National Aeronautics and Space Administration

Space Technology Mission Directorate

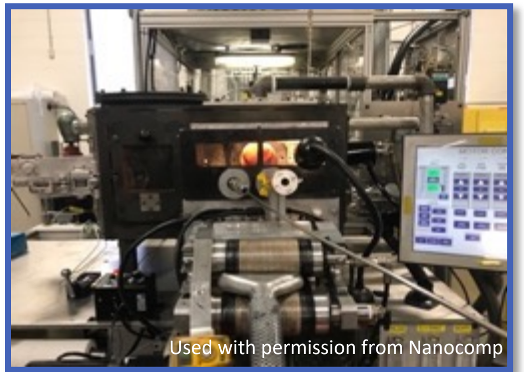
Game Changing Development Program

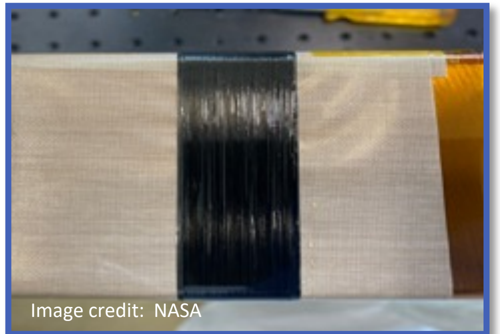
Presenter: Mia Siochi | Moderator: Godfrey Sauti | FY22 Superlightweight Aerospace Composites (SAC) Annual Review Presentation | 09.15.22

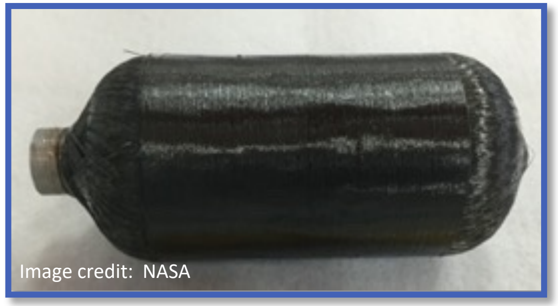
POC: Mia Siochi (emilie.j.siochi@nasa.gov)

Technology Overview

- Technology Product Capability
  - Superlightweight Aerospace Composites (SAC) technology aims to develop a carbon nanotube (CNT) based composite structural material with nearly double the specific strength of state-of-the-art carbon (SOA) fiber composites. The product capability offers a viable technology that can reduce overall vehicle structural mass by ~ 25 % to 50 %.
- Technical Capabilities (Technical Tall Poles)
  - High volume manufacturing of high strength CNT
  - Availability of CNT composite mechanical properties
  - Multiscale CNT composite modeling
  - CNT composite prototypes
- Exploration & Science Applicability
  - Availability of commercial quantities of high strength CNT enables the fabrication of high strength composites that can influence design paradigms for aerospace structures.
  - SAC technology will enable missions where high strength lightweight structures are needed.







Superlightweight Aerospace Composites Technology Goals*

Technology Goals	
Goal #1	Maturation of CNT manufacturing production rates to yield commercial scale volumes of CNT reinforcement.
Goal #2	Production of CNT reinforcement with mechanical properties that outperform SOA fibers.
Goal #3	Development of optimal materials processing approaches to capitalize on the performance enhancements promised by this emerging reinforcement material.

* Goals from draft project plan

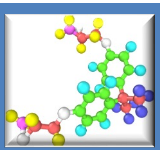
Superlightweight Aerospace Composites Project Objectives*

Project Objectives	
Objective #1	Increase the spool length of high strength CNT.
Objective #2	Increase the manufacturing rate of high strength CNT.
Objective #3	Increase the specific strength and fracture toughness of CNT composites.
Objective #4	Increase the manufacturing readiness level (MRL) from 3 to 4 of composite fabrication techniques that enhance the inter-laminar properties of CNT composites to enable the maximum retention of the fiber mechanical properties.
Objective #5	Expand the set of mechanical properties for CNT composites beyond tensile properties to permit the broader consideration of aerospace applications.
Objective #6	Develop models and simulations that will inform the materials processing and manufacturability of CNT composite structures.
Objective #7	Conduct system analyses to illustrate systems mass savings in vehicles when project performance goals are attained.
Objective #8	Fabrication of prototype articles suitable for demonstration of manufacturability using CNT materials.

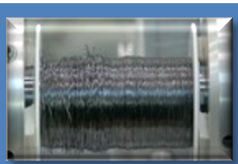
* Objectives from draft project plan

Team Members

- Joseph Smith
- Scott Zavada



Resin Selection and Processing



CNT Yarn Characterization and Development

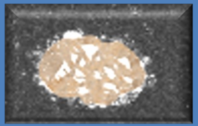
- Jae-Woo Kim
- John Gardner
- Godfrey Sauti
- Russell Wincheski

