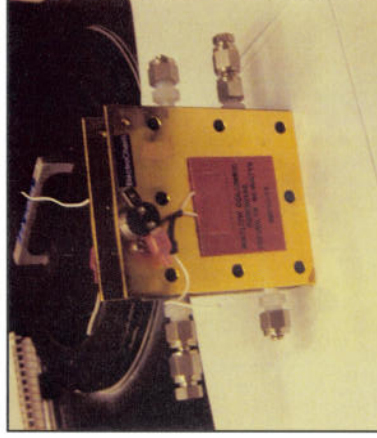
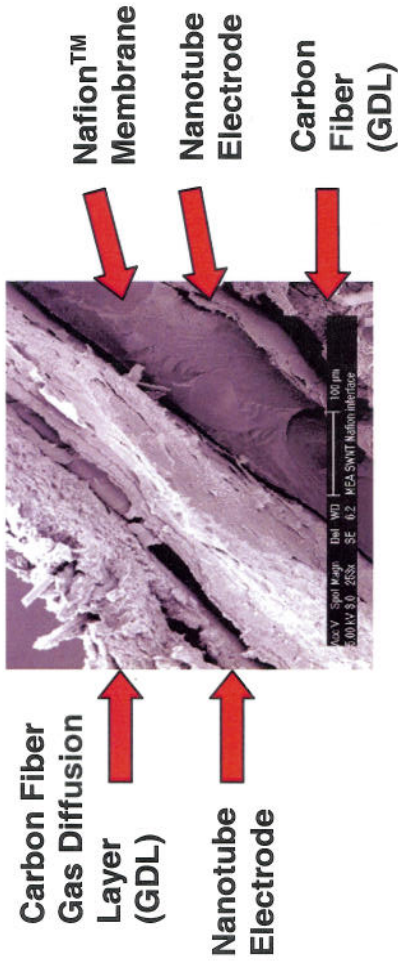
SOLUTION:

- Novel carbon nanotube high surface area, high thermal & high gas diffusivity catalyst support
- Reduced activation polarization – increased reliability
- Higher power density from more efficient utilization of platinum catalysts

COLLABORATION:

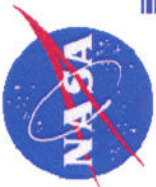
- NASA Glenn: High temperature membranes
- JSC (EP): Testing, requirements

Prototype Membrane Electrode Assembly



PEM Fuel Cell Schematic

(Dept. of Energy)



NanoMaterials for EMI Shielding

CHALLENGE:

- Control of electromagnetic emission and susceptibility characteristics of electronic, electrical and electromechanical equipment and subsystems for space exploration

SOLUTION:

- Single-wall carbon nanotubes (SWCNT) offer low material density and high electrical conductivity
- Can be integrated into polymer matrices as well as applied onto surfaces as thin **transparent** coatings
- Cheap & ease of fabrication for application to off-the-shelf products: Laptops, PDAs etc.

COLLABORATION:

- UTD: Nanotube materials
- UTPA: EMI testing & test development
- U of Florida: Nanomaterials functionalization
- Rice: Nanomaterials functionalization
- JSC (EV): Testing, requirements



Translucent Appliqués: Potential coatings for LCD screens

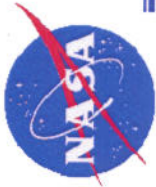


EMI testing in collaboration with UTPA



RICE





Active Radiation Dosimeter

CHALLENGE:

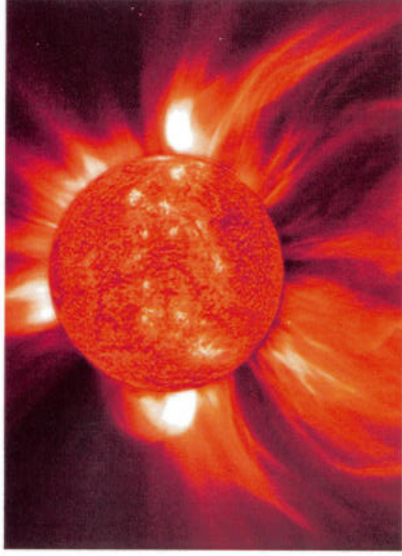
- Acute radiation sickness poses a risk to astronaut health for interplanetary travel
- Currently no “real-time” personal radiation detecting sensor for extravehicular activity
- Current technologies lack desired sensitivity

