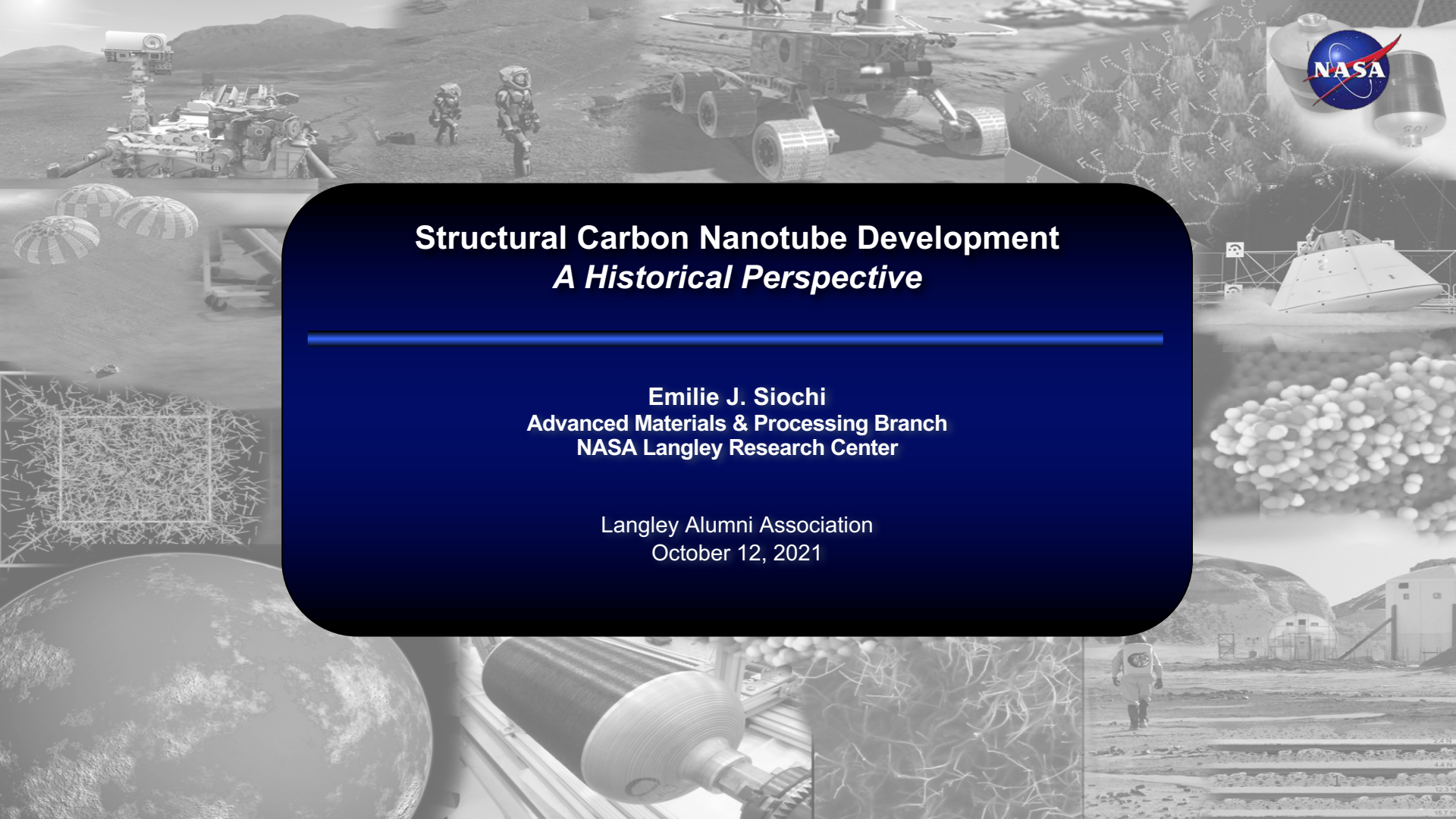




Structural Carbon Nanotube Development *A Historical Perspective*

Emilie J. Siochi
Advanced Materials & Processing Branch
NASA Langley Research Center

