National Aeronautics and Space Administration

# Novel Power Transmission Solutions for Megawatt Scale Electric Aircraft

Dr. Maricela Lizcano

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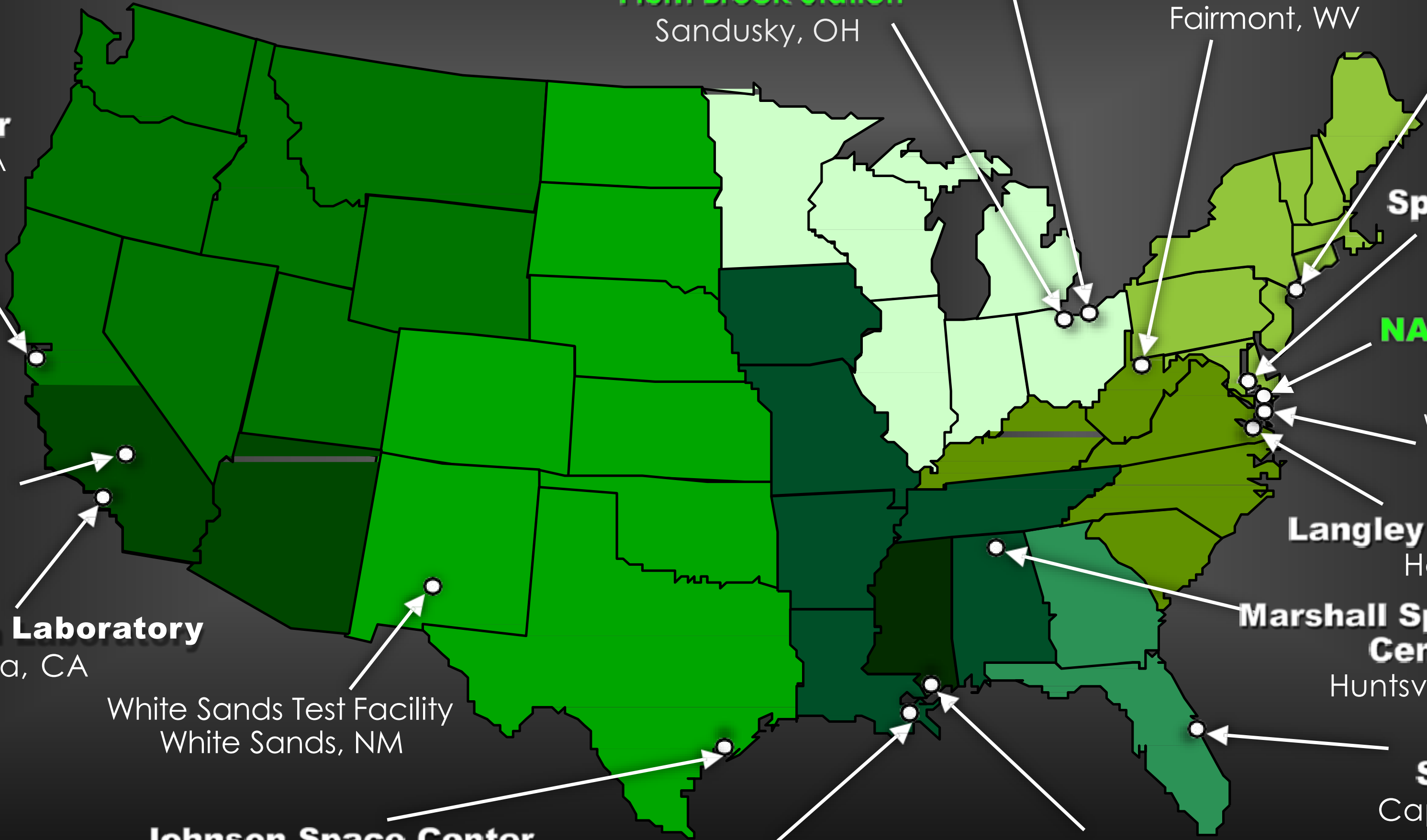
# NASA Centers and Installations

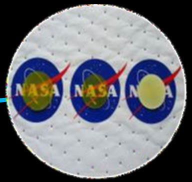
Deep Space Network Facilities:

- Goldstone, in California, Mojave Desert
- Near Madrid, Spain
- Near Canberra, Australia