SOLUTION:

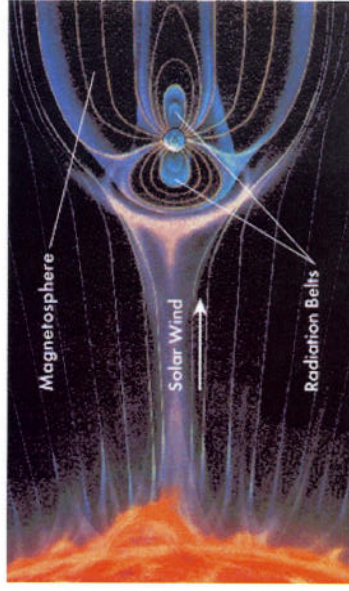
- Use radiation sensitive functionalized SWCNTs to measure radiation dose rates and total dose.
- High surface area nanomaterials can increase sensitivity

COLLABORATION:

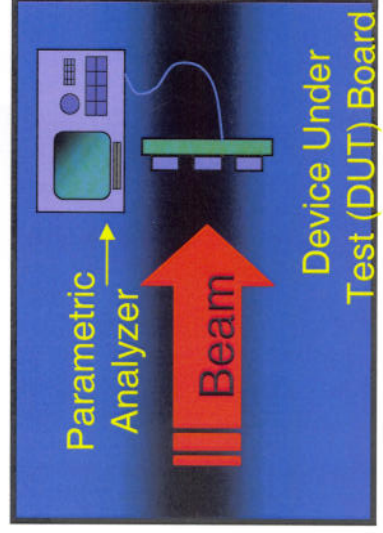
- JSC (SF) Dosimeter
- JSC (EB) Sensors
- JSC (EC) Advanced EVA
- NASA Ames Gas sensors
- Rice Univ. Nanotube functionalization
- PVAM Radiation Testing



Solar Particle Event



Earth's Protection





Advanced Thermal Protection System (TPS) Repair

CHALLENGE:

- Improve and expedite curing and repair processes for current missions
- Long duration missions need more effective repair processes: On Orbit/En Route/On the surface

SOLUTION:

- Use microwave energy to heat nanotubes in polymer and ceramic matrices for localized heating, curing & bonding
- Repair of RCC and tiles, CEV materials
- Potential commercial applications including composite curing

COLLABORATION:

- Rice: Nanotube microwave research (Tour) Functionalized nanomaterials



↑
700 W
2.45 GHz
↑

SWCNTs in UHV tube
during irradiation

Room lights off

~ 1:1 Energy transfer in nanotubes

Microwaves:Heat



RICE



Thermal Radiation & Impact Protection (TRIPS)

CHALLENGE:

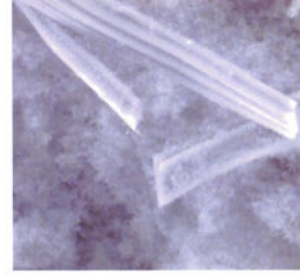
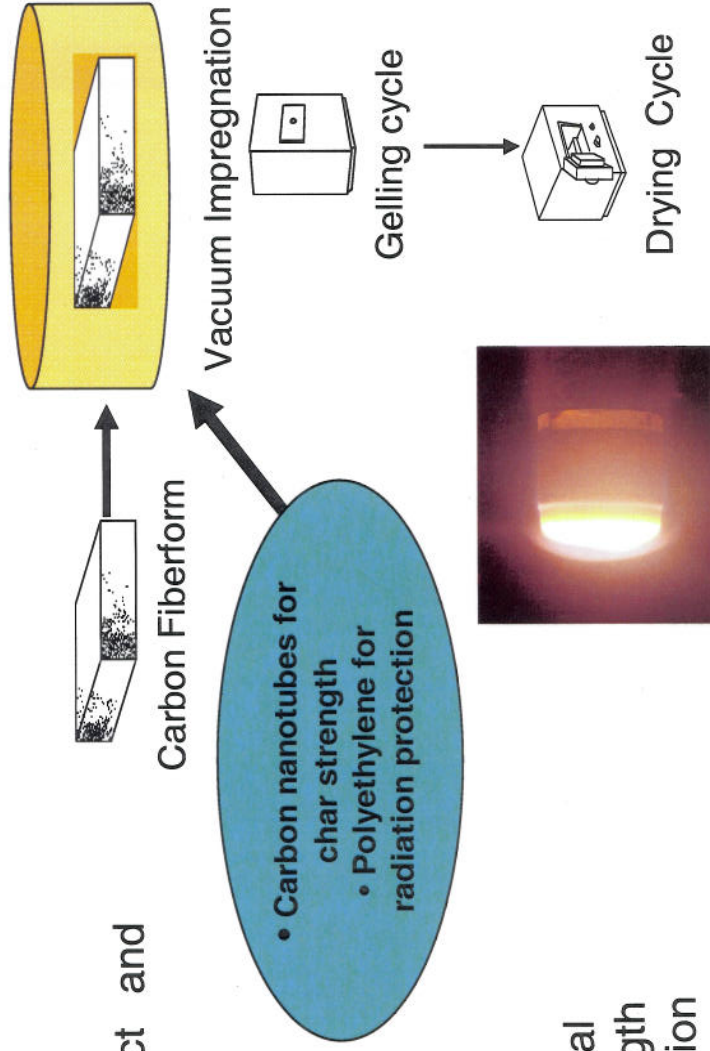
- Thermal protection system with impact and radiation protection
- Lower weight = Greater performance
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety

SOLUTION:

- Use SWCNT impregnated into Phenolic Impregnated Carbon Ablator (PICA) Thermal Protection System (TPS) – additional strength of polyethylene
- Nextel and/or Kevlar fabric incorporated for impact protection

COLLABORATION:

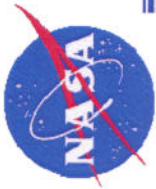
- NASA Ames: TPS Lead
- JSC (ES3): Composites, Arc Jet Testing



PICA with phenolic resin impregnated



PICA - Fiberform before impregnation



Nanotechnology: Astronaut Health Management

Basic Biomedical Research

- The role that forces play on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

Major Medical Operations

- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

Personal Biomedical Monitoring

- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

Life Support

- High surface area materials for CO₂ removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor/gases

Personal Countermeasures

- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

Toxicology & Ethics

- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

Systems Integration

- Develop 'common toolkit' for bio-nano chemistry and assembly processes

JSC Nanomaterials Group Collaborations



Government

NASA Langley Research Center
• Production / purification (JSC) for use in SWNT composites (Stochi, Park, Smith)

NASA Ames Research Center
• Nanotubes (JSC) for sensors / modeling of HiPco (Meyyappan, Shrivastava)

NASA Glenn Research Center
• Functionalization, purification, high temp. mat'ls (Meador, Gray)

NASA Marshall Space Flight Center
• Nanotubes, IMCs (Gill, Hudson)

Los Alamos National Lab
• Purification (O'Connell)

National Institute of Standards and Technology
• Development of nanoscale measurement standards (Frieman)

Central Intelligence Agency
• Nanotube characterization (Carr)

Air Force Research Lab.
• Composites, characterization, purification (Maruyama, Strong)

Naval Research Lab.
• Composites (Imam, Petrason)

National Institute for Occupational Safety and Health
• Nanotube toxicology studies (Shvedova)