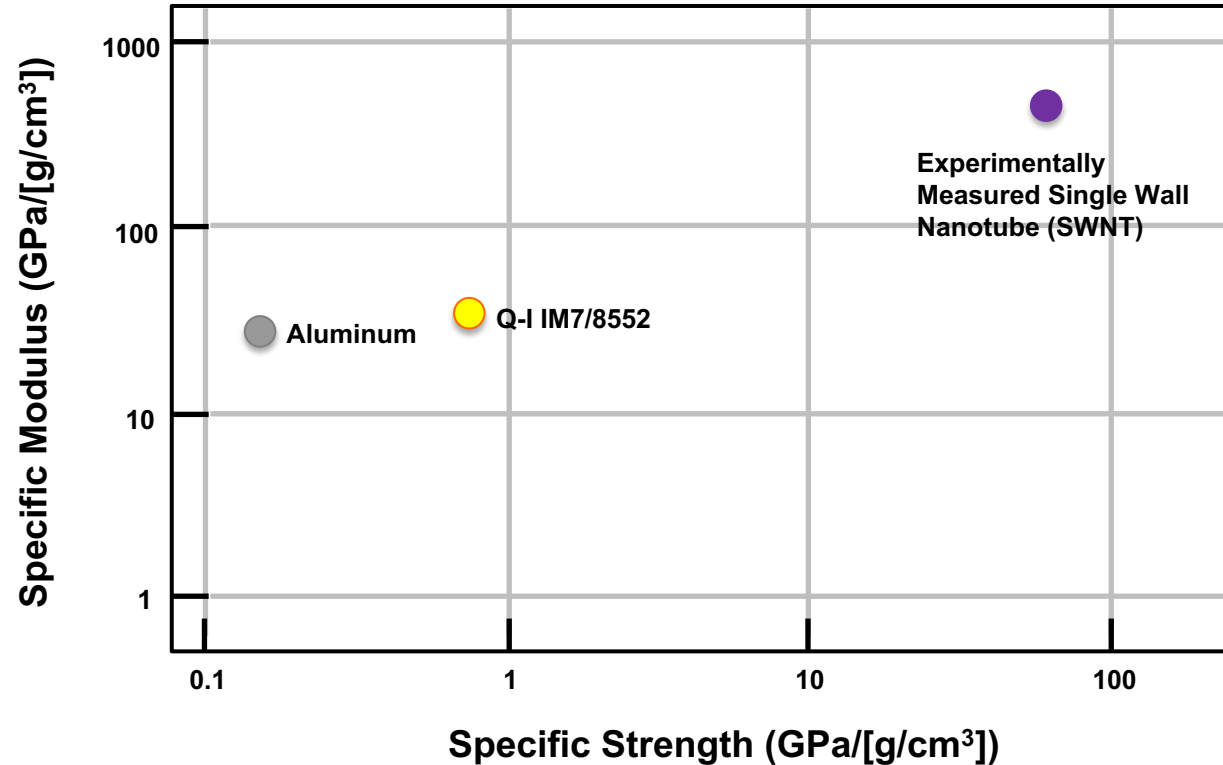
Langley Alumni Association
October 12, 2021

Summary of the Problem

- Cost increases in proportion to the mass ratio.
- Mass ratio increases linearly with the dry mass and exponentially with Δv .
- Reducing structural mass reduces mission cost at constant payload or increases mission capability at constant cost.