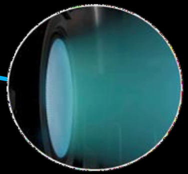

# GRC Core Competencies

Power, Energy Storage and Conversion



*Materials and Structures for Extreme Environments*

Physical Sciences and Biomedical Technologies in Space

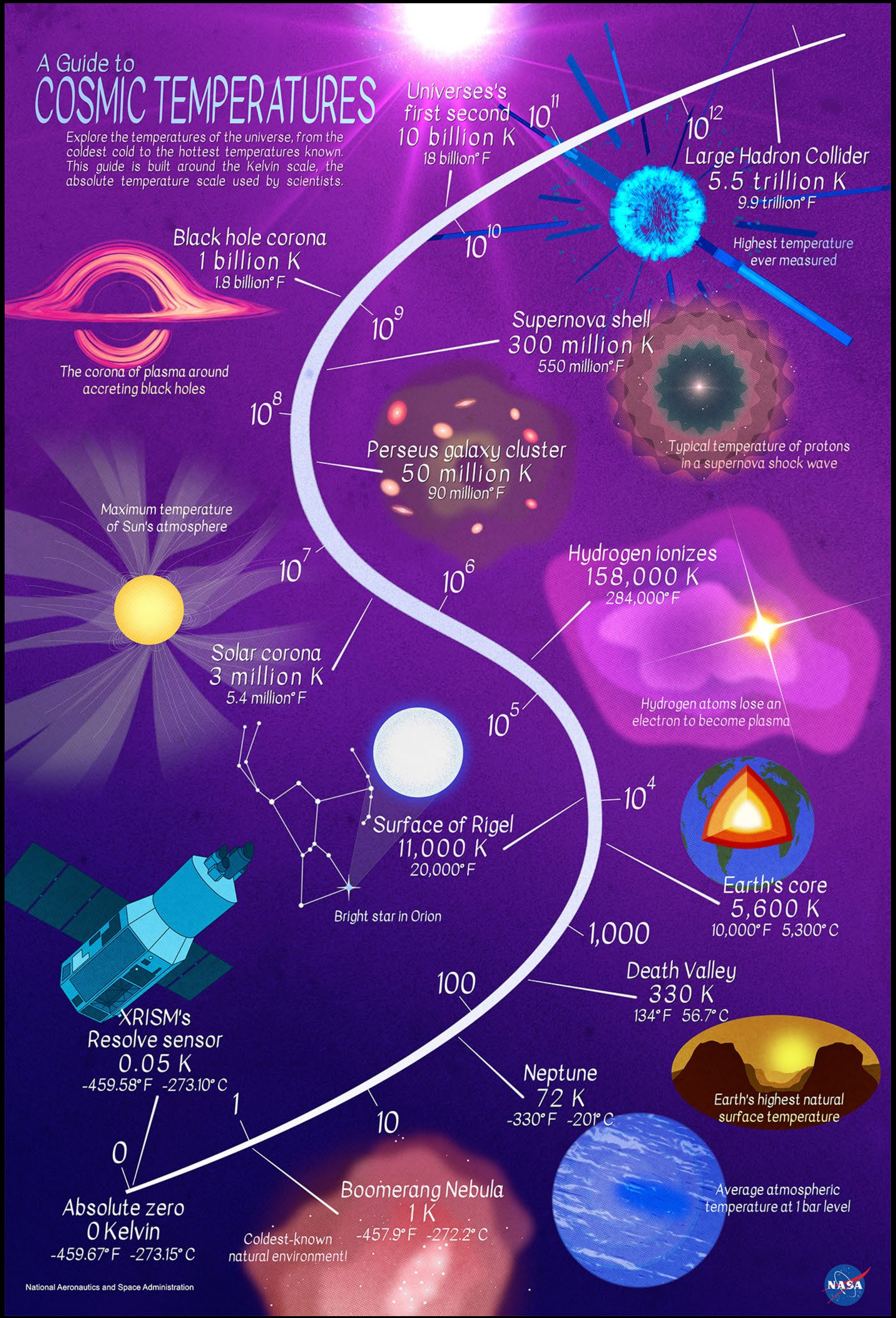


In-Space Propulsion and Cryogenic Fluids Management

Communications Technology and Development

Air-Breathing Propulsion

# Extreme Environments




# Extreme Temperatures

Deep Space
-459 °F/-273 °C
to
Super Nova
550,000,000 °F

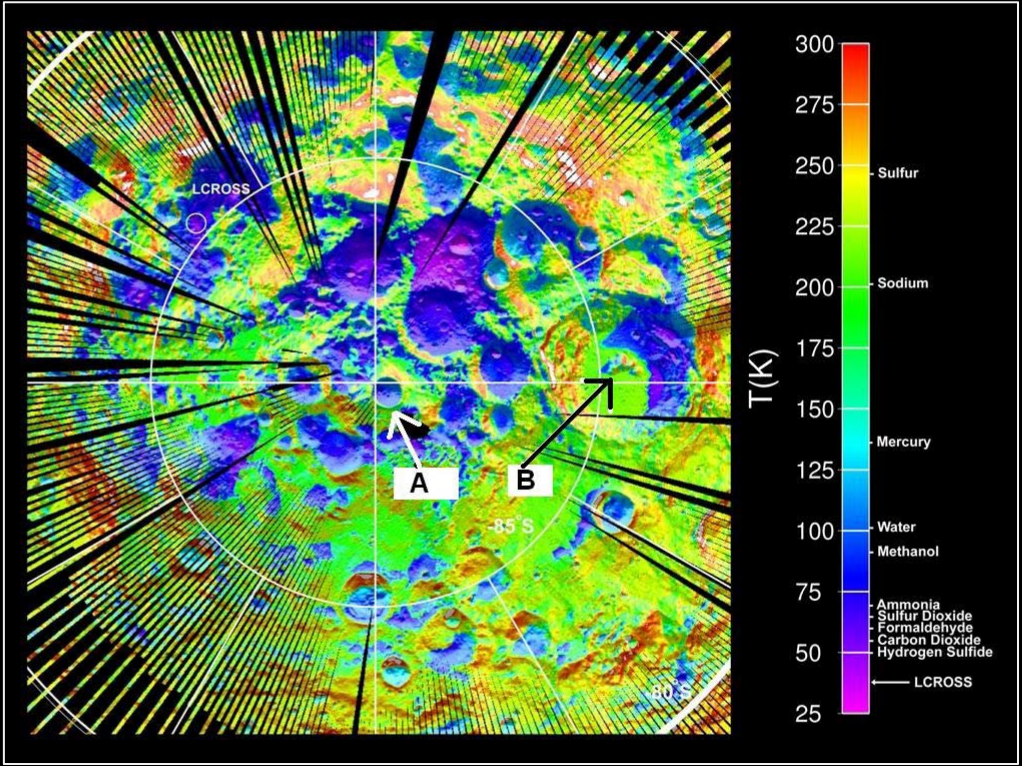
Big Bang
18 Billion °F

Man Made
Large Hadron Collider
9.9 Trillion °F

https://svs.gsfc.nasa.gov/vis/a010000/a014300/a014374/Cosmic_Temperatures_Horizontal_Scale_Full.jpg

# Lunar Temperatures

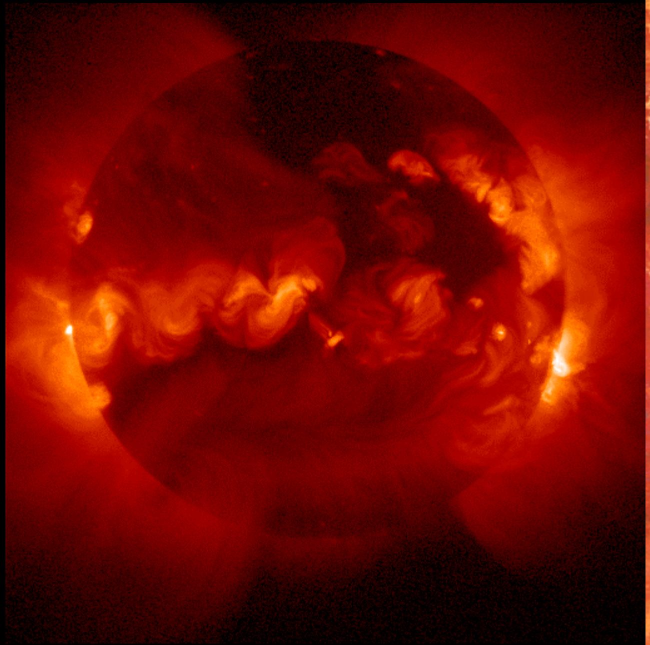
## Lunar South Pole Temperature Mapping

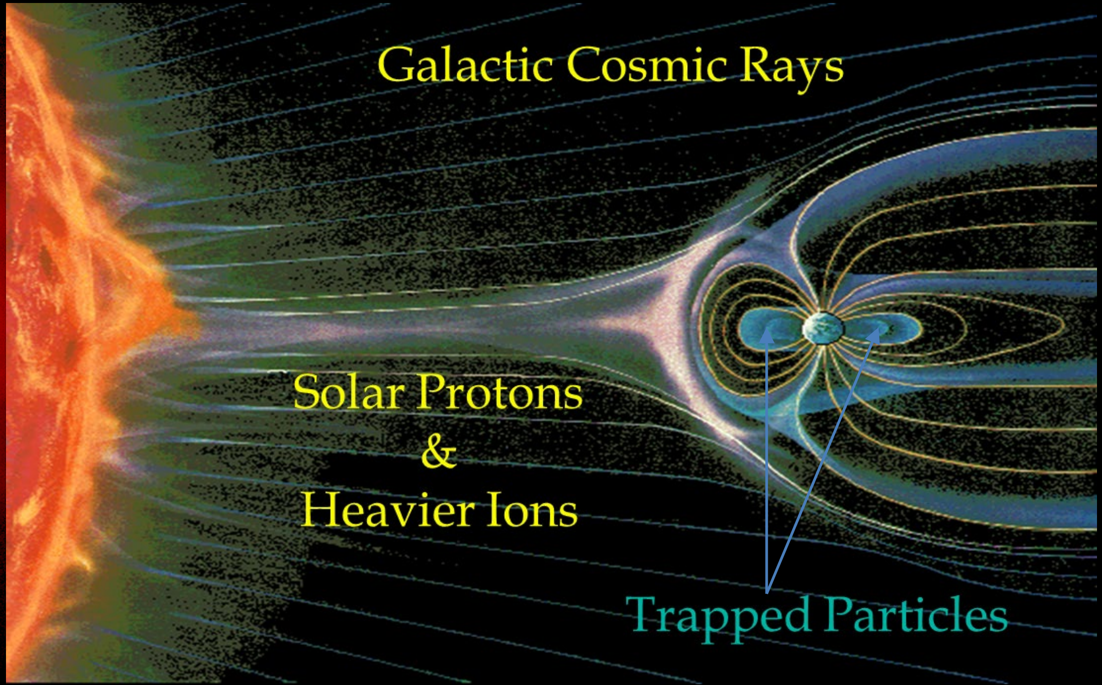



https://www.jpl.nasa.gov/edu/images/news/apollo11_moonwork_collage.jpg

- Daylight temperatures near the Moon's equator ~ -208 °F (-133 °C) to 250 °F (121 °C)
- Nightfall at the equator drops to -208 °F (-133 °C).
- NASA's Lunar Reconnaissance Orbiter has measured temperatures lower than -410 °F (-246 °C).

# The Radiation Environment



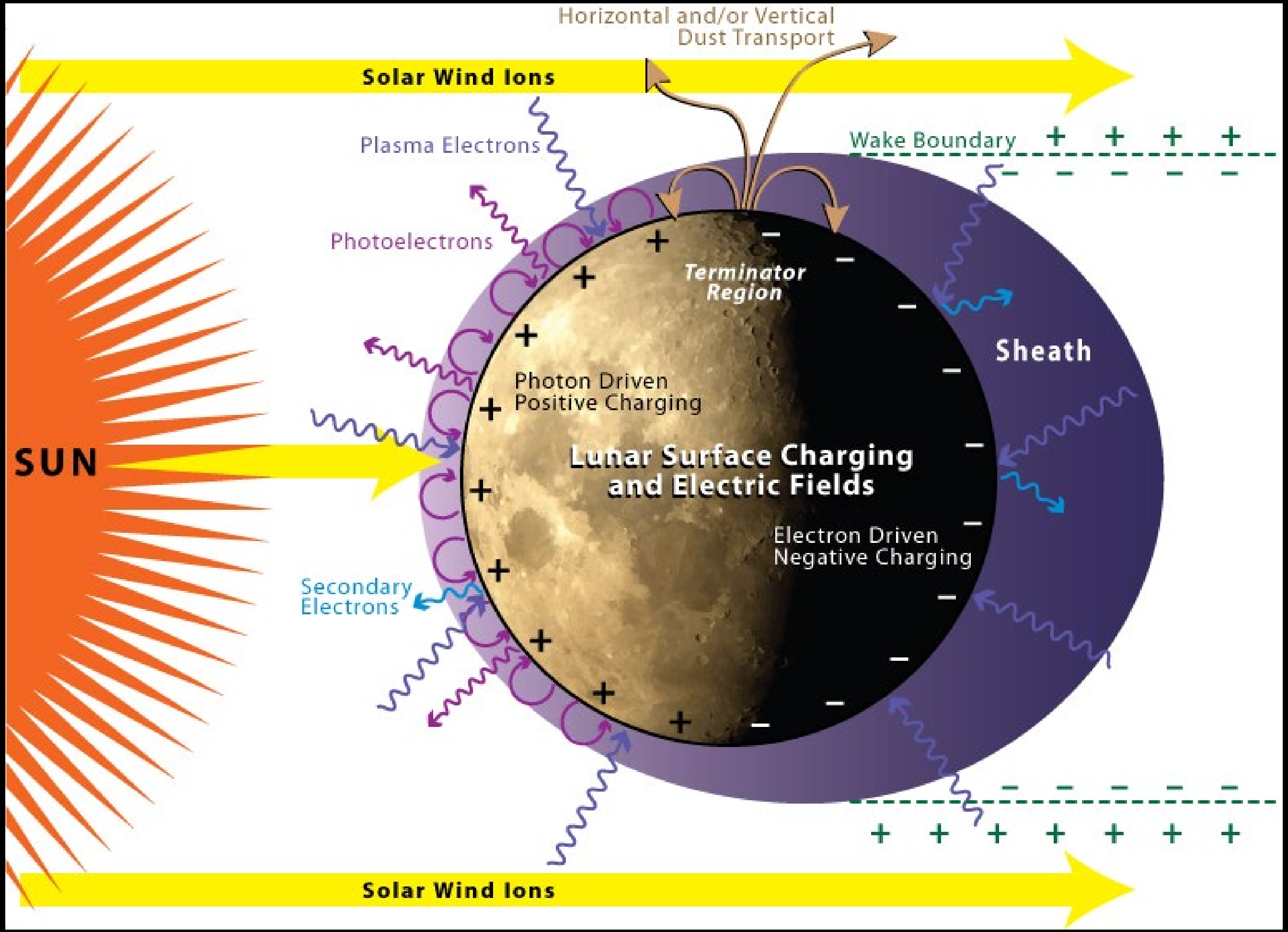



- Charged Particles: Protons, heavy ions, neutrons includes X-rays, UV rays
- Planetary asteroid debris as micrometeors

https://radhome.gsfc.nasa.gov/radhome/RPO_slides.htm

# The Moon is Like a Giant Capacitor

- The Moon is charged by all the charged particles in the heliosphere
- UV light also deposit photoelectrons or creates ion and secondary electrons from striking regolith particles
- During Corona Mass Ejections while traveling the wake of  the Earth's Magnetosphere, negative potentials of -4000 volts as well as dielectric breakdown have been observed



