Image Credit: NASA

# Superlightweight Aerospace Composites

## *Technology Maturation of Structural Carbon Nanotubes*

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# Acknowledgements

- Financial Analysts
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  - Lauren Bonine
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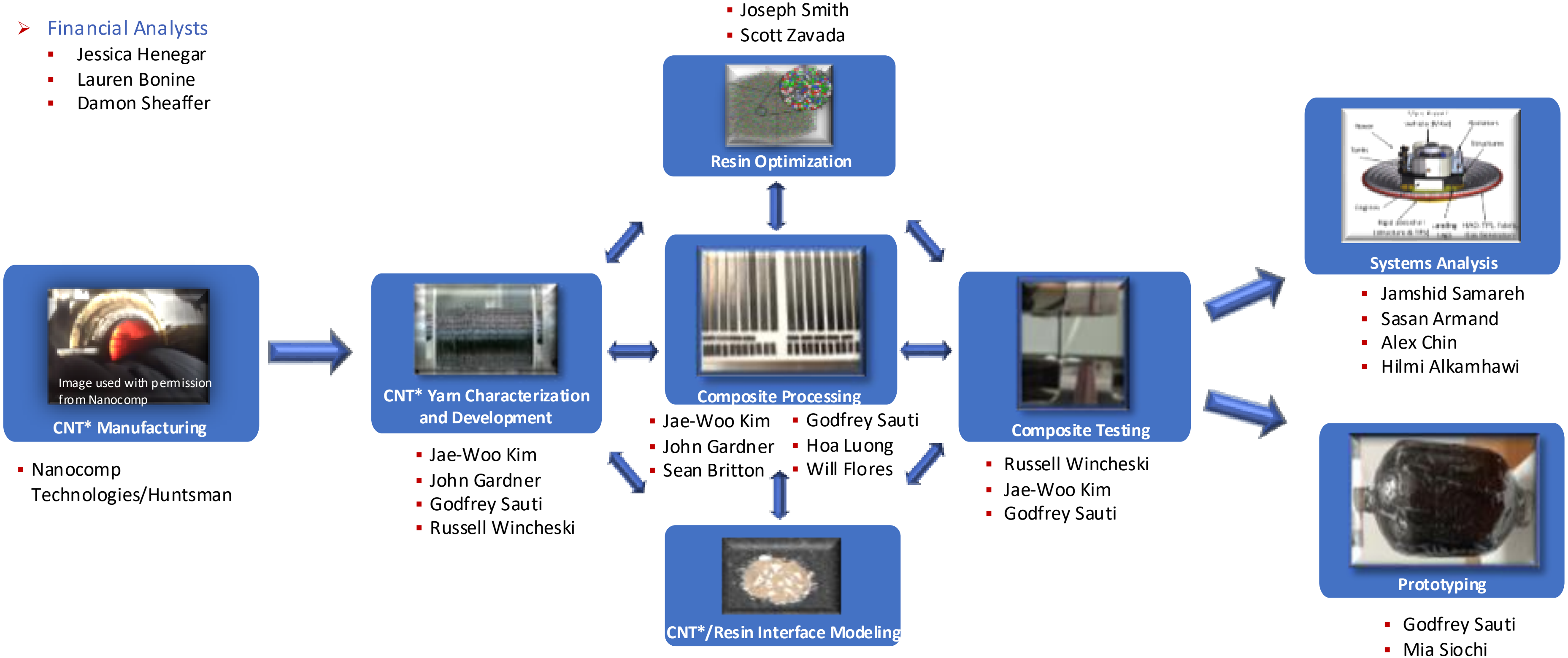


**CNT* Manufacturing**

Image used with permission from Nanocomp

- Nanocomp Technologies/Huntsman

**CNT* Yarn Characterization and Development**

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

**Resin Optimization**

- Joseph Smith
- Scott Zavada

**Composite Processing**

- Jae-Woo Kim
- John Gardner
- Sean Britton
- Godfrey Sauti
- Hoa Luong
- Will Flores

**CNT*/Resin Interface Modeling**

- Benjamin Jensen
- Kristopher Wise
- Jacob Gissinger

**Composite Testing**

- Russell Wincheski
- Jae-Woo Kim
- Godfrey Sauti

**Systems Analysis**

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

**Prototyping**

- Godfrey Sauti
- Mia Siochi

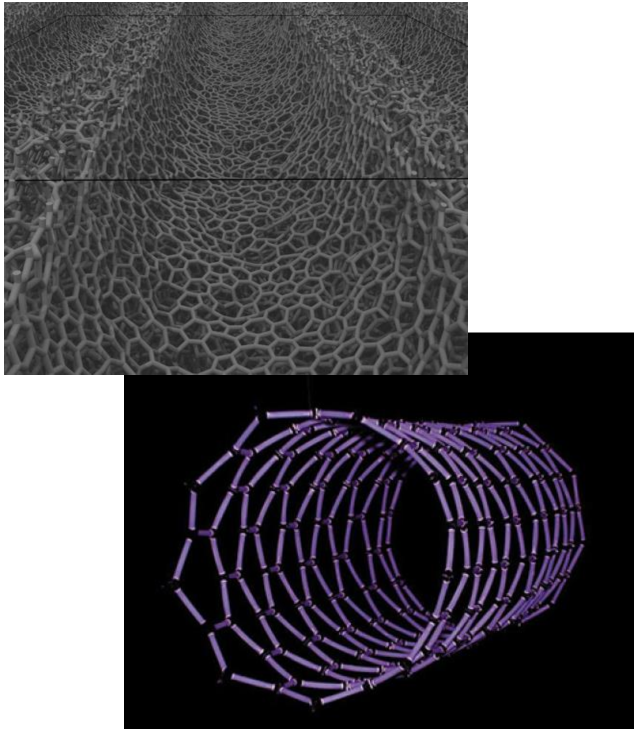
*CNT – Carbon Nanotube

Image credits: NASA

# Outline

- Background
    - Carbon Nanotubes
    - Previous Nanotechnology Project
- Superlightweight Aerospace Composite Project
    - Manufacturing
    - Composite Mechanical Properties
        - Computational Modeling
        - Composite Processing
        - Mechanical Properties
- Technology Transitions
    - Systems Modeling
    - Prototyping
- Summary

# Motivation


Carbon Nanotubes

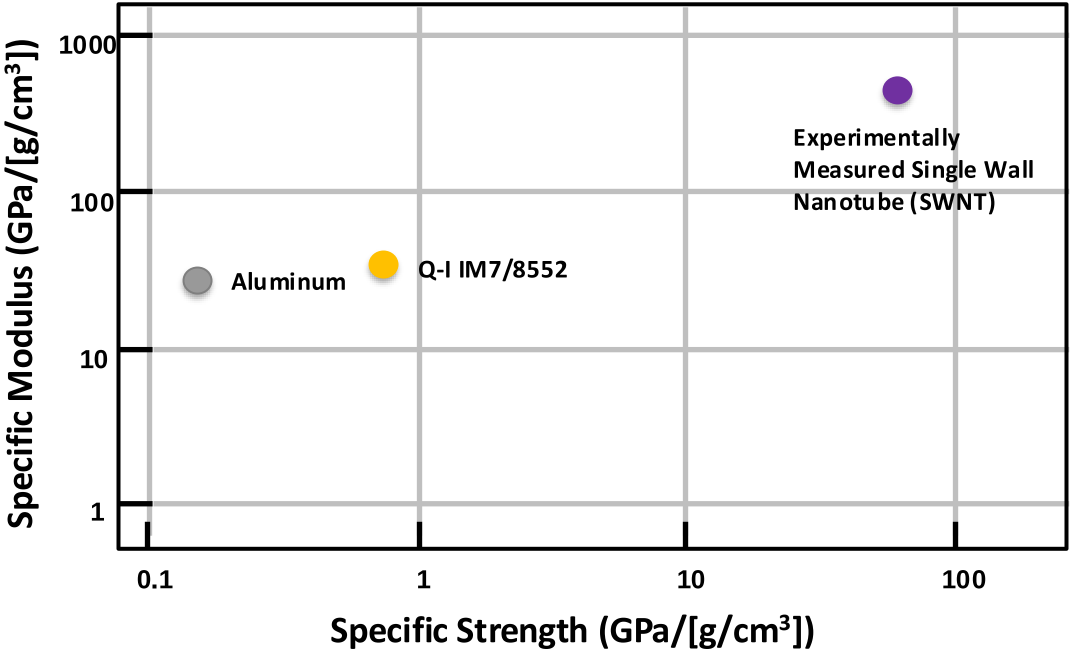


Image credits: NASA

Harris, C. E. et al., NASA TM 211664, 2002.

# Motivation

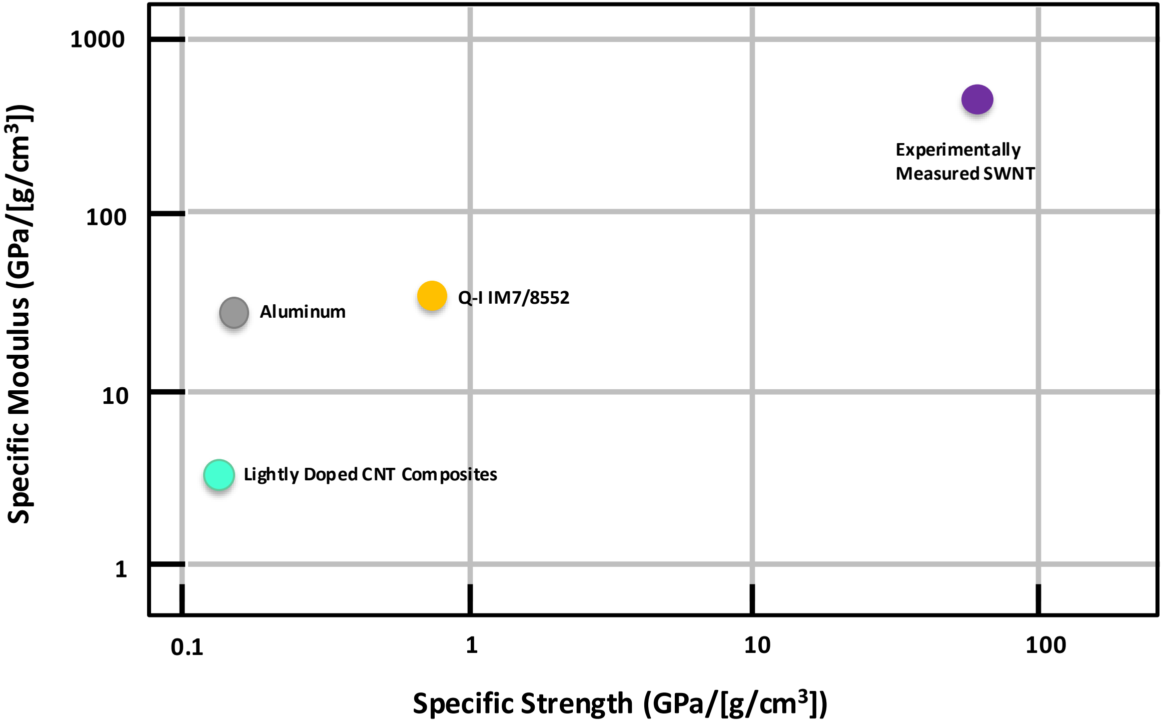
## Summary of the Problem

| | 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 $\Delta\upsilon$.
- Costs for exploration escalate beyond low Earth orbit.
- Reducing structural mass reduces mission cost at constant payload or increases mission capability at constant cost.