	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

Motivation

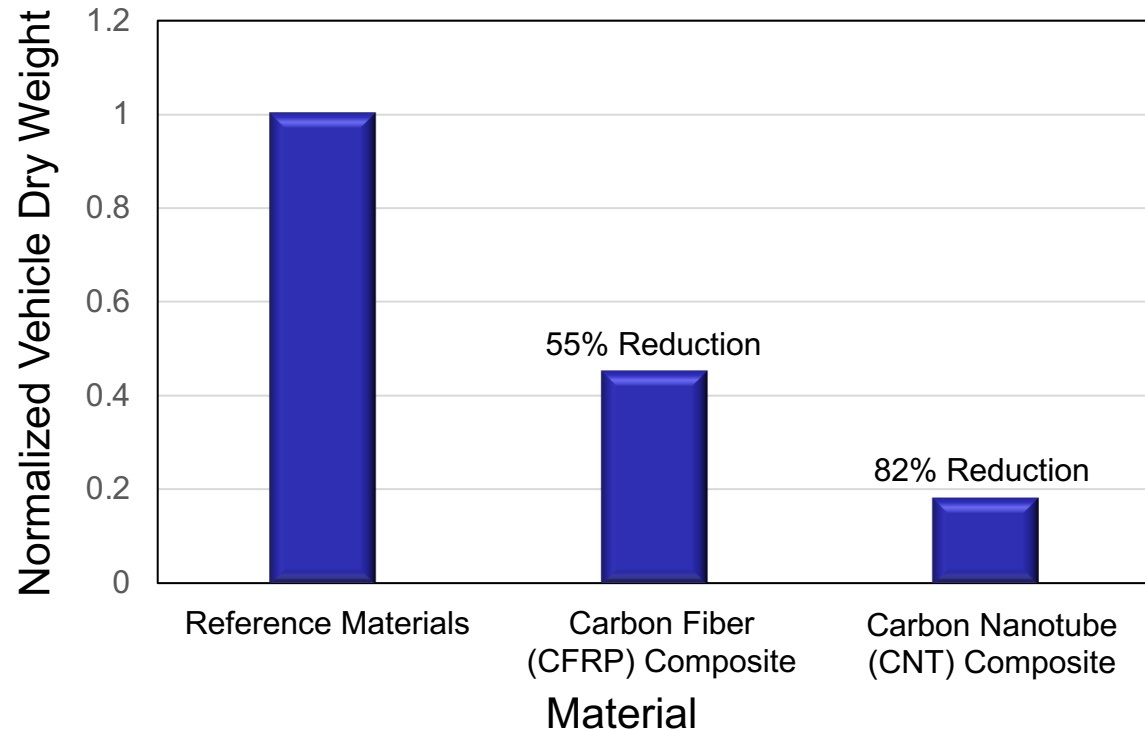


Motivation



Reusable Launch Vehicle
Systems Analysis Model

Reusable Launch Vehicle Systems Analysis



