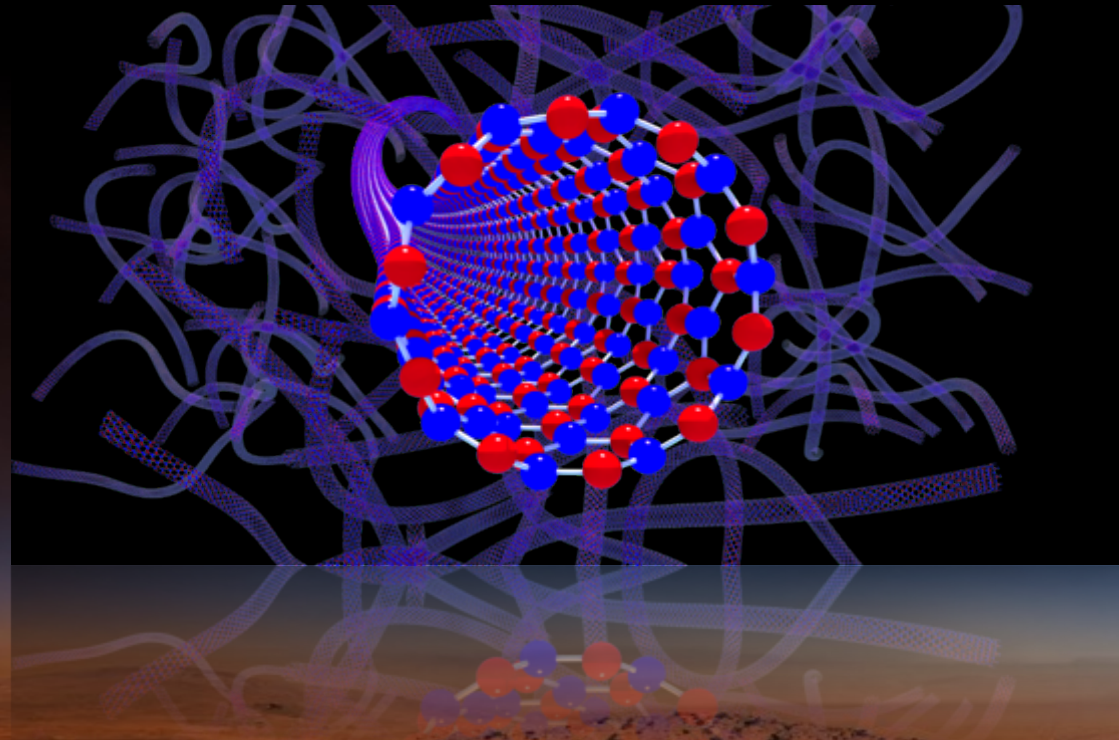




NASA Langley Research Center

High Temperature Pressure (HTP) Boron Nitride Nanotube (BNNT): Discovery and Commercialization

Cheol Park, Sang-Hyon Chu*, and Catharine Fay



Advanced Materials and Processing Branch, NASA Langley Research Center
**National Institute of Aerospace, Hampton VA USA*

NASA Langley Research Center



NASA Langley Research Center Hampton, Virginia

Founded in 1917 (NACA): first civil aeronautical research laboratory converted to NASA in 1958

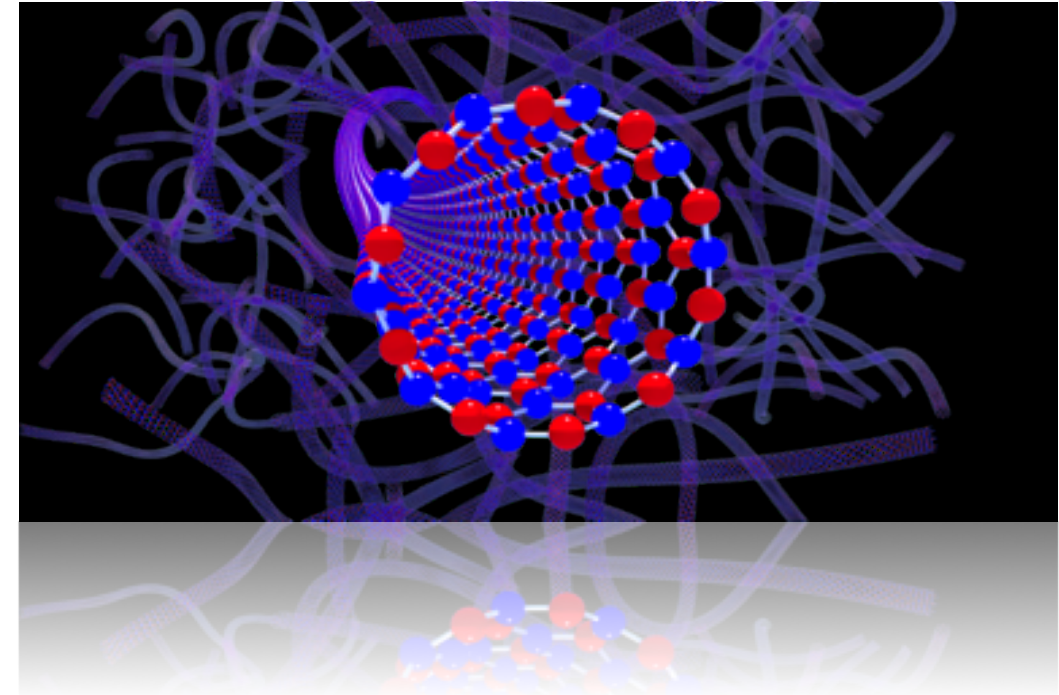
Facilities: \$4 billion value

People: 2000 Civil Servants ; 1700 Contractors

All images credit: NASA

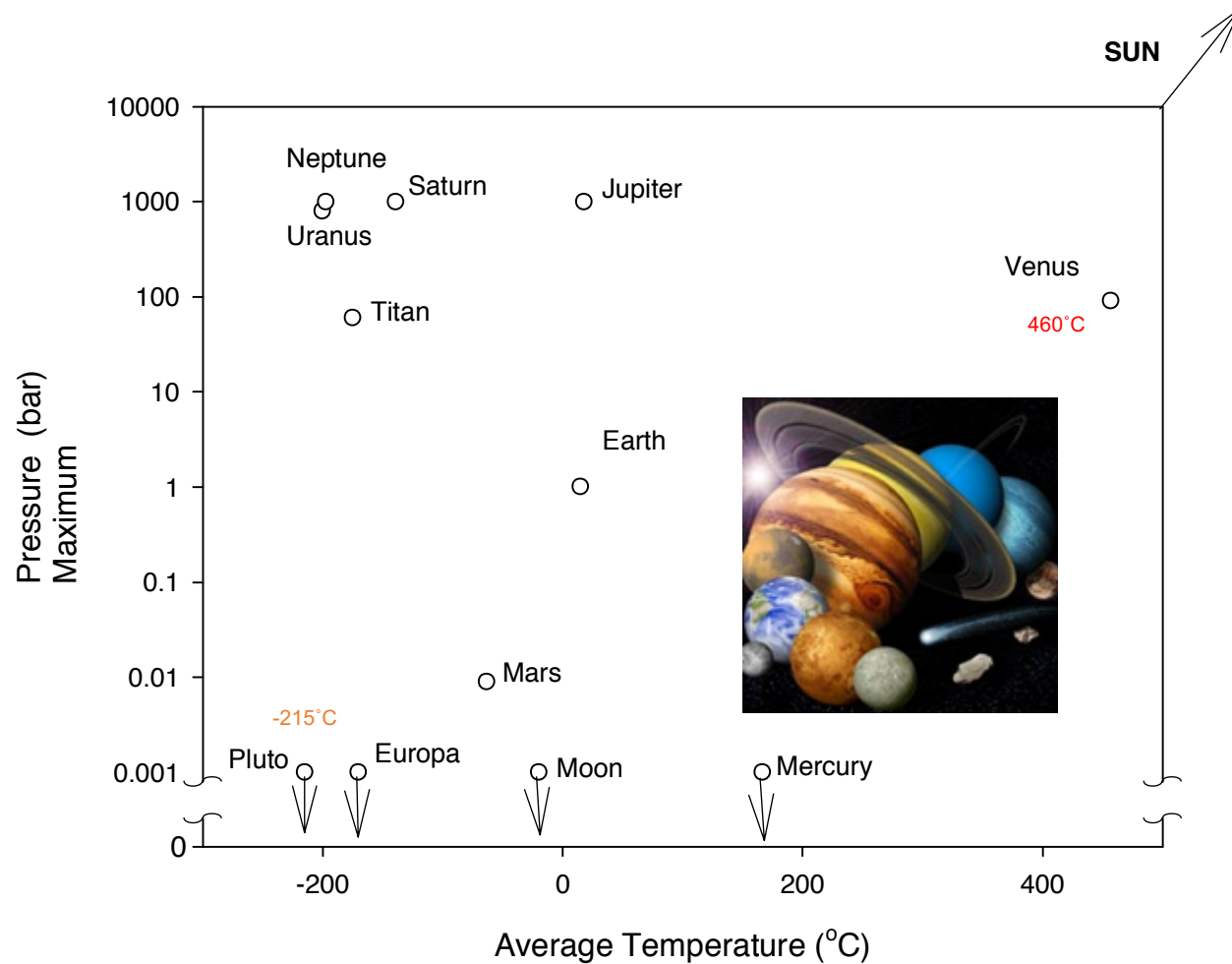
Outline

- Motivation: Extreme Environments in Space
- BNNT Synthesis (High Temperature Pressure (HTP) Method)
- BNNT and BNNT Composite Application
- Dispersion and Purification
- Mechanical Properties
- Thermal Properties
- Multifunctional Properties in Extreme Environments
 - Sensor/Actuator/Energy Harvester
 - Radiation Shielding
- Summary



Artemis Program: About \$40B by 2024

Extreme Environments in Space Exploration



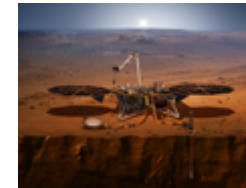
http://www.jpl.nasa.gov/solar_system/

17NASA Extreme Environments Tech Space missions Report FINAL



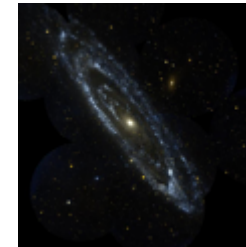
Lunar surface

-173 to 127°C
 -247°C (25K) at pole
 Sharp abrasive edge dust
 Radiation
 1/6 Earth gravity



Mars surface

-126 to 21°C
 Sand storm
 Radiation
 Entry, Descent, & Landing



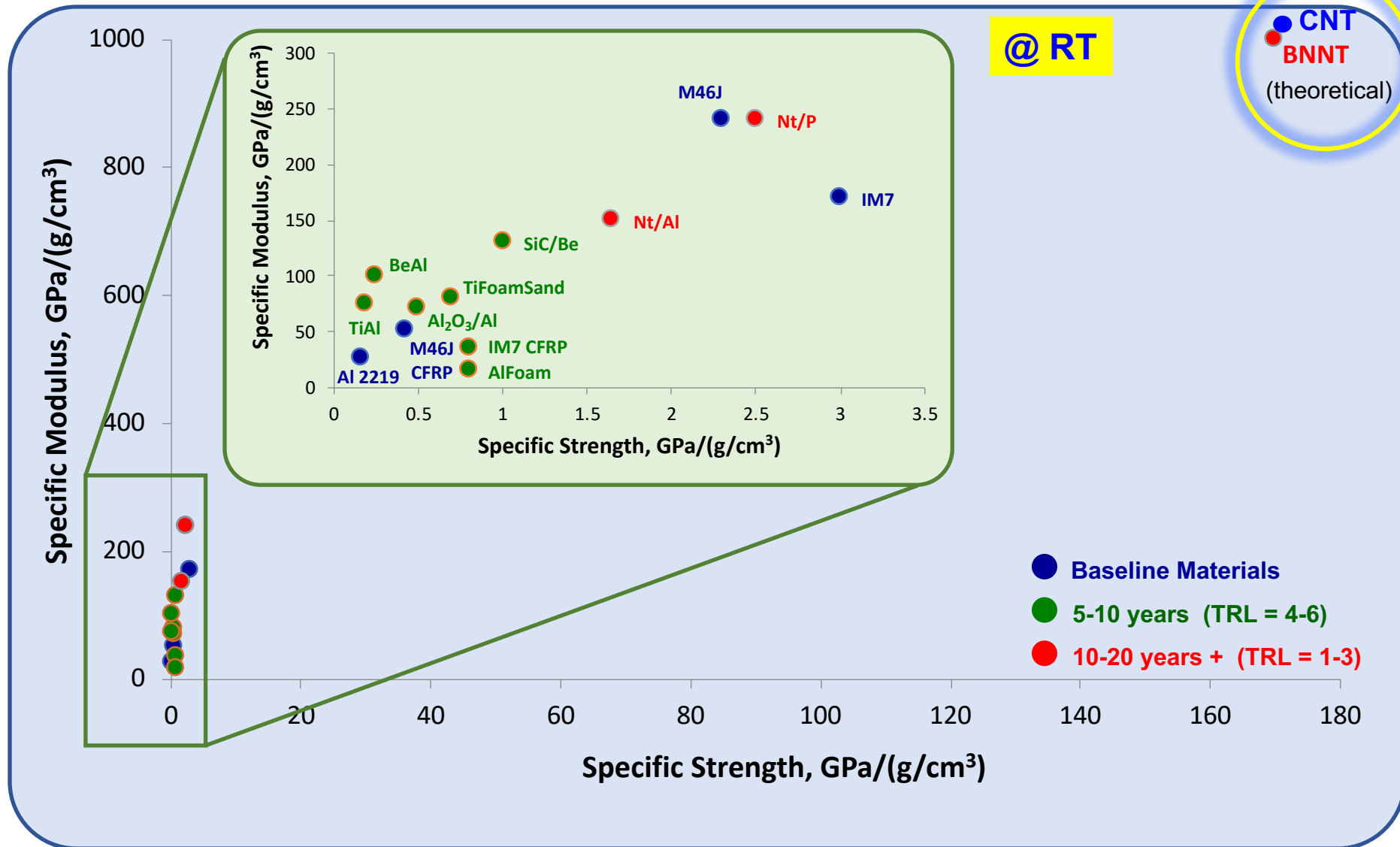
Deep space

2.7K
 Radiation
 Microgravity

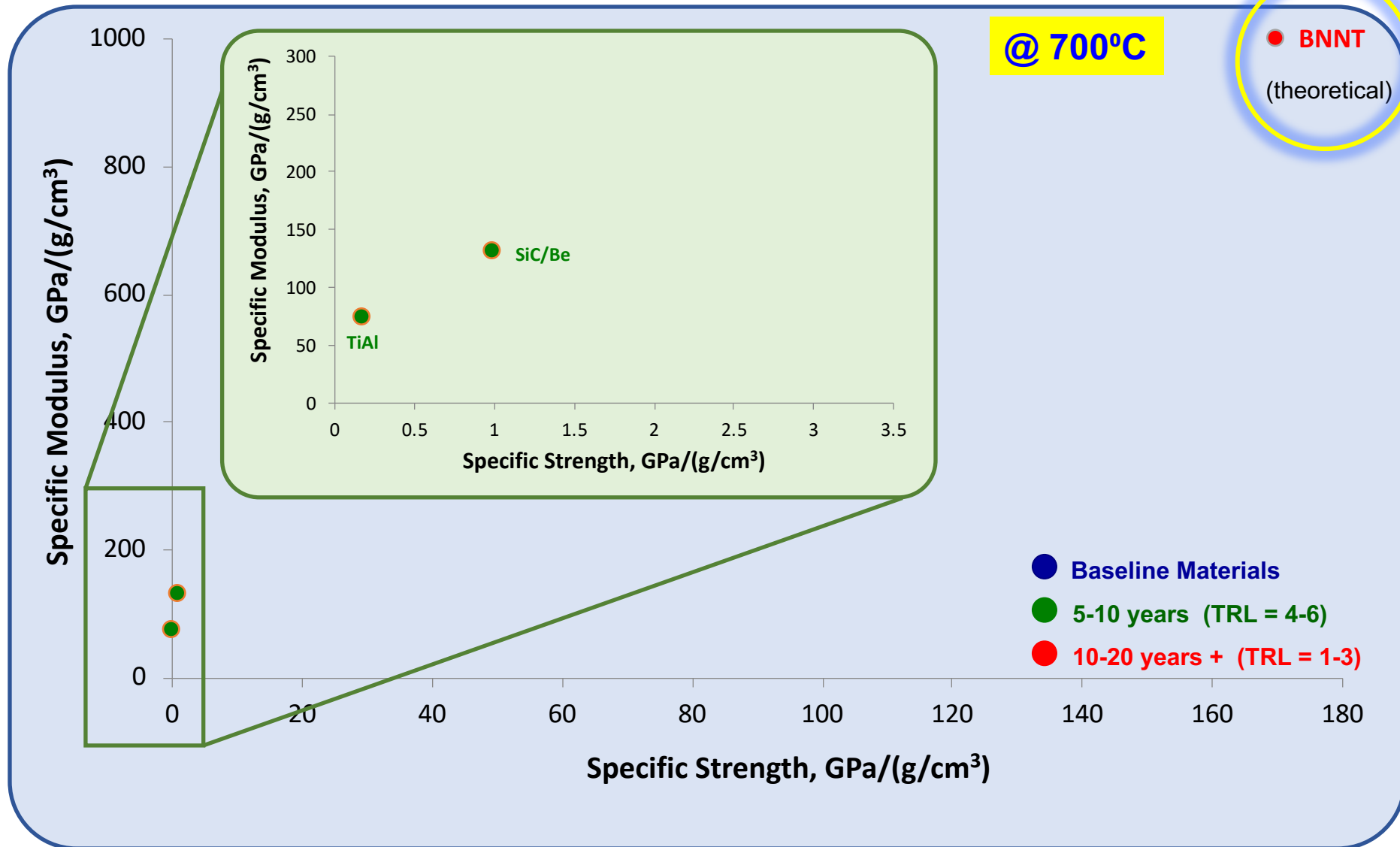
Heat flux at atmospheric entry: Heat fluxes often exceeding 10's W/cm²
 Hypervelocity impact: Higher than 3 km/sec
 Low and high temperature: Lower than -55°C and Exceeding +460°C
 Thermal cycling: Cycling between temperature extremes outside of the military standard range of -55°C to +125°C
 High pressures: Exceeding 20 bars
 High radiation: Total ionizing dose (TID) exceeding 300 krad (Si), GCR, SPE, Neutron
 Low and High gravity: microgravity on comets, 2.5g on Jupiter, launch, entry, descent

Artemis Program: Send 1st Woman & next Man to the Moon by 2024 (about \$40B), and then Mars and Beyond

Motivation: Properties of Materials for Vehicle Structure



Motivation: Properties of Materials for Vehicle Structure

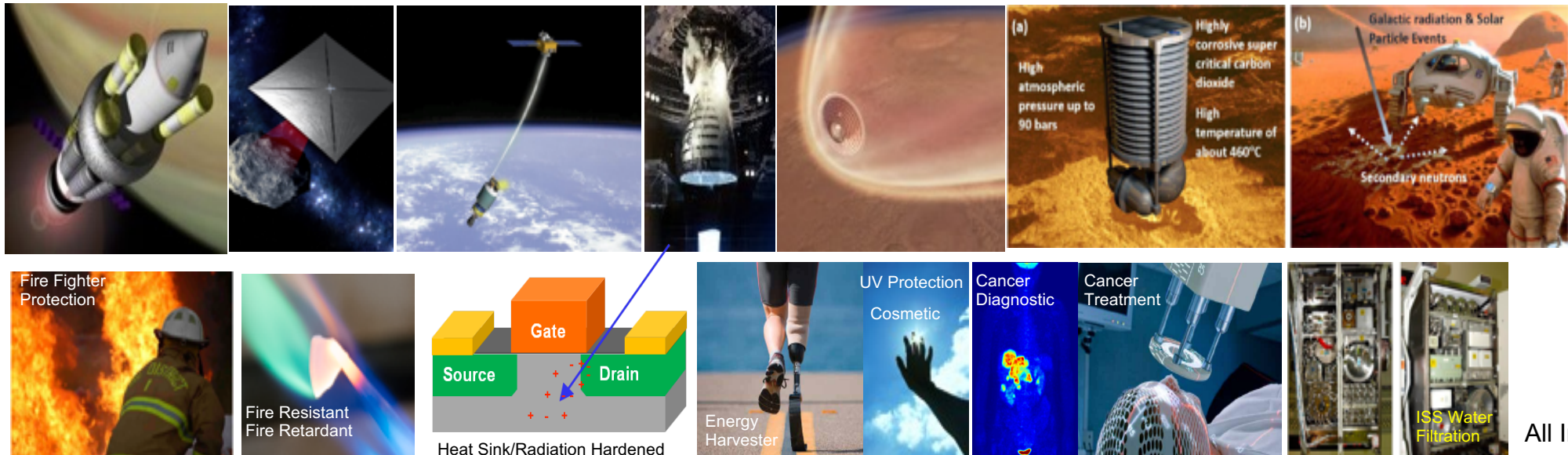


Nanotube Comparison (Theoretical)

	Carbon Nanotubes	Boron Nitride Nanotubes
Electric Properties	Metallic or semiconducting	Wide band gap (about 6.0 eV) Insulation, corrosion resistant
Mechanical Properties (Young's Modulus)	1.33 TPa (very stiff)	1.18 TPa (very stiff)
Thermal Conductivity	>3000 W/mK (highly conductive)	~300–3000 W/mK (highly conductive)
Thermal Oxidation Resistance	Stable up to 300-400 °C in air	Stable to over 900 °C in air
Neutron Absorption Cross-Section	C = 0.0035 barn	B = 767 barn (B ¹⁰ ~3800 barn) N = 1.9 barn Excellent radiation shielding
Polarity	No dipole	Permanent dipole Piezoelectric (0.25-0.4 C/m ²)
Surface Morphology	Smooth	Corrugated Better interfacial strength for composites, ionic bonding
Color	Black	White (can be colored)
Coefficient of Thermal Expansion	-1 x 10 ⁻⁶ K ⁻¹ (very low)	-1 x 10 ⁻⁶ K ⁻¹ (very low)

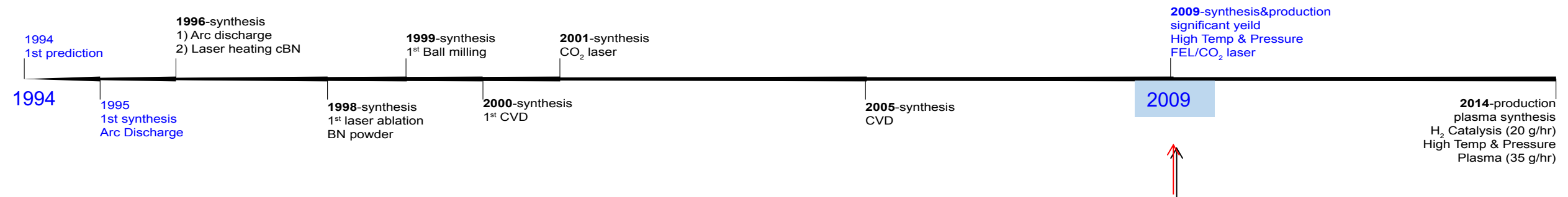
Significance of the BNNT Innovation

- **Structural/Mechanical: lightweight** composite armor, thermal protection, engine components, and radiation shielding materials for **extreme environments**.
- **High stiffness as well as high toughness** for spacecraft and space suits, ultrastrong tethers, meteorite impact protection layers, protective gear for astronauts.
- **Space lubricants** without moisture.
- **High temperature** thermal protection systems (TPS) used in the **nose cap**, wing **leading edges**, **engine parts**, lubricants, and planetary **Entry, Descent, & Landing (EDL) TPS**.
- **Fire resistant and retardant**.
- **High temperature sensor, actuator, energy harvesting devices** in extreme environments.
- **Radiation shielding, UV (ultraviolet) protection**, and electromagnetic transparency while decreasing aircraft weight.
- **Radar transparency** mitigates Electromagnetic Interference (EMI) and Radio Frequency (RF) blackout.
- **Efficient zero-energy water filter and desalination membrane in microgravity**.



