



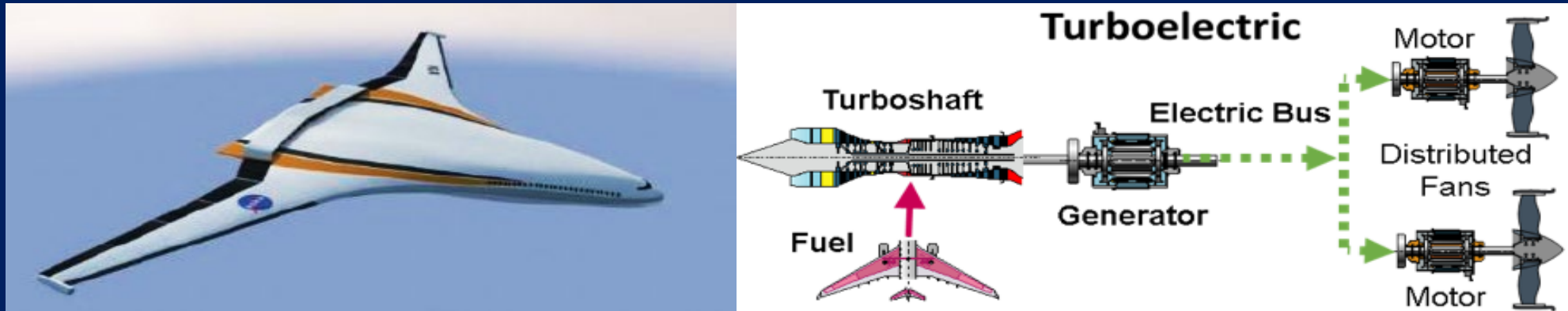
NASA-GRC RESEARCH ACTIVITIES IN HIGH VOLTAGE (HV) ELECTRICAL MATERIALS FOR AEROSPACE

IEEE/AIAA ITEC + EATS
PEASA High Voltage Workshop
Anaheim, CA
June 15-17, 2022

Maricela Lizcano, PhD
NASA Glenn Research Center
Cleveland, Ohio

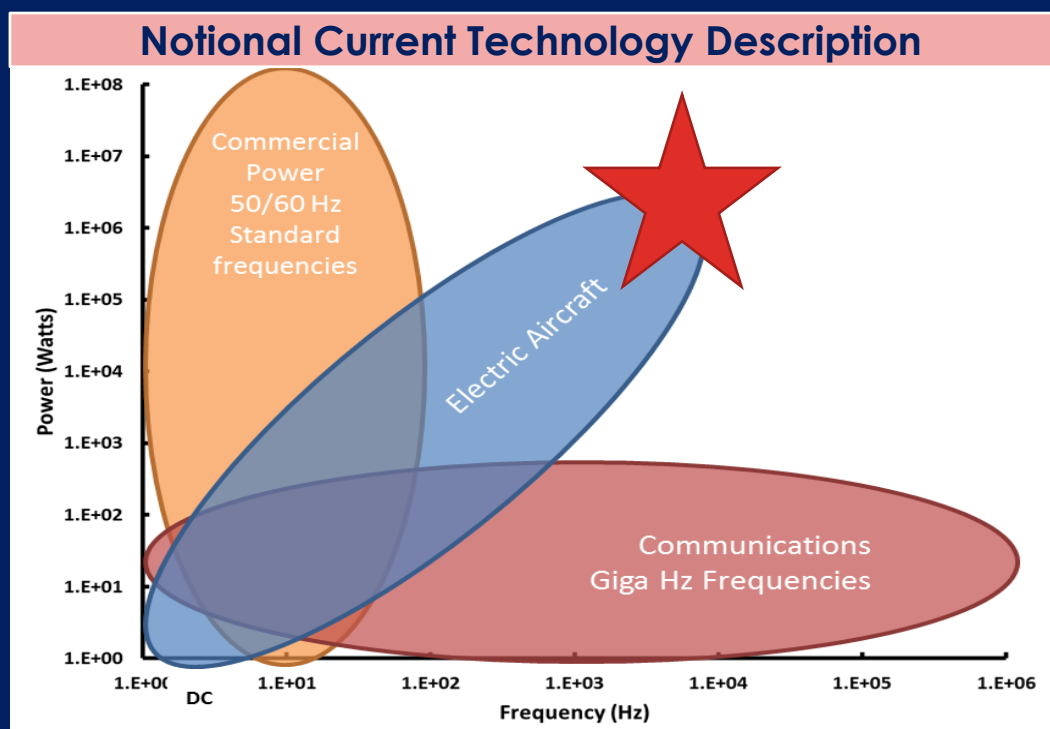
NASA Convergent Aeronautic Solutions Project Sub-Task: High Voltage Hybrid Electric Propulsion

- > 10- 20 MW Class
- High Voltage, $VAC_{max} = 20 \text{ KV}$
- 3-Phase
- Variable Frequency 400 Hz to 4000 Hz



Currently funded under NASA's Transformational Tools and Technology Project (TTT) under the Transformative Aeronautics Concepts Program (TACP)

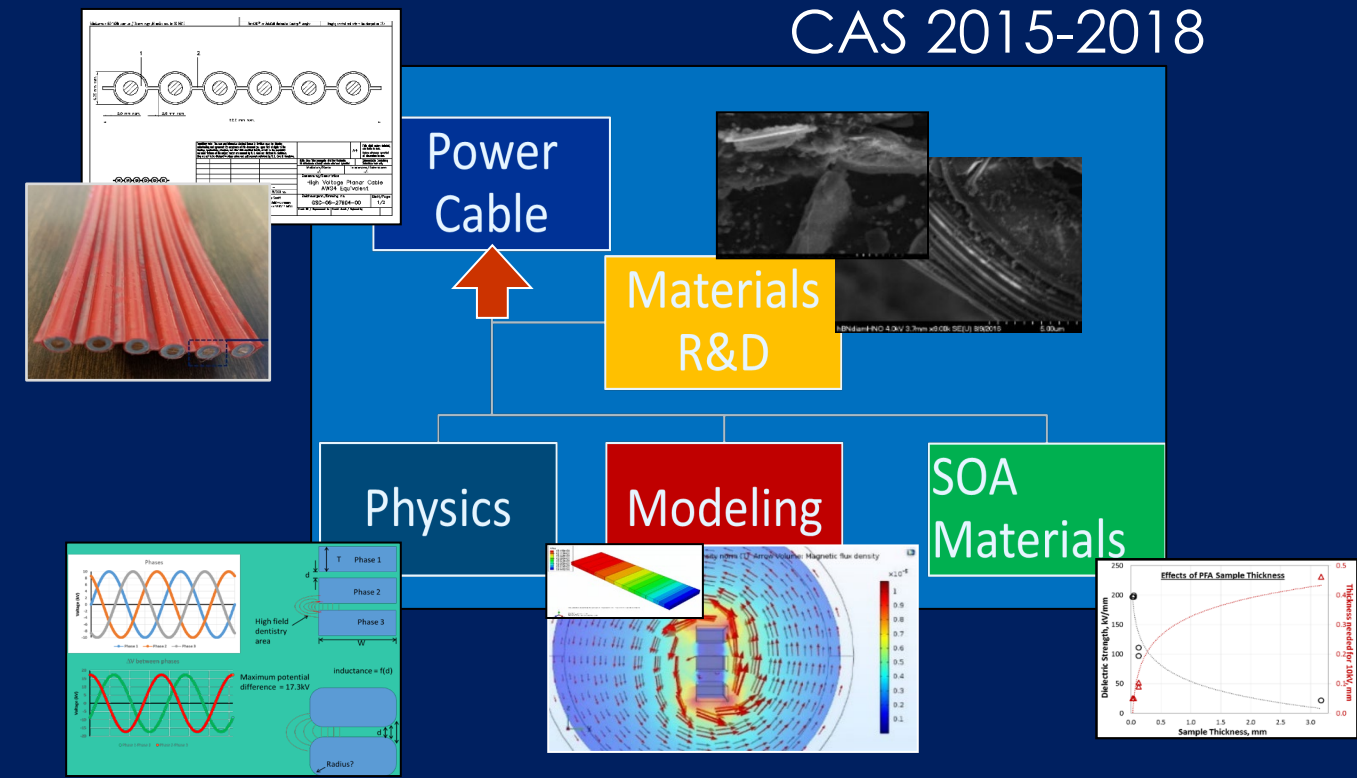
Electrical challenges for aerospace
 With high altitude, high voltage
 (>600 V) and high frequency



No HV power transmission for high altitude aircraft (> 25,000 feet)