Composite Processing

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

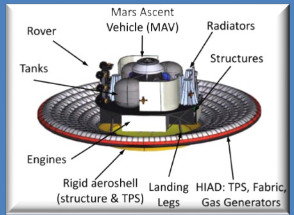
Composite Testing

- Russell Wincheski
- Jae-Woo Kim
- Godfrey Sauti



CNT/Resin Interface

- Benjamin Jensen
- Kristopher Wise
- Jacob Gissinger



Systems Analysis

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

- Financial Analyst
  - Lauren Bonine
  - Damon Sheaffer

Image credits: NASA

Mission Infusion & Partnerships

NASA Centers
- LaRC
- MSFC

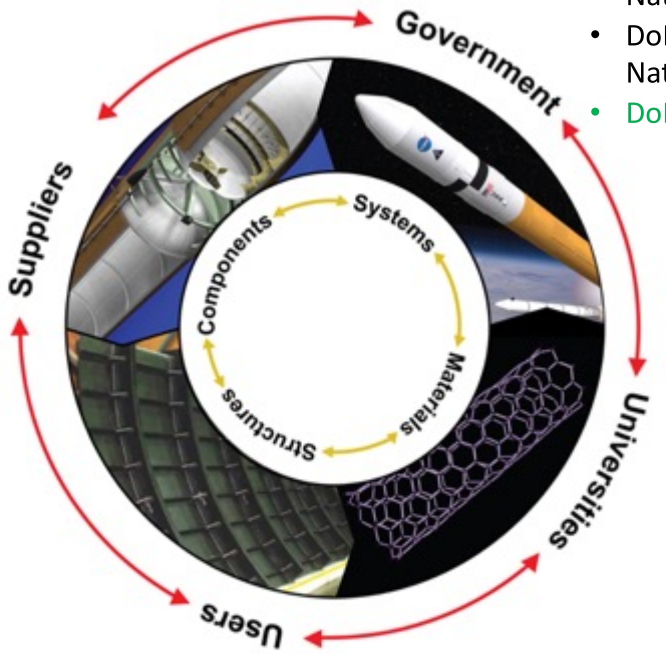
Public/Private Partnerships
- Northrup Grumman
- University of Dayton Research Institute/State of Ohio

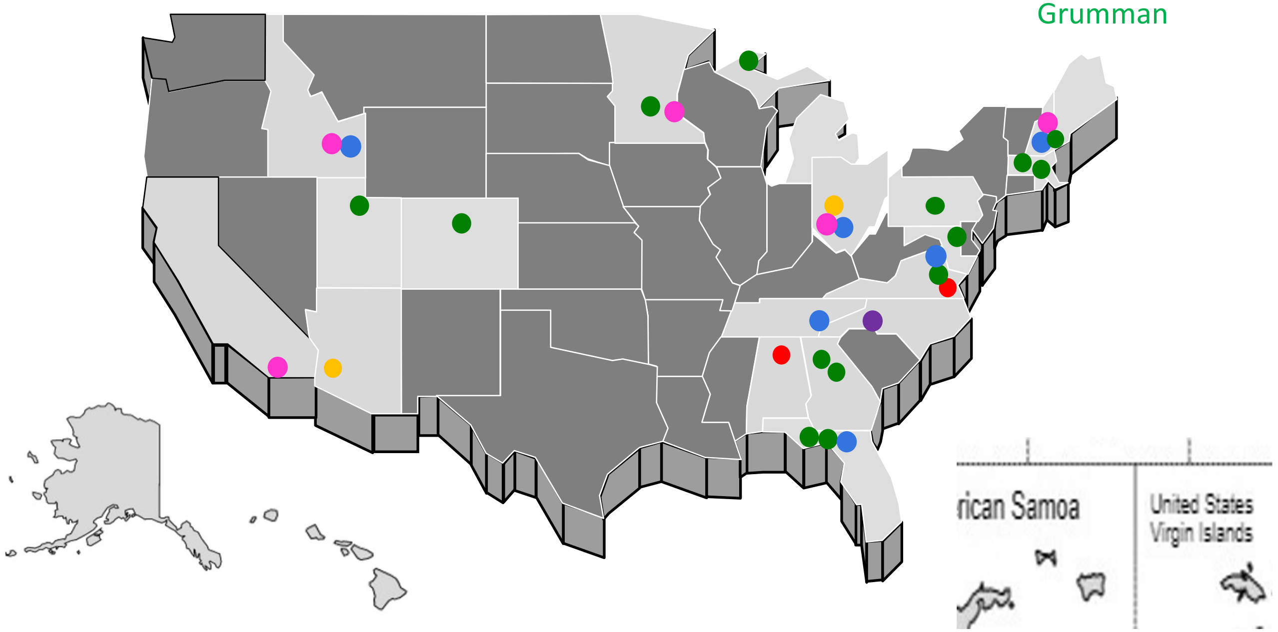
OGA Leveraging
- AFOSR
- AFRL – ManTech Program
- DoD
- DoE - ARPA-E
- DoE – Idaho National Lab
- DoE – Oak Ridge National Lab
- DoE - EERE

Small Business
- Textum, Inc.

SBIR/STTR
- Nanocomp
- Cornerstone Research Group
- Minnesota Wire & Cable
- Applied Composites
- Advanced Ceramic Fibers