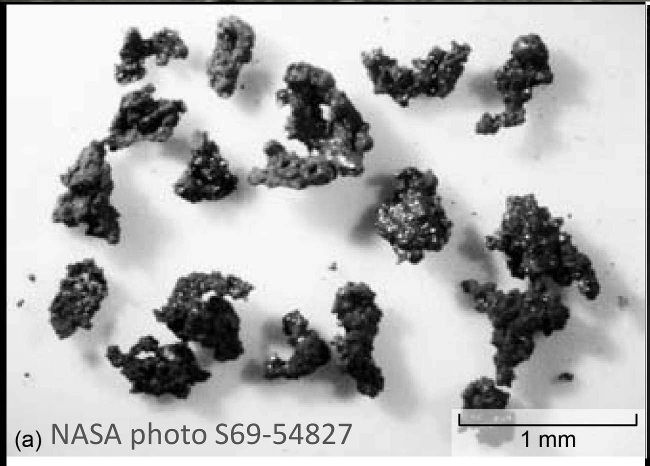

**CHARACTERIZING THE NEAR LUNAR PLASMA ENVIRONMENT.** T. J. Stubbs, Goddard Earth Science and Technology Center, and NASA Goddard Space Flight Center, Mail Code 674, Greenbelt, MD 20771, (Timothy.J.Stubbs.1@gsfc.nasa.gov)

# The Lunar Regolith

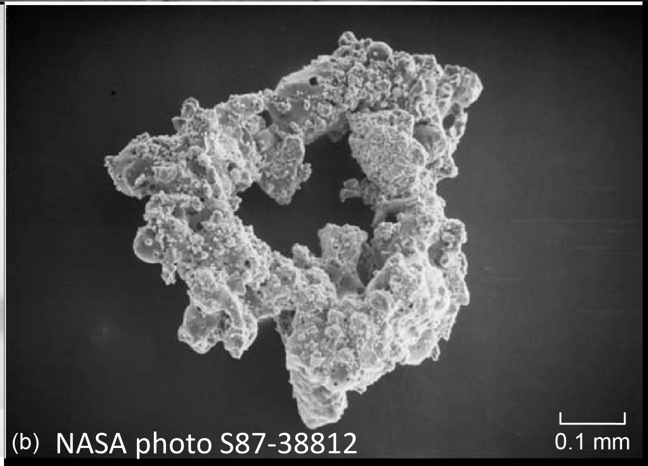
Regolith is unconsolidated rocky material (minerals, glasses, volcanic rock) that covers bedrock.

Lunar Regolith Dust:

- <20 microns to ~1 cm
- Electrostatic
- Abrasive with sharp edges

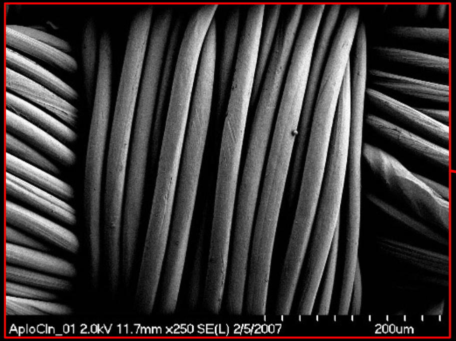

(a) NASA photo S69-54827



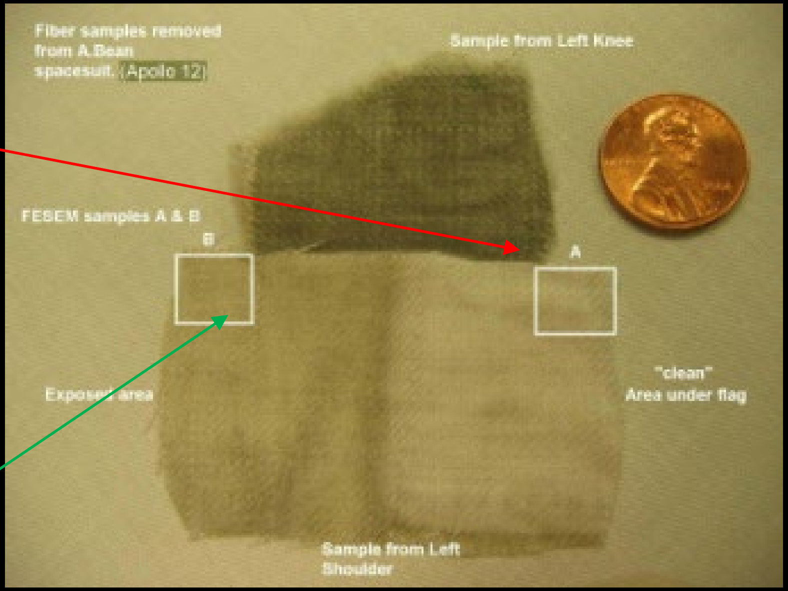

(b) NASA photo S87-38812

# Apollo Era Space Suit and Lunar Dust

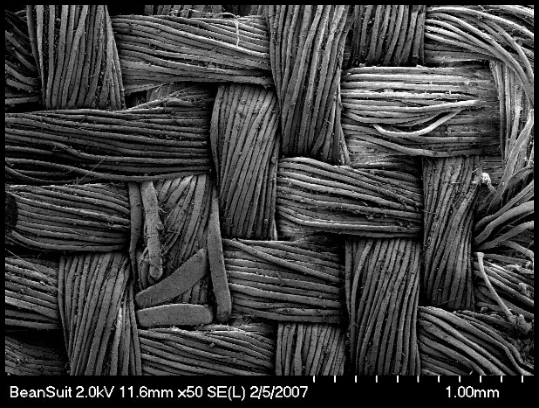
Spacesuit: Teflon coated fiber glass fibers Alan Bean Apollo 12 Mission