*Gordon, G. D., AIAA SPACE 2007, paper 6278.

# Early Outcomes



● Representative data point from Siochi, E. J. et al., *MRS Bulletin*, **40**, 829-835, 2015.

# Carbon Nanotubes on Juno Spacecraft

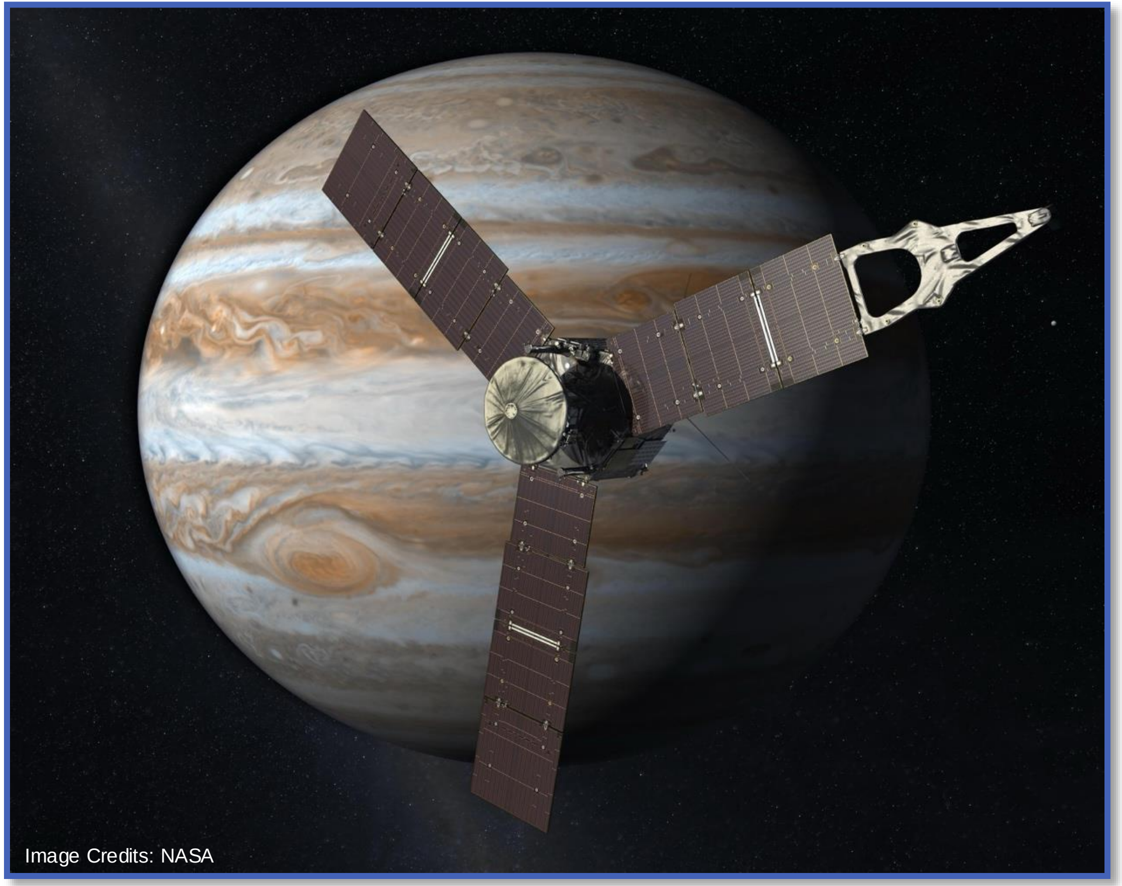
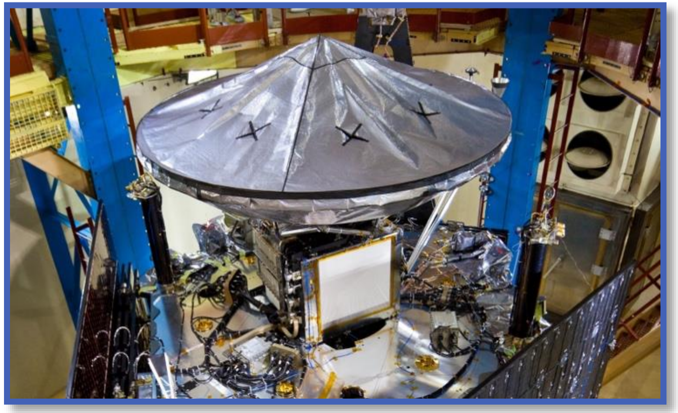


Image Credits: NASA



Composites and carbon nanotubes were implemented in four components on the Juno spacecraft: the rocket engine tubes, the engine cover and the outside and inside face sheets.

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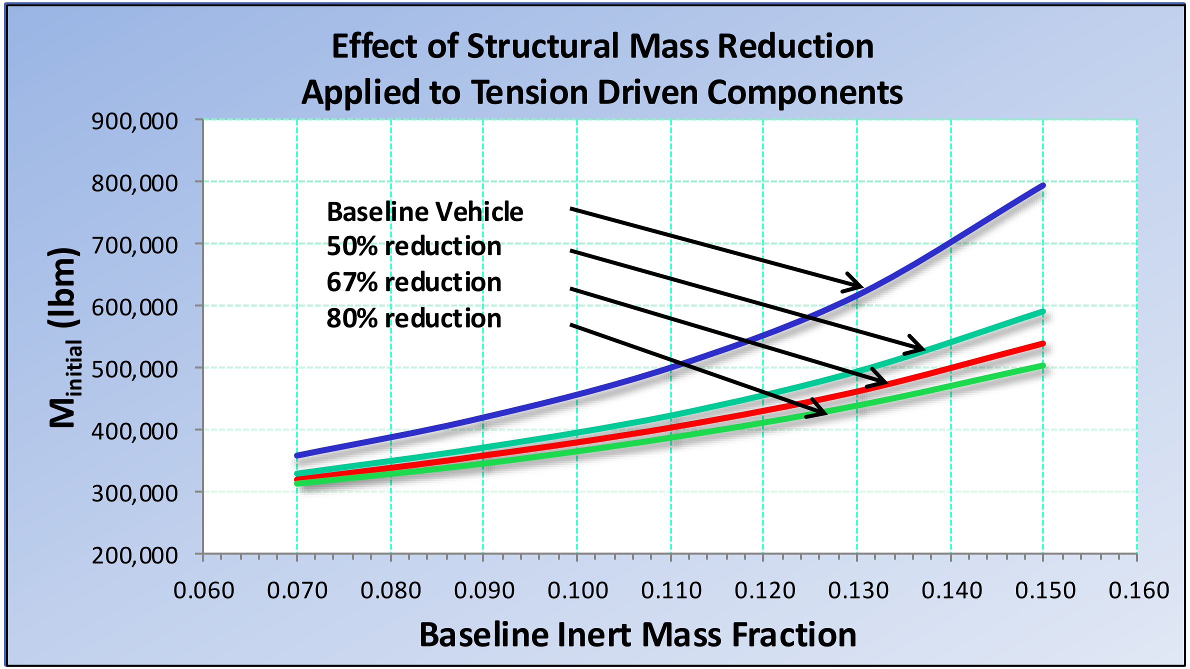
  - Summary

# 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.

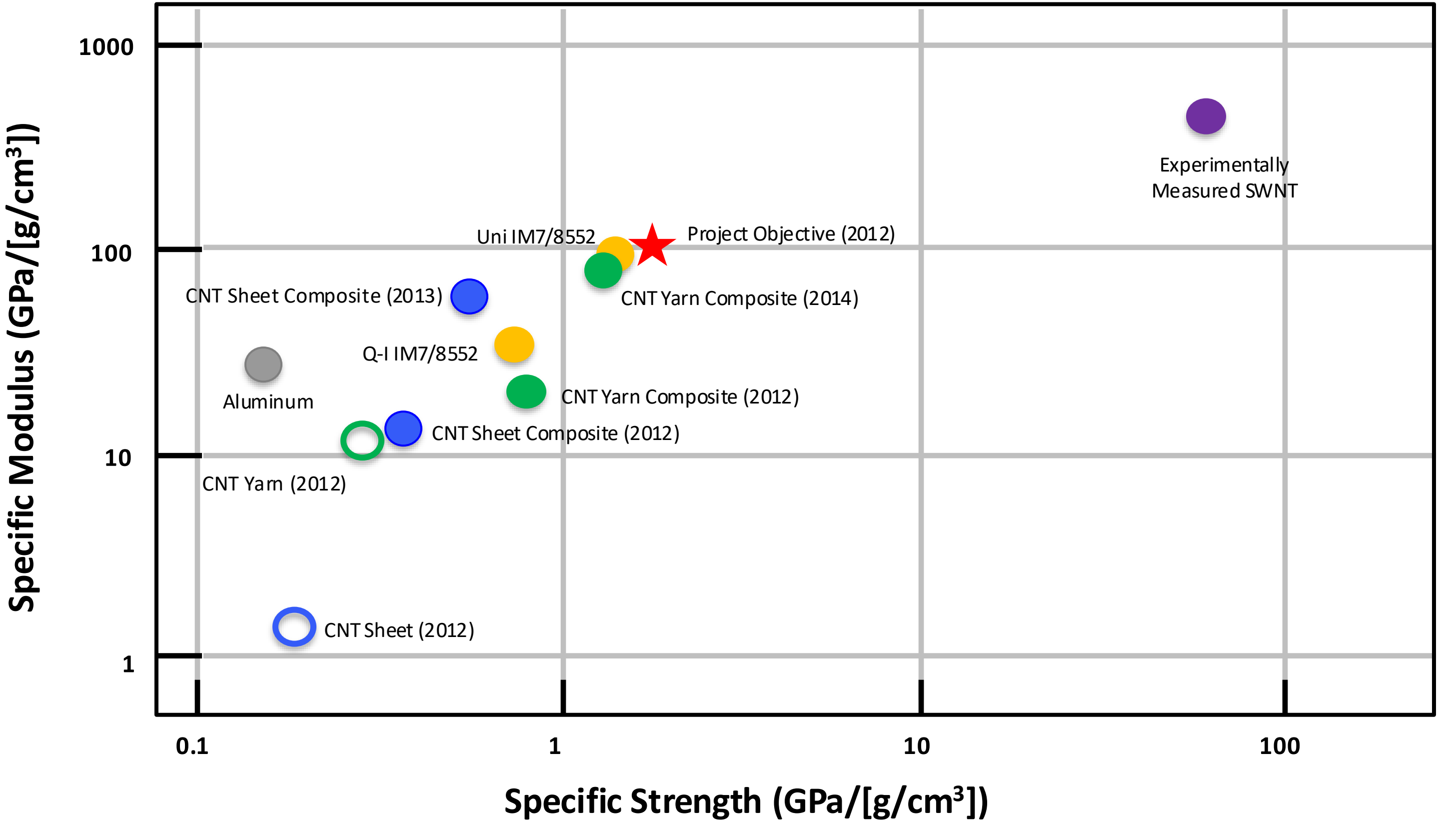
McMillan, M., White Paper, March, 2013.