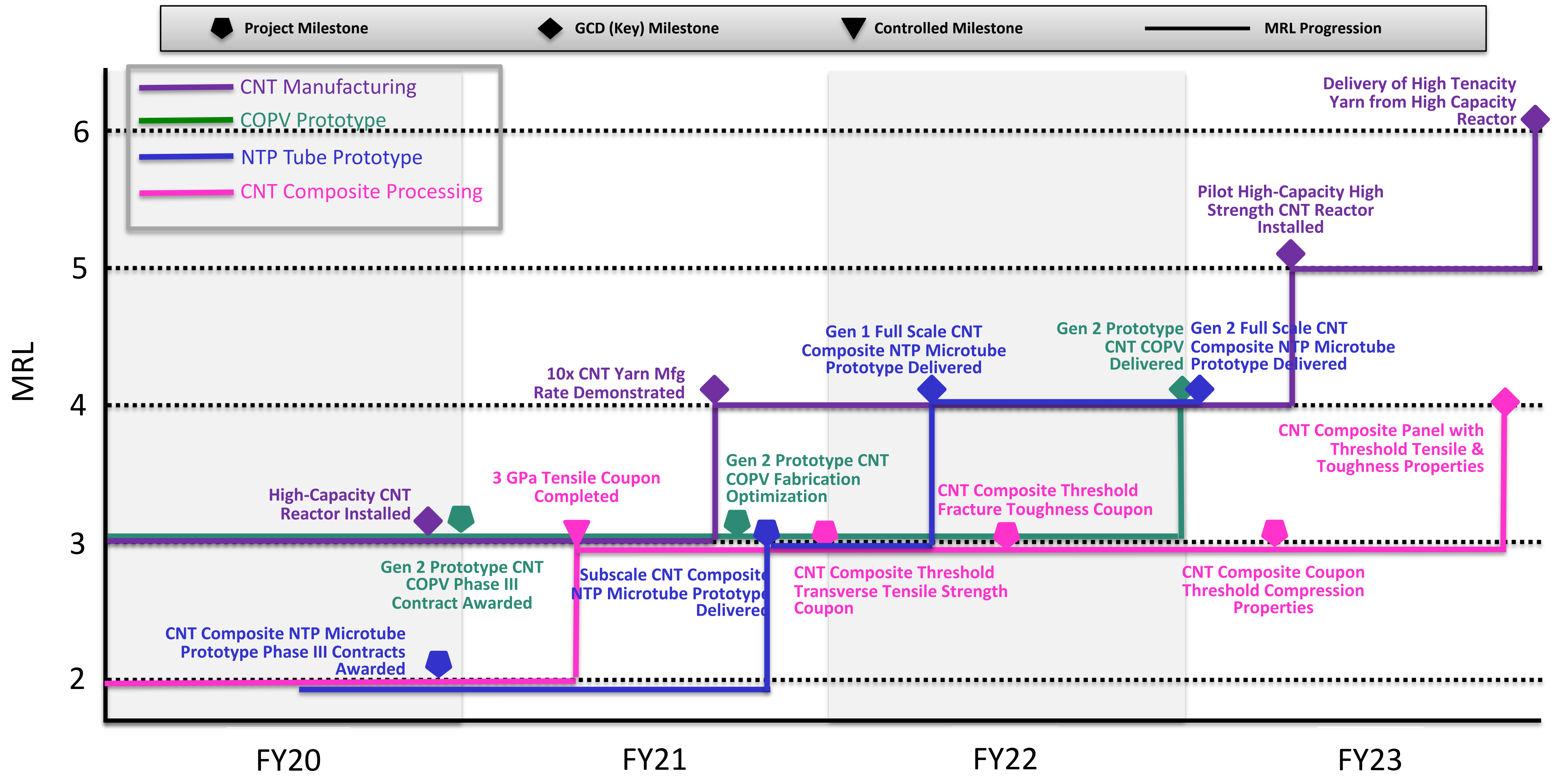
NSTRI
- Florida State U
- MIT
- VCU
- Ga Tech
- Penn State U
- FL A&M U
- Solvay
- Michigan Tech
- U of Utah
- U of Colorado
- Johns Hopkins
- U of Minnesota
- UMass Lowell
- Nanocomp
- Northrup Grumman





