Multifunctional Polymers and Composites for Aerospace Applications

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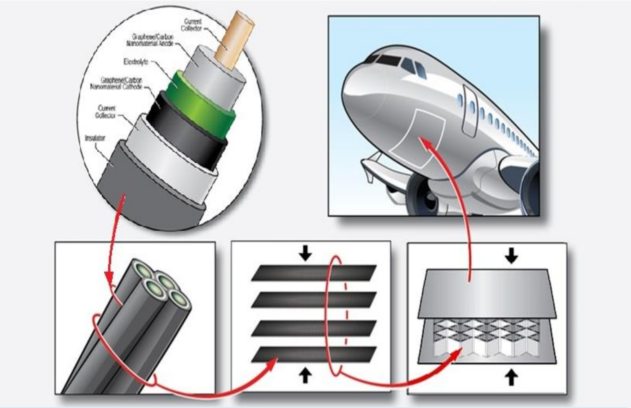
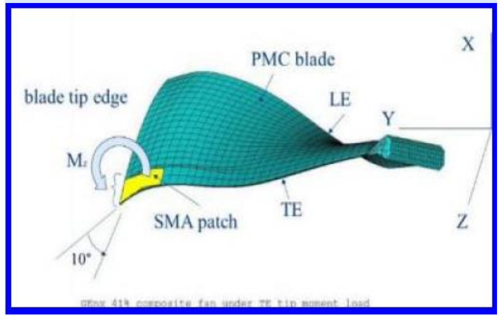
Typical System Needs and Challenges in Aeronautics and Space

- **System Challenges in Aeronautics**
  - Efficiency (power, cost)
  - Mass, noise, emissions reduction
- **Needs**
  - Higher strength and stiffness lightweight composites
  - High temperature, toughened composites
  - Thermal management
  - Multi-functionality
    - Morphing structures
    - Electrically conductive composites



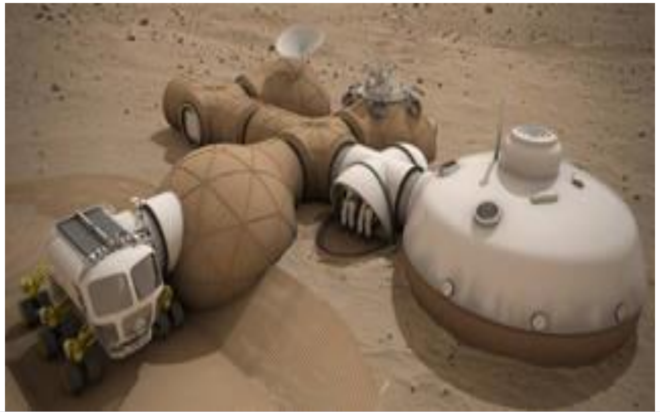
Multi-functional structure with energy storage capability

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 resistant
    - Smart materials

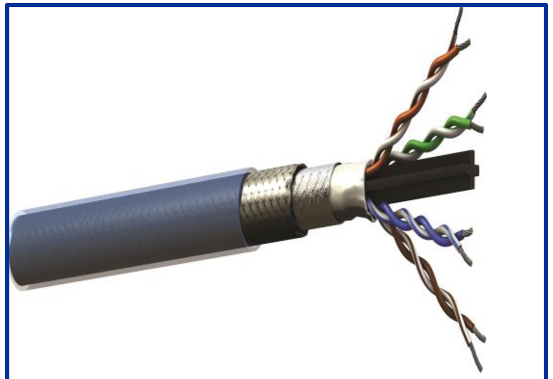


Novel Electrical Insulation

Polymeric Materials for High Power Density Electric Motors

- **Benefits**:
  - Fuel Savings
  - Noise Reduction
  - Carbon and NOx Reduction
- **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
- **System challenges**
  - Pre-mature electrical insulation failure due to excessive heating and corona discharge
  - Higher operating voltages, temperatures, and frequencies

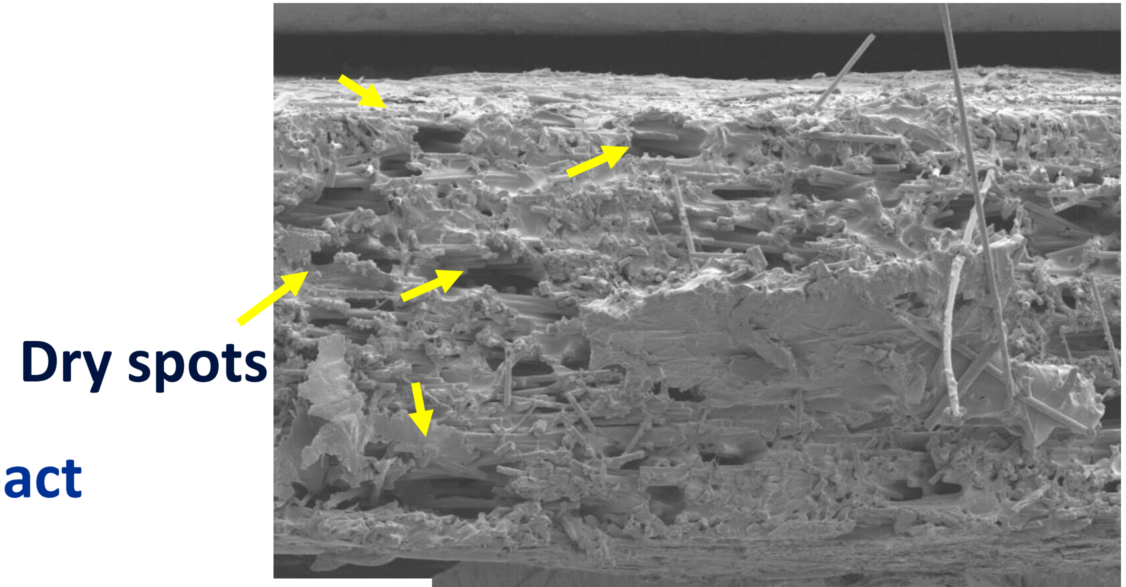
X-57 Maxwell all-electric

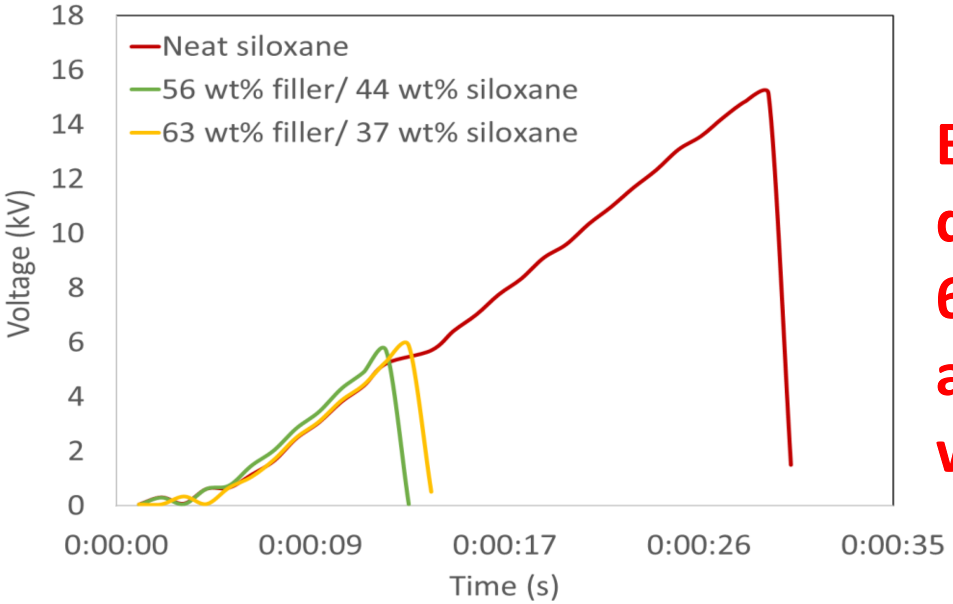


Lightweight power transmission system

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





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

Twin Screw Extrusion to Develop Thermally Conductive Electrical Insulation

- **Advantages**
  - Improved polymer orientation
  - Better filler dispersion and distribution
  - Preferred filler directionality and alignment
  - Capable of extruding large volumes of thin films and wire coating

