Multifunctional Polymers and Composites for Aerospace Applications

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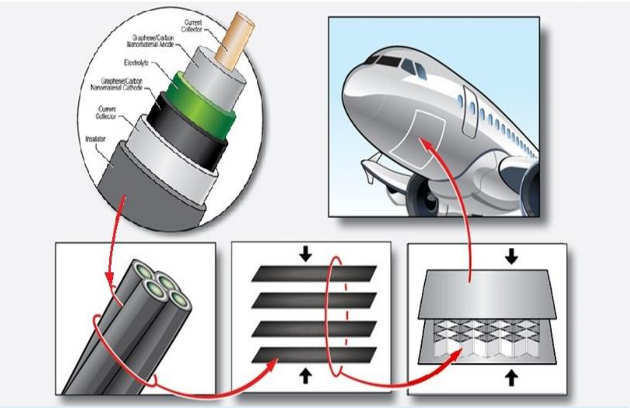
Typical System Needs and Challenges in Aeronautics and Space

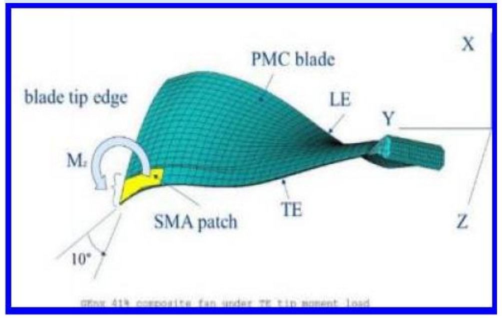
- **System Challenges in Aeronautics**
  - Efficiency (power, cost)
  - Mass, noise, emissions reduction

- **Needs**
  - Lightweight composites with higher strength and stiffness
  - High-temperature, toughened composites
  - Thermal management
  - Multi-functionality
    - Morphing structures
    - Electrically conductive composites



Multi-functional structure with energy storage capability

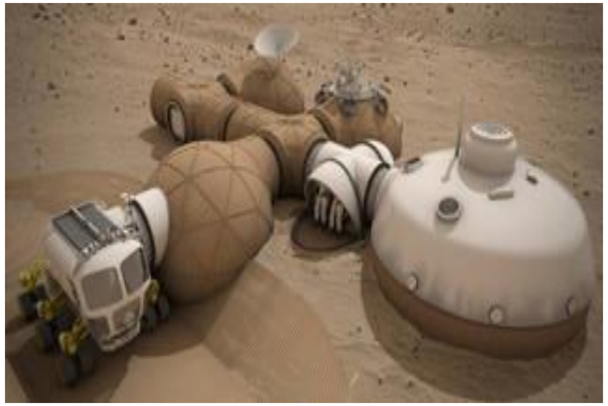
Shape Changing SMA - PMC Fan Blade



Min, J., Williams, T. et al, AIAA 2016-1501

- **System Challenges in Space**
  - Efficiency (mass and volume reduction)
  - Degradation in harsh space environments

- **Needs**
  - Lightweight materials and structures
  - Materials and structures that can perform reliably in extreme environments
  - Multi-functionality
    - Radiation protection
    - Impact resistance
    - Smart materials

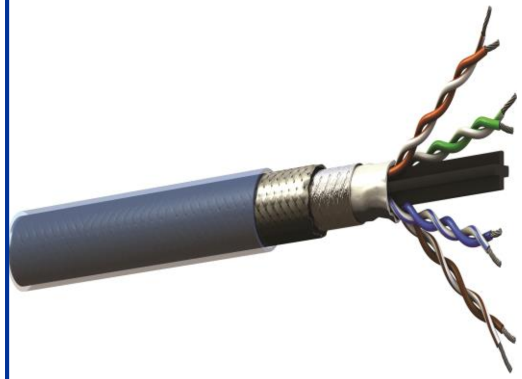


Novel Electrical Insulation

Polymeric Materials for High Power Density Electric Motors

- **Benefits**:
  - Fuel Savings
  - Noise Reduction
  - Carbon and NOx Reduction
- **System challenges**
  - Higher operating voltages, temperatures, and frequencies
  - Pre-mature electrical insulation failure due to excessive heating and corona discharge
- **Electrical Insulation Development**
  - System need: Better thermal management for MW class, high power density (>13 kW/kg) electric machines
  - Thermally conductive electrical insulation necessary to optimize engine performance in hybrid electric motors
  - Thermal conductivity of most electrical insulators: ~0.1 – 0.2 W/mK
  - Goal: ~1 W/mK thermal conductivity