Electrical Insulation Materials Development Approach

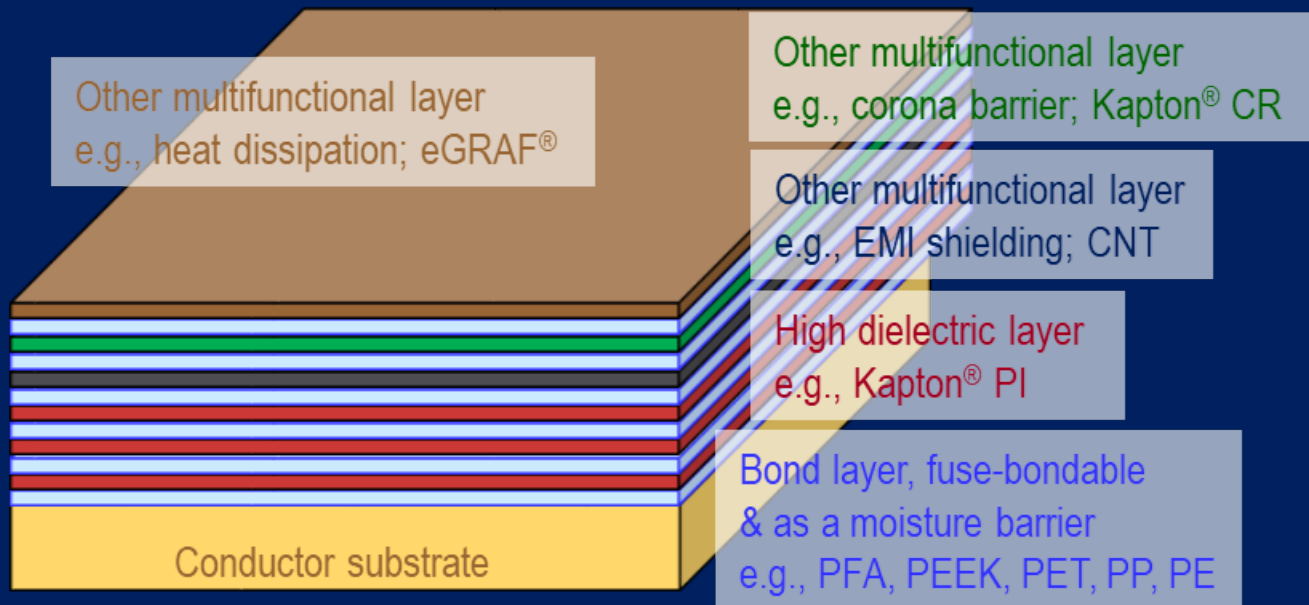
CAS 2015-2018



+ TTT 2018

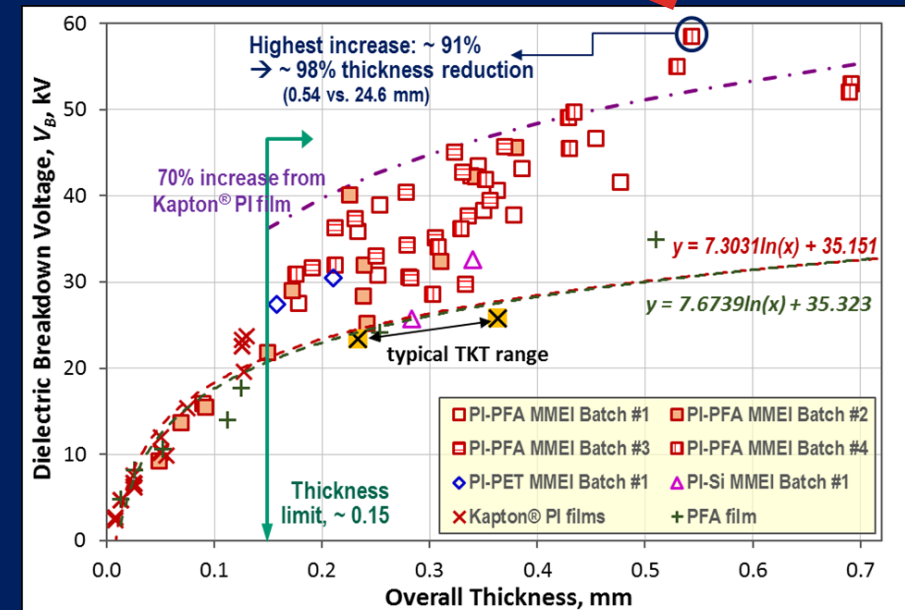
Standards
 Community
 Involvement

NASA developed a Micro-Multilayered- Multifunctional Electrical Insulation (MMEI)



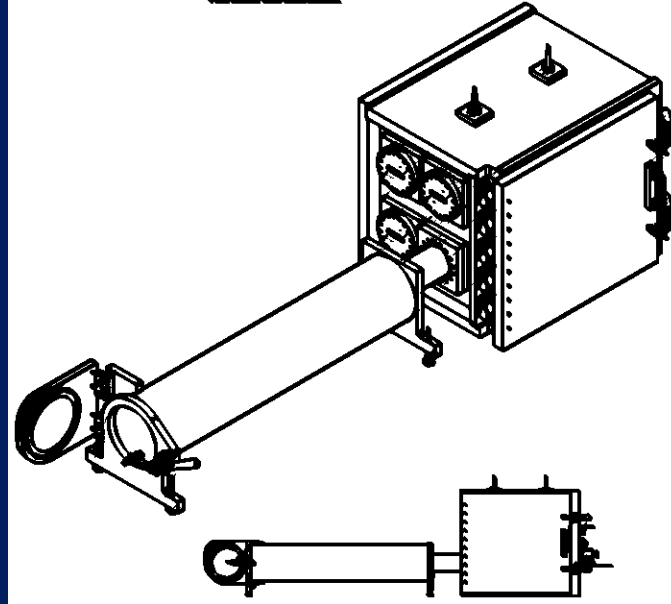
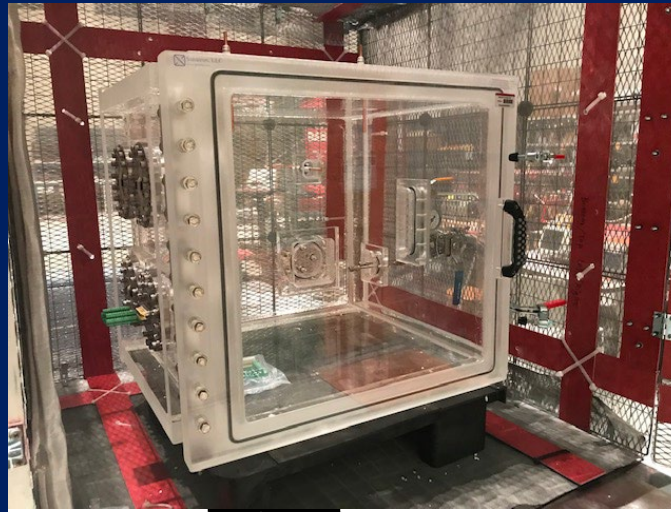
Compared to SOA Teflon-Kapton-Teflon (TKT)

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

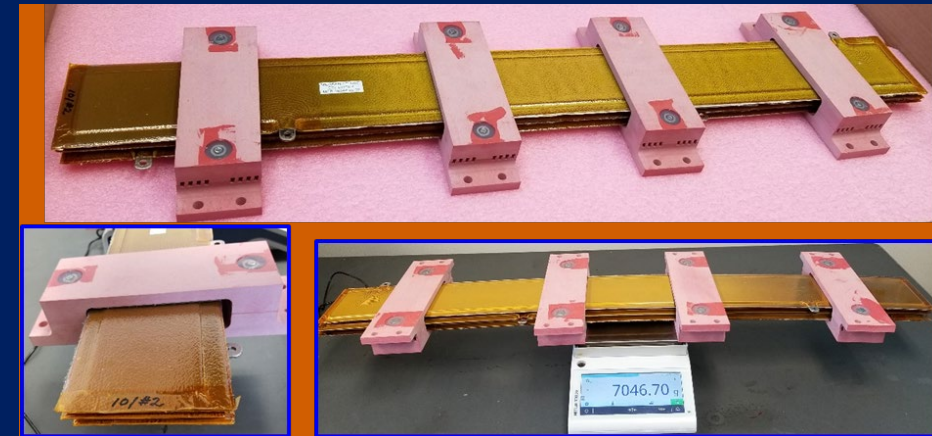


Collaborations with Ohio State University Conducting coupon testing of various SOA and MMEI insulation materials to optimize PD-resistant MMEI structures:

- Capacitance as a function frequency from 1 kHz to 10 MHz
- PDIV and PDEV @ 60 Hz AC at 100 Torr (48k ft alt.) and 760 Torr (1 atm)
- Developed a cylinder extension for the OSU PD test chamber to evaluate the 40" L bus bar prototypes



Development of Bus bar prototype with MMEI system with MERSEN.



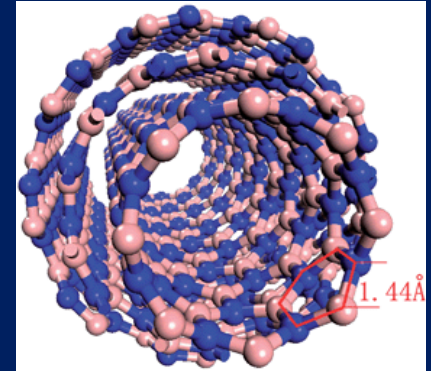
Completed the full-scale 1 m long, 3-phase prototypes for 10 MW at 20 kV, 400-4000 Hz.