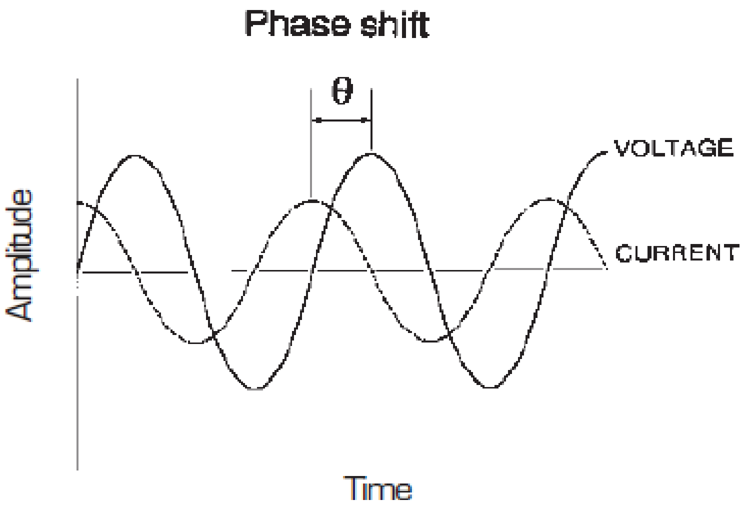
High temperature extruder

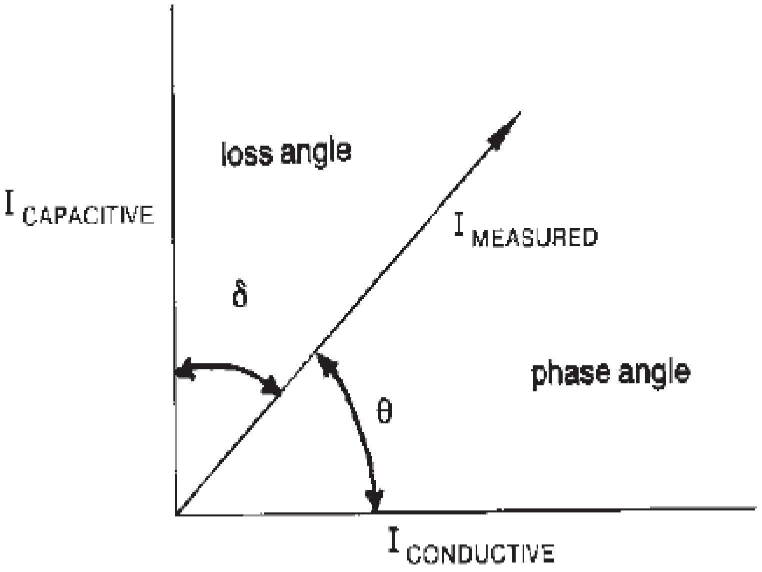
- **Process parameters**
  - Nanofillers? Micro-fillers? Nano/ micro- fillers?
  - **Effect of particle concentration**
  - **Effect of filler material**
    - BN
    - Mica
  - **Effect of filler geometry**
    - Sheets/platelets
    - Particles
- Strand extrusion can be used for additive manufacturing

Extruded wire coating

Characterizing Novel Electrical Insulation Candidates for Electric Machines

- **Dielectric Analysis (DEA): Correlates chemical structure and end-use performance**
  - Thermal analysis tool traditionally used in manufacturing to optimize processing conditions and reduce scrap
  - Provides information about dipole orientation and molecular relaxations, magnitude of conductivity, and magnitude of energy loss
- Electrical properties + molecular activity → better understanding of thermo-electrical properties and chemistry to help design better insulation materials





Capacitance

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

Conductance

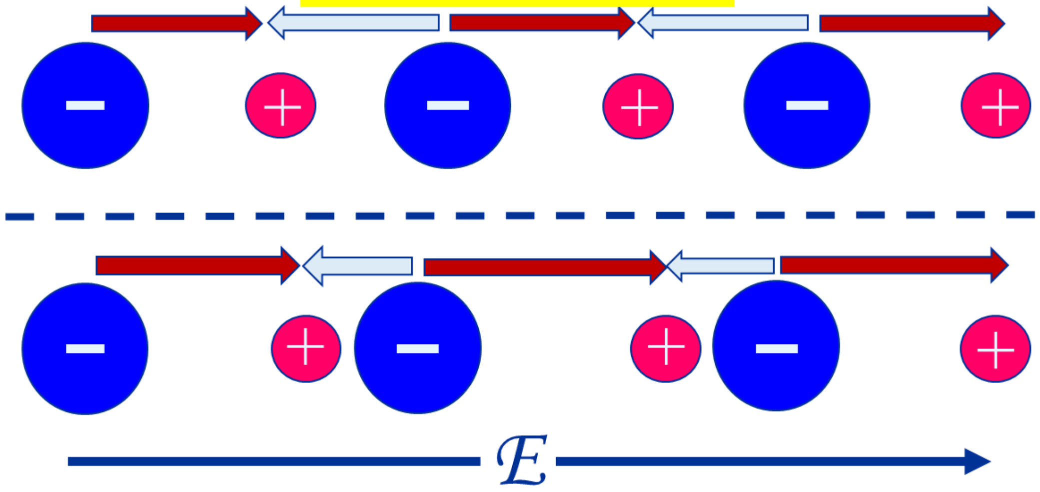
$$1/R\ (\text{mhos}) = \frac{I_{\text{measured}}}{V_{\text{applied}}} \times \cos\theta$$

DEA: Performance Prediction of Novel Electrical Insulation Candidates

- What can DEA data tell us?
    - Influence of crystallinity
    - Cure-related information (kinetics, rheology)
    - Frequency and temperature-dependent changes
    - Changes in electrical properties due to environmental exposure (thermal breakdown, defects, moisture)

- Information Pertinent to Insulation Performance
    - ε’ (relative permittivity)
    - ε ”
    - tan δ
    - Ionic conductivity
    - ε * (complex permittivity)

No applied field

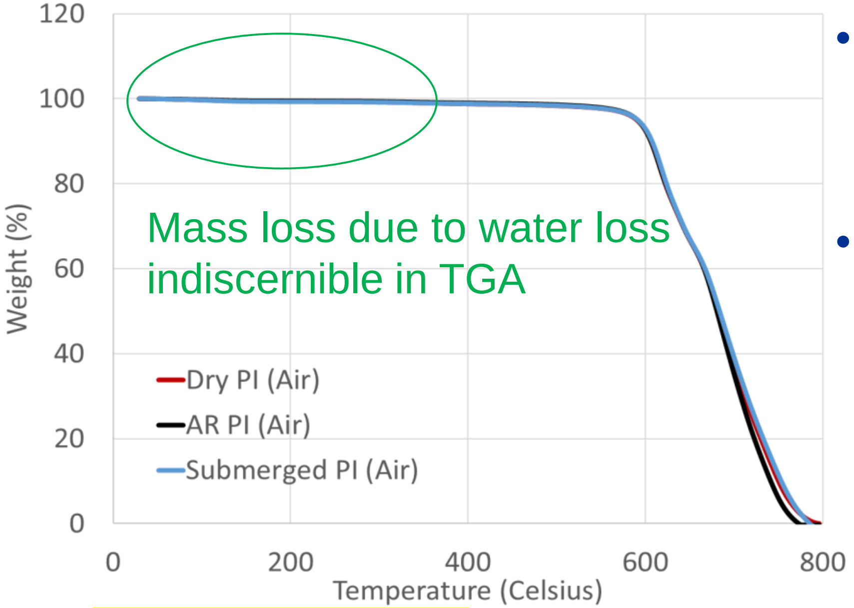


Applied field

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

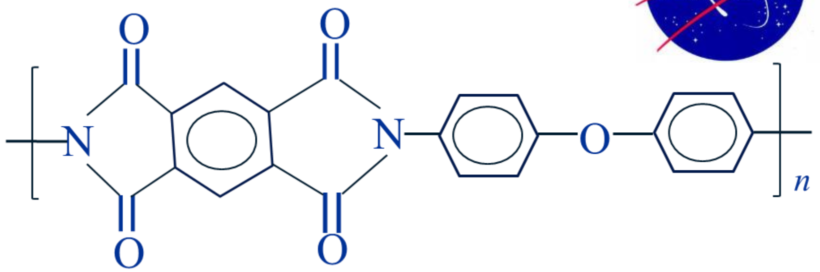
Induced dipole moment = polarizability × electric field