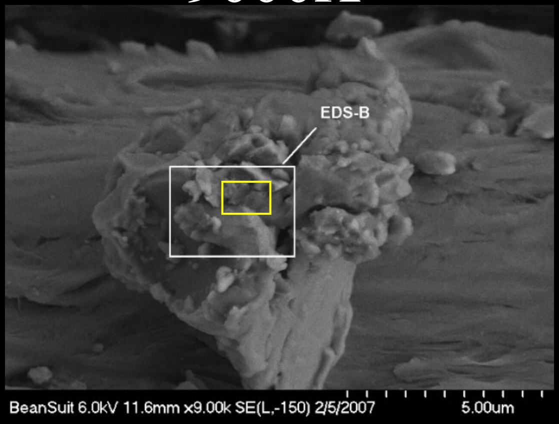


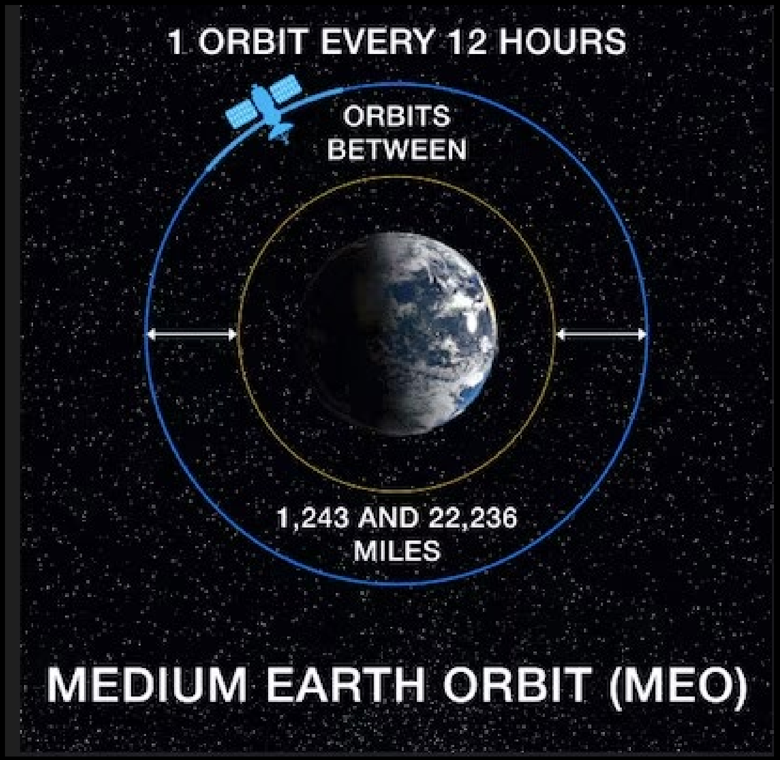

**50X**




**1000X**


**9000X**



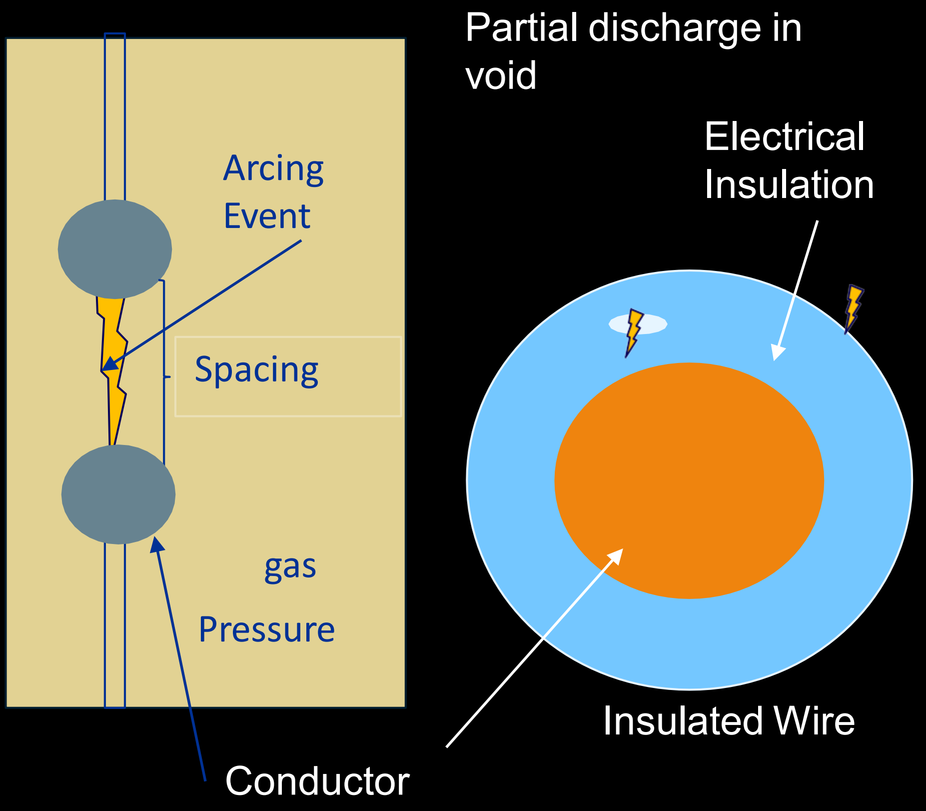



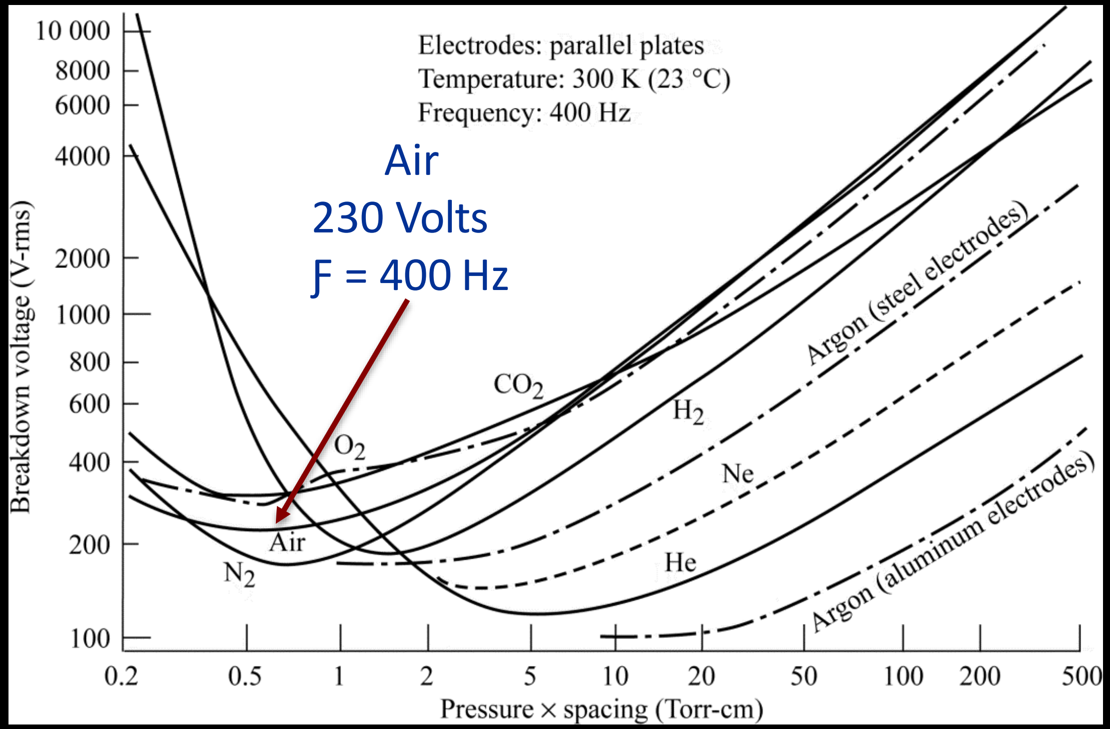

# Challenges with High Power Transmission In Space

# Thermal, Electrical, Mechanical and Environmental Challenges

- Temperature Swings
- Electrical Stress and High Electric Fields
- Mechanical Stress from manufacturing, transport, handling onto spools, loading or installing in spacecraft and deployment
- Environments from sitting on launch site, lift-off conditions, time of flight in  standard atmospheric pressures to vacuum

# Technical Challenges: Partial Discharge and Corona



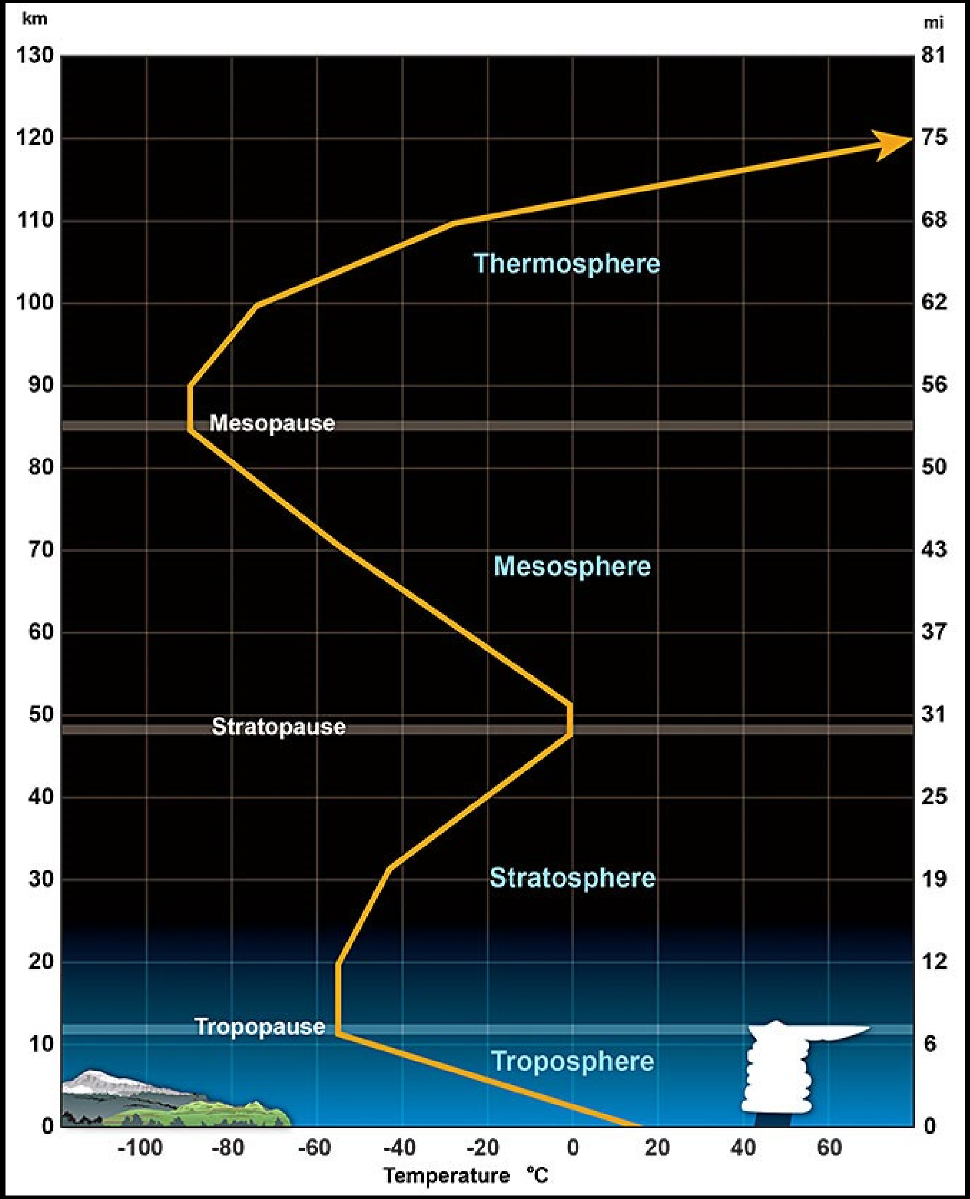




**Breakdown Voltage of Several Gases as a Function of *pd* at Room Temperature**

The minimum voltage for electrical discharge between two metal conductors at ***high altitude*** will occur at ~ 327 V. ***At 400 Hz the minimum voltage drops to 230 V for arcing to occur***. Additionally, voids, defects and contaminants in electrical insulation can experience intensified local discharge called partial discharge.