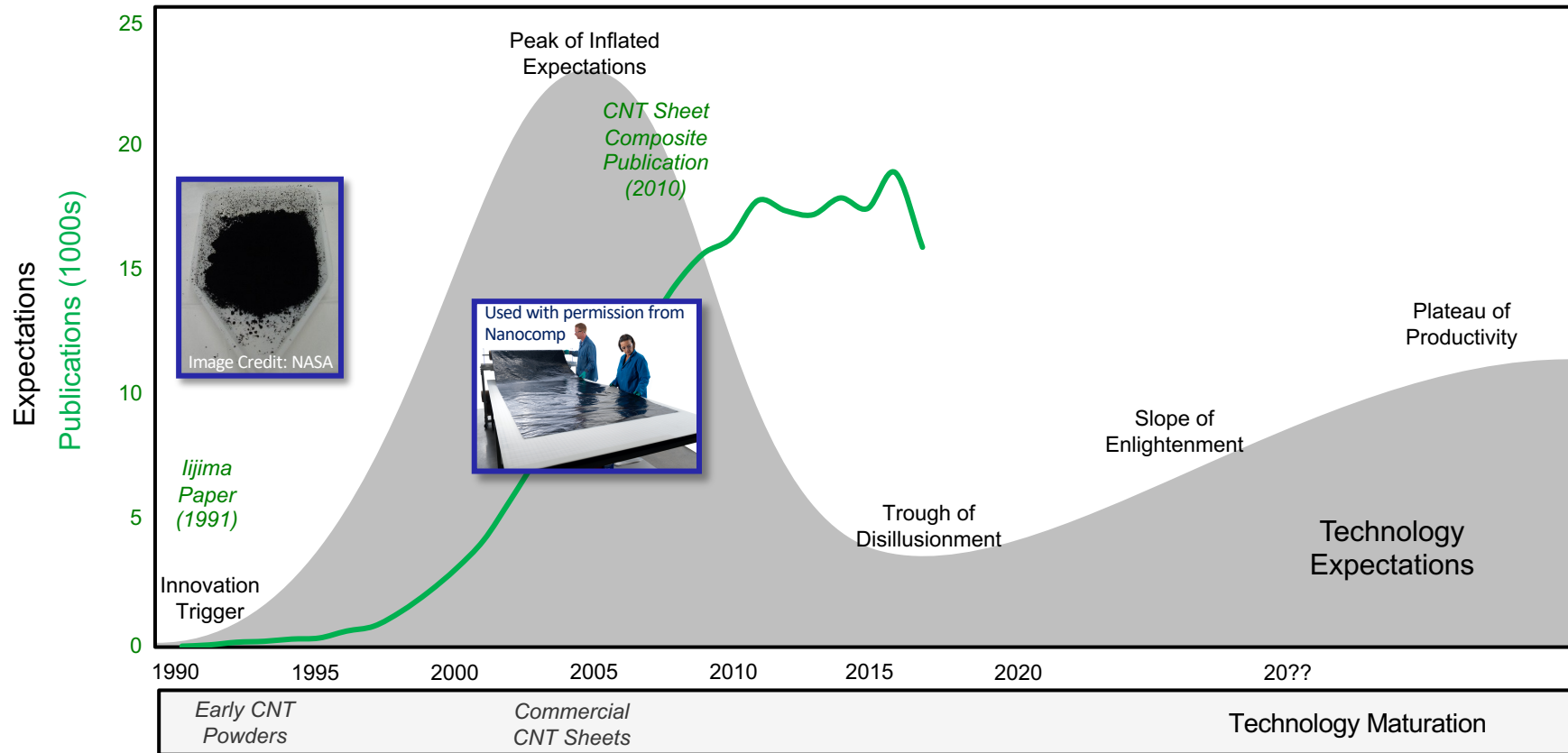
Technology Development Approaches

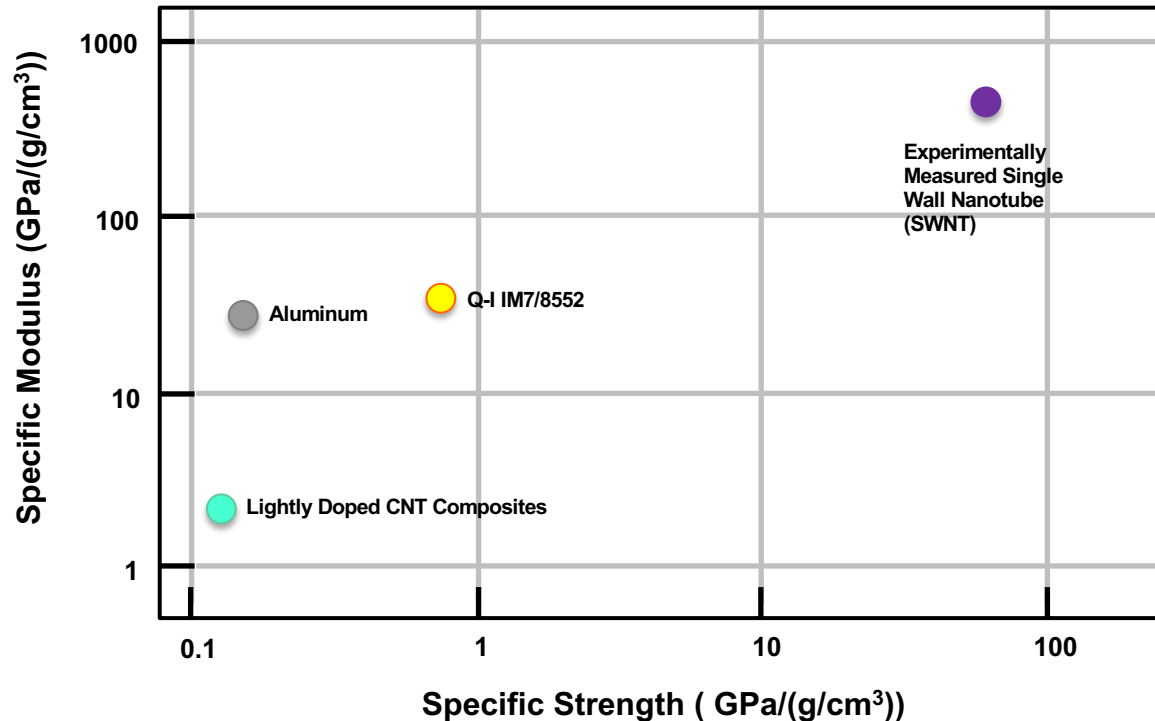


- **Technology Push**
- **Technology Pull**
- **Technology Pull Guided Technology Push**