BNNT Synthesis History

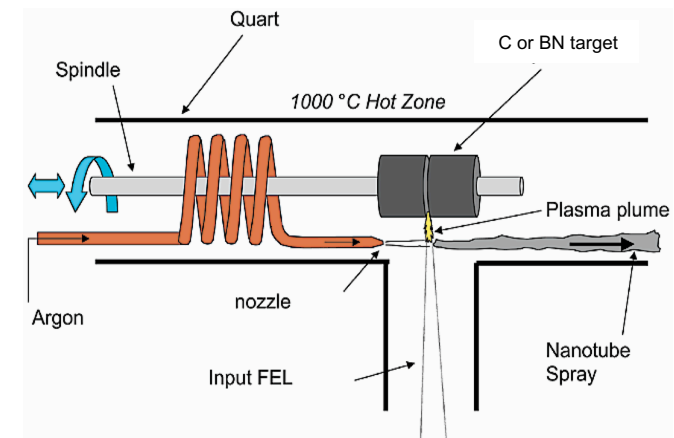
- *First Theoretical prediction: PRB 49 5081–5084 (1994) (UC Berkeley, Cohen), computation*
- *First Synthesis Arc Discharge: Science 269 966 (1995) (UC Berkeley, Cohen/Zettl) BNNT by Arc Discharge*
- Arc Discharge: PRL 76 4737 (1996) (ONERA France, Loiseau) Arc Discharge HfB₂ with N₂ gas
- Laser heating: APL 69 2045 (1996) (NIMS Japan, Golberg, Bando), Diamond Anvil, c-BN target laser heating High pressure
- Laser ablation: APL 72 1966 (1998) (Yu, BN powder with Co/Ni, first laser ablation)
- Ball milling/thermal annealing: CPL 74 2782 (1999) (ASU Australia, Chen) Ball milling of B powder in NH₃ gas
- CVD: Chem. Mater. 12 1808 (2000) (WA Univ, Lourie, Ruoff, Buhro) CVD Borazine (B₃N₃H₆)
- Laser ablation, PRB 64 121405(R) (2001) (ONERA Lee, Loiseau) CO₂ laser, no catalyst
- CVD: Solid State Comm. 135 67 (2005) (NIMS, Zhi. Bando, Golberg) CVD NH₃ B₂O₃ from MgO/B powder
- *High Temp, High Pressure, Laser vaporization: Nanotechnology 20 505604 (2009) (NIA/NASA/Jlab) High Temperature, Pressure (HTP) BNNT, Free Electron Laser/CO₂ Laser*
- High Temp Induction Thermal Plasma: ACS Nano 8 6211 (2014) (NRC Canada, Kim, Kingston, Simard): 20g/hr, need H₂
- High Temp, High Press Induction Thermal Plasma: NL 14 4881 (2014) (UC Berkeley, Zettl): 35g/hr



BNNT Synthesis

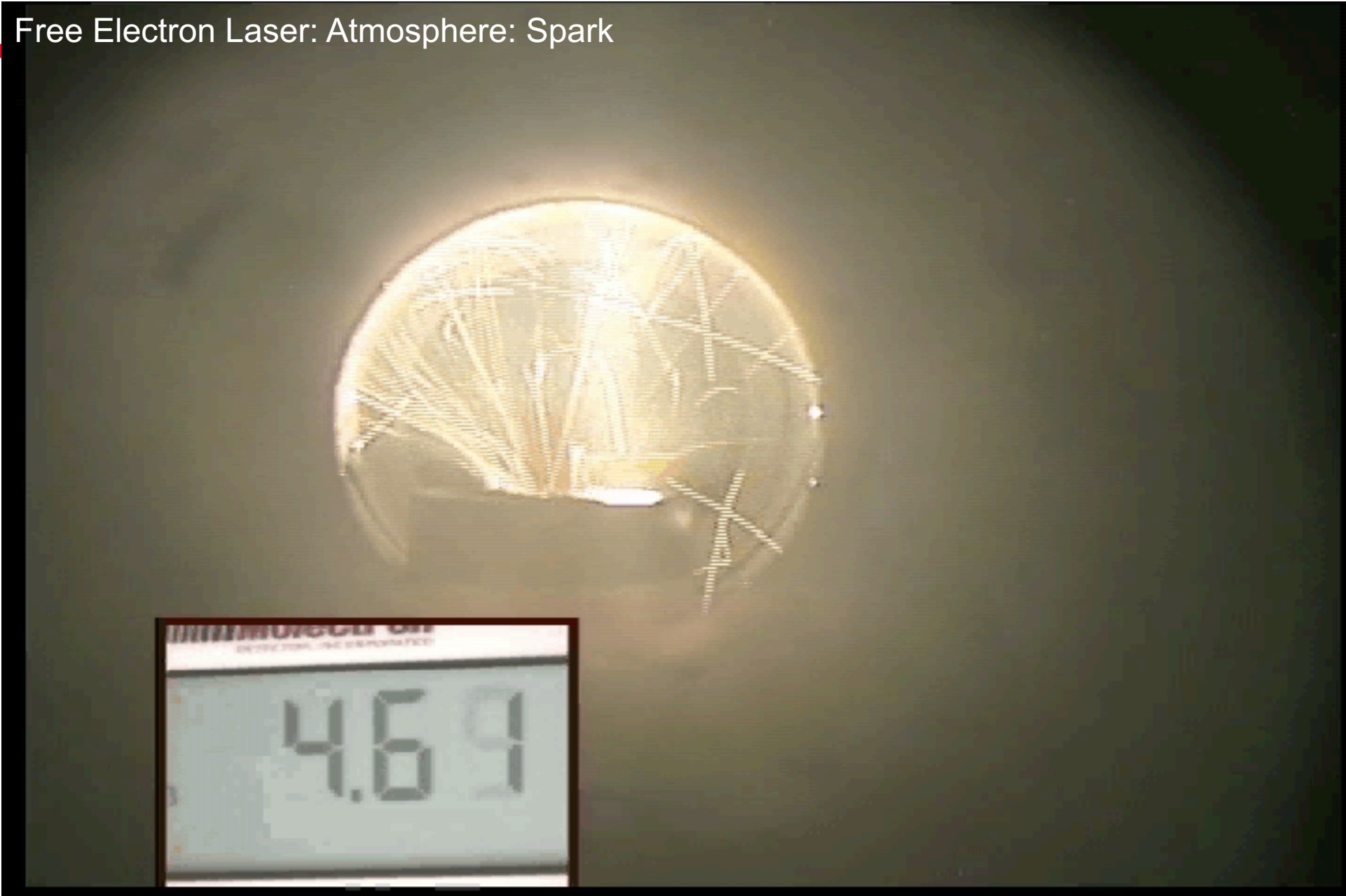
High Temperature-Pressure (HTP) BNNT

- Free Electron Laser (FEL) or CO₂ laser
- **No Catalyst, only B and N resource**
- Very long, small diameter, highly crystalline BNNT



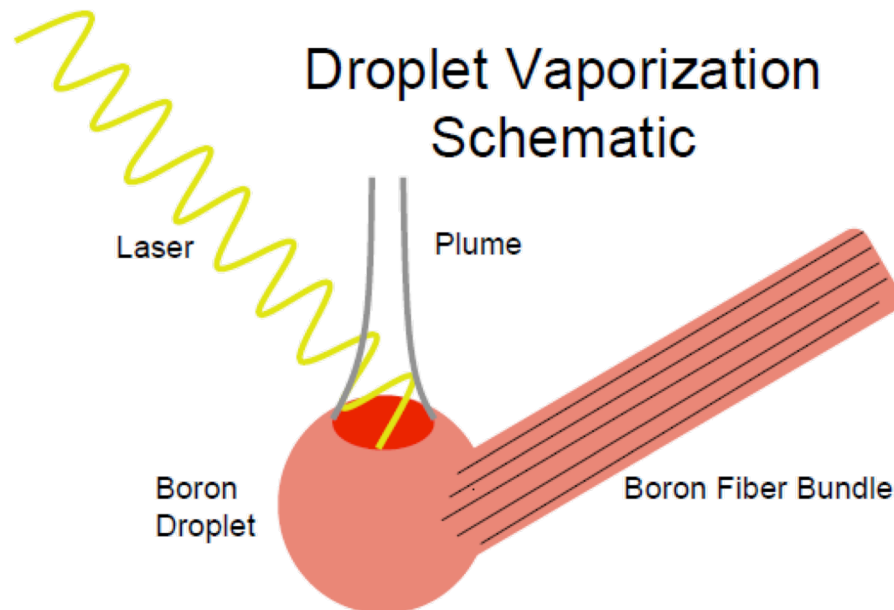
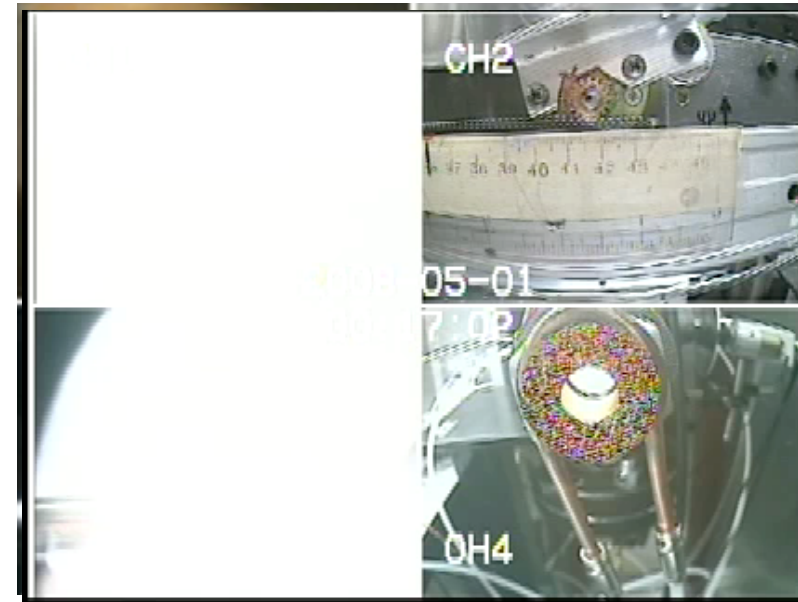
Nanotechnology, **20** 505604 (2009)
US Patent 8206674 B2 (2012)

Free Electron Laser: Atmosphere: Spark





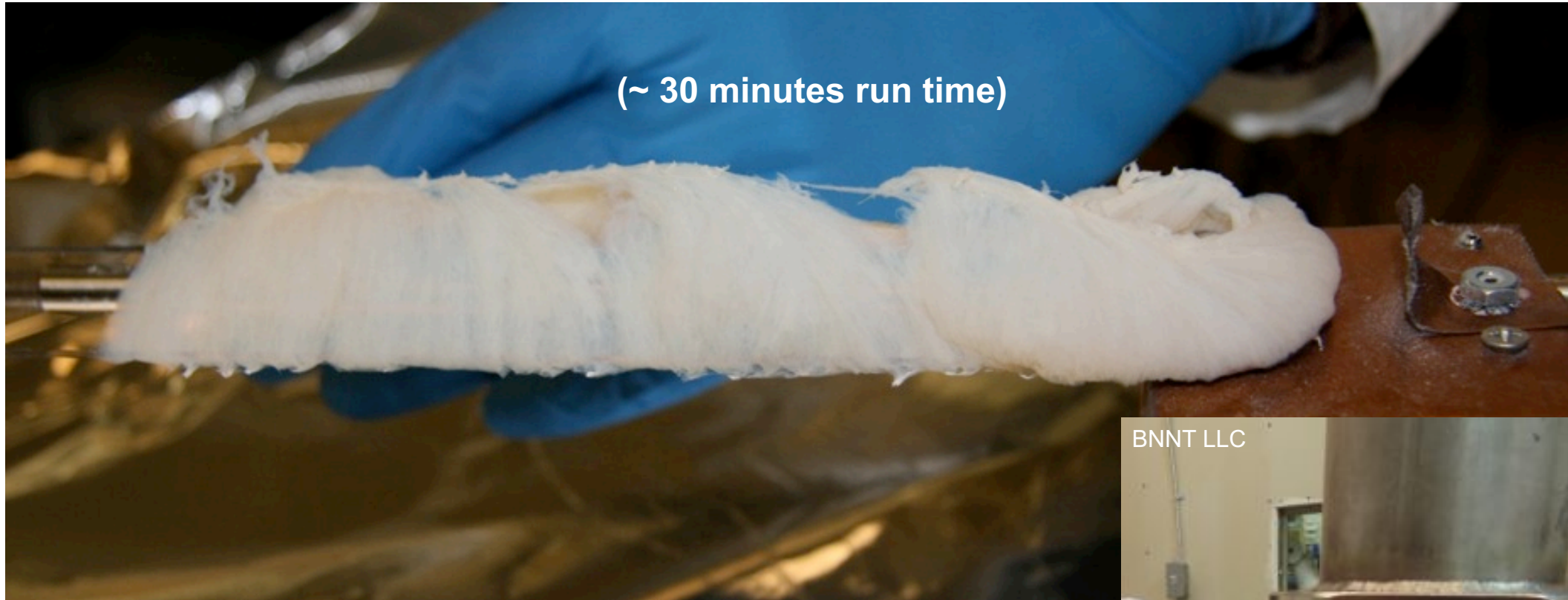
BNNT Synthesis Lab: NASA Langley (1st Gen)



- 5 kW of infrared radiation @ 10.6 μ m
- Heat source for vaporizing Boron feed stock above 3500°C
- Pressurized with Nitrogen to 13.6 atm (200 psi)

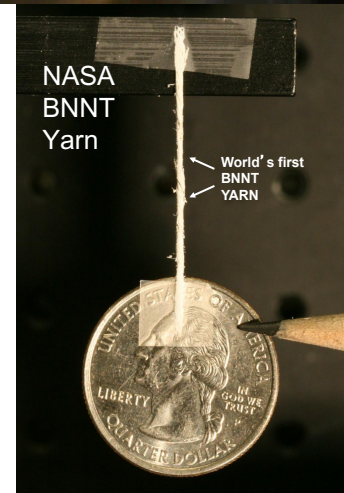
Nanotechnology, **20** 505604 (2009)
J. Thermophysics and Heat Transfer **27** 369 (2013)
Proc. SPIE **9060** 906006 (2014)

Cotton-like High Pressure and Temperature (HTP)-BNNT



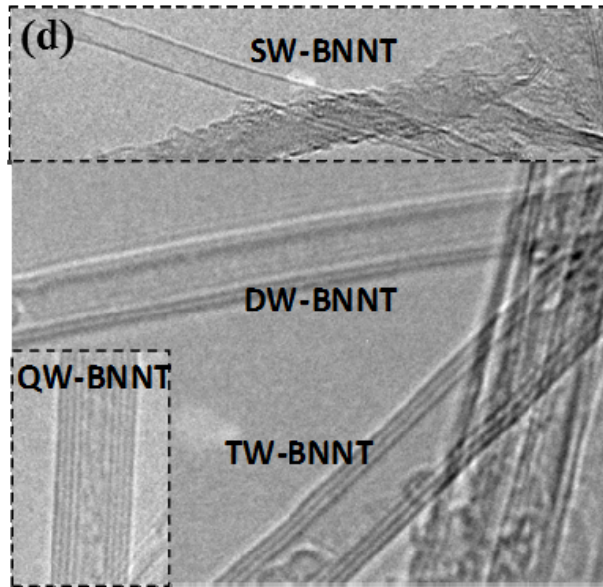
Benefits

- One-to-few-walled tubes with high crystallinity
- Very long, high-aspect ratio tubes
- High scale-up potential
- No toxic catalysts (only B and N as reactants)
- Standard industrial cutting/welding lasers
- High service temperature (over 800°C)
- Highly electroactive (due to the B-N polar bond)
- Neutron radiation shielding (due to their B content)

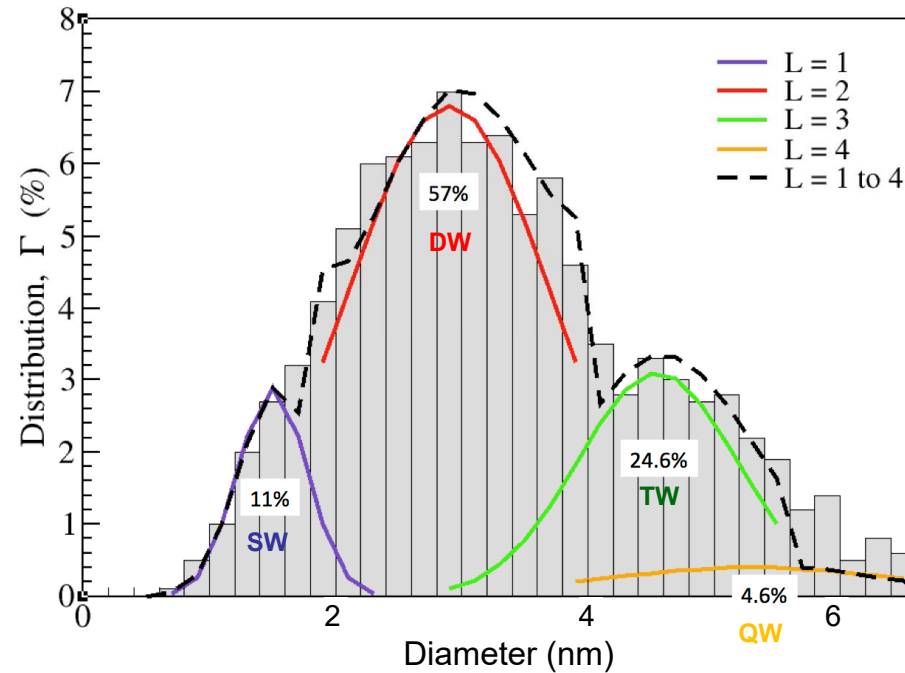


Nanotube Wall Number and Distribution of HTP-BNNTs

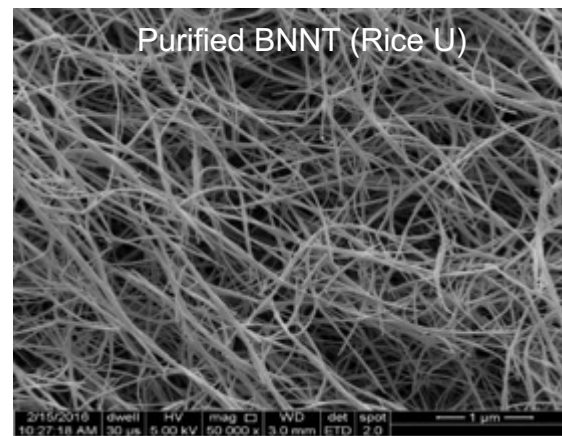
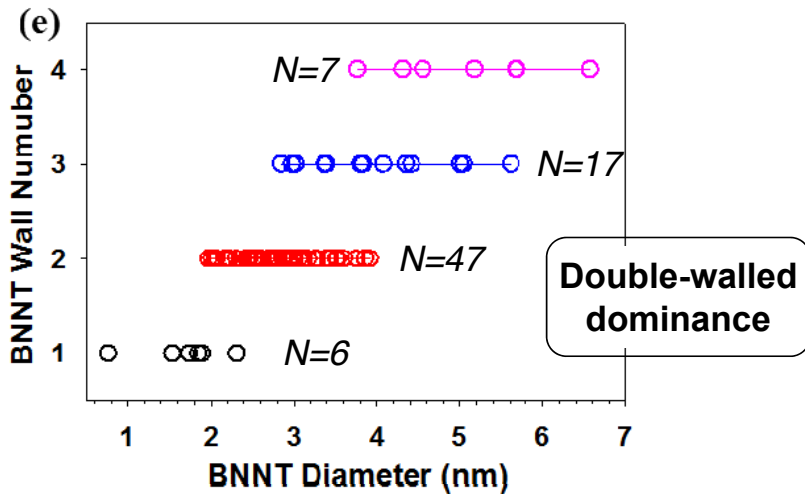
TEM Micrographs



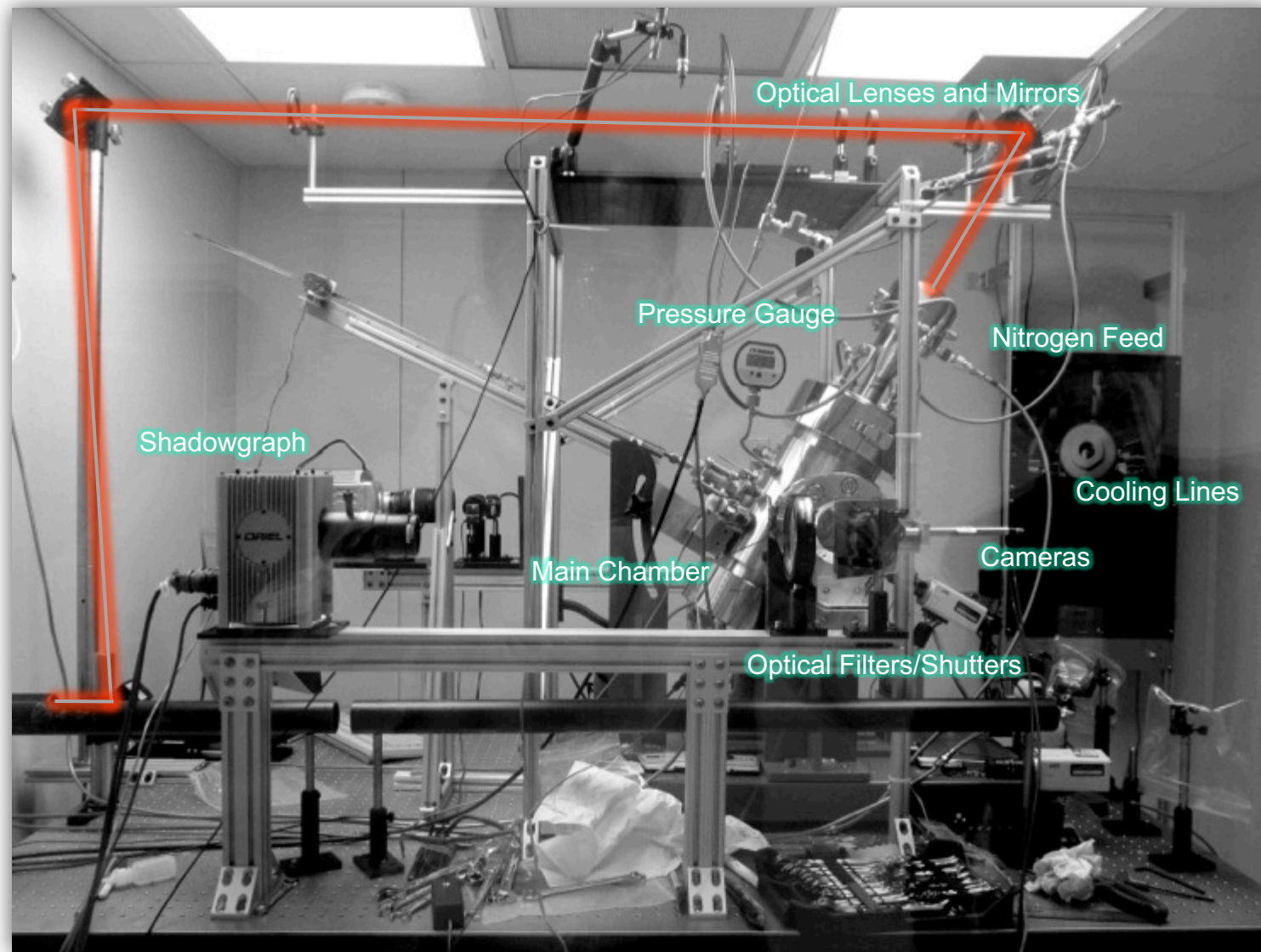
Based on AFM measurements of 1,000 randomly selected individual BNNTs



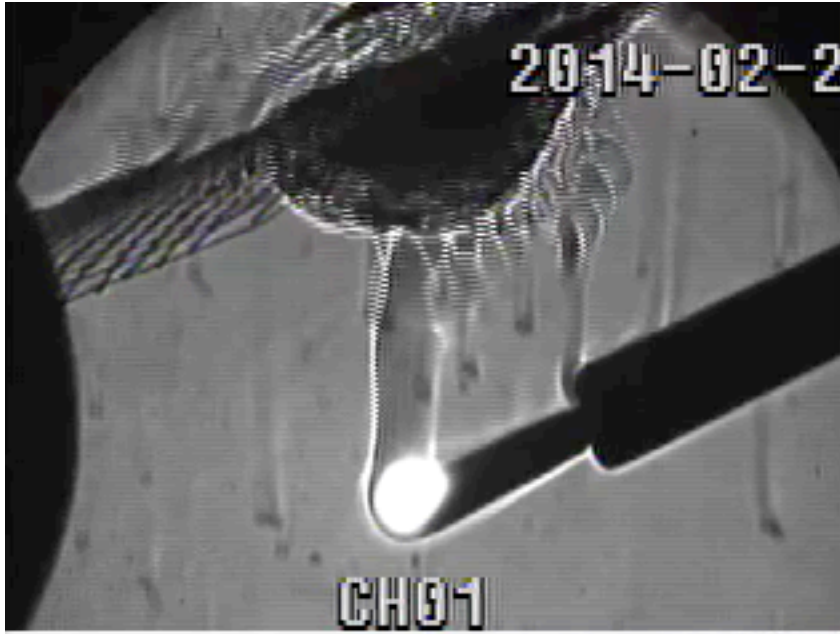
SW: 11%
DW: 57%
TW: 24.6%
QW: 4.6%
Total: 97.2%



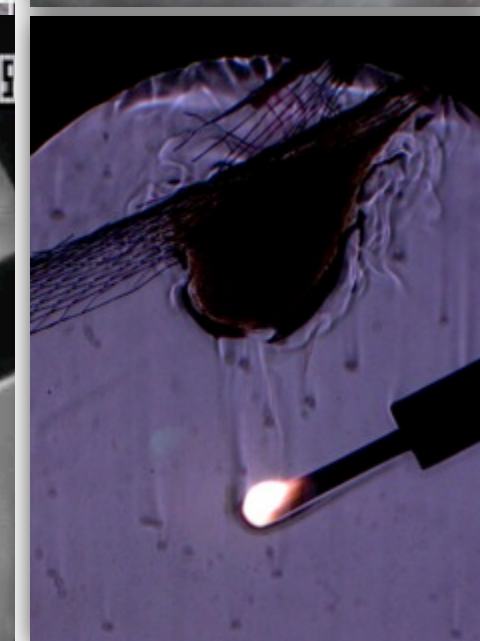
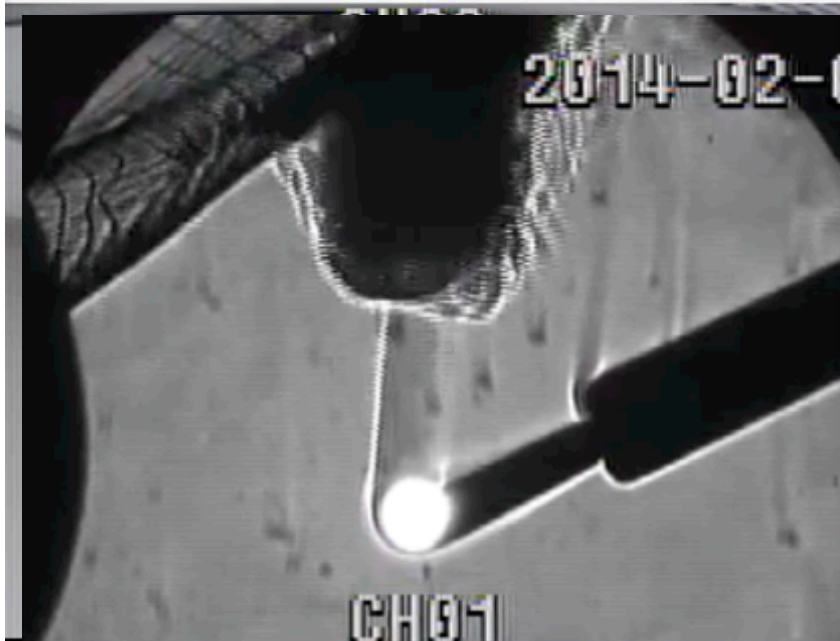
National Institute of Aerospace (NIA) BNNT Science Chamber



NIA Science Rig HTP BNNT Run (Snapshots)

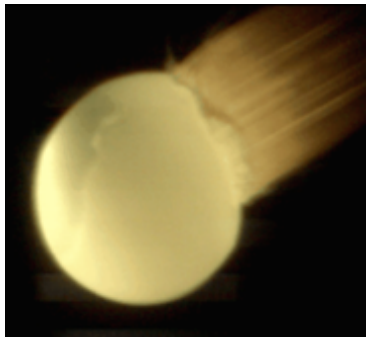


All images credit: NASA/NIA

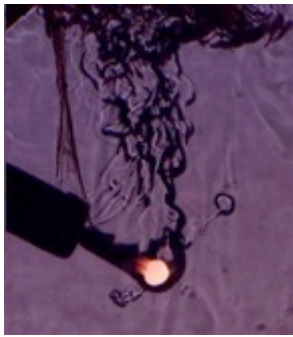


In-situ Optical Diagnostics

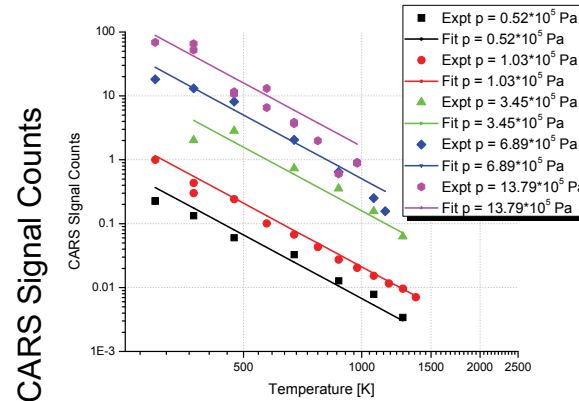
- Understand chemistry and flow physics of nanotube generation
- Improve and validate simulation/modeling
- Optimize material properties, production rate
- Specific Goals:
 - Determine gas and melt-ball temperatures
 - Determine amount of B₂, B, BN, N and N₂
- In-situ, on-surface measurement:
 - High speed imaging; high speed (1 kHz) optical pyrometer being developed to study melt-ball dynamics
- Off-surface, gas phase measurement:
 - High-speed, high-resolution imaging
 - Shadowgraph and visible emission
 - Species sensitive imaging (BN PLIF)
 - Temperature measurements (CARS)



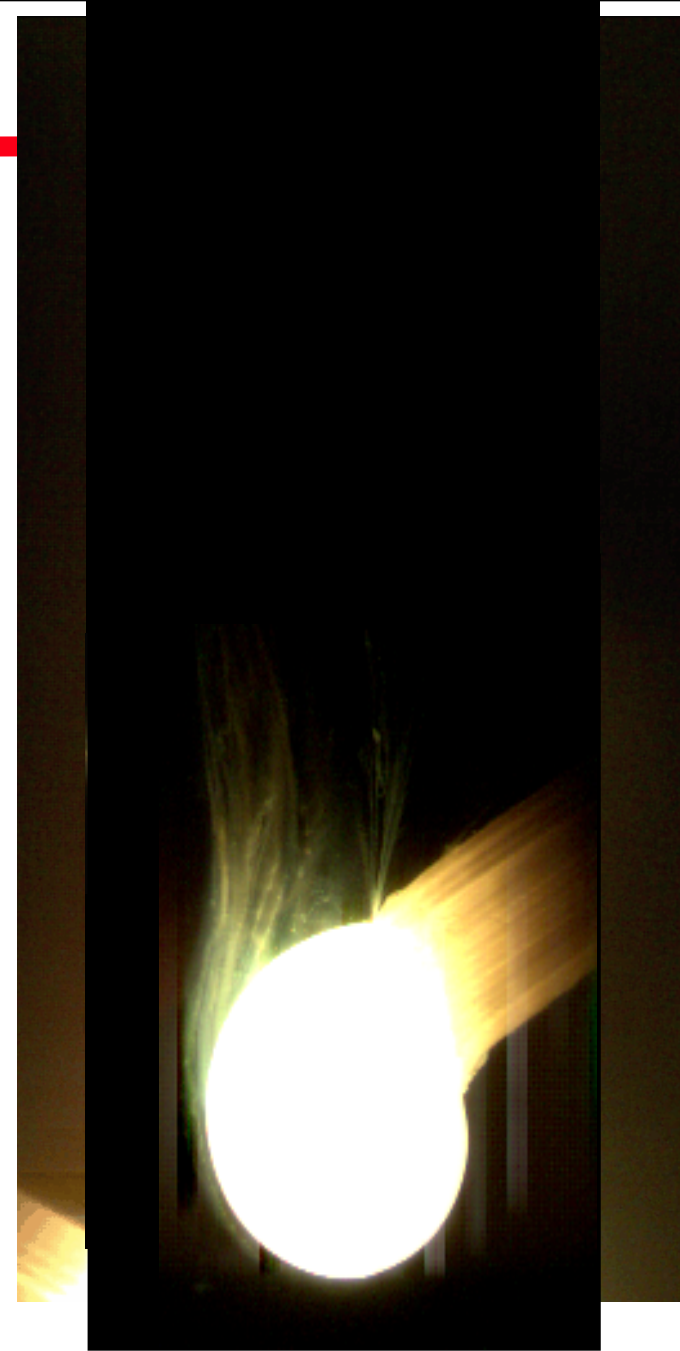
High Speed Camera



Shadowgraph

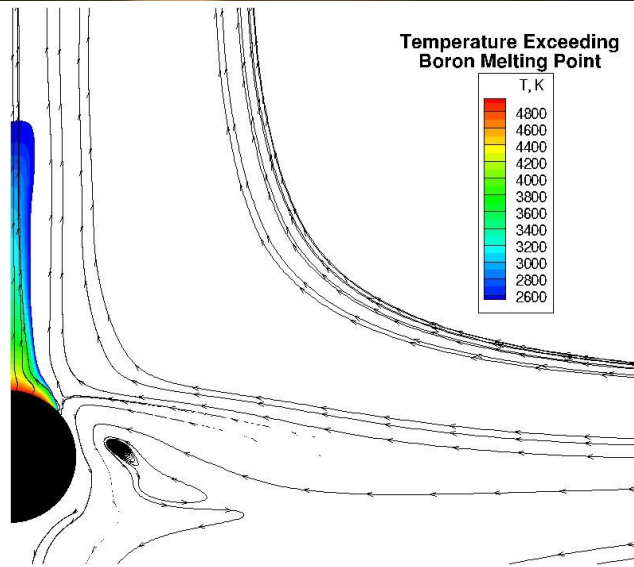


CARS Intensity Measurement



AIAA SciTech2014-1098 (2014)
Proc. SPIE 9060 906006 (2014)

Modeling of Laser Ablation and Plume Chemistry in a Boron Nitride Nanotube Production Rig



Contour lines of temperatures and mass fraction of BN in the plume

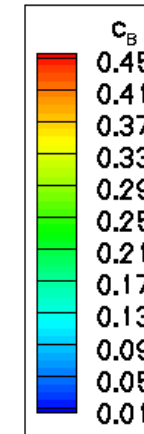
Mass fraction of B, Plume Base

Pressurized Cylinder
Radius = 5 cm
Height = 10 cm

Vertical line on left is cylinder axis.
The second vertical line is offset 1 mm from axis.
The right boundary is a porous wall designed to maintain internal pressure.

Top and bottom boundaries - except for laser spot on bottom left - are fixed temperature, no-slip, equilibrium catalytic.

At time $t=0$ a laser delivers constant energy flux to the 1 mm radius spot on lower left, initiating vaporization of boron target and buoyancy driven plume to rise from hot spot.

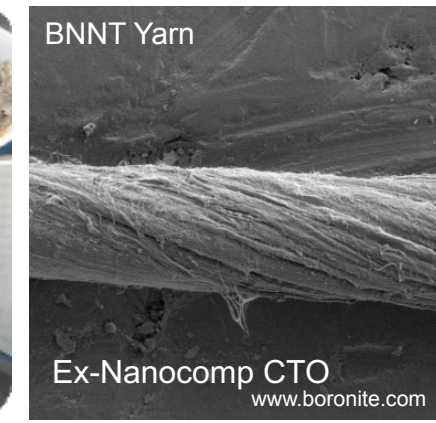
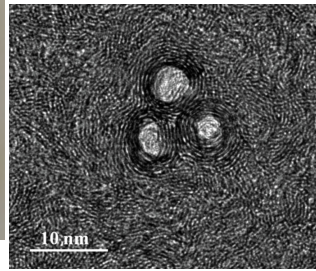
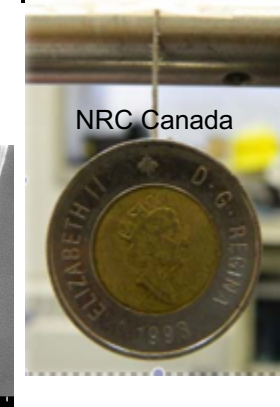
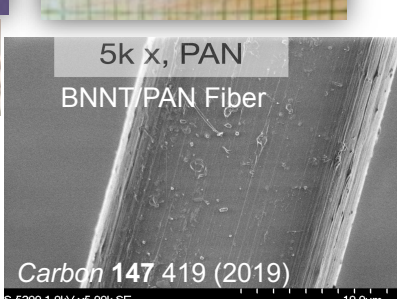
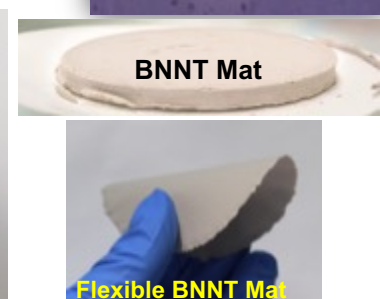
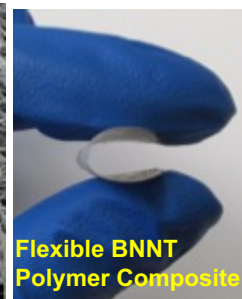
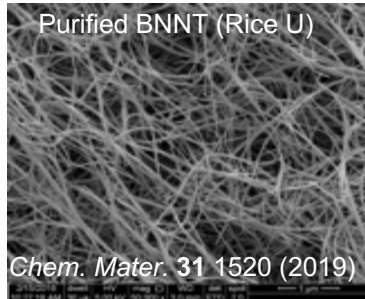
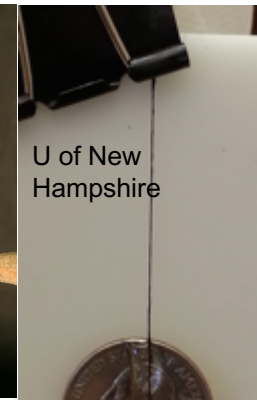
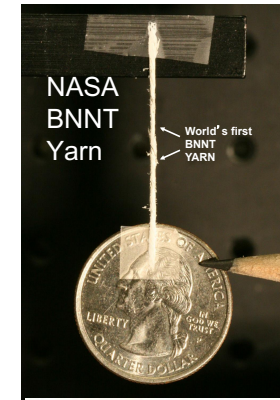
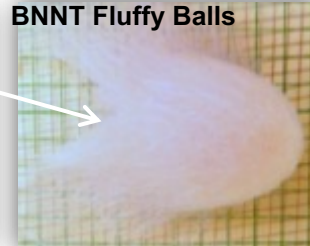
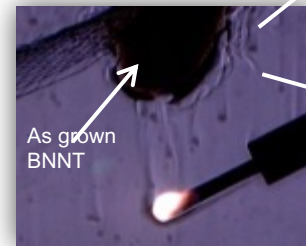
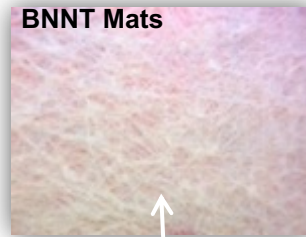
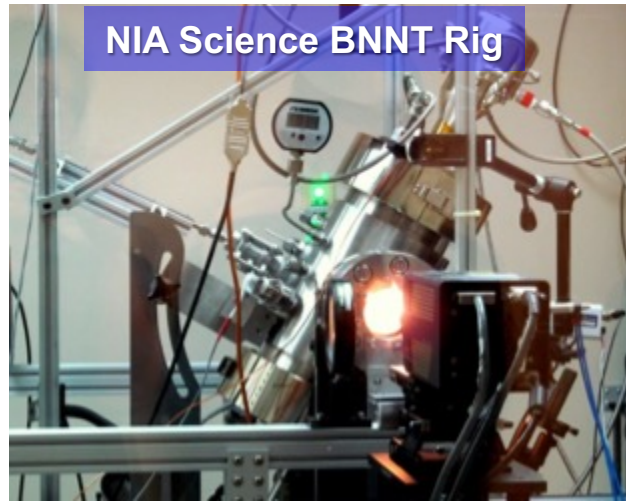


Peter Gnoffo (D305)
Aerothermodynamics Branch
LAURA Code

Proc. SPIE 9060 906006 (2014)

J. Thermophysics and Heat Transfer 27 369 (2013)

BNNT Scale-Up and Various Forms of BNNT



2016 NASA Government Invention of the Year Award

NASA
News, features & press releases

MISSIONS
Current, future, past missions & launch dates

MULTIMEDIA
Images, videos, NASA TV & more

CONNECT
Social media channels & NASA apps

ABOUT NASA
Leadership, organization, budget, careers & more

Bringing NASA Technology Down to Earth

ICB
Inventions and Contributions Board

TECHNOLOGY TRANSFER PROGRAM



NASA Invention of the Year Award

NASA develops and funds the development of many valuable innovations. The annual IOY program recognizes those inventions that have significantly contributed to NASA programs, or that exemplify NASA's mission to transfer cutting edge technology to U.S. industry.

Two distinct awards are presented: the NASA Government Invention of the Year, and the NASA Commercial Invention of the Year. The Invention and Contributions Board makes recommendations on the competition outcome, based on nominations it receives, to the General Counsel. The General Counsel, as the competition sponsor, makes the final recommendation to the NASA Administrator, who has final authority to approve the monetary awards.

2016 Government Award Winner: Boron Nitride Nanotubes

The NASA Government Invention of the Year Award is awarded to the invention **Boron Nitride Nanotubes**, from the Langley Research Center. The invention includes a novel approach to synthesizing high quality boron nitride nanotubes (BNNTs) without a metal catalyst using a high pressure and temperature method. This is the first breakthrough discovery to produce high quality BNNTs without any catalyst at a scalable amount since the first BNNT synthesis was reported back in 1994. The BNNTs produced from this process are lightweight, stable, and exhibit high strength. This heat resistant material can be used at high service temperatures and for radiation shielding.

2016 Commercial Award Winner: Hydrogen Leak Detection

NASA Langley BNNT Lab



As grown BNNT





Dispersion and Purification

Thermodynamic Approach: Effective BNNT Dispersion

Essential for Quality Yarn, Fabric, and Composite Formation



Thermodynamic Approach:
Gibbs Free Energy of Mixing

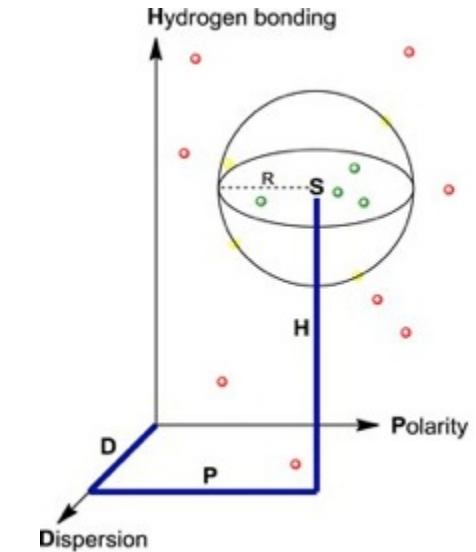
$$DG_{mix} = \downarrow H_{mix} - T^* \uparrow DS_{mix}$$

If DG_{mix} is negative,
spontaneous mixing happens
to form a homogeneous
solution

Hansen Solubility Parameters (HSP)
(d_d, d_p, d_h): "like dissolves like"

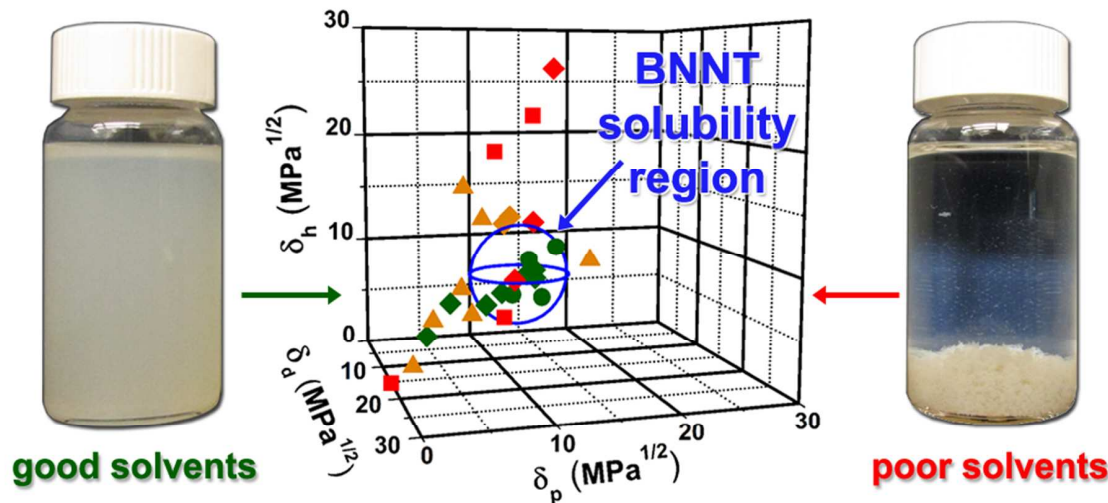
$$\delta_t^2 = \delta_d^2 + \delta_p^2 + \delta_h^2$$

d_t^2 : Hildebrand parameter
 d_d : dispersion component
 d_p : polar component
 d_h : hydrogen bonding component



Example of 3D Hansen space*

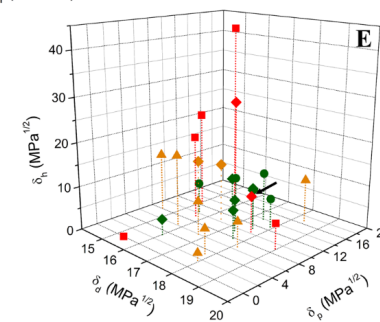
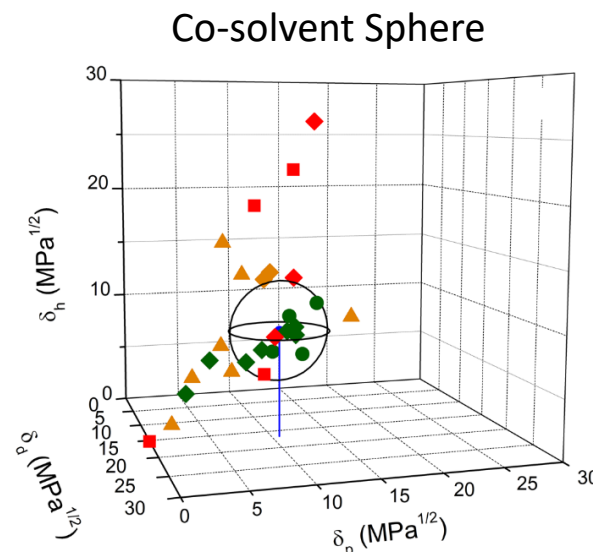
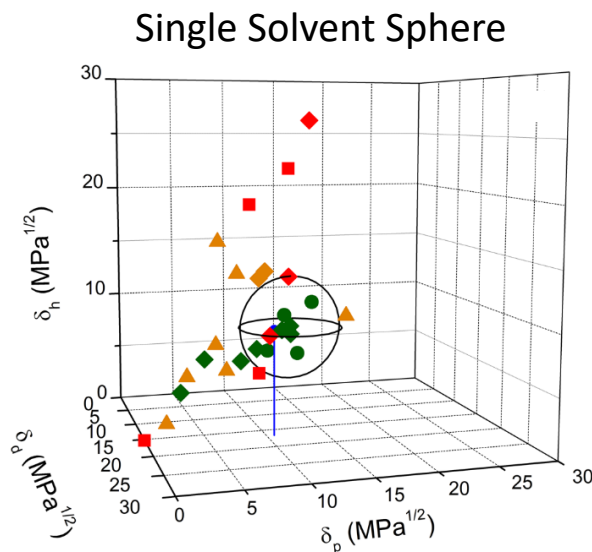
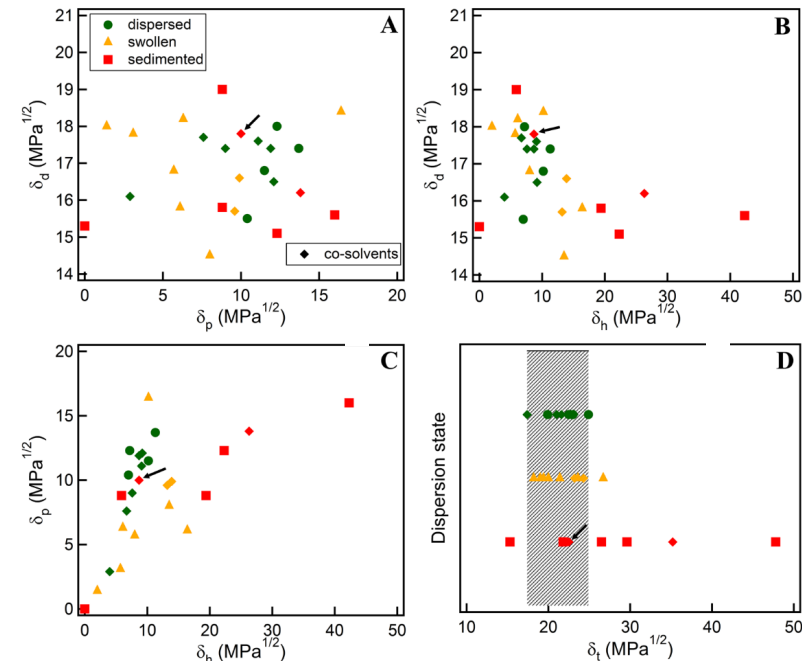
Single and Co-solvents



BNNT Hansen Solubility Parameters
 $\delta_d, \delta_p, \delta_h = 16.8, 10.7, 9.0 \text{ MPa}^{1/2}$
 $\delta_t = 21.8 \text{ MPa}^{1/2}$

Dispersion: Dispersion State of Single and Co-solvents

Co-solvent	δ_d , MPa ^{1/2}	δ_p , MPa ^{1/2}	δ_h , MPa ^{1/2}	δ_t , MPa ^{1/2}	Dispersion state (stirring only)	Dispersion state (stirring + 30 mins sonication)	R_a^c	RED ^d
THF-NMP	17.4	9.0	7.6	21.0	swollen	dispersed/swollen ^b	2.51	0.58
DMF-acetone	16.5	12.1	9.2	22.4	swollen ^a	dispersed/swollen ^b	1.54	0.36
DMAc-NMP	17.4	11.9	8.7	22.8	swollen ^a	dispersed/swollen	1.72	0.40
DMSO-THF	17.6	11.1	9.1	23.1	swollen	dispersed/swollen ^b	1.65	0.38
DMF-toluene	17.7	7.6	6.7	21.6	swollen	dispersed	4.26	0.99
IPA-DMF	16.6	9.9	13.9	24.3	sediment	dispersed/swollen ^b	4.98	1.16
ethanol-acetone	15.7	9.6	13.2	23.2	swollen	dispersed/swollen ^b	4.87	1.13
DMF-DCM	17.8	10.0	8.7	22.5	swollen	dispersed/swollen ^b	2.14	0.50
THF-hexane	16.1	2.9	4.0	17.4	sediment	dispersed/swollen	9.37	2.18
DMAc-water	16.2	13.8	26.3	35.2	swollen	sediment	17.62	4.10



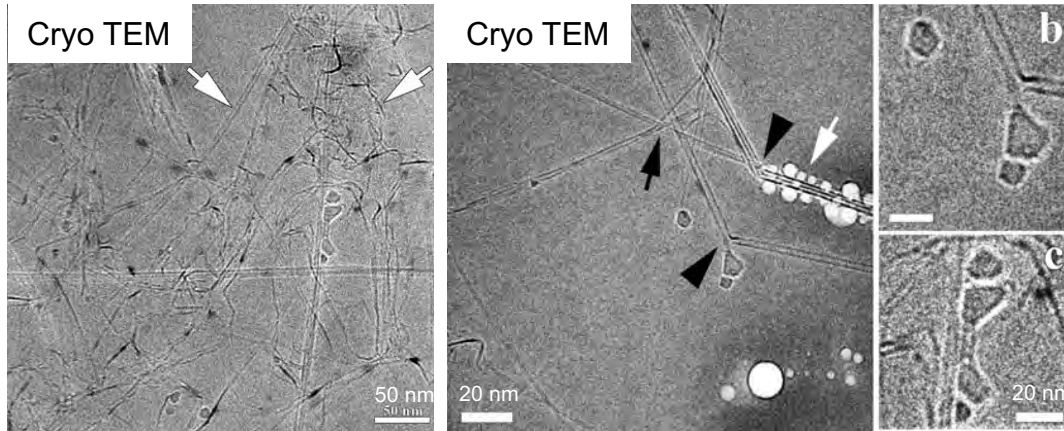
BNNT HSP

$\delta_d, \delta_p, \delta_h = 16.8, 10.7, 9.0$ MPa^{1/2}

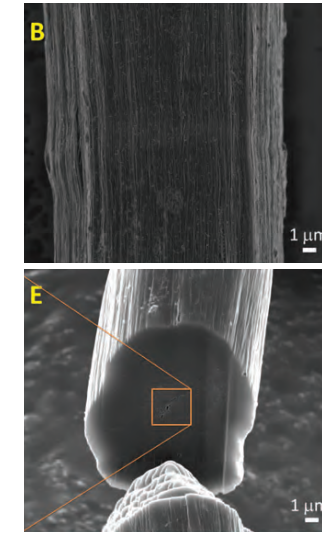
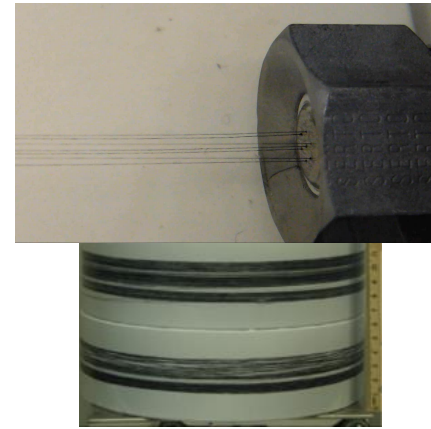
$\delta_t = 21.8$ MPa^{1/2}

Dispersion and Purification

Dispersion in a Superacid (Chlorosulfuric acid)



BNNT in Chlorosulfuric acid (HSO_3Cl)



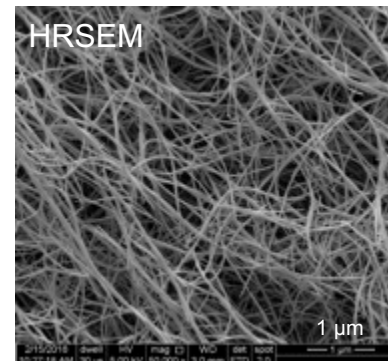
Rice U Nanotube Spinning (*Science* **339** 182 (2013))

Purification: Wet Thermal Oxidation

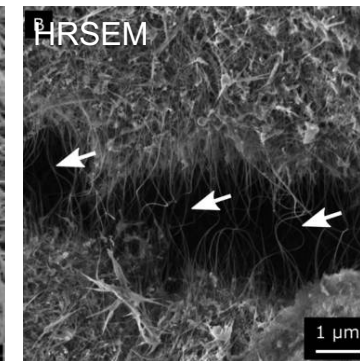


As grown BNNT

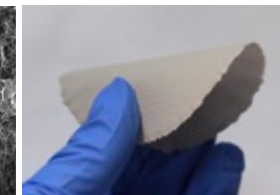
Purified BNNT



Purified BNNT



BNNT Film (superacid)



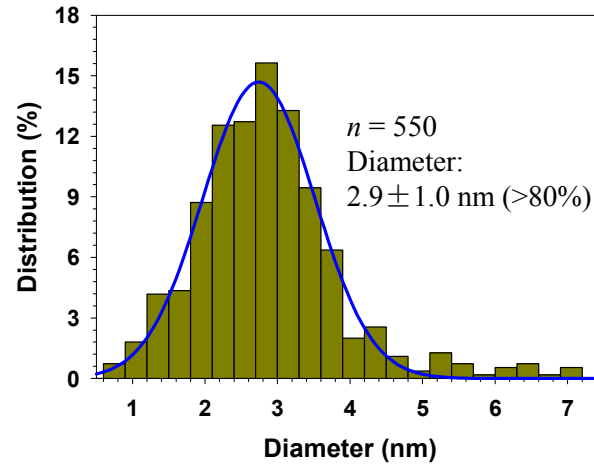
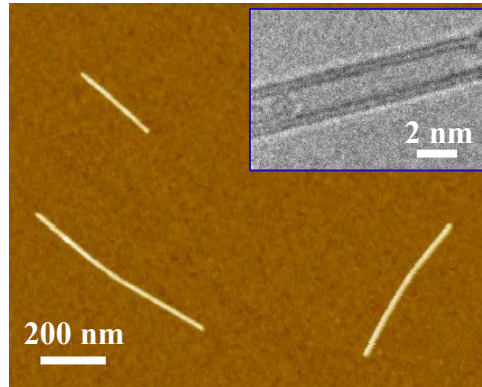
Flexible
BNNT Mat



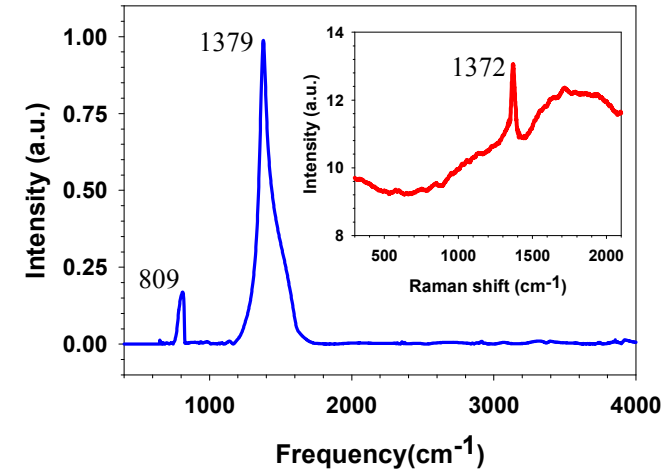
Mechanical and Thermal Properties

In-situ Single BNNT Test inside of an SEM

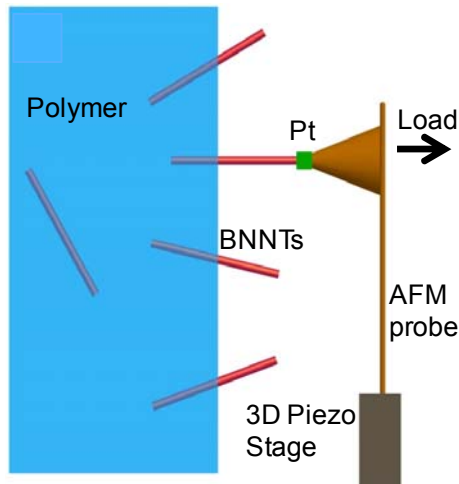
AFM



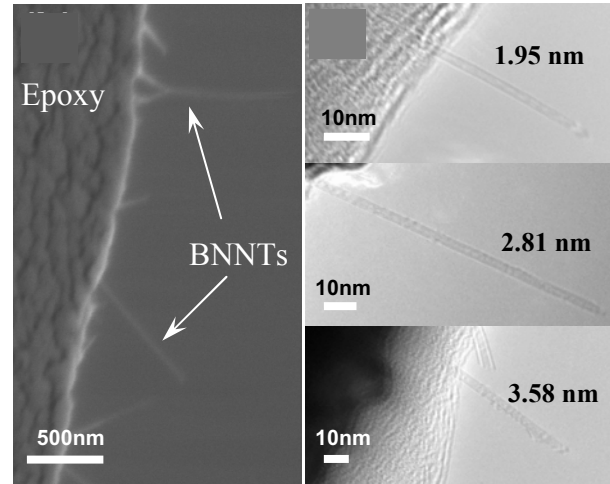
FTIR and Raman



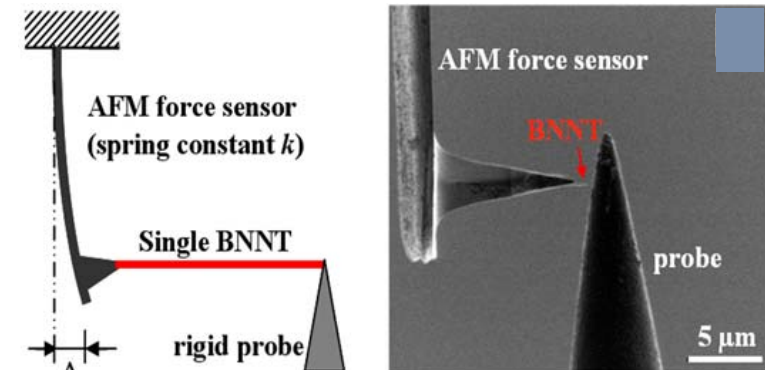
Pull-Out Test



SEM

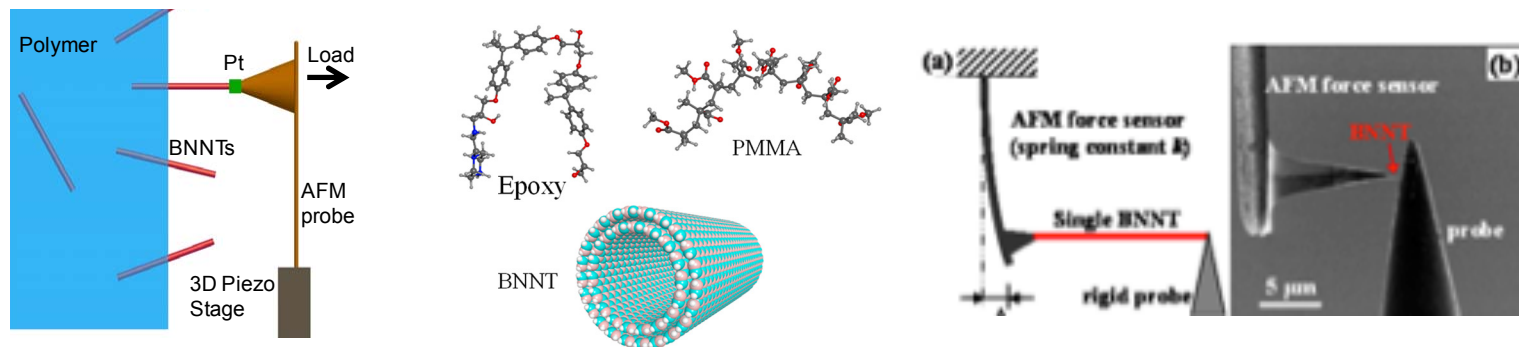
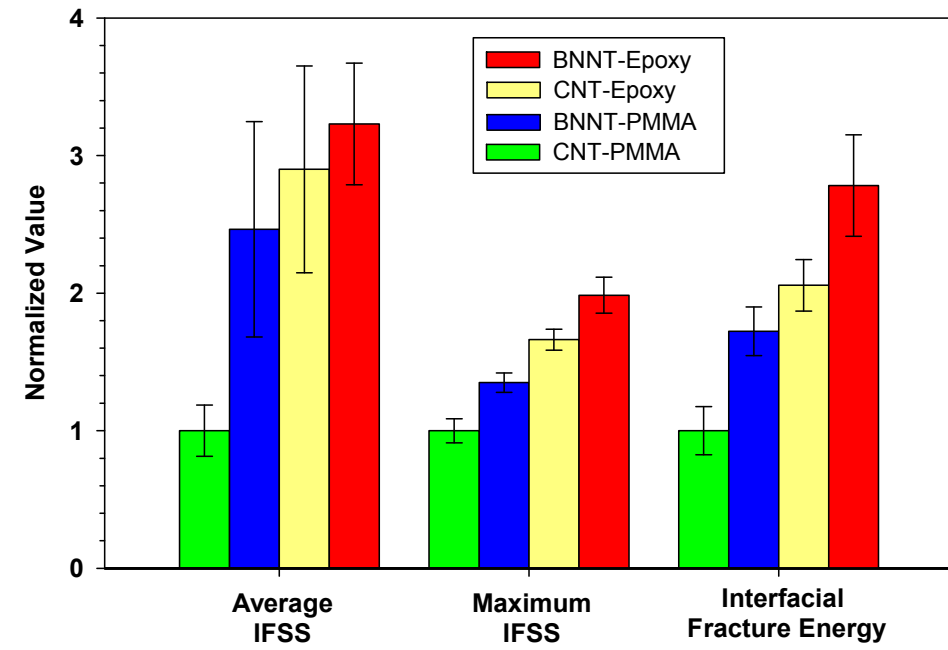
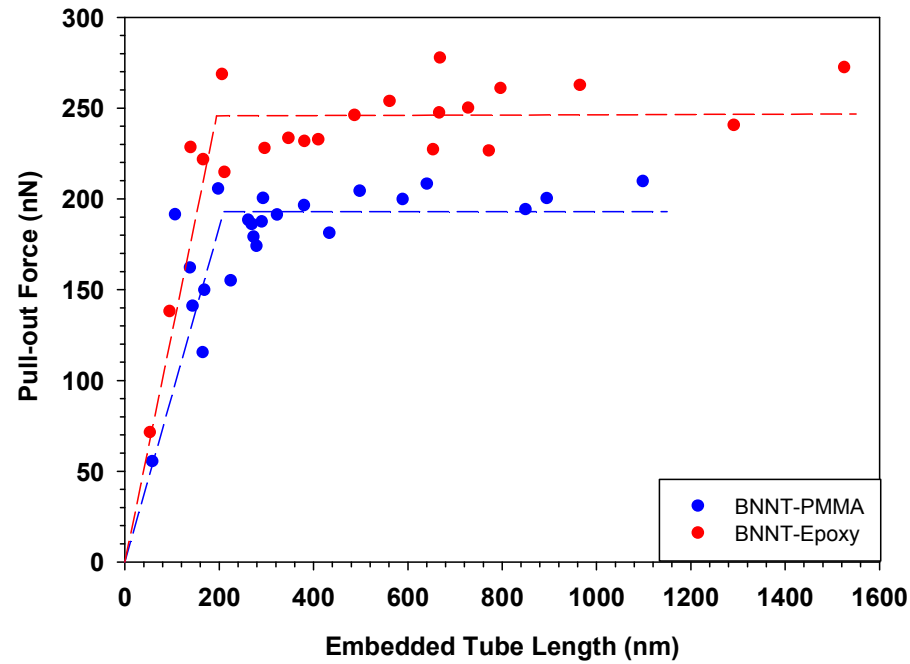


Tensile Test



Small **9** 3345 (2013), *Carbon* **82** 214 (2015), *APL* **107** 253105 (2015)
Carbon **25** 93 (2017), *Carbon* **132** 548 (2018)

Interfacial Strength: *In-situ* Single Nanotube Pull-Out Test

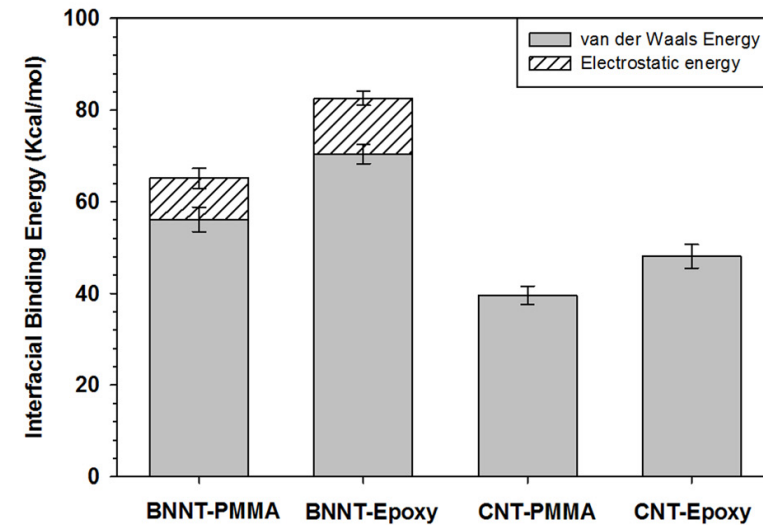
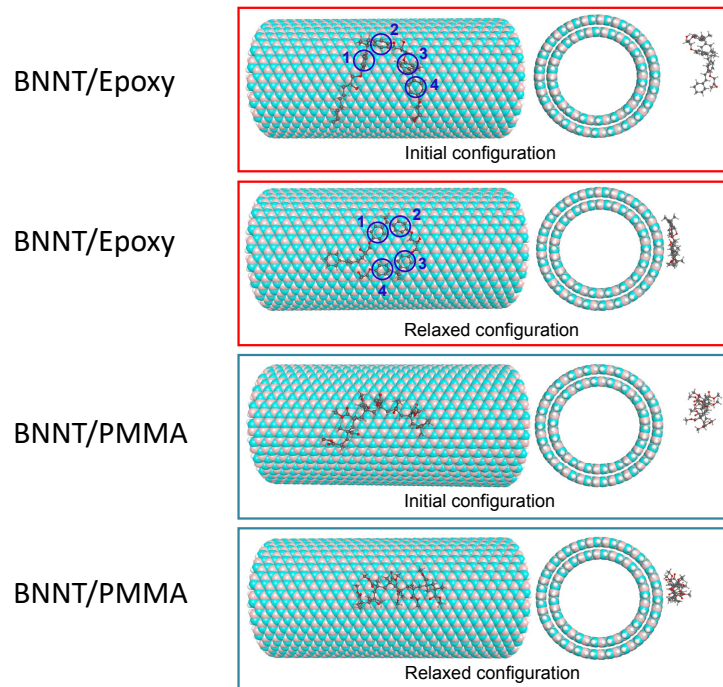
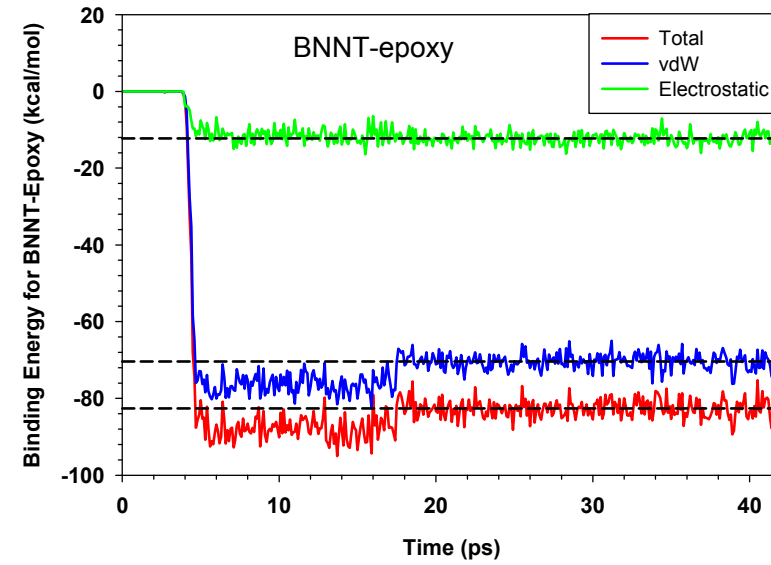
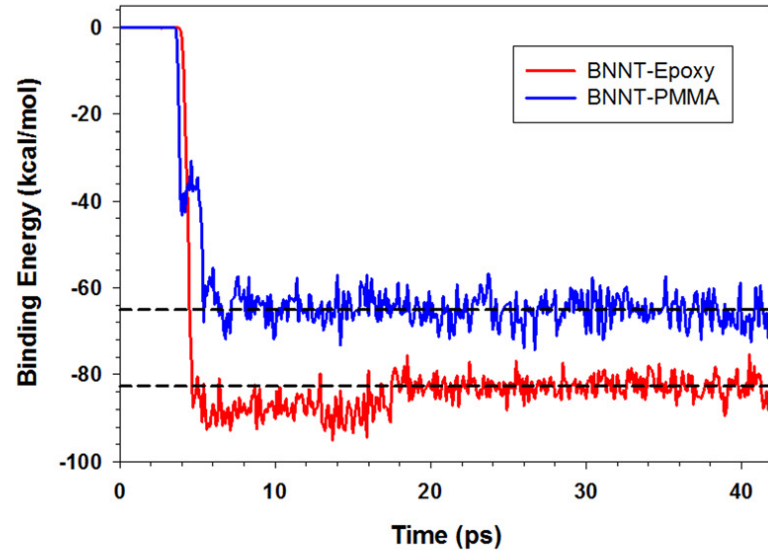


BNNT Tensile Test Results

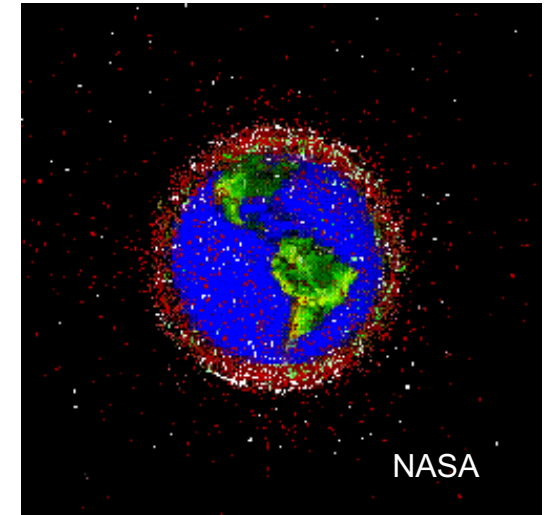
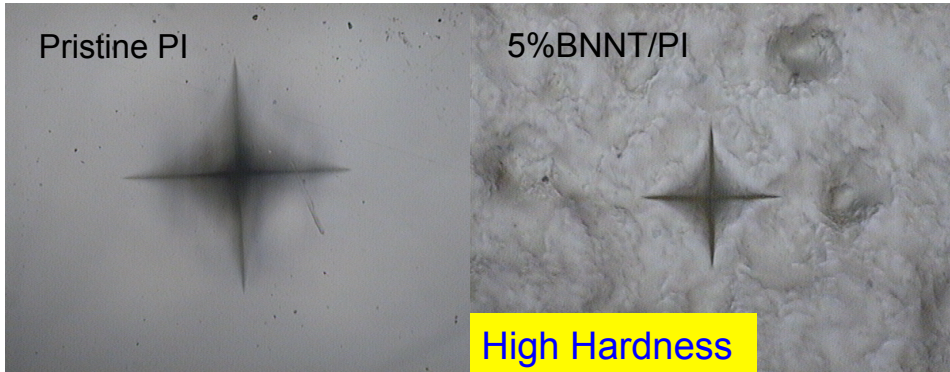
Diameter	Elastic modulus (GPa)	Breaking Strength (GPa)
D = 2.5 nm	760-960	14-38

Interfacial Strength: *In-situ* Single Nanotube Pull-Out Test

Credit: Prof Ke (SUNY Binghamton)

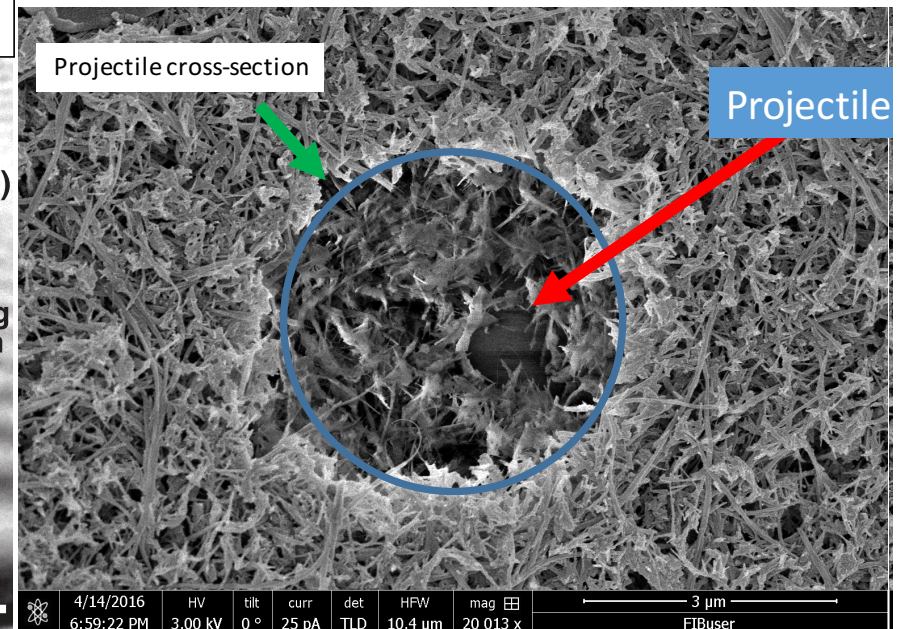
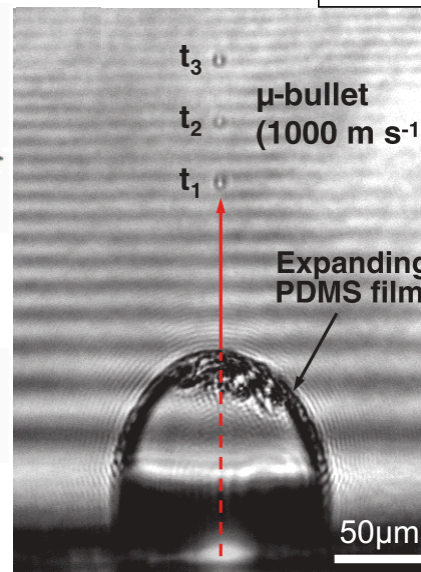
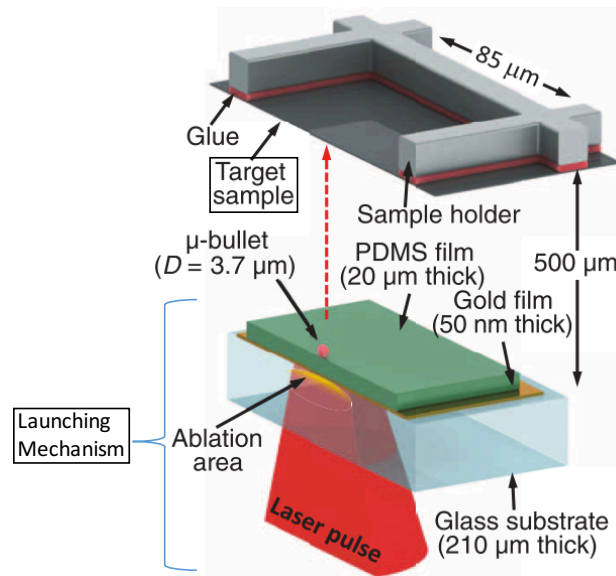


High Velocity Laser Induced Micro-Bullet Impact Test: BNNT Nonwoven Mat (Micro-Ballistics)

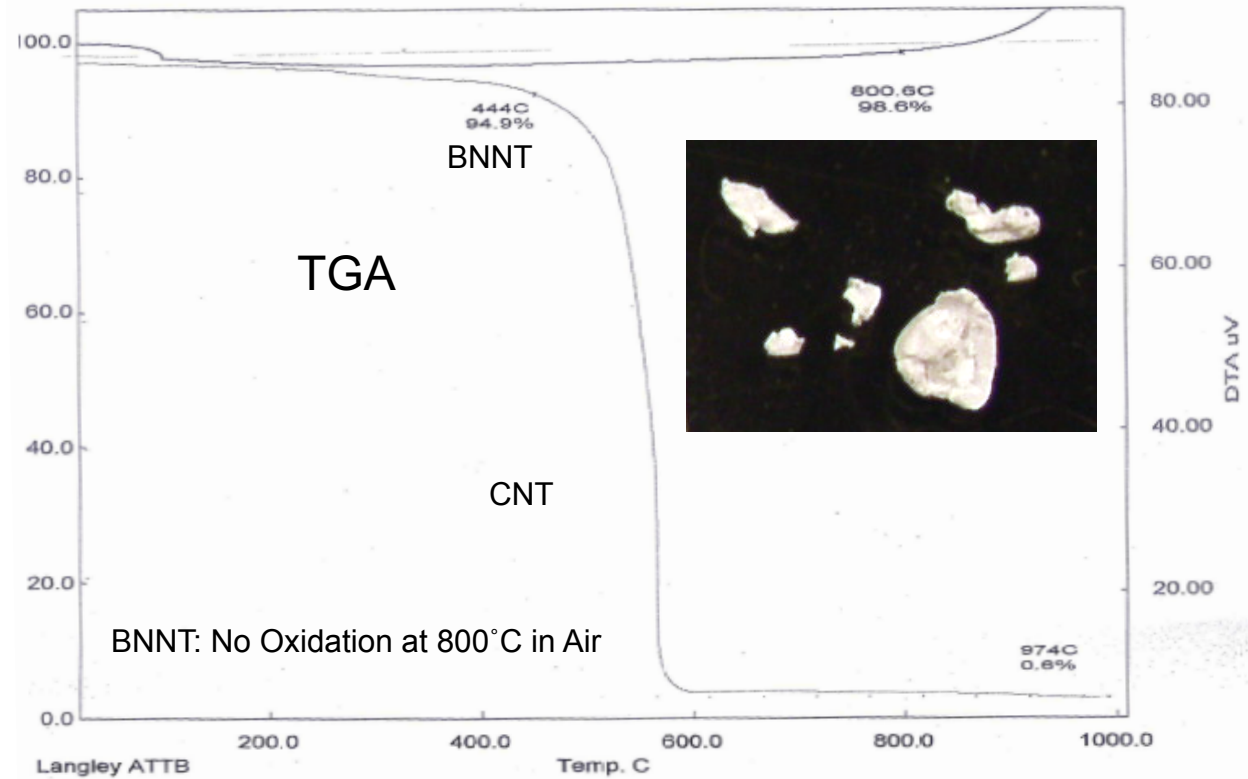
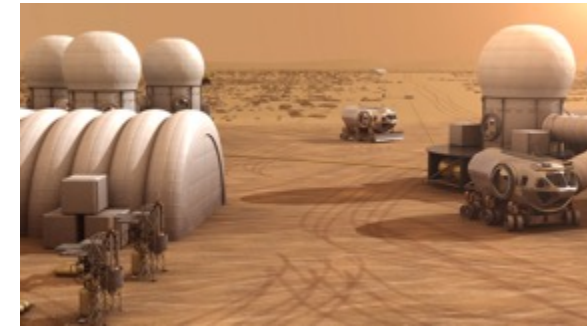
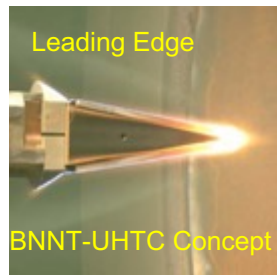
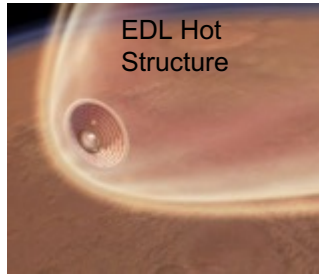


Simulated Micrometeorite Impact Test

Ballistic Velocities: 100-1500 m/s
Laser Induced Projectile Impact Test (LIPIT)



Thermal Properties of BNNT



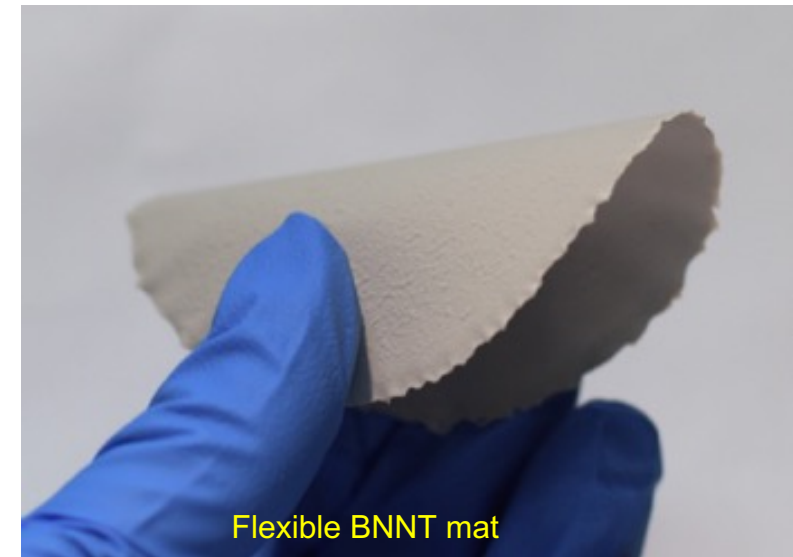
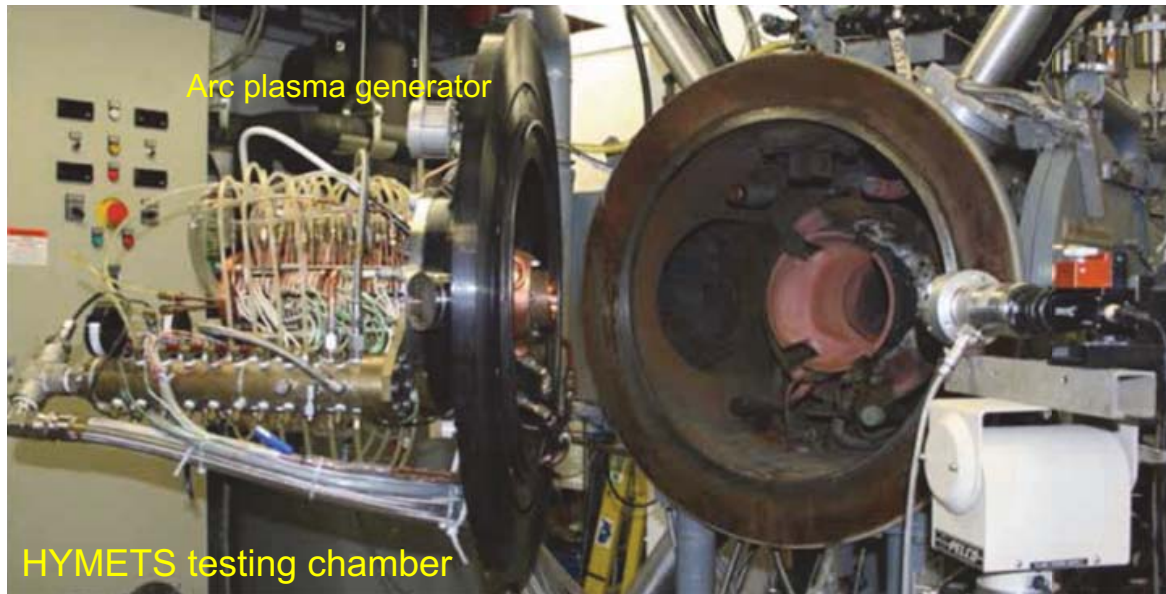
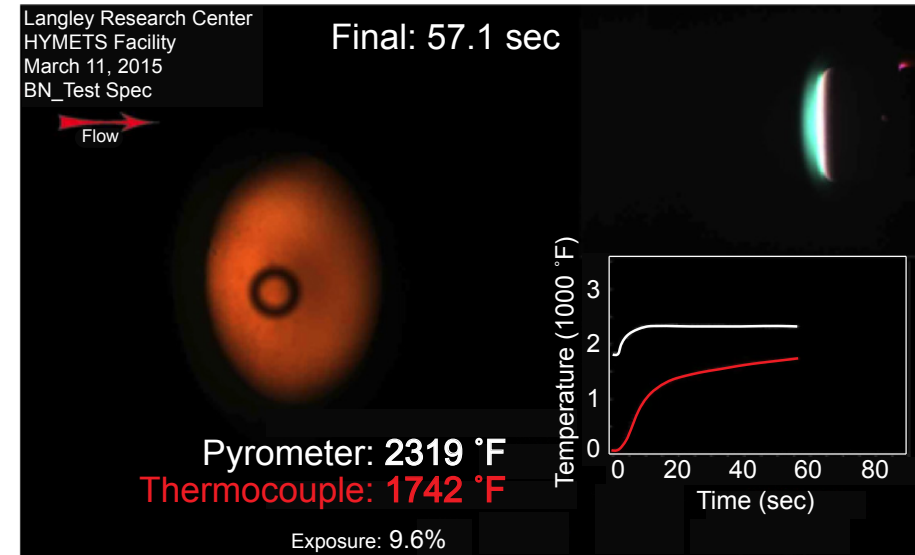
Hypersonic Materials Experiment Test System (HyMETS)

LaRC HYMETS Test Conditions

- Specimen Surface Temperature (°C): 1260
- Specimen Stagnation Pressure (atm): 0.013-0.079
- Free Stream Mach Number: 5.0
- Free Stream Enthalpy (kJ/kg): 5350-26749

HYMETS TEST for BNNT Mats

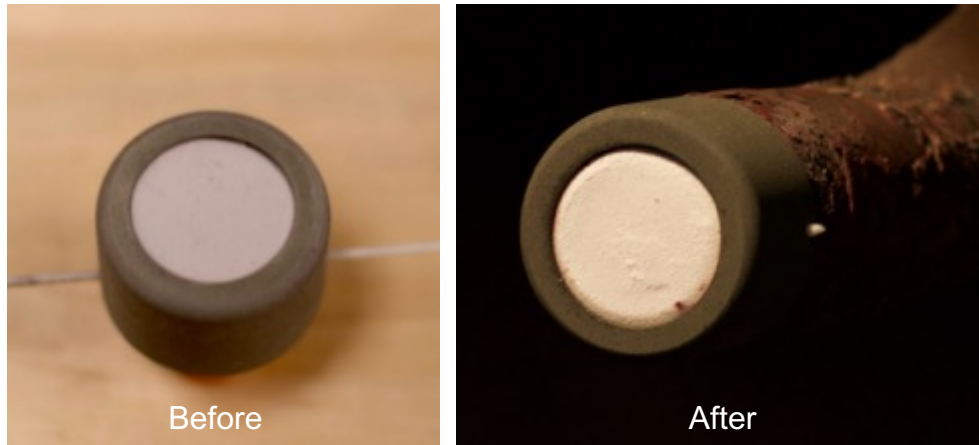
- Heat flux: Set at **50 W/cm²** (2nd Gen Mars EDL)
- Duration: 1 min - 5 min
- Atmosphere: Air (with 5% Ar)
- Cooled under Vacuum



Hypersonic Materials Experiment Test System (HYMETS)

Sample: BNNT Mat (as grown, nonwoven)

- Fabricated by a vacuum filtration process
- Diameter: 25 mm, Thickness: 2 mm, Density: $\sim 0.3 \text{ g/cm}^3$

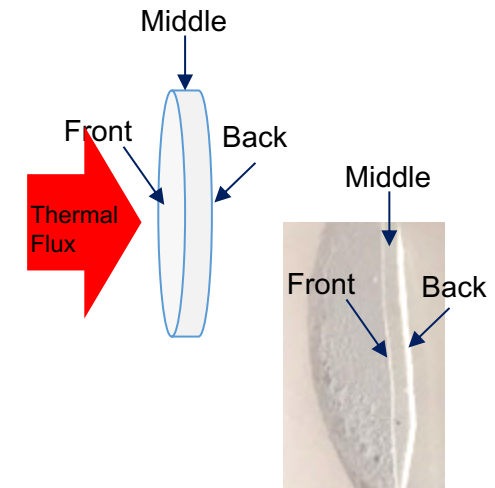
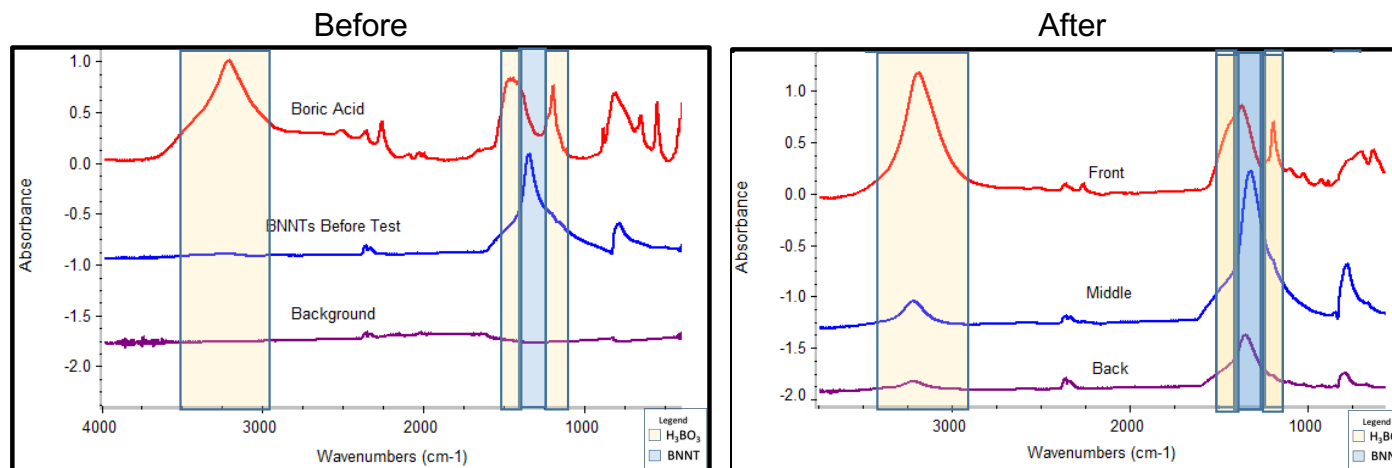


HYMETS Test Conditions

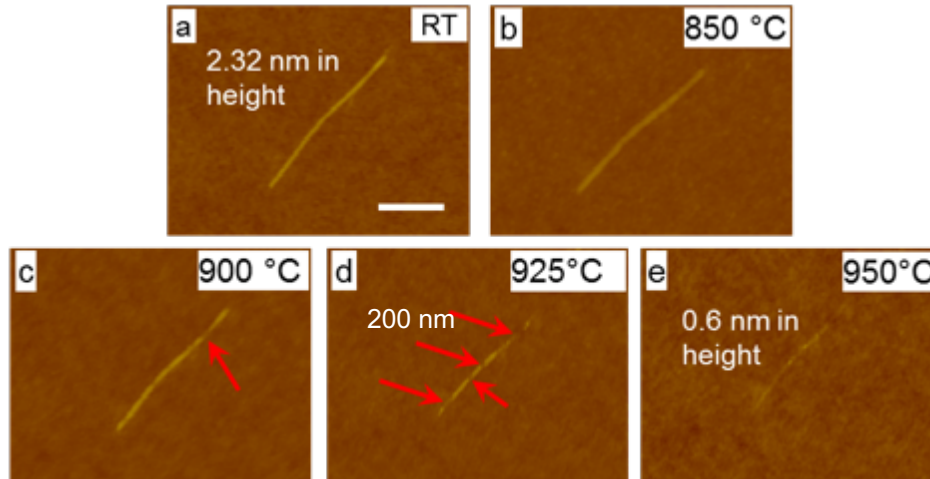
- Test duration: 1 min
- Surface temperature: 2400 °F (1315 °C)



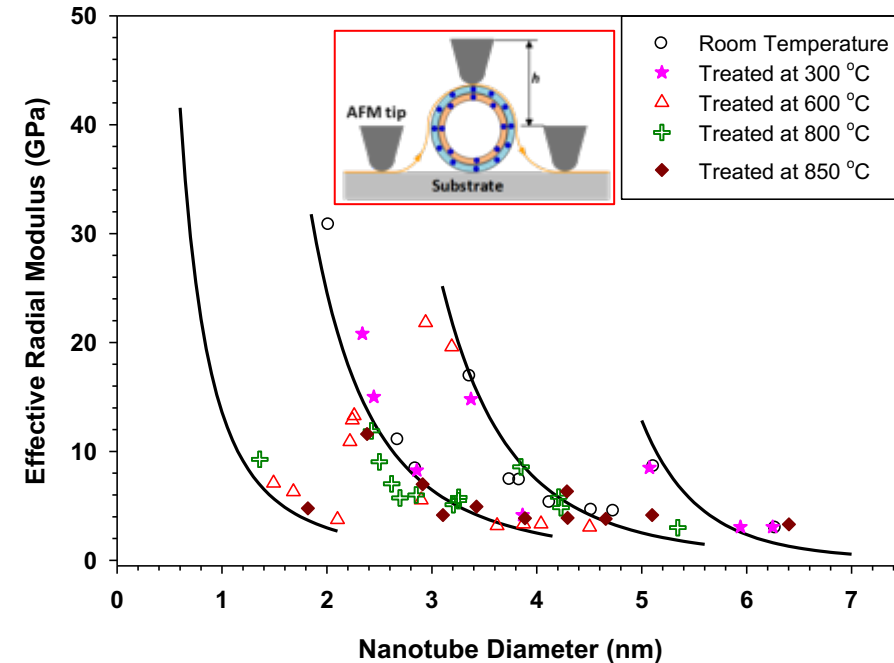
FT-IR Analysis of BNNT mat



Superior Structural and Mechanical Properties of BNNTs in High Temperature Environments

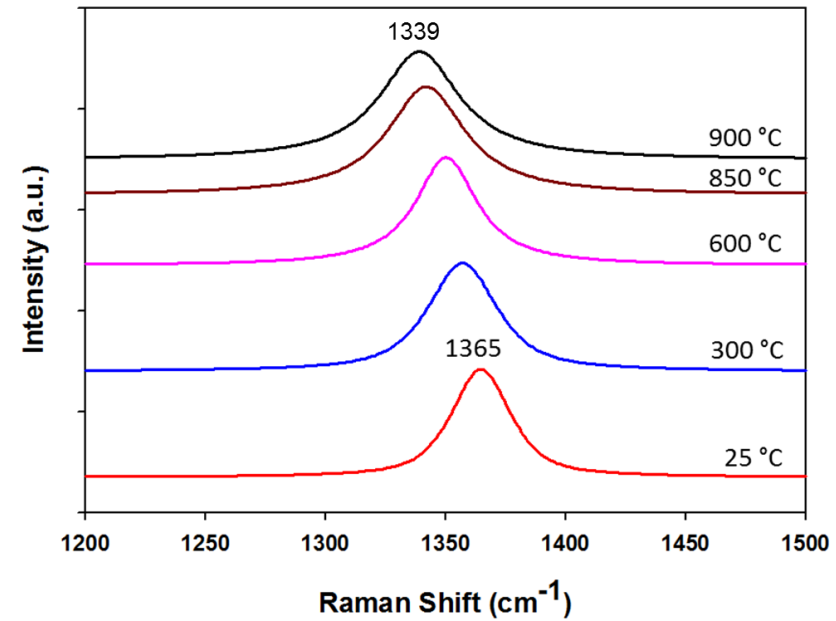
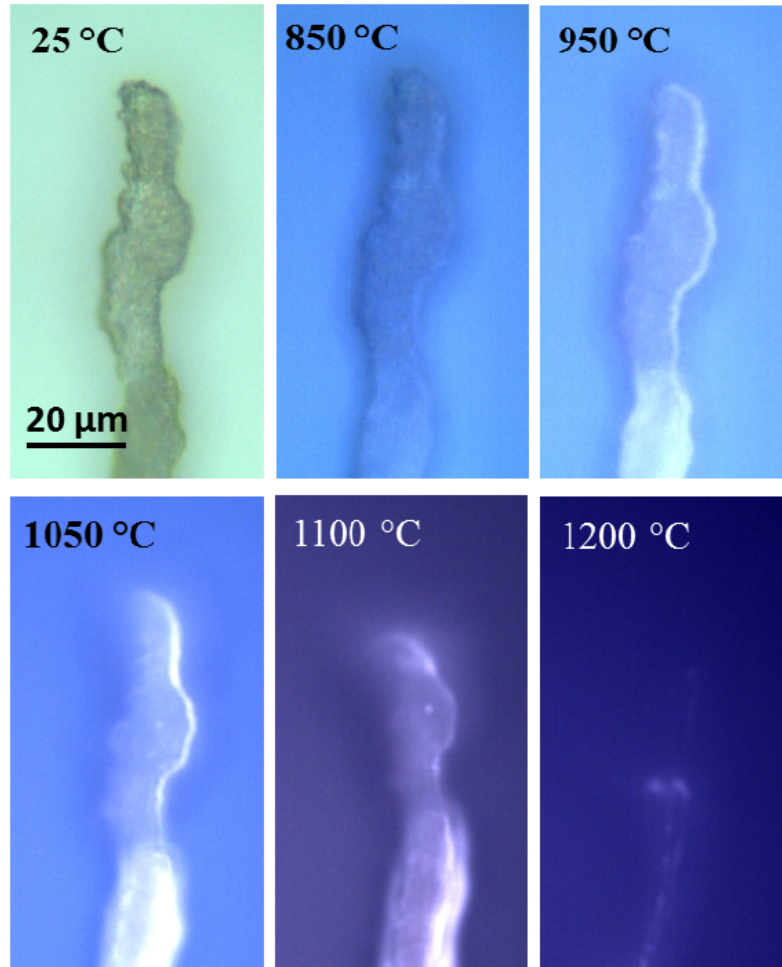


AFM studies show that **individual** BNNTs can survive at up to 850 °C in air and captures the sign of their structural degradation at 900 °C and above. (the red arrows mark the positions of the oxidation-induced tube broken sites).



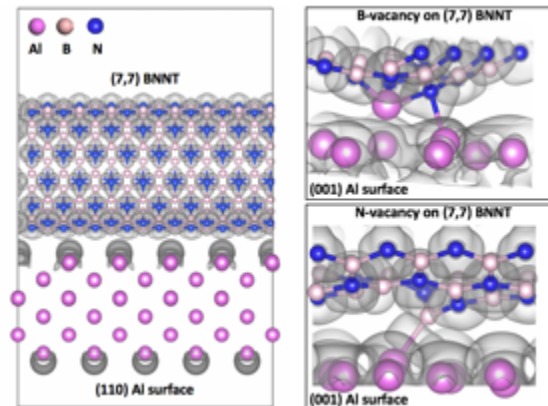
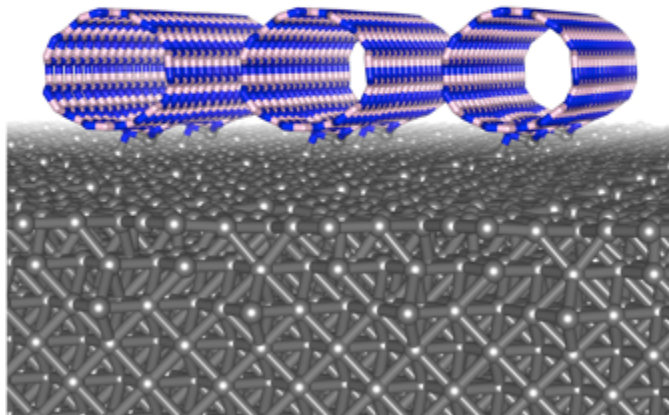
AFM-based nanomechanical compression tests (illustrated in inset drawing) show that the mechanical properties of **individual** BNNTs remain intact after thermally baked at up to 850 °C in air.

In Air



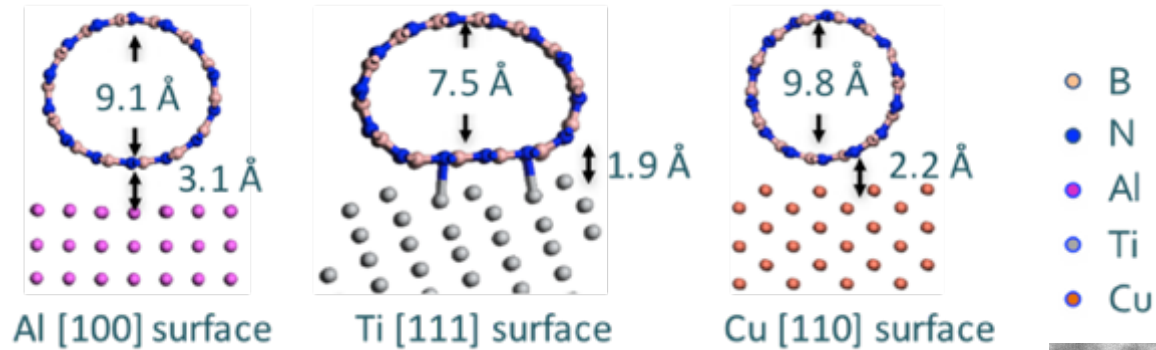
Noticeable structural damage to BNNT occurs at ~ 1050 °C in Air

BNNT Metal Matrix Composite (MMC)

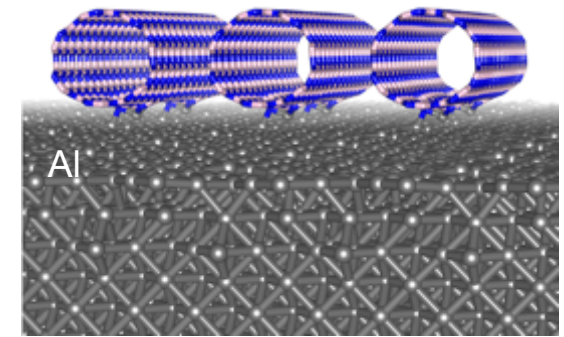


BNNT Metal Matrix Composite (BNNT-MMC)

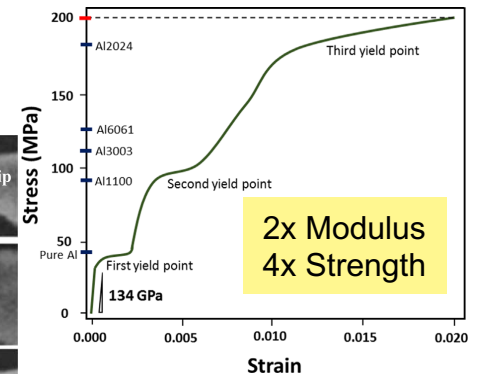
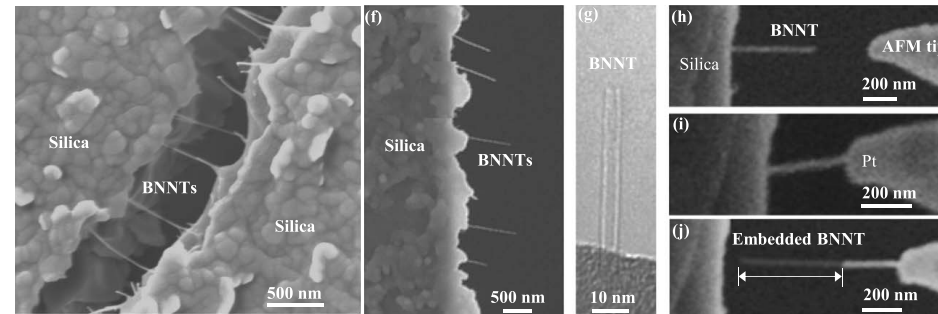
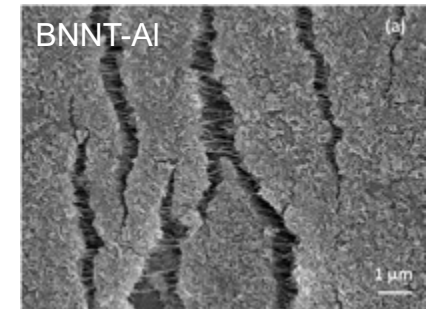
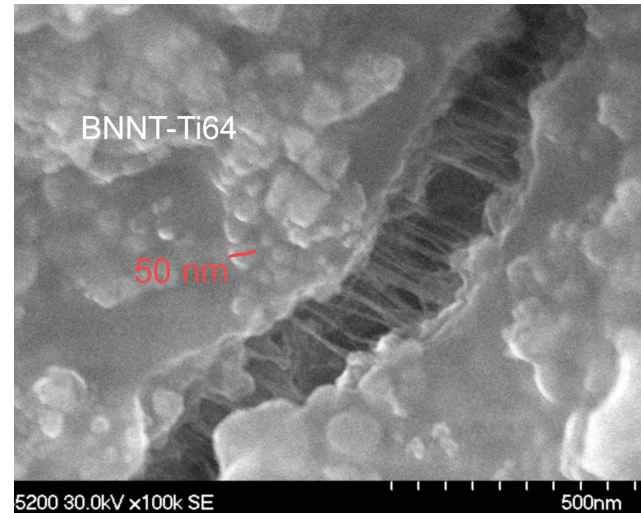
Pristine BNNT (7, 7)



U Queensland: Prof Bernhardt & Dr. Rhomann (AFOSR/AOARD)



Binding Energies**	Al[100] Surface	Ti[111] Surface	Cu[110] Surface
Pristine	-0.41	-1.77	-0.95
N-vacancy	-0.69	-2.00	-1.23
B-vacancy	-1.26	-3.30	n/a
C sub N	-0.64	-2.17	-1.26
C sub B	-0.51	-1.41	-1.00

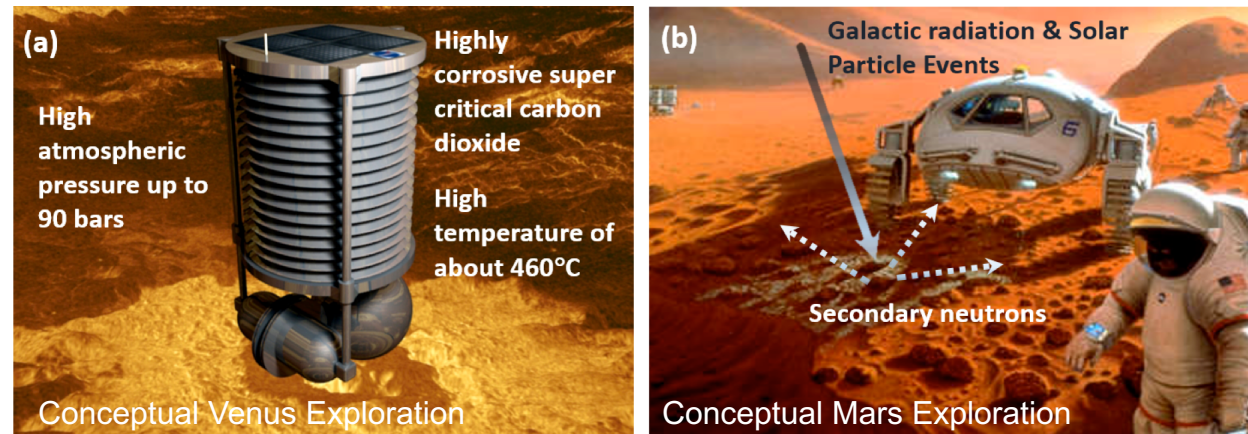


Adv. Eng. Mater. **18** 1747 (2016)
Agarwal Group FIT

J. Phys. Chem. C **120** 3509 (2016)
J. Phys. Chem. C **122** 15266 (2018)
Nanotechnology, **30** 25706 (2019) BNNT-ceramic interfacial strength
J. Am. Cer. Soc. Early view, BNNT-PDC composite (k: 2000% increase)

Multifunctional BNNT Polymer Composites

- Electroactive Properties
- Radiation Shielding Properties



Polymer Matrix:

- Polyimides [CP2, (b-CN)AMPB/ODPA (bCNAO), (b-CN)APB/PMDA (bCNAP)]
- Polyurethane
- PMMA
- Nylon 6,10

Inclusions:

- h-BN (hexagonal boron nitride powders)
- BNNT (purchased CVD, large, large diameter tubes)
- BNNT (high pressure, high temp, CO₂ laser as grown)

Alignment (stretched)

No alignment (unstretched) and stretched (up to 100%)

Polyimide (CP2)

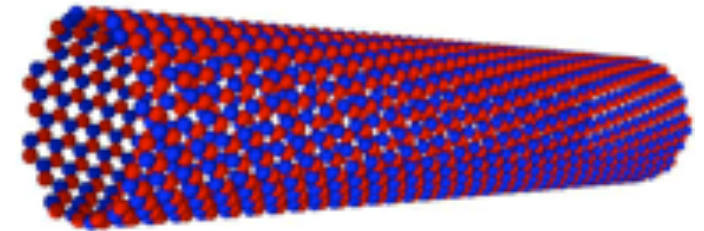
Polyimide (bCNAO)

Polyimide (bCNAM) (unstretched and stretched 100%)

5wt%hBN/polyimide (stretched 110%)

5wt%BNNT(CVD)/polyimide

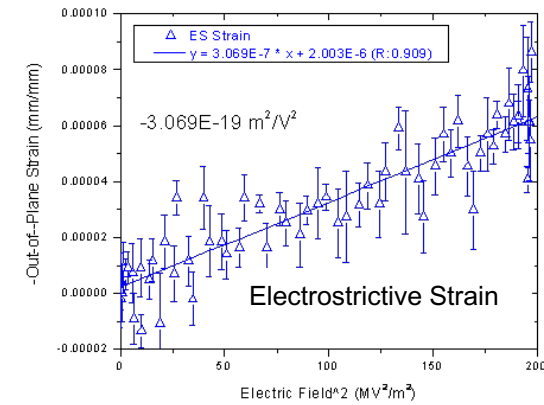
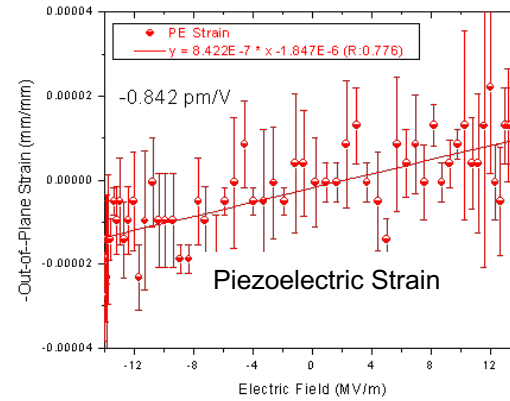
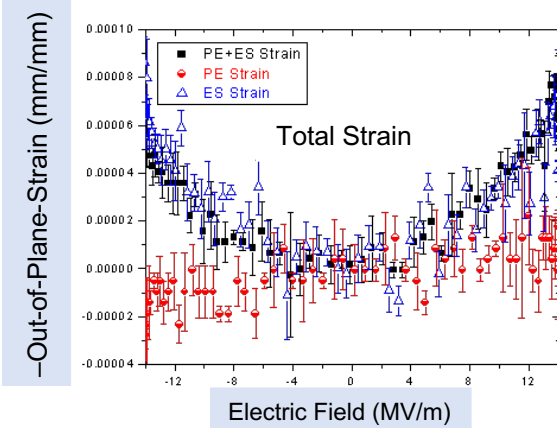
2wt%BNNT(laser)/polyimide (unstretched and stretched 100%)



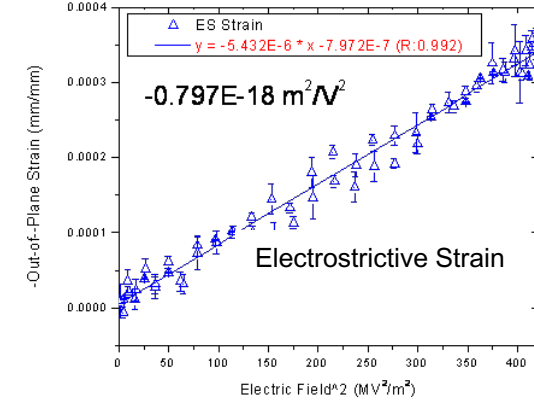
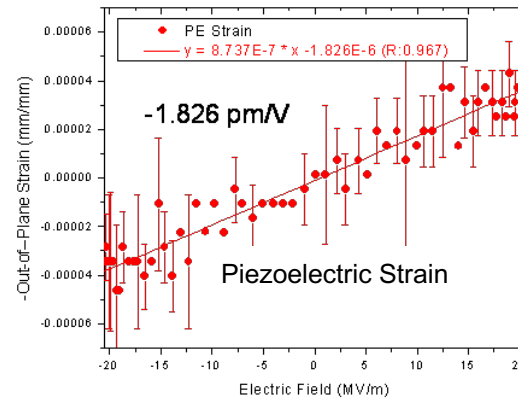
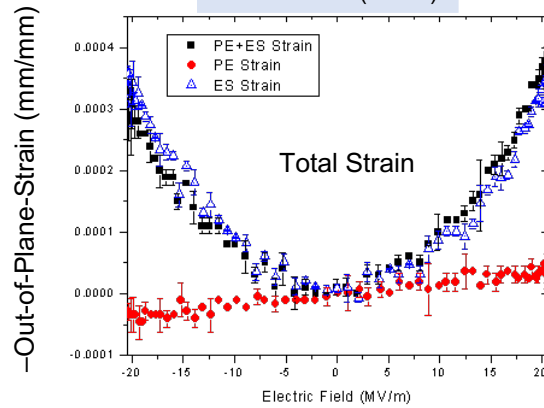
Actuation of Unstretched/Stretched 2% BNNT/Polyimide

Origin of Actuation → BNNT

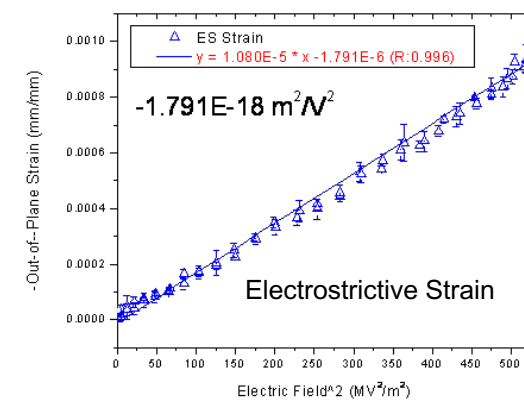
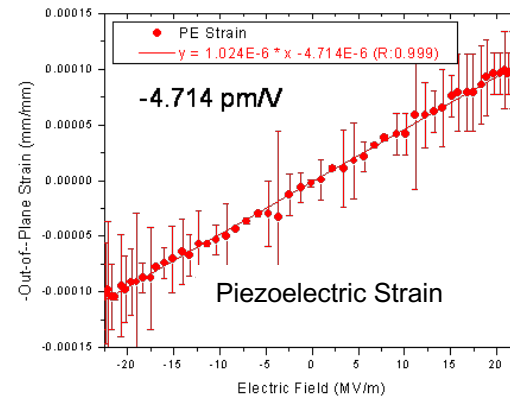
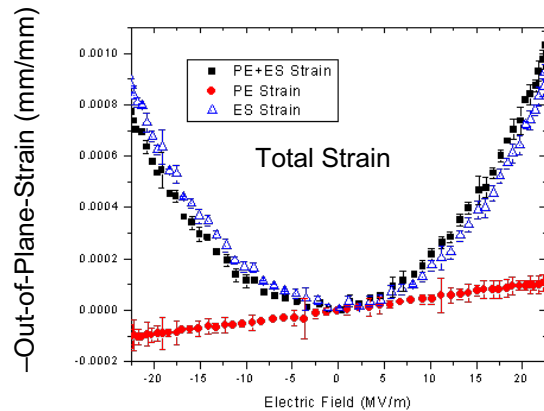
Unstretched



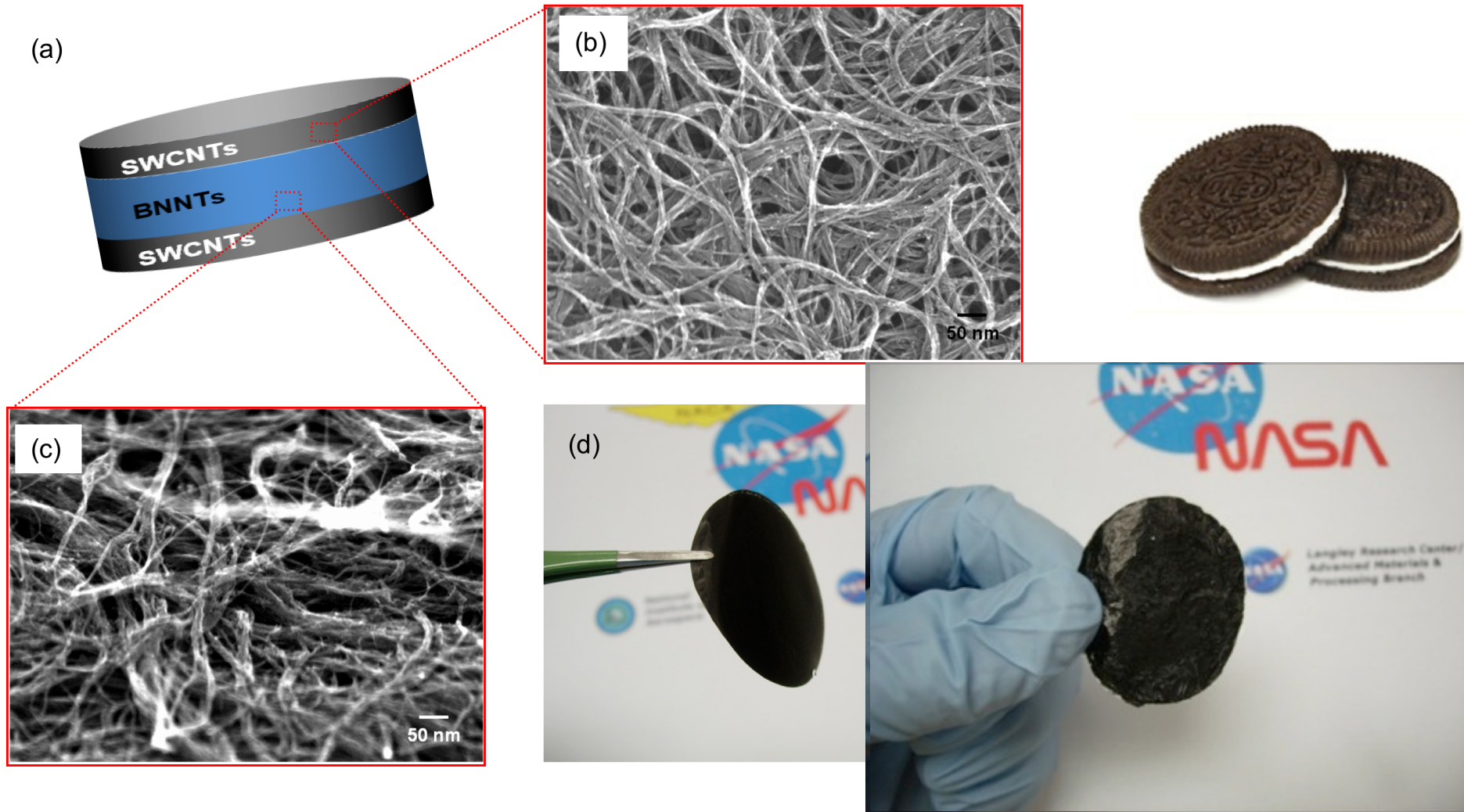
100% Stretched @225°C, Quenching



100% Stretched @225°C, Annealing

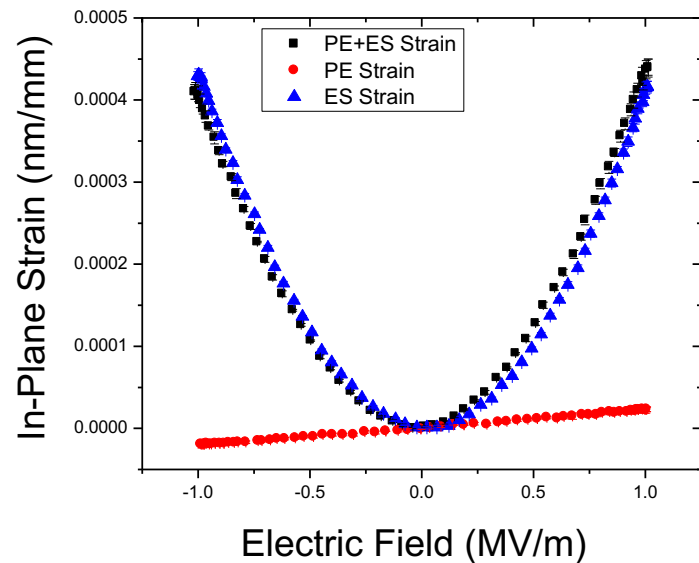


Langley All-Nanotubes Actuator/Sensor (LaRC-ANAS) Film



Goal: Flexible, transparent, large actuation, high sensitivity, mechanically durable

All-Nanotubes Actuator/Sensor Film: In-Plane Strain



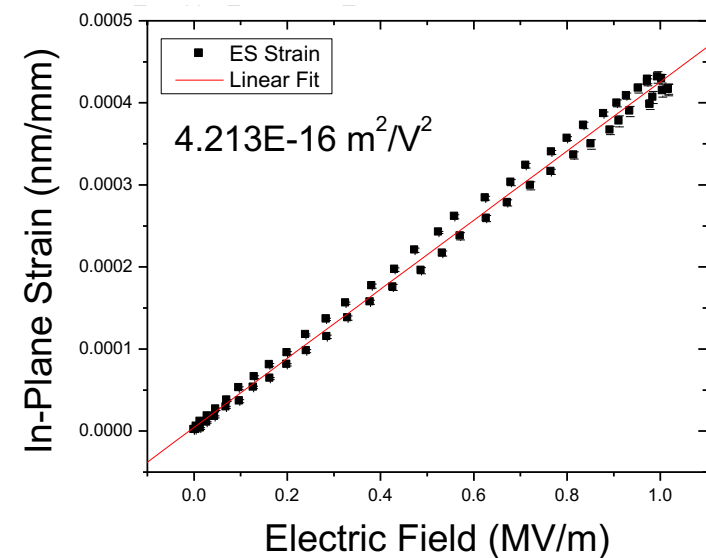
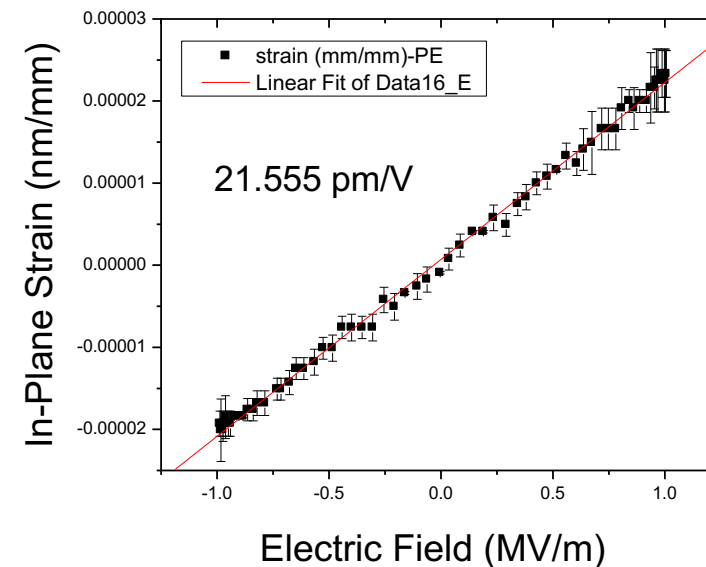
Field induced strain (e_{33})

$$e_{33} = d_{33} \cdot E + M_{33} \cdot E^2 + \dots$$

d_{33} : piezoelectric coefficient

M_{33} : electrostrictive coefficient

E : applied electric field

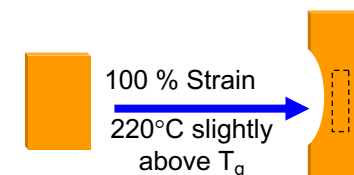


Actuation of Unstretched/Stretched h-BN/BNNT Materials



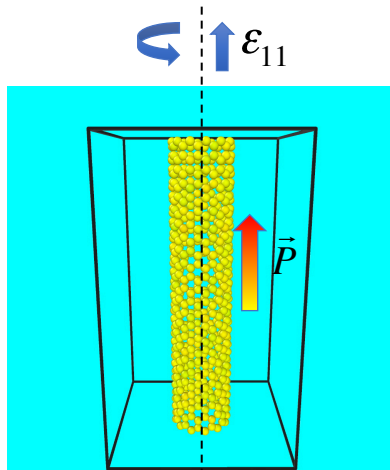
Materials	Inclusions	Polymer	Actuation
Polyimide (PI)	None	Polyimide	None
5%hBN/Polyimide (100% stretched)	5%hBN	Polyimide	None
5%BNNT (CVD)/Polyimide	5%BNNT (CVD)	Polyimide	None
Polyimide (100% stretched)	None	Polyimide	None
2%BNNT (laser)/Polyimide	2%BNNT	Polyimide	
2% BNNT (laser)/Polyimide (100% stretched)	2%BNNT	Polyimide	
20%BNNT/Polyurethane	>20% BNNT	Polyurethane	

h-BN → No Actuation
Commercial BNNT (CVD) → No Actuation
 Polymer → No Actuation
 Stretched Polymer → No Actuation
BNNT (high pressure, high temp laser) → Origin of the Actuation



Results: Piezoelectricity under Deformation

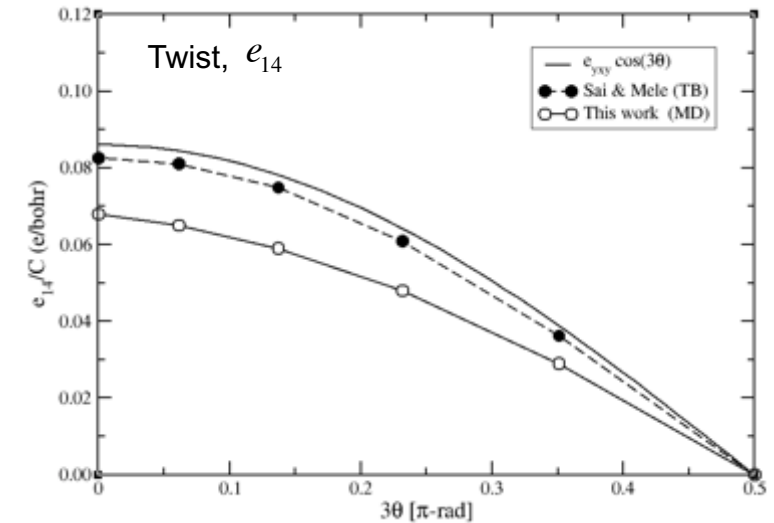
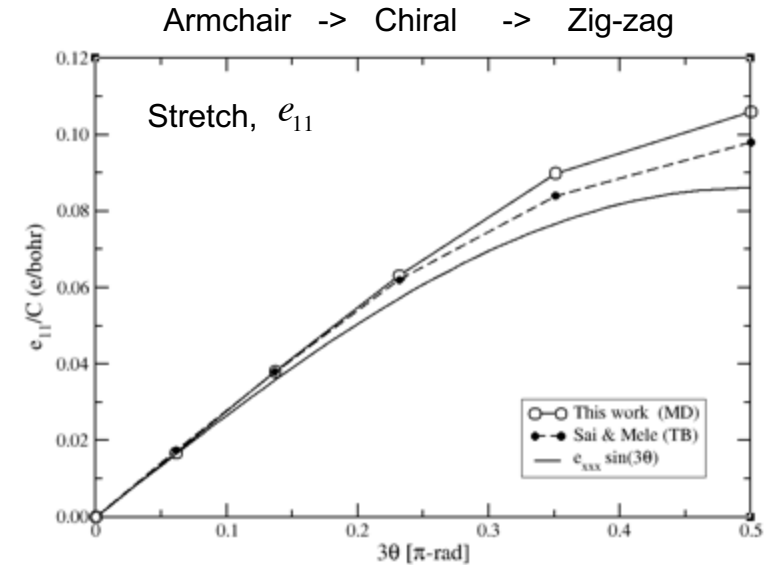
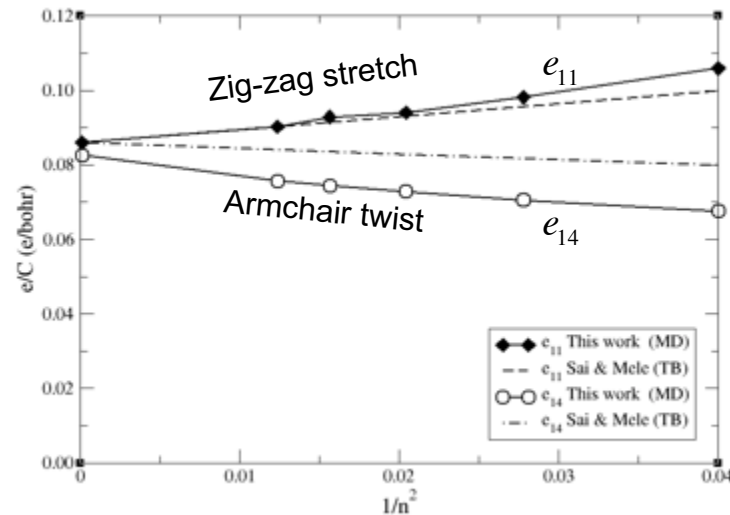
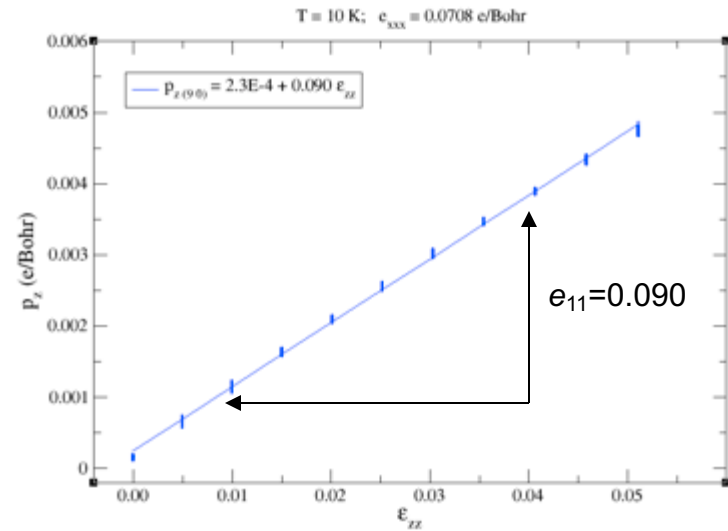
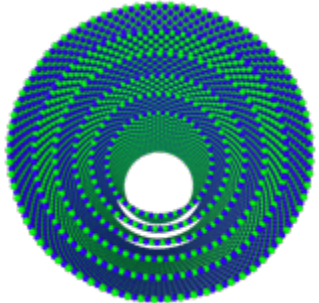
The Molecular Dynamics (MD) model is successful in representing the piezoelectric properties of BNNTs



$$p_z(\text{stretch}) = e_{11}\epsilon_s$$

$$p_z(\text{twist}) = e_{14}\epsilon_t$$

MWBNNT

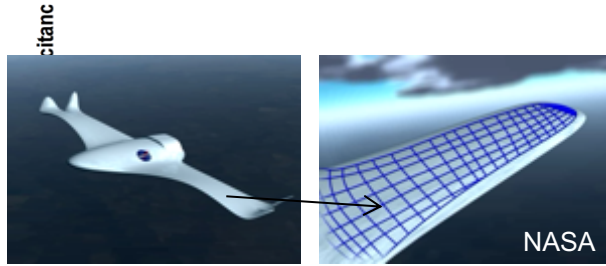
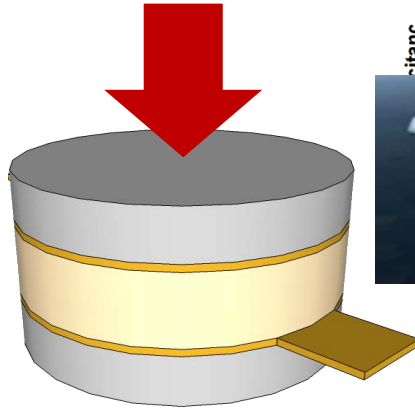


2D Printed Electronics as Sensory Applications: BNNT Composites Capacitive Sensors

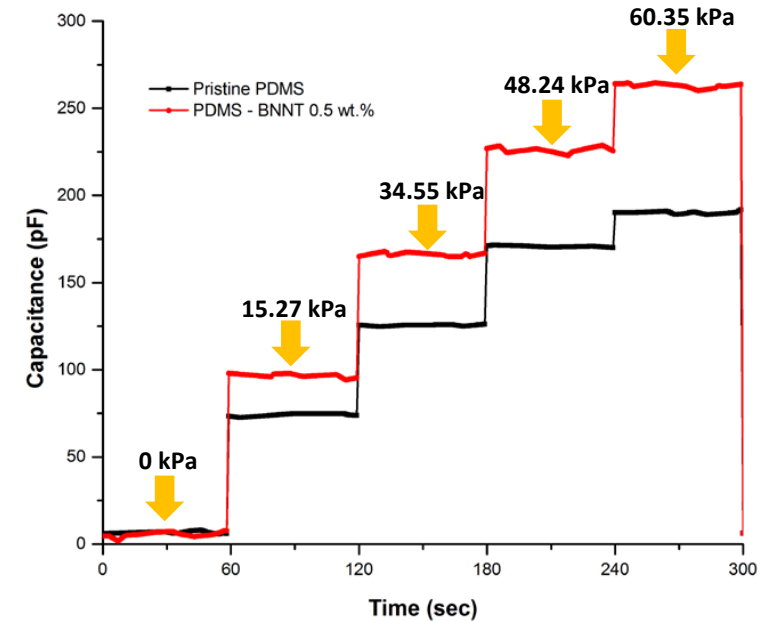
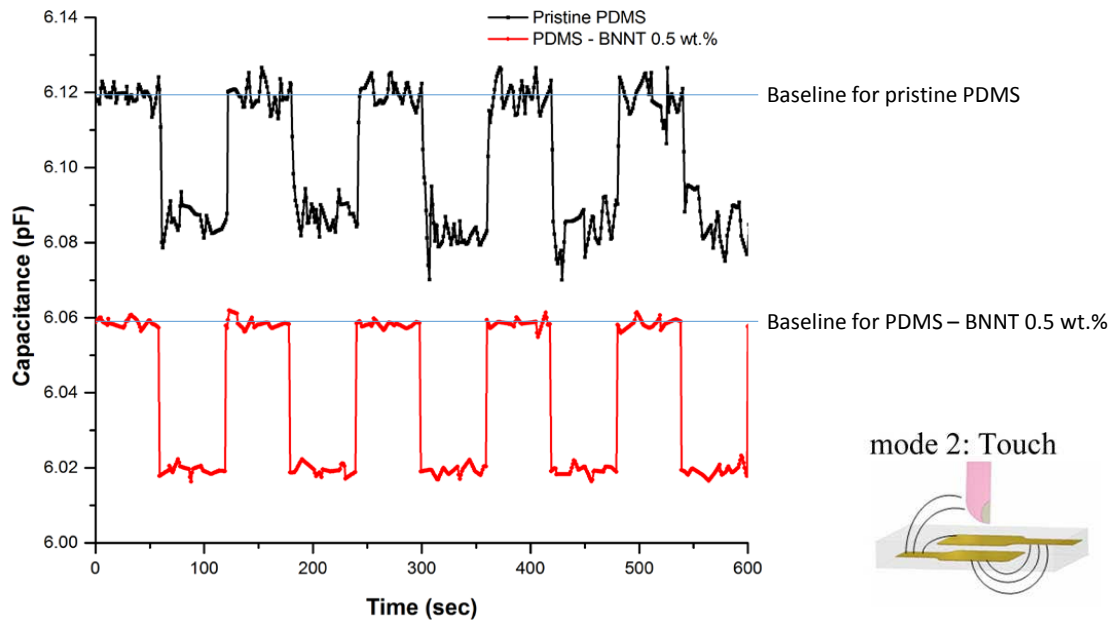
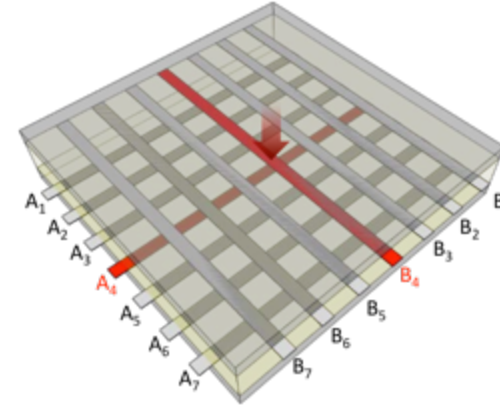


Touch Sensitive Sensor

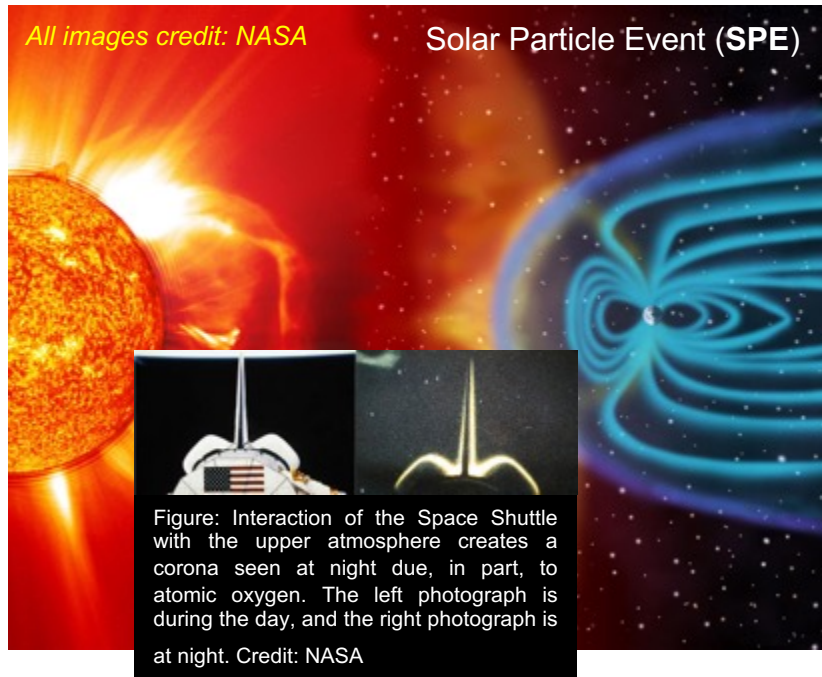
By touch



Pressure Sensitive Sensor



Radiation Shielding Properties



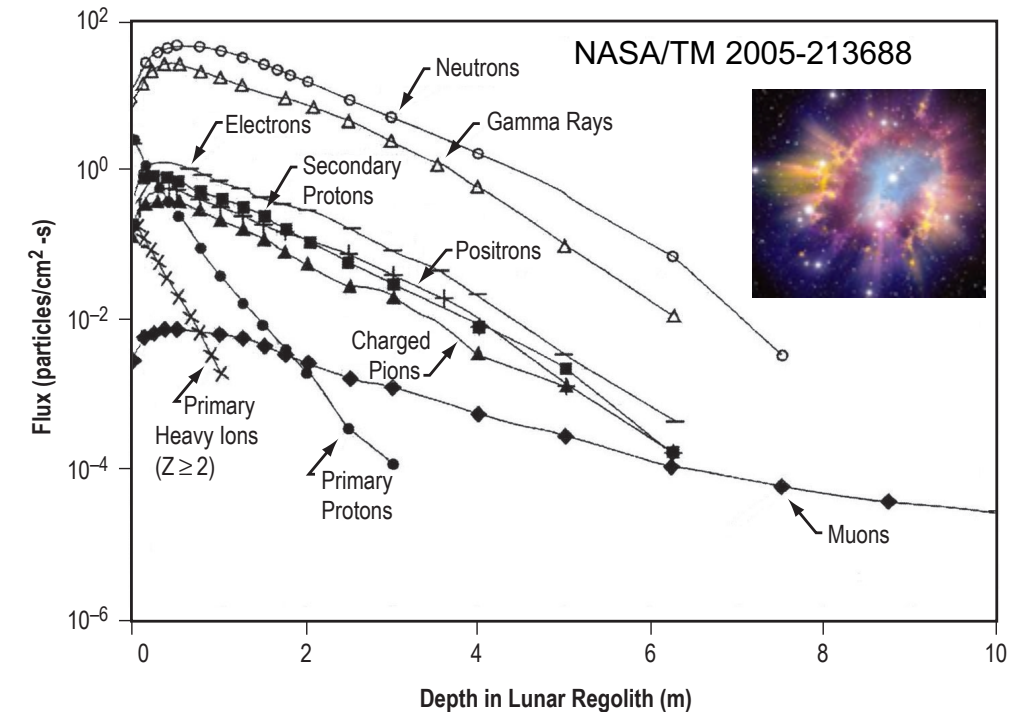
Science 340 1080 (2013)

Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory

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The Mars Science Laboratory spacecraft, containing the Curiosity rover, was launched to Mars on 26 November 2011, and for most of the 253-day, 560-million-kilometer cruise to Mars, the Radiation Assessment Detector made detailed measurements of the energetic particle radiation environment inside the spacecraft. These data provide insights into the radiation hazards that would be associated with a human mission to Mars. We report measurements of the radiation dose, dose equivalent, and linear energy transfer spectra. The dose equivalent for even the shortest round-trip with current propulsion systems and comparable shielding is found to be 0.66 ± 0.12 sievert.

Galactic Cosmic Ray (GCR) and produced Secondaries in lunar regolith



Spacecraft data nails down radiation risk for humans going to Mars

Nature News, May 30, 2013, Ron Cowan

Interviewed Sheila Thibeault at NASA Langley about the study published in *Science*

Mars Science Laboratory (MSL) during its cruise to Mars between 6 December 2011 and 14 July 2012 (253 days)

Mars Round Trip Dose Equivalent is around 0.66 Sievert

Neutron Radiation Shielding Study

Materials

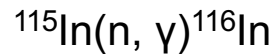
- Hydrogen, Boron, Nitrogen
- BN, BNNT, Gd
- Low density polyethylene (LDPE), polyimide (Kapton, CP2, (b-CN)APB/ODPA), polyurethane

Radiation Shielding Structural Materials

- In-situ polymerization under simultaneous sonication and shear
- Supercritical Fluid Infusion

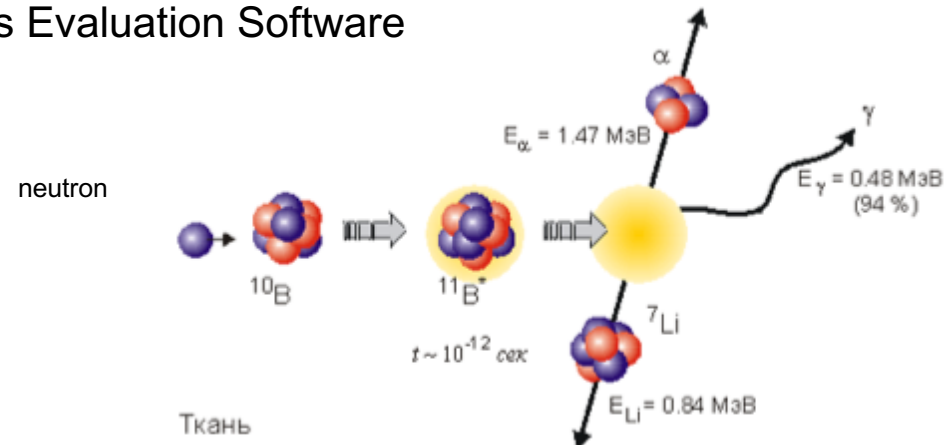
Characterization

- Neutron Radiation Exposure Lab: Source: Am/Be 1Curie
- Moderated by borated polyethylene cylinder block (44mm thick): 45 mrem/hr thermal neutrons
- Sample: 2 x 2" polymer and BN polymer composites
- Detection Foil: 1.25" Indium Foil (0.5mm, 19 barns)
- RSMES: Radiation Shielding Materials Evaluation Software



Modeling

- OLTARIS



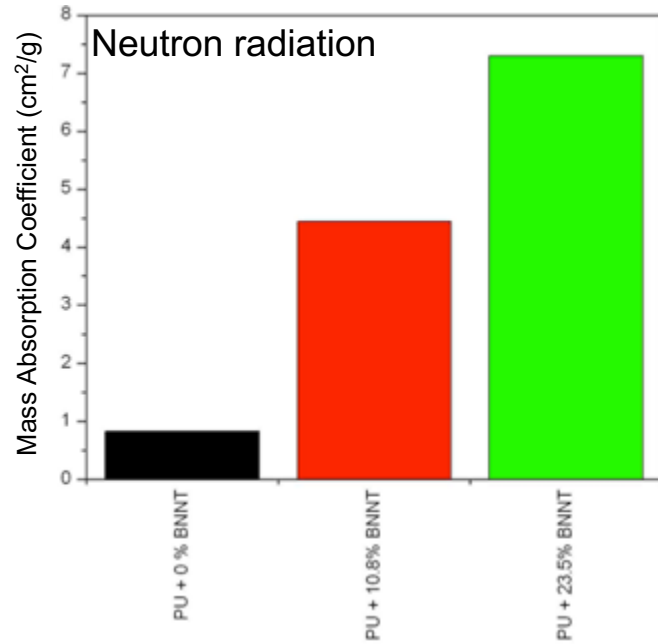
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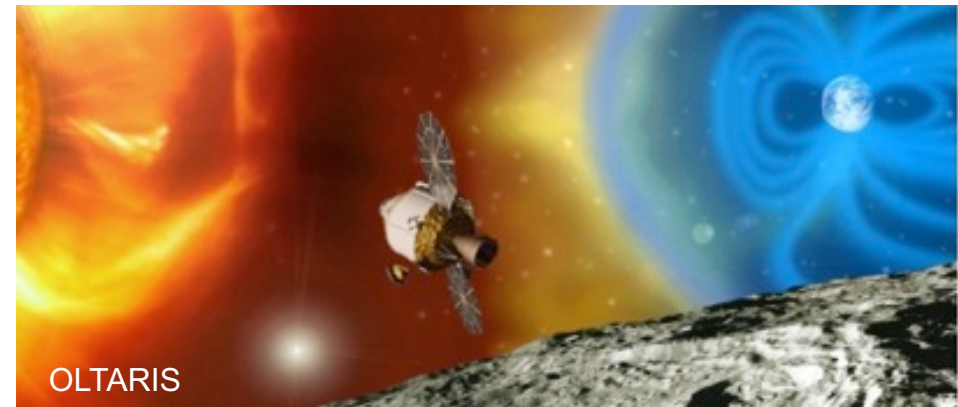
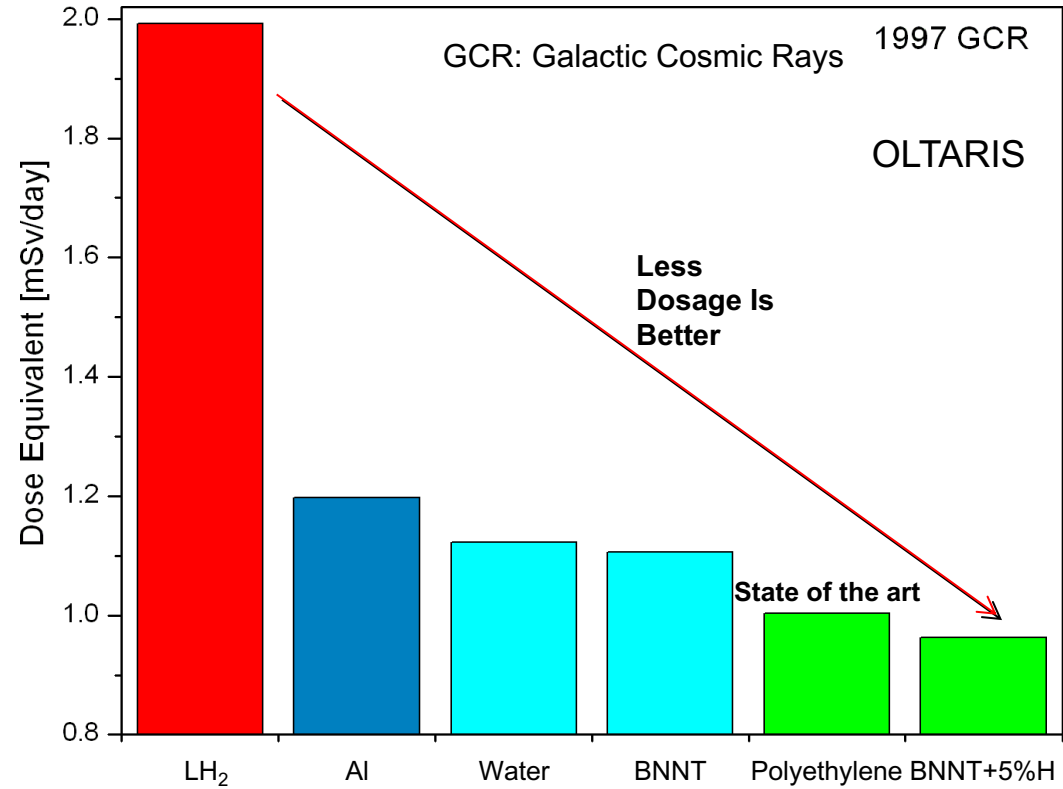
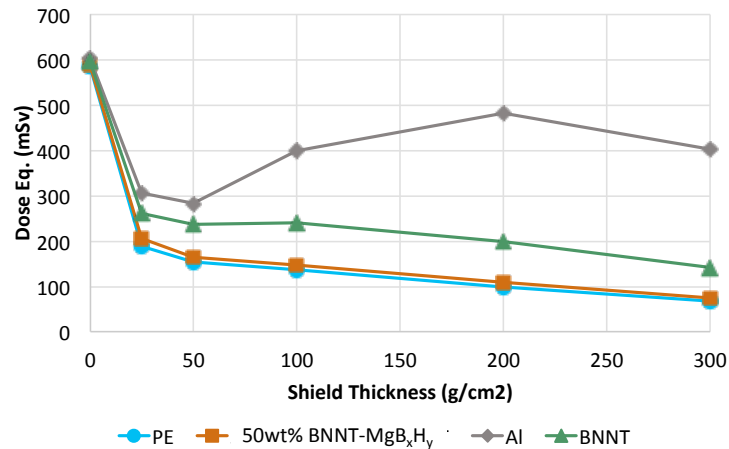
Geiger-Müller Tube

All images credit: NASA

Radiation Shielding Effectiveness of BNNT Composites



BON-14 GCR Model in Free Space with 1977 Solar Min. incident on Vehicles with varying thicknesses



Summary



- High Temperature-Pressure BNNT synthesis method was introduced.
- BNNT dispersion was successfully achieved by thermodynamic approach using Hansen solubility parameters for single and co-solvent systems.
- Interfacial shear strength and fracture energy of BNNT with polymers were superior to those of CNT.
- BNNT exhibited excellent thermal stability under a simulated planetary entry environment along with flame resistance and retardation properties
- BNNT and BNNT polymer composites exhibited excellent piezoelectricity as well as electrostrictive behavior even without poling.
- BNNT exhibited excellent neutron radiation shielding effectiveness and hydrogen containing BNNT showed superb shielding effectiveness against GCR and SPE.

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Thank you

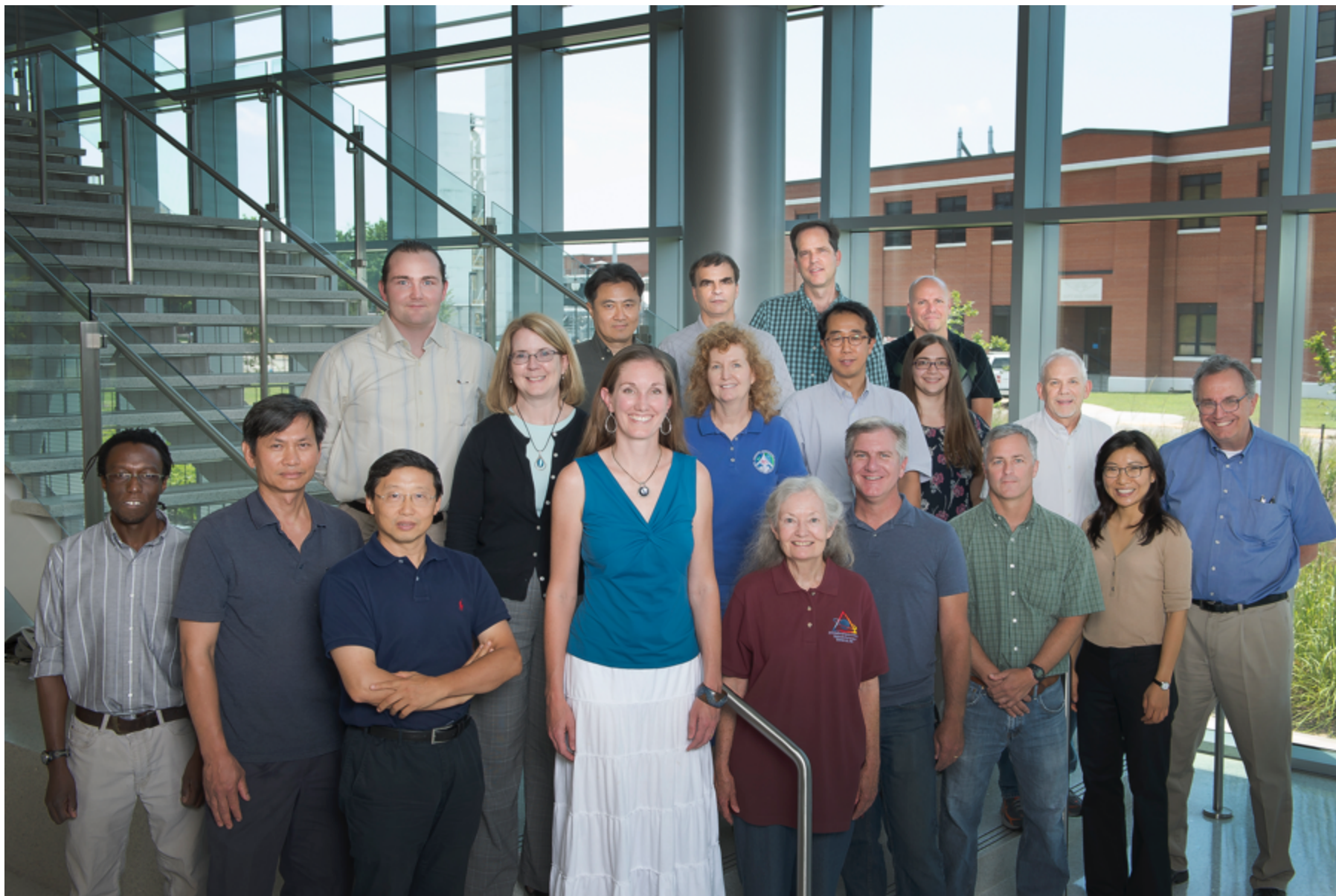


Image credit: NASA

Team BNNT