

Advanced Materials & Processing Branch
NASA Langley Research Center

Image Credit: NASA

Acknowledgements

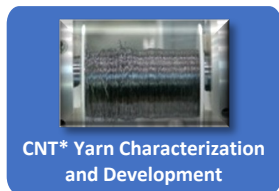
- **Advising Principal Technologist:** Mark Hilburger
– Structures, Materials and Lunar Construction

- **Financial Analysts**

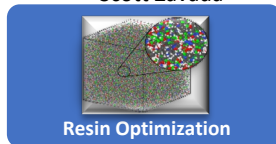
- Jessica Henegar
- Lauren Bonine
- Damon Sheaffer



- Nanocomp Technologies/Huntsman



- Jae-Woo Kim
- John Gardner
- Godfrey Sauti
- Russell Wincheski



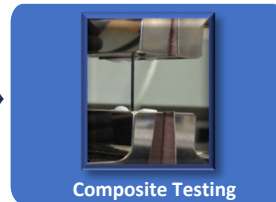
- Joseph Smith
- Scott Zavada



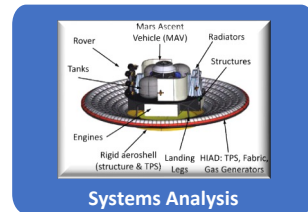
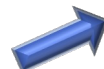
- Jae-Woo Kim
- John Gardner
- Sean Britton
- Godfrey Sauti
- Roberto Cano
- Hoa Luong



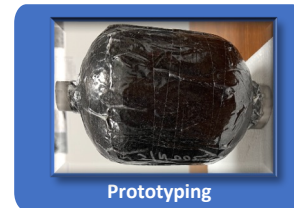
- Benjamin Jensen
- Kristopher Wise
- Jacob Gissinger



- Russell Wincheski
- Jae-Woo Kim
- Godfrey Sauti

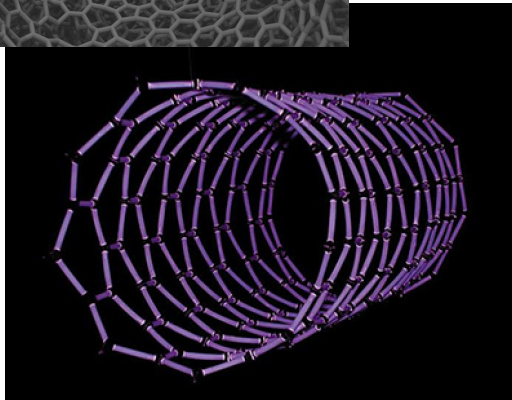
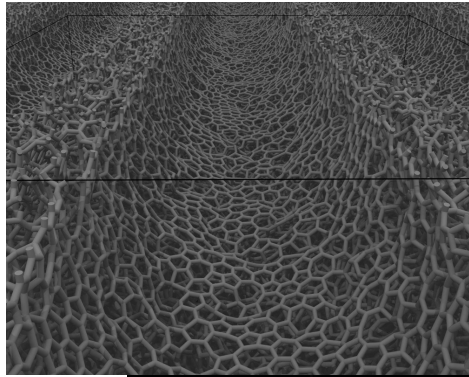


- Jamshid Samareh
- Sasan Armand
- Alex Chin
- Hilmi Alkamhawi

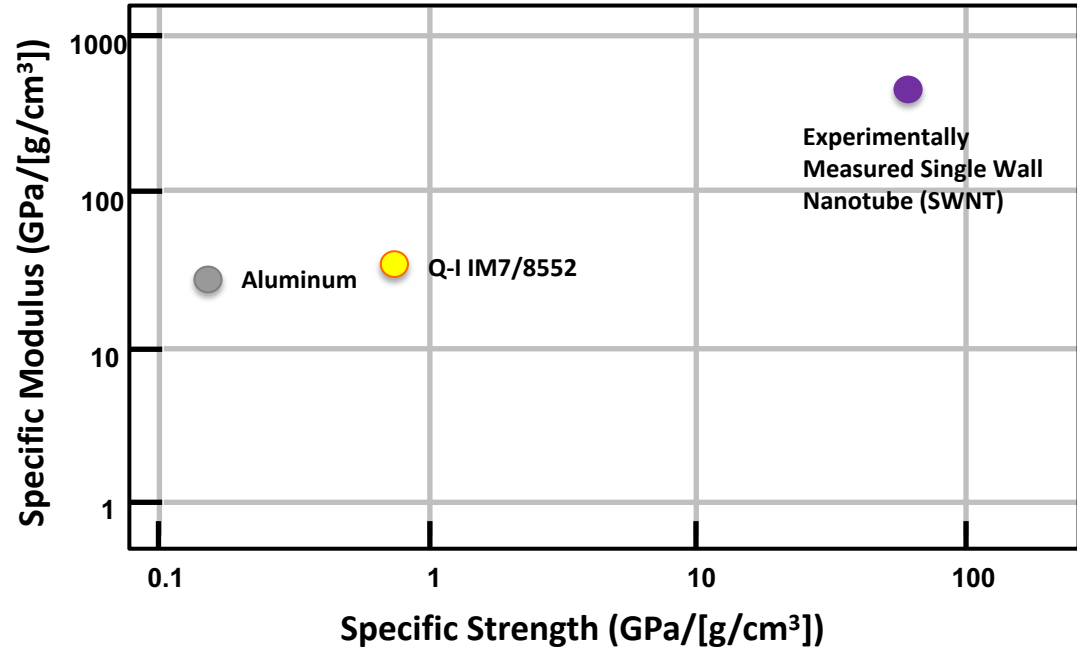


- Godfrey Sauti
- Mia Siochi

Motivation



Carbon Nanotubes



Summary of the Problem

	Mass Ratio*	Cost per pound*
Low Earth Orbit	20	\$4,000
Earth to Moon	200	\$40,000
To Moon, Return to Earth	500	\$100,000
Earth to Mars	500	\$100,000
To Mars, Return to Earth	5000	\$1,000,000

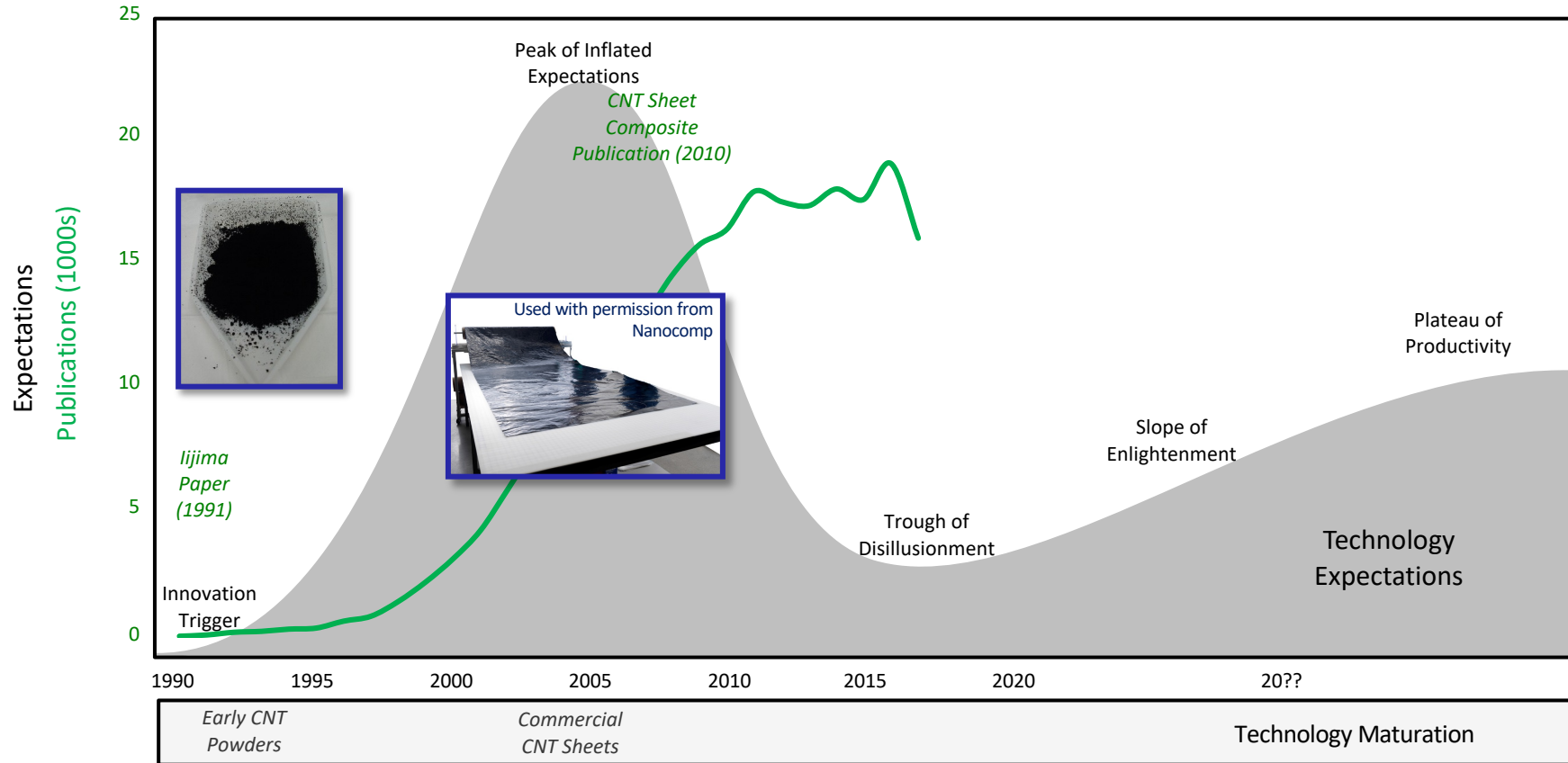
- Cost increases in proportion to the mass ratio.
- Mass ratio increases linearly with the dry mass and exponentially with Δv .
- Costs for exploration escalate beyond low Earth orbit.
- Reducing structural mass reduces mission cost at constant payload or increases mission capability at constant cost.