- 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

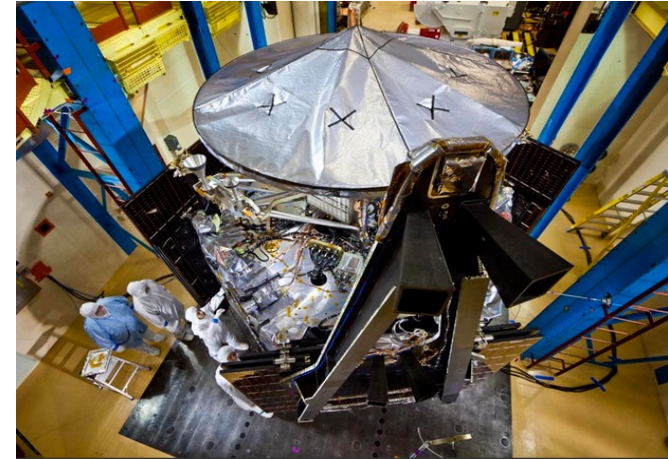
Technology Development Approaches



- Technology Push
- **Technology Pull**
- Technology Pull Guided Technology Push

- Performance needs identified
- Schedule driven
- Solution space defined by what is ready for insertion
- Typically risk averse

Carbon Nanotubes on Juno Spacecraft



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.

Lessons Learned

- Emerging technology can be implemented if it meets a performance requirement for which there is no other existing solution.
- Technology must be evaluated for the required function.
- Technology must be ready to insert on schedule.
- Structural performance objective still not realized, but technology was flown due to other performance benefits.

Technology Development Approaches



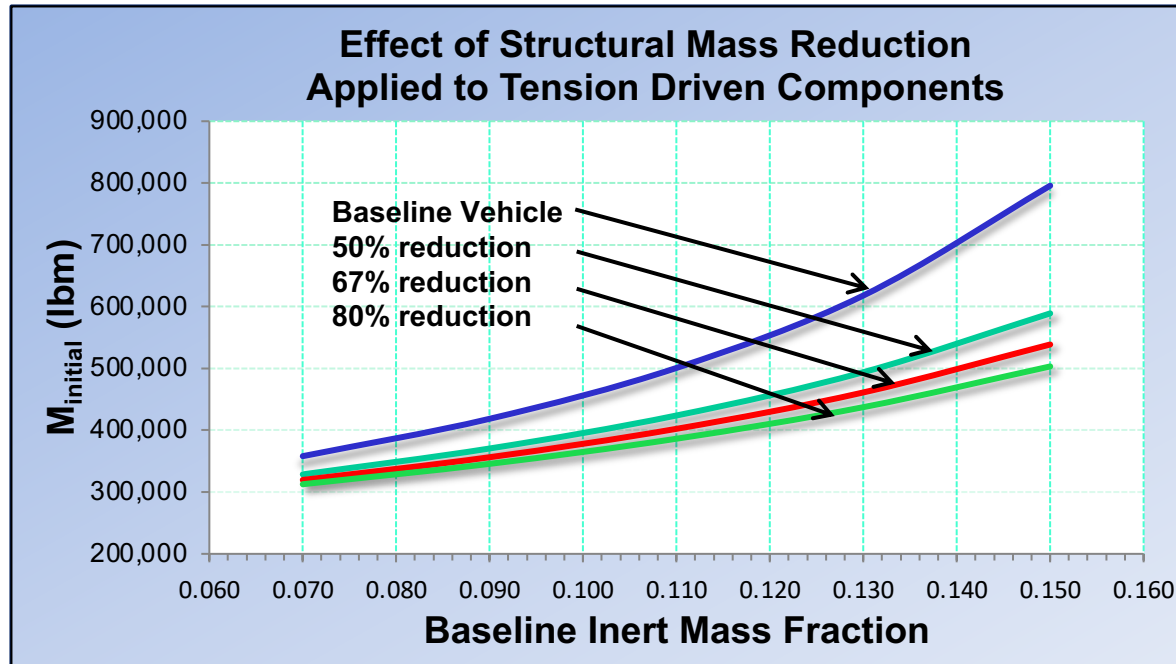
- Technology Push
- Technology Pull
- **Technology Pull Guided Technology Push**