DEA: Moisture and Thermal Effects on Dielectric Properties in Polyimide (PI)



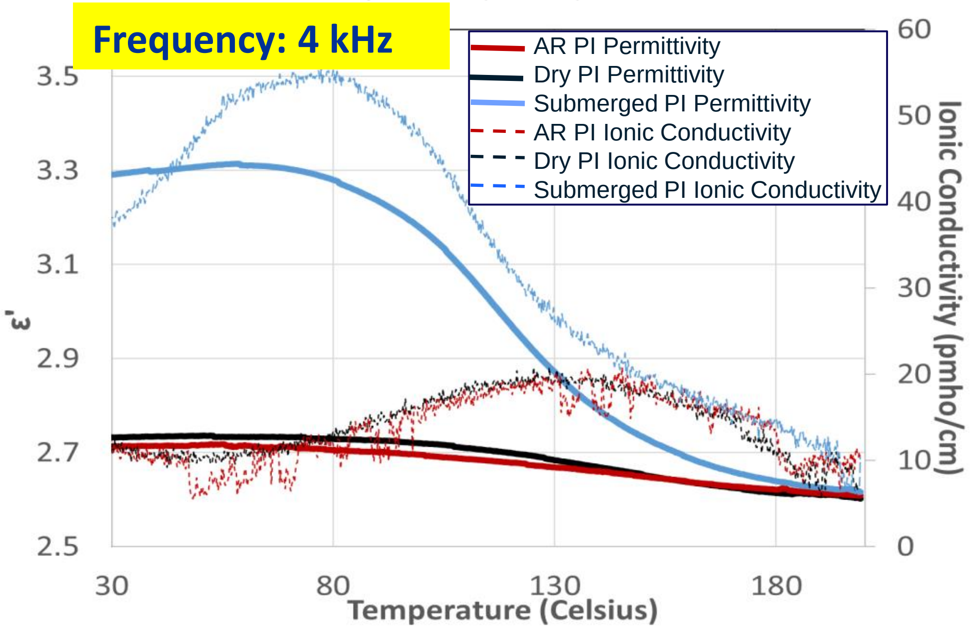
Mass loss due to water loss indiscernible in TGA

- Three commercial polyimide films investigated: (1) As received (AR); (2) Oven-dried; (3) Submerged in water
- Water uptake in submerged polyimide was ~**2.1 wt%** according to mass measurements



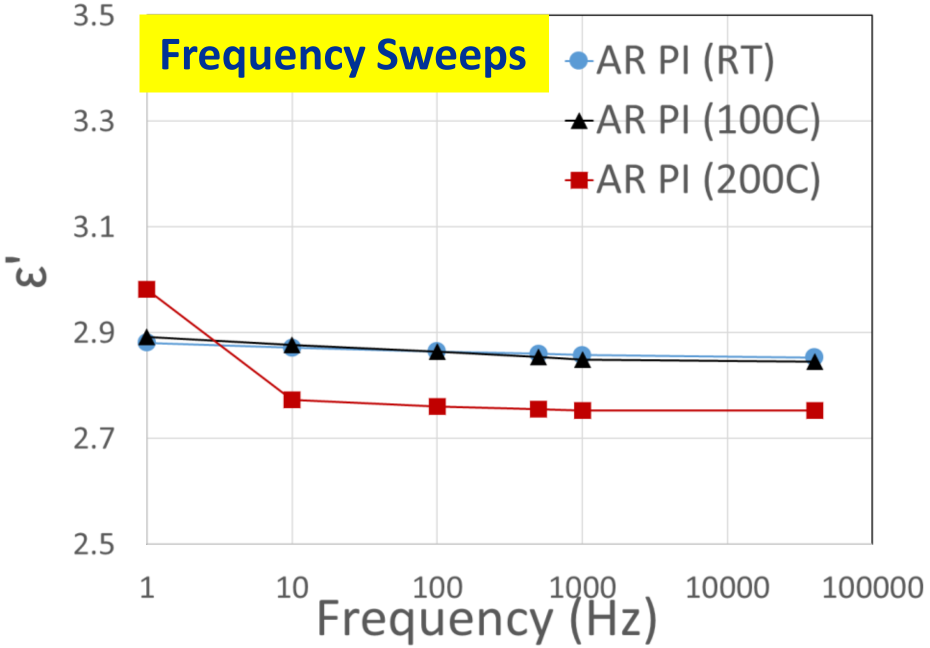
Kapton

Frequency: 4 kHz



More polarizability in water submerged samples

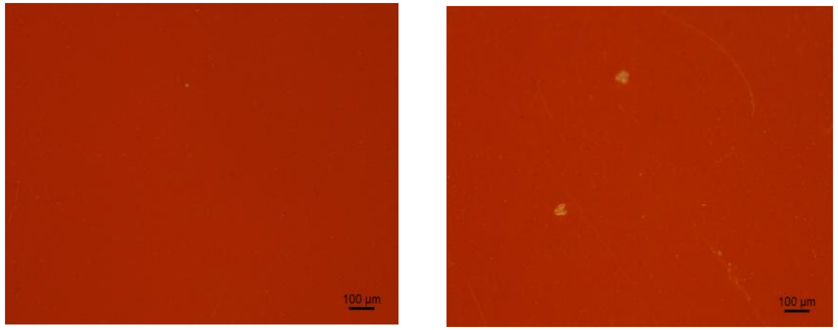
Frequency Sweeps



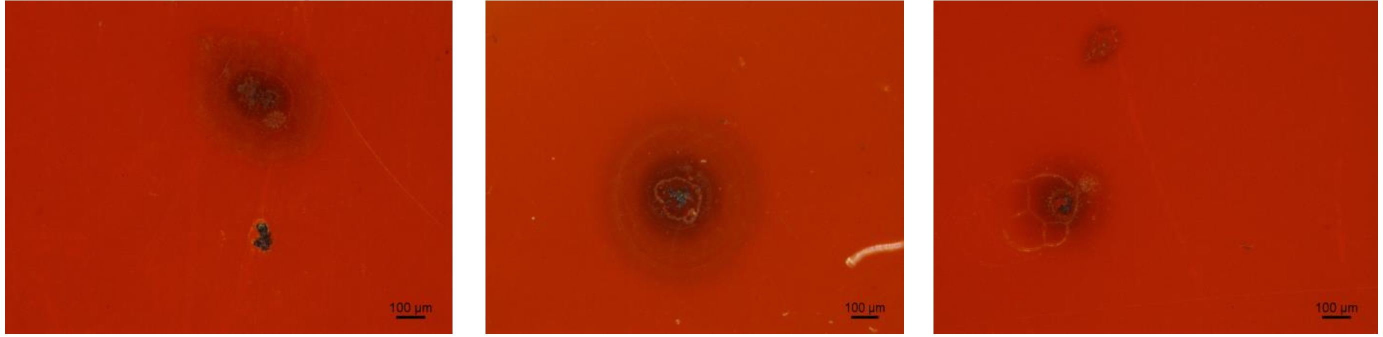
DEA: Thermal Aging Effects on Dielectric Properties