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

Superlightweight Aerospace Composites Lifecycle Milestone/Maturity Schedule

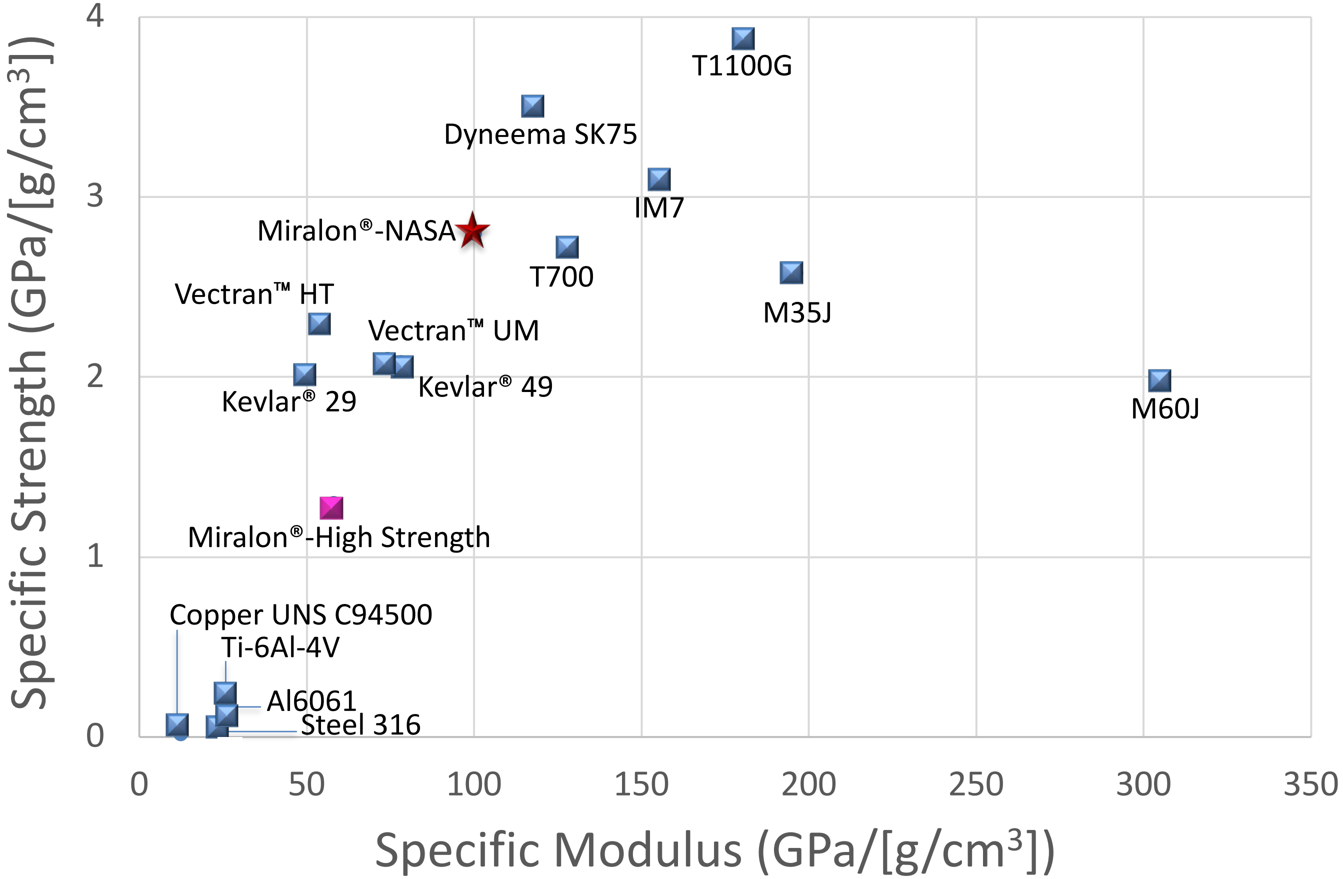


Superlightweight Aerospace Composites
Key Performance Parameters (KPP)

KPP #	Parameter Name	Unit
1	**CNT Reinforcement Specific Strength**	N/tex
2	**Unidirectional CNT Composite Specific Strength**	$GPa/(g/cm^3)$
3	**CNT Composite Fracture Toughness**	N/mm
4	**CNT Manufacturing Rate**	m/hr
5	**CNT Composite Transverse Strength**	MPa

Accomplishments
Large Scale CNT Yarn Manufacturing

Objectives 1 & 2
KPP 1 & 4



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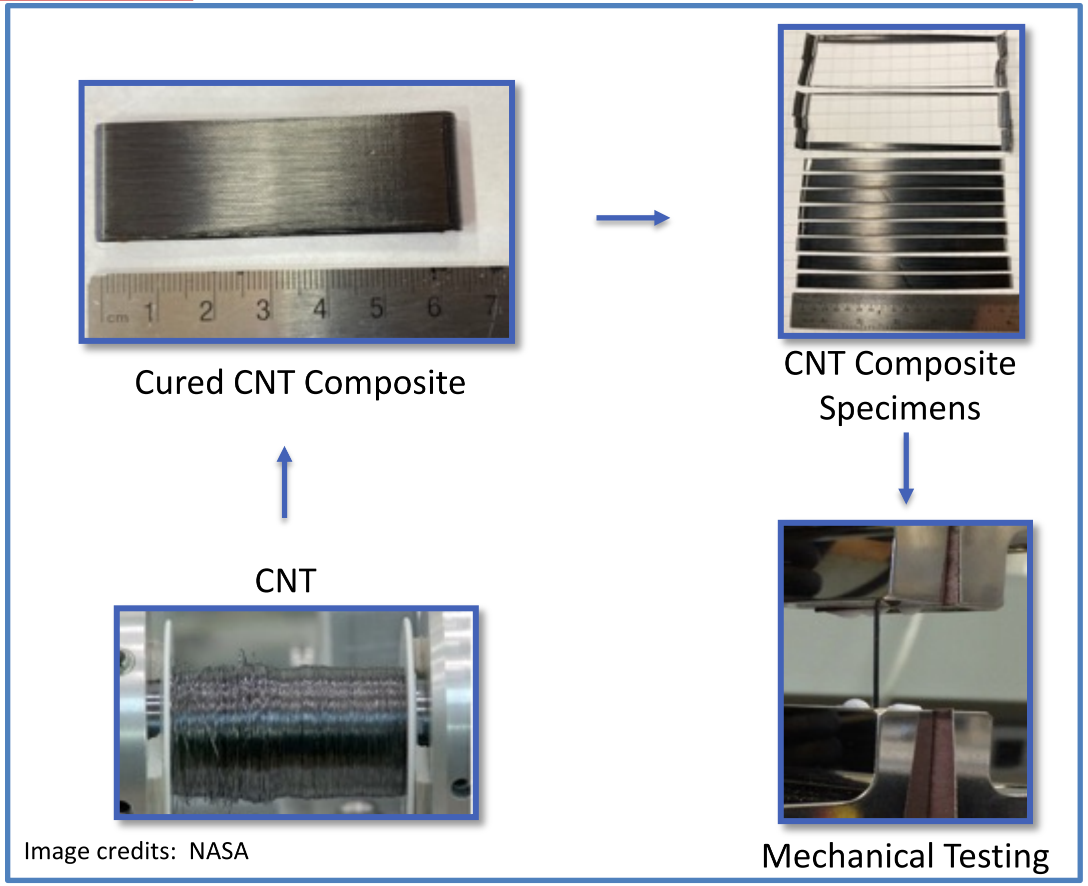
Large scale manufacturing of high strength yarn enables technology infusion.

Accomplishments

CNT Composite Tensile Properties

Objectives 3, 4 & 5
KPP 2 & 5



- Specimens for both axial and transverse tensile testing 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 are underway
  - Preliminary data indicate processing method tailored to CNT material yields axial and transverse tensile properties that are higher than those of carbon fiber composites.

CNT composite process development and testing inform manufacturing parameter optimization.