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

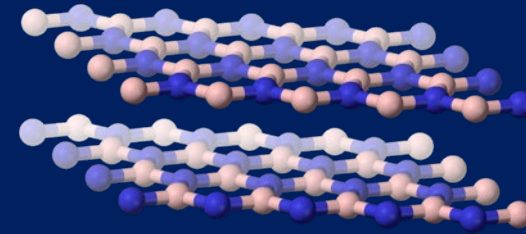
BN Applications:

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

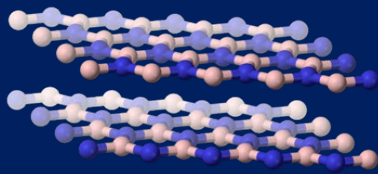
- **Good Insulation Properties**
 - ✓ Constant wide band gap above 5.2 eV
- **Good Mechanical Strength**
- **High Thermal Conductivity**
 - ✓ Thermal Conductivity ($\text{W}/(\text{m}\cdot\text{K})$):
 - ✓ BNNT > 600, $\text{W}/\text{m}\cdot\text{K}$
 - ✓ h-BN in plane > 100, $\text{W}/\text{m}\cdot\text{K}$
 - ✓ h-BN through plane ~ 30 $\text{W}/\text{m}\cdot\text{K}$
 - ✓ Ability to dissipate heat in nanoelectrics
 - Promising results in thermal shock experiments
- **Chemically and Thermally Stable**
 - ✓ Hydrophobic
 - ✓ Chemical stability
 - ✓ Oxidation in air above 1100 °C



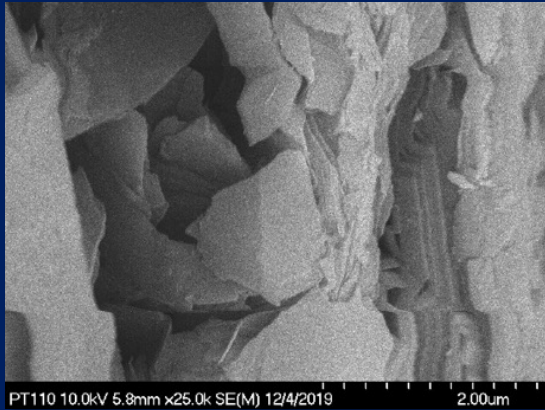
BNNT



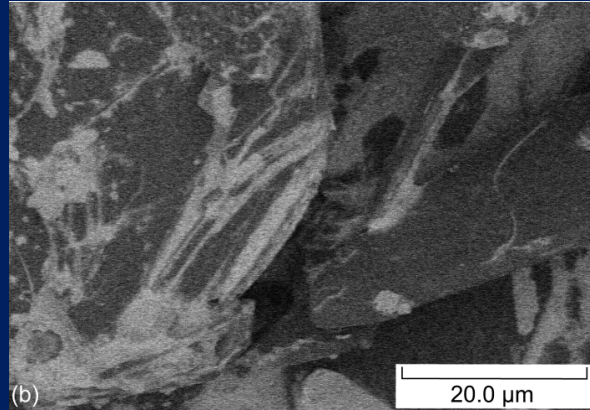
h-BN



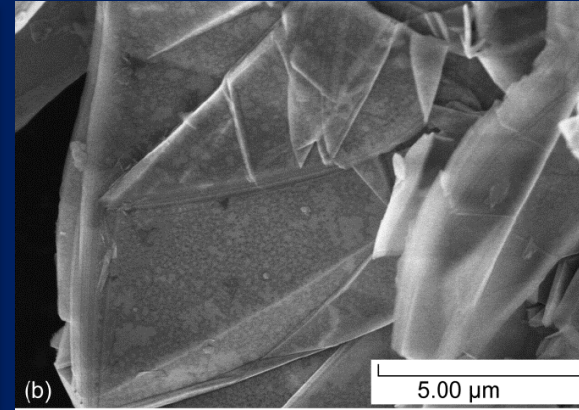
ENGINEERED CERAMIC NANOPARTICLES AND COMPOSITES DEVELOPED AT GRC



Pristine PT110



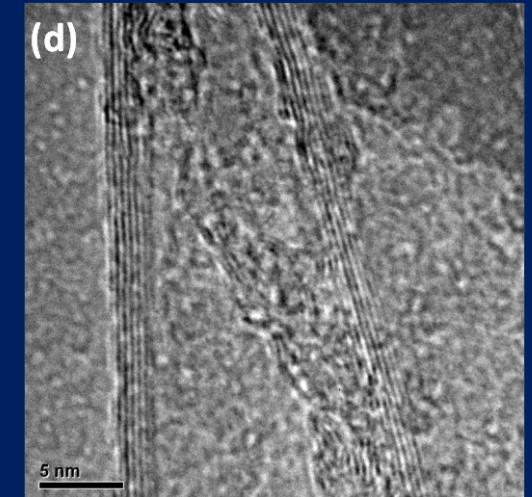
Intercalated PT110 with FeCl_3 – Backscatter Detector



PT110 Exfoliated 1 Time

Momentive hBN used for Intercalation and Exfoliation

- ✓ PT110: $\sim 45 \mu\text{m}$, $0.6 \text{ m}^2/\text{g}$
- ✓ AC6097: $\sim 0.5 \mu\text{m}$, $31 \text{ m}^2/\text{g}$

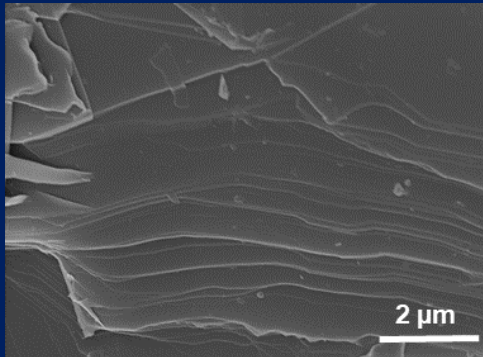
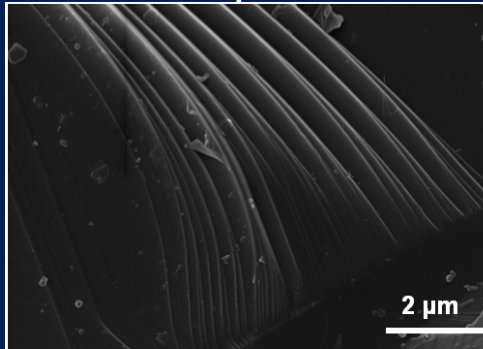
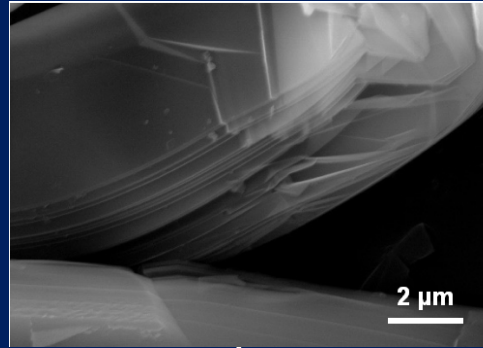
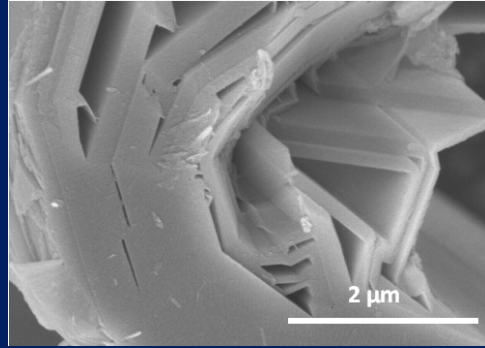
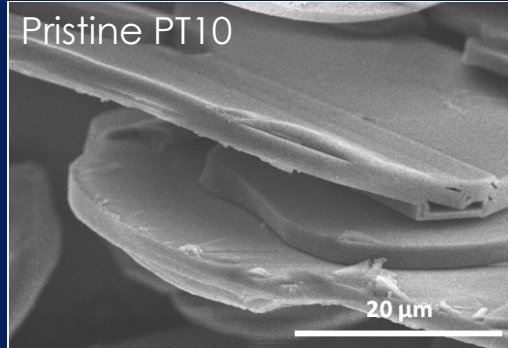


For “stand alone” h-BN sheet (or boron nitride nanosheets BNNS), the above process needs to be repeated several times

Methodology Process: Iron Chloride Intercalation

- ✓ Process analogous to graphite intercalation to make graphene
- ✓ Activation agent is needed to make BN reactive: NaF
- ✓ Intercalation and exfoliation happen in 2 reactions
- ✓ Repeating these reactions were examined to see if the additional effort cause further exfoliation
- ✓ Further chemical treatment with HCl is done to remove impurities and intercalates and obtain a clean and thinner BN