X-57 Maxwell all-electric

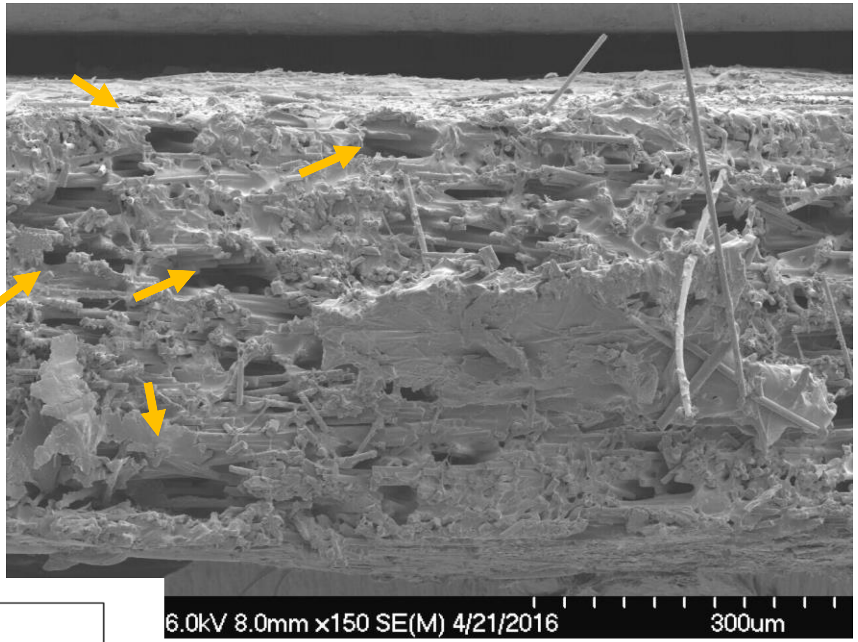


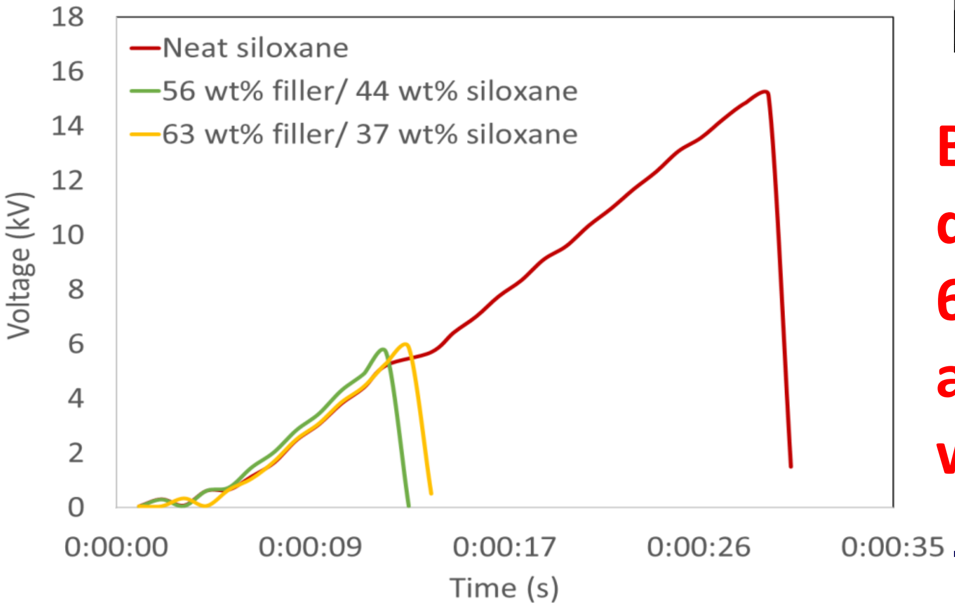
Lightweight power transmission system

Thermally Conductive Electrical Insulation

- **Thermally Conductive, Electrical Insulation Needed**
  - Copper wire
  - Slot liner
  - Potting material
- **Incorporate conductive fillers to increase thermal conductivity of polymer insulation**
- **Adding dissimilar materials typically negatively impact insulation performance**
  - – Lower dielectric strength
  - – Higher chances of charge build up
  - – Decreased flexibility
  - – More interfacial polarization
    - Grains and grain boundaries

Dry spots

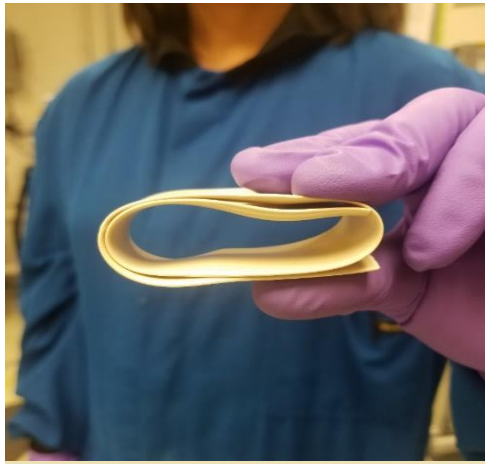




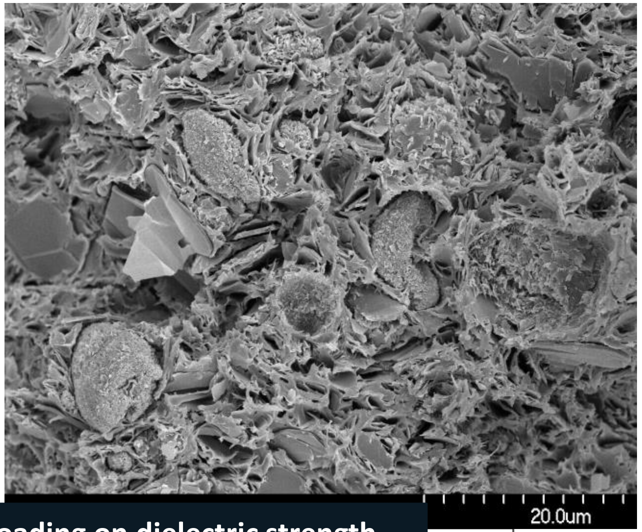
Breakdown voltage decreased by as much as 61% after large volume of additives were mixed with polymer

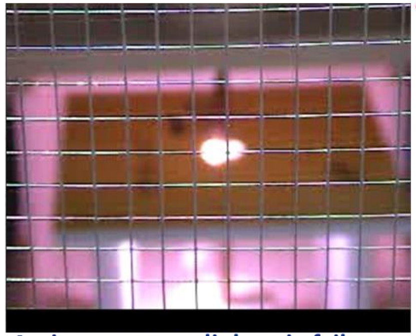
Thermally Conductive Electrical Insulation