Accomplishments
CNT Composite Fracture Toughness

Objectives 3, 4 & 5
KPP 3

Based on ASTM D5528
Double Cantilever Beam (DCB) Test

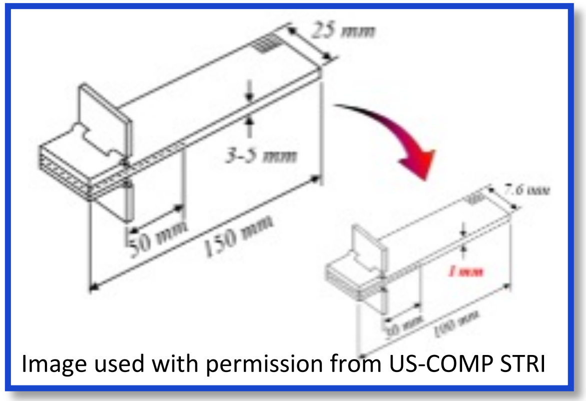


Image used with permission from US-COMP STRI

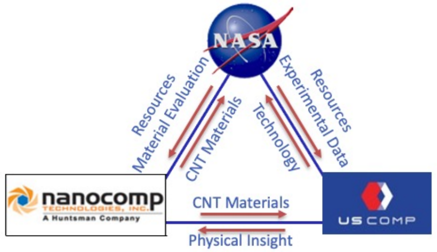
CNT Composite DCB Specimens

Image credit: NASA

DCB Testing

Image credit: NASA

- Capitalized on miniaturization of ASTM standard test for fracture toughness developed by US-COMP STRI.
- Several sets of samples tested.
- Data analysis is underway.

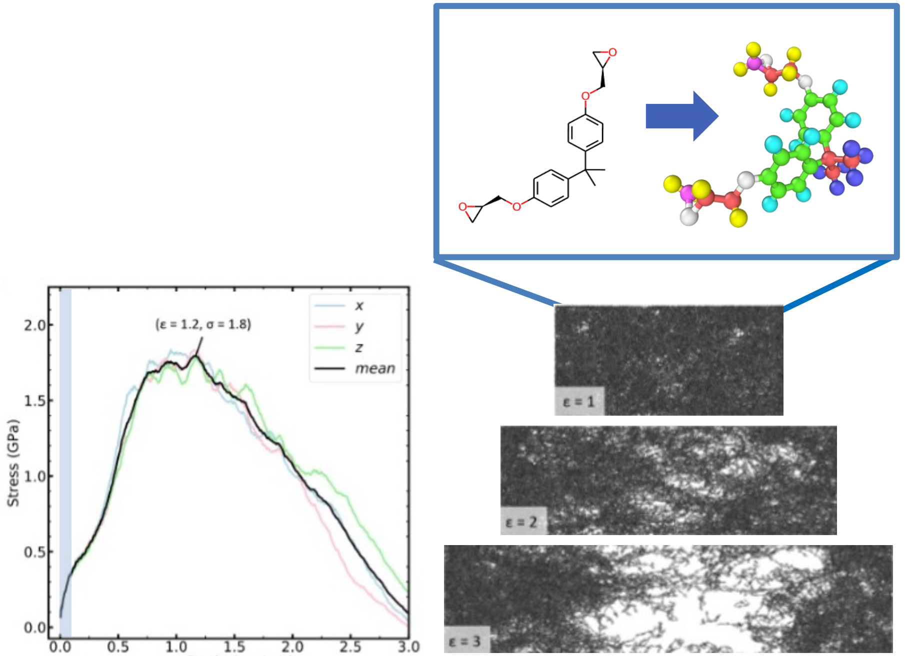


Expanding CNT composite mechanical properties is necessary to inform infusion paths.

Accomplishments
CNT/Matrix Interface Modeling

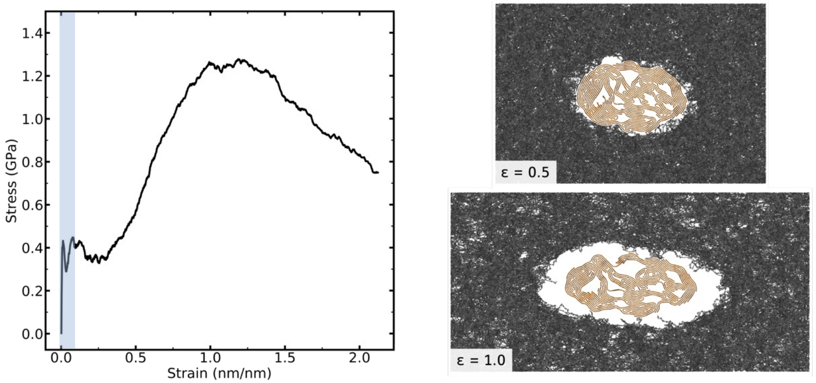
Objectives 5 & 6
KPP 3 & 5

Neat Polymer Baseline System



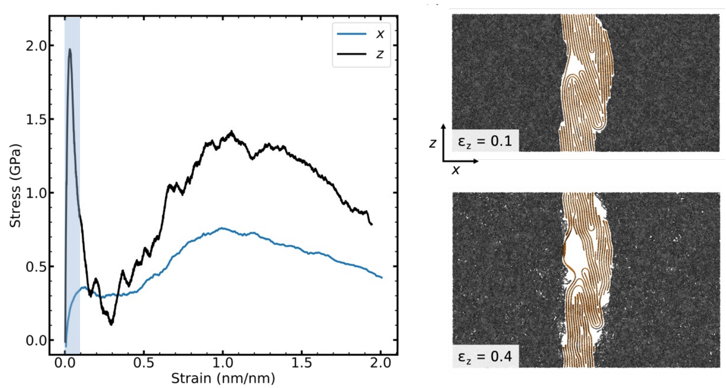
- Typical stress-strain curve for polymer in molecular dynamics model
- Qualitatively similar behavior seen in reinforced models beyond ~ 0.25 strain, after interfacial failure
- Initial yield and ultimate strains are overestimated for all three models due to high simulation strain rates