Higher processing temperature →



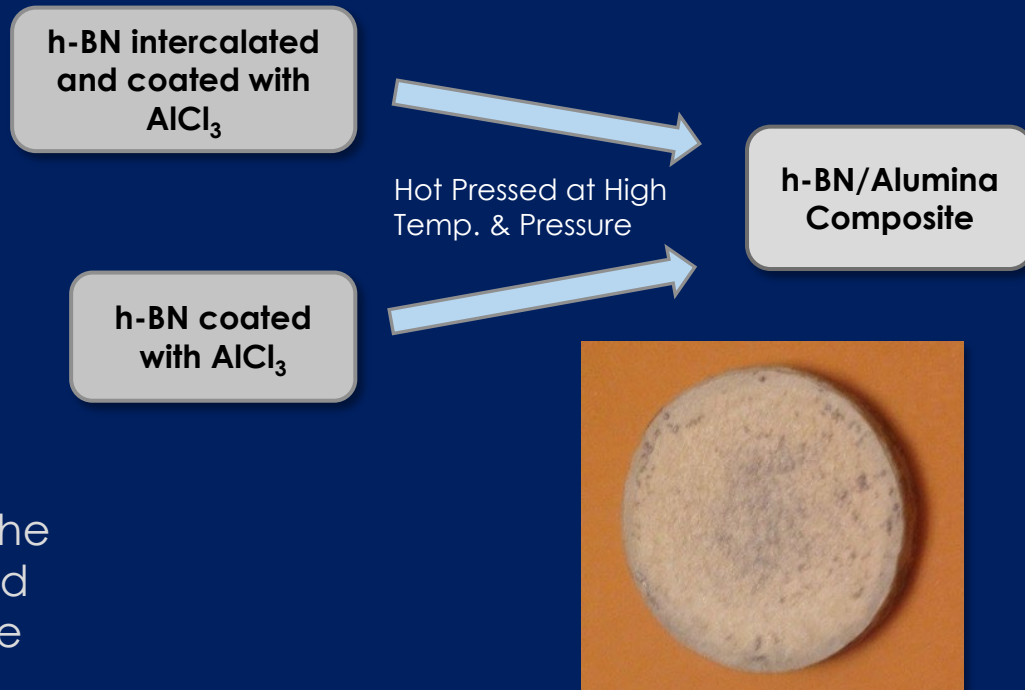
Longer processing time ↓

- **Activation Agent Study** was done using NaF, KF, LiF, NaCl, KCl and LiCl to optimize the intercalation and exfoliation process.
 - KCl is the best activation agent (and a more environmentally friendly chemical)
- **Processing temperature and time study** is being done.
 - Initial observation: Higher temperatures and longer processing times are helping to exfoliate more the hBN platelets

- ✓ hBN modifications will help us to target multifunctional properties in a component.
- ✓ Studies of the optimization of processing temperature and time will help us to decrease the number of steps needed to obtain thinner hBN sheets.

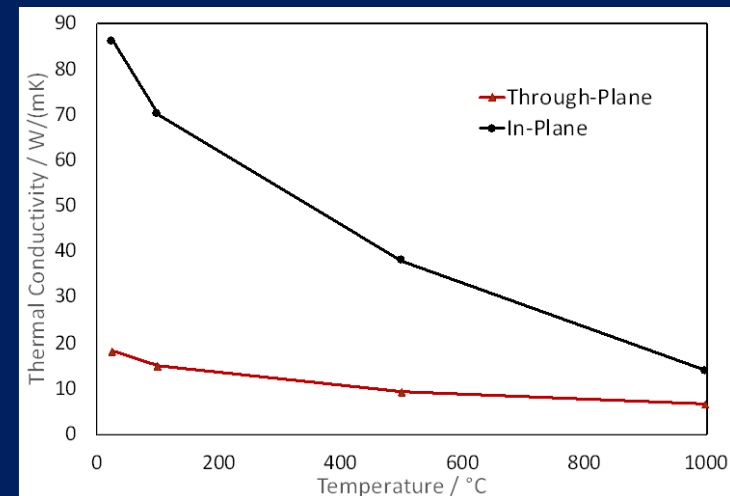
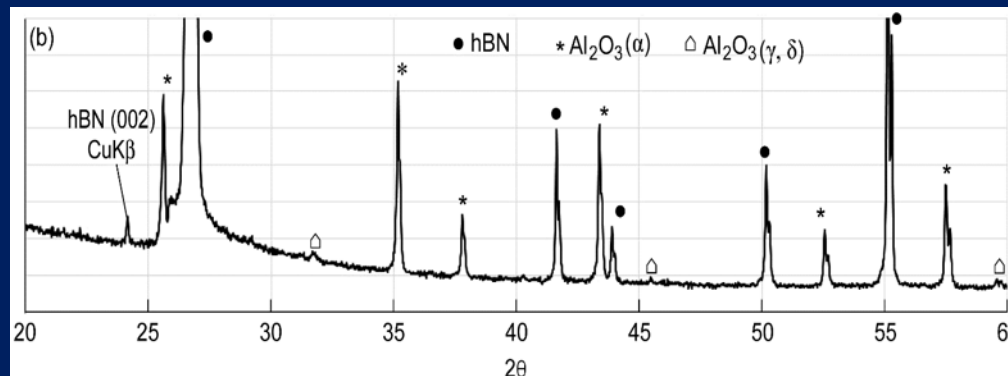
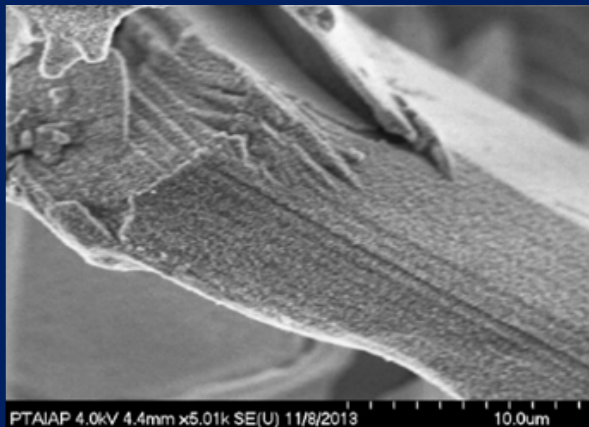
Adding Alumina to *h*-BN for Ceramic Composite

- ✓ Alumina properties:
 - Chemical and physical stability
 - Thermal conductivity: 30 W/m·K
 - High heat resistance
 - High strength and hardness
- ✓ Alumina can help decrease the hot press temperature needed to make a ceramic composite with *h*-BN



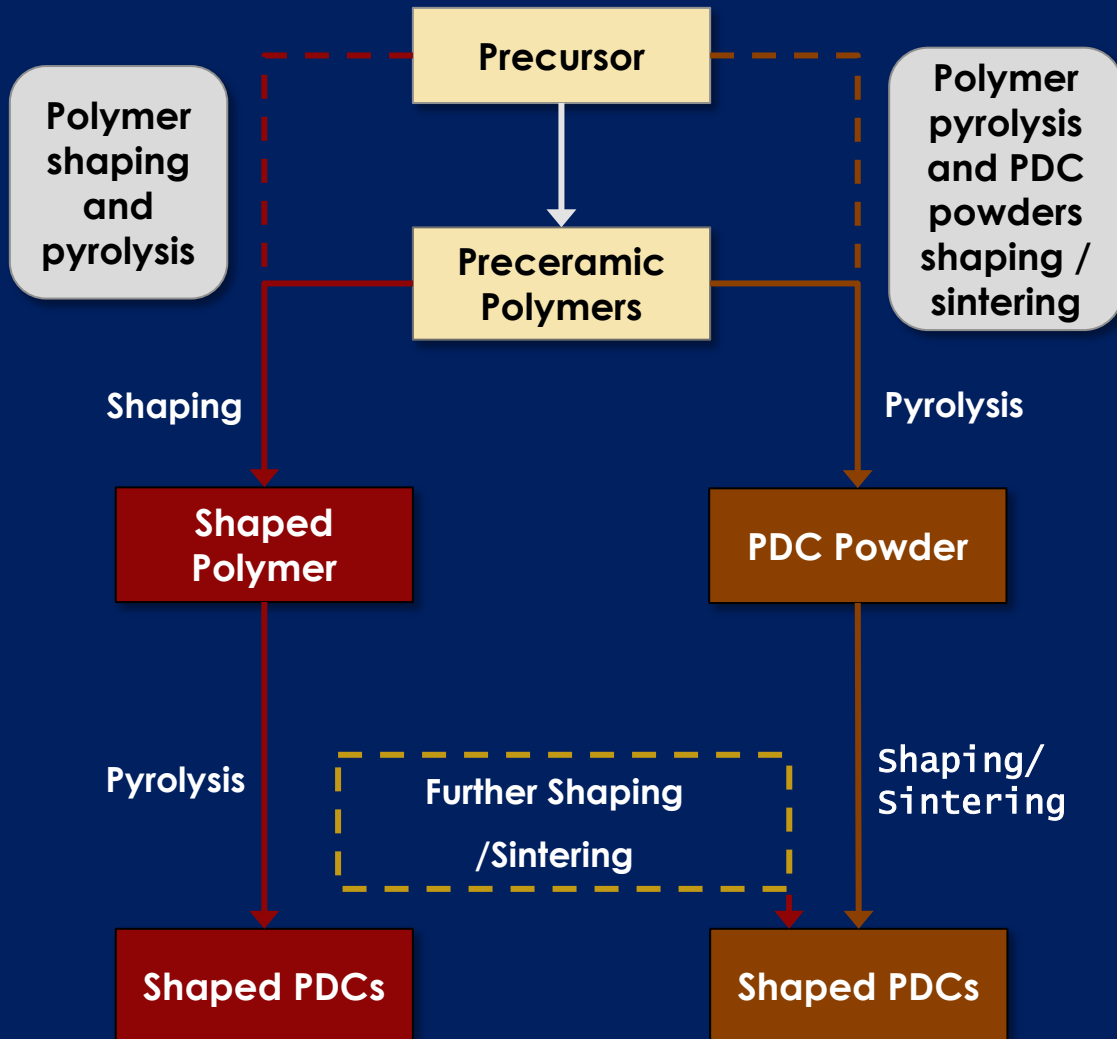
Thermal Conductivity Tests done at Netzsch:

- ✓ *h*-BN/Alumina composite of 60 wt.% *h*BN and 40 wt.% alumina with a density of 2.45 g/cm³
- ✓ Tests indicate an in-plane thermal conductivity value much higher than the through-plane value, as expected