Technology Pull Guided Technology Push



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

Setting Goals using Systems Analysis



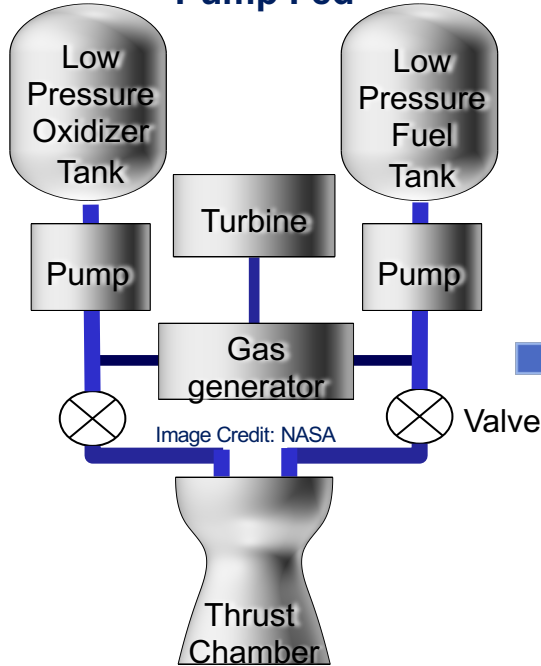
- A 2-3x improvement in specific mechanical properties will permit substantial mass reduction in structural and non-structural components.

Setting Goals using Systems Analysis

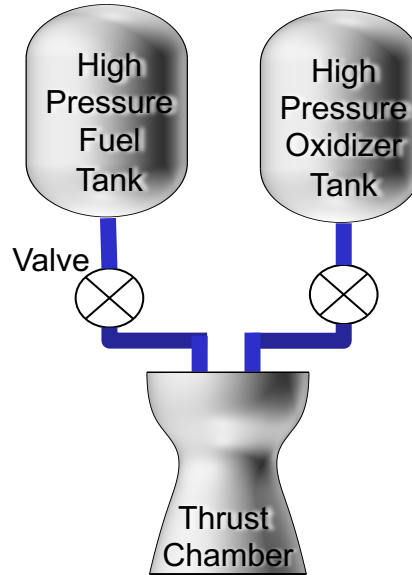


Cargo Mars Ascent Vehicle (MAV)

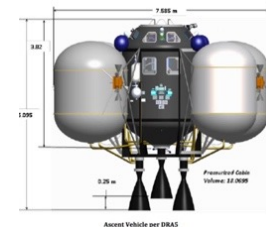
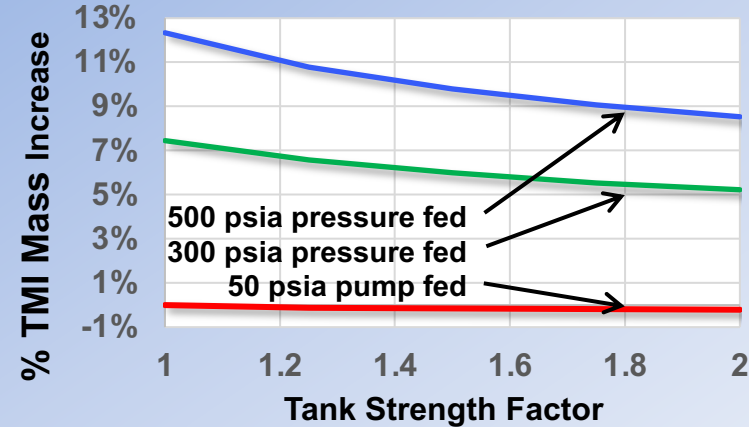
Pump Fed