# State-of-the-Art Lightweight Structural Material

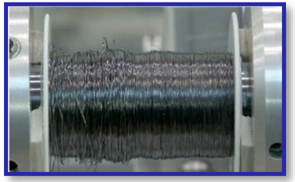

Image Credit: NASA

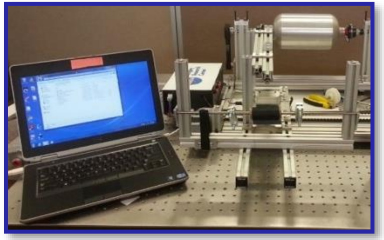
6 ft x 10 ft PETI-5/IM7 Skin Stringer Panel from High-Speed Research (HSR) Program

# Nano to Macro Challenge



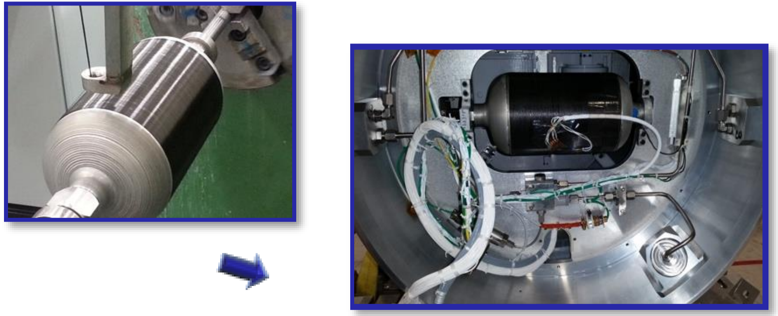
# Prototyping to Support Materials Development


High Strength CNT Yarn


Composite Process Prototyping


CNT Composite Overwrapped Ring

Commercial Scale CNT Composite Winding

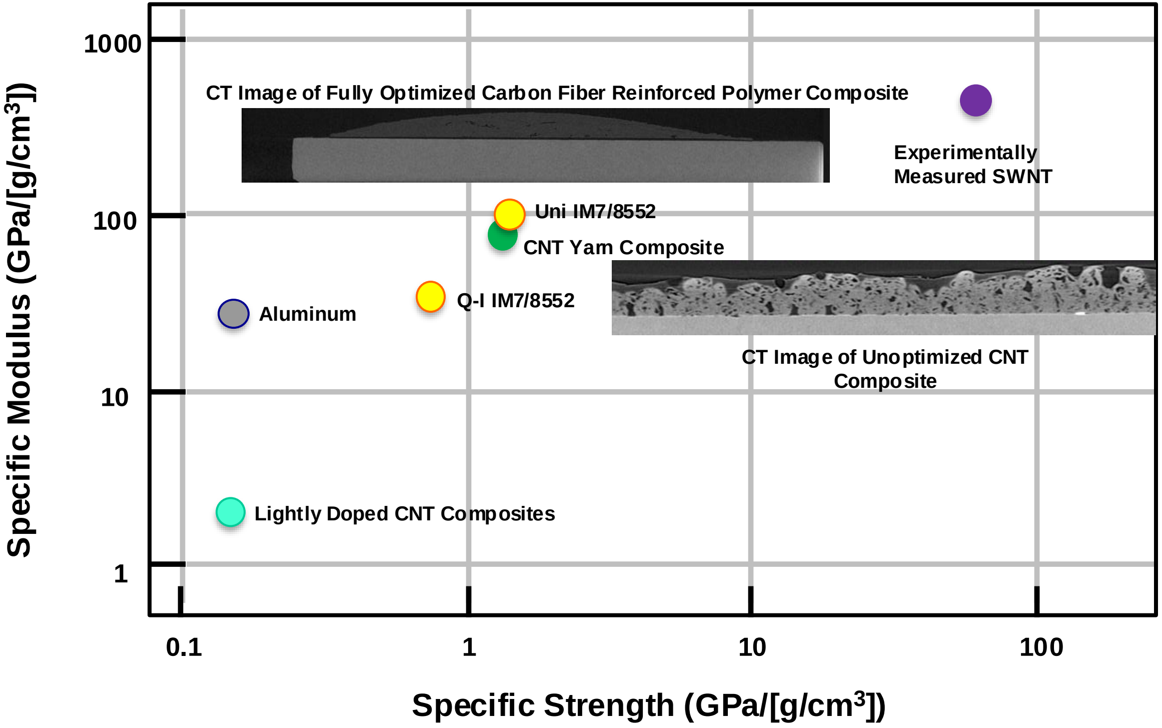


CNT Composite Overwrapped Pressure
Vessel Cold Gas Thruster


Sounding Rocket Integration


Sounding Rocket
Flight Test

Image Credit: NASA

# Outcomes from Nanotechnology Project - 2015



**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.

Image Credit: NASA

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# Large Scale CNT Yarn Manufacturing

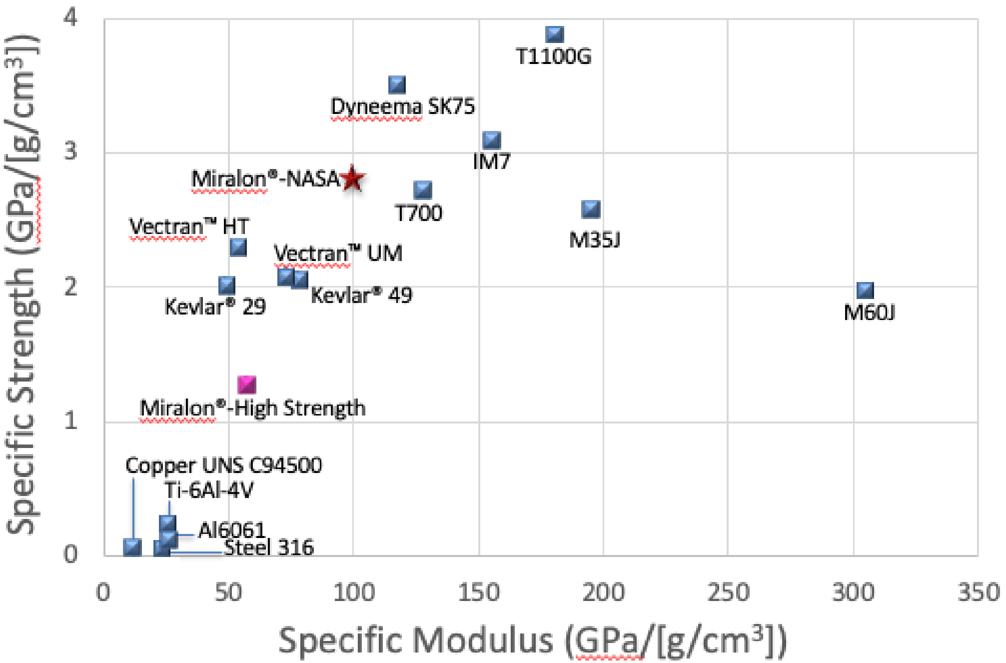


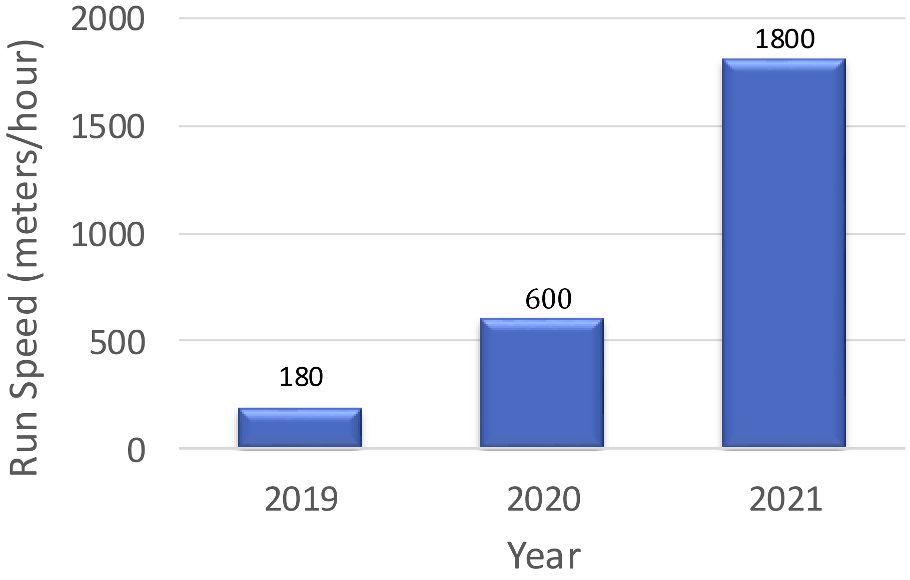
Image used with permission from Nanocomp

Image used with permission from Nanocomp

**Large scale manufacturing of high strength yarn enables technology infusion.**

# CNT Yarn Manufacturing Rate


Image used with permission from Nanocomp



**Manufacturing rate increased by 10x with larger scale reactor.**

# Large Scale Low Iron CNT Yarn Manufacturing

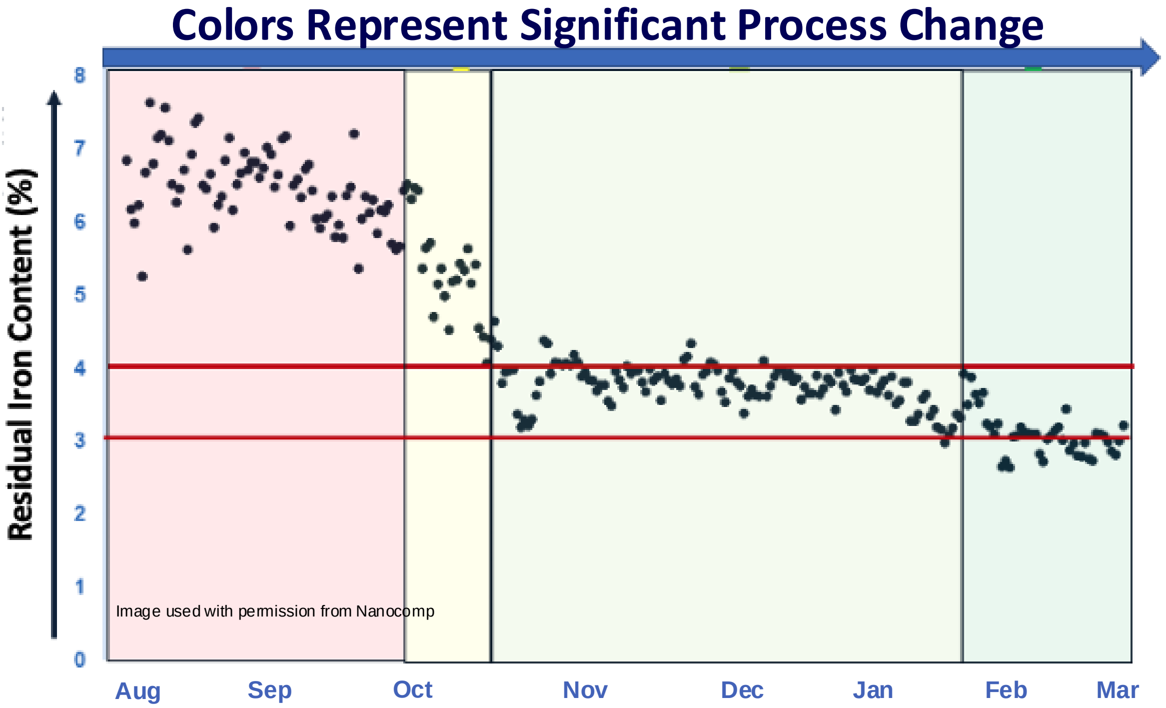


Image used with permission from Nanocomp

- Significant process changes enabled significant reduction in residual iron content in CNT yarns.