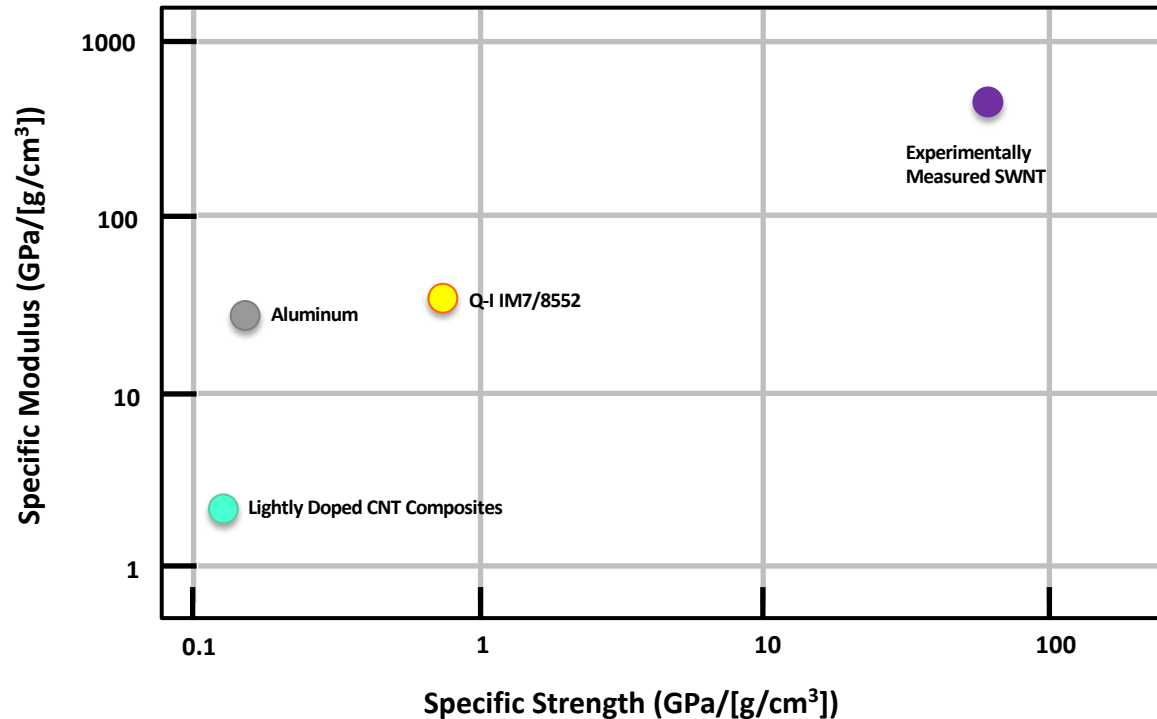


- **Technology Push**
- **Use-Inspired Technology Development**
- **Collaborative Technology Maturation**

- New/Different
- Immature
- Hyped
- Potentially disruptive
- Can spur significant basic research investments

Carbon Nanotube (CNT) Gartner Hype Cycle





Lessons Learned

- Analogous to very short chopped fiber composites
- Limited by material supply and quality
- Very low volume fraction ($< 5\%$)
- Limited improvement over matrix mechanical properties
- Payoffs noted in electrical/multifunctional properties
- Output: Papers, presentations, patents
- Structural applications envisioned did not materialize

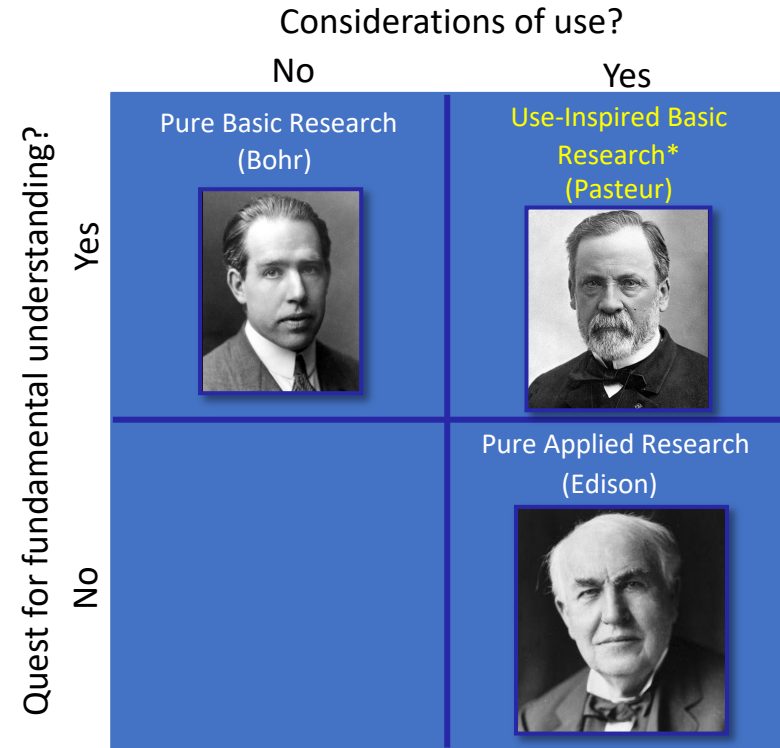


- Technology Push
- **Use-Inspired Technology Development**
- Collaborative Technology Maturation