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

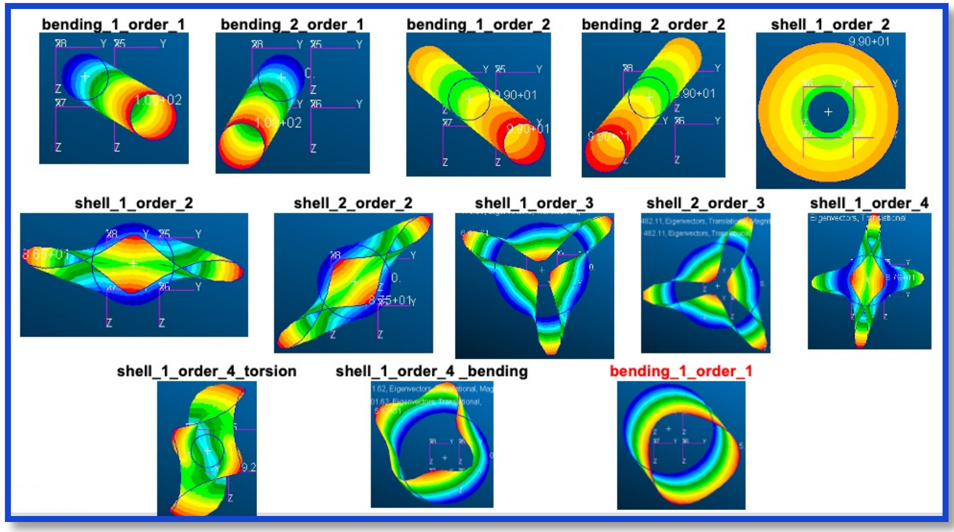


- More realistic model than planar graphitic surface often used for fiber-matrix models
- Larger initial modulus increase than small fiber model as more CNTs must disentangle

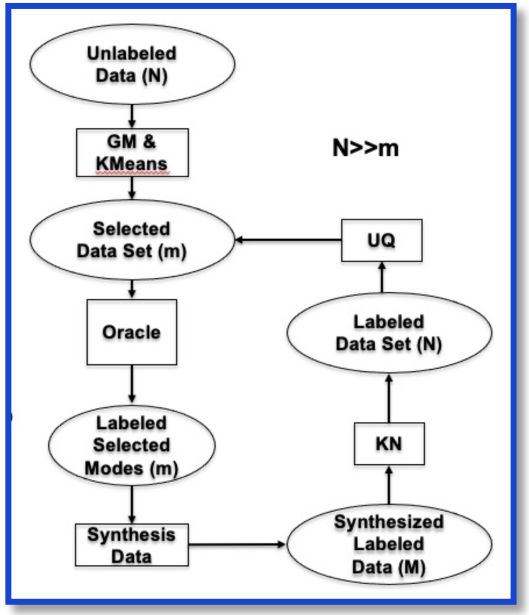
Realistic modeling of fiber/matrix interface will be used to guide process development.

Image credits: NASA

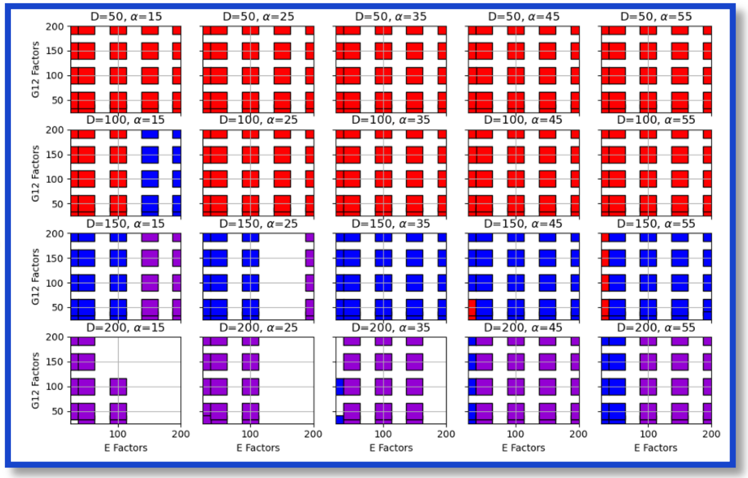
Accomplishments
Systems Analysis



Parameters that Influence Component Performance



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.
- Analysis will guide definition of demo article to be defined in the next FY.

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

Accomplishments

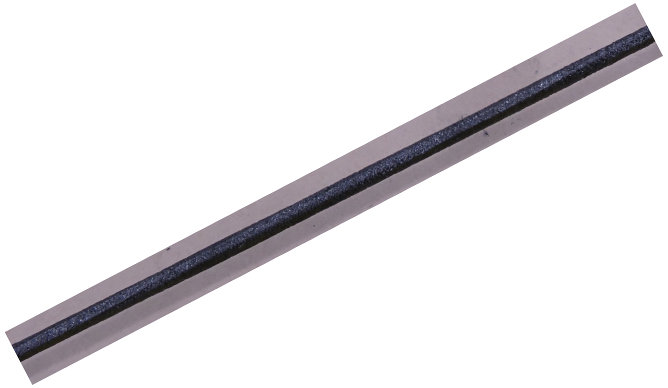
CNT Structure Prototype Fabrication in Progress

Second Generation Linerless CNT Composite Pressure Vessel (COPV)

- Made with microcrack resistant resin designed for cryogenic applications.
- First generation CNT COPV resulted in recommendation for modified CNT better suited for COPV fabrication.

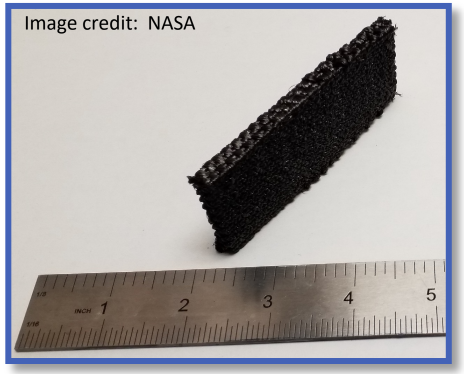
Nozzle Extensions

- High strength CNT yarn used for net shape composite.