**Lower iron-containing high strength yarn broadens technology infusion potential.**

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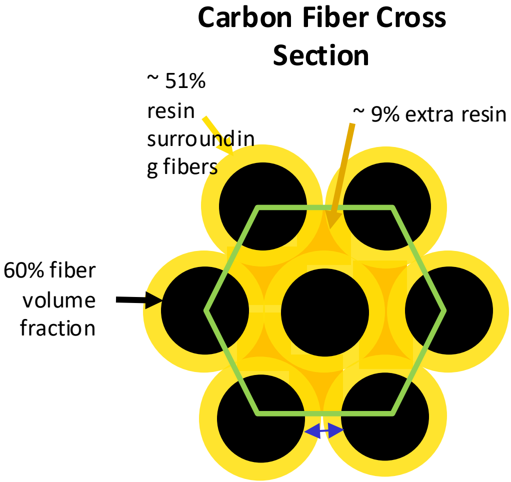
# Simulation of CNT Fiber/Polymer Composite Load Transfer Mechanisms

## Motivation

- CNT fiber reinforcements are different from carbon fiber (CF) reinforcements
  - CF fiber volume fractions limited to 0.907 due to geometry and non-uniform matrix thickness
    - ~ 9% of resin used to fill extra volume
  - CNT fiber shear load transfer in transverse direction
    - Micromechanics analytic equations and some numerical software do not capture transverse shear load transfer to fibers and requires special treatment for rectangular CNT fibers
- Modeling Goals
  - Understand tape-like fiber design space
  - Reduce the scope of composite fabrication options and estimate impact of trade-offs that need to be made at the laminate and lamina level
  - Get some low-hanging guidance quickly with simple models that explore the boundaries of the problem
  - Probe the design space with simple models, with the option to pursue more sophisticated analysis on a subset of the design space

## Idealized Structures



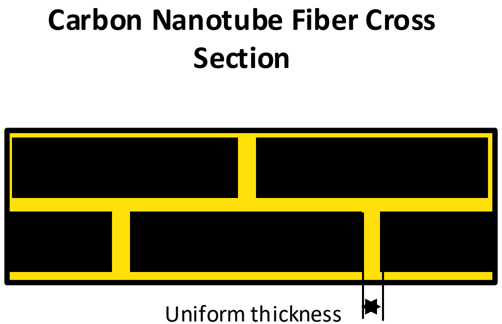
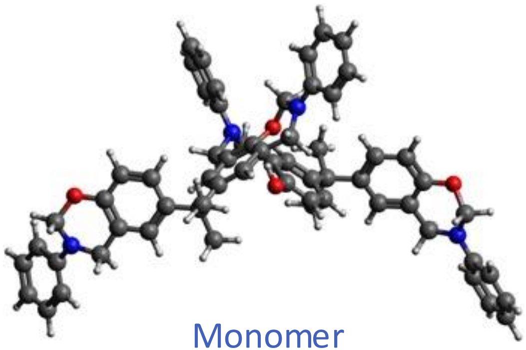


Image credits: NASA

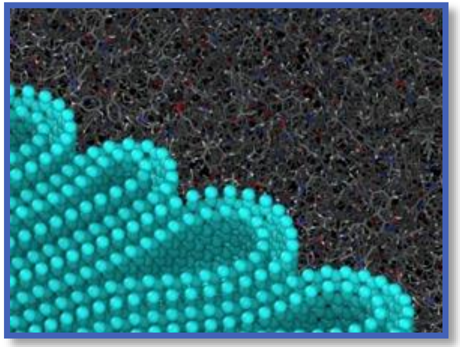
**Realistic modeling of fiber/matrix interface is needed to guide process development.**

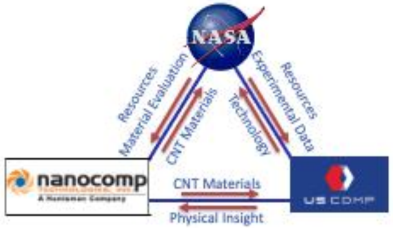
# Predicting Mechanical Properties by Simulating Deformation at Resin/CNT Interface


Monomer

**REACTER**

- REACTER is a tool for modeling reactions in molecular dynamics simulations.
- Developed at LaRC with support from this project.
- Enables construction of complex polymer models.
- Can also model bond breaking, necessary for strength prediction.
- New advanced reaction constraint features being added.


**Resin/Flattened CNT Interface**

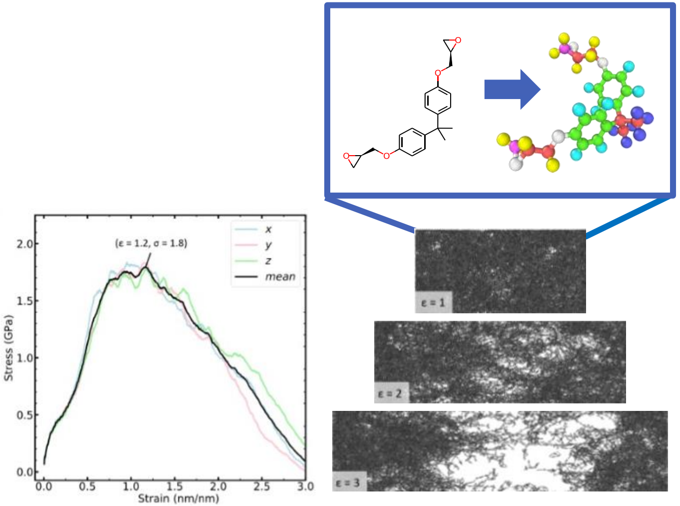


Polymer 128, 211-217, 2017
Macromolecules 53, 9953–9961, 2020

**Computational modeling guides choice of resin composition to yield best interaction with CNT reinforcement.**

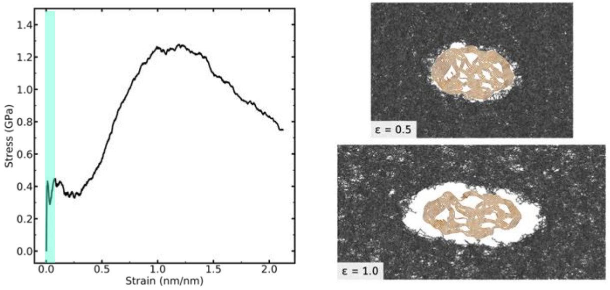
# CNT/Matrix Interface Modeling

## Neat Polymer Baseline System



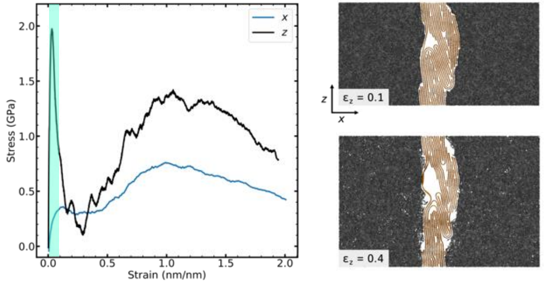
- ➢ Typical stress-strain curve for polymer in molecular dynamics model
- ➢ Qualitatively similar behavior seen in reinforced models beyond ~ 0.25 strain, after interfacial failure
- ➢ Initial yield and ultimate strains are overestimated for all three models due to high simulation strain rates

## Small Fiber Reinforcement



- ➢ Very small fiber, similar diameter to CNT bundle
- ➢ Modest initial modulus increase due to fiber
- ➢ Interface and fiber fail by ~ 0.25 strain
- ➢ Fiber failure shows load transferred from matrix

## Model Surface Reinforcement



- ➢ More realistic model than planar graphitic surface often used for fiber-matrix models
- ➢ Larger initial modulus increase than small fiber model as more CNTs must disentangle

**Realistic modeling of fiber/matrix interface developed to guide process development.**

Image credits: NASA

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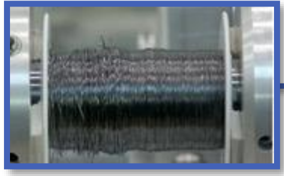
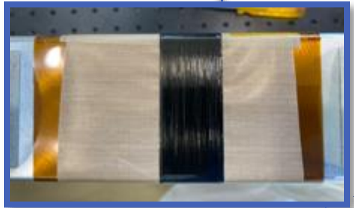
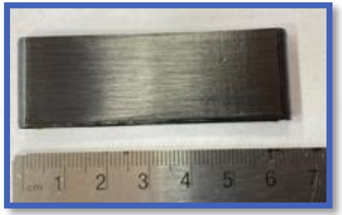
# Composites Process Development

CNT Yarn

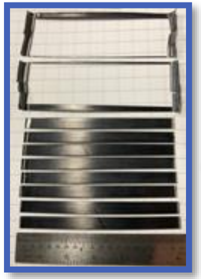




CNT Composite Fabrication

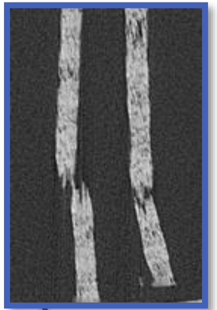


Cured CNT Composite

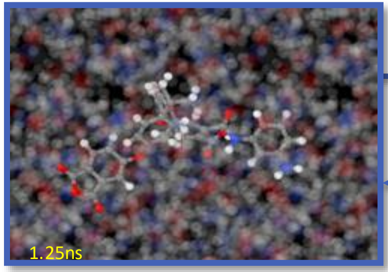


Test Specimen Prep

Mechanical Testing

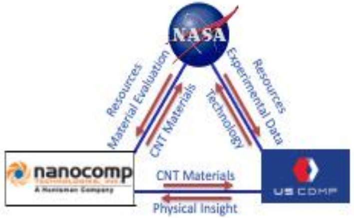


Post-Test Analysis



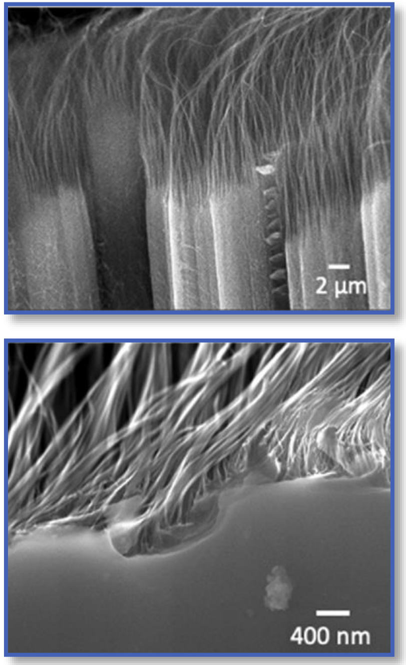
Polymer/CNT Interaction

- ➢ Composite process development yielded improved CNT composite axial and transverse tensile properties.
- ➢ Computational guidance for process development was done at LaRC and in collaboration with US-COMP STRI.