**Chart Reference: NASA-HDBK-4007 W/CHANGE 3**

# Example




https://www.noaa.gov/jetstream/atmosphere/layers-of-atmosphere

Earth's Atmospheric Temperature Profile
~-90 °C to 60 °C

The low density of air at high altitudes. extreme temperatures and high-power electrical systems can make future high altitude electric aircraft (> 25,000 feet) susceptible to partial discharge when exposed to high electric fields.

https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/n3x/

# Powering Up The Future

Best Electrical Insulation Candidates
- Fluoropolymer (FP)
- Polyimides (PI)

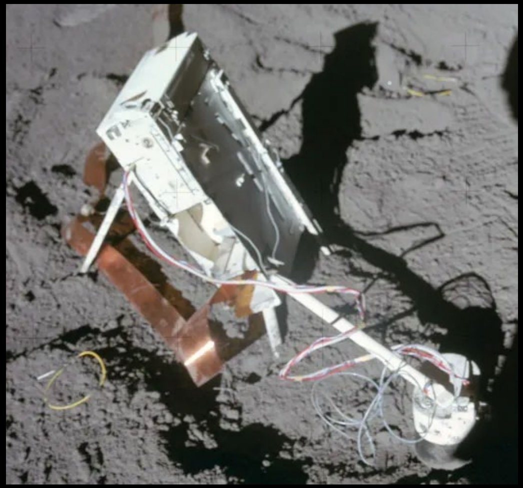
Challenges for Reliable HV Power Transmission
- High electric fields (HEF)
- FP susceptible to radiation and creep effecting reliability
- Tape wrapped PI is not extrudable

Historically Apollo ALSEP missions,
- PI, 70 W, 16 V, 400 Hz (Apollo 17)

Future High Altitude All Electric Aircraft
- ≥ 1KV, 400 Hz (avionics)  to  20 KHz )switching frequencies)

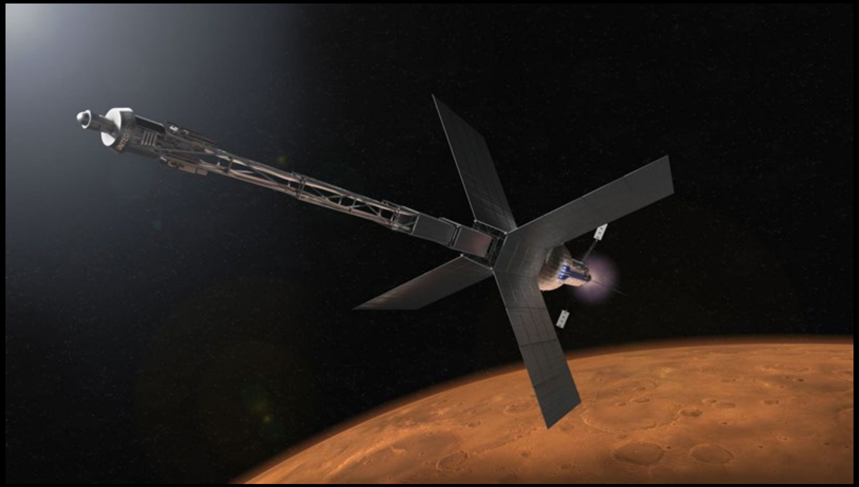
Future Lunar Economy
- 1 kV, 1 kHz and ~60 kW, 2.5 $kV_{AC}$ or 3 $kV_{DC}$ at 1 kHz power grids, power needs could grow to MW levels

Best SOA candidate materials are well known on Earth, the HV stress, fields and aging rates are unknown in extreme environments



Apollo 15
Cold Cathode Ion Gauge (CCIG) Experiment

Photo AS15-86-11595



Concept of Nuclear Electric Propulsion Spacecraft

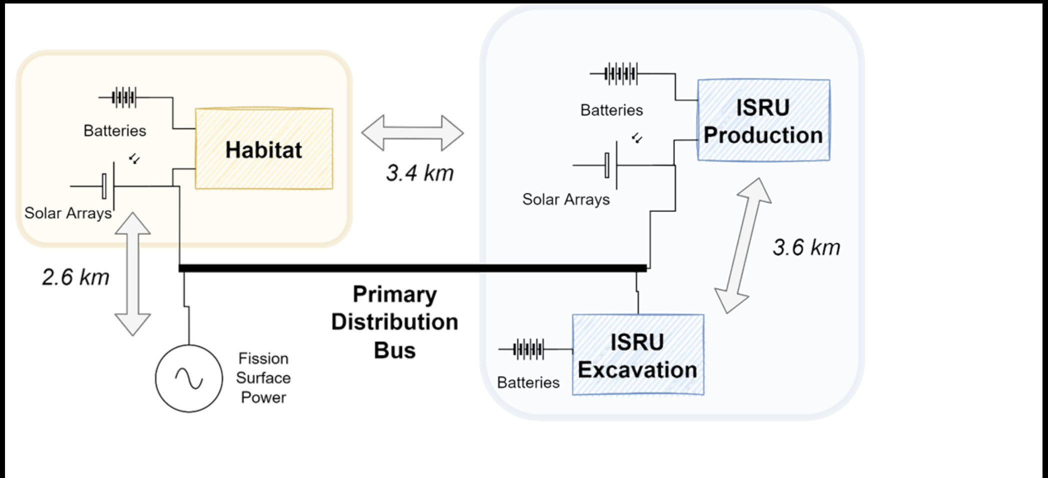
# Concept of Artemis Base Camp Micro-grid

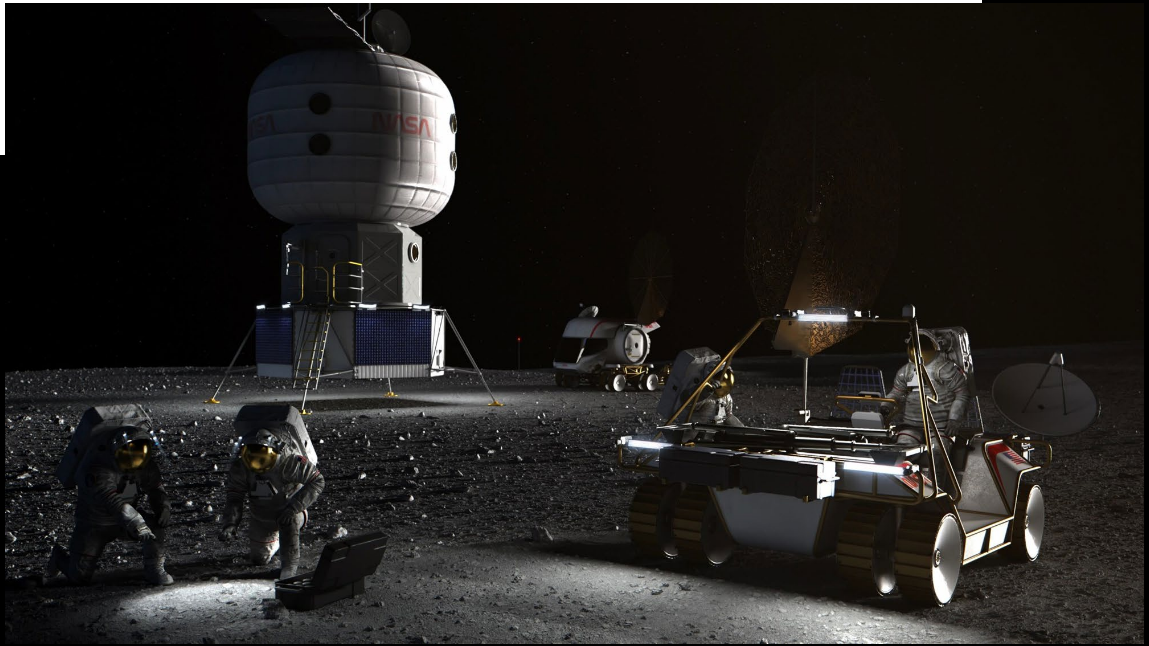
Trade studies focused on primary power distribution system

- Architecture (radial, ring, mesh)
- Power type (AC vs DC)
- Voltage: (600 V – 6 kV)
- Data contains estimated mass of converters + cables

Results

- Voltage 3 kV has mass advantages
- AC vs DC is marginal difference
- Technology limitations need to be considered