Use-Inspired Technology Development

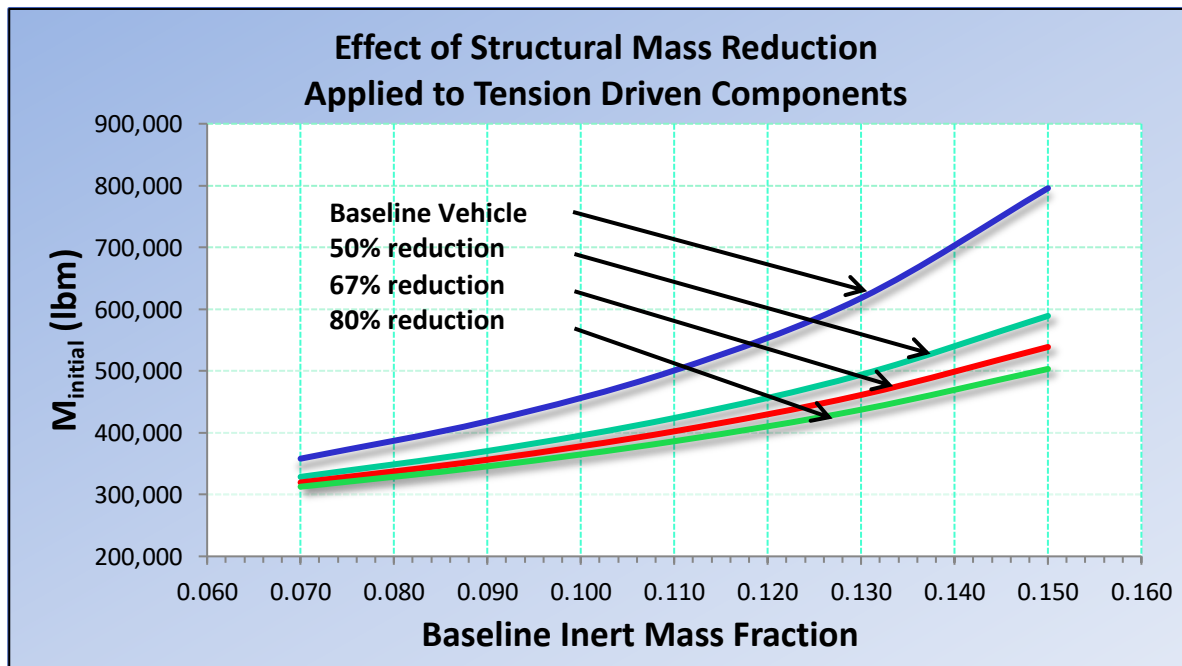


- Use-driven fundamental research
- Considers systems level benefits
- From lab to demonstration



* Stokes, D. L., Pasteur's Quadrant: Basic Science and Technological Innovation, Washington, D. C.: Brookings Institution Press, 1997.
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Setting Goals Using Systems Analysis



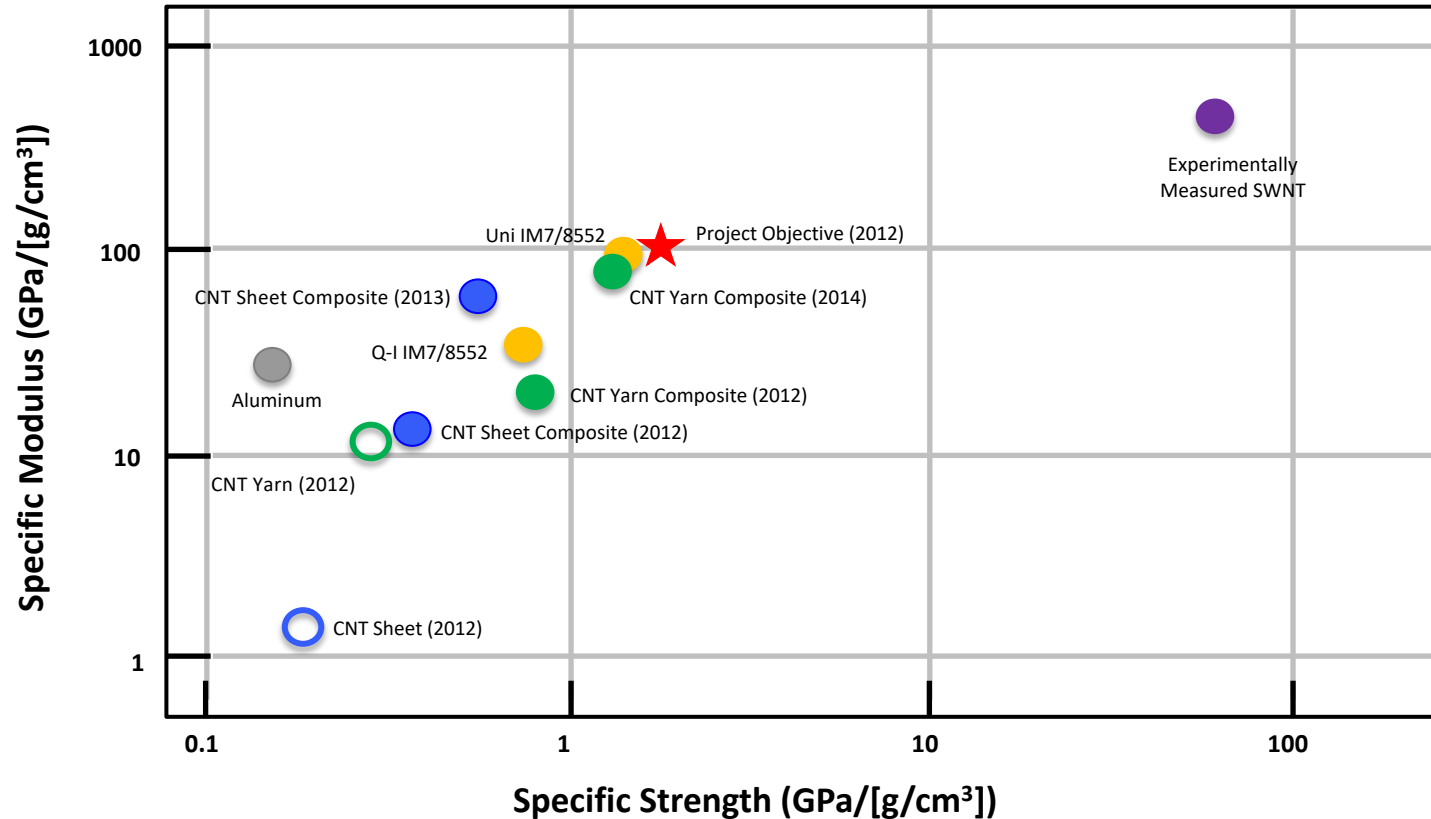
- A 2x to 3x improvement in specific mechanical properties will permit substantial mass reduction in structural and non-structural components.

State-of-the-Art Lightweight Structural Material

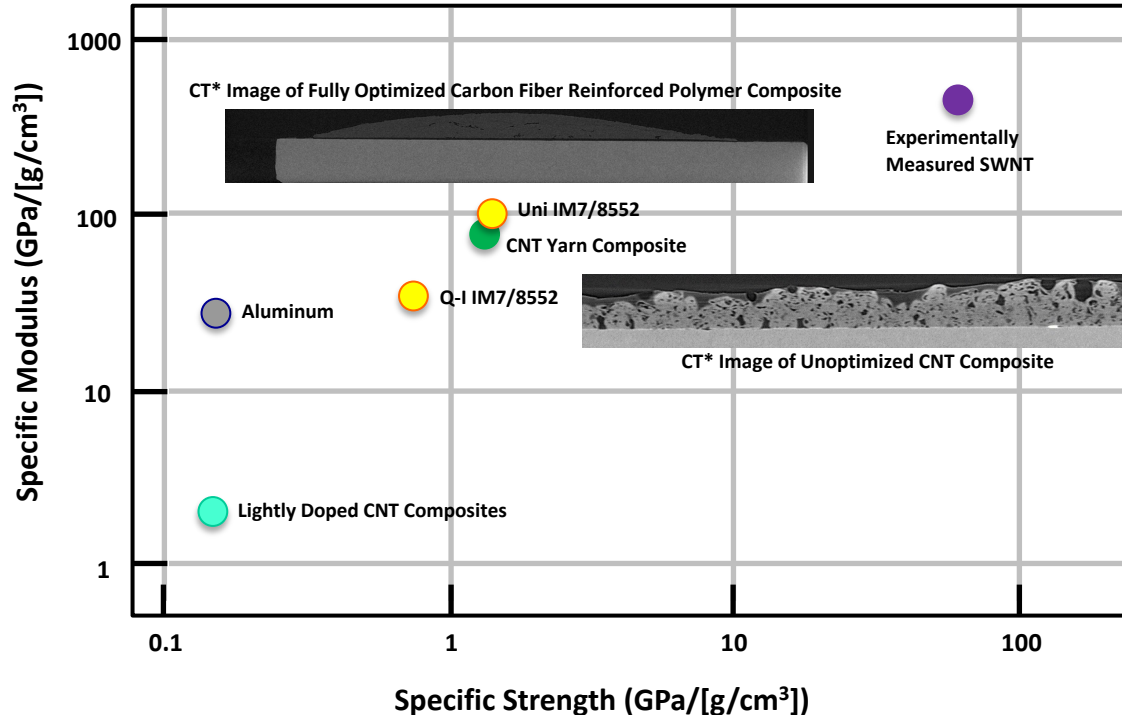


6 ft x 10 ft PETI-5/IM7 Skin Stringer Panel from High Speed Research (HSR) Program