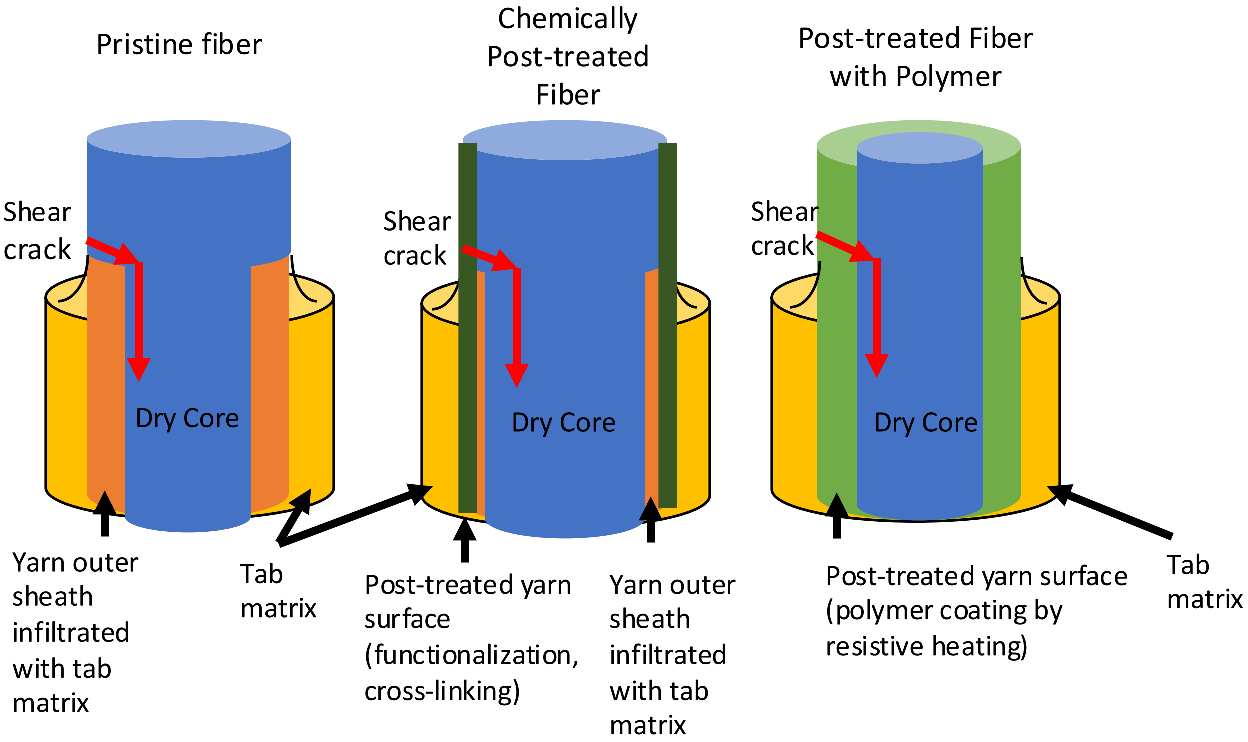


**CNT composite process development and testing inform manufacturing parameter optimization.**

# Challenge:  Poor CNT Yarn/Resin Interface



Representative Failure Surfaces



Pristine fiber

Chemically Post-treated Fiber

Post-treated Fiber with Polymer

Yarn outer sheath infiltrated with tab matrix

Tab matrix

Post-treated yarn surface (functionalization, cross-linking)

Yarn outer sheath infiltrated with tab matrix

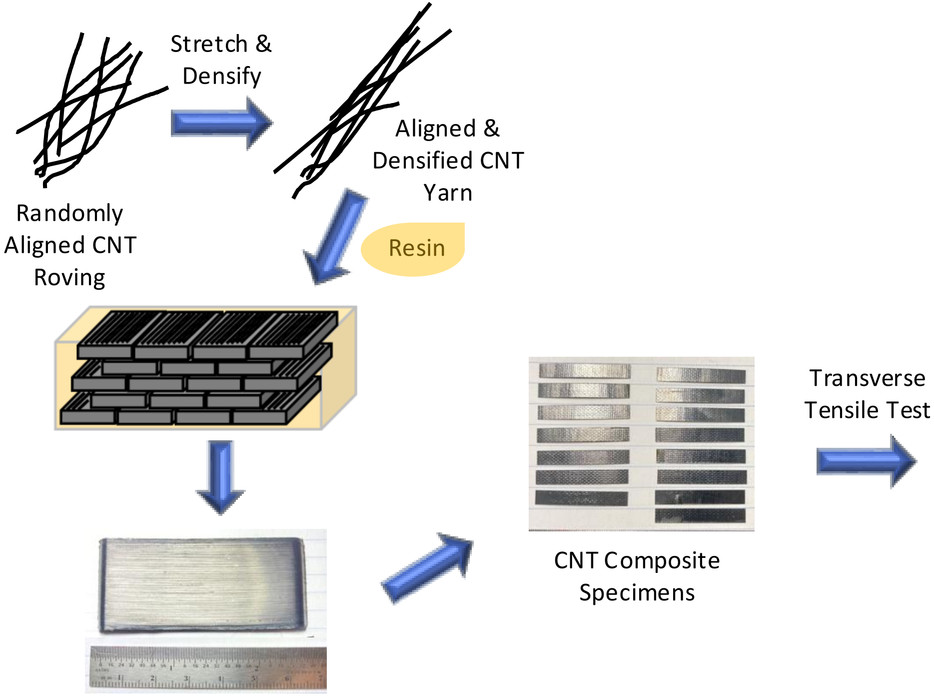
Post-treated yarn surface (polymer coating by resistive heating)

Tab matrix

Image Credits: NASA

Kim, J-W., et al., *Carbon*, **173**, 857-869, 2021.