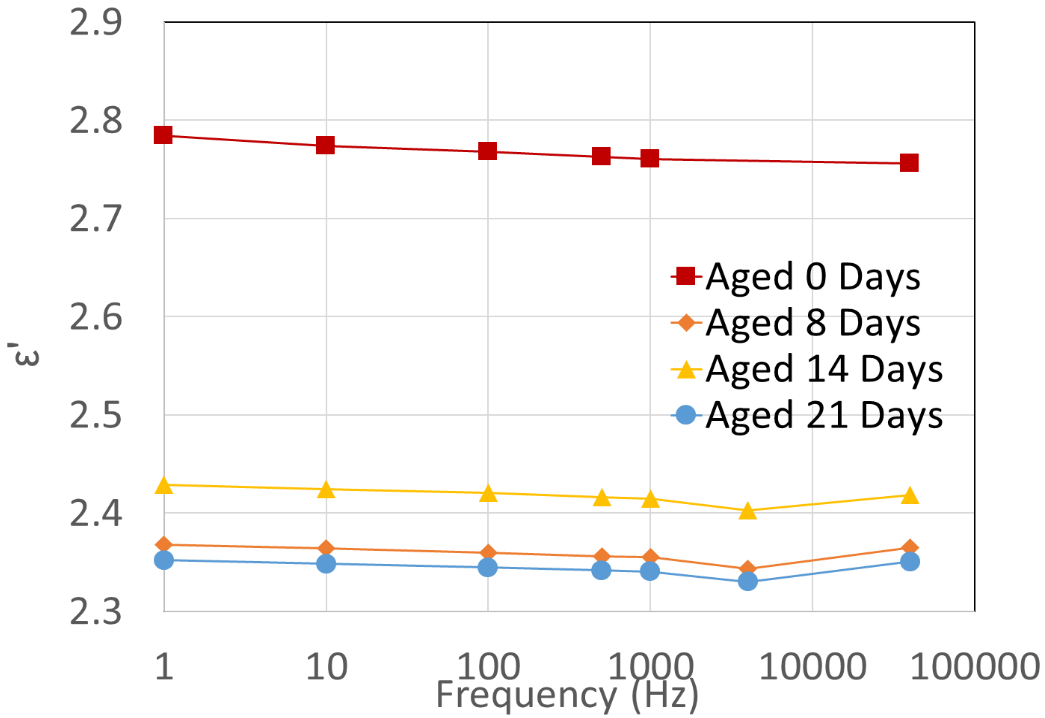
- Thermal aging carried out to evaluate changes in chemical structure at potential operating temperatures
- Frequency sweeps on DEA performed at ambient temperature
- Polyimide T_g = ~381°C

As-received PI film



Aged at 275°C (530°F) for 190 hours





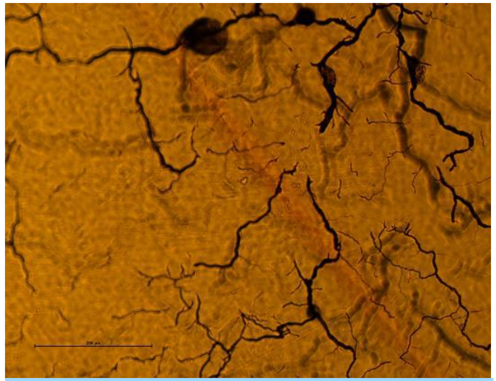
Relative permittivity decrease suggests more rigid network formation during aging

Self-healable Electrical Insulation

- **Challenge**: Polymeric aircraft electrical insulation is highly prone to damage by:
  - – Corona discharge at altitude
  - – Abrasion and cuts (maintenance)
  - – Damage to electrical insulation leads to electrical shorts and/or fires

- **Need:** Increase aircraft safety and longevity of electrical insulation over state-of-the-art insulation through self-healing

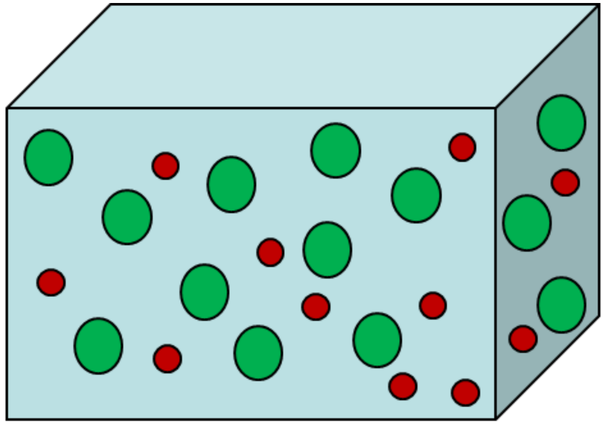
- **State-of-the-Art Insulation:** Polyimides
  - **Advantages**
    - Low dielectric constant and high dielectric breakdown voltage
    - High thermal stability
  - **Disadvantages**
    - Moisture absorbance → Electrical fires



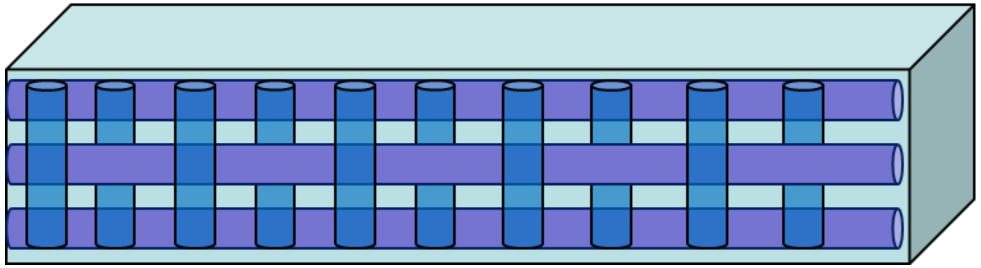
Micro-cracks in polyimide after dielectric failure

Typical Self-healing Mechanisms in Polymers

Extrinsic Healing

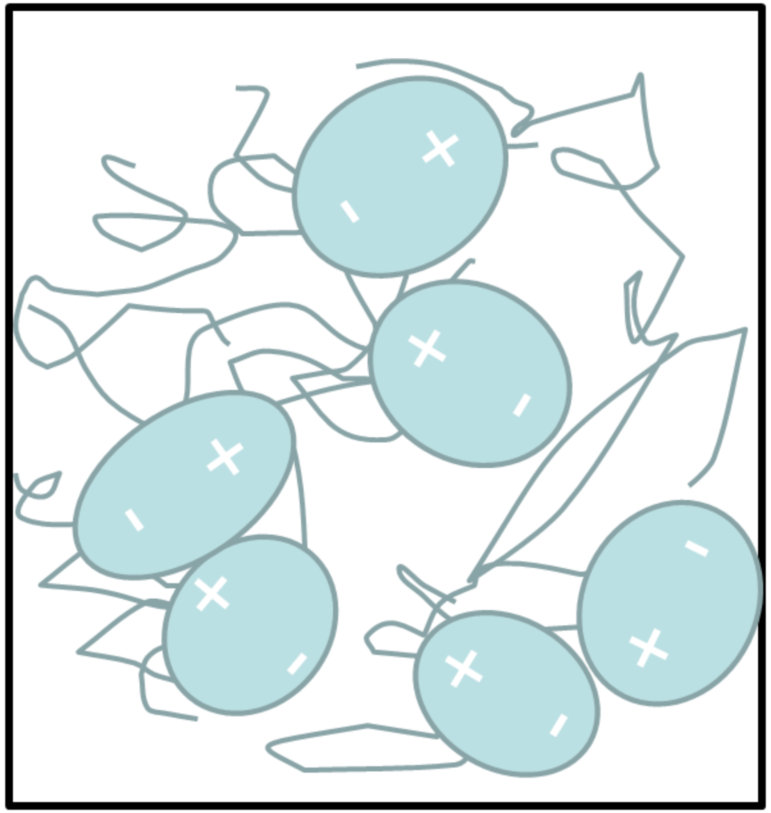


Embedded microcapsules filled with healing agents that flow and polymerize when cracks are formed.



Microvascular networks filled with healing agents that flow and polymerize when cracks are formed.