PPSU-BN composite ribbon extrusion

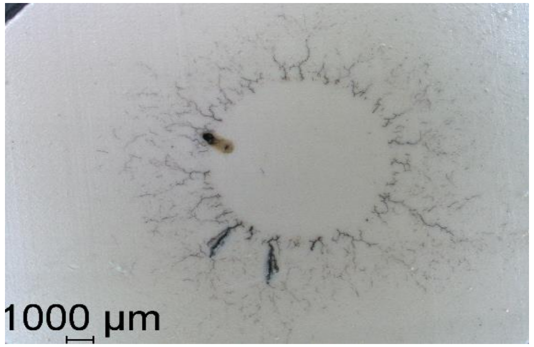


High-bend radius

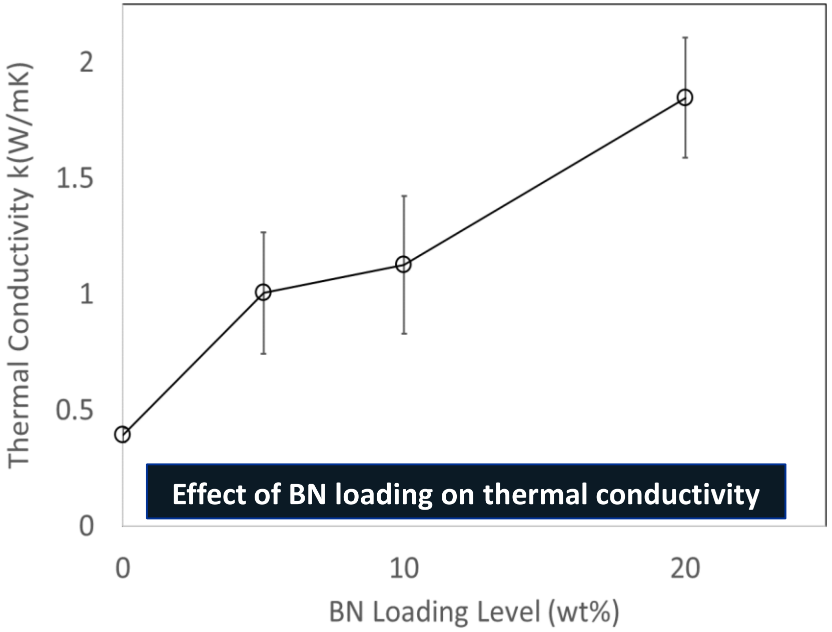


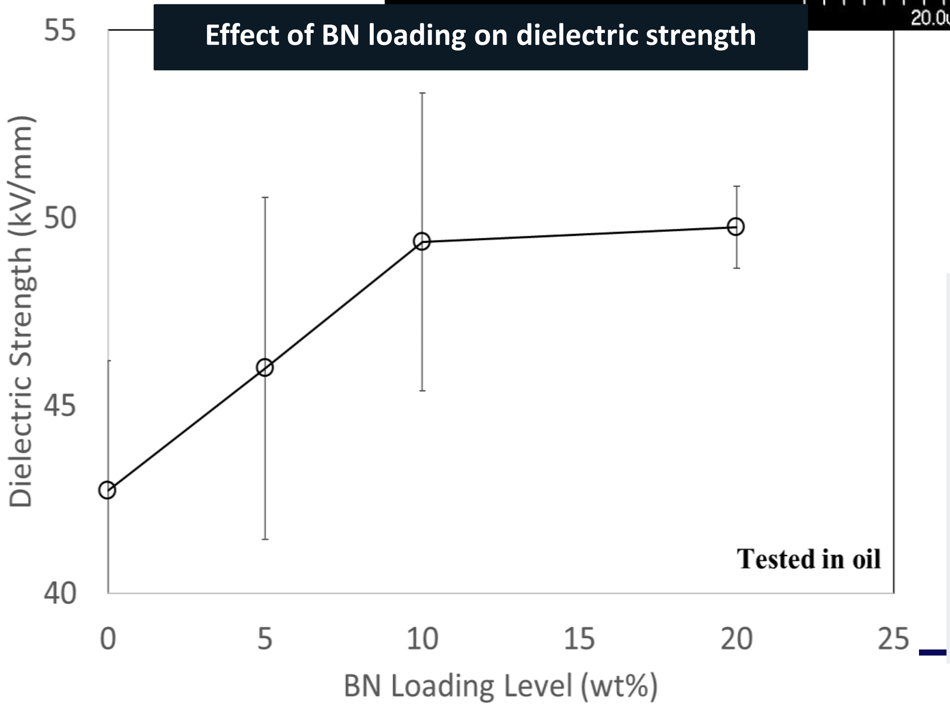


Arcing event at dielectric failure



Electrical treeing in composite insulation at breakdown site





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

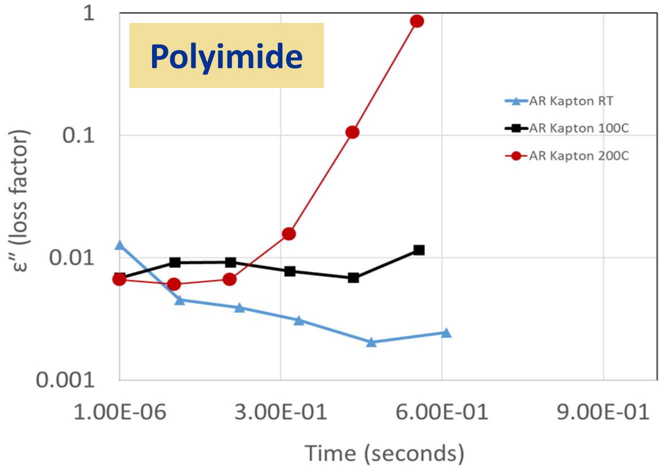
PPSU- polyphenylsulfone

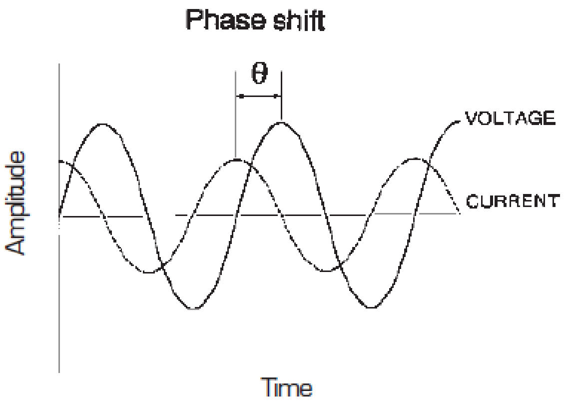
Characterizing High Voltage Electrical Insulation Candidates