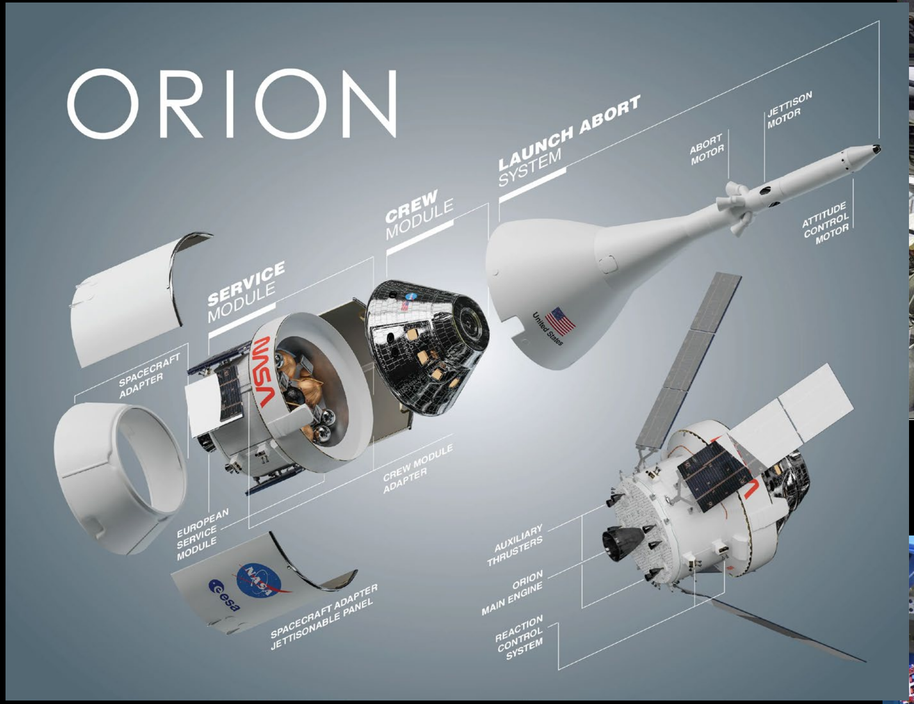


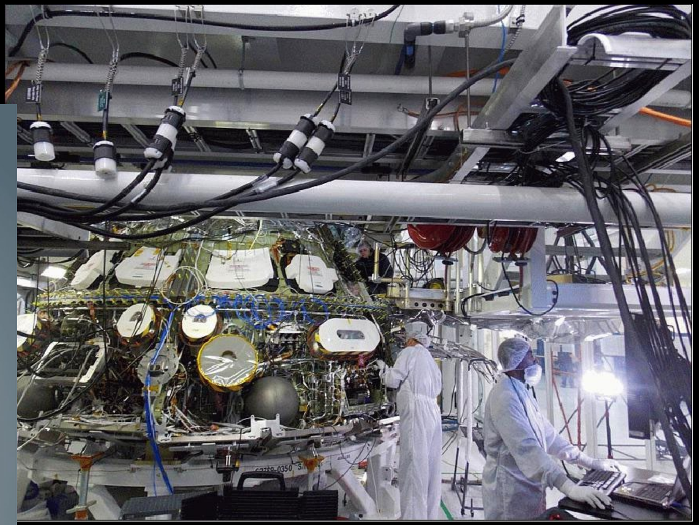



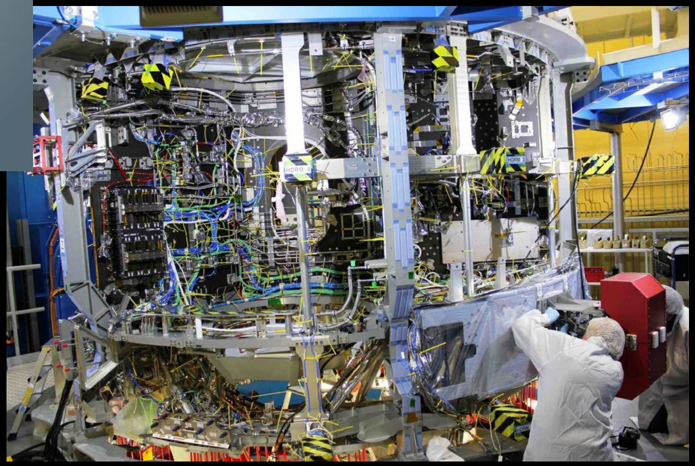
J. Csank, J. H. Scott, Advanced Research Projects Agency Energy, April 29, 2022

# Other Considerations

- Wires and cables for mega Watts of power in a future Aircraft, Lunar economy  or nuclear propulsion vehicles must be safe and reliable
- Wiring can contribute 50% or more of the payload increasing costs
- We need lightweight, safe and reliable solutions



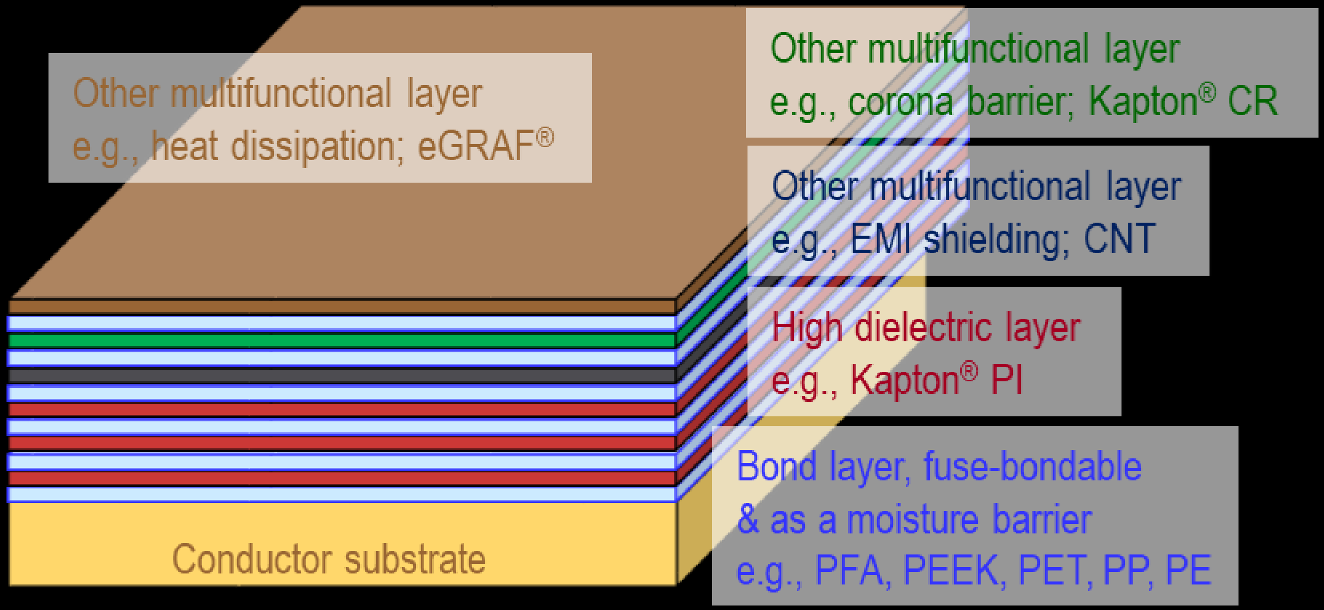


Orion Crew Capsule


Orion Service Module

credits: NASA

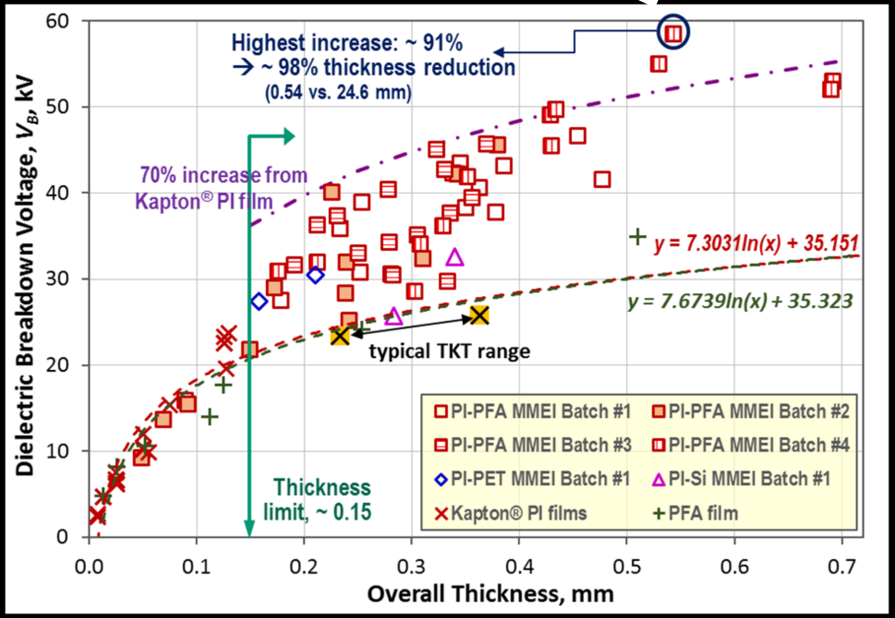
# NASA Materials R&D for High Power High Voltage Transmission

# NASA Developed a Micro-Multilayered-Multifunctional Electrical Insulation (MMEI)

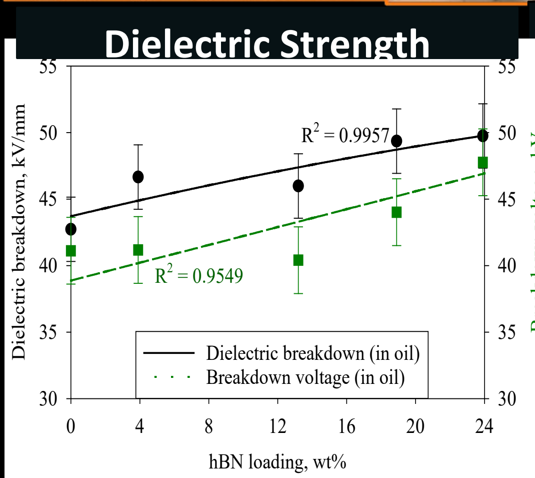


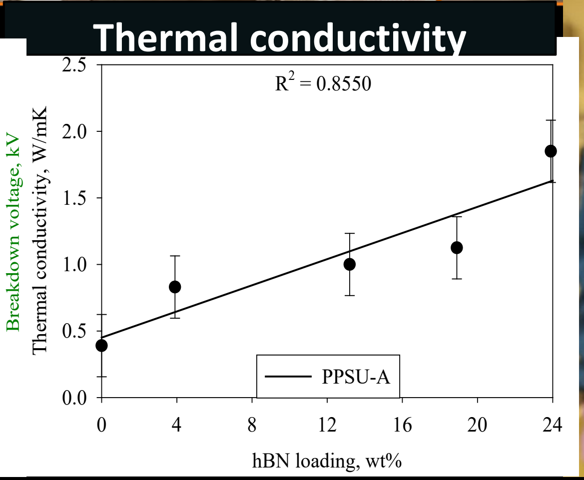

Compared to SOA Teflon-Kapton-Teflon (TKT)

- 91 % increase in dielectric break-down voltage
- 99% decrease in insulation thickness



# Improved Properties of Polymer with Fillers



Demonstrated better Thermal and Electrical Performance with ceramic fillers.