# Transverse Mechanical Performance



Randomly Aligned CNT Roving

Stretch & Densify

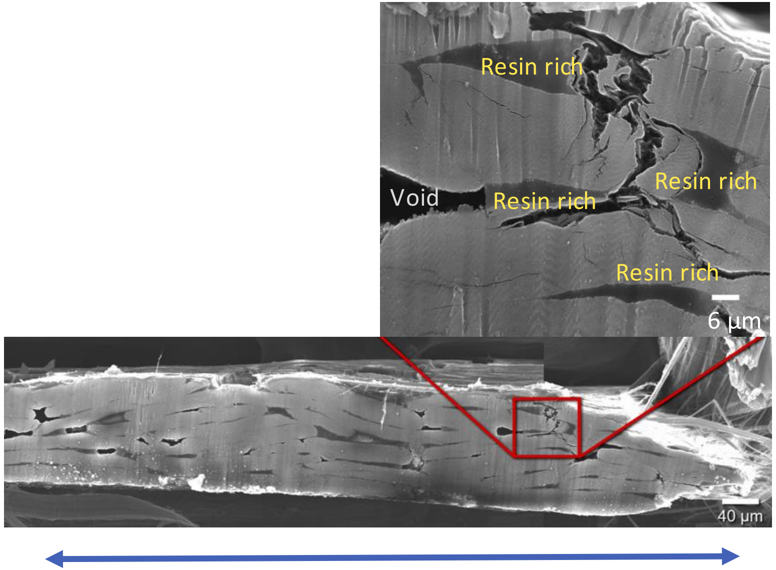
Aligned & Densified CNT Yarn

Resin

CNT Composite

CNT Composite Specimens

Transverse Tensile Test



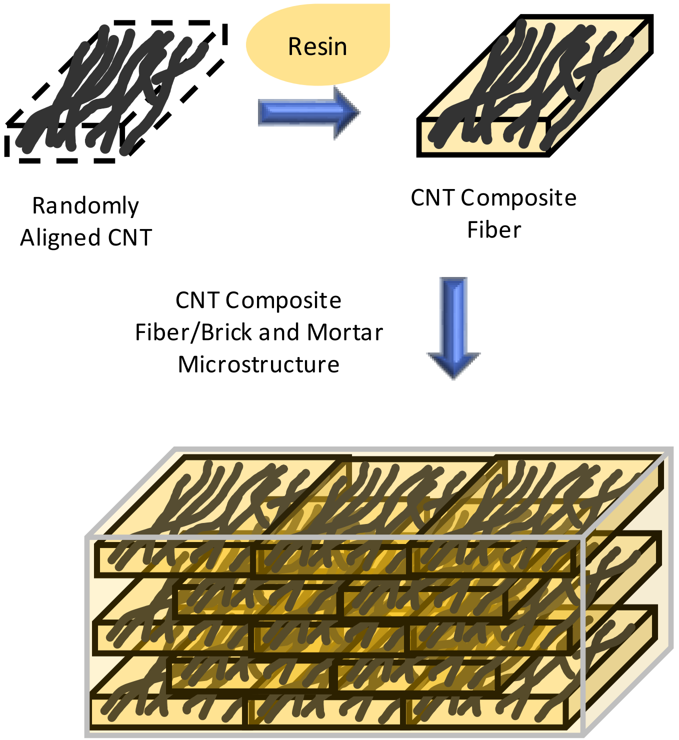
Applied Strain

Failure Mode of Unidirectional CNT Yarn Composite

Image Credits: NASA

Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

# Multiscale Hierarchical CNT Composite Fabrication



Resin

Randomly Aligned CNT

CNT Composite Fiber

CNT Composite Fiber/Brick and Mortar Microstructure

Transverse Tensile Test Results

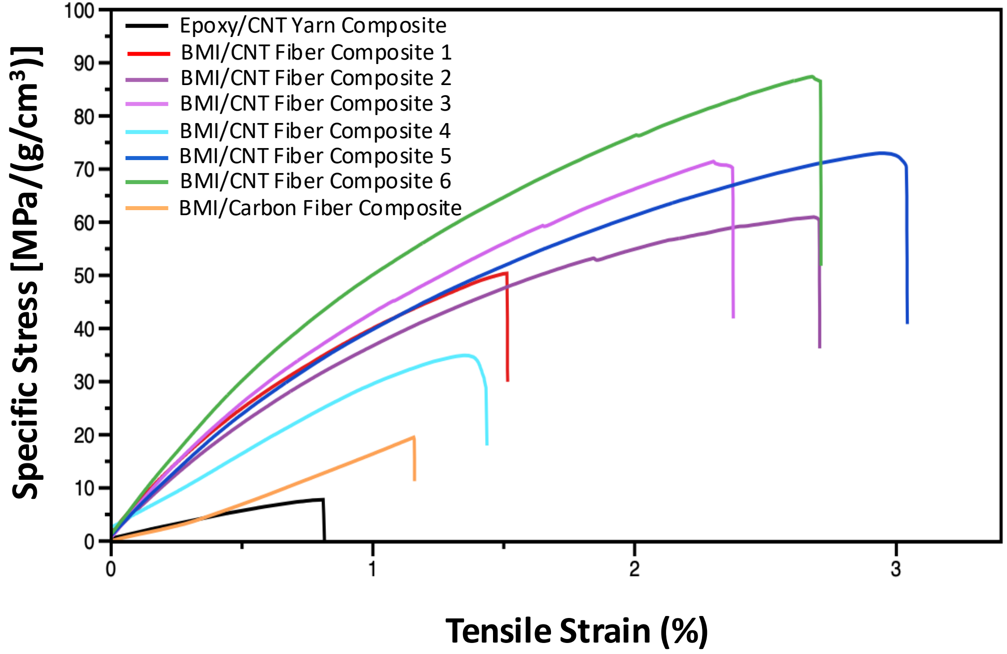


Image Credits: NASA

Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

# CNT Composite Fracture Toughness

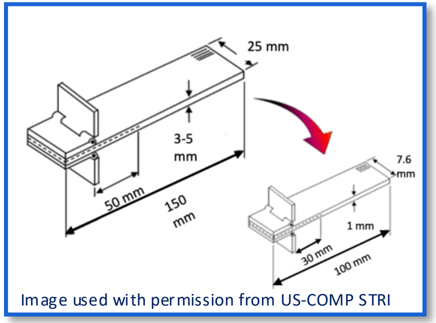


Image used with permission from US-COMP STRI

Based on ASTM D5528
Double Cantilever Beam (DCB) Test

Image credit: NASA

DCB Test

Fracture Toughness Data

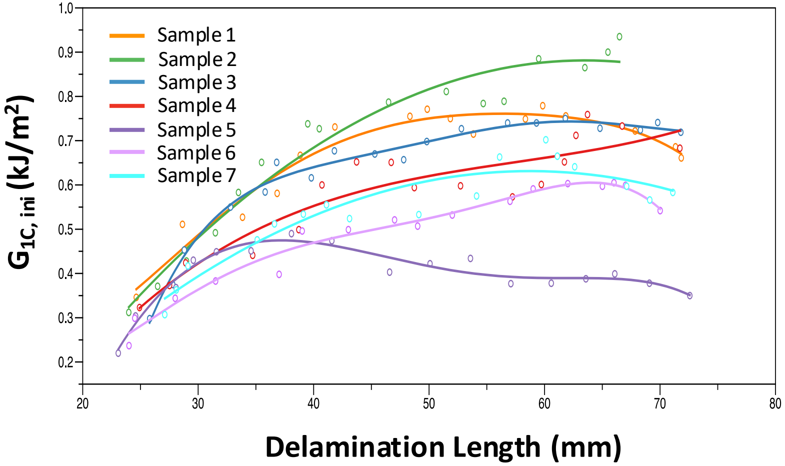
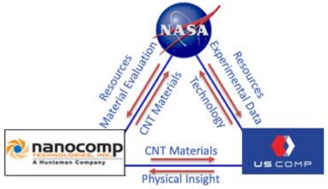


Image Credit: NASA

CNT Composite DCB Samples

- Capitalized on miniaturization of ASTM standard test for fracture toughness developed by US-COMP STRI.



Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

# CNT Composite Fabrication

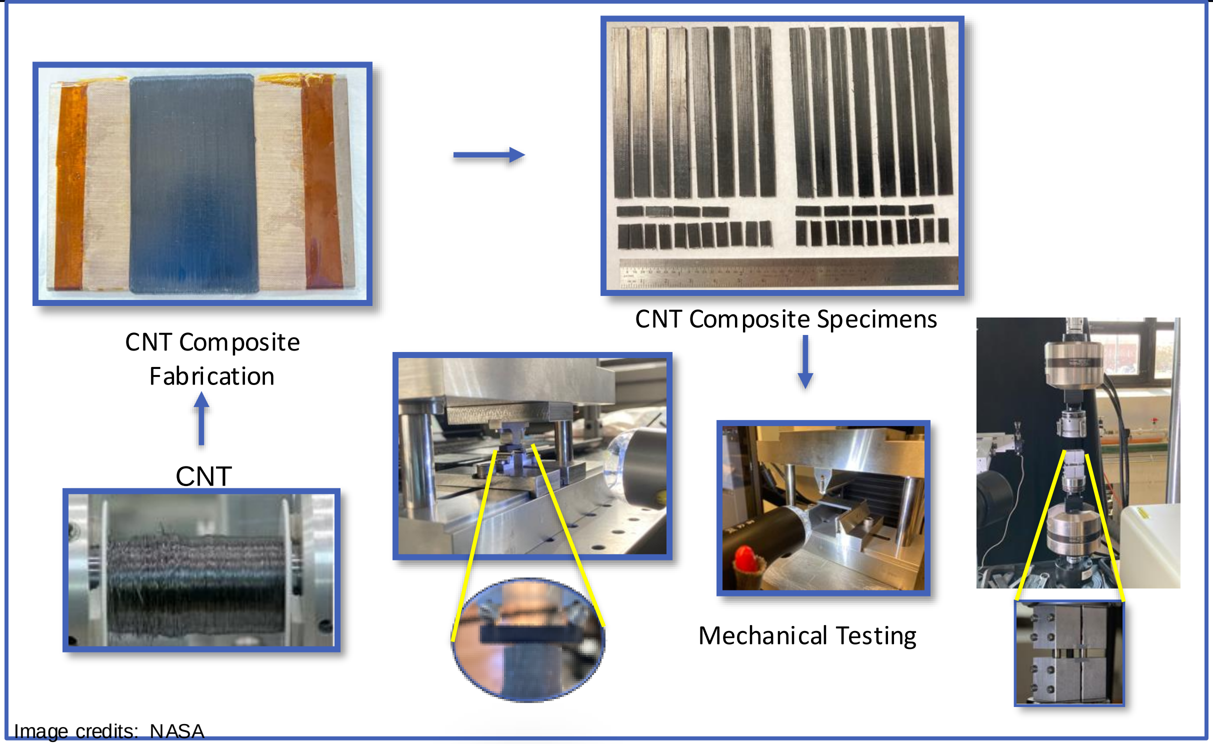


Image credits: NASA

- Specimens for axial, transverse, and compression properties were produced from a single fabrication process.
- Successful demonstration of the processing method was evidenced by the measured mechanical properties of the CNT composite coupons benchmarked against carbon fiber composite properties.
- Tests completed to date
  - Total specimens tested: 368
    - Short beam shear specimens: 70
    - Transverse flexure specimens: 93
    - Axial flexure specimens: 33
    - Combined load compression specimens: 72

**CNT composite process development and testing inform manufacturing parameter optimization.**

# CNT Mechanical Properties

- Composite process development has yielded expanded set of CNT composite mechanical properties in the transverse direction that are better than baseline carbon fiber composites.
- Processing improvements continue to evolve to improve compressive properties.
- CNT composite fiber process is being patented, and the processing technology has been licensed.

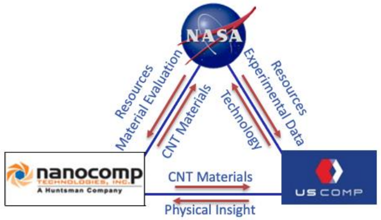
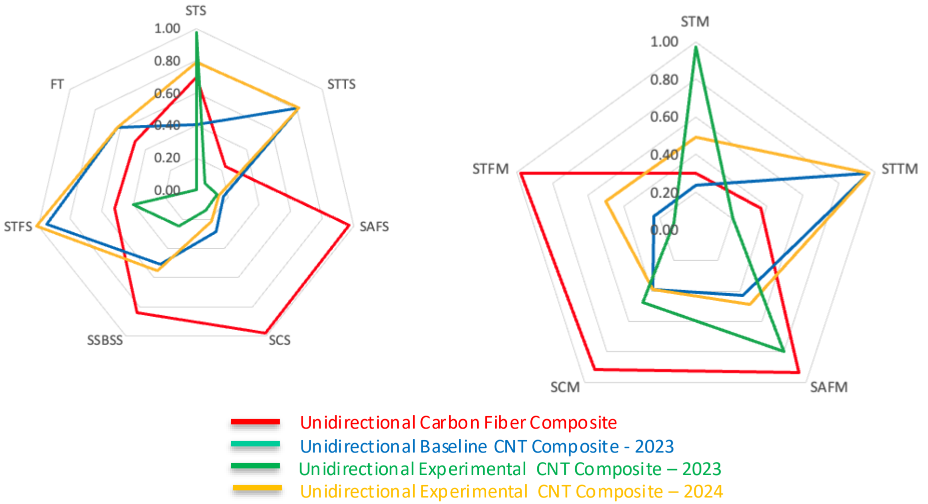


Image credits: NASA



STS: specific tensile strength
STTS: specific transverse tensile strength
SAFS: specific axial flexural strength
SCS: specific compression strength
SSBSS: specific short beam shear strength
STFS: specific transverse flexural strength
FT: Mode I fracture toughness

STM: specific tensile modulus
STTM: specific transverse tensile modulus
SAFM: specific axial flexural modulus
SCM: specific compression modulus
STFM: specific transverse flexural modulus

Expanding CNT composite mechanical properties is necessary to inform infusion paths.

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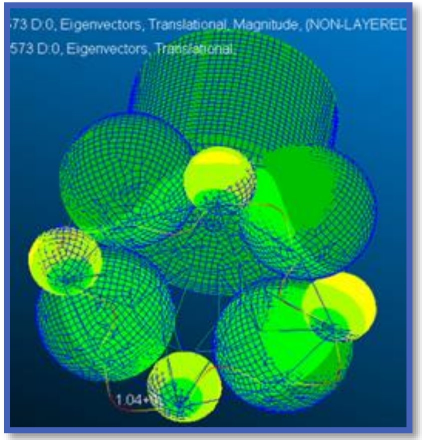
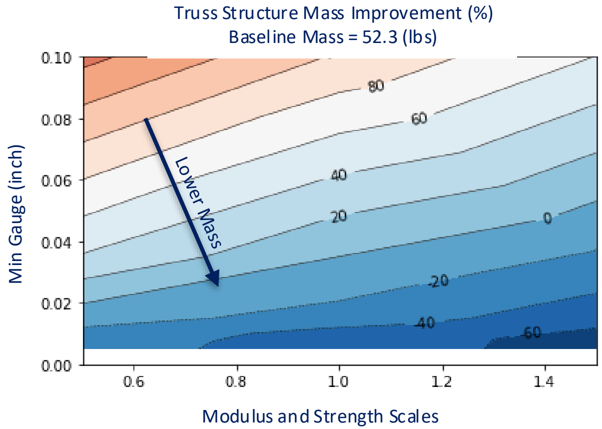
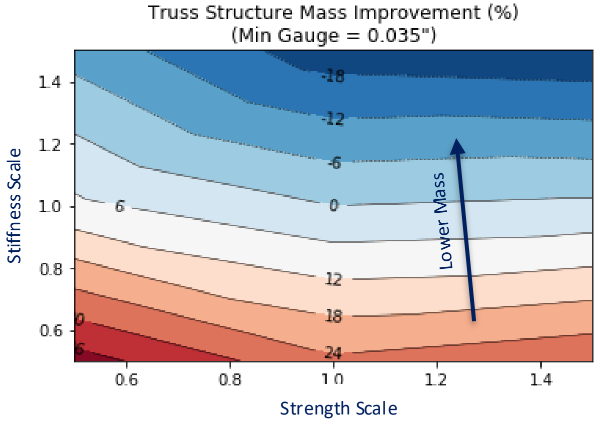
# Systems Level Assessment of Material Performance on Structures



Parametric finite element model of generic lunar ascent model

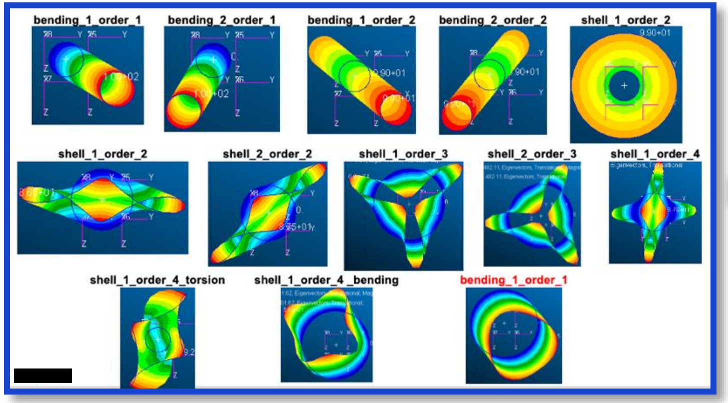




- Preliminary results suggested that:
  - For the same mass, increasing stiffness and strength allows increase of minimum thickness, which can lead to simpler, faster, less costly fabrication process and better micrometeoroid impact tolerance.
  - For this structural concept, improving stiffness has much greater impact on mass than strength.