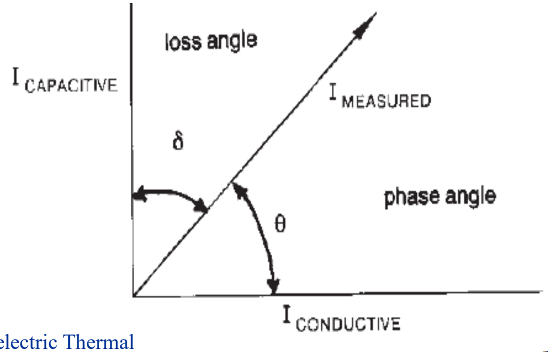
- **Dielectric Analysis (DEA): Correlates chemical structure with end-use performance**
  - Thermal analysis tool traditionally used in manufacturing to optimize curing profiles and reduce scrap
  - Provides temperature- and frequency-dependent information about dipole orientation, molecular relaxations, magnitude of conductivity, and magnitude of energy loss
- Electrical properties + molecular activity → Understand how insulation candidates respond in electrical field to help design insulation materials suitable for the anticipated environment

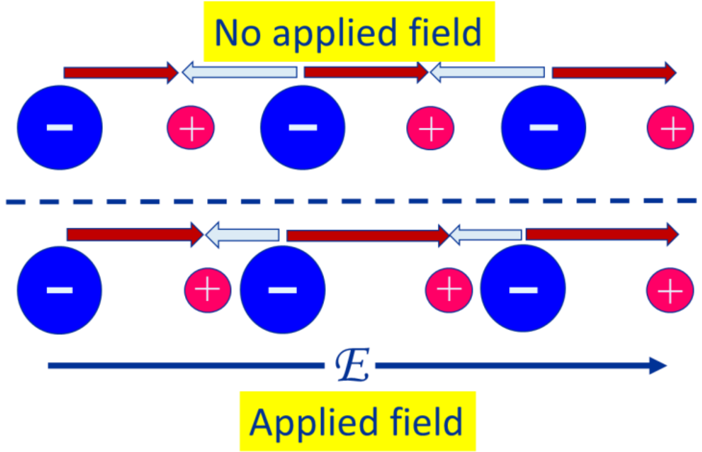
Information pertinent to insulation:

- Frequency and temperature-dependent changes
- Changes in electrical properties due to environmental exposure (thermal breakdown, defects, moisture)
- ε′ (relative permittivity)
- ε ″ (dielectric loss or loss factor)
- tan δ
- Ionic conductivity
- ε * (complex permittivity)









$$p_{induced} = \alpha E$$

Induced dipole moment = polarizability × electric field

Capacitance

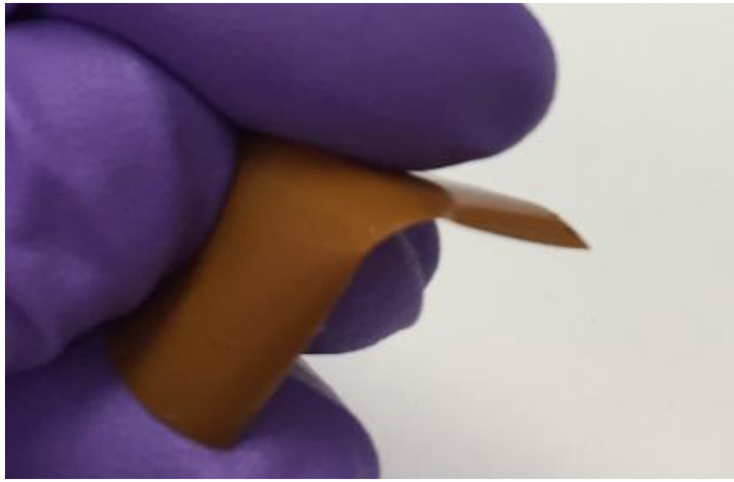
$$C\ (\text{farads}) = \frac{I_{\text{measured}}}{V_{\text{applied}}} \times \frac{\sin\theta}{2\pi f}$$

Conductance

$$1/R\ (\text{mhos}) = \frac{I_{\text{measured}}}{V_{\text{applied}}} \times \cos\theta$$

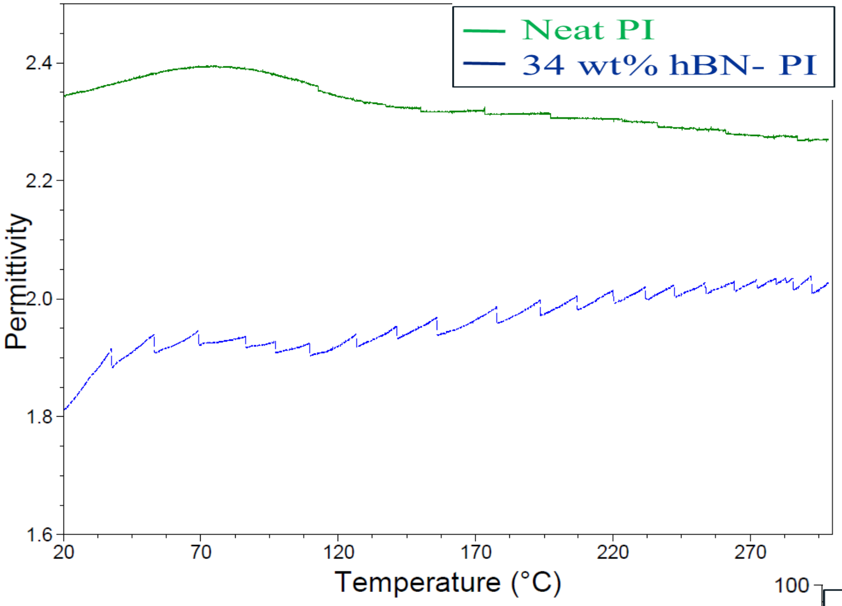
Williams, T. (2019) Application of Dielectric Thermal Analysis to Screen Electrical Insulation Candidates, Manuscript in Preparation