Composite insulation showed <u>improvement in dielectric strength</u> and <u>increase in thermal conductivity</u> relative to the neat polymer

T. Williams, B. Nguyen and W. Fuchs, 2020 IEEE 3rd International Conference on Dielectrics (ICD), 2020, pp. 541-545, doi: 10.1109/ICD46958.2020.9341910

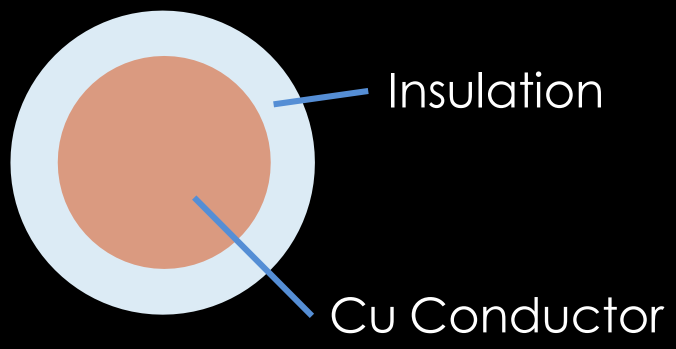
Dr. Tiffany Williams, Dr. Baochau Nguyen, Dr. Witold Fuchs

# Lightweighting Conductor

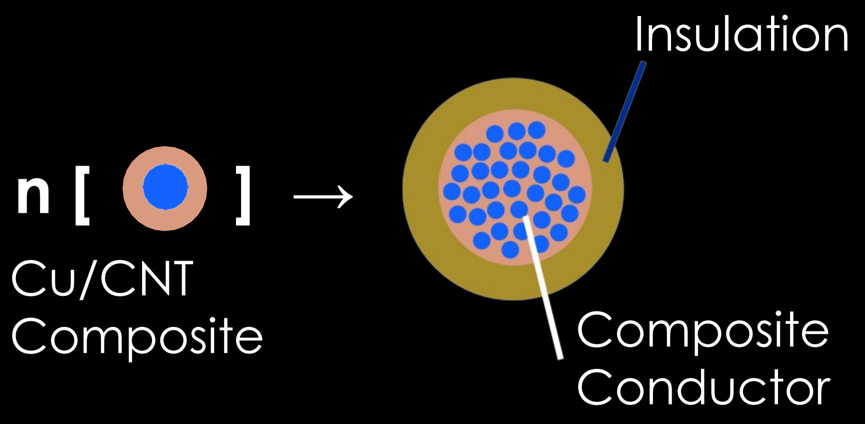
| | Copper | Carbon Nanotube (CNT) Yarn |
| --- | --- | --- |
| **Electrical Conductivity ($\kappa$, S/m)** | $5.8 \times 10^7$ | *$1.3 \times 10^6$ |
| **Tensile Strength ($\sigma$, MPa)** | 2 00 | 1500 |

| Key Feature | ($\sigma_{TS}$, MPa) | Electrical Conductivity ($\kappa$) |
| --- | --- | --- |
| Electroless plating [2] | - | 90% IACS |
| Self-fueled electrodeposition [3] | 500-650 | 51% IACS |
| Super-aligned CNTs [4] | 287 | 46.8 MS/m |
| Cu-Ti alloy matrix [5] | 362 *$\sigma_{YS}$ | 93% IACS |
| SPS composites, not aligned [6] | 275 | 93% IACS |
| Higher ampacity [4,7] | - | 46-47 MS/m |

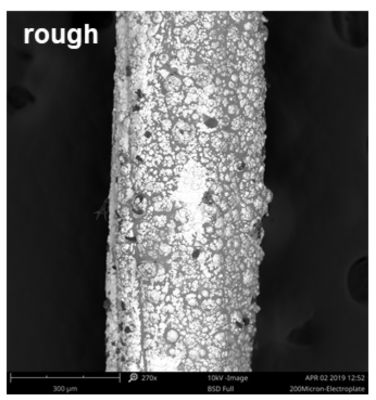
Now

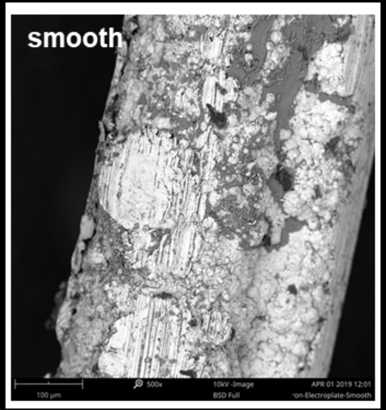



Future

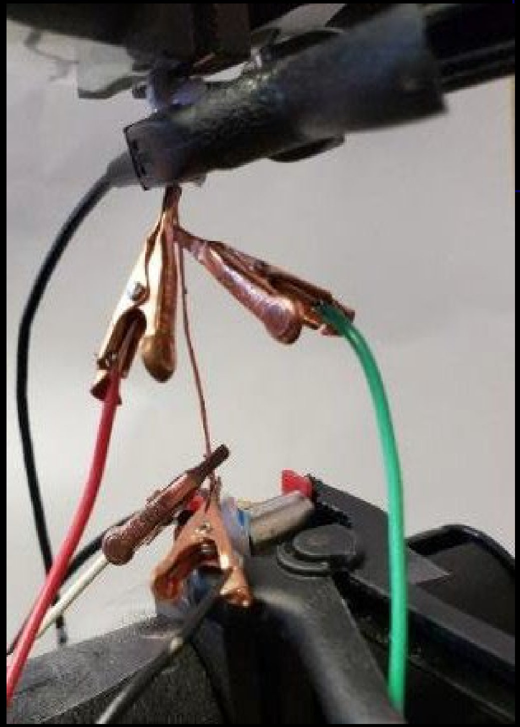


# Lighter Weight Cu/CNT Conductor

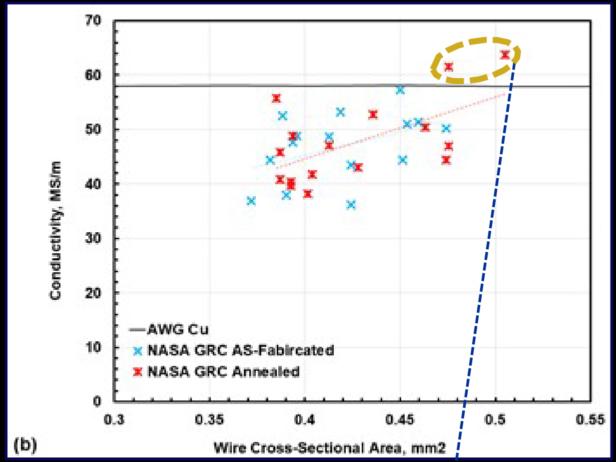


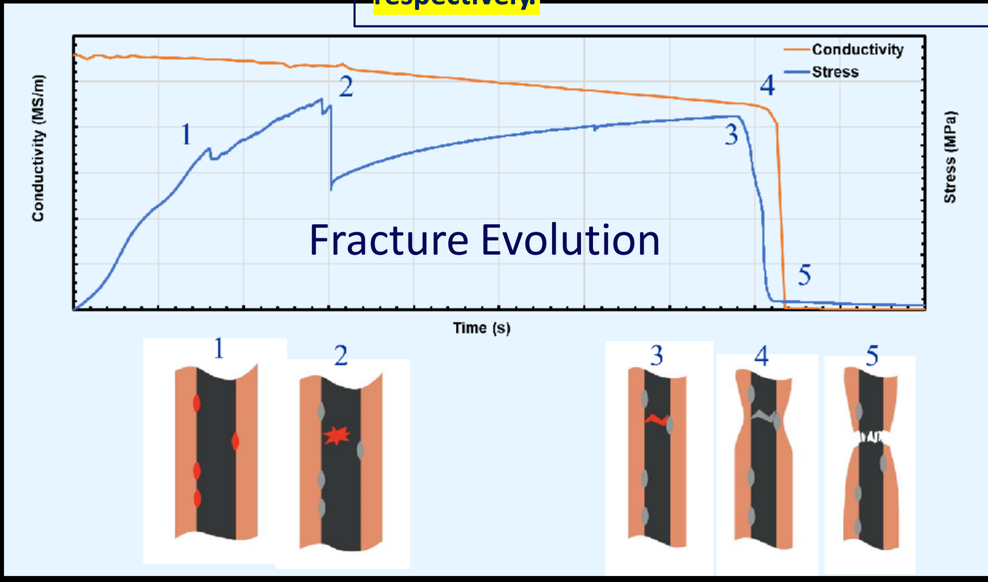

Correlate electrical and mechanical behaviors via 4-probe electrical resistance (ER) and acoustic emission (AE) monitoring



Cu/ CNT composite provides opportunity to further reduce wire/cable weight while maintain most of the electrical conductivity of the conductor and increase strength.