**Systems analysis is being used to quantify the impact of advanced materials on elements of NASA missions.**

# Systems Analysis Guidance for Potential Applications



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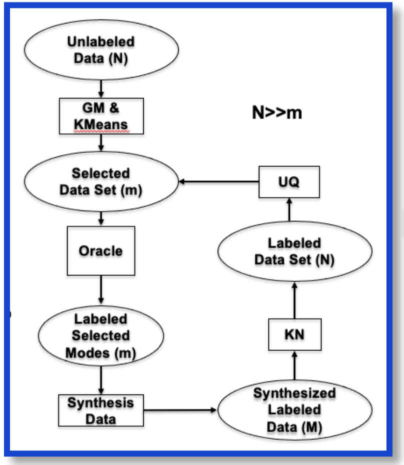
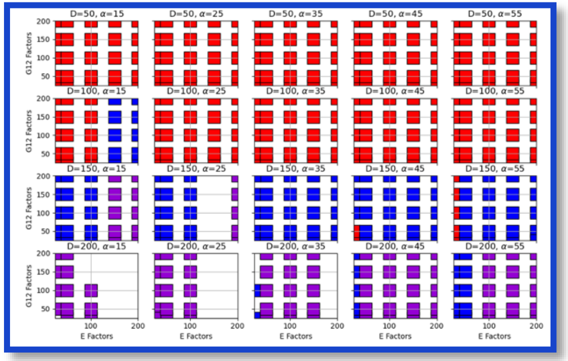
Parameters that Influence Component Performance



Unlabeled Data (N)
GM & KMeans
Selected Data Set (m)
Oracle
Labeled Selected Modes (m)
Synthesis Data
Synthesized Labeled Data (M)
KN
Labeled Data Set (N)
UQ
N>>m

Machine Learning to Analyze Massive Data Sets



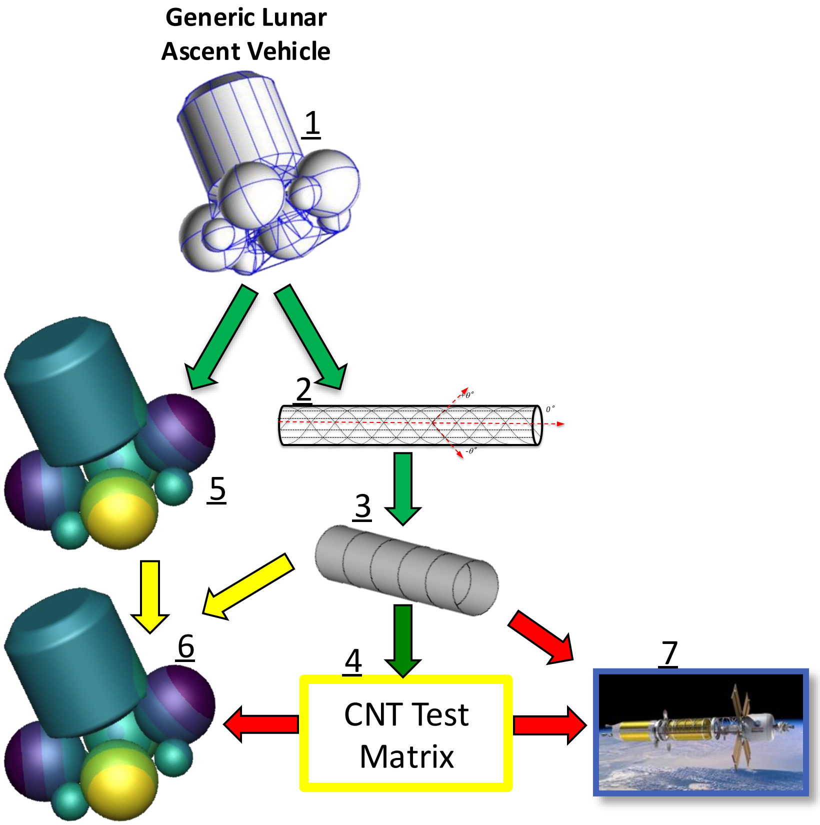
Output Reveals Key Performance Parameters for Component

- ➢ Systems analysis employing machine learning allowed exploration of array of cases where advanced materials can improve component parameters with greater efficiency than possible previously.
- ➢ Systems analysis revealed that there are advantages to using high specific modulus materials in non-pressurized structures to improve systems performance.

**Systems analysis is being used to quantify the impact of advanced materials on elements of NASA missions.**

# Systems Analysis Guidance for Potential Applications

- Started with a generic lunar ascent vehicle (1).
- Extracted a representative tube from the support structure (2) and created a parametric finite element analysis (FEA) model (3).
- Ran parametric model and extracted 840 mode shape solutions for various material types (CNT and IM7), tube diameters, and number of fiber layers.
- Developed a preliminary test matrix based on 840 solutions (4). Funding and material availabilities will narrow the test matrix .
- Created a parametric FEA model for the ascent vehicle (5) and extracted 350 mode shape solutions for further assessment.
- Use results from steps 3, 4, and 5 to modify the ascent model to assess the impact of advanced materials (6).
- Assess the impact of advanced materials on a generic truss structure of a nuclear propulsion vehicle (7).

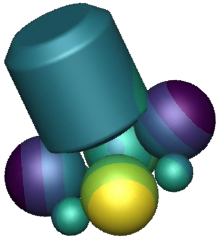


# Systems Analysis Guidance for Potential Applications

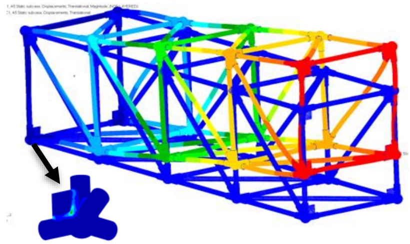
**Objectives 8 and 9**
**KPP 3 and 4**

- Developed an analysis model with appropriate parameters for advanced material assessment.
- Quantified the benefits of using carbon nanotubes (CNT) for a generic lunar ascent vehicle.
  - Benefits include enabling stiffer secondary load bearing structures, which could lower the vehicle mass and/or improve risk posture.
  - Benefits of using CNT for a generic truss structure concept were demonstrated by systems modeling.
  - Developed generic 4-, 8-, and 12-bay truss models.
- Identified NASA missions with significant secondary non-pressurized elements that could benefit from CNT.
- Initiated the development of a test model for a generic 4-bay truss structure.
  - Selected a truss that is representative of structures ranging from Commercial Lunar Payload Services (CLPS) landers to large integrated truss structure (ITS) like Artemis Gateway ITS.

Generic Lunar Ascent Vehicle



Generic Truss Structure



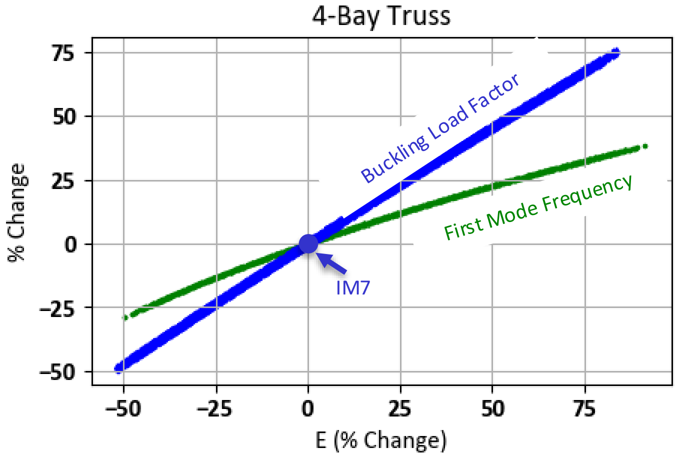
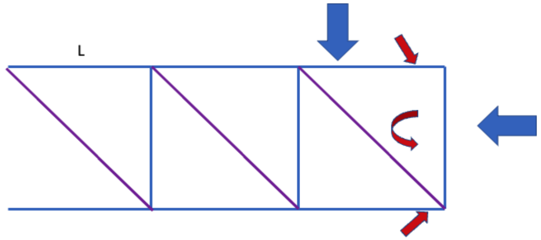


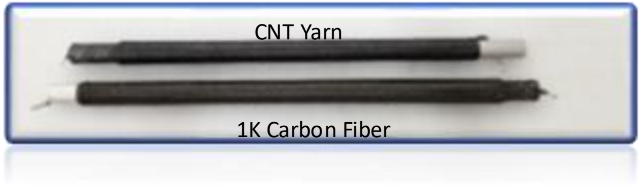
Image credits: NASA

# Prototype Fabrication

Spacecraft Truss Element Prototyping



Systems analysis for 2D truss elements



24” braided truss preforms

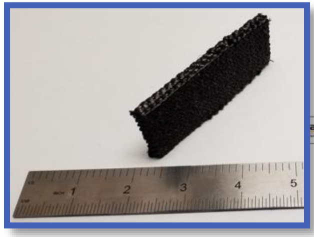
- ➢ Systems modeling conducted as part of the project showed that there are benefits from higher stiffness composites made from CNT preforms relative to carbon fiber preforms.
- ➢ Model is in the process of being verified using plastic piping and 3D printed joints.
- ➢ Benefits predicted will also be validated by the fabrication and testing of truss elements made with carbon fiber and CNT reinforcement.
- ➢ Phase 3 SBIR was awarded to produce 24” braided preforms that are 1” in diameter to represent truss elements ubiquitous in spacecraft was completed.
- ➢ Composite truss elements will be fabricated and tested.

Image credits: NASA

# Transition/Infusion Opportunities

**Lightweight Data Cables**

- Benefits are mass savings over state-of-the-art cables
- CNT does not cold weld compared to copper

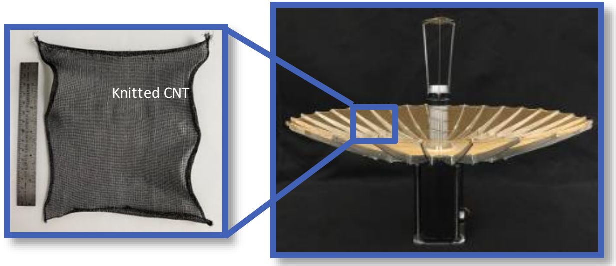


**3D Woven Preforms for Composites**

- Topologically optimized 3D woven CNT reinforced composite for space vehicle component.