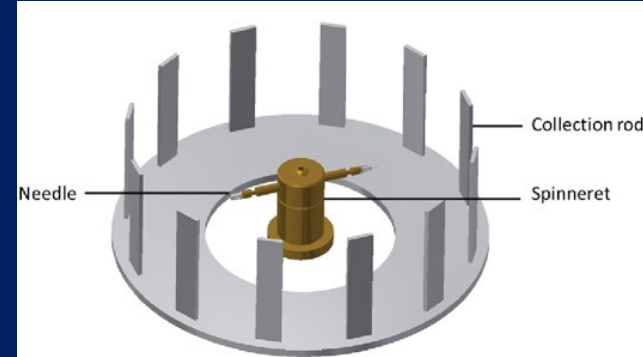


C.C. Hung, J. Hurst, D. Santiago, M. Lizcano, M. Kelly, NASA/TM-2017-219472

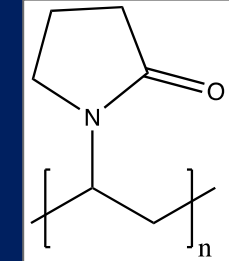
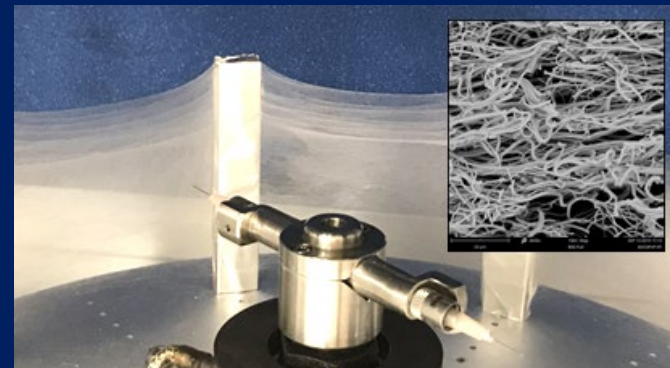
Polymer Derived Ceramic Process



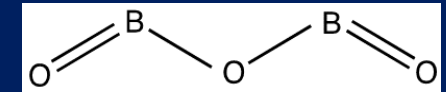
Forcespinning Machine Sample Collection Setting



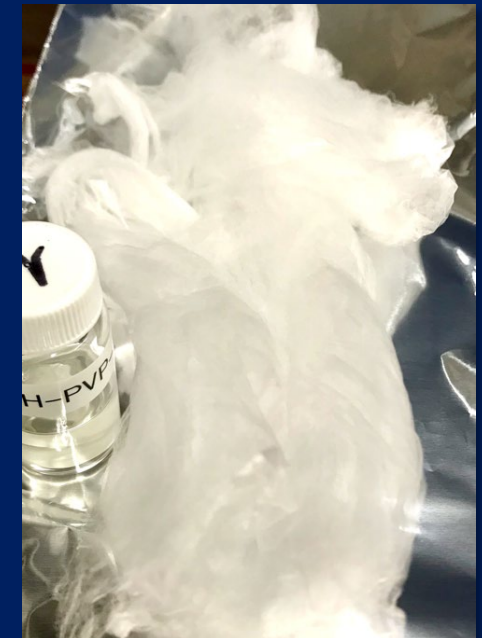
- ✓ Fibers were spun in under 3 minutes
- ✓ PVP/B₂O₃ fibers were very dry and fluffy



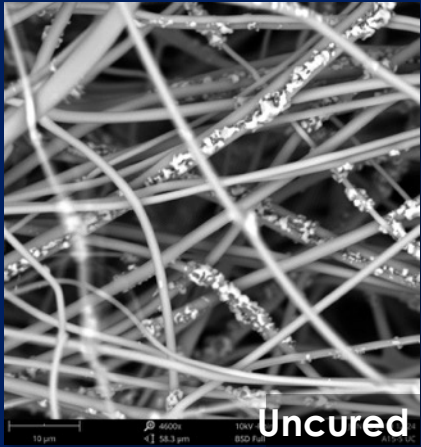
Polyvinylpyrrolidone (PVP), C₆H₉NO



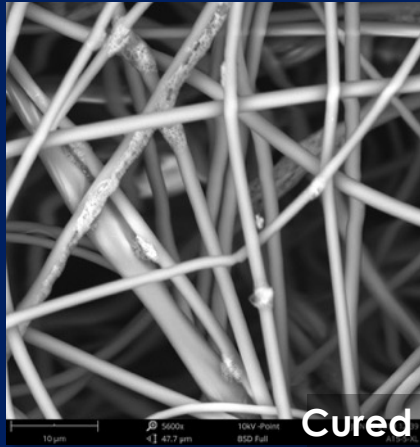
Boron Oxide, B₂O₃



PVP/B₂O₃ Fibers



Uncured

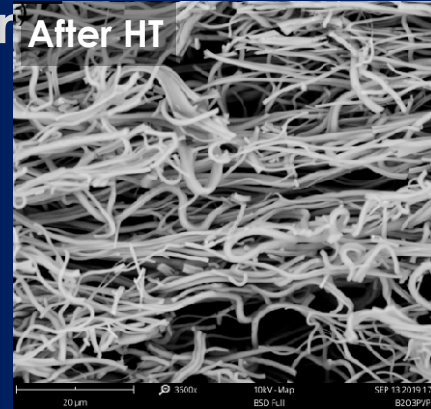


Cured

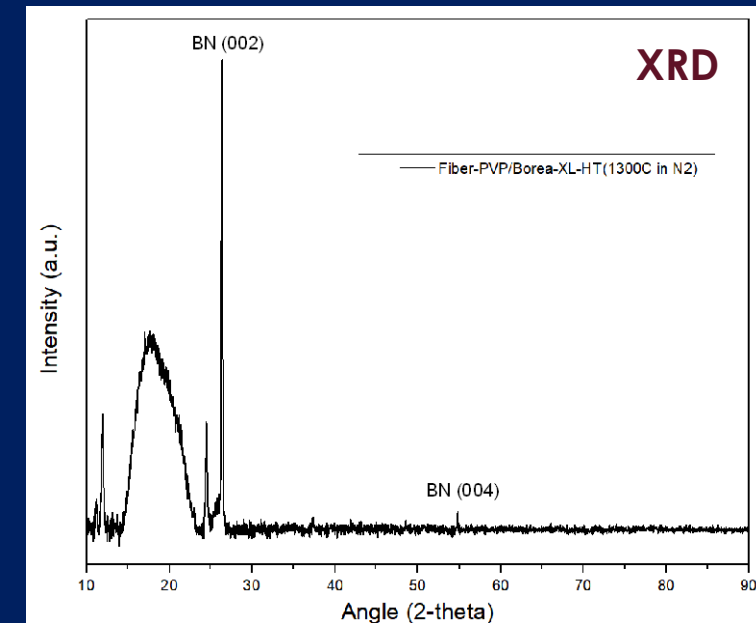
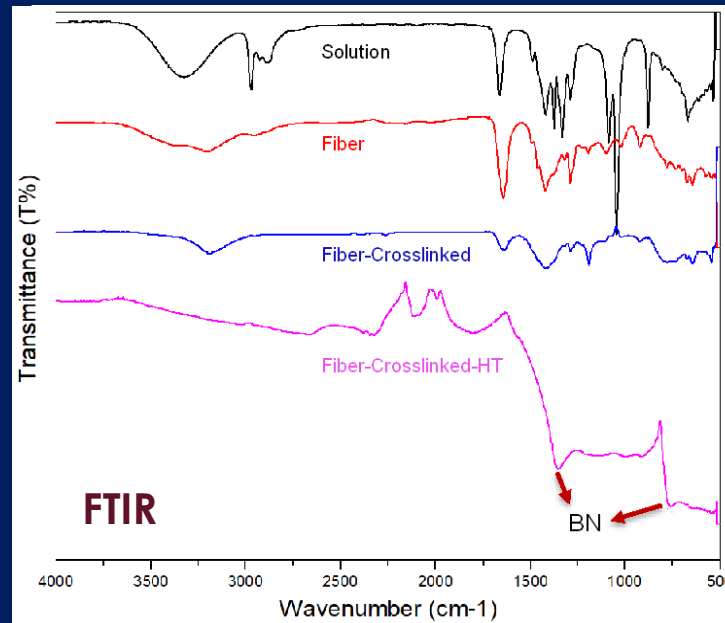
Before and after Heating



Before HT



After HT



After Heat Treatment Process:

- ✓ Dark gray in color
- ✓ Mechanically strong at touch
- ✓ On SEM they look shorter or like being cut

- ✓ FTIR and XRD confirmed heat-treatment process produced BN
- ✓ Proved feasibility

THERMALLY CONDUCTIVE AND ELECTRICALLY INSULATING POLYMER COMPOSITES

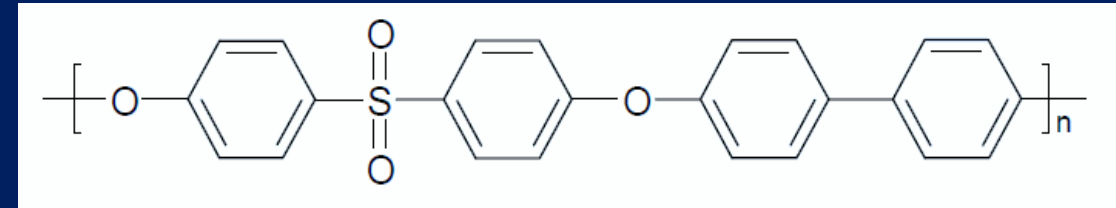
PPSU Characteristics:

- High toughness and impact resistance
- 230 °C T_g
- Heat deflection temperature of ~207 °C
- Inherently flame retardant
- Chemical resistance
- Low moisture absorption
- Limited to 190 °C continuous operating temperature
- Not UV stable

Boron nitride (BN):

- Exceptionally high thermal conductivity
- Electrically insulating

Polyphenylsulfone (PPSU)



PPSU

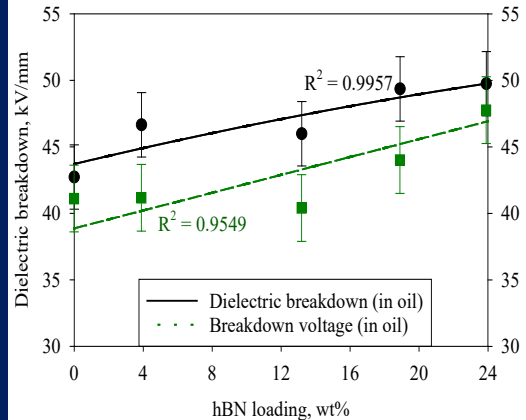
Literature on the dielectric properties of PPSU and their composites are limited.