Pressure Fed



Mass Characteristics of Traditional Cryo Pressure Tanks

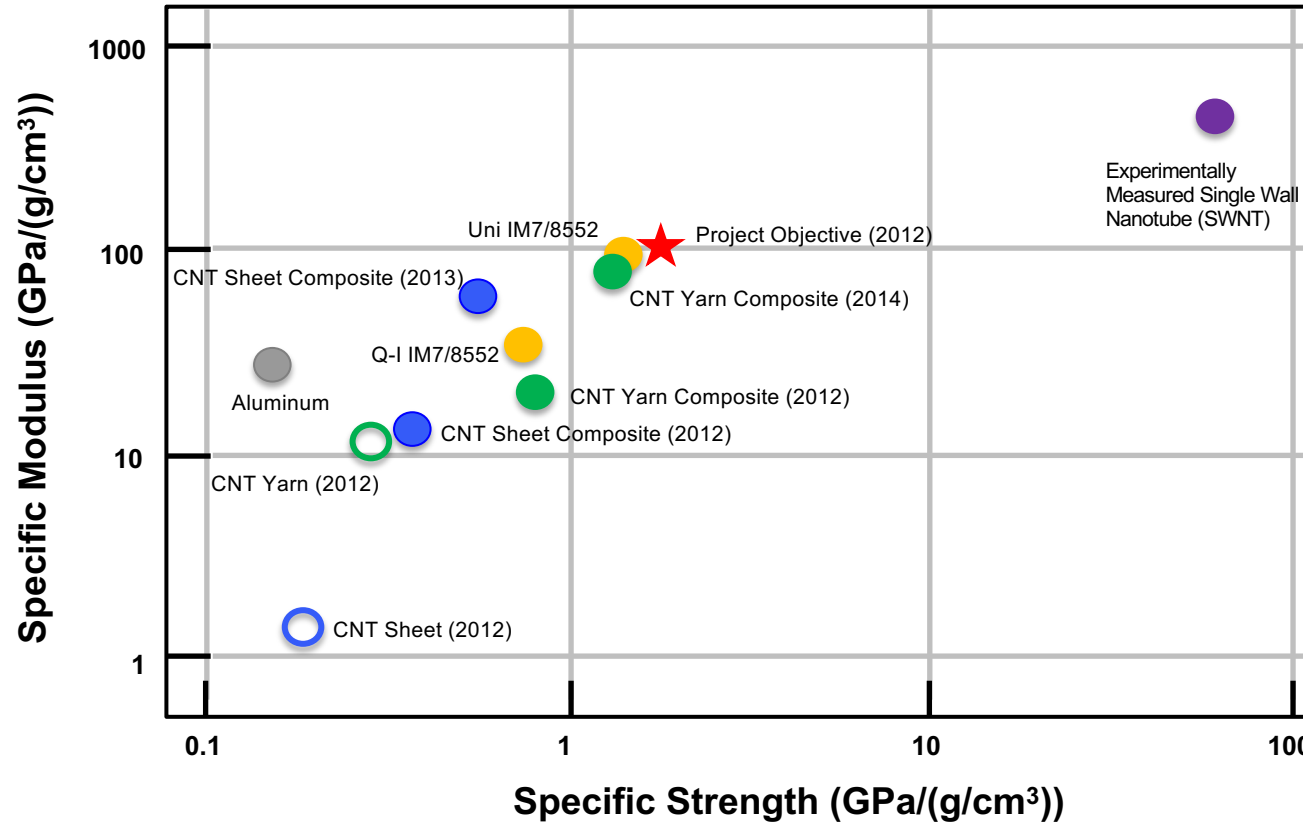


➤ Mass savings are potentially large enough to change propulsion system design concept.

State of the Art Lightweight Structural Material



Nano to Macro Challenge

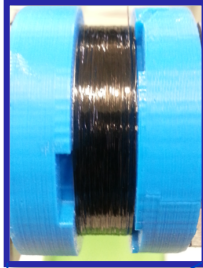


Rapid Prototyping of CNT Composite Fabrication

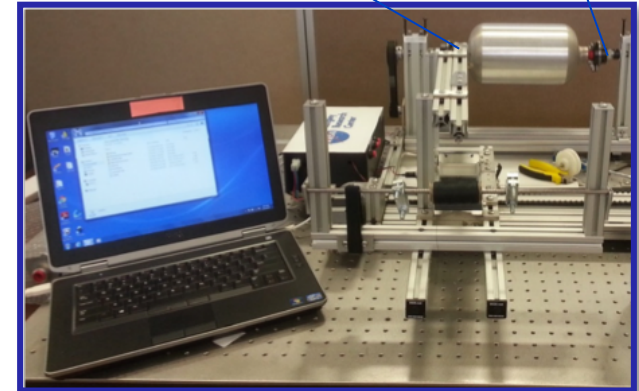
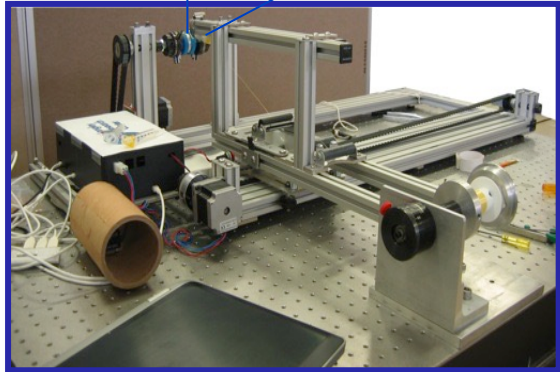
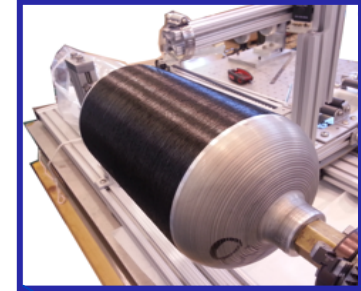