Nano to Macro Challenge



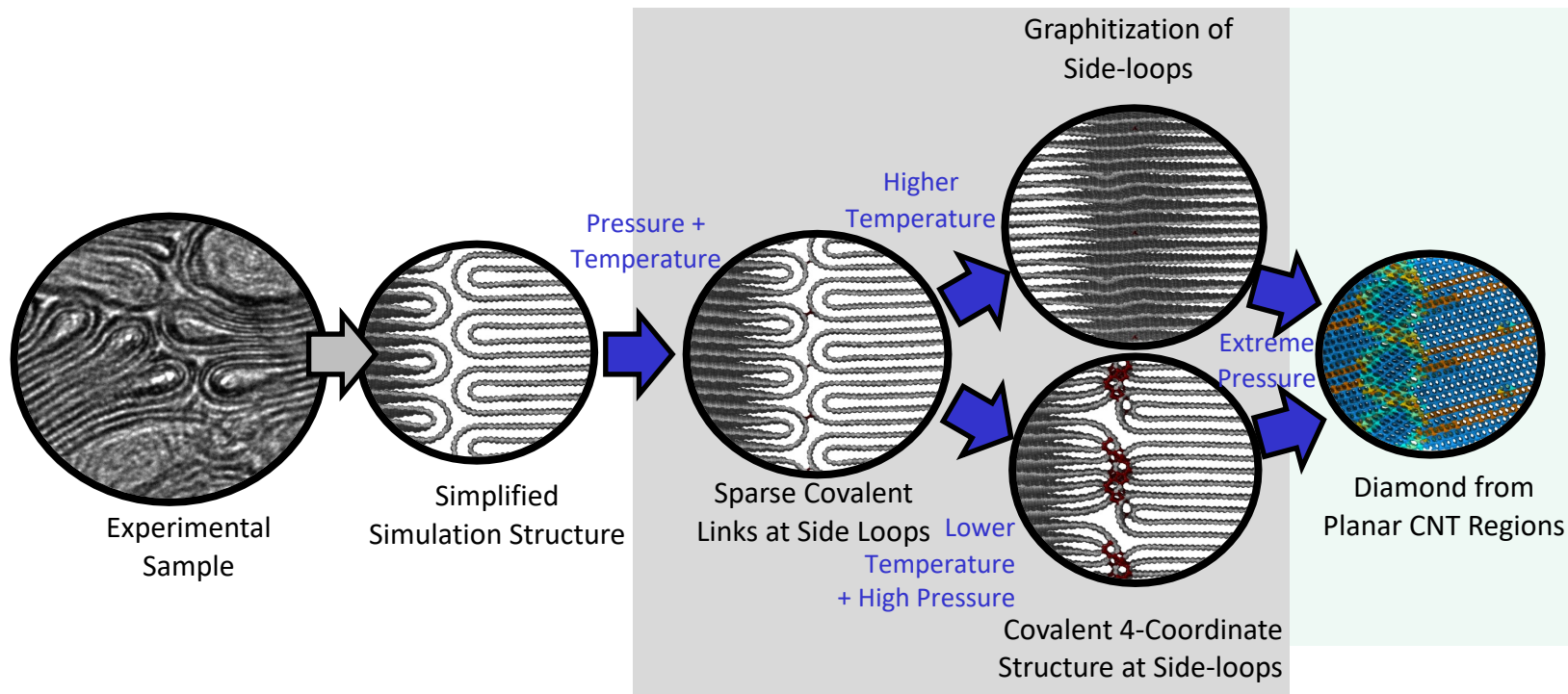
Outcomes for Early CNT Fibers



Measurable Advancements

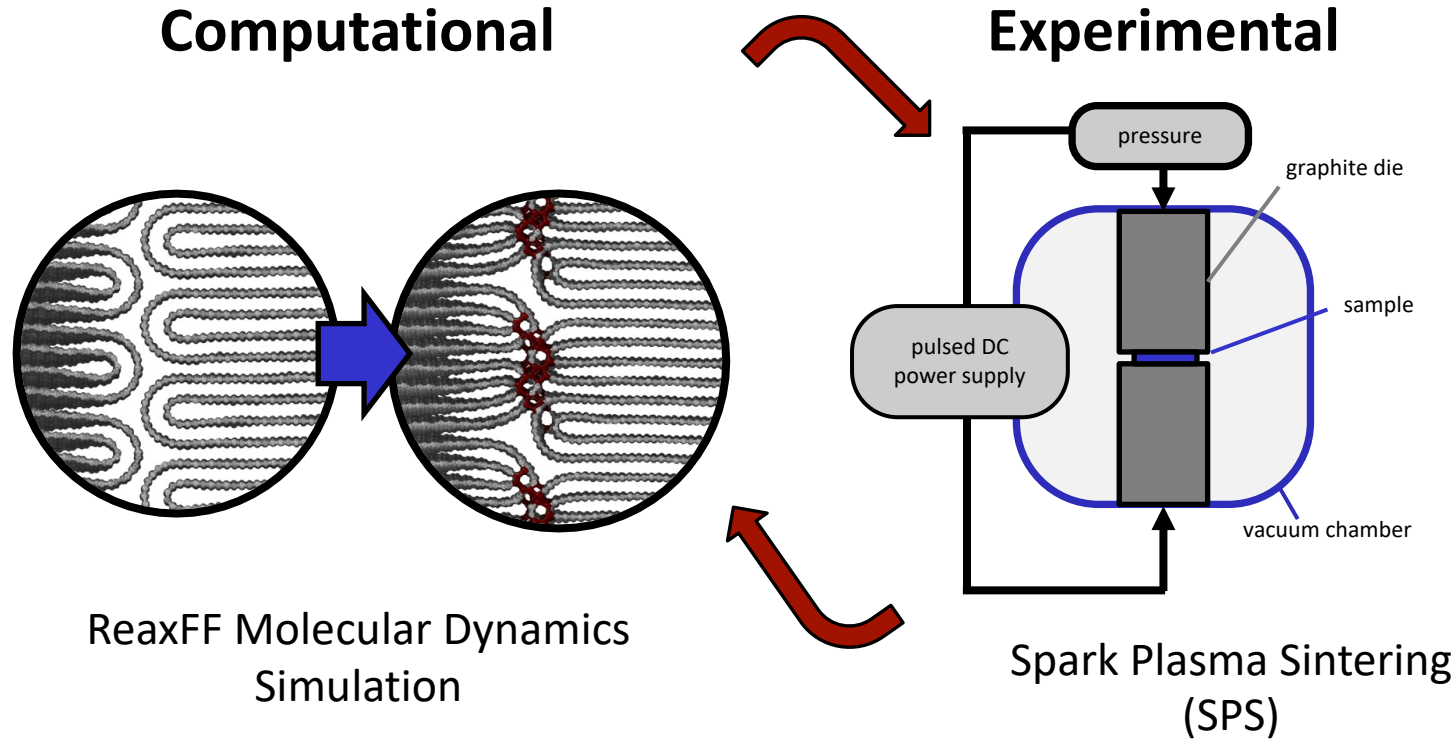
- Improvement in mechanical properties
 - Systems level guided, goal focused research
 - Project objective provided basis for objective decisions
- Increase in Manufacturing Readiness Level
 - Volume – material available in spool lengths of hundreds of meters
 - Consistency – materials met A-basis allowable of at least 20 N breaking force