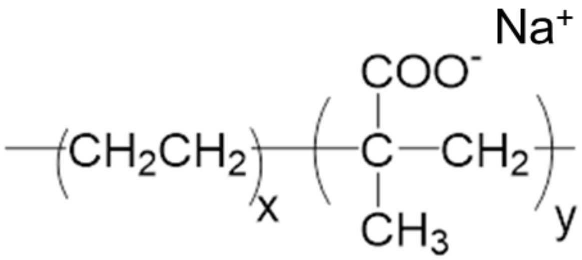
Intrinsic "Reversible" Healing



Ionic clusters and other bonds that can break and reform

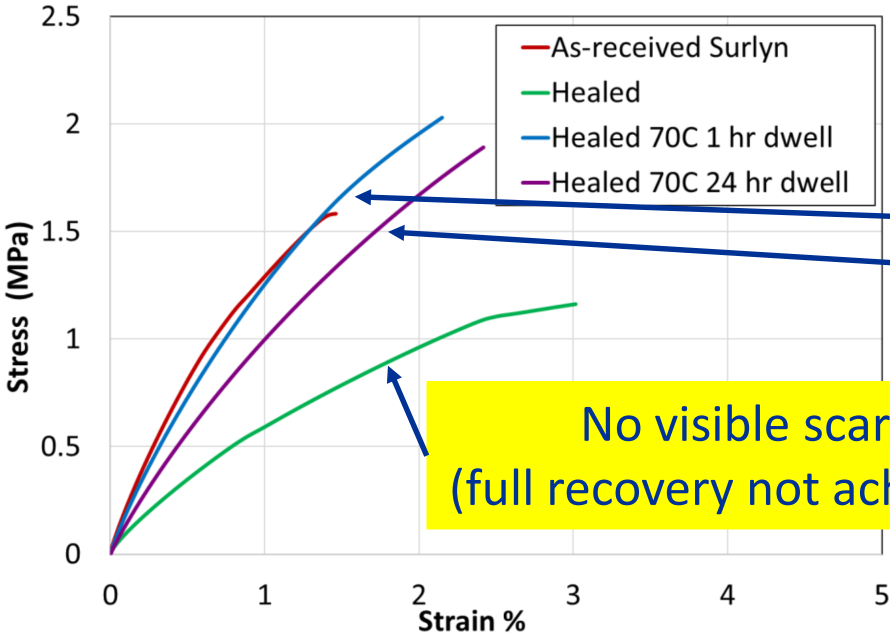
The number of healing cycles is limited with extrinsic healing approaches

Ionically-crosslinked Polymers for Self-healable Electrical Insulation



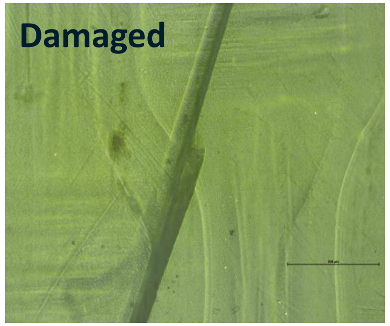
$-(CH_2CH_2)_x-(C(COO^-\,Na^+)(CH_3)-CH_2)_y-$

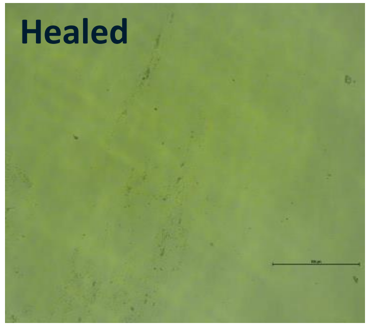
Sodium Ionomer



Extended temperature dwell allows rearrangement of ionic networks

No visible scars
(full recovery not achieved)





	Surlyn Ionomer	Damaged Surlyn Ionomer	Healed Surlyn Ionomer
Average Breakdown Voltage (kV)	16.8 ± 1.09	~9.7	~15.7
ε	1.567		

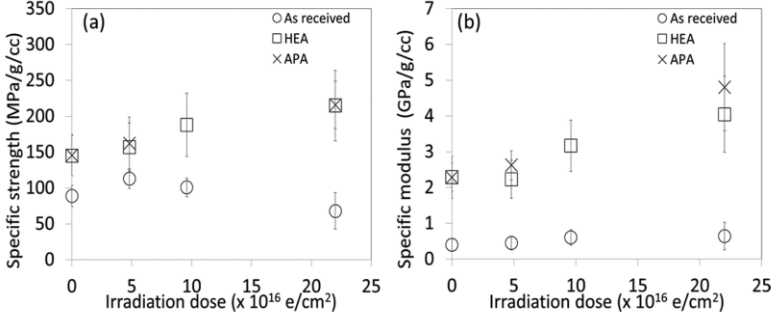
Na^+ ionomer achieved ~93% recovery in dielectric strength after healing. Over 85% recovery in mechanical strength.

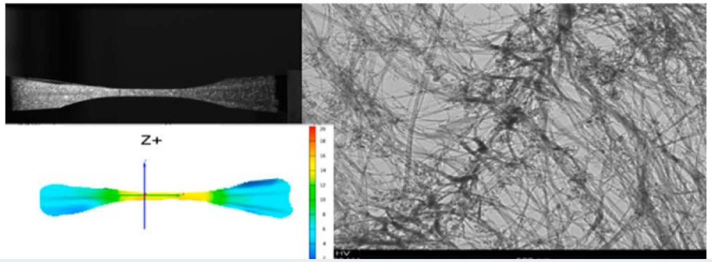
Material not suitable for applications with high operating temperature.

Textiles and Nano-reinforcement

Structural Nanocomposites: Lightweight Structures

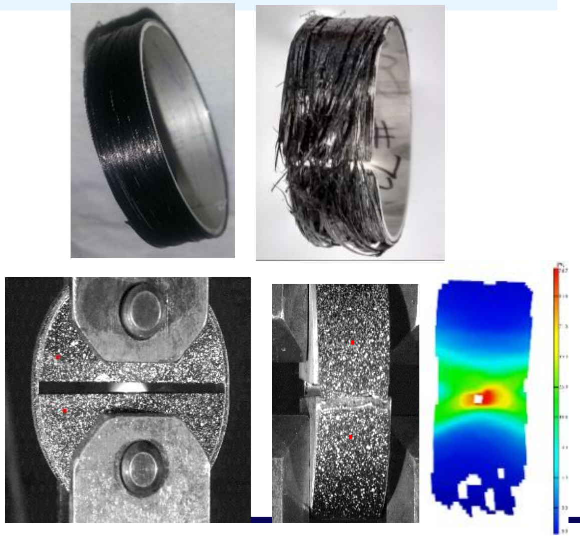
- PMCs continue to play a significant role with reducing mass of aerospace structures
- **Objective**: Determine if nanocomposites are a viable alternative to CFRP for composite overwrap pressure vessels (COPVs)
- Challenges with nanocomposites:
  - Synthesis
  - Processing → properties
- **Goals**:
  - 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



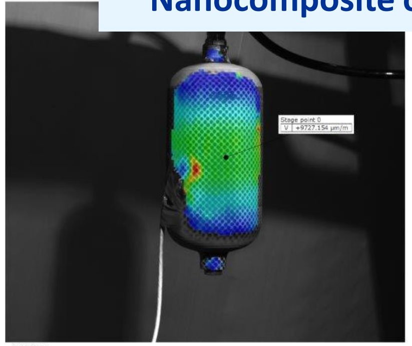


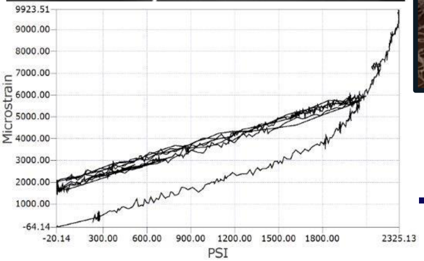
Williams, T., et. al, ACS Appl. Mater. Interfaces 2016, 8, 9327-9334