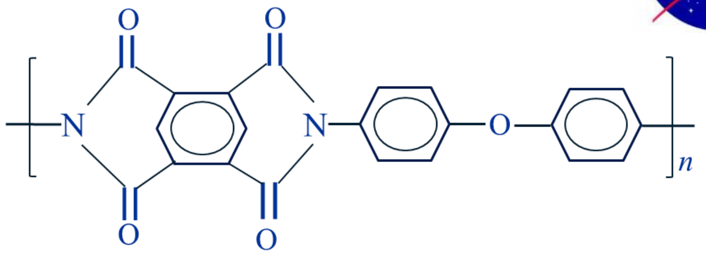
DEA: Effects of filler on dielectric properties



Synthesized polyimide with BNNS

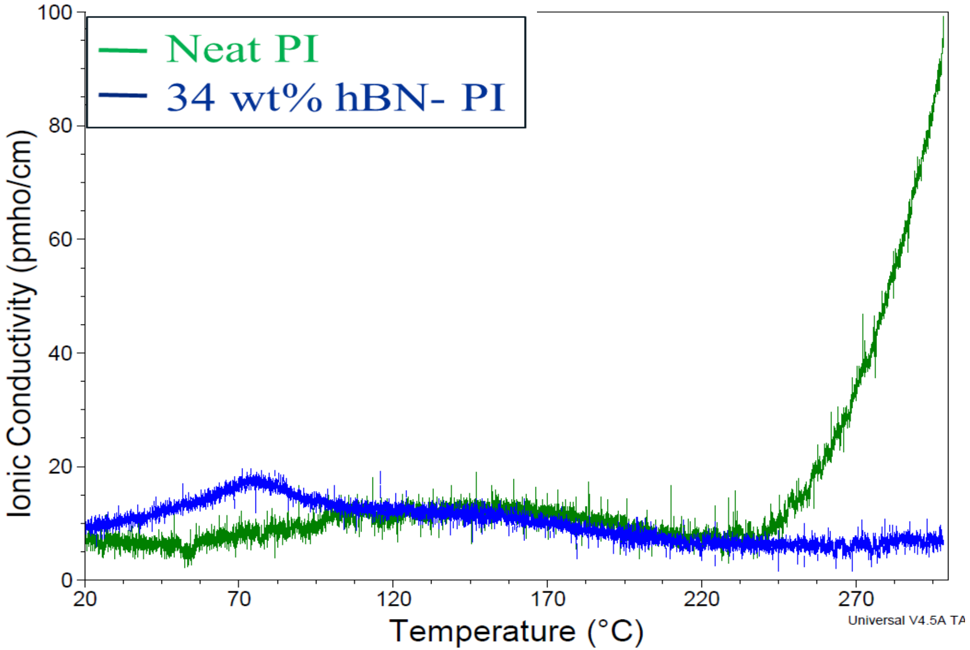
DEA frequency: 4 kHz (anticipated operating frequency)





Polyimide

Addition of hBN nanosheets to PI appeared to keep ionic conductivity stable over a broad temperature range at the anticipated operating frequency

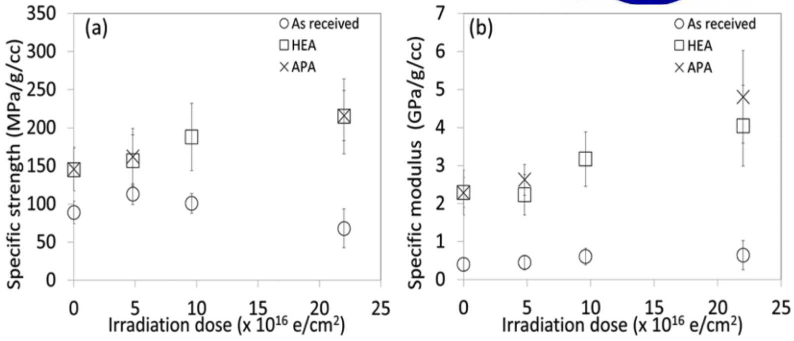


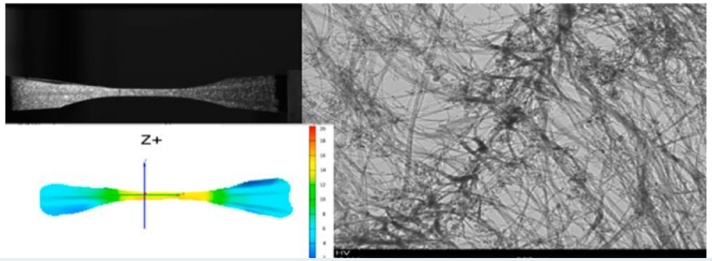
*hBN: Hexagonal boron nitride nanosheets

Textiles and Nano-reinforcement

Structural Nanocomposites: Lightweight Structures

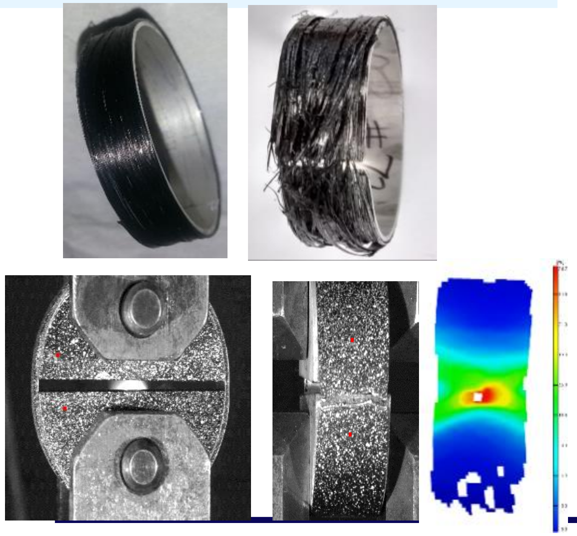
- PMCs have potential to significantly reduce mass of aerospace structures
- **Objective**: Determine if nanocomposites are a viable alternative to CFRP for composite overwrap pressure vessels (COPVs)
- Challenges with nanocomposites:
  - Synthesis
  - Processing → properties
- **Goals**:
  - Develop carbon nanotube (CNT) reinforced composites with 1.5 to 2x's specific strength of conventional carbon fiber composites
  - Improve strength of bulk CNT reinforcement through processing and post-processing methods
  - Validate materials by design, fabrication, ground and flight testing of nanocomposite overwrap pressure vessel