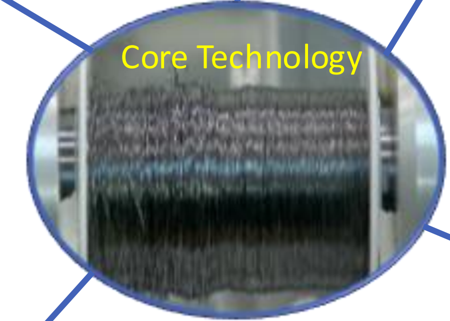
**Prototype Heat Exchanger Tube**

- Exploring benefits of fabricating composites for extreme environments such as carbon/carbon composites

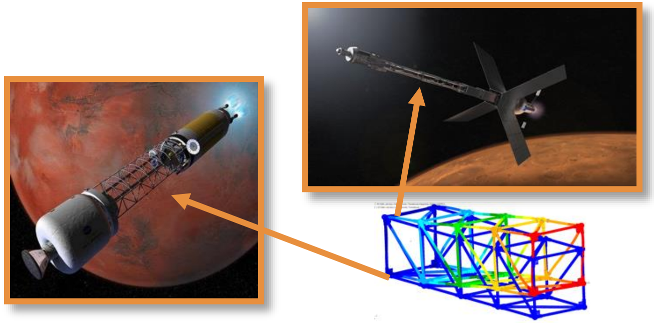


**Deployable Mesh Antenna**

- Previously investigated as a deployable antenna
- Substitute for gold coated molybdenum
- Manufacturing scale-up enabled required cost reduction



High Strength CNT Yarn



**Prototyping of Truss Structure Components**

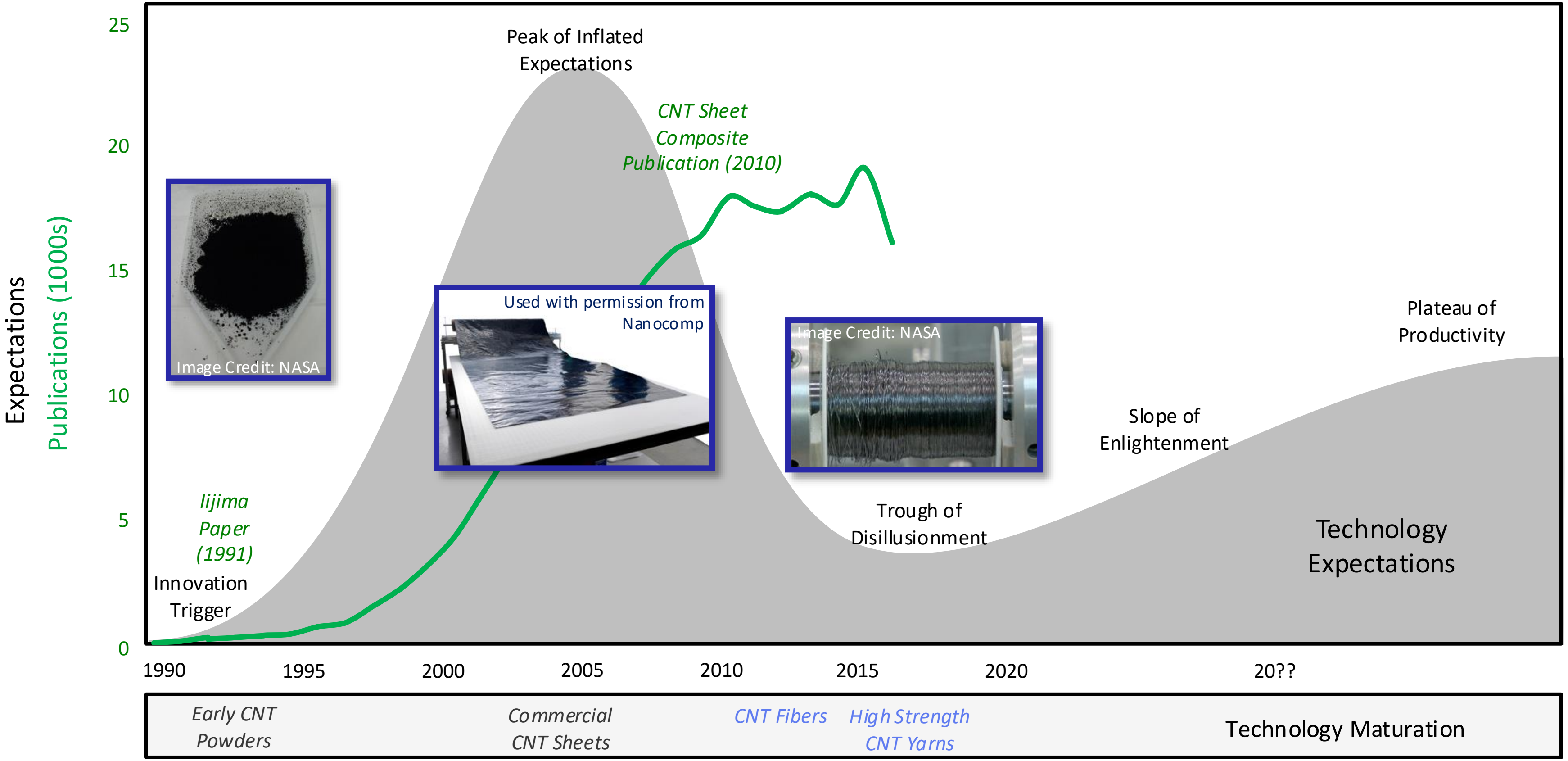
- Mechanical properties enhanced and systems analyses indicated benefits for truss structure elements
- In process of validating systems analysis models with prototype truss element fabrication and testing

Image credits: NASA

# Outline

- Background
  - Carbon Nanotubes
  - Previous Nanotechnology Project Outcomes
- Superlightweight Aerospace Composite Project
  - Manufacturing
  - Composite Mechanical Properties
    - Computational Modeling
    - Composite Processing
    - Mechanical Properties
  - Technology Transitions
    - Systems Modeling
    - Prototyping
- Summary

# Use Driven Technology Maturation



# Summary

- 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.

# Systems Defined Goal Provides Common Objective

**NASA Centers**
- LaRC

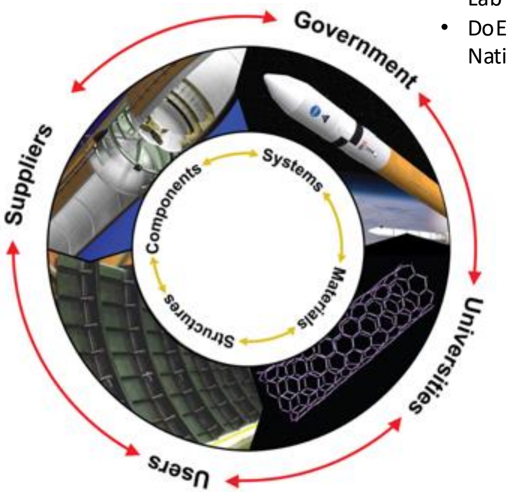
**Public/Private Partnerships**
- Northrup Grumman
- University of Dayton Research Institute/State of Ohio

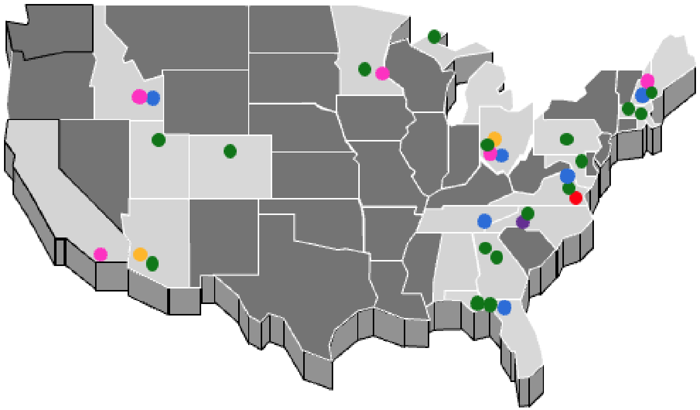
**OGA Leveraging**
- AFOSR
- AFRL – ManTech Program
- DoD
- DoE - ARPA-E
- DoE – Idaho National Lab
- DoE – Oak Ridge National Lab

**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
- Textum
- Michigan Tech
- U of Utah
- U of Colorado
- Johns Hopkins
- U of Minnesota
- Columbia University
- Nanocomp
- Northrop Grumman

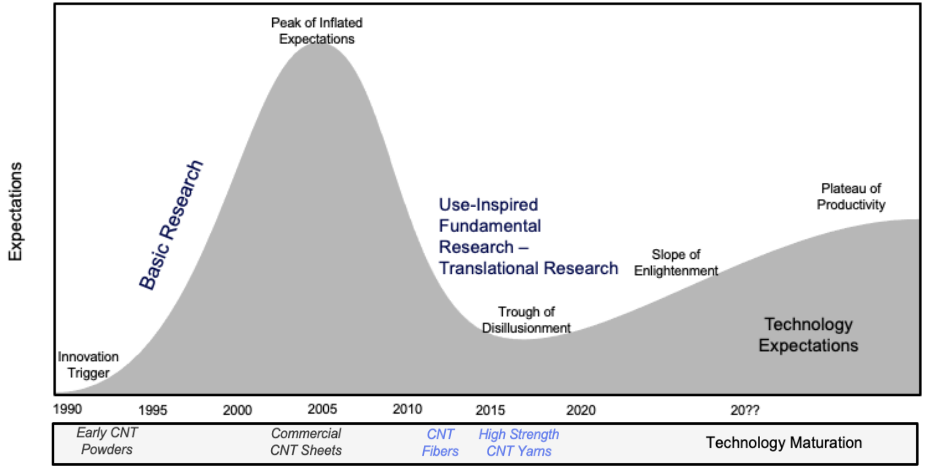


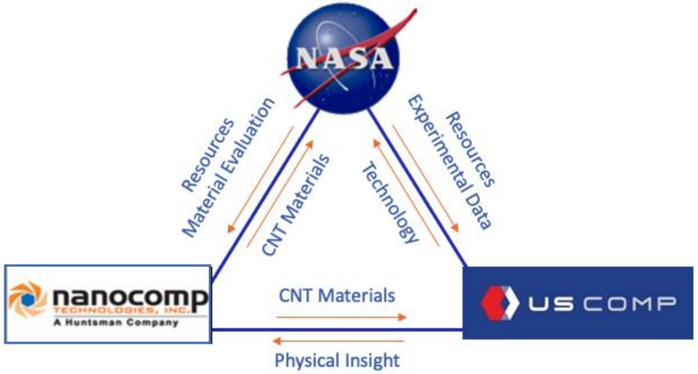


**Incentivize multidisciplinary partnerships to accelerate maturation of an emerging material ecosystem.**

Image Credit: NASA

# TechMat Capability End State for Scope of the Project





- ➢ Manufacturing maturation of high strength CNT is anticipated to advance from MRL 3 at the project inception to MRL 6 at the end of the project.
- ➢ Application dependent use of high strength CNT will advance from MRL 2 at the project inception to MRL 4 at the end of the project.

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

# Maturing Emerging Technologies . . .

For Societal Benefits on Earth . . . And Beyond

Image Credit: NASA