Composite Heat Exchanger Tubes for Nuclear Thermal Propulsion

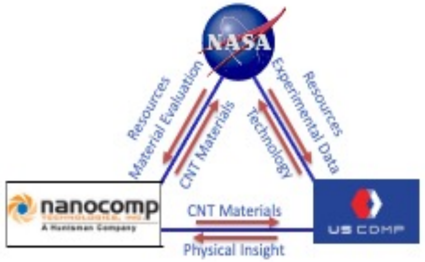
- High strength CNT yarn used as reinforcement for extreme temperature structure.



Woven Fabric

- High strength CNT yarn is being used to produce 3d woven preforms.

Objective 8
KPP 1, 2, 3, 4 & 5

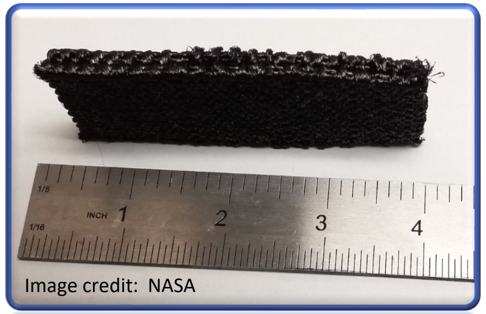


Prototyping engages new ecosystem entities and provides product feedback to CNT manufacturer for process optimization.

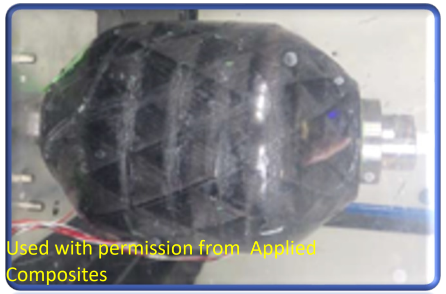
Project Assessment Summary

SAC	Performance				Comments
	C	S	T	P	
Mid Year					Cost – No issues Schedule – Milestone completion for fracture toughness test data had to be shifted to the end of the FY due to technical challenges. Technical – There were process development challenges for the fracture toughness milestone. Programmatic: No issues
Annual					Cost – No issues Schedule – Milestone for fracture toughness in on track to be met. Technical – Challenges related to fracture toughness specimen fabrication were resolved. Programmatic: No issues

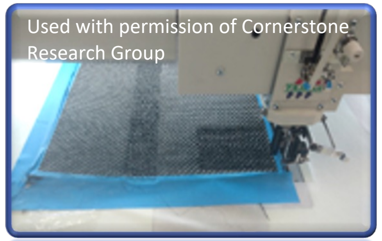
Plans Forward and Transition / Infusion Plan



Woven Preform Net Shaped Aerospace Components

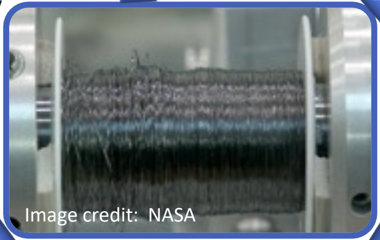


Lightweight Linerless CNT Composite Pressure Vessel



Lightweight Net Shaped Aerospace Components

Nozzle Extensions
SBIR/State of Ohio/DoE

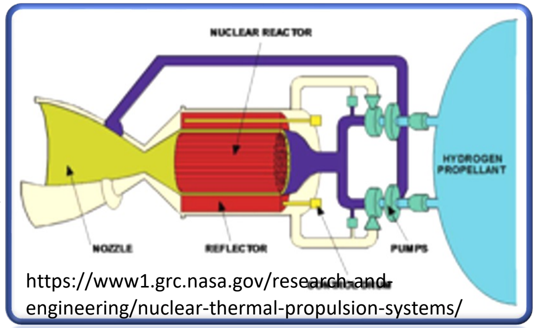


High Strength CNT Core Technology

Structural Health Monitoring for Urban Air Mobility
ARMD/SBIR/RVLT
(Revolutionary Vertical Lift Technology)

Embedded Sensors

Lightweight Heat Exchanger Tubes



Nuclear Thermal Propulsion

Education/Public Outreach

- **Journal Publications**
  - Xu, H., Drozdov, G., Park, J. G., Jensen, B. D., Wise, K. E., Liang, Z., Odegard, G. Siochi, E. J., Dumitrică, T., “Computationally-Guided Design of Large-Diameter Carbon Nanotube Bundles for High Strength Materials,” *ACS Applied Nano Materials*, **4**(10), 11115-11125, 2021.
  - Baber, F., Kim, J-W., Sauti, G., Wincheski, R. W., Wise, K. E., Siochi, E. J., Guven, I., “Microstructural Exploration of a Carbon Nanotube Yarn Reinforced Composite Using a Peridynamic Approach*,” Journal of Composite Materials,* **56**(6), 861-876, 2022.
  - Kim, J-W., Gardner, J. M., Sauti, G., Wincheski, R. A., Jensen, B. D., Wise, K. E., Siochi, E. J., "Multi-scale Hierarchical Carbon Nanotube Fiber Reinforced Composites: Tensile Properties and Fracture Toughness," *Manuscript in preparation*, 2022.

- **Patent**
  - U. S. Patent No: 11,097,499: Polyaniline/Carbon Nanotube Sheet Nanocomposites.