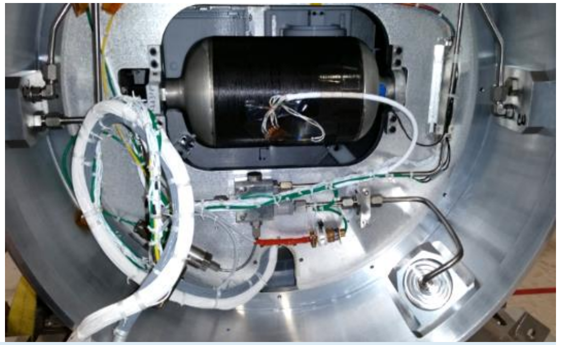
Split D-ring Mechanical Testing



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







COPV tank with nanocomposite overwrap

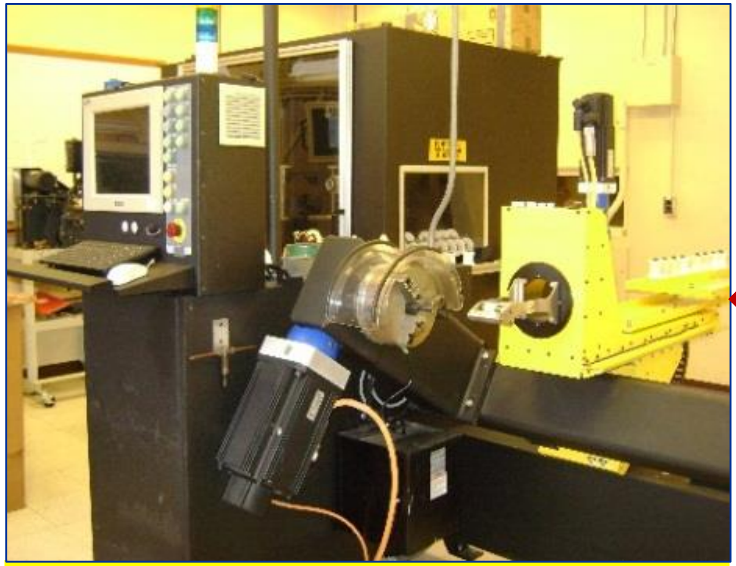
CNT COPV Manufacturing: CNT Overwrap Development via Prepreg Filament Winding

SUCCESSES

- Developed scalable 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

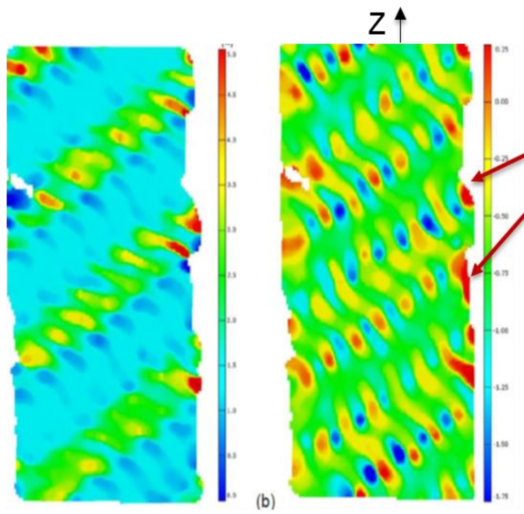
Tailorable Textiles: Hybrid Reinforcement with Increased Toughness

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 difficult to process
- Lack of controlled nanoparticle synthesis methods
- Ply stitching damages carbon fibers



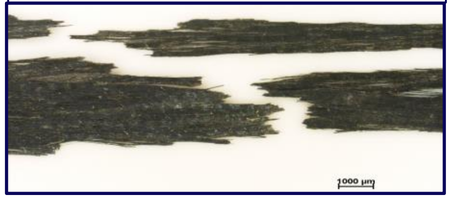
Full field strain DIC data NASA/TM—2015-218814

Tow splitting

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

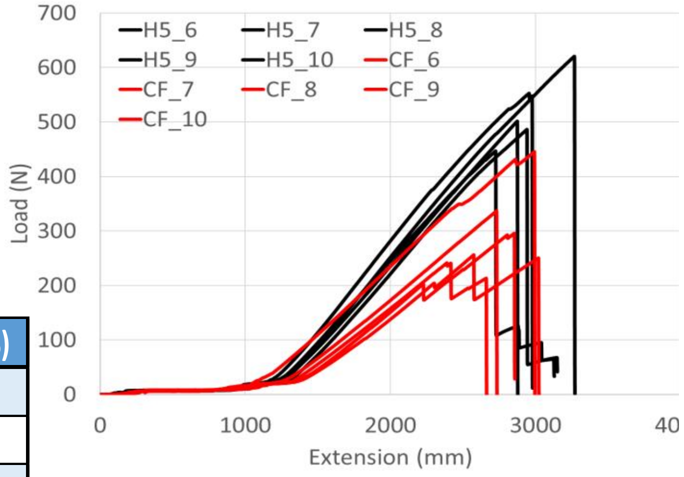
Tensile Failure of Fiber Tows

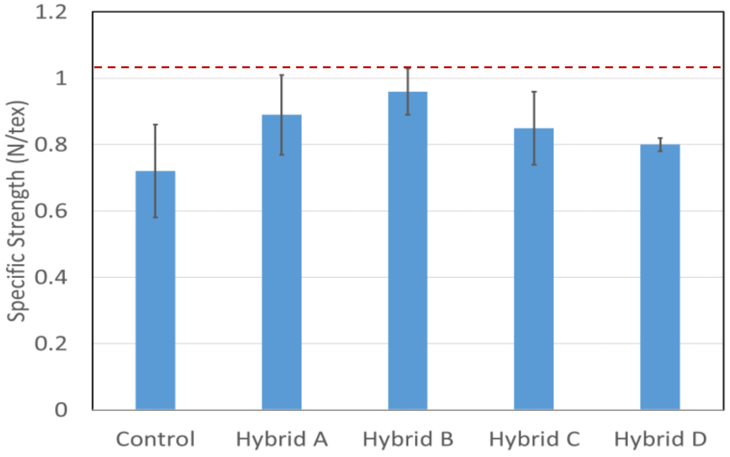
Carbon Fiber/ Epoxy Control



CNT Yarn – Carbon Fiber/Epoxy Hybrid

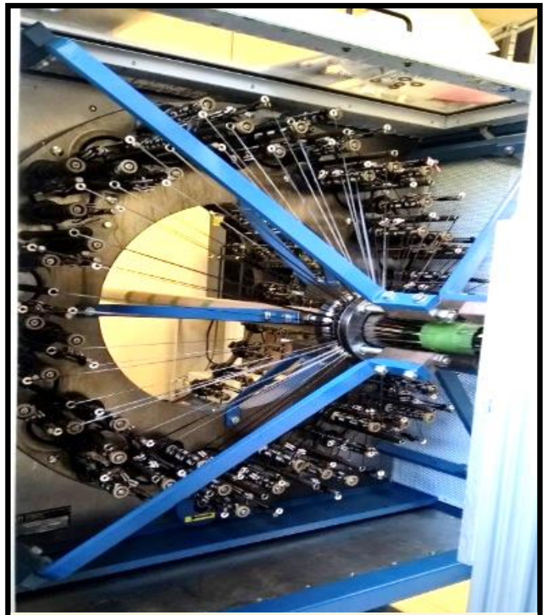
Resin Impregnated Tows	Max Load (N)	Tex Value (g/km)	Density Increase (%)
Control	282.6 ± 73.1	392.6 ± 24.0	0.0
Hybrid A	445.1 ± 43.8	505.9 ± 46.5	28.8
Hybrid B	521.6 ± 60.0	543.0 ± 52.0	38.3
Hybrid C	494.9 ± 56.2	582.6 ± 45.2	48.4
Hybrid D	541.9 ± 13.5	675.5 ± 14.7	72.1





Hybrid textiles enable integration of functional fibers into conventional reinforcement

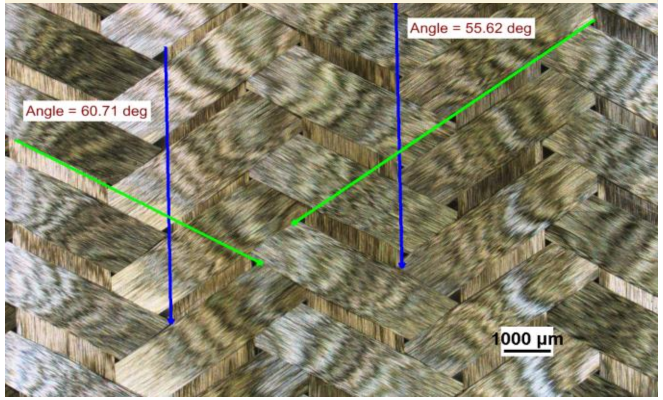
Tailorable Textiles: Toughened Hybrid Reinforcement



2D Circular Braider

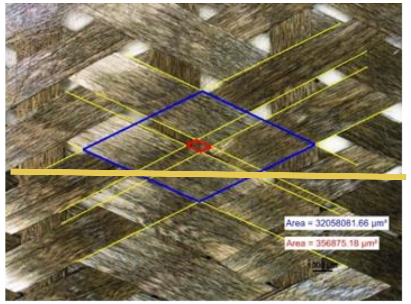
Triaxial braid – A&P Technologies

IM7 Carbon Fiber Control Braid



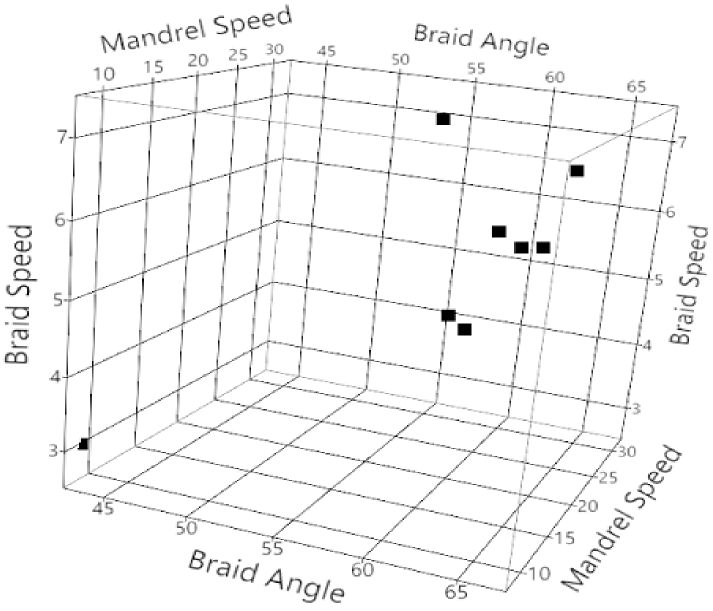
$$\frac{\alpha}{2} = tan^{-1}\left(\frac{R\Omega}{V}\right)$$

R: Mandrel radius
Ω: Rotational speed of braiding
V: Translational mandrel speed

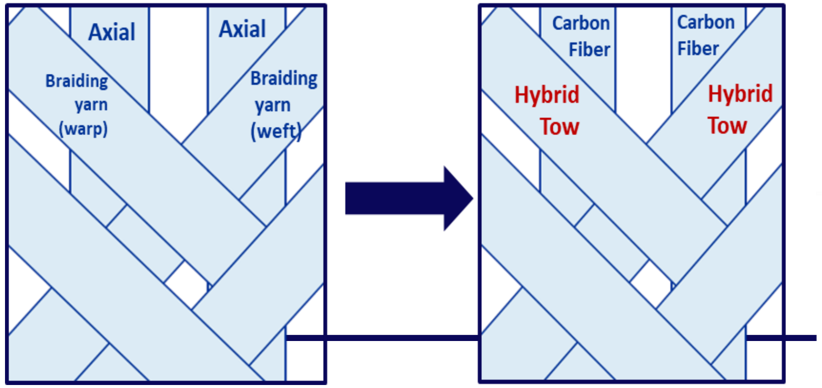


Coverage Factor (C.F.)

$$C.F. = \frac{S.A._{fiber}}{S.A._{mandrel}}$$



Braid speed (rpm)
Mandrel speed (in./min)



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

Carbon Fiber-CNT Yarn Hybrid Braid

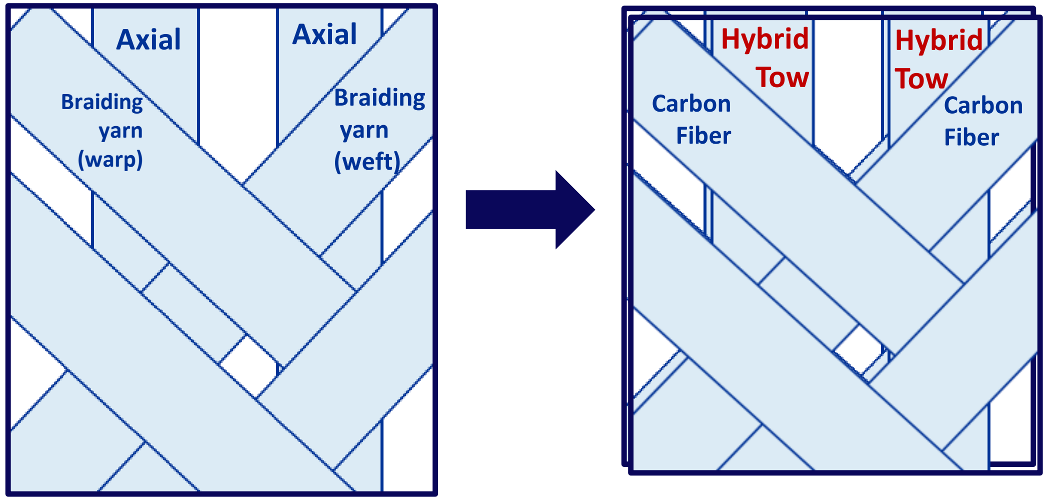
Tailorable Textiles: Durable Electrically Conductive Textiles (E-textiles)

- **E-textile uses in aerospace**
  - Spacesuits
  - Sensors
  - Inflatables
  - Blankets
  - Health monitors

- **Challenges with e-textiles**
  - Durability
  - Reliability
  - Manufacturing challenges
  - Reparability
  - May not have good flexibility depending on method

- **Production**
  - Screen printing with conductive polymers
  - Embroidery and stitching
    - Stainless steel fibers
    - Metallic coating on non-conductive fibers
  - Fabrics

CNT yarn stitched circuit on ballistic Kevlar

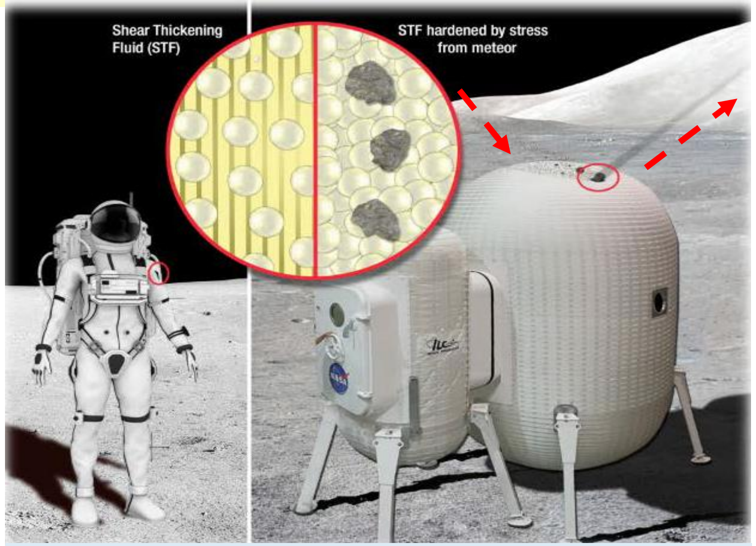


Enhanced toughness
Electrical conductivity

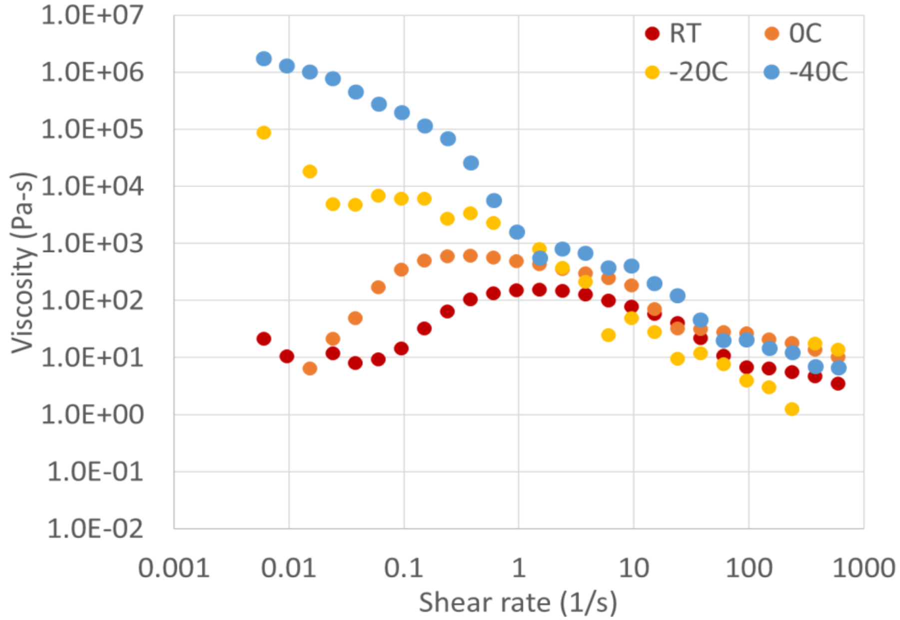
Tailorable Textiles: Shear Thickening Fluid (STF)– Enhanced Fabrics for Impact Energy Dissipation

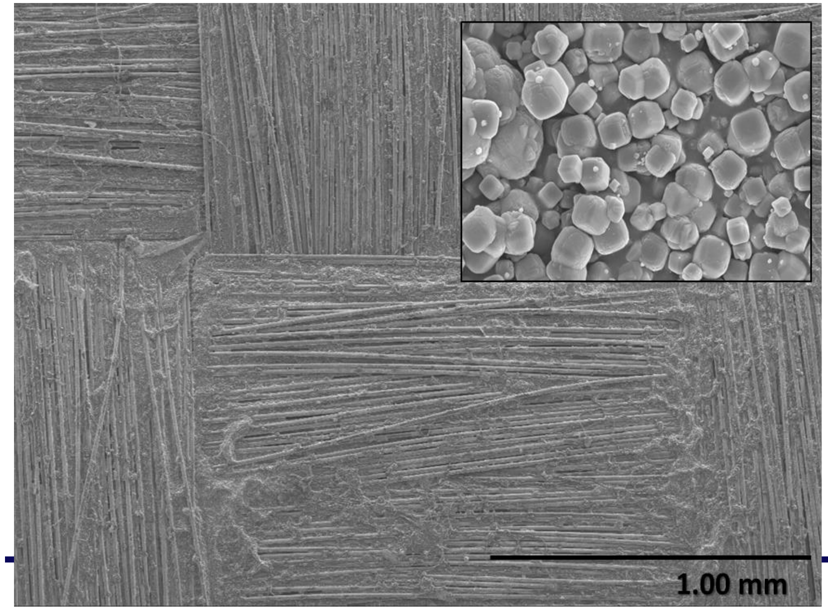
Goal: Develop lightweight, flexible, impact-resistant textiles for inflatable habitat shells to provide protection against micro-meteoroid orbital debris→ fewer redundant layers → mass reduction

- 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?



Impact-resistant habitat shells and spacesuits



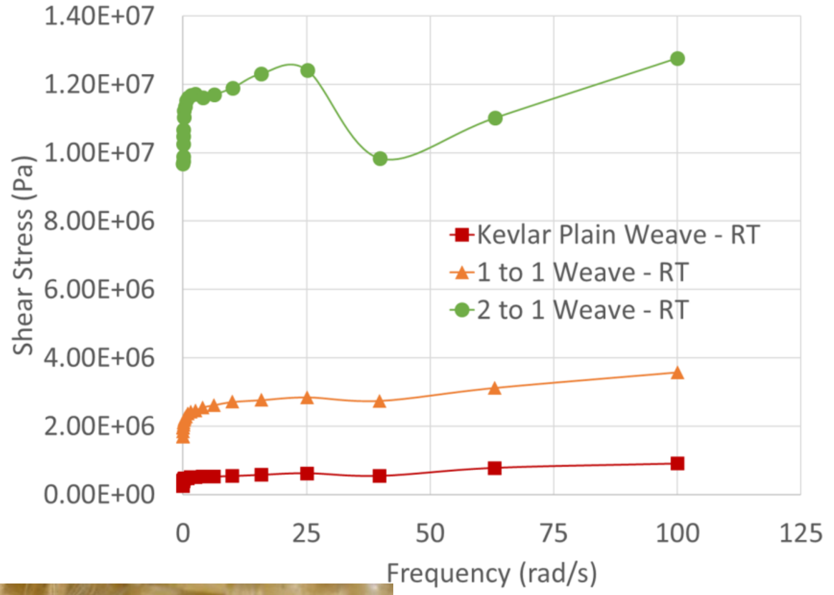


Cubic nanoparticles create stronger hydrodynamic interactions than spherical nanoparticles

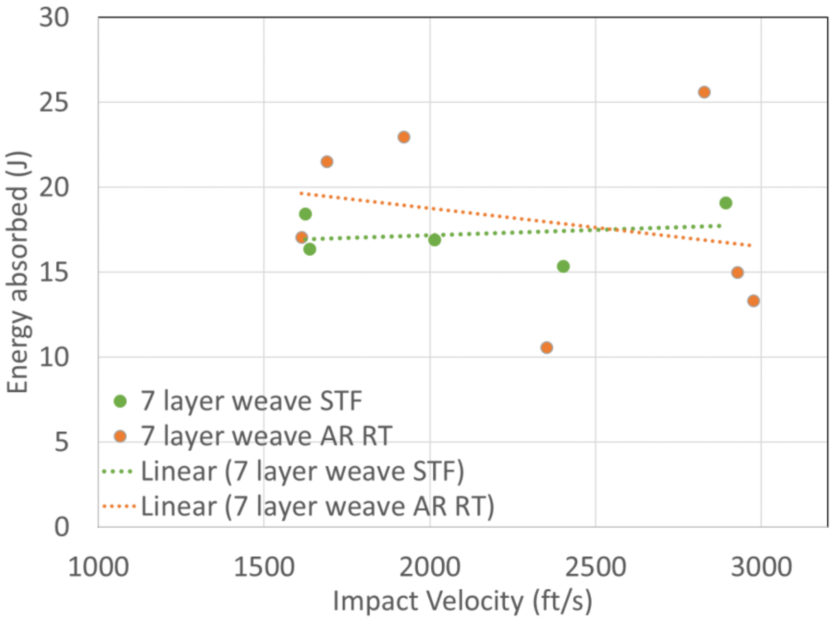
Textiles: Shear Thickening Fluid – Enhanced Fabrics

- Torsional rheology of STF-treated fabrics showed slight increase in shear stress at higher frequencies
- Preliminary results from impact tests did not show improvement in energy absorption in STF-treated fabrics
    - Fabric too concentrated
    - Layup not ideal
    - Mixing/test methods not optimized
- Need better understanding of shear thickening mechanism in STF-treated textiles

Torsional Rheology of STF-treated Fabrics



Impact Testing STF-treated Fabrics



Untreated Weave
Impact velocity: 2350 ft/s
(Back)

STF-treated Weave
Impact velocity: 2401 ft/s
(Back)

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 production
  - Braiding
  - DEA
- Lots of potential to integrate multifunctionality into textiles

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Questions?