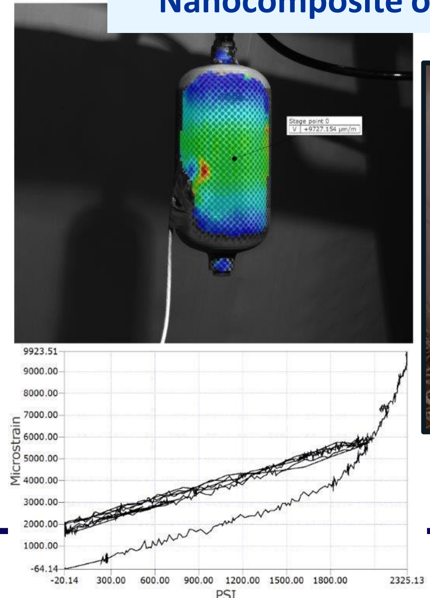


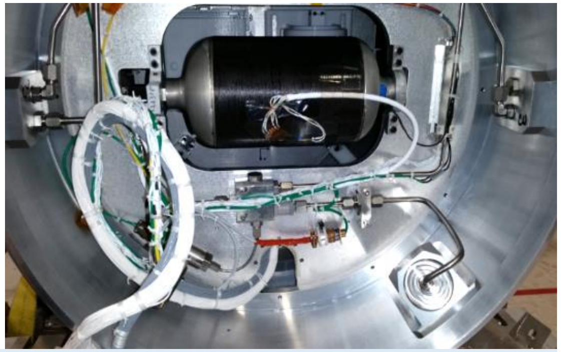
Williams, T., et. al, *ACS Appl. Mater. Interfaces* **2016**, 8, 9327-9334

Split D-ring Mechanical Testing



Flight-test preparation: Nanocomposite overwrap scale-up and burst-testing





COPV tank with nanocomposite overwrap

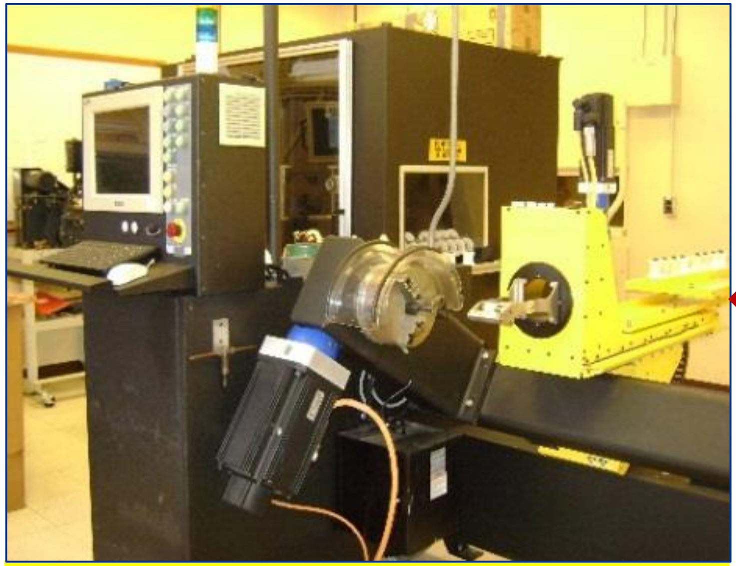
NanoCOPV Manufacturing: CNT Overwrap Development via Prepreg Filament Winding

SUCCESSES

- Developed <u>**scalable**</u> processes to impregnate, filament wind, and cure CNT composites
- Over 2 km of prepreg processed and filament wound during materials development stage
- After 2017 flight test, nano-COPV effort led to Phase III SBIR with Nanocomp to further improve CNT yarn and tape to reduce mass in aerospace structures

CNT Yarn Prepregger

Spool of CNT yarn prepreg



Four axis CNC controlled Filament Winder

Rings of CNT prepreg on mandrel

Autoclave-cured CNT overwrap

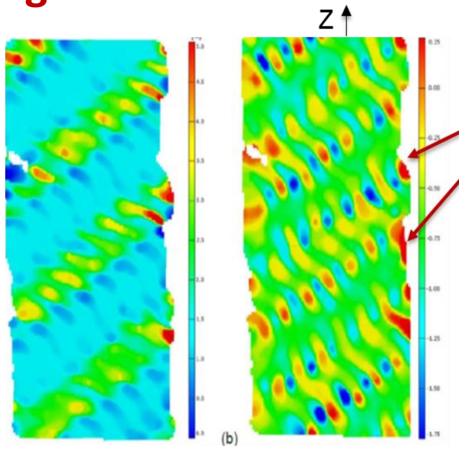
Tailorable Textiles: Hybrid Reinforcement with Increased Toughness

PMCs are limited in their ability to provide adequate toughness for some aerospace applications

- Resin modifiers and additives
- Nanostructures grown on reinforcement
- Ply Stitching

Challenges

- Toughened resins: $$$$ and viscous
- Lack of controlled nanoparticle synthesis methods
- Ply stitching damages carbon fibers



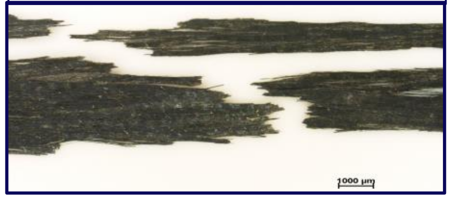
Full field strain DIC data NASA/TM—2015-218814

Strategic placement of more ductile fibers in reinforcement could minimize areas of high axial strains

