Images Credit: NASA

Multifunctional Structural Materials for Sustainable Human Exploration in Extreme Space Environments

Cheol Park, Sang-Hyon Chu, and Catharine Fay

Advanced Materials and Processing Branch, NASA Langley Research Center, Hampton VA USA

Outline

- Human Space Exploration and Motivation
- Extreme Environments in Space
- Introduction of Advanced Materials in Extreme Space Environments: Boron Nitride Nanotube (BNNT)
- BNNT and BNNT Composite Application
- Multifunctional Properties in Extreme Environments
  - Dispersion and Purification
  - Mechanical Properties
  - Thermal Properties
  - Sensor/Actuator/Energy Harvester
  - Radiation Shielding
- Summary

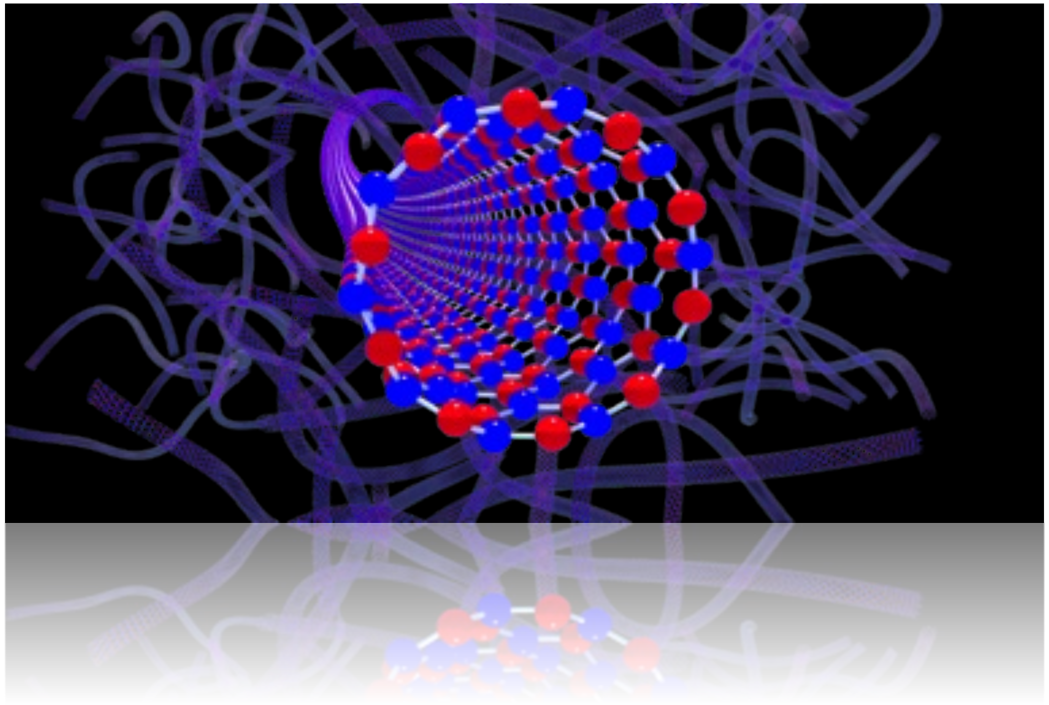
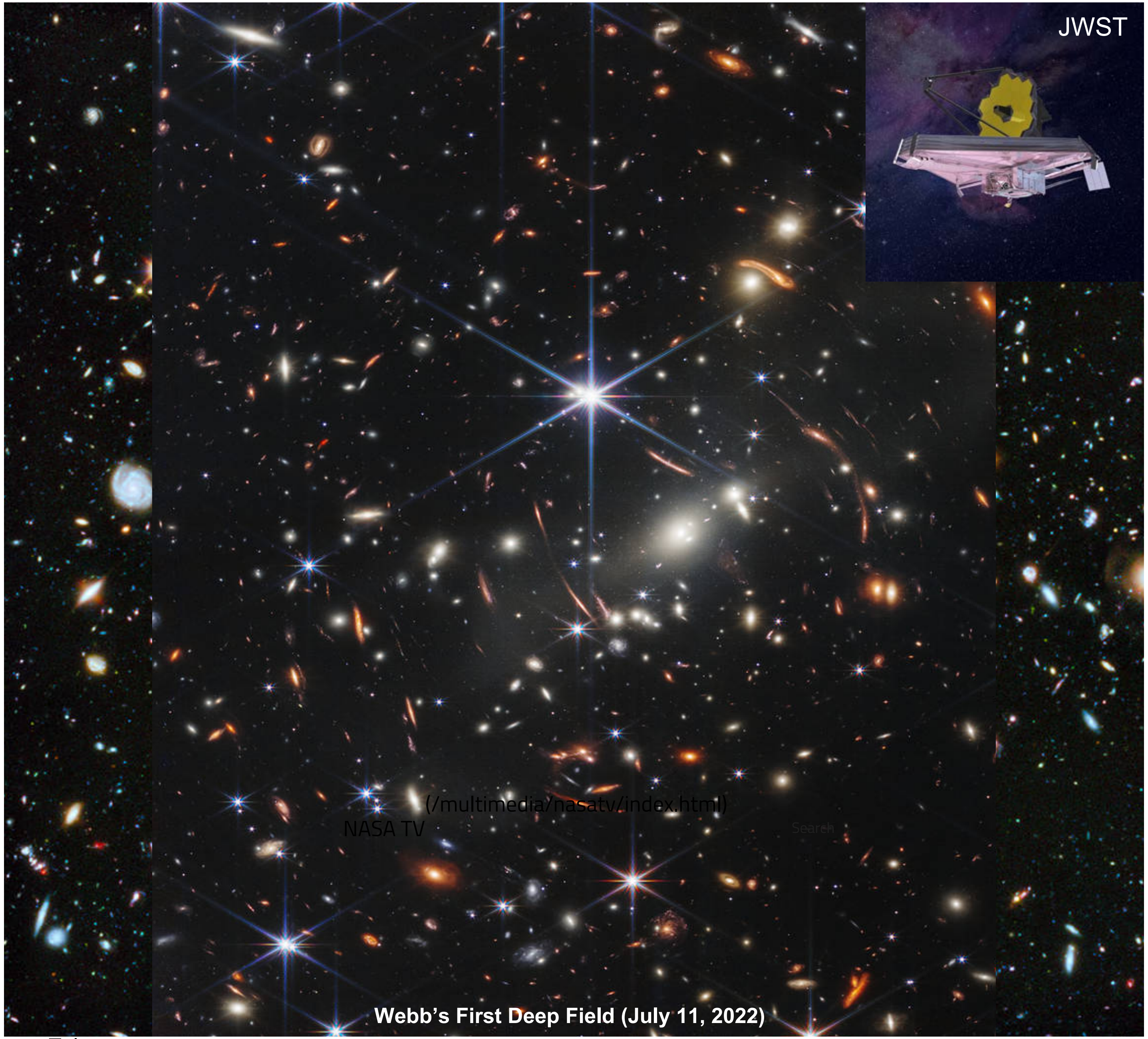


Image Credit: NASA

Are We Alone in Universe?

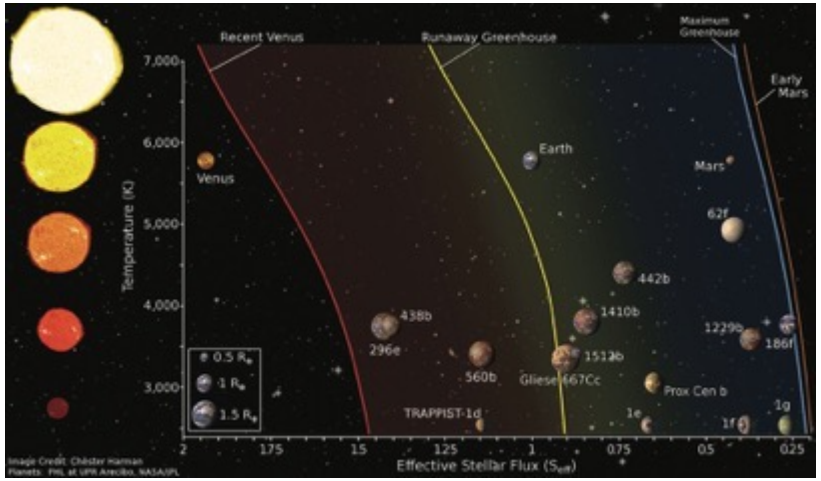


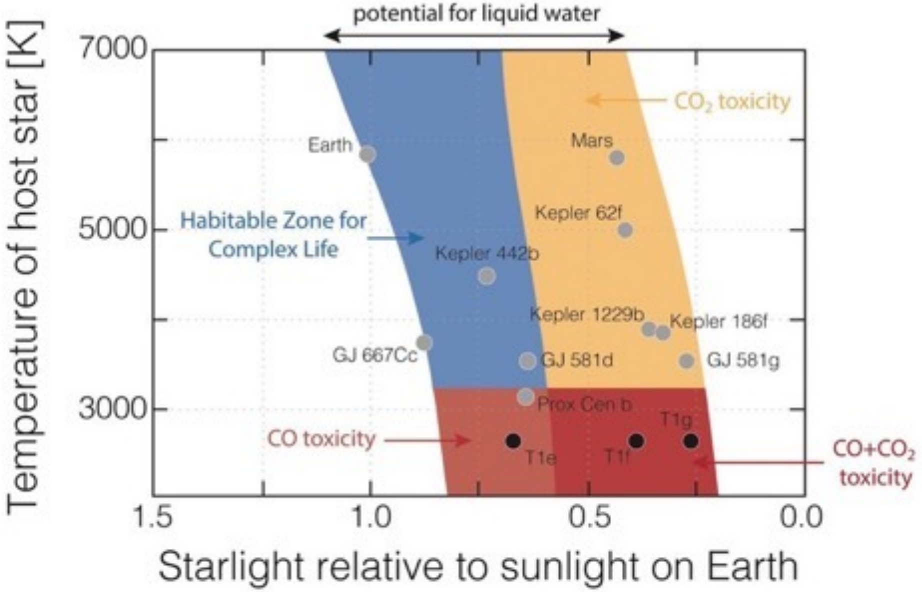
Webb's First Deep Field (July 11, 2022)

Images Credit: NASA   JWST: James Webb Space Telescope

Are We Alone in Universe?

Exoplanet (Habitable zone for complex life)





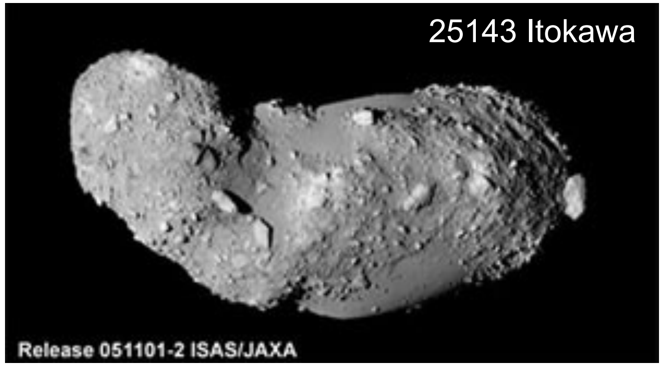
This artist’s impression shows a view of the surface of the planet **Proxima b** orbiting the red dwarf star Proxima Centauri, the closest star to the solar system. Credit: ESO/M. Kornmesser (Movie Avatar1: Unobtainium in Pandora)

An artist's concept of what **Kepler-1649c** could look like from its surface. Credit: NASA/Ames Research Center/Daniel Rutter

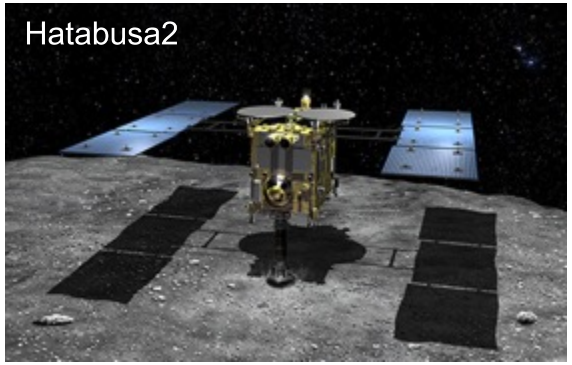
Astrobiology **18**, 663 (2018)
Astrophysical J **19**, 878 (2018)

Images Credit: NASA

Can We Harness Energy and Resources From Outer Space?



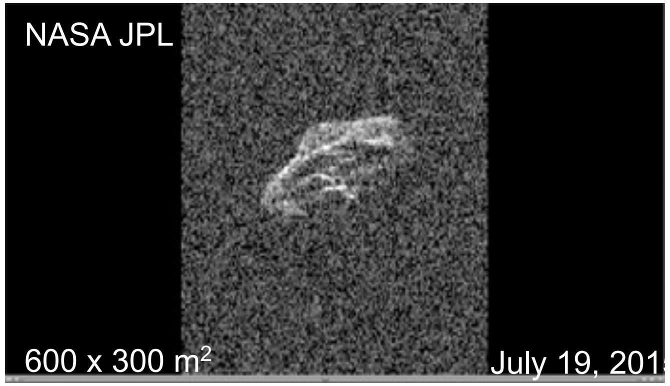
Hayabusa (JAXA: Japan Aerospace Exploration Agency) Landed on Small (550 x 180 m^2) asteroid 25143 Itokawa (1998 SF36) and returned safely to the Earth on June 13, 2010 (with less than 1mg sample)



Hayabusa2 (JAXA) was launched on December 3, 2014, arrived at the asteroid Ryugu in June 2018, stayed around there for one and half years before leaving the asteroid Nov 2019, and returned to Earth in Dec 2020 safely with asteroid sample (delivered to NASA in Nov 2021)

An artist's concept of ESA's (European Space Agency) Rosetta (top) and Philae (middle) spacecraft, and comet (bottom). Credit: ESA–C. Carreau/ATG medialab. Spacecraft launched on Mar 2, 2004 and the comet orbiting and landing mission ended on Sept 30, 2016 successfully.

Double Asteroid Redirect Test (DART) spacecraft successfully collided with Dimorphos (minor-planet moon of the asteroid Didymos) to change the orbit (Sept 26, 2022)



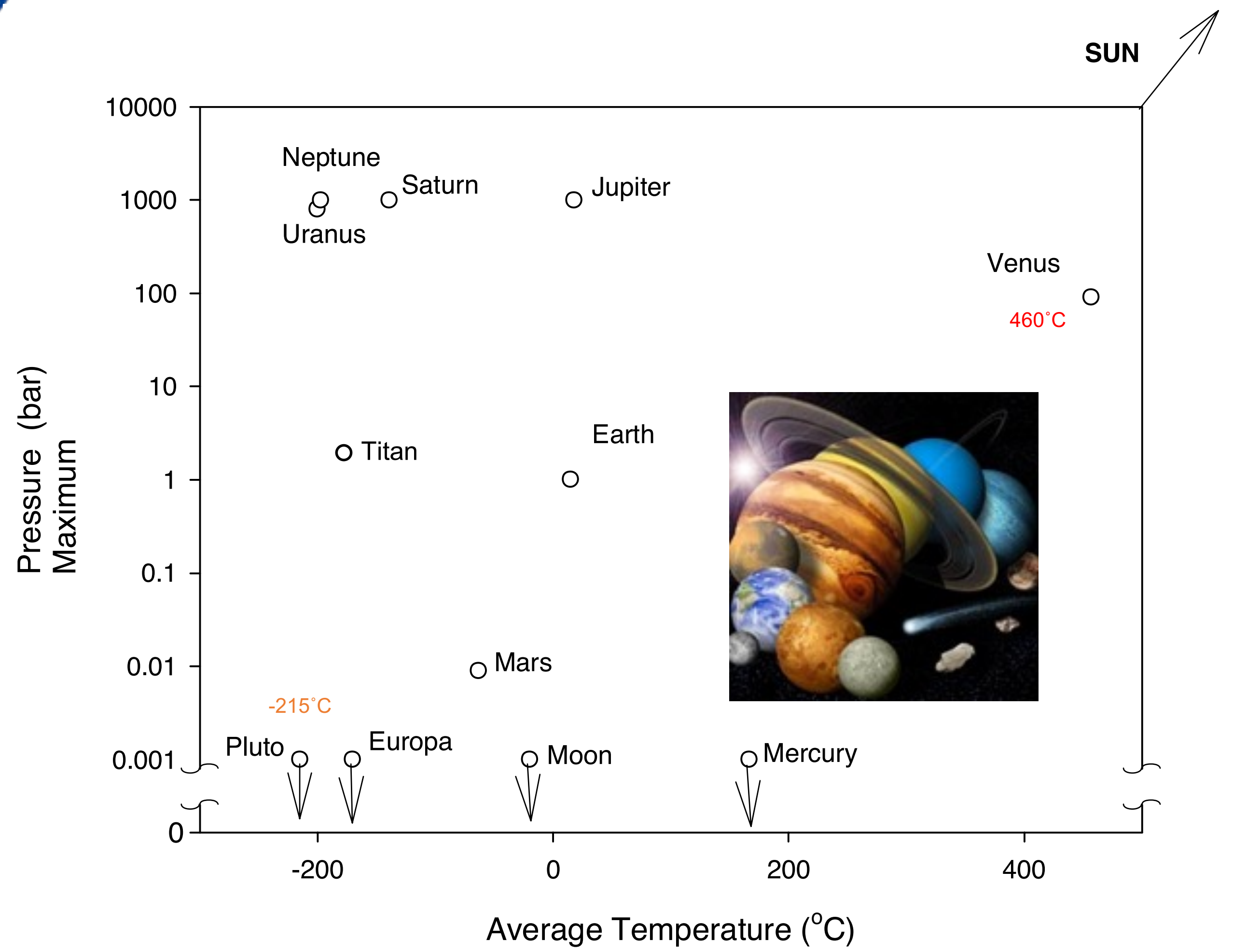
Near-Earth Asteroid 2011 UW158 (300 m in diameter)
Closest distance: 2.4×10^6 km in 2015 (6 times of Earth and Moon)
$5.4 Trillion worth of platinum (estimated by planetary resources)

^{3}He: Over 1M ton on the Moon surface → 10 times more energy of total earth energy resources

$^2H + {}^3He \rightarrow {}^4He + {}^1p + 18.3$ MeV

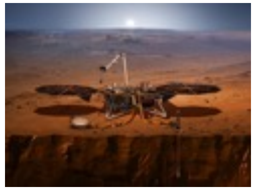
Images Credit: NASA

Extreme Environments in Space Exploration



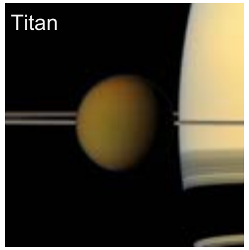
https://vfm.jpl.nasa.gov/files/EE-Report_FINAL.pdf
17NASA Extreme Environments Tech Space missions Report FINAL

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



Mars surface
-126˚C to 21˚C
Sand storm
Radiation
Entry, Descent, & Landing

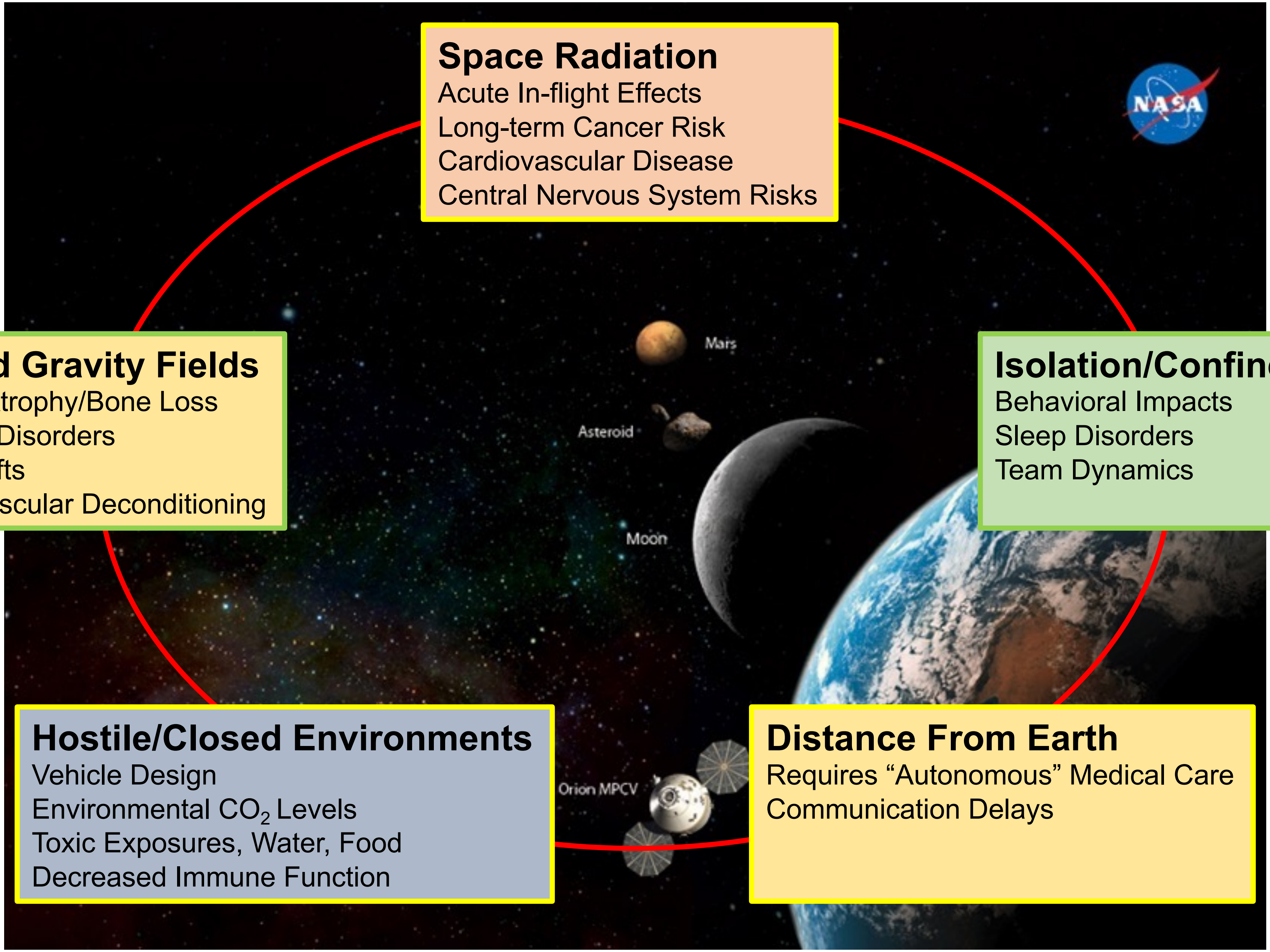
Deep space
2.7K
Radiation
Microgravity



Hypersonic heat flux at atmospheric entry: Heat fluxes often exceeding 1 kW/cm^2
Hypervelocity impact: MicroMeteoroids Orbital Debris (MMOD), > 20 km/sec, plume ejecta
Extreme temperatures: Lower than −240˚C and Exceeding +460˚C
Thermal cycling: Cycling between temperature extremes outside of the military standard range of −55˚C to +125˚C
High Vacuum: 10^{-12} torr
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

Images Credit: NASA

Primary Hazards to Humans During Spaceflight



Space Radiation
- Acute In-flight Effects
- Long-term Cancer Risk
- Cardiovascular Disease
- Central Nervous System Risks

Altered Gravity Fields
- Muscle Atrophy/Bone Loss
- Balance Disorders
- Fluid Shifts
- Cardiovascular Deconditioning

Isolation/Confinement
- Behavioral Impacts
- Sleep Disorders
- Team Dynamics

Hostile/Closed Environments
- Vehicle Design
- Environmental CO_2 Levels
- Toxic Exposures, Water, Food
- Decreased Immune Function

Distance From Earth
- Requires “Autonomous” Medical Care
- Communication Delays

Images Credit: NASA

Images Credit: NASA

Space Radiation Challenges

Solar Particle Events (SPE)

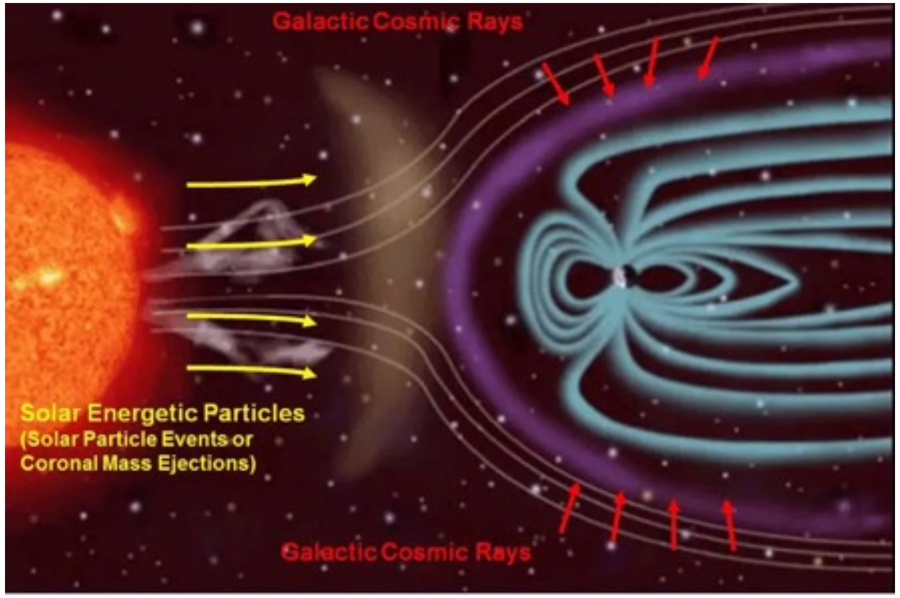
Mostly high energy protons
More readily shielded
Unpredictable

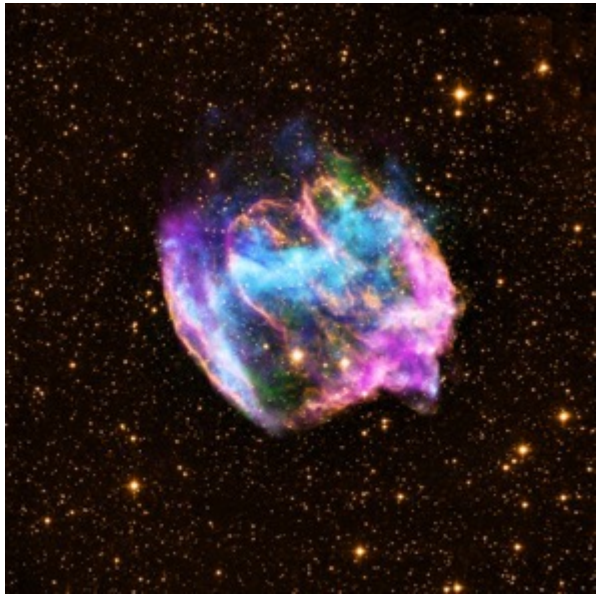
Galactic Cosmic Rays (GCR)

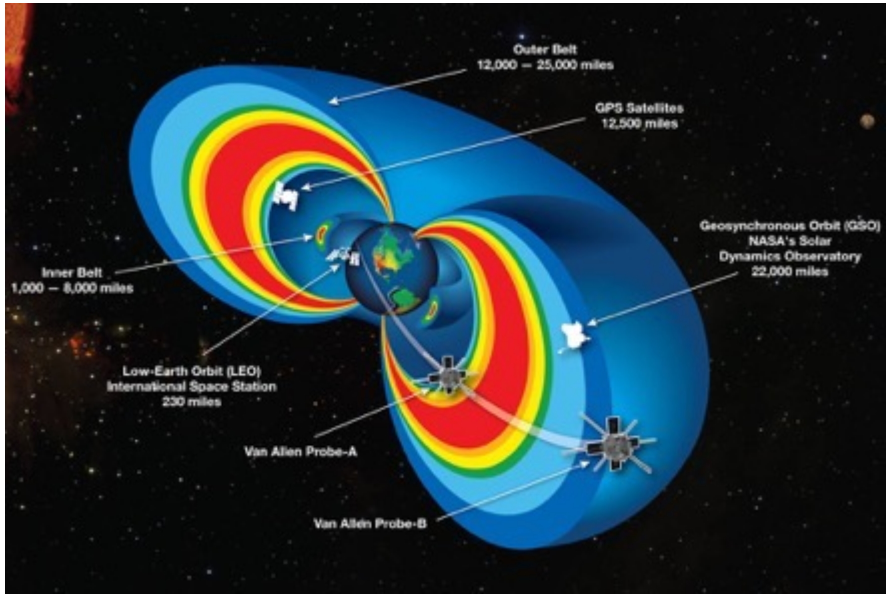
High energy ionized atoms
Most HZE* ions are harmful
Predictable

Van Allen Belt

Trapped energetic particles
Inner belt: mostly proton
Outer belt: mostly electron

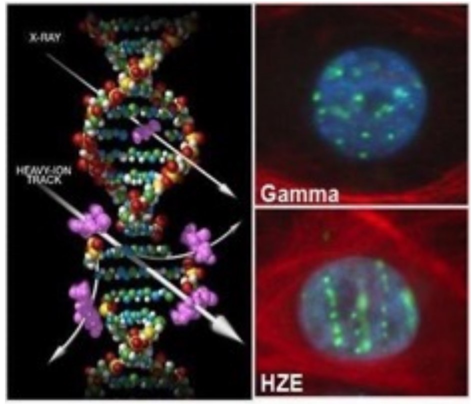




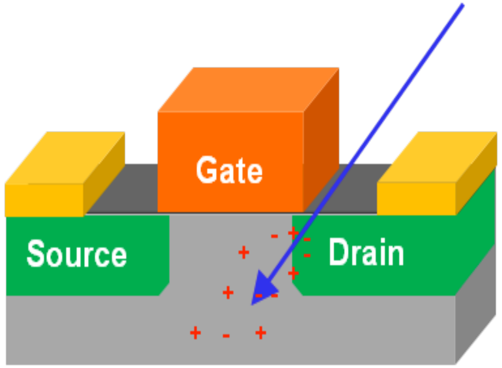


*HZE (high atomic number (Z) energy)

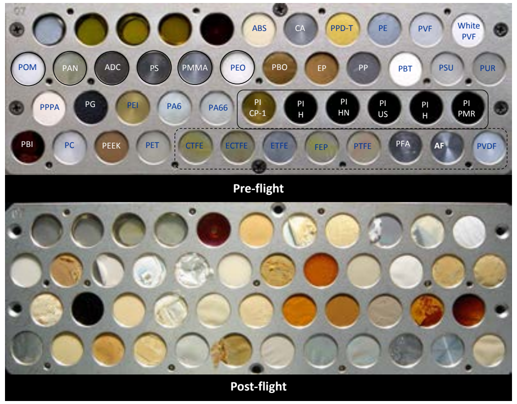
Secondary radiation: **neutron**, gamma, etc.



Damage or mutate DNA



Induce microelectronics errors



Damage materials: MISSE 2

Moon to Mars Exploration Architecture

Operations and Science on and around the Moon will help prepare for the first human mission to Mars

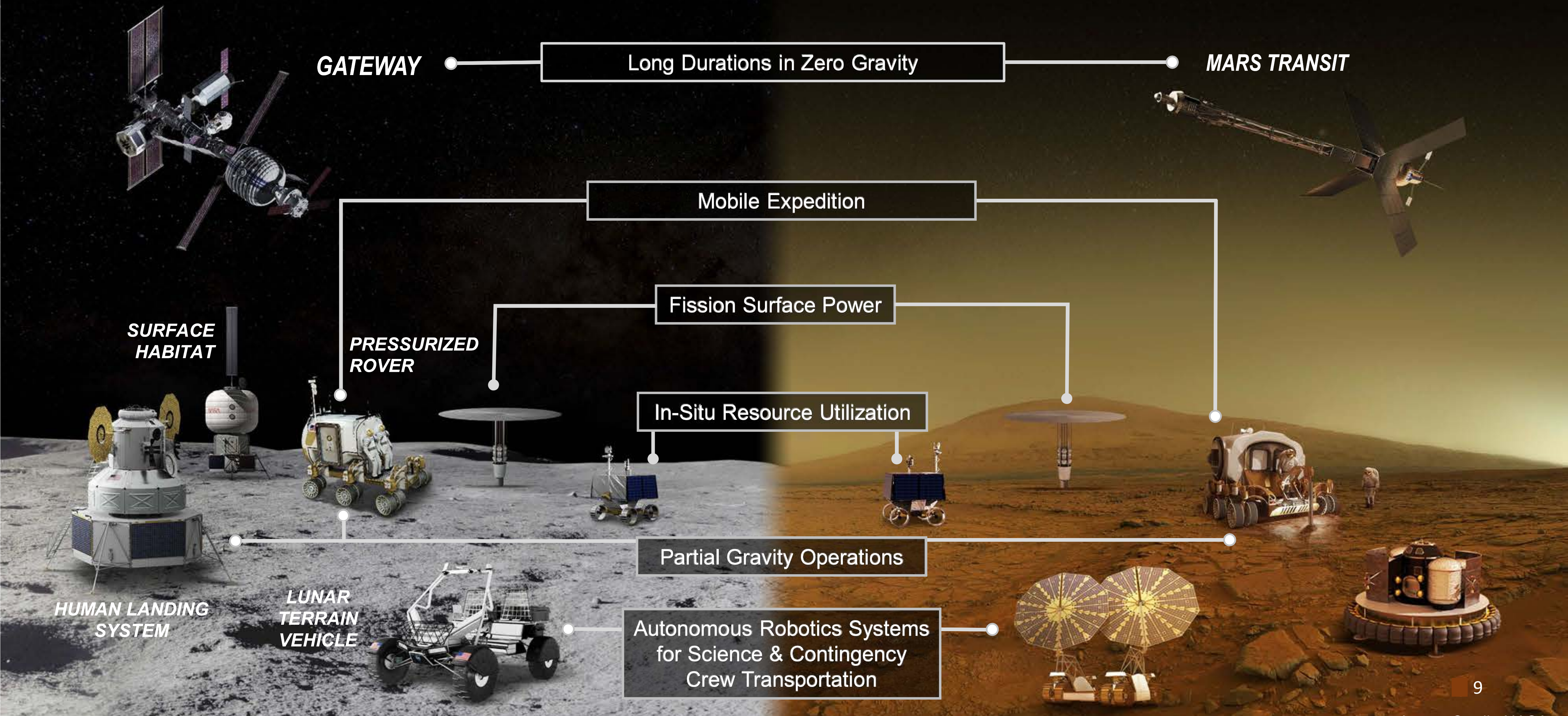


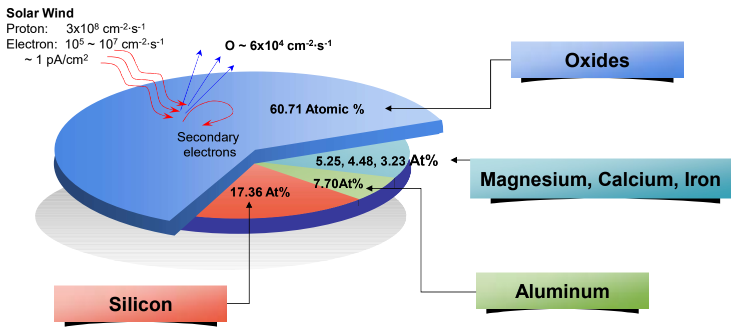
Image Credit: NASA

Lunar Surface In-Situ Resource Utilization (ISRU) Concepts

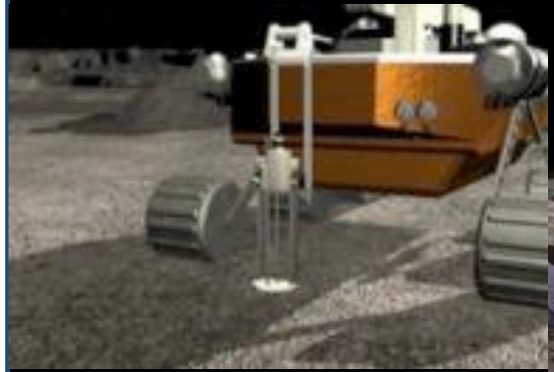
Focus Areas
- Sustainable Power
- Lunar Dust Mitigation
- ISRU
- Extreme Environments
- Extreme Access
- Surface Excavation and Construction

Lunar Surface innovation Consortium (LSIC)
http://lsic.jhuapl.edu

Lunar Regolith Composition

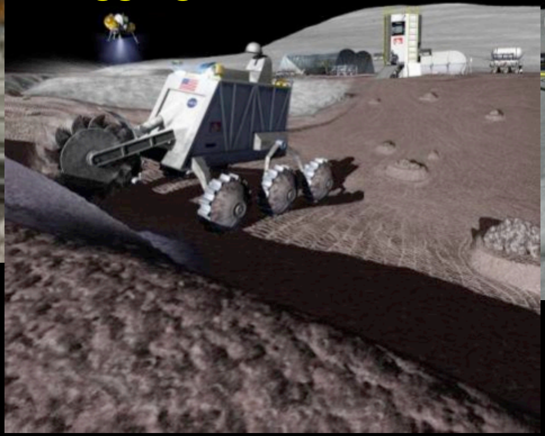


Lunar Mission Space Civil Engineering Capability Concepts

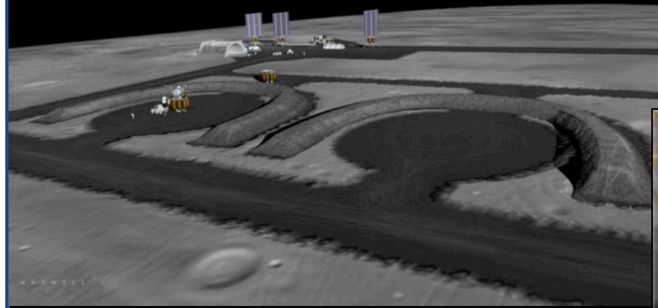


Resource Prospecting – Looking for Resources

Excavation & Regolith Processing for O_2 Production, Binders & Aggregates

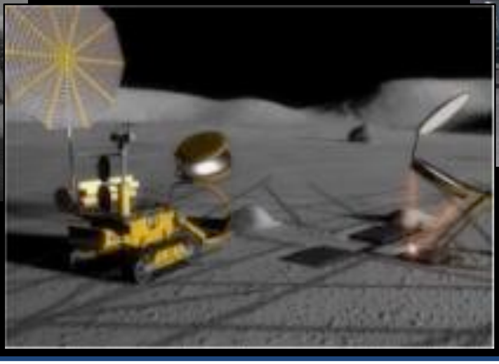


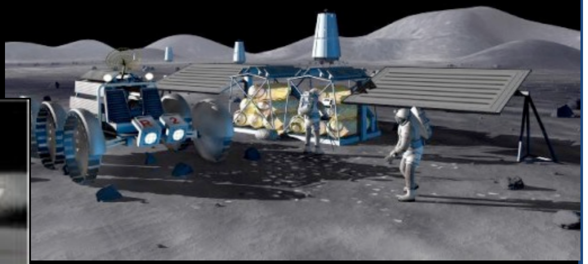
Propellant Processing with Lander & Pad Infrastructure



Habitat, Hangars, Dust Free Zones, Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction





Construction of Consumables Depots for Crew and Power (O_2, H_2)

Choi et al., NASA/TM-20205009040 (2020)

Images Credit: NASA

Advanced Materials for Extreme Space Environments

Structures and Materials Figures of Merit

- ***Performance Reliability and Sustainability***
  - *Perform without failure (crushing, cracking, buckling…)*
  - *Perform with minimum maintenance*
  - *Durable for planned life in space environment*

- ***Low Mass***
  - *High specific strength and specific stiffness*
  - *Gear ratio for deep space magnifies importance*

- ***Low Cost***
  - *Manufacturability, verifiable, life cycle cost*
  - *Recyclable, reusable, repurposable*
  - *Cost of materials is usually small if available (ISRU)*

- ***Multifunctionality***
  - *Mechanically durable/Wear resistant/Dust mitigation*
  - *Sensing/Actuating/Energy harvesting/Health monitoring*
  - *Thermal management/Thermal protection*
  - *Radiation shielding/Radiation resistance*
  - *MMOD and plume ejecta protection*
  - *Self sterilization/CO_2 sequestration/Fuel conversion*
  - *Waste recovery/Water recycle*

Advanced Materials

BNNT Polymer Matrix Composite (PMC)
BNNT Metal Matrix Composite (MMC)
BNNT Ceramic Matrix Composite (CMC)

- ***Lightweight Mechanically Strong Materials***
  - *Nanocomposites (PMC, MMC, and CMC)*
  - *High entropy materials*

- ***Materials for Extreme Temperatures and Cycles***
  - *Phase change material*

- ***Lunar Dust Mitigation***
  - *Wear and abrasion resistant materials*
  - *Dust adhesion mitigation material*

- ***Radiation Shielding and Radiation Resistant Materials***
  - *Low Z and high absorption cross-section materials*

- ***Recyclable, Reusable, Repurposable Materials***

- ***Rapid Manufacturable Processes and Materials***
  - *Additive manufacturing in space environment*

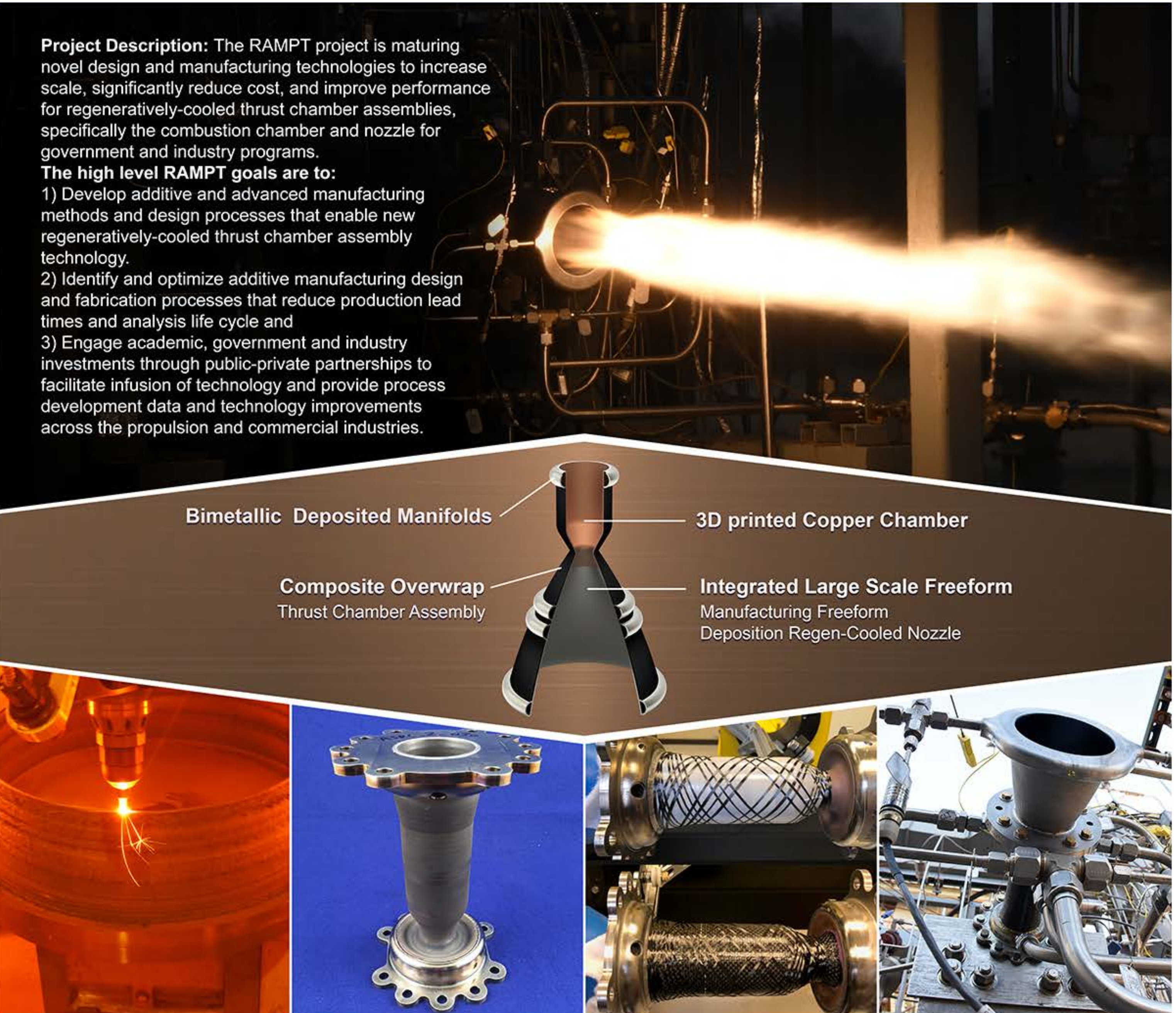
- ***Flame Resistant/Retardant Materials***
  - *Space suit, habitat and crew module interior*

Additive Manufacturing: Rapid Analysis & Manufacturing Propulsion Technology (RAMPT)

Project Description: The RAMPT project is maturing novel design and manufacturing technologies to increase scale, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies, specifically the combustion chamber and nozzle for government and industry programs.

The high level RAMPT goals are to:

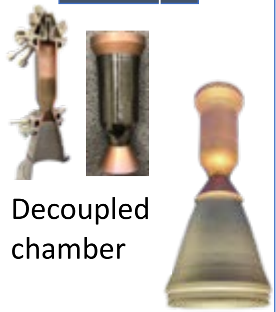
1) Develop additive and advanced manufacturing methods and design processes that enable new regeneratively-cooled thrust chamber assembly technology.
2) Identify and optimize additive manufacturing design and fabrication processes that reduce production lead times and analysis life cycle and
3) Engage academic, government and industry investments through public-private partnerships to facilitate infusion of technology and provide process development data and technology improvements across the propulsion and commercial industries.



Large-Scale 3D Printing for Rocket Engines
https://www.youtube.com/watch?v=_JHqdVU9Ebo&t=3s

CAMX, Dallas, TX (2021)

2k-lb$_f$



Decoupled chamber

Coupled chamber

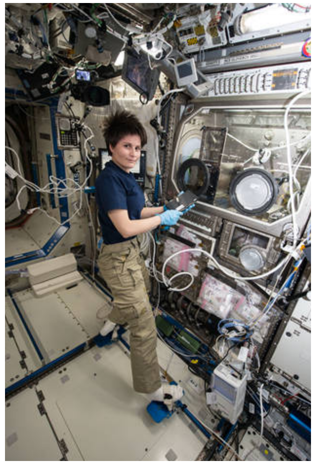
7k-lb$_f$

Decoupled chamber

Coupled chamber

40k-lb$_f$

Coupled chamber



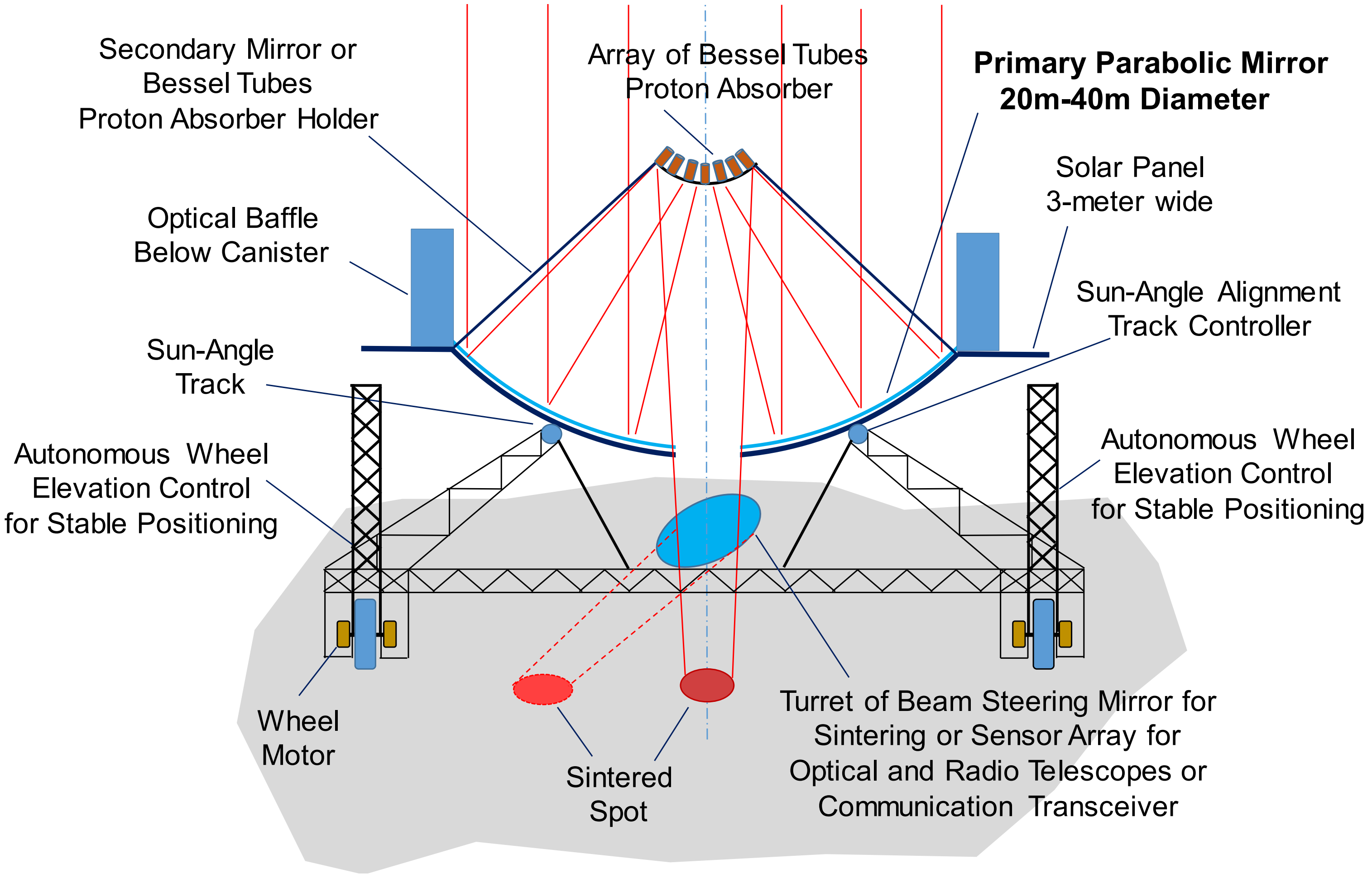
ESA Astronaut Samantha Cristoforetti working on the 3D Printer aboard the space station

NASA will support ICON in developing construction technology that could be used on the Moon and Mars

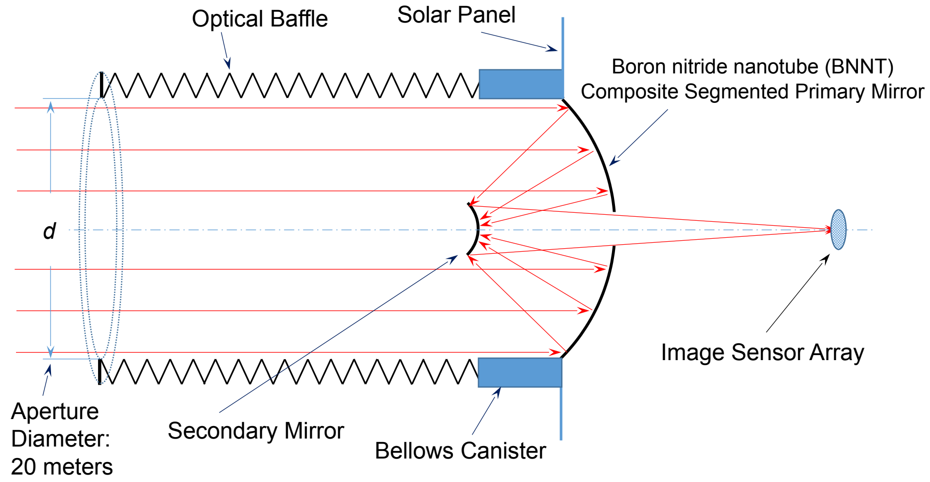
Images and Video Credit: NASA

Multipurpose Cassegrain System

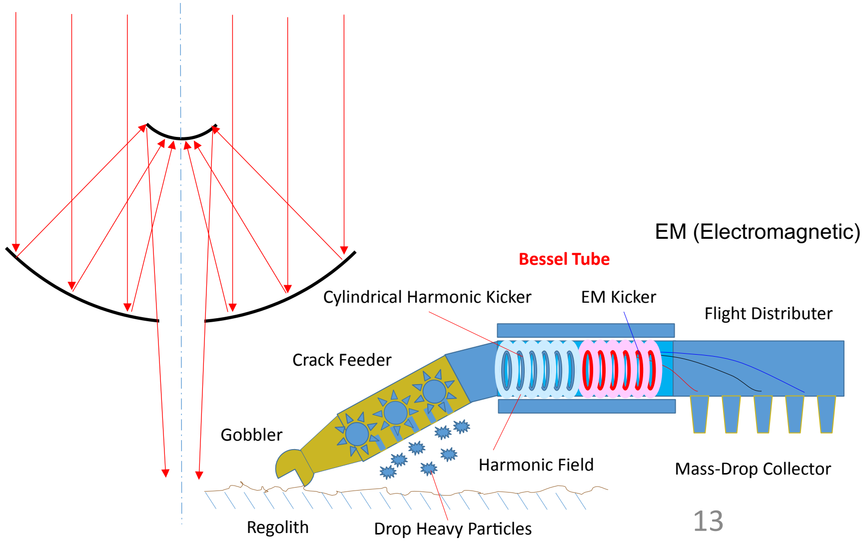
Multipurpose Cassegrain System



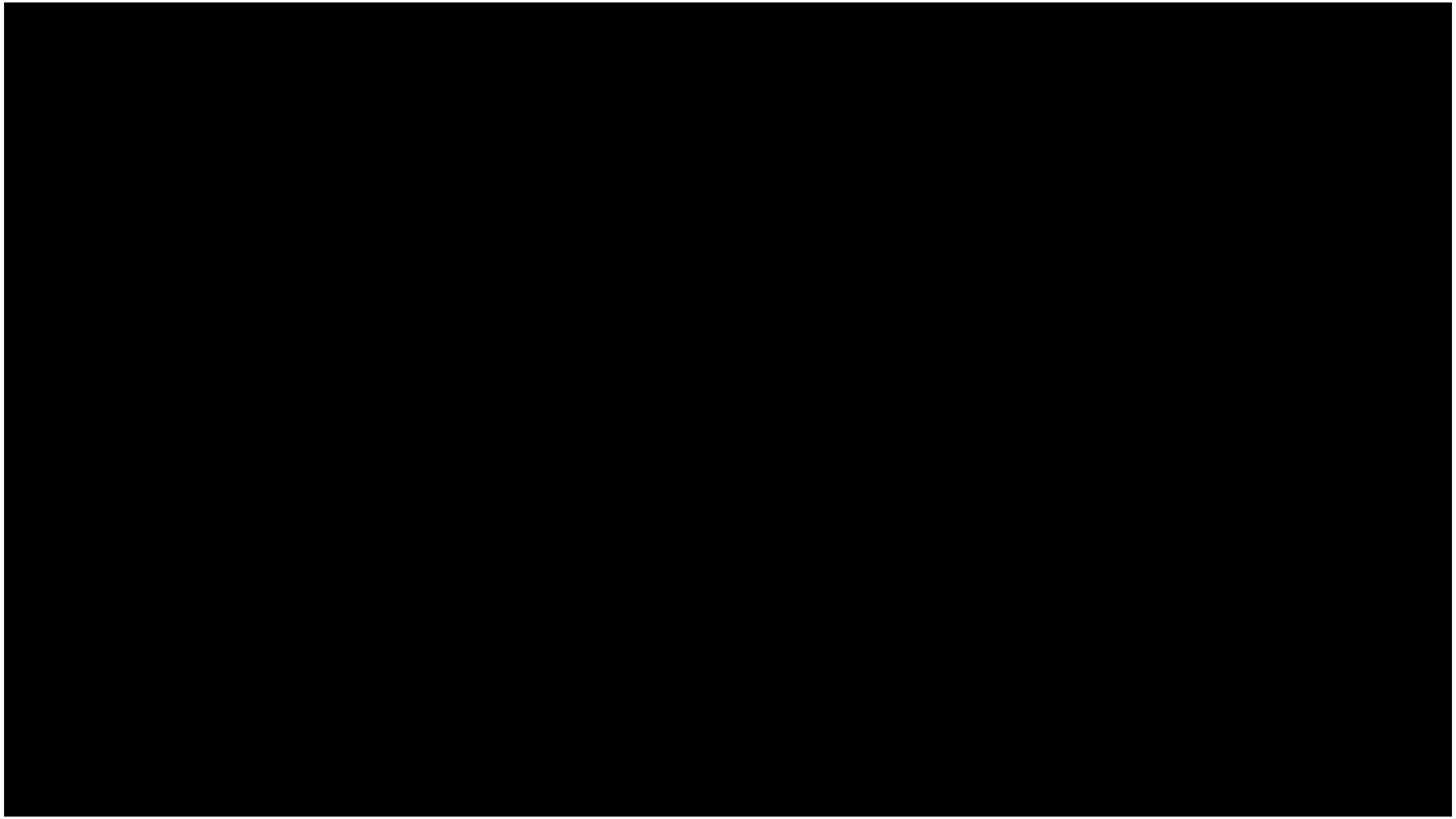
Space Telescope



He-3 Volatile Mining Technology



ISRU Landing Pad: Multipurpose Cassegrain System

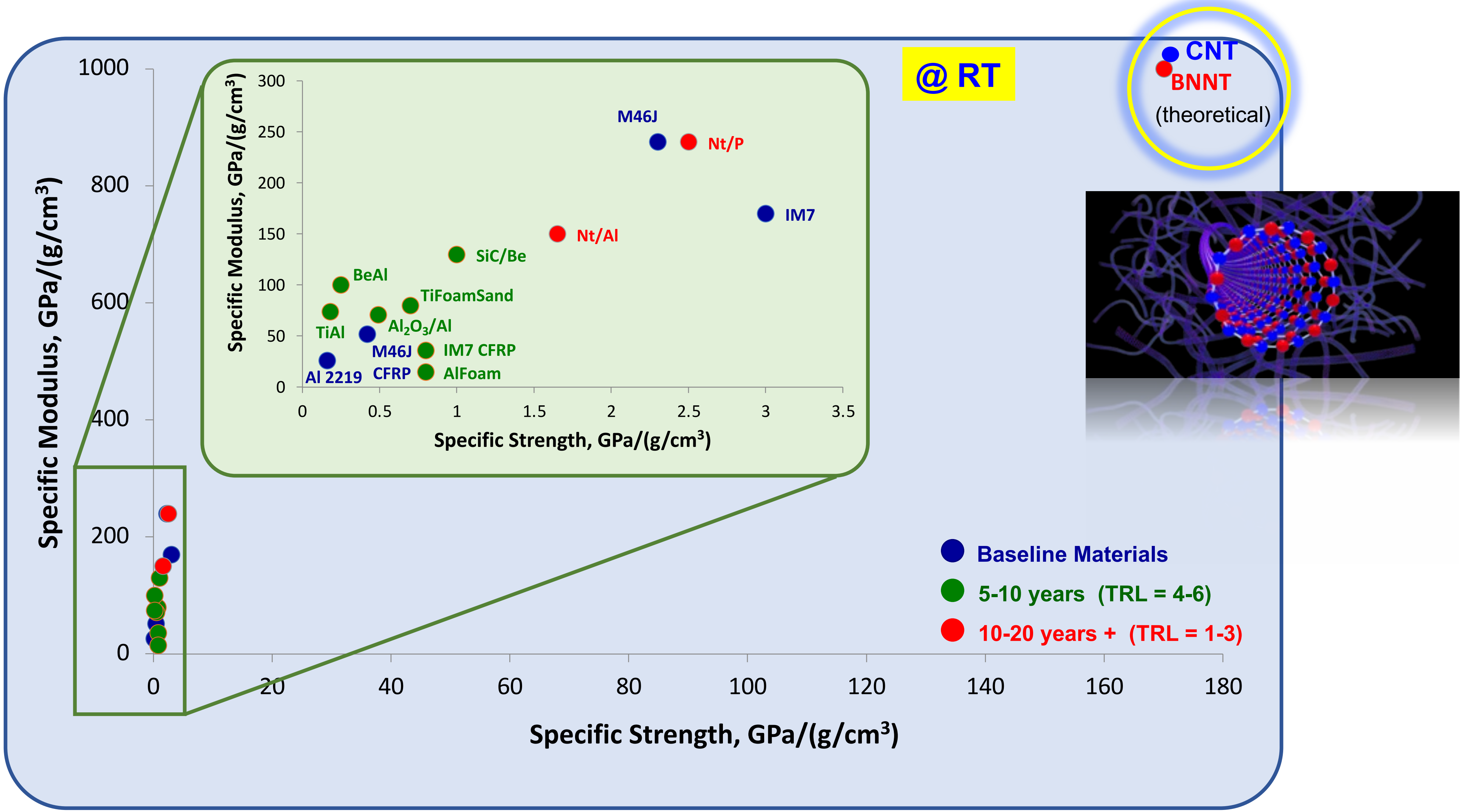


https://www.youtube.com/watch?v=mpXdY2v5FDI&feature=youtu.be

Credit: Bob Moses and Sang H. Choi (NASA Langley Research Center (LaRC))

Video Credit: NASA

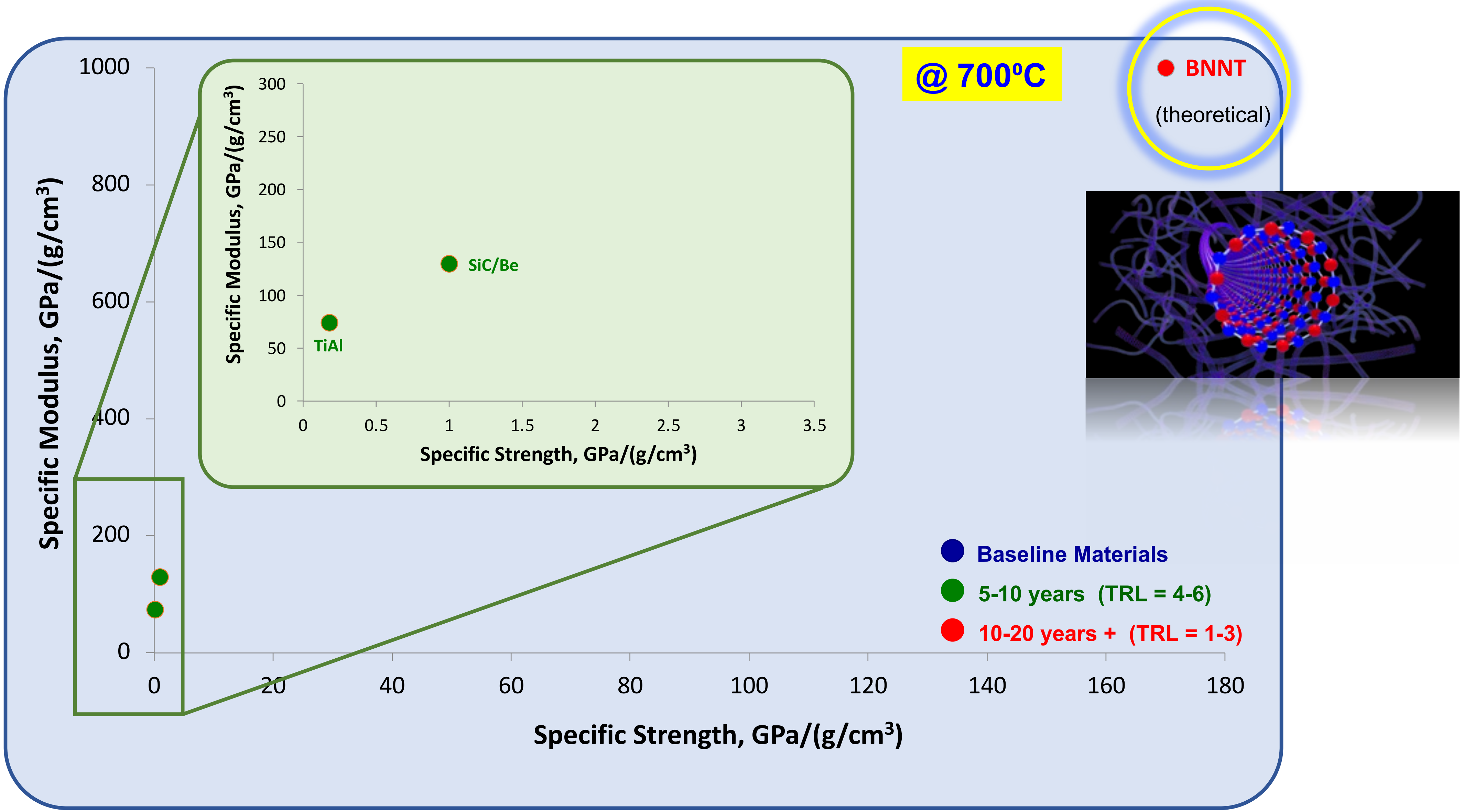
Motivation: Properties of Materials for Vehicle Structure



Charlie E. Harris, M. J. Shuart, H. Gray, *NASA TM* 2002211664 (2002)

Nanotube values are theoretical.

Motivation: Properties of Materials for Vehicle Structure

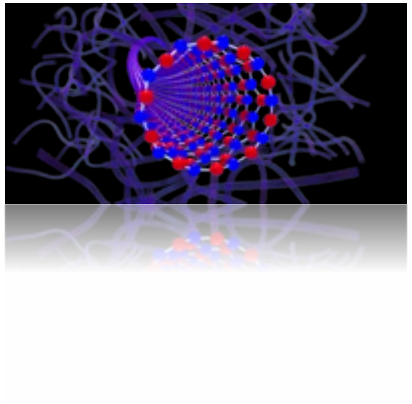


Charlie E. Harris, M. J. Shuart, H. Gray, *NASA TM* 2002211664 (2002)

Nanotube values are theoretical.

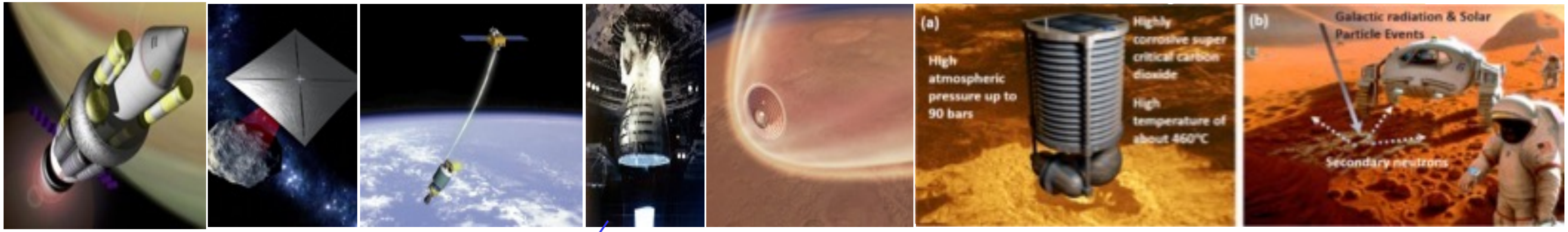
Nanotube Comparison (Theoretical)

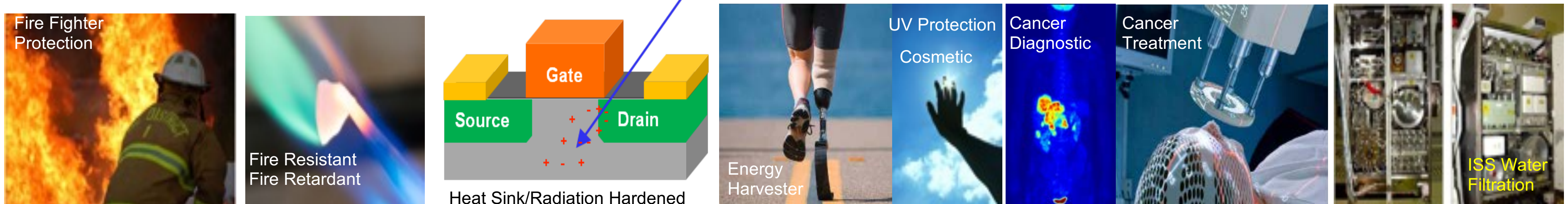
	Carbon Nanotubes	Boron Nitride Nanotubes
Electric Properties	Metallic or semiconducting	Wide band gap (about 6.0 eV) Insulation, corrosion resistant
Mechanical Properties (Young's Modulus)	1.33 TPa (very stiff)	1.18 TPa (very stiff)
Thermal Conductivity	>3000 W/mK (highly conductive)	~300–3000 W/mK (highly 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 $\times 10^{-6}$ K^{-1} (very low)	-1 $\times$ 10^{-6} K^{-1} (very low)



Significance of the BNNT Innovation

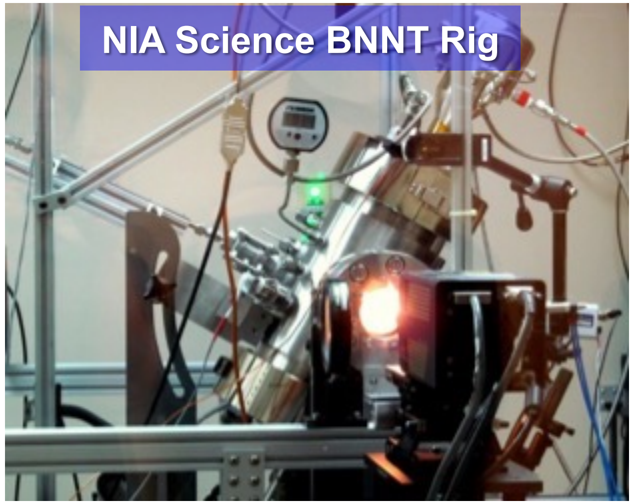
- **Structural/Mechanical**: **lightweight** composite armor, thermal protection, engine components, and radiation shielding materials for **extreme environments**.
- **High stiffness as well as high toughness** for spacecraft and space suits, ultrastrong tethers, meteorite impact protection layers, 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**.

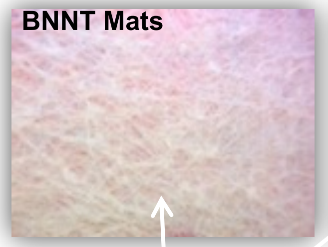


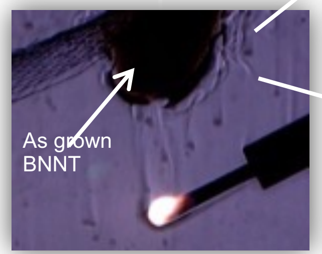


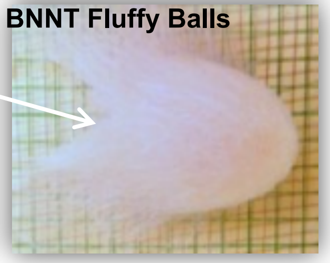
Images Credit: NASA

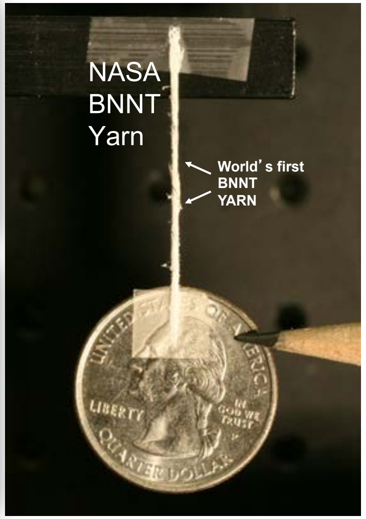
BNNT Scale-Up and Various Forms of BNNT



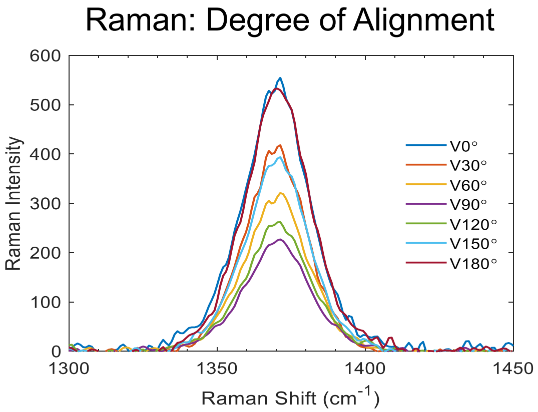


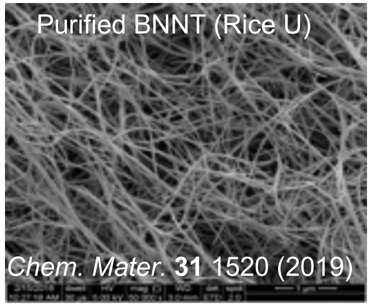


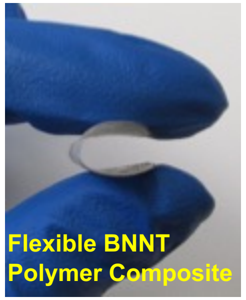


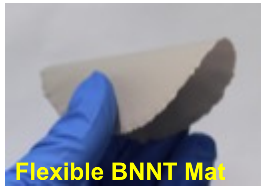


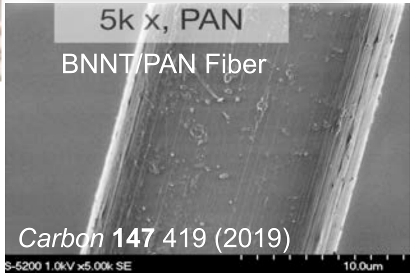
(From: M. W. Smith et al, Nanotechnology, 20, 505604 (2009))

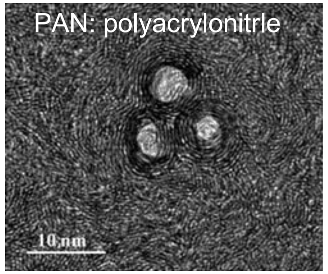


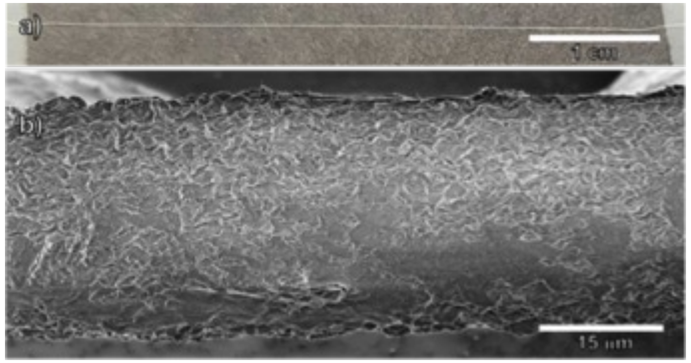








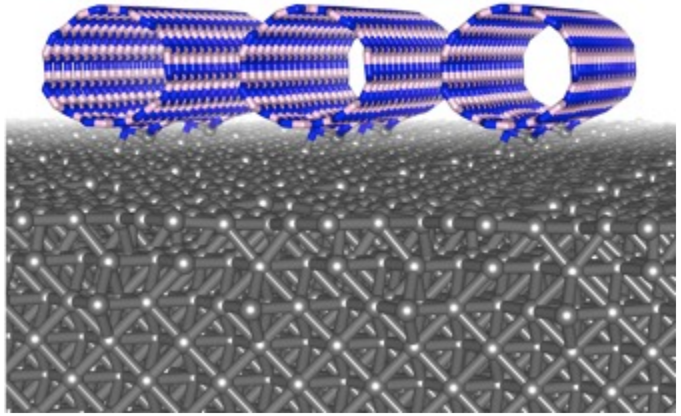


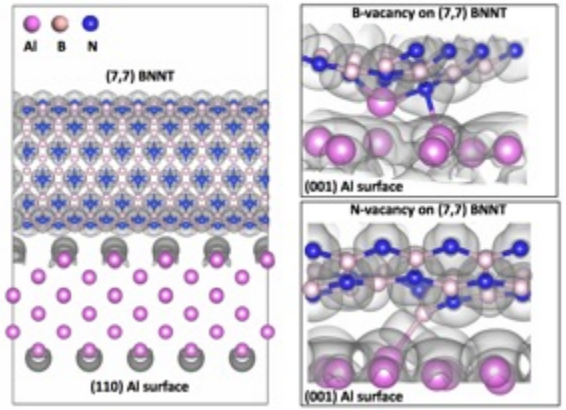


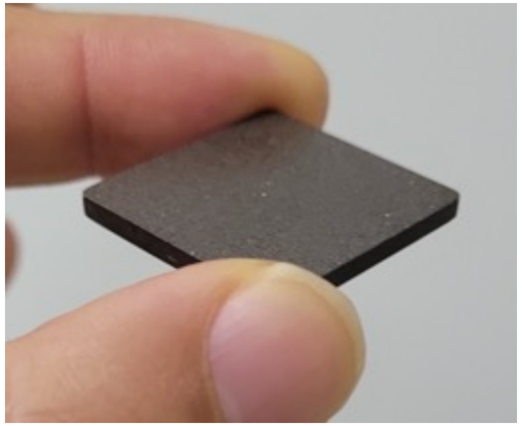
Nature Communications, **13**, 3136 (2022)

Images Credit: NASA

BNNT Polymer Matrix Composite (PMC)
BNNT Metal Matrix Composite (MMC)
BNNT Ceramic Matrix Composite (CMC)







15% BNNT/Epoxy Composite

J. Phys. Chem. C **120** 3509 (2016)
J. Phys. Chem. C **122** 15266 (2018)

Metal Matrix Composite (MMC) Processing (Bulk and Coating)

- **MMC Trusses and Joints (Bulk Fabrication and Coating Methods)**
  - Bulk: Vacuum Hot Press (VHP) / Stir-Cast / Hot-Rolling / Liquid Pressing Process / Plasma Spray Metal Foils / Spart Plasma Sintering
  - Coating: Thermal Spray Coating and Polymer-Derived Ceramic (PDC) Coating

Vacuum Hot Press at B1205

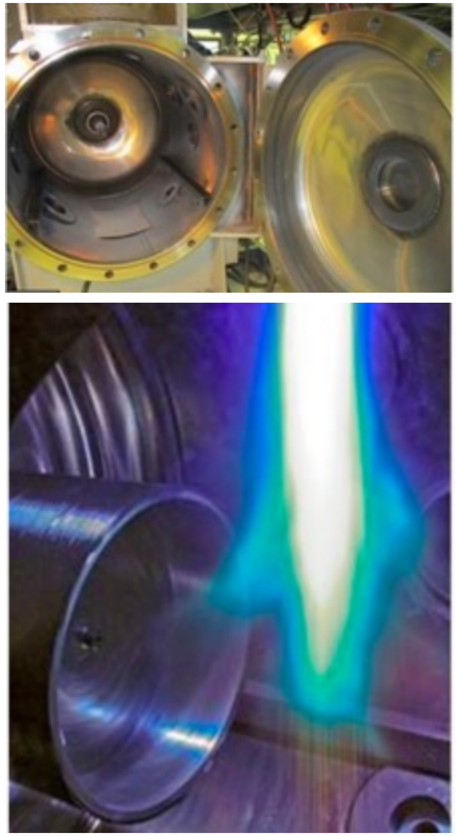
*Vacuum Hot Press performed by **Joel Alexa***

*BNNT-Al sample **after** vacuum hot pressing*

*Rolling mill operated by **Joel Alexa** and **Harold Claytor.***

Rolling Mill at B1267

BNNT-Al sample during first pass in rolling mill.



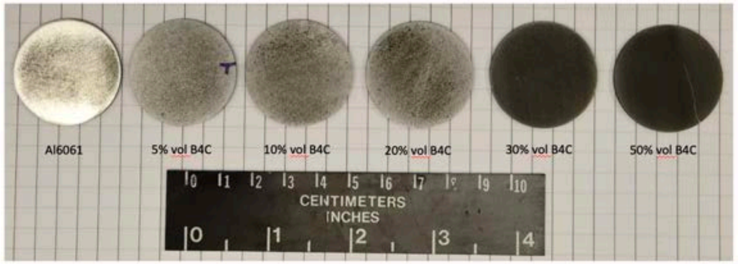
RF Plasma Spray Facility at B1205 (Image Credit: NASA/TP-2016-219194)

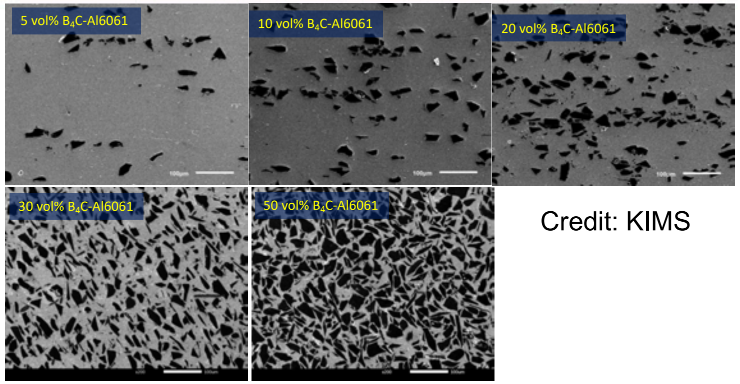
MOOSE Plasma Spray Coating of Ti64 MMC
Credit: Thermal Spray Solutions Inc.

Images Credit: NASA

B_4C-Al6061: Mechanical, Tribological, and Thermal Tests

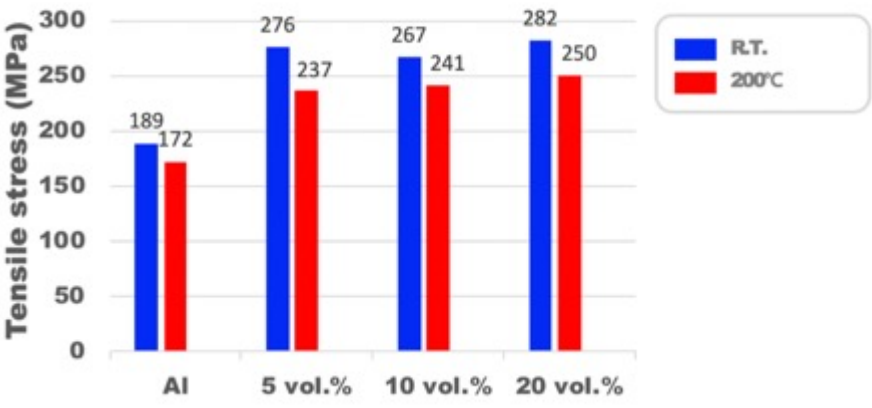
- **In collaboration with Marshall Space Flight Center (MSFC) KIMS, and FIU**
  - Test samples : B_4C-Al6061 (0-50 vol%)
  - Significant wear resistance
    2.4 times wear volume reduction from 5 vol% B_4C
    6.5 times wear volume reduction from 50 vol% B_4C
  - Minimal change in COF < 2%
    0.43 (0 vol% B_4C), 0.42 (5 vol% B_4C), 0.42 (50 vol% B_4C)
  - The addition of B_4C into Al6061 tends to increase the strength and hardness of the material and as a result the wear volume is seemed to be decreasing considerably



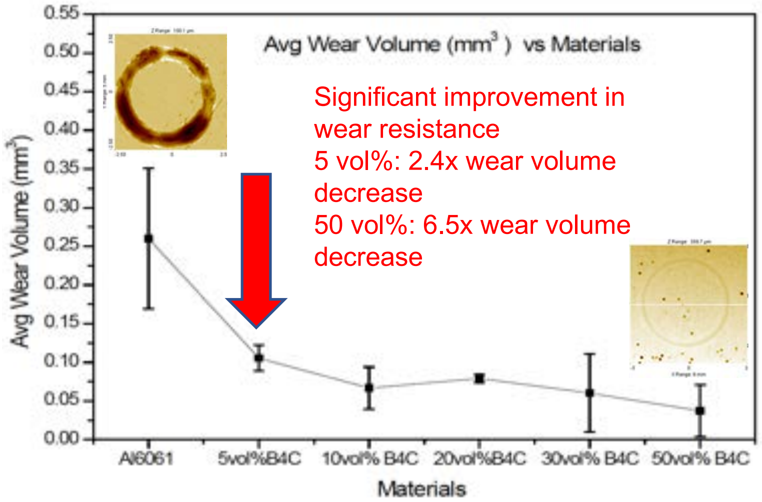


Credit: KIMS

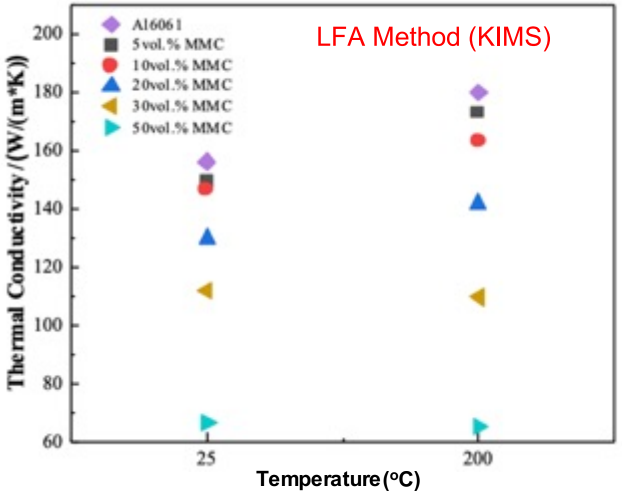
Mechanical Improvement of B_4C-Al6061 MMCs



Wear Test



Thermal Conductivity of B_4C-Al6061 MMCs



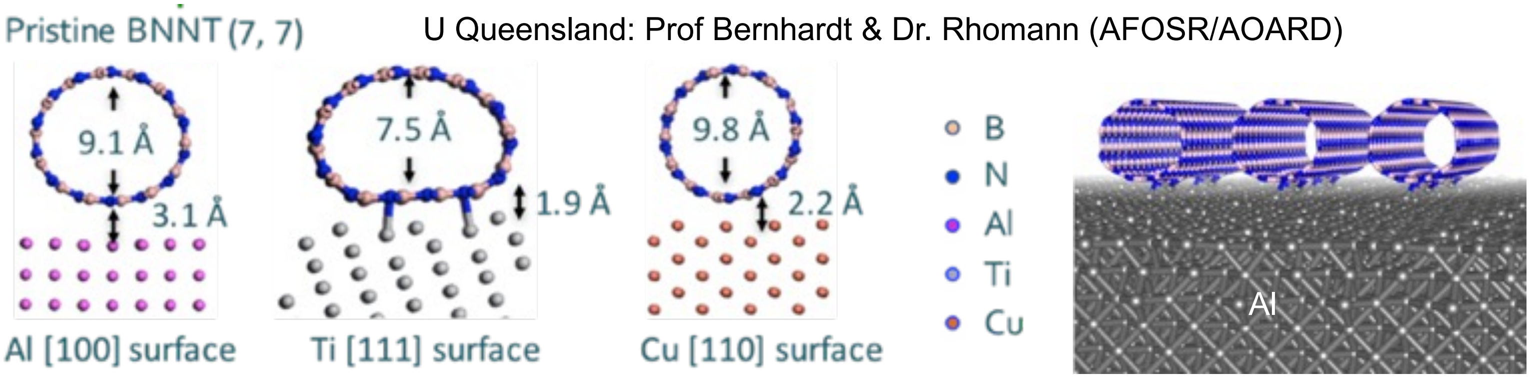
Credit: Florida International University (FIU), Korea Institute of Materials Science (KIMS)

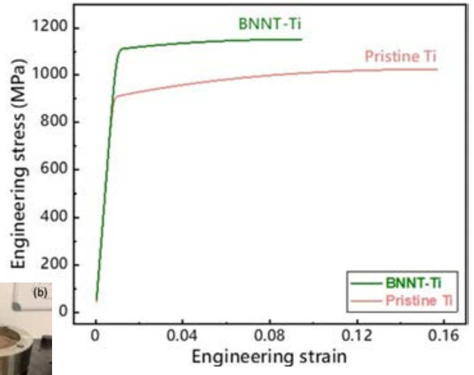
NASA/TM-20230003044 (2023)

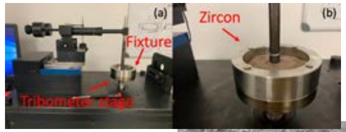
BNNT Metal Matrix Composite and Ceramic Matrix Composite

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

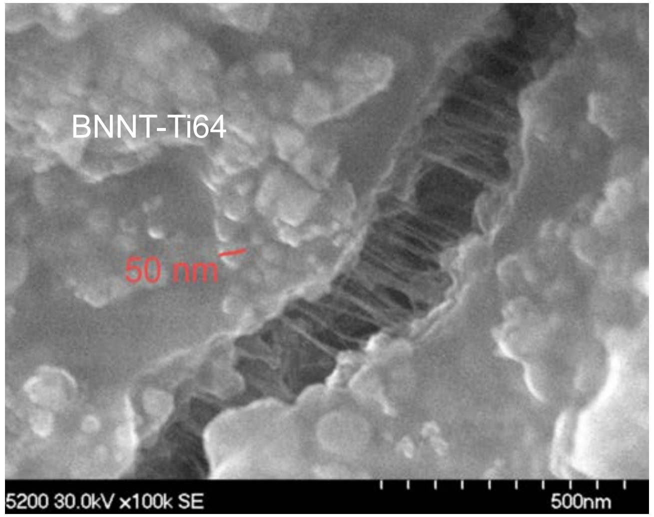
J. Mater. Res. **37** 4582 (2022)

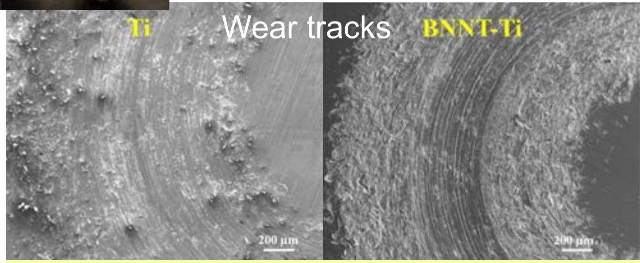






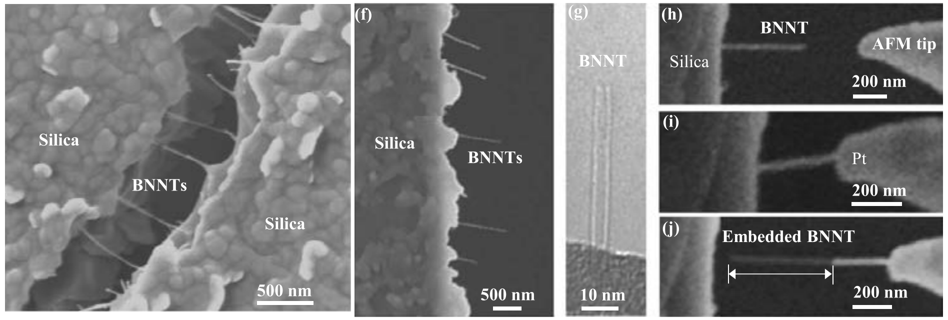
Binding Energies**	Al[100] Surface	Ti[111] Surface	Cu[110] Surface
Pristine	-0.41	-1.77	-0.95
N-vacancy	-0.69	-2.00	-1.23
B-vacancy	-1.26	-3.30	n/a
C sub N	-0.64	-2.17	-1.26
C sub B	-0.51	-1.41	-1.00

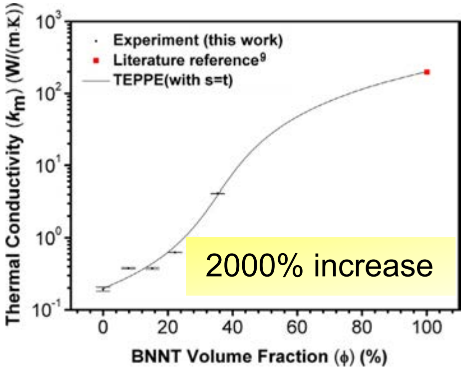




Wear volume and coefficient of friction decreased with BNNT with Lunar regolith simulant

Interfacial strength of BNNT is greater than that of CNT for all PMC, MMC, and CMC





J. Phys. Chem. C **120** 3509 (2016)
J. Phys. Chem. C **122** 15266 (2018)
Nanotechnology, **30** 25706 (2019) BNNT-ceramic interfacial strength
Credit: Prof. Agarwal, Florida International University (FIU)

J. Am. Cer. Soc. **109** 7584 (2019)

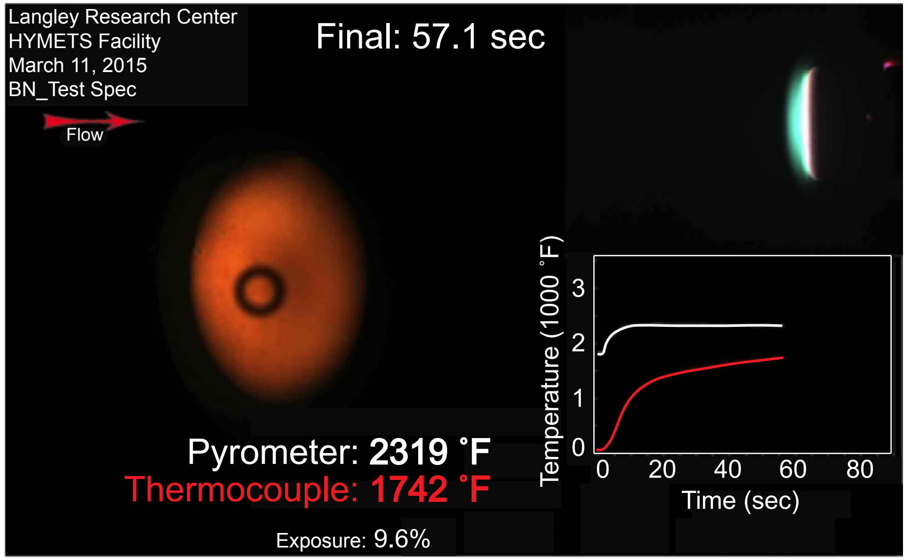
Hypersonic Materials Experiment Test System (HyMETS)

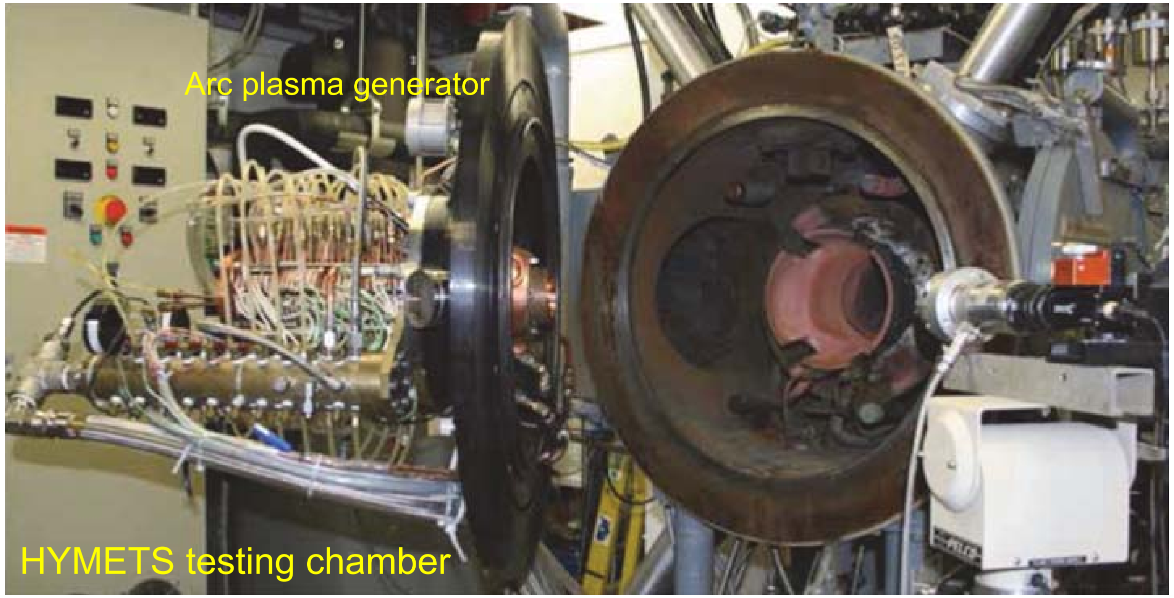
<u>LaRC HYMETS Test Conditions</u>

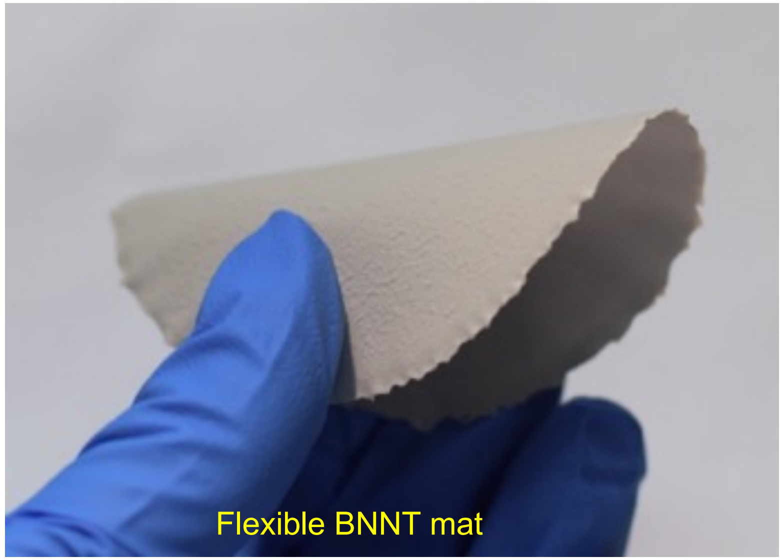
- Specimen Surface Temperature (°C): 1260
- Specimen Stagnation Pressure (atm): 0.013-0.079
- Free Stream Mach Number: 5.0
- Free Stream Enthalpy (kJ/kg): 5350-26749

<u>HYMETS TEST for BNNT Mats</u>

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





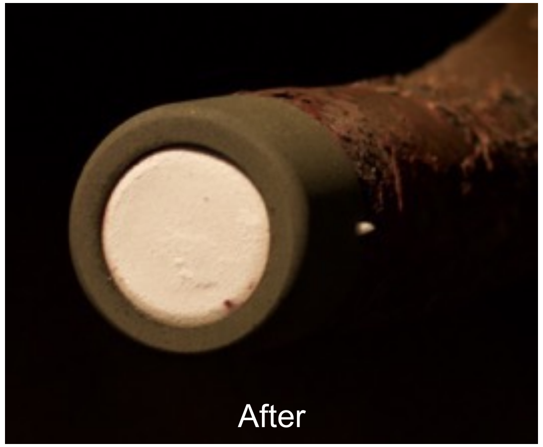


Images Credit: NASA

Collaborators: Scott Splinter, Jeff Gragg, Kamran Daryabeigi (AIAA, 2011)

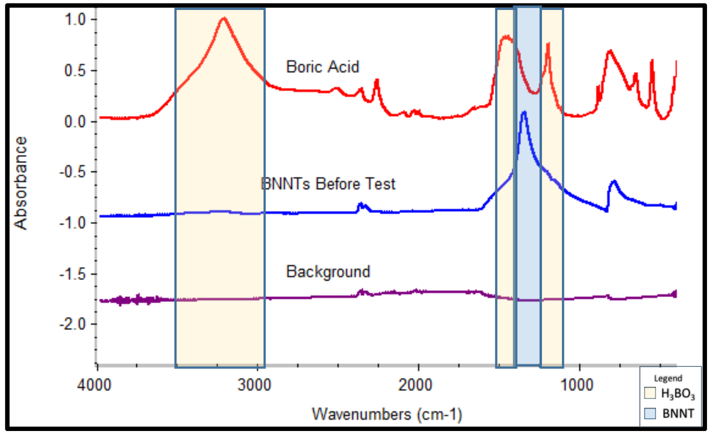
Hypersonic Materials Experiment Test System (HYMETS)

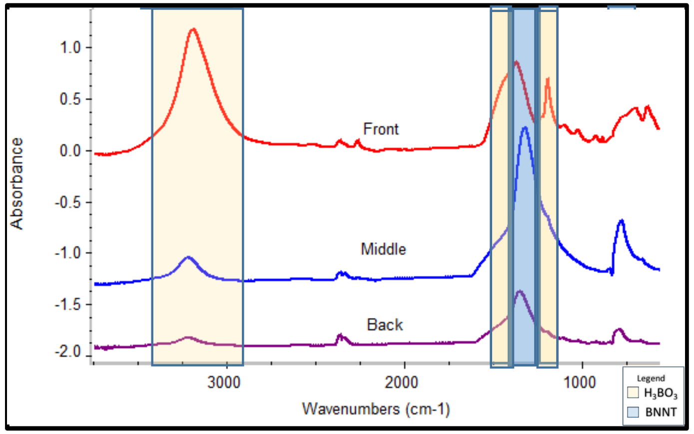
Sample: BNNT Mat (as grown, nonwoven)
- Fabricated by a vacuum filtration process
- Diameter: 25 mm, Thickness: 2 mm, Density: ~ 0.3 g/cm^3

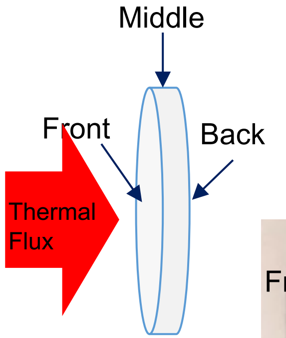


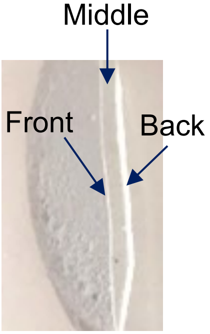
HYMETS Test Conditions
- Test duration: 1 min
- Surface temperature: 2400 ^oF (1315 ^oC)

FT-IR Analysis of BNNT mat



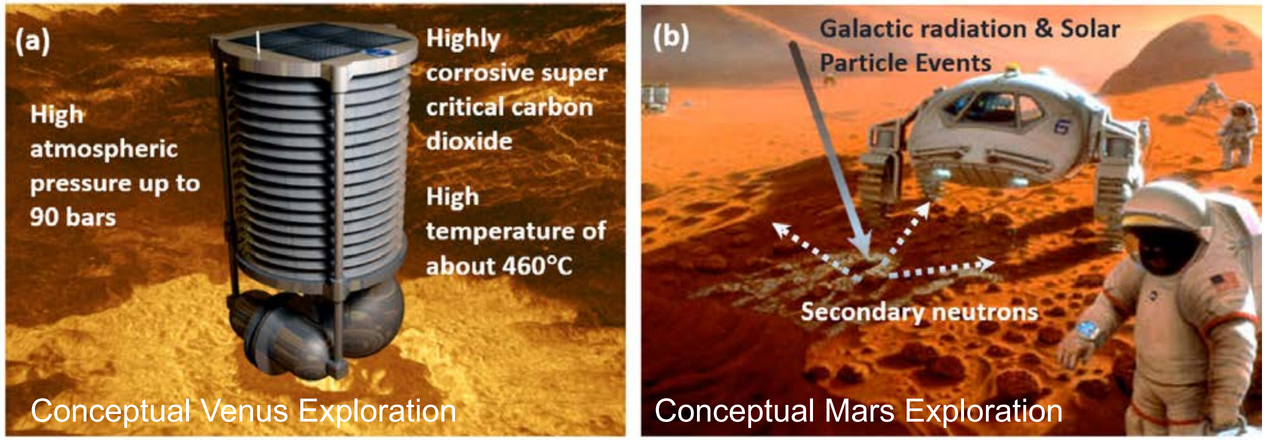






Multifunctional BNNT Polymer Composites

- Electroactive Properties
- Radiation Shielding Properties

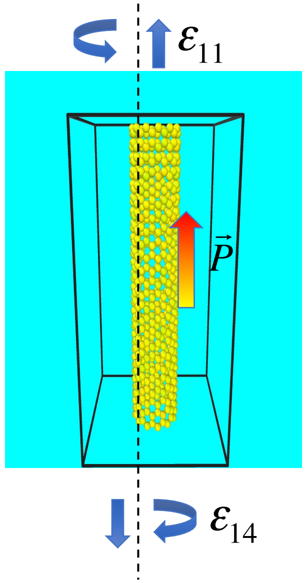


MRS Bulletin **40** 836 (2015)
Comp. Mater. Sci., **95** 362 (2014)
ACS Nano **9** 11942 (2015)

Images Credit: NASA

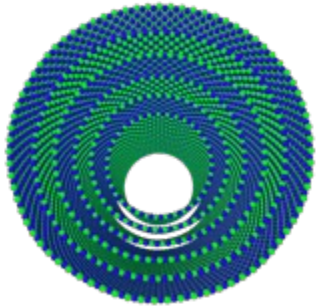
Results: Piezoelectricity under Deformation

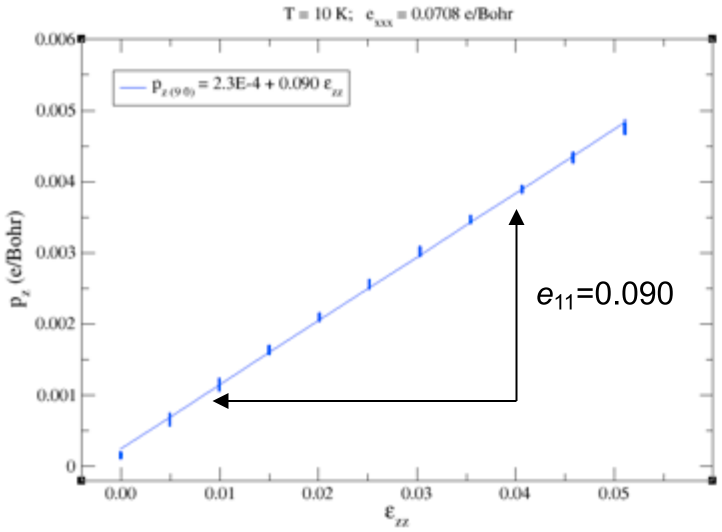
The Molecular Dynamics (MD) model is successful in representing the piezoelectric properties of BNNTs

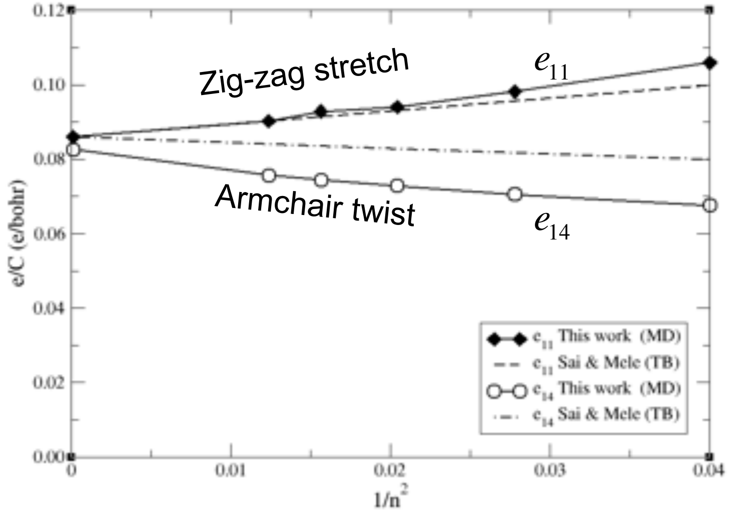


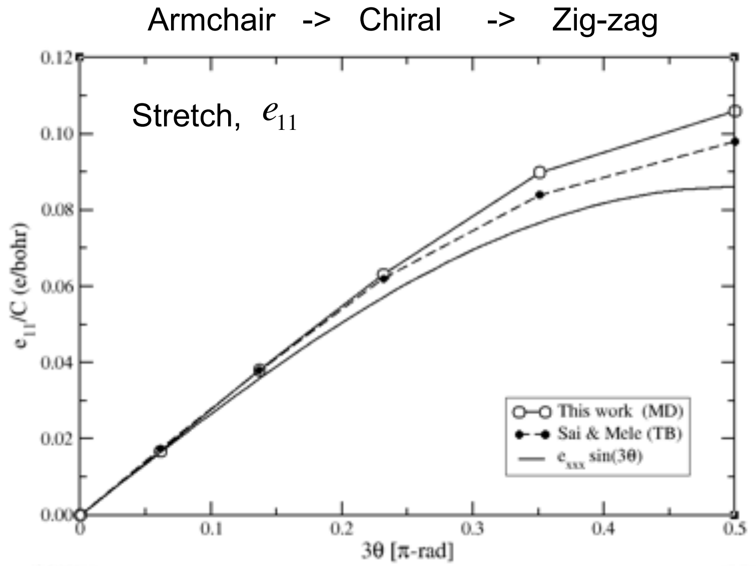
$$p_z(stretch) = e_{11}\varepsilon_s$$
$$p_z(twist) = e_{14}\varepsilon_t$$

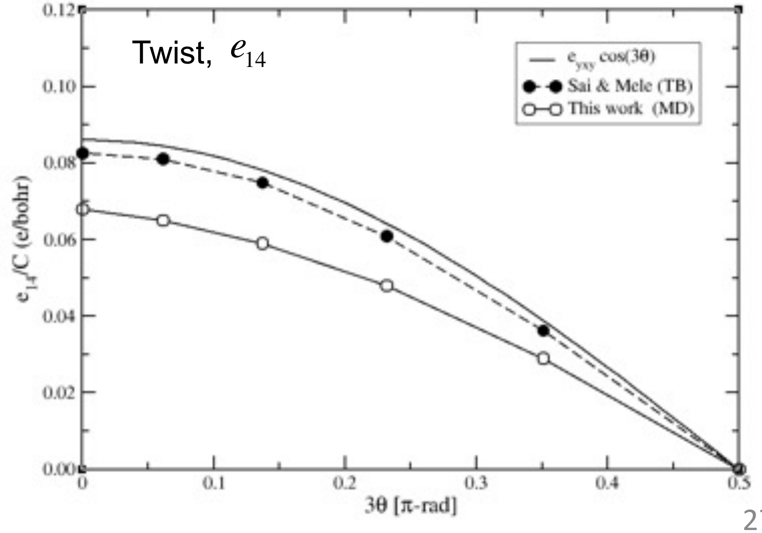
MWBNNT







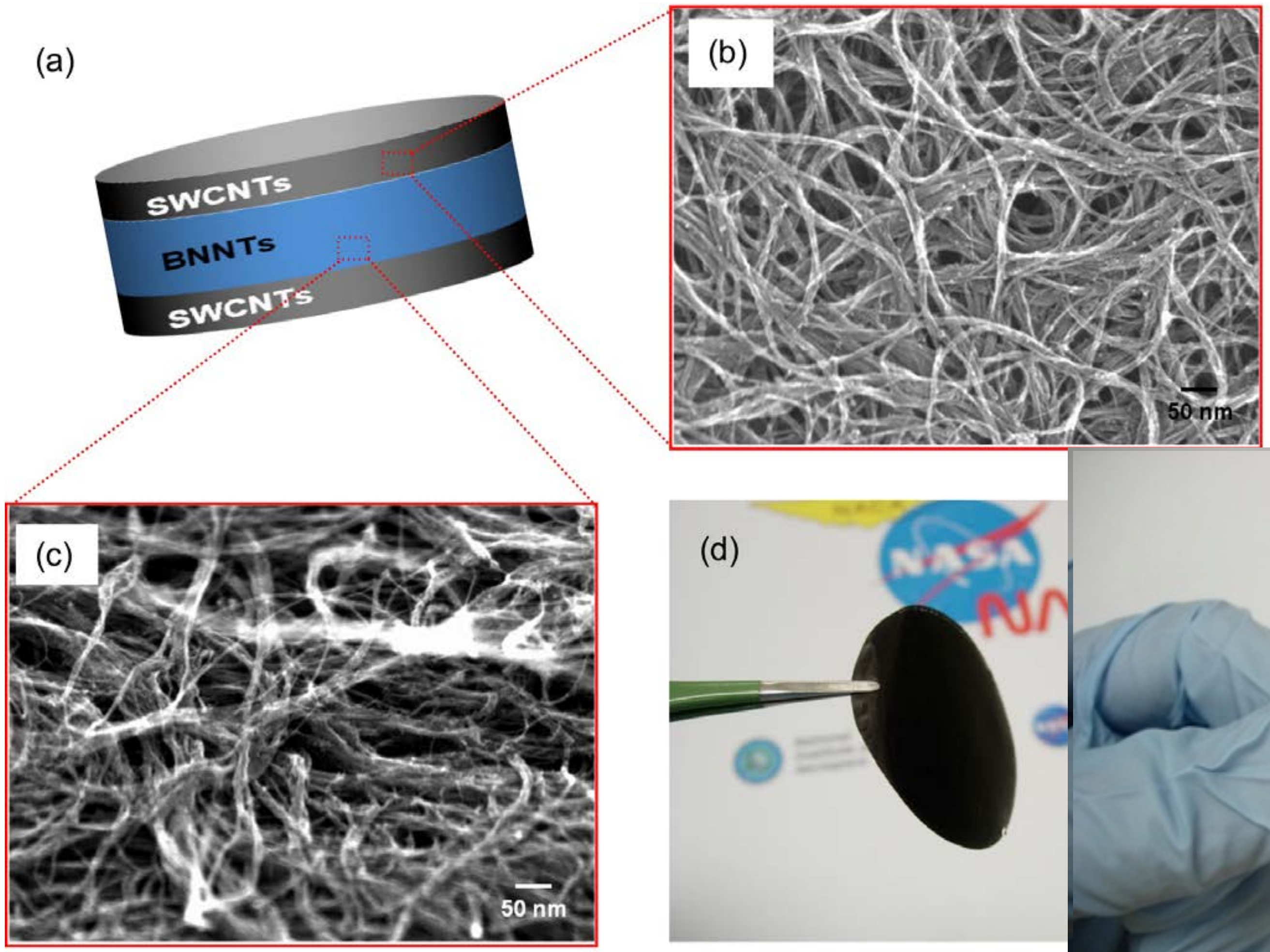


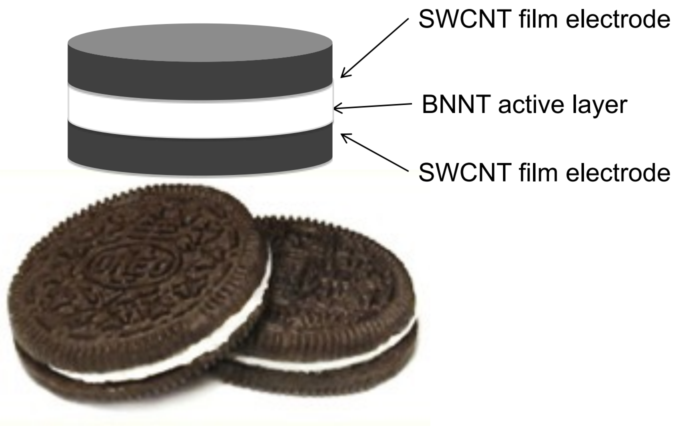


Comp. Mater. Sci., **135** 29 (2017)

Comp. Mater. Sci., **95** 362 (2014)

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





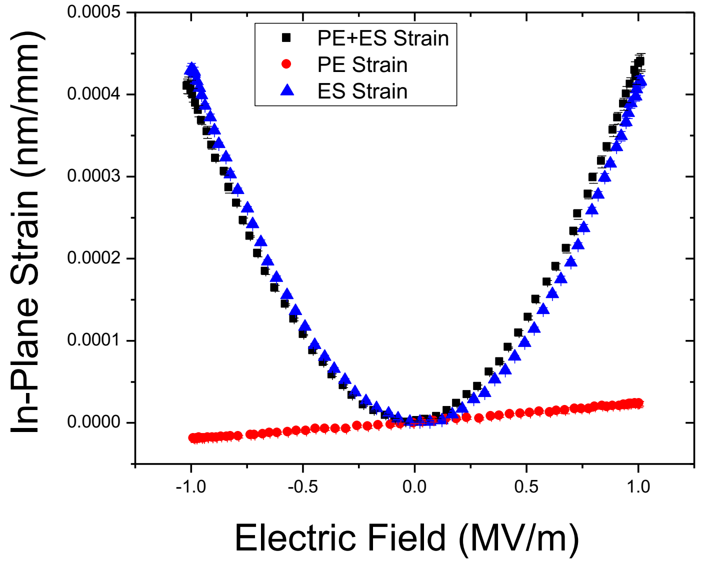
SWCNT: Single Wall Carbon Nanotube

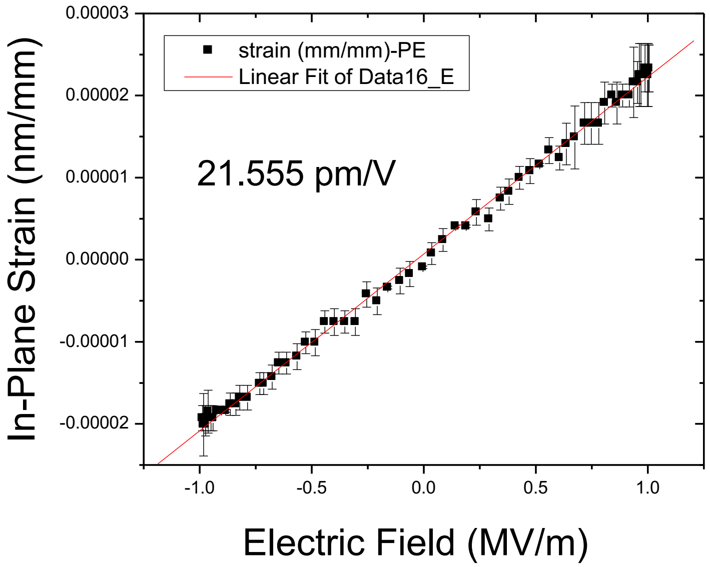
Goal: Flexible, transparent, large actuation, high sensitivity, mechanically durable

Images credit: NASA

ACS Nano **9** 11942 (2015)

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

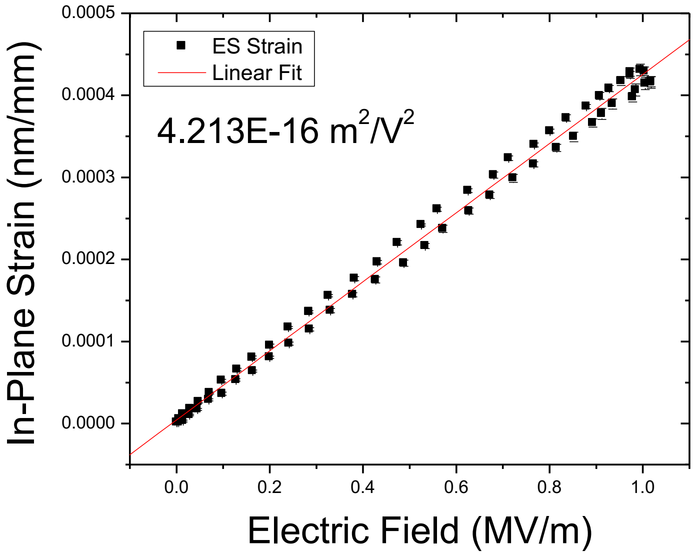




Field induced strain (e_{33})

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

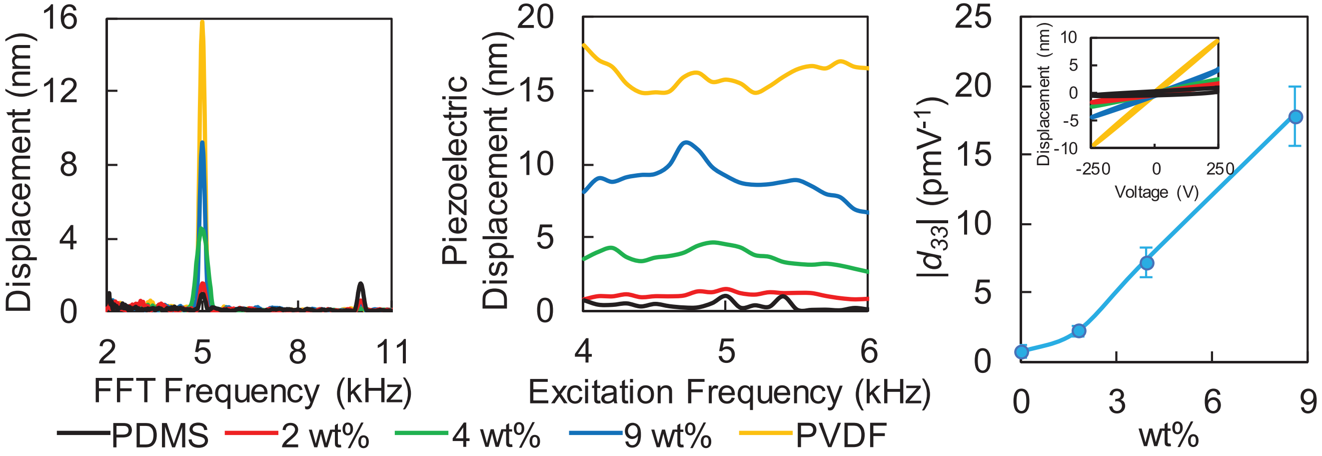
$d_{33:}$ piezoelectric (PE) coefficient
$M_{33:}$ electrostrictive (ES) coefficient
E: applied electric field



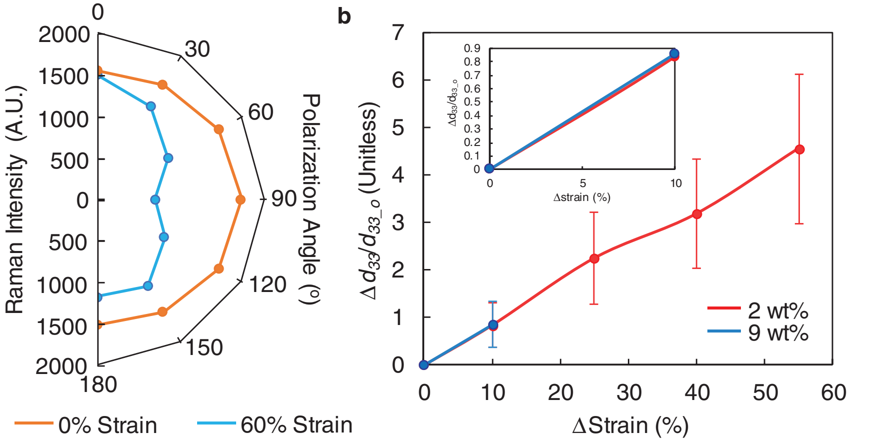
ACS Nano **9** 11942 (2015)

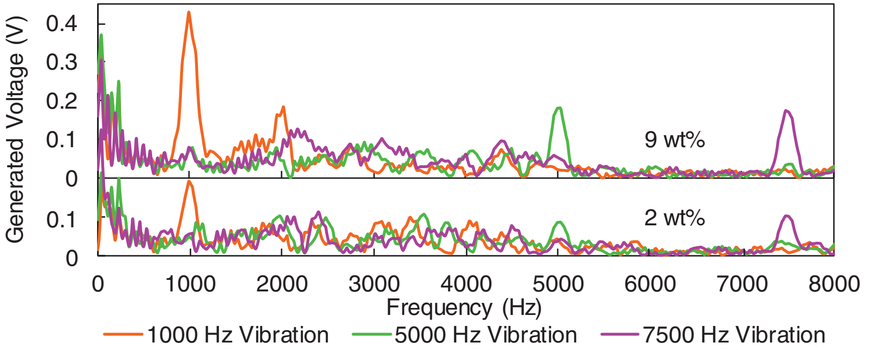
Multifunctional Properties of BNNT/PDMS (Poly(dimethylsiloxane))

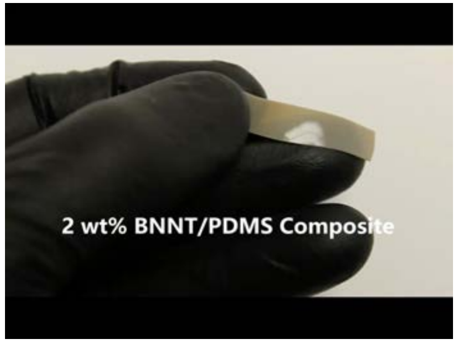
Piezoelectric Properties of BNNT/PDMS



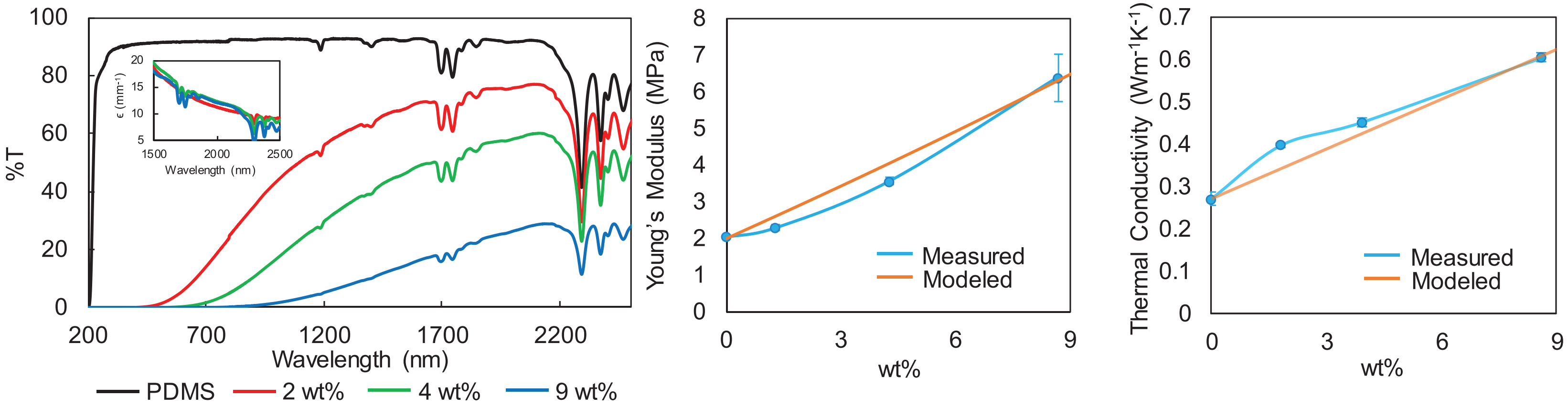
Alignment Effect & Vibration Sensing of BNNT/PDMS







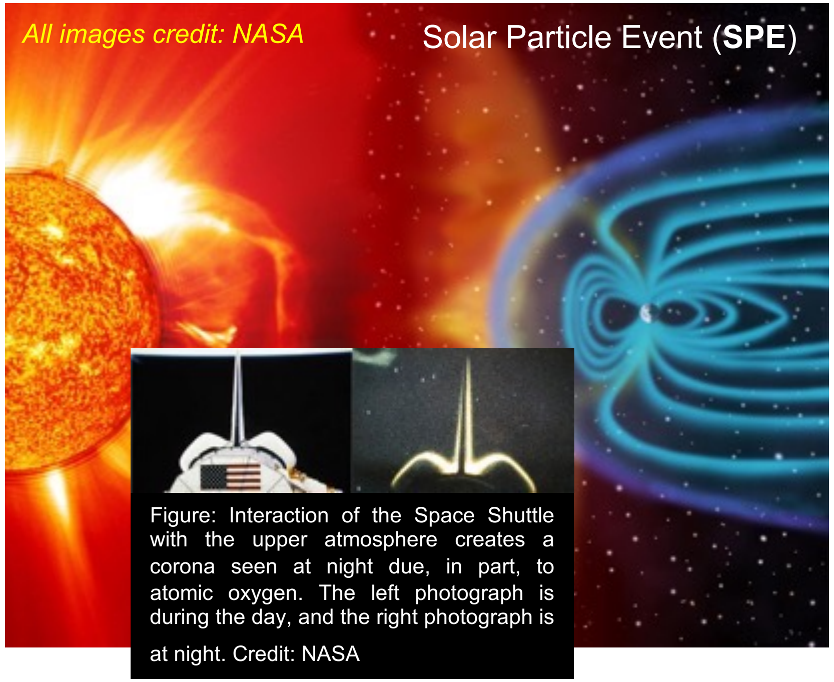
Optical, Mechanical, and Thermal Properties of BNNT/PDMS



Credit: Dr. Peter Snapp (NASA GSFC) and Professor SungWoo Nam

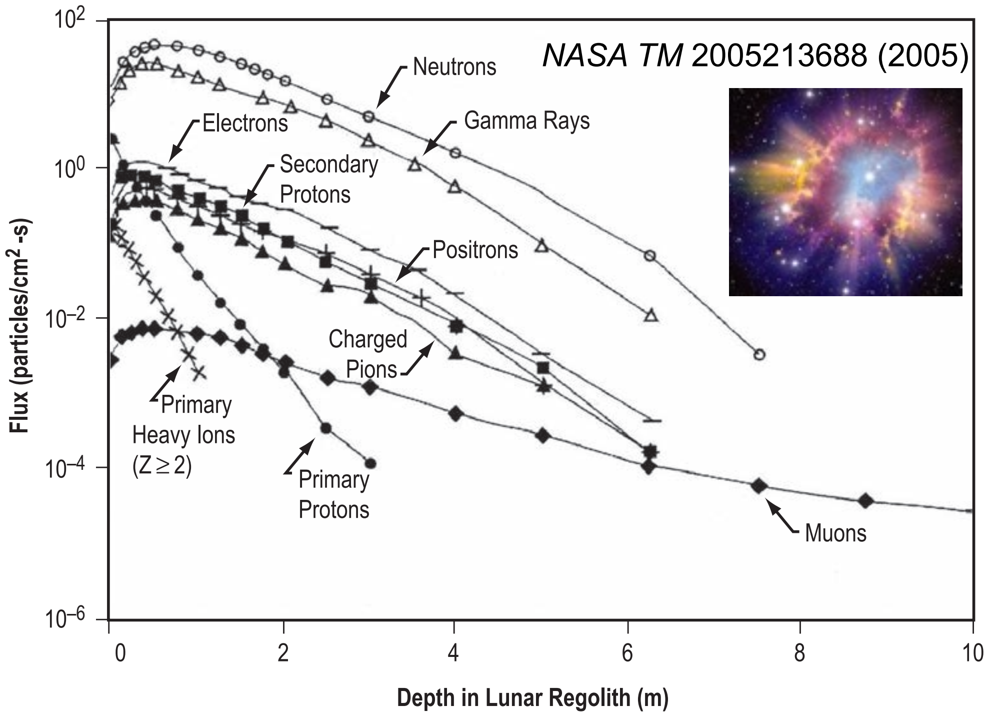
Advanced Materials, **32**, 2004607(2020)

Radiation Shielding Properties



Science **340** 1080 (2013)

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



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

C. Zeitlin,[1*] D. M. Hassler,[1] F. A. Cucinotta,[2] B. Ehresmann,[1] R. F. Wimmer-Schweingruber,[3] D. E. Brinza,[4] S. Kang,[4] G. Weigle,[5] S. Böttcher,[3] E. Böhm,[3] S. Burmeister,[3] J. Guo,[2] J. Köhler,[3] C. Martin,[3] A. Posner,[6] S. Rafkin,[1] G. Reitz[7]

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.

Space Radiation Risks

Risk to:	Examples of Risks
Humans	Acute risks (e.g. acute radiation syndrome form SPE) Chronic risks (e.g. Cancer from GCR
Electronics	Single event effects (ex. Latch errors)
Materials	Degradation

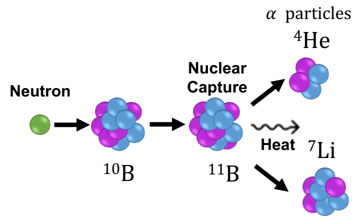
Mars Round Trip Dose Equivalent is around 0.66 Sievert

MRS Bulletin **40** 836 (2015)

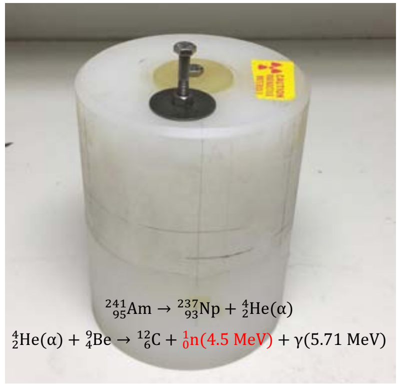
Radiation Tests: LaRC Radiation Exposure Test Facility

Neutron Source

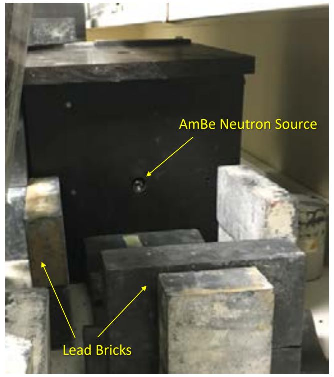
- Radioactive Source: Am/Be (1 Curie) source produces fast neutron (4.5 MeV) and thermal neutrons (<0.5 eV) by borated PE cylinder (44 mm thick)
- Sample: 2"x 2"
- Detection Foil: 1.25" Indium Foil (0.5mm, 19 barns), $^{115}In(n, \gamma)^{116}In$

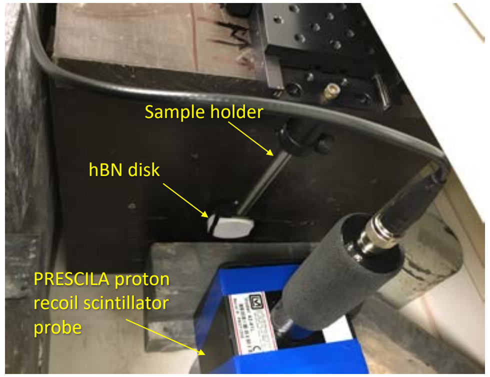


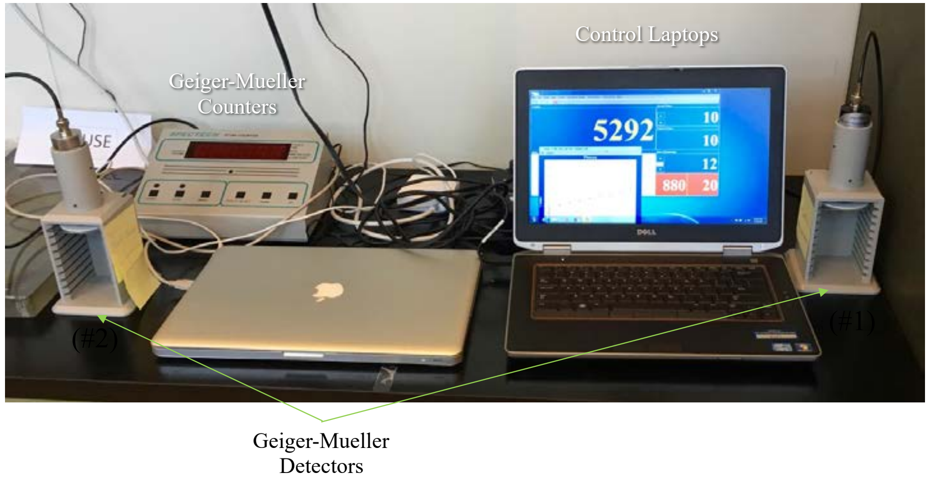
Low Dose Rate
(45 mrem/hr, dose equivalent rate)



High Dose Rate
(800 mrem/hr, dose equivalent rate)

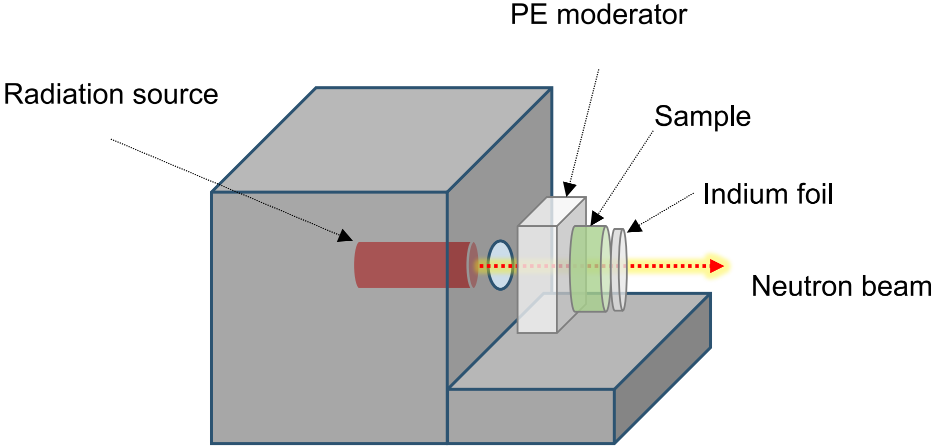




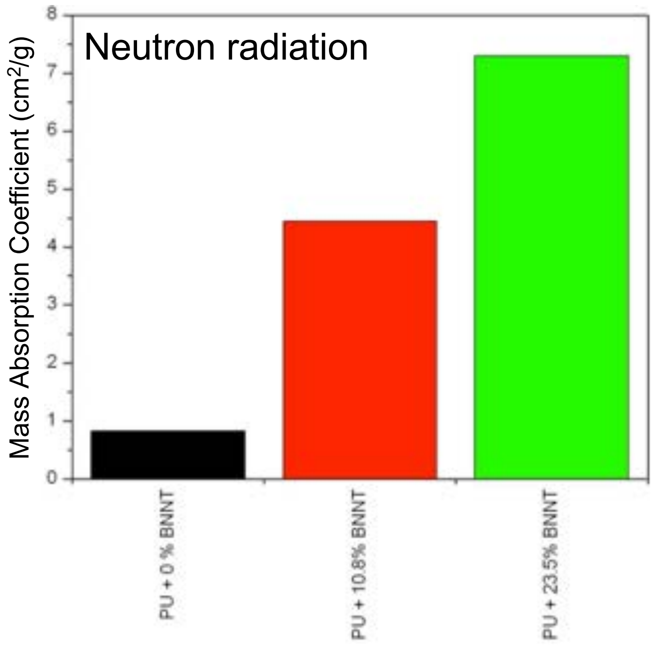


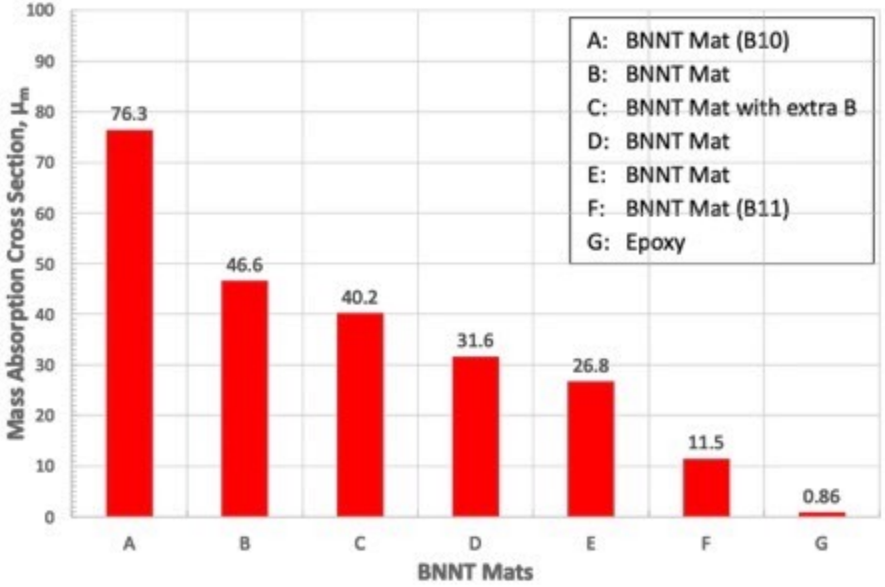
Dose Equivalent Rate Measurement

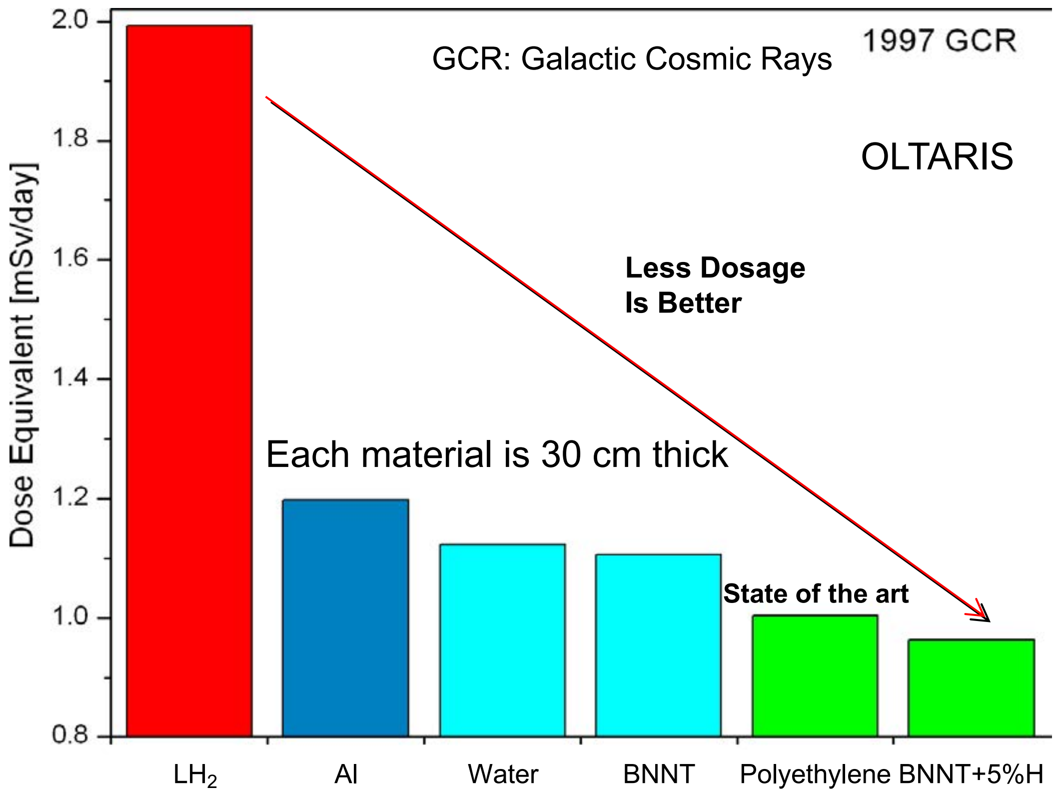
- Neutron survey meter: Ludlum Portable Survey, Model 2363
- Probe: PRESCILA proton recoil scintillator probe (Model 42-41L)
- Detection range: 0.1 mrem/hr to 1 rem/hr



Radiation Shielding Effectiveness of BNNT Composites



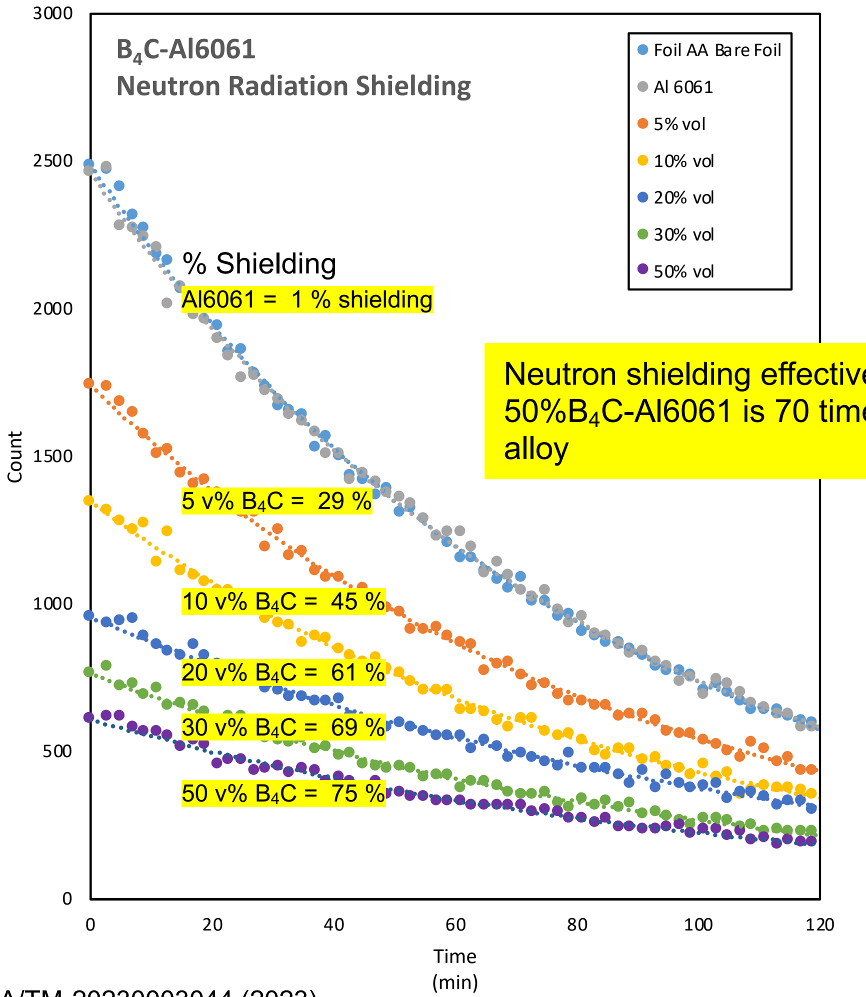




http://www.nasa.gov/pdf/716082main_ Thibeault_2011_PhI_Radiation_Protection.pdf (NASA NAIC Phase I Report)

Neutron Shielding Test and OLTARIS Modelling for Bulk MMC

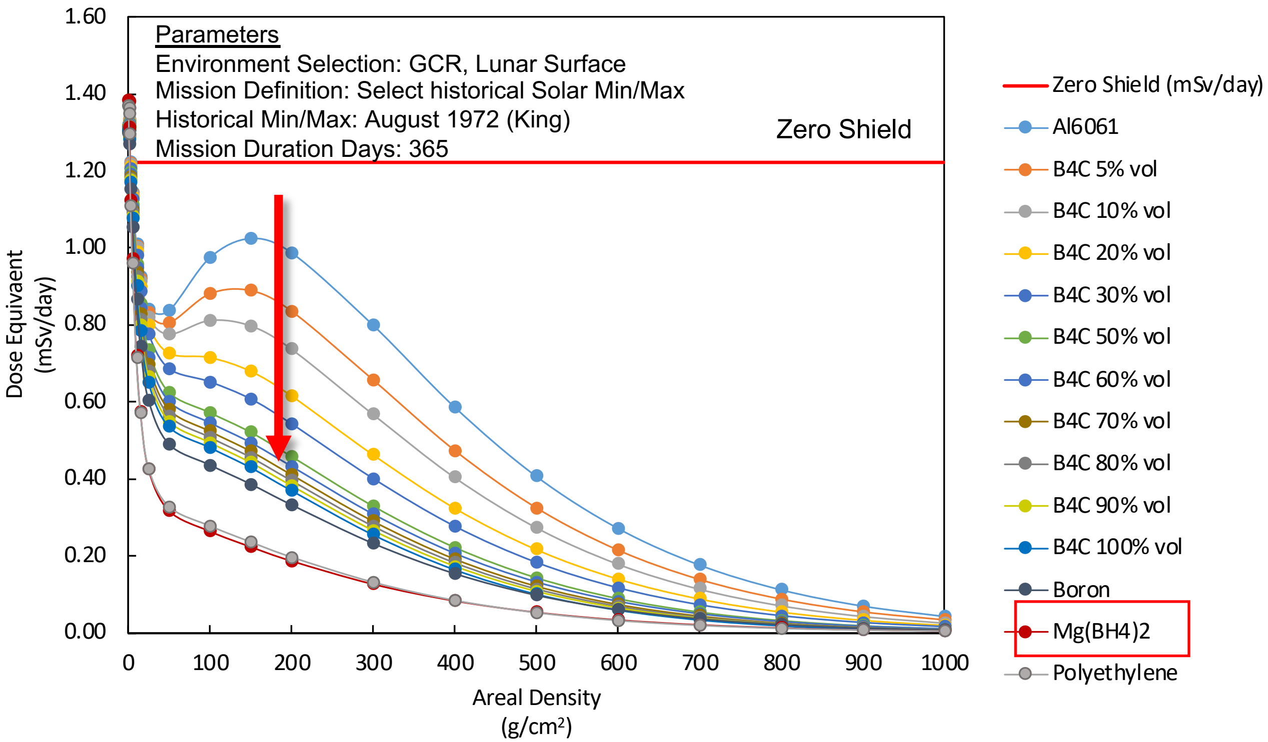
- **Performance Evaluations**
  - Space Radiation Shielding Test: Neutron Shielding Test at LaRC
  - Excellent Neutron Shielding Effectiveness with B_4C reinforcement



Neutron shielding effectiveness of 50%B_4C-Al6061 is 70 times over Al alloy

- Space Radiation GCR Shielding and OLTARIS Modeling for Lunar Surface

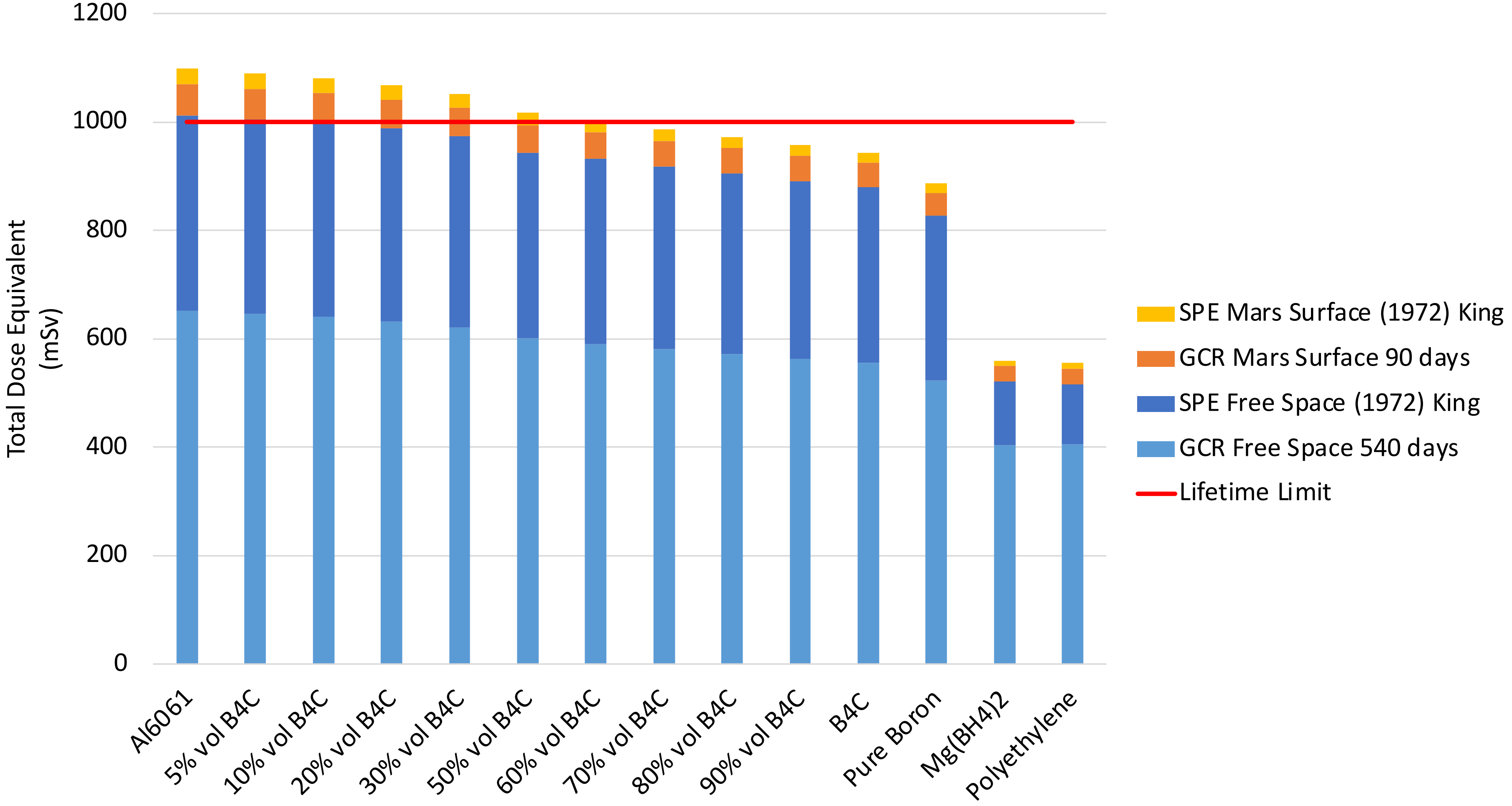
BON-14 GCR Model on Lunar Surface with 1977 Solar Min. Incident on Vehicles with varying thickness



- Al6061 indicated adverse effect on shielding effectiveness around 150 g/cm^2 due to secondary radiation.
- The adverse effect was substantially suppressed by the presence of boron and no adverse effect was predicted at 20 vol% B_4C-Al6061.
- $Mg(BH_4)_2$ shows shielding effectiveness equivalent to polyethylene.

NASA/TM-20230003044 (2023)

Total Dose Equivalent for a Roundtrip Mars Mission Using Various Materials (25 g/cm^2)



The total dose equivalent for a roundtrip mission (21 months duration) is significantly lower for vehicles with higher boron and hydrogen content materials. From 60 vol.% B_4C and on the total dose equivalent falls below the 1000 mSv astronaut lifetime limit established by Johnson Space Center. This decrease in dose equivalent could increase a mission period by up to 409 more days leading to the execution of vital research.

Summary

- Current NASA missions and extreme space environments were introduced.
- High Temperature-Pressure (HTP) BNNT and BNNT composites were introduced.
- Interfacial shear strength and fracture energy of BNNT with polymer, metal, and ceramic matrices 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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