Water-chilled rollers and air knife

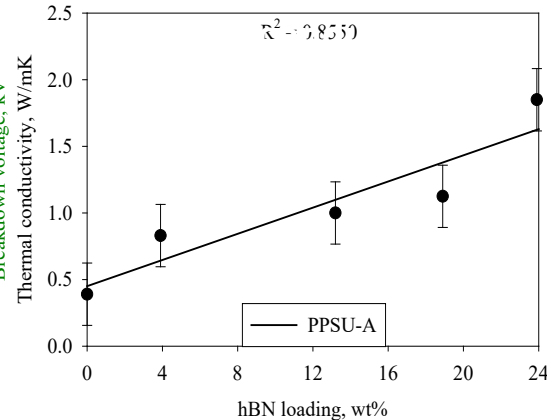


Take up spool

Effect of BN loading on



Effect of BN loading on



High-bend radius

Electrical Insulation Development: Thermally conductive electrical insulation necessary to optimize high energy density components. Goal: ~ 1 W/mK thermal conductivity

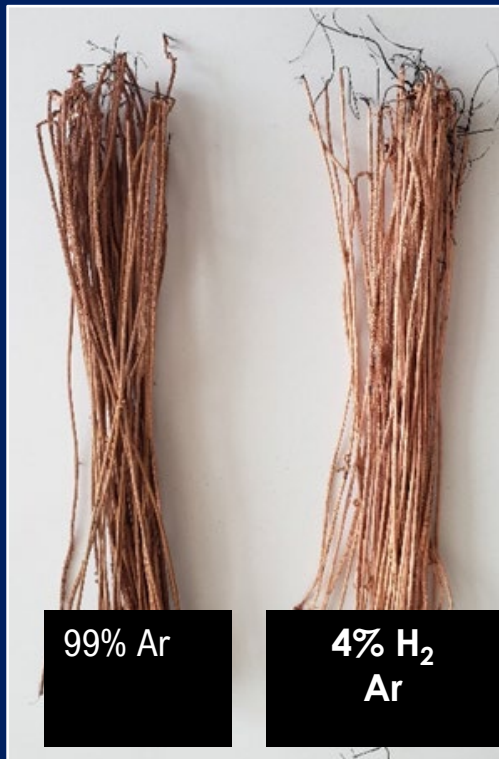
h-BN/Polymer

Composite insulation showed **16% improvement in dielectric strength** and **5x's increase in thermal conductivity** relative to the neat polymer

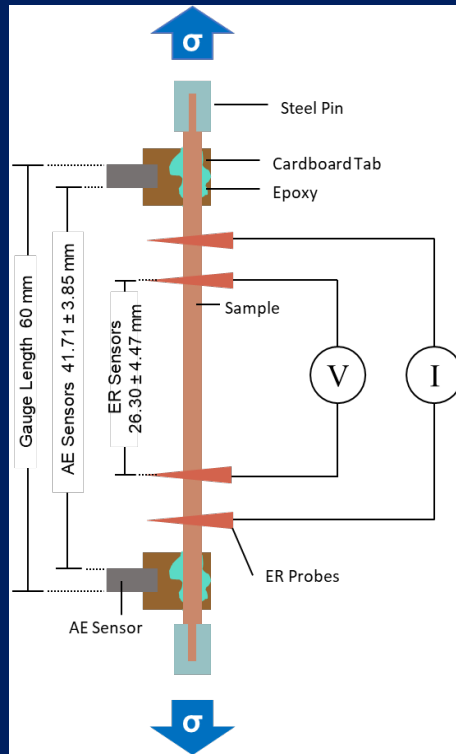
T. Williams, B. Nguyen and W. Fuchs, 2020 IEEE 3rd International Conference on Dielectrics (ICD), 2020, pp. 541-545, doi: 10.1109/ICD46958.2020.9341910.

Loading profile, Conductivity and Acoustic Emission helps understand failure modes.

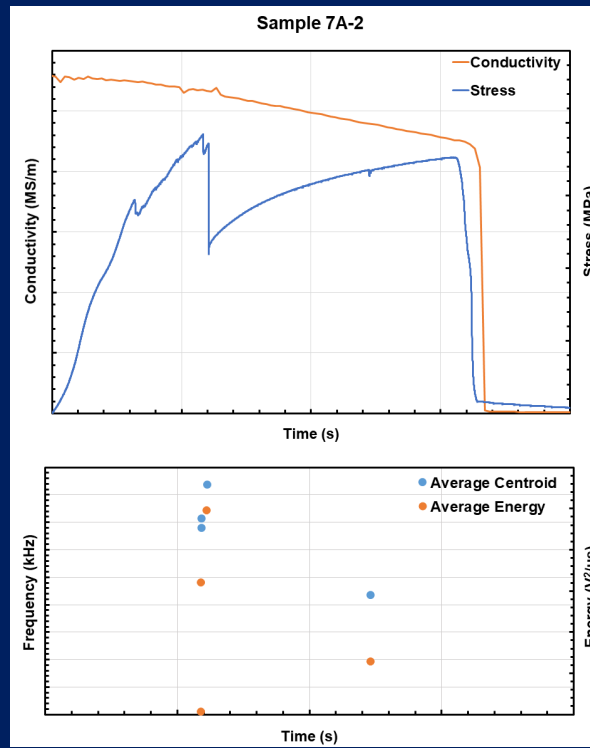
Cu/CNT



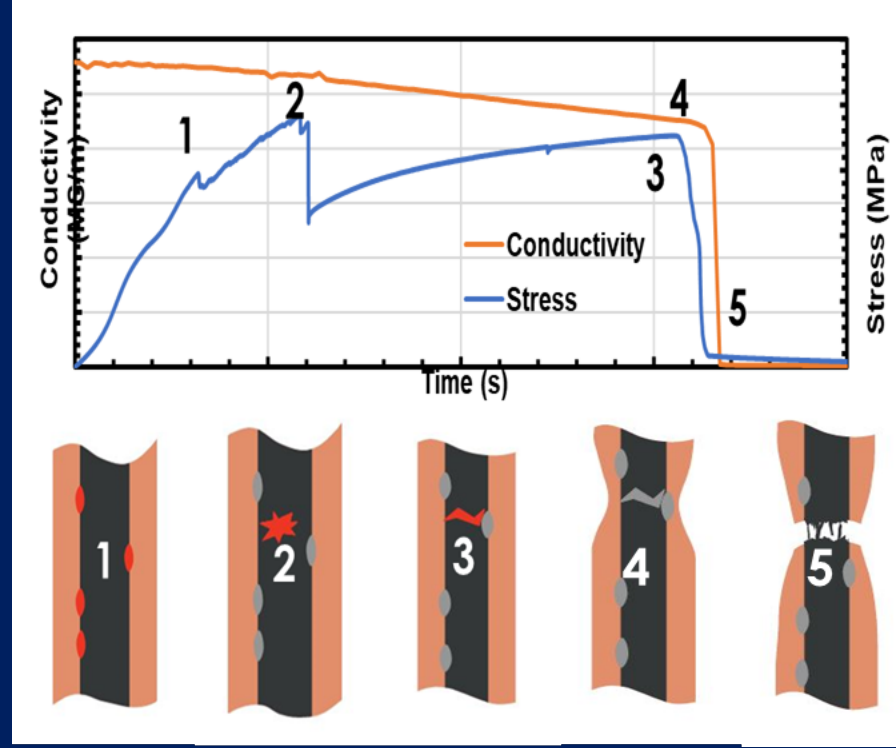
Testing



Results



Correlating Failure Modes

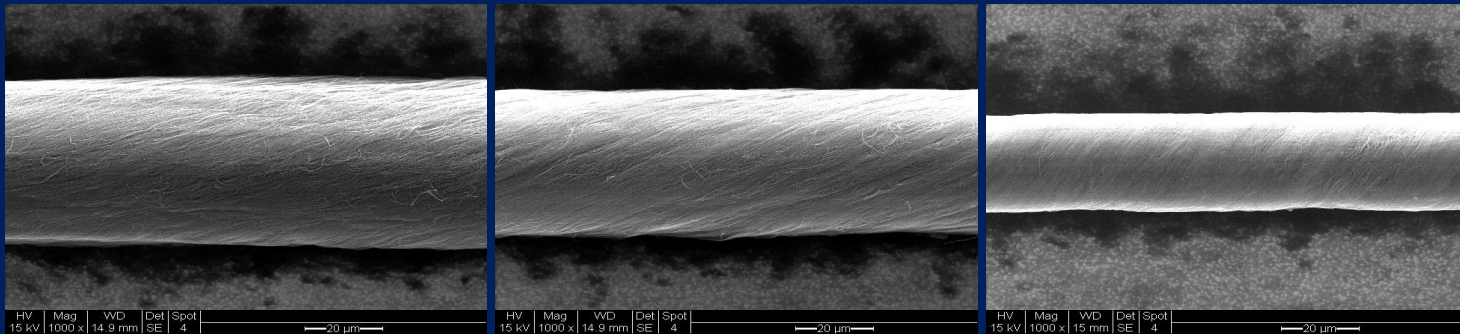




NANOWORLD

University of Cincinnati Team:

Dr. Vesselin Shanov, Dr. David Mast, Yanbo Fang, Vamsi Krishna Reddy Kondapalli, Kavitha Joseph, Mahnoosh Khosravifar, Kyle Brittingham, Nhat Phan

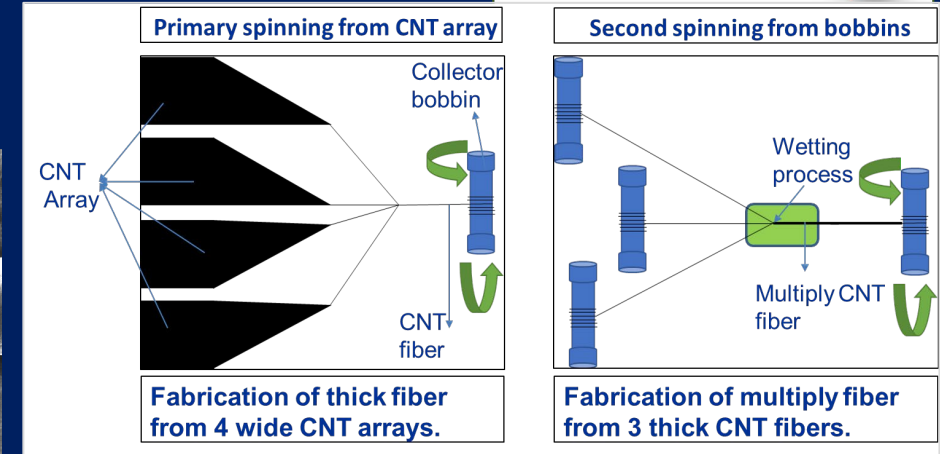
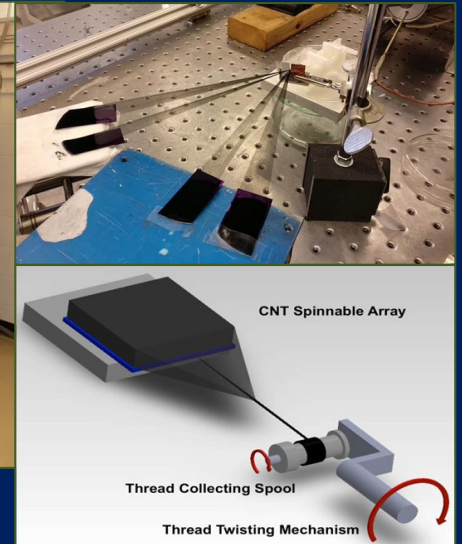


$D = 44.99 \mu\text{m}$

$D = 38.5 \mu\text{m}$

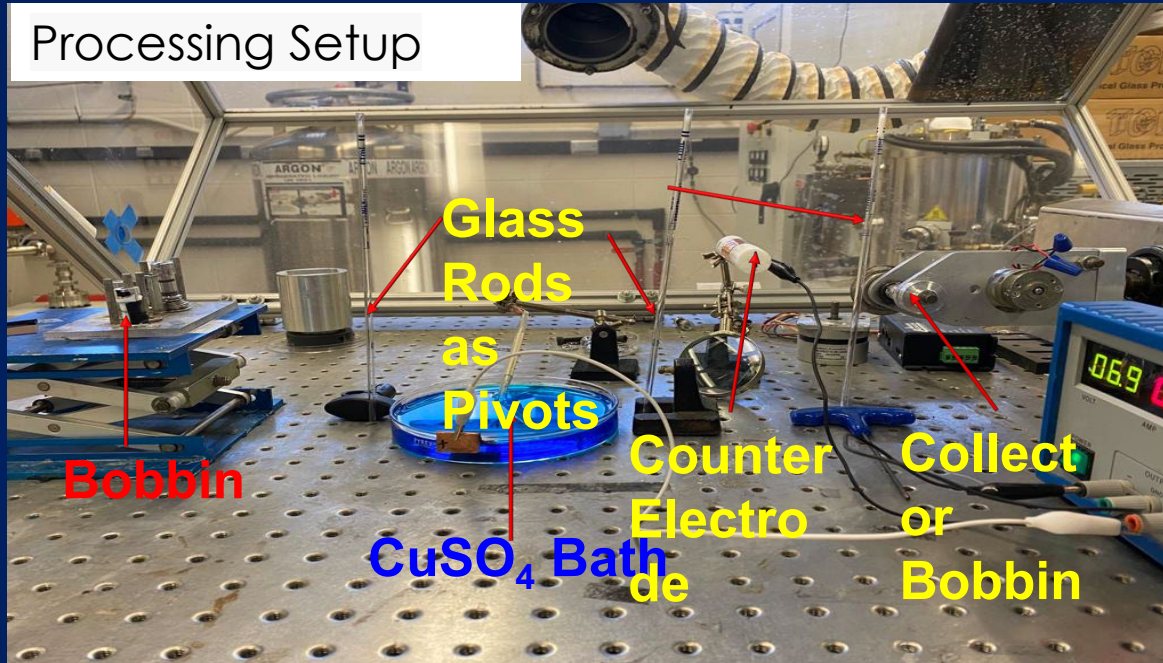
$D = 33.22 \mu\text{m}$

Controlled diameter CNT filaments

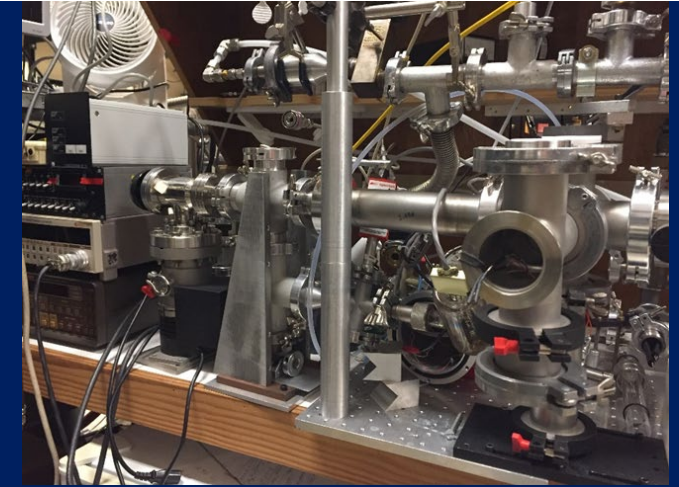


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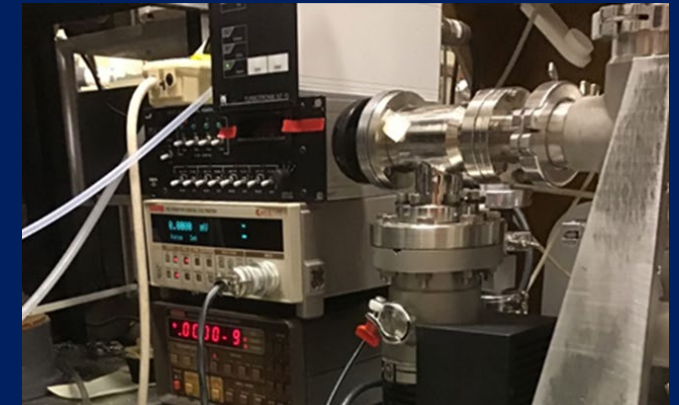
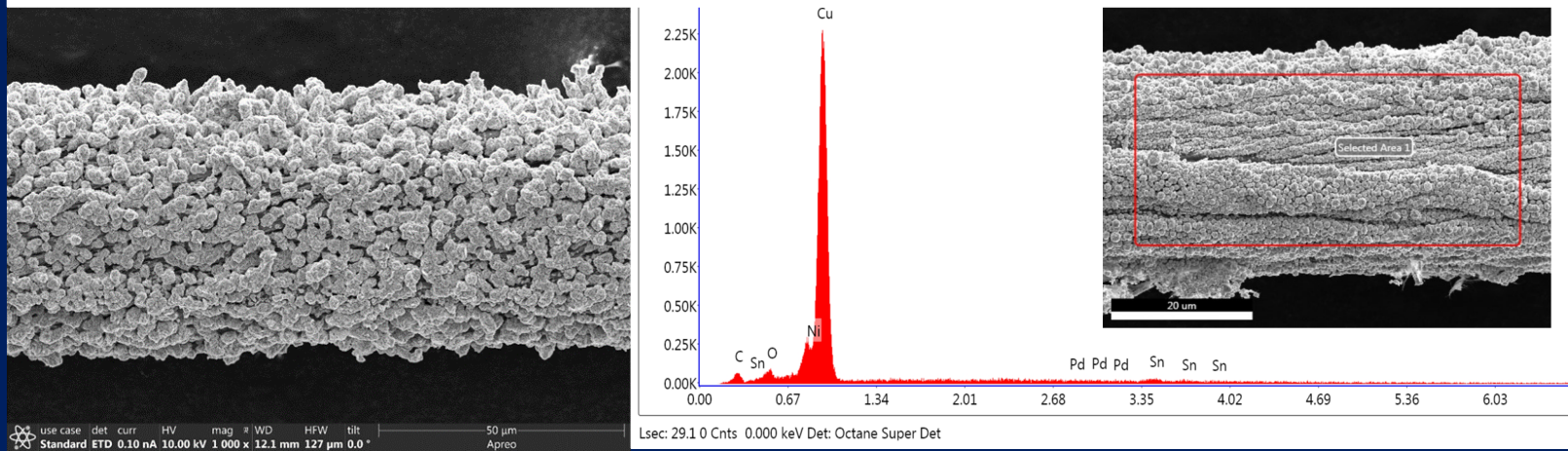
Processing Setup