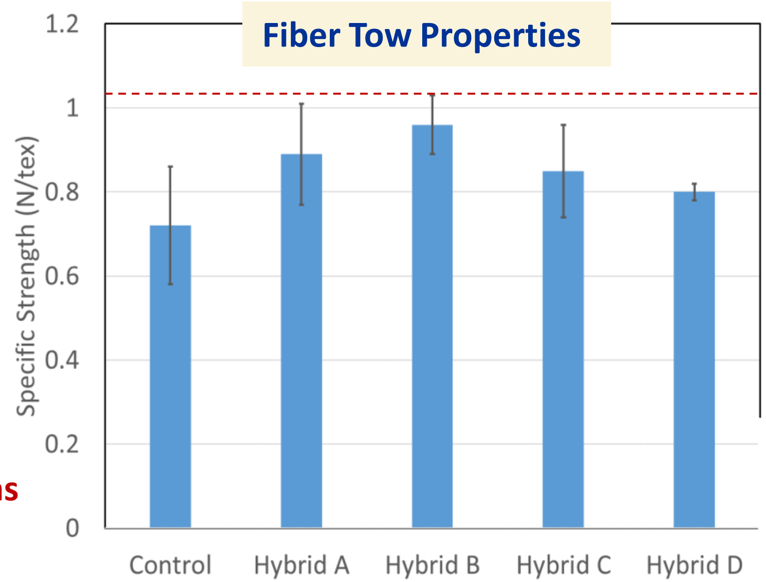
Goal

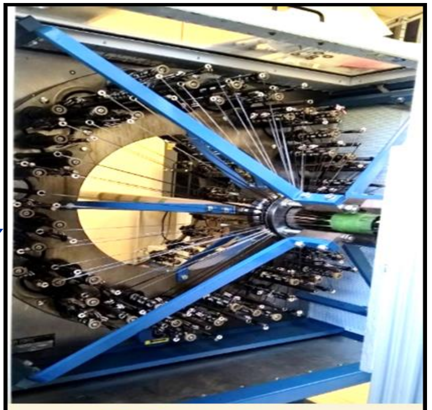
High strength carbon fibers + ductile CNT yarns → Toughened hybrid reinforcement

Tensile Tow Failure

Carbon Fiber/ Epoxy Control	CNT Yarn – Carbon Fiber/Epoxy Hybrid
	

Brittle failure observed in tows that did not contain CNT yarns





2D Circular Braider

28" long
Carbon fiber – CNT Yarn Hybrid Triaxial Braided Tube

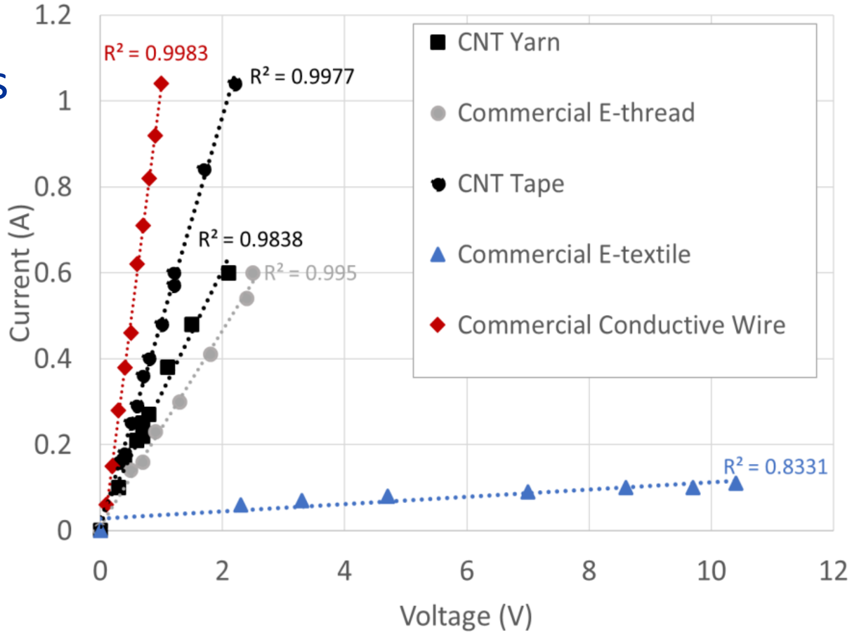
Tailorable Textiles: Durable Electrically Conductive Textiles (E-textiles)

- **Potential applications for e-textiles in aerospace**
  - Spacesuits
  - Sensors
  - Inflatables
  - Blankets
  - Health monitors

- **Challenges with e-textiles and wires**
  - Flexibility
  - Durability
  - Reliability
  - Manufacturing challenges
  - Reparability

Approach: Use CNT yarns to develop lightweight, flexible, and durable e-textiles

- **Common production methods**
  - Screen printing with conductive polymers
  - Embroidery and stitching
    - Stainless steel fibers (breaks easily)
    - Metallic coating on non-conductive fibers (fuzziness and fraying)
  - Fabrics

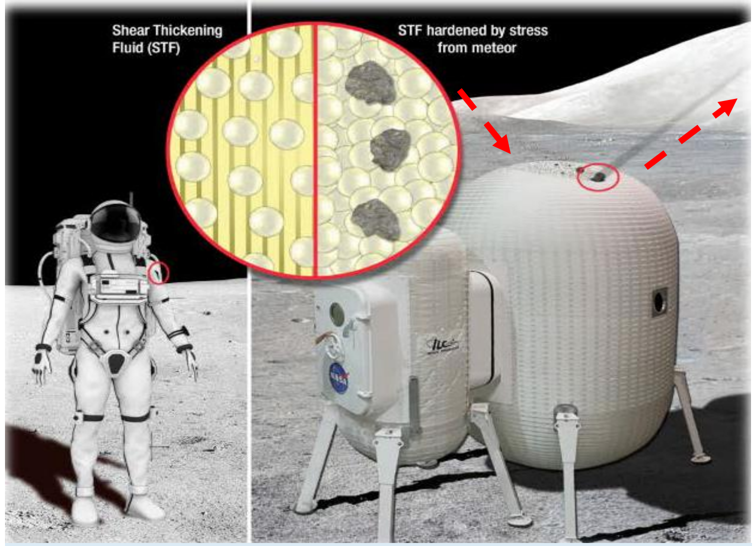


IR thermal image of preliminary heating pad construction: Heat distribution dependency on CNT stitch spacing

Tailorable Textiles: Shear Thickening Fluid (STF)– Enhanced Fabrics for Impact Energy Dissipation

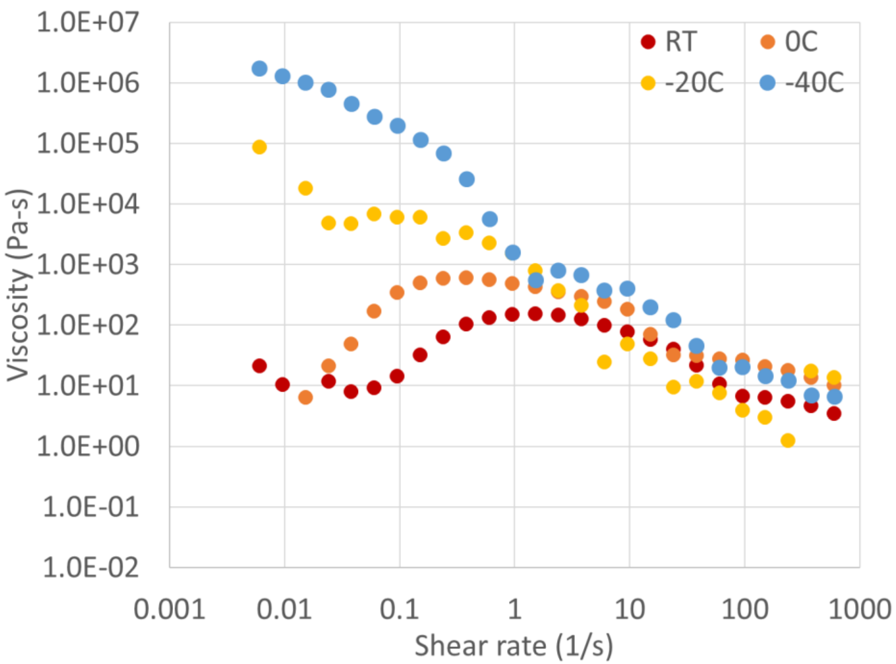
Goal: Develop lightweight, flexible, impact-resistant textiles for inflatable habitat shells to provide protection against micro-meteoroid orbital debris→ fewer redundant layers → mass reduction

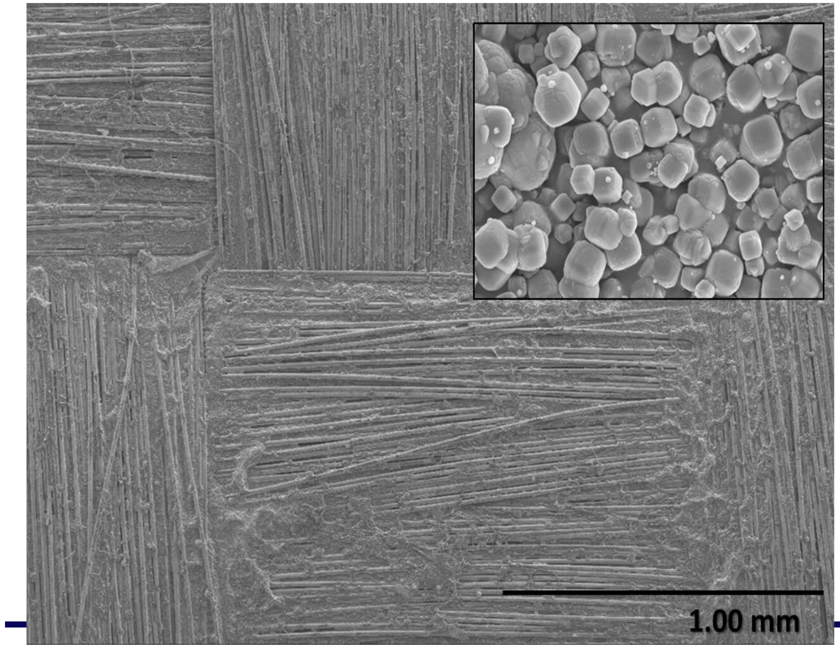
- STFs are dilatant, colloidal suspensions that behave like a solid above a critical shear rate
- Hydrodynamic interactions between nanoparticles lead to stiffness increase
- STF-treated fabrics have been used as effective, puncture-resistant textiles for flexible body armor *(Army Research Lab/ Univ. of Delaware)*
- Can STFs provide protection against micro-meteor impacts in space?
- MMOD hypervelocity impacts > 1 km/sec



Impact-resistant habitat shells and spacesuits

Image credit: Terence Condrich, NASA





Cubic nanoparticles create stronger hydrodynamic interactions than spherical nanoparticles

Cwalina, C. et al, *Soft Matter* **2016**, 12, 4654-4665

Summary

- Polymers play an important role in multifunctional materials development→ many projects are ongoing
- Mature polymer and composites processing and characterization methods are still viable to develop multi-functional materials
  - Extrusion
  - Filament winding/ prepreg development
  - Braiding
  - DEA
- Preliminary findings show that 1 – 2 W/mK thermal conductivity was achieved in extruded composite insulation. Dielectric strength was not negatively impacted with BN addition.
- Interfaces (or pre-existing defects) between fillers and host polymer must be improved to reduce electrical treeing or cracking and improve breakdown voltage
  - Processing technique
  - Filler size, geometry
- Multi-functional characteristics integrated through textiles offer advantages of tailorability and mass savings

Acknowledgements

- **Aeronautics Research Mission Directorate**
  - Transformational Tools and Technologies (TTT)
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  - Game Changing Development Program

Insulation Development

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- Kathy Chuang

Nanocomposites and Textiles

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