Batch 5 conductivities were greater than both theoretical predictions and pure annealed Cu by 9.8 and 4.8 percent, respectively.



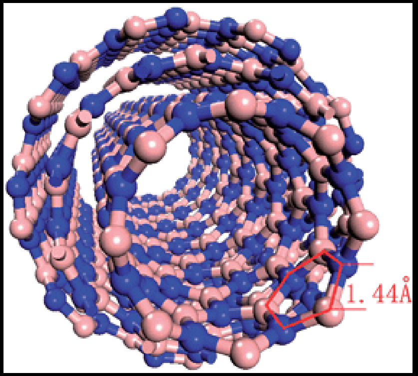
# Hexagonal Boron Nitride Nanomaterials

**NASA Glenn Research Center (GRC) has 2 decades of expertise synthetizing BNNTs and other BN nanomaterials for different Aerospace applications due to their multifunctionality**

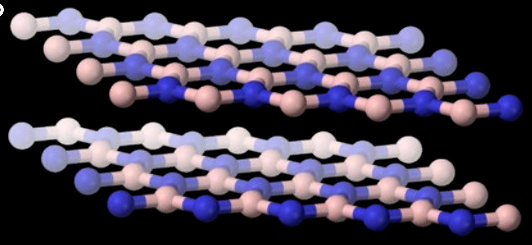
**BN Applications:**

- ✓ Aerospace structures and components
- ✓ Radiation Shielding
- ✓ Electric propulsion components
- ✓ Energy Storage
- ✓ Tribology
- ✓ Thermoelectric
- ✓ Ballistic Armor
- ✓ Cosmetics

- **Good Insulation Properties**
  - ✓ Constant wide band gap above 5.2 eV
- **Good Mechanical Strength**
- **High Thermal Conductivity**
  - ✓ Thermal Conductivity (W/(m·K)):
    - ✓ BNNT > 600, W/m·K
    - ✓ h-BN in plane > 100, W/m·K
    - ✓ h-BN through plane ~ 30 W/m·K
  - ✓ Ability to dissipate heat in nano electrics
  - Promising results in thermal shock experiments
- **Chemically and Thermally Stable**
  - ✓ Hydrophobic
  - ✓ Chemical stability
  - ✓ Oxidation in air above 900 °C

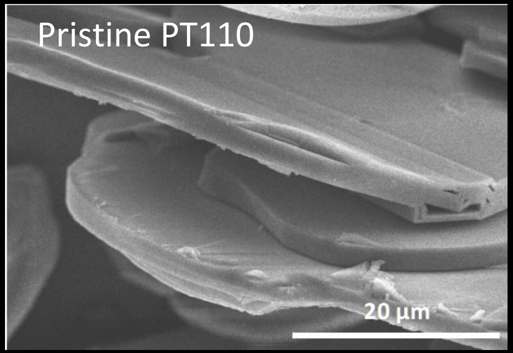


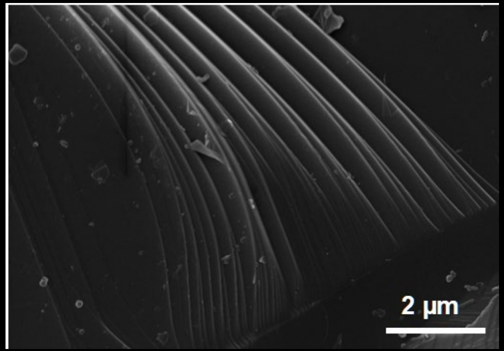

BNNT

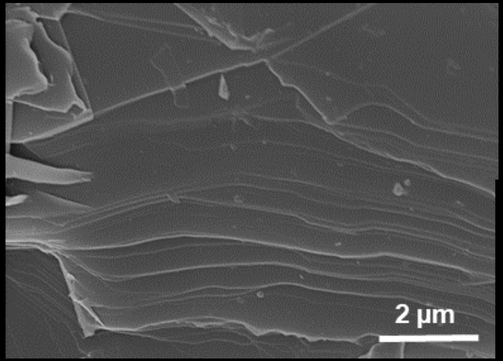


h-BN

# What Can We Do With h-BN?

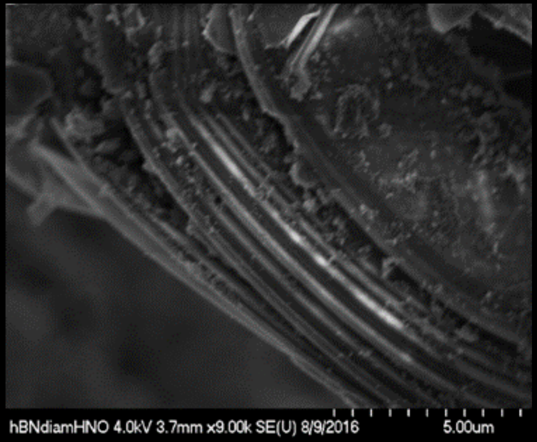


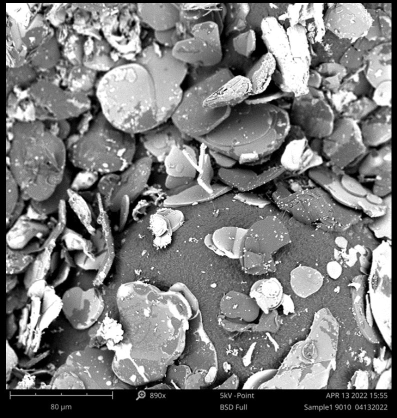




Make them into nanosheets to increase surface area

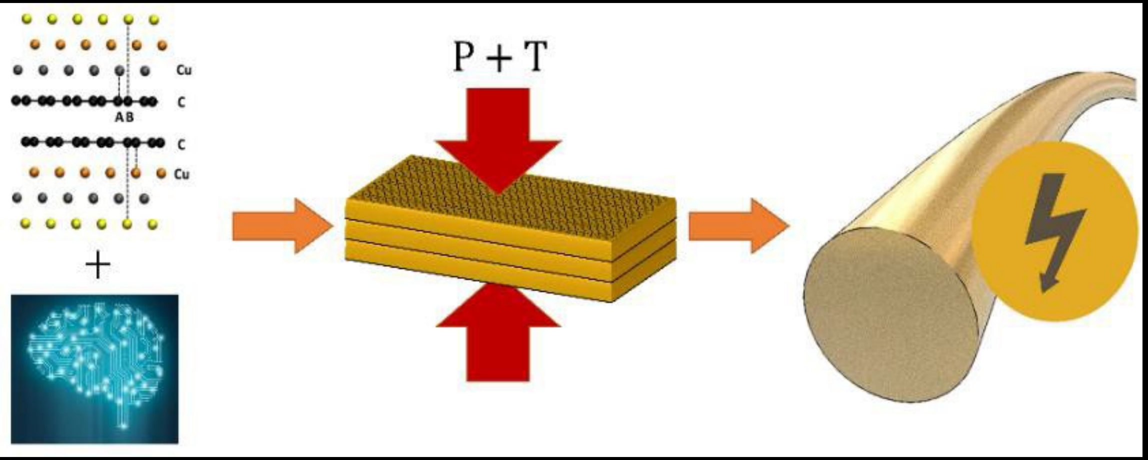
We can fill them or coat them with other materials to change properties and make composites.



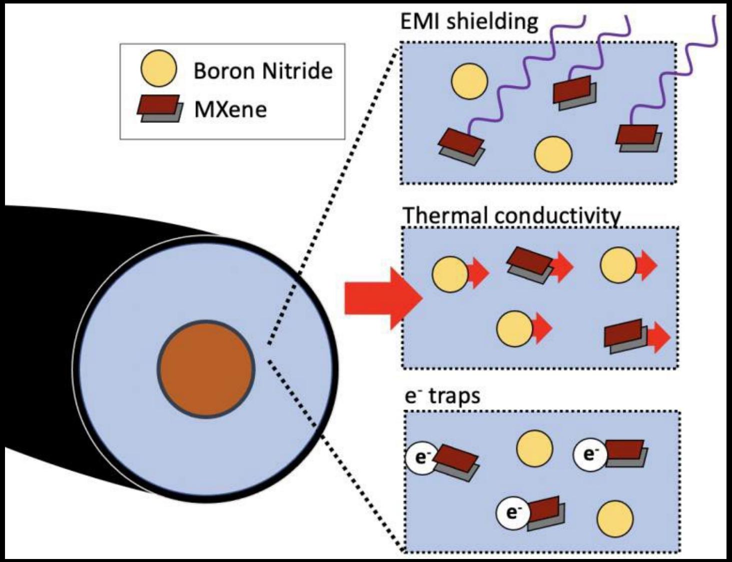
# ESI 21 Topic 1: Materials For High Voltage Power Transmission on the Moon

PI: Mehran Tehrani and
Co-PI: Michael Cullinan,
University of Texas at Austin




Objectives: Design, manufacture, and characterize ultra-conducting graphene-copper wires for high voltage applications.

Dr. Zhiting Tian,
Cornell University




Objectives: Create multifunctional nano composites with improved thermal, electric & shielding properties.

# Thank you!

**NASA Fellowships:**
https://www.nasa.gov/stem/fellowships-scholarships/index.html

**NASA Internships:**
https://intern.nasa.gov/

**NASA Careers:**
https://www.usajobs.gov/

**Acknowledgements:**

NASA STMD ESI Program

NASA TACP TTT Project

NASA AAVP AATT