Current Density Testing

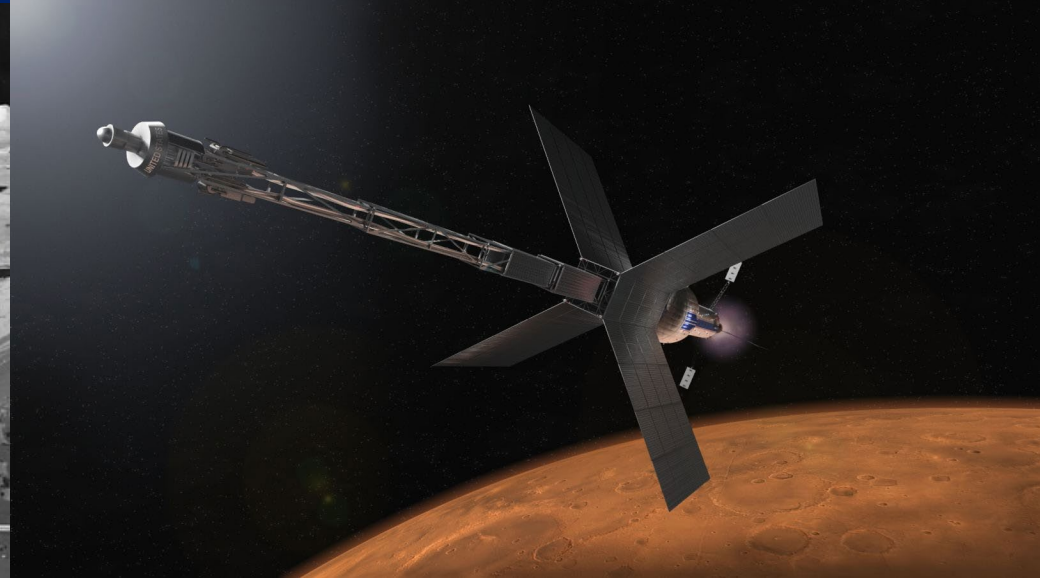


Coated CNTC and EDS Characterization



Turbo-pumped vacuum system with nano-voltmeter and current source

SPACE APPLICATIONS IN HV POWER TRANSMISSION



NASA STMD Early -Stage Innovations (ESI21)

Topic 1 : Advanced Materials for High-Voltage
Power Transmission on the Moon

2 University Grants awarded.

NASA Team Members collaborating with Universities

Maricela Lizcano, Diana Santiago

Proposal to NASA STMD Technology Demonstration
Mission Program
Space Nuclear Propulsion

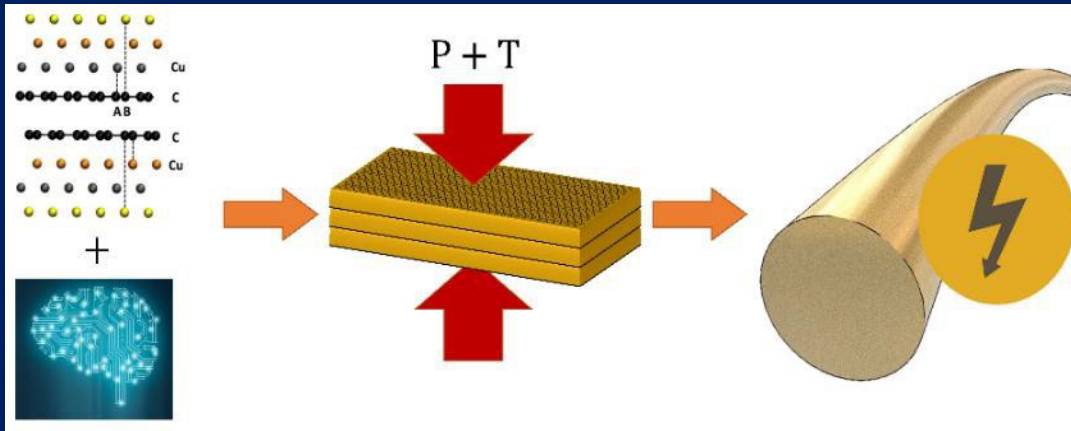
NEP PMAD

ESI21 TOPIC 1: ULTRA-CONDUCTIVE COPPER WIRES FOR LUNAR HVPT

PI: Mehran Tehrani, University of Texas at Austin

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

Co-PI: Dr. Yuanyue Liu, University of Texas Austin

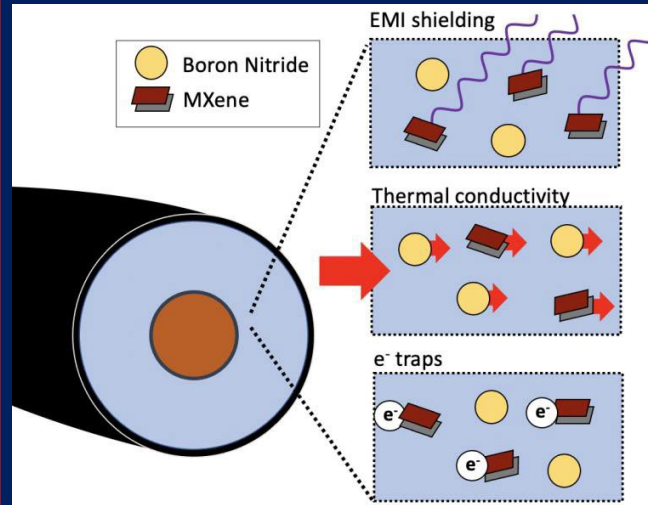


Research Objectives:

- **Objectives:** Design, manufacture, and characterize ultra-conducting graphene-copper wires for high voltage applications.
- **Innovations:** design of novel ultra-conductors using atomistic simulations and machine learning, fabrication and characterization of the designed multi-layered nanostructures, and their assessment for lunar applications.
- State-of-the-art advanced electrical conductors are only a few percentages more conductive than copper. This project aims to fabricate copper-graphene ultra-conductors that significantly outperform copper's specific conductivity.
- The proposed project is currently at a TRL2 and will transition to a TRL3 upon completion.

ESI21 TOPIC 1: LIGHTWEIGHT, MULTIFUNCTIONAL NANO-COMPOSITES FOR HIGH-VOLTAGE INSULATION ON THE MOON

PI: Dr. Zhiting Tian, Cornell University



These nanocomposites will have improved electromagnetic interference (EMI) shielding, thermal conductivity, and dielectric strength for use in high voltage power transmission (HVPT) cables. This multifunctionality will be given by the addition of BN and MXene nanofillers.

Research Objectives

Create multifunctional nanocomposites with improved thermal conductivity, dielectric strength, EMI shielding, and mechanical durability in relation to current state of the art.

- Study BN fillers for thermal conductivity and dielectric strength.
- Study MXene fillers for EMI shielding and dielectric strength
- Investigate combining BN and MXene fillers for multifunctionality
- Advance from TRL 1 to TRL 3

- **HVCC: High-Voltage Coordinating Committee**
 - Key focus on SAE HV roadmap and prioritization, coordination between SAE committees, and develop strategic partnerships with industry stakeholders
- **AE-10: High-Voltage Committee**
 - Key focus on performance, aging factors, failure mechanisms, and design considerations for HV components
 - AIR7058: High Voltage DC Electromechanical, Solid State and Hybrid Switching Devices in Aerospace Applications
 - AS7499: Aircraft High Voltage DC Power Quality Standard
 - AS8441: Minimum Performance Standard for Permanent-Magnet Propulsion Motors and Associated Variable-Speed Drives
- **AE-11: Aging Models for Electrical Insulation in High Energy Systems**
 - Key focus on material science, aging factors and failure mechanisms
 - AIR7374: Aging Mechanisms of Electrical Insulation Materials in a High Energy System
 - ARP7375: Test Guidelines for assessment of Electrical Insulation Materials Ageing in a High Voltage System
 - ARP7380: Electrical Insulation Aging and Life Models for a High Energy System
- **E-40: Electrified Propulsion Committee**
 - Key focus on complete propulsion system, accounting for electrical and mechanical factors
 - AIR8678: Architecture Examples for Electrified Propulsion Aircraft
 - ARP8676: Nomenclature & Definitions for Electrified Propulsion Aircraft
 - ARP8677: Safety Considerations for Electrified Propulsion Aircraft
 - ARP8689: Endurance tests for Aircraft Electric Engine



THANK
YOU!