Tabletop Filament Winder for Rapid Prototyping of Composite Processing

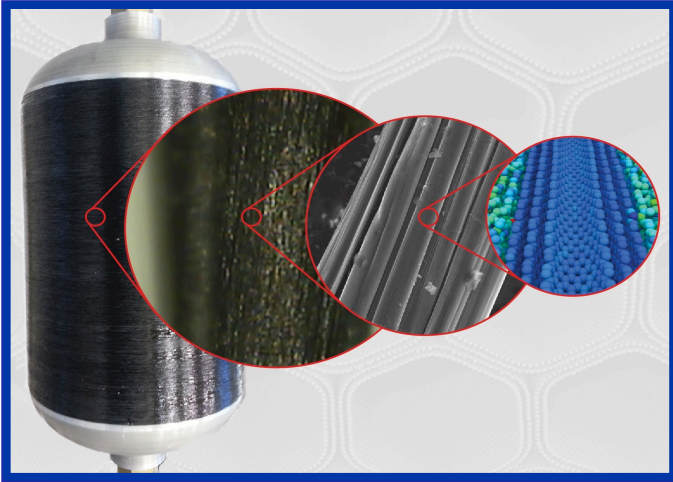
Aluminum Ring



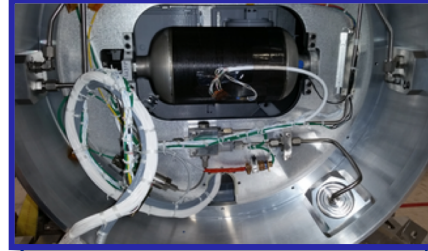
CNT Composite Overwrapped Pressure Vessel



Computationally Guided Use Driven Materials Research



October 2013 – September 2015



October 2016



May 2017

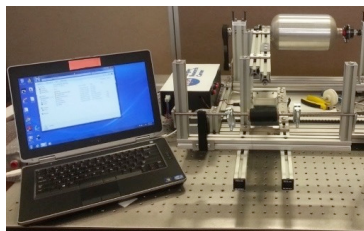
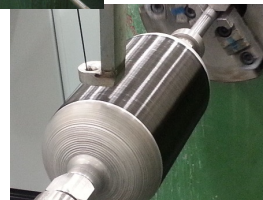
Image Credit: NASA

<https://www.nasa.gov/feature/nanotechnology-flight-test-material-impact-on-the-future>

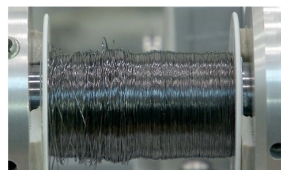
Prototyping to Support Materials Development



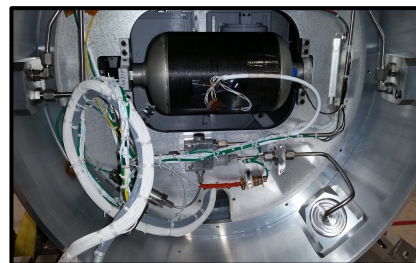
Commercial Scale CNT Composite Winding



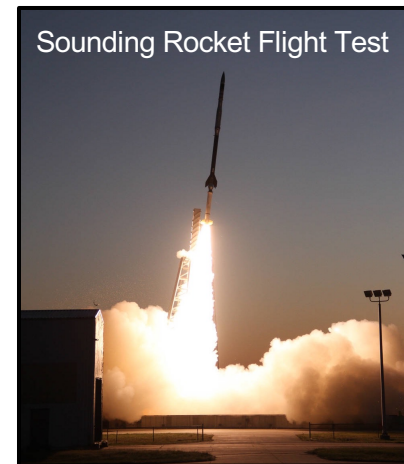
Composite Process Prototyping