- **Presentations**
  - Siochi, E. J., Panel speaker on TRL 1-3 - Cutting Edge of Composites Panel, Auburn University Center for Polymers and Advanced Composites Colloquium, Auburn University, November 15, 2021.
  - Siochi, E. J., “Fast Tracking Emerging Technology Development for Space Exploration A Carbon Nanotube Example,” Advanced Materials for Defense Summit, Alexandria, VA, November 3, 2021.
  - Siochi, E. J., Panel speaker on CNT Publication Landscape, Guadalupe Workshop X on Single Wall Carbon Nanotubes & Related Materials on May 14, 2022 as a panel member to discuss the CNT publication landscape.
  - Siochi, E. J., Briefing to NASA Advisory Council, Technology, Innovation, and Engineering Committee Meeting, "US-COMP NSTRI," August 3, 2022.
  - Siochi, E. J., "Accelerating the Maturation of New Technologies, A Carbon Nanotube Example," Chemical Marketing & Economics NASA Symposium, American Chemical Society Fall Meeting, August 22, 2022.

- **Research Collaborators**
  - Several members of the SAC team supported the US-COMP annual review in Richmond, VA.

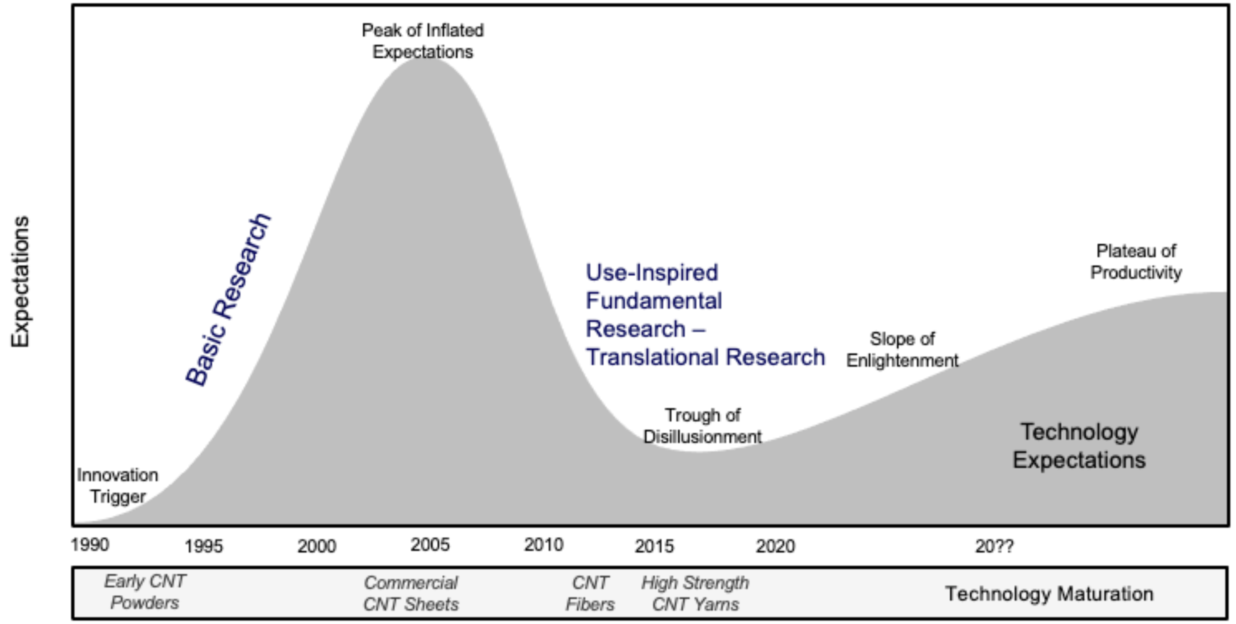
- **Workshop Participation**
  - Gissinger, J. G., Wise, K. E., C/C Process Modeling Workshop, November 9-10, Dayton, OH.

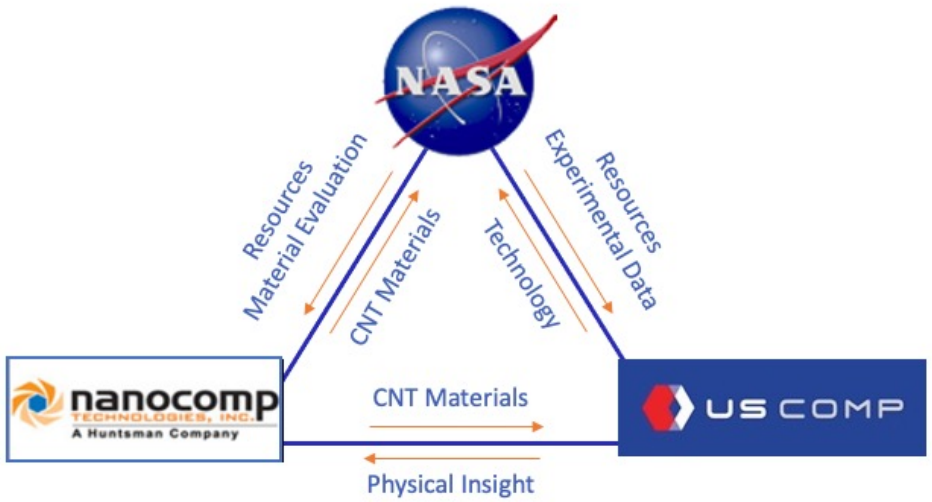
Summary
Accomplishments for the Year

- CNT manufacturing advances have yielded CNT yarn properties competitive with high performance fibers.
- CNT yarn mechanical properties in combination with electrical properties open up applications that benefit from CNT reinforcement properties.
- Realistic computational model of CNT/matrix was developed and provides insight on CNT composite processing factors that enhance transverse mechanical properties.
- CNT composite mechanical properties were expanded to include transverse tensile properties and fracture toughness.
- Systems analysis revealed that there are advantages to using high specific modulus materials in non-pressurized structures to improve systems performance.
- Multiple prototyping efforts are engaging external collaborators in the production of articles for aerospace applications, allowing the evaluation of high strength CNT materials as its manufacturing evolves.

Summary

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.