Computationally Guided Process Development

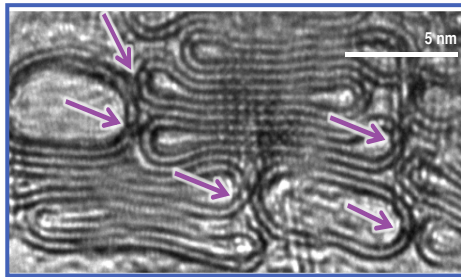
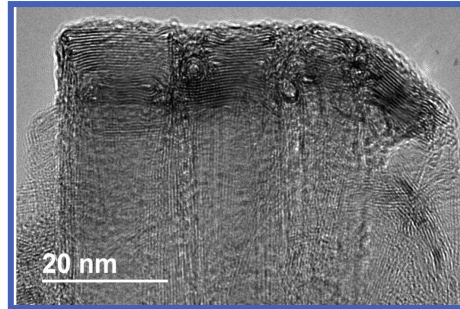


Side-loop to Side-loop Mechanisms

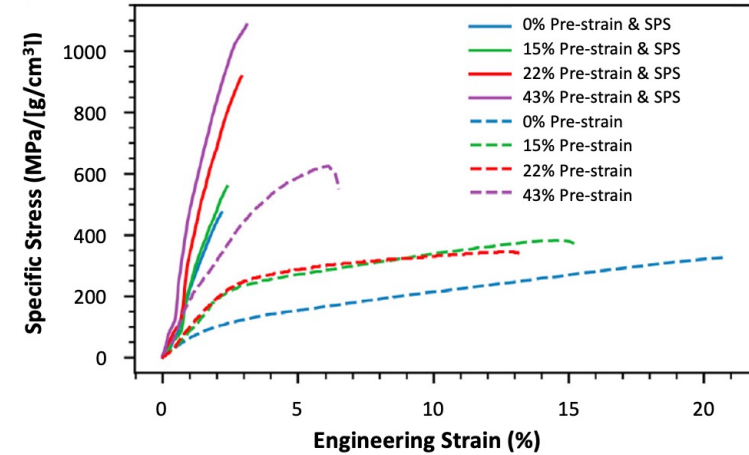
Experimental Validation of Simulation Results



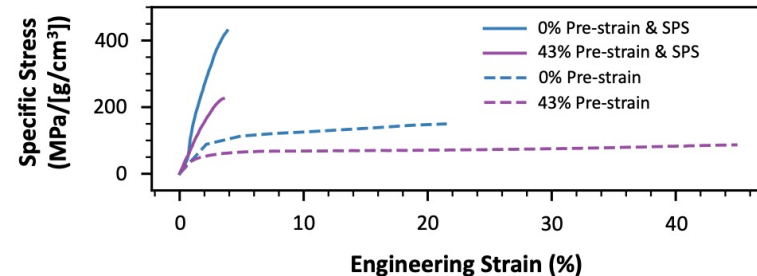
Experimental Validation of Simulation Results



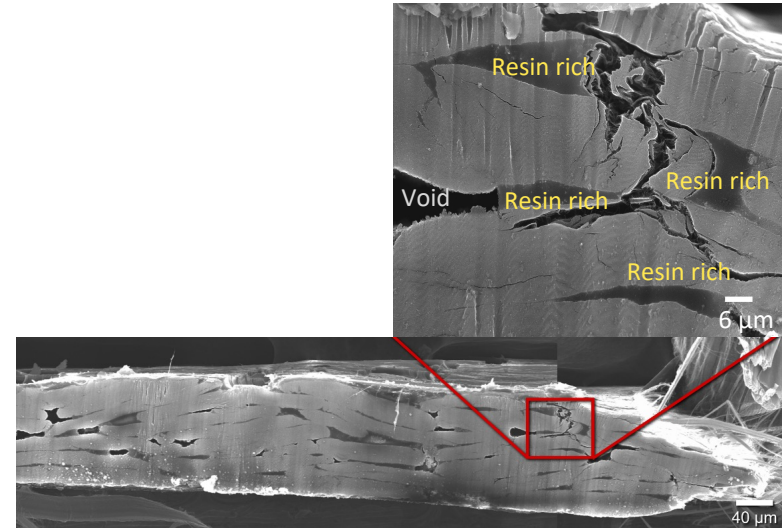
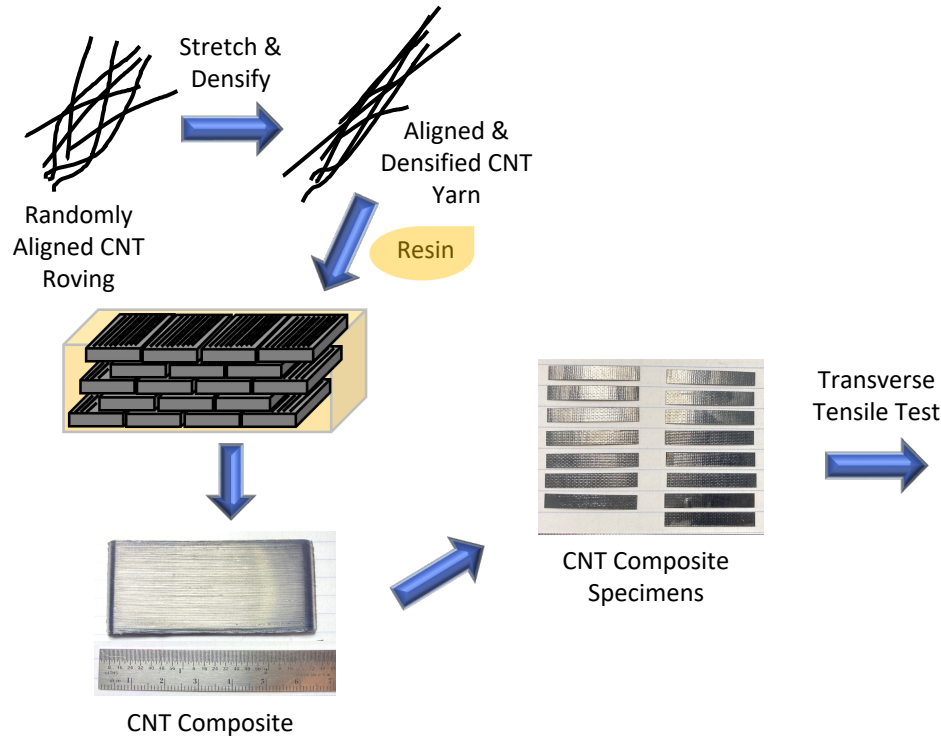
Axial Response



Transverse Response



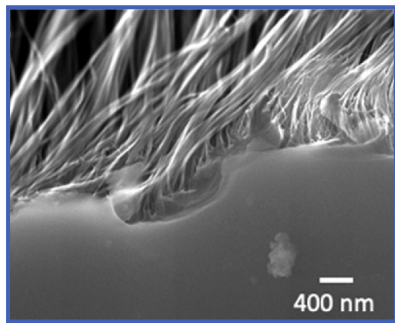
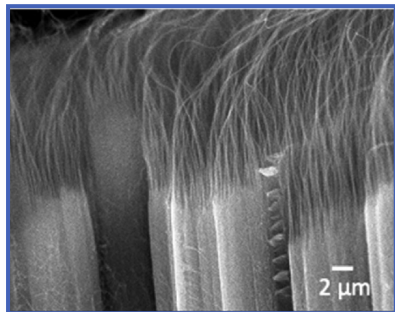
Transverse Mechanical Performance



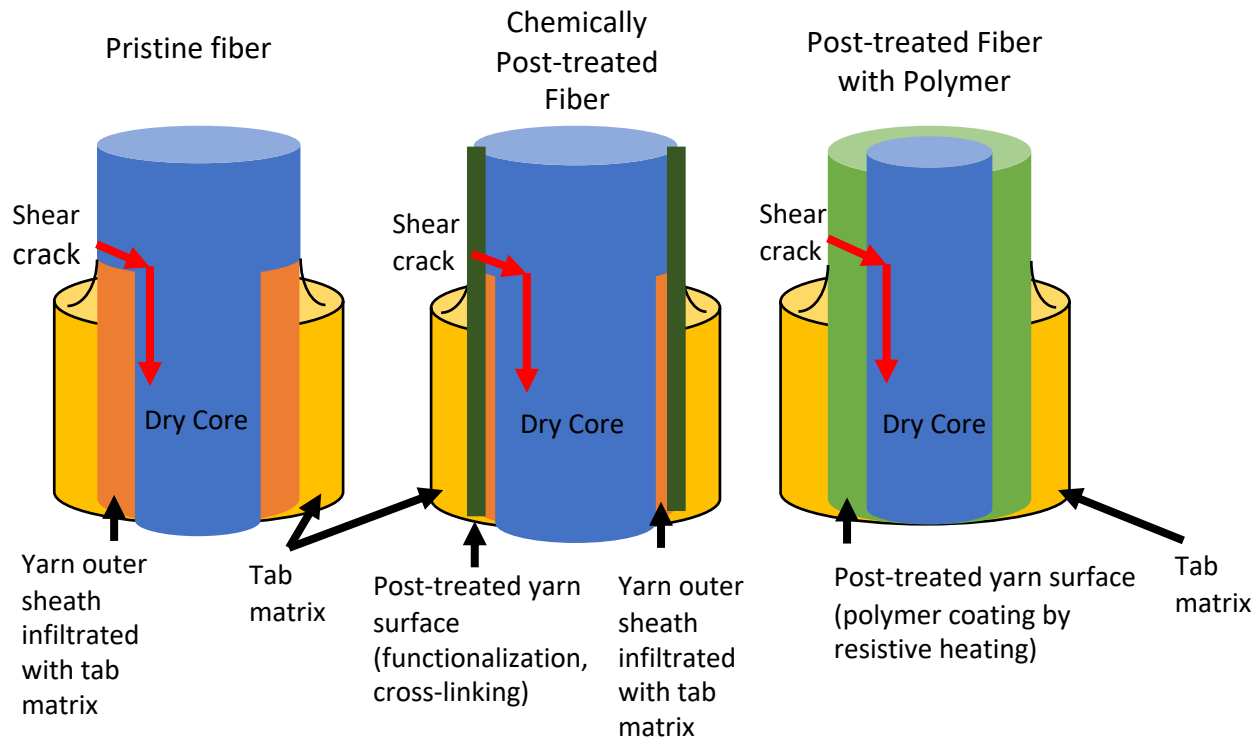
← Applied Strain →

Failure Mode of Unidirectional
CNT Yarn Composite

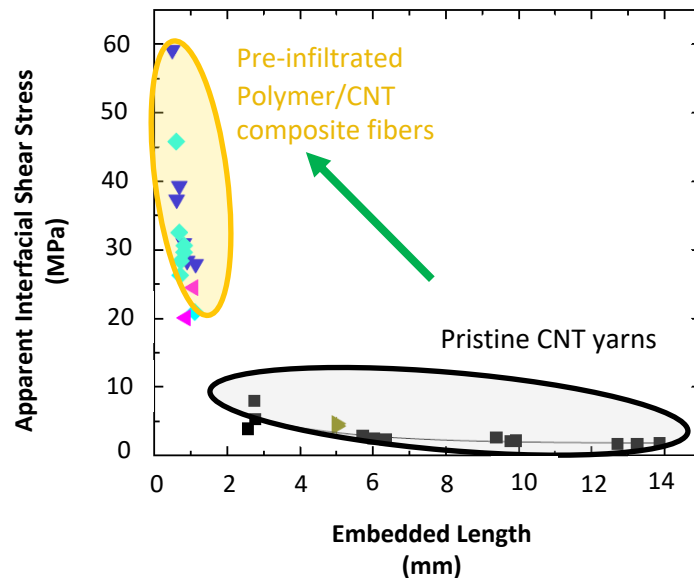
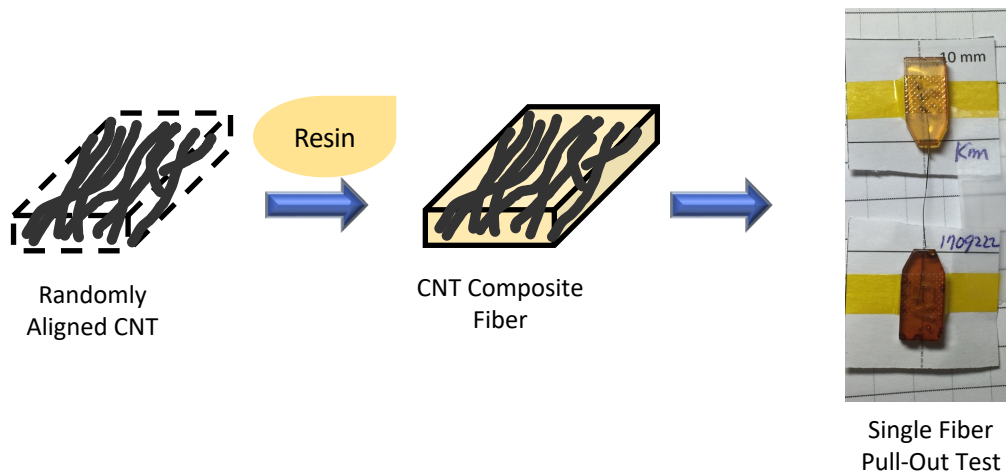
Challenge: Poor CNT Yarn/Resin Interface



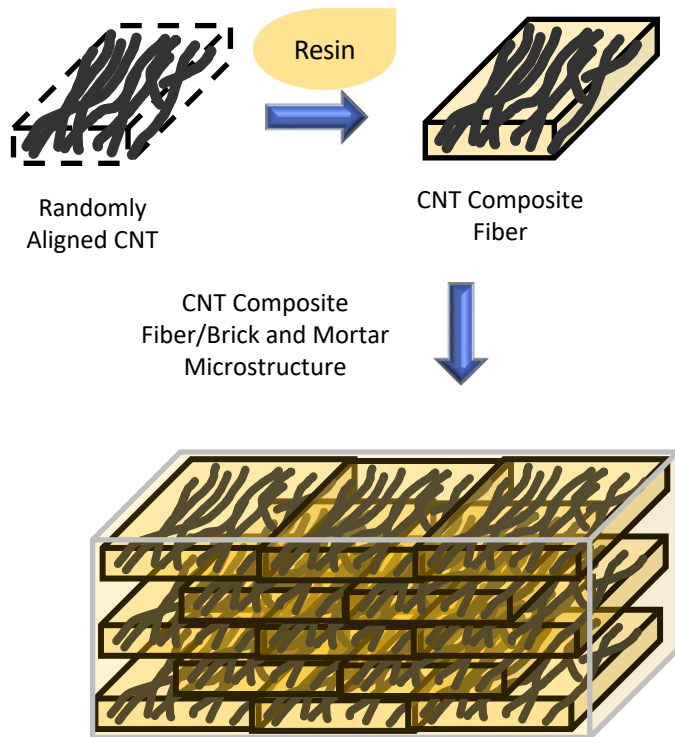
Representative Failure Surfaces



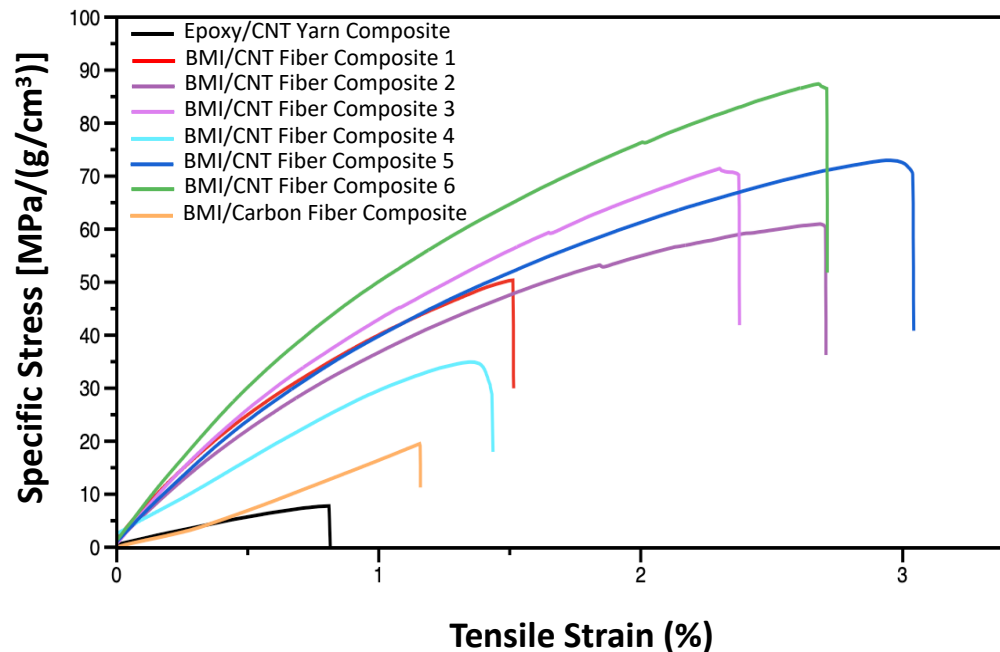
Improving Resin Infiltration



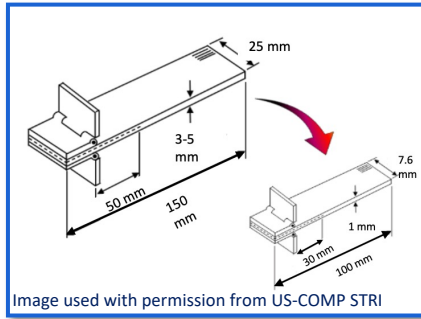
Multiscale Hierarchical CNT Composite Fabrication



Transverse Tensile Test Results



CNT Composite Fracture Toughness

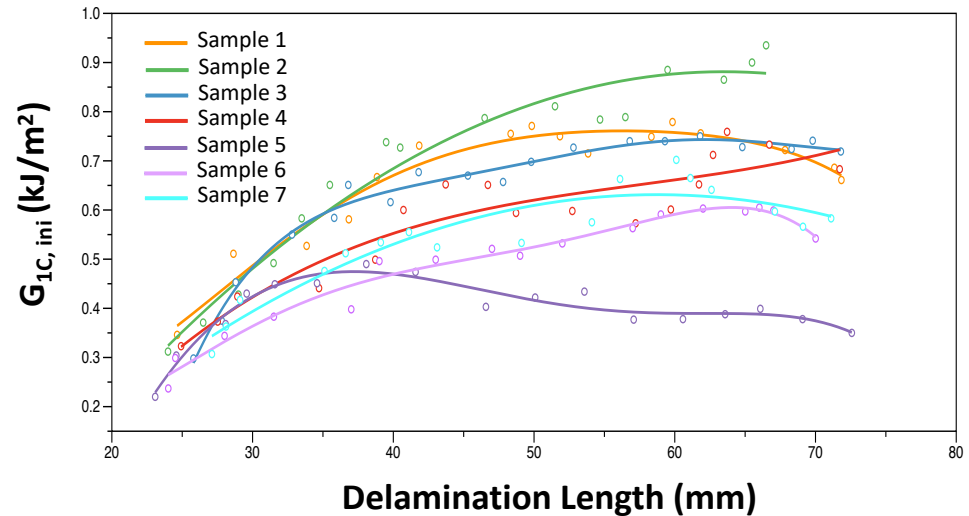


Based on ASTM D5528
Double Cantilever Beam (DCB) Test



CNT Composite DCB Samples

Fracture Toughness Data



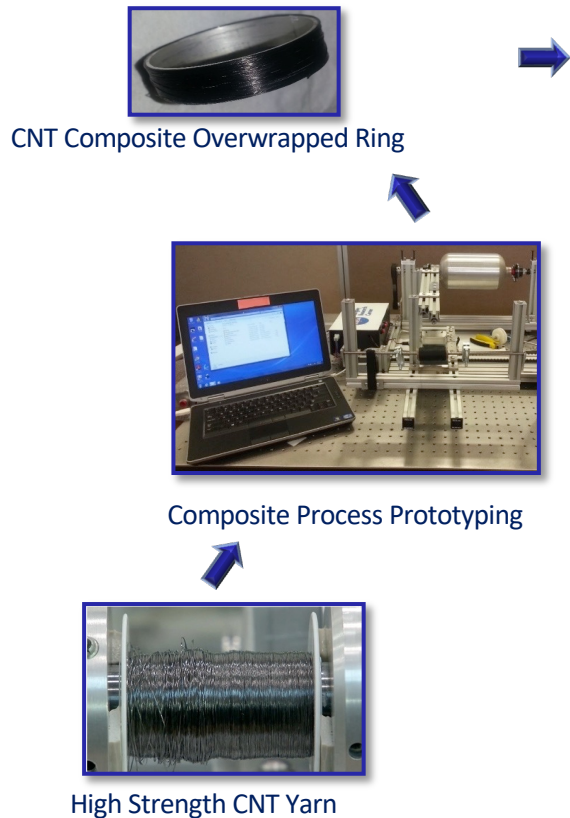


- Technology Push
- Use-Inspired Technology Push
- **Collaborative Technology Maturation**

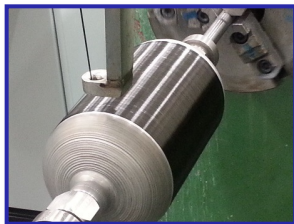
- Displacement of state-of-the-art technologies
 - Performance
 - Scale
 - Schedule
 - Risk
 - Cost

- Decision making for prioritization
 - Systems benefits analysis
 - Clear, quantified metrics for goals

Prototyping to Support Materials Development

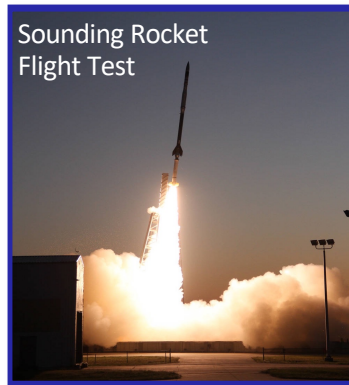


Commercial Scale CNT Composite Winding



CNT Composite Overwrapped Pressure Vessel Cold Gas Thruster

Sounding Rocket Flight Test



Sounding Rocket Integration

Systems Defined Goal Provides Common Objective



NASA Centers

- LaRC
- MSFC

Public/Private Partnerships

- Northrup Grumman
- University of Dayton Research Institute/State of Ohio

OGA Leveraging

- AFOSR
- AFRL – ManTech Program
- DoD
- DoE - ARPA-E
- DoE – Idaho National Lab
- DoE – Oak Ridge National Lab

Small Business

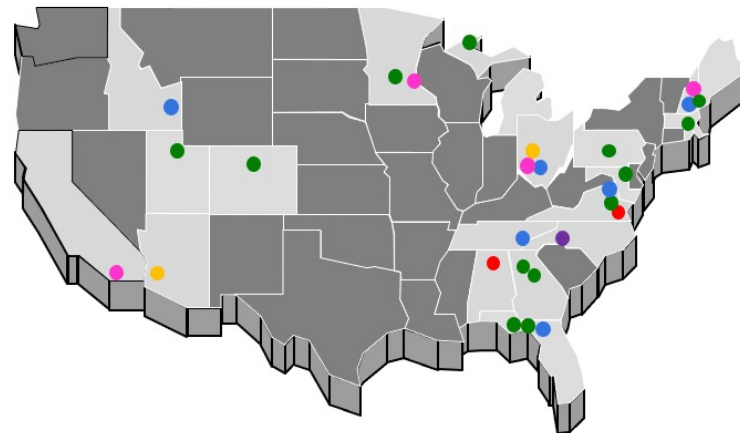
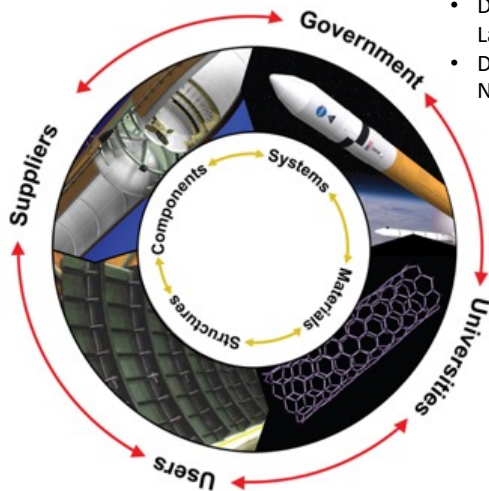
- Textum, Inc.

SBIR/STTR

- Nanocomp
- Cornerstone Research Group
- Minnesota Wire & Cable
- Applied Composites

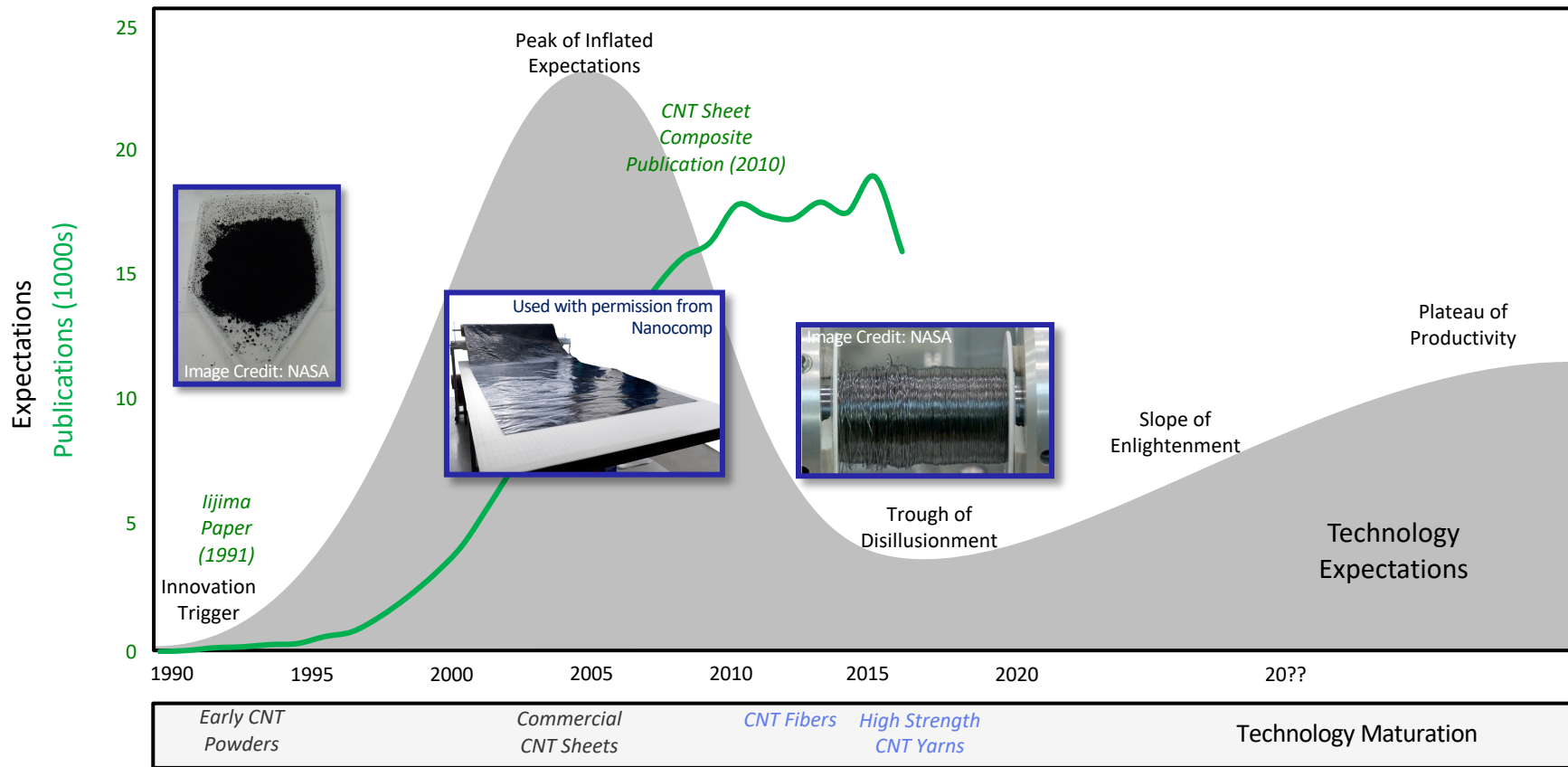
STRI

- Florida State U
- MIT
- VCU
- Ga Tech
- Penn State U
- FL A&M U
- Solvay
- Michigan Tech
- U of Utah
- U of Colorado
- Johns Hopkins
- U of Minnesota
- Nanocomp



Incentivize multidisciplinary partnerships to accelerate maturation of an emerging material ecosystem.

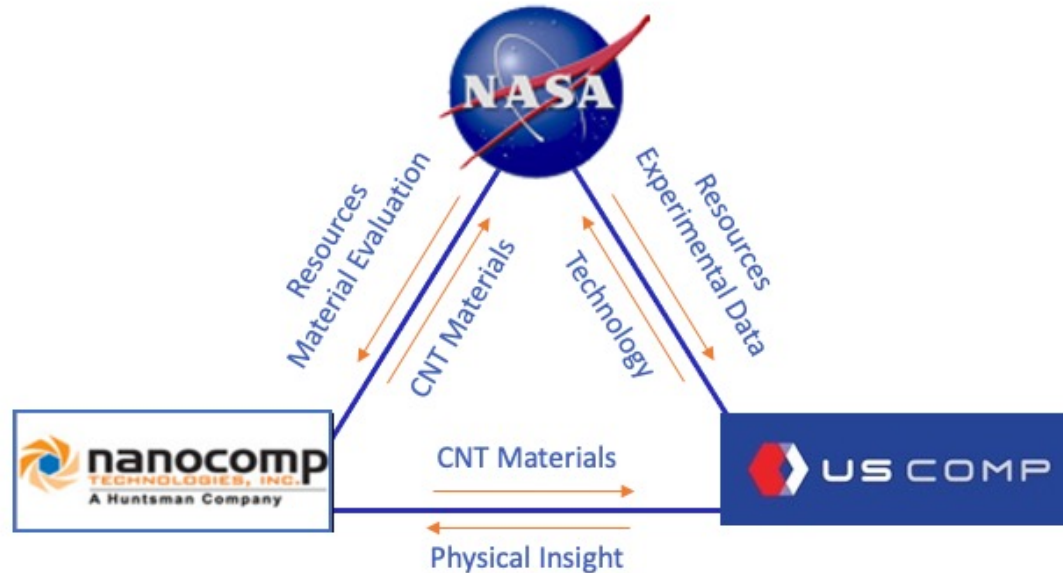
Use Driven Technology Maturation



- Advances in structural CNT development
 - CNT material is available in formats and quantities that permit their evaluation as structural materials.
 - CNT composite mechanical properties presented included axial tensile, transverse tensile, and fracture toughness.
 - CNT microstructure is different from carbon fiber.
 - Hierarchical structures in CNTs present resin infiltration challenges that require a different approach for composite fabrication.
 - CNT/matrix interface needs to be improved for further enhancements in mechanical properties.
 - Modeling guided CNT composite processing helps to accelerate optimization of CNT composite fabrication method.

- Accelerating the technology maturation of emerging technologies requires coordinated efforts.
 - Defining the problem is critical to accelerated technology maturation.
 - Rallies entire team around a common goal
 - Allows setting metrics to measure progress
 - Supports experimental design targeted to answering relevant questions
 - Provides data-driven decision making
 - Teaming across the ecosystem is important.
 - Engages willing early adopters
 - Exposes key barriers to adoption
 - Filters set of potential solutions
 - Supports most effective deployment of talent resources
- Objective measures of success are crucial.
 - Provides reality check
 - Supports decision making

Summary – Role of NASA



NASA mission needs serve as technology pull to guide accelerated maturation of emerging technologies.



Technology pull can guide accelerated maturation of emerging technologies.