Academia

NASA-URETI: Texas A&M, Rice, UT Arlington, TSU, PrairieView A&M and UH
• Nanotube characterization
• Radiation protection
• Mechanics / composites

Michigan Tech
• Summer Faculty Fellow - Composites (Cameba)

UC Riverside
• Purification / characterization (Haddon)

University of Paris 13
• Arc process (Farhat)

University of Florida
• Isolated SWNTs (Rinzler)

Northwestern
• Nanomechanics (Ruoff)

LeTourneau University
• Summer Faculty Fellow
• Nanotube growth process (DeBoer)

Penn State
• Purification / characterization (Eklund)

GB Tech
• Fuel cells / CO₂ scrubber (Huffman)

Rice University
• Advanced Nanotechnology Mat'ls and Applications (Smalley, Tour, Barrera)
• Computational Mat'ls Sci. (Yakobson)
• Nanosheils (Hales)

University of Houston
• GSRP year 3 - Polymer chemistry, dispersion, composites (Mitchell, Krishnamoorti)

Georgia Tech
• Nanotube composite films (Ready)

University of Pennsylvania
• GDFE - Thermal Mgmt. Mat'ls (Fischer)
• Composites (Luzzi, Winey)

University of Tennessee, Knoxville
• Nanofabrication (Penunzadu)

University of Oklahoma
• Thermal stability of nanotubes (Resasco)

University of California - Davis
• Nanocrystalline Ceramics (Mukherjee)

University of Texas - Tyler
• Summer Faculty Fellow - CFD of Laser process (Greenhofke)

Wake Forest
• Characterization of nanotubes (Carroll)

Industry

Carbon Nanotechnologies, Inc.
• Production, purification, applications (Smith)

Hamilton-Sundstrand
• CO₂ Scrubber (Papale)

Nantero, Inc.
• NanoRAM development (Siegel)

Nanospectra
• Thermal control coatings (Watkins)

Zyvex
• SBIR - Dispersion (Randall)

Resolution Performance Products
• Epoxy / nanotube composites (Stark)

ReyTech
• SBIR - Ultracapacitors (Reynolds)

Eikos
• EMI Shielding (Glatkowski)

SouthWest NanoTechnologies, Inc.
• SBIR - Nanotube production (Resasco)

NanoTechnologies of Texas, Inc.
• SBIR - Conductive fabrics (Choante)

Inorganic Specialists
• SBIR - Electrochemical capacitors (Frisch)

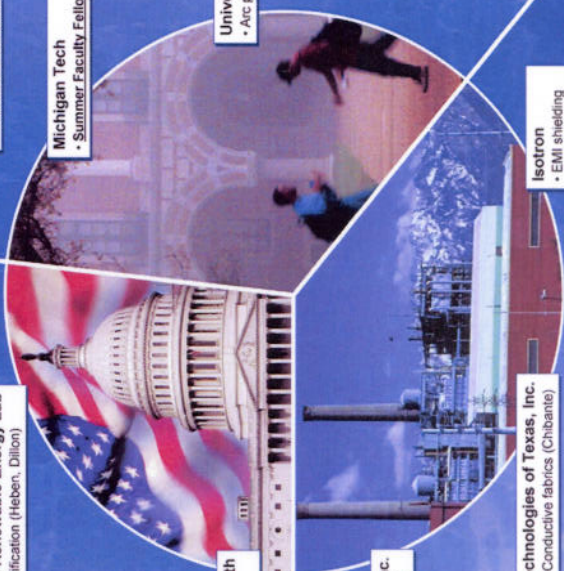
COI Ceramics
• RTF - Ceramic / nanotube composites (Riedell)

Materials and Electrochemical Research
• SBIR - Nanotube production (Loutfy)

Isotron
• EMI shielding

Ionwerks
• Mass spectrometry (Schulz)

Honda
• Magnetic characterization (Harutyunyan)



Applied Nanotechnology for Human Space Exploration

Questions?

leonard.yowell-1@nasa.gov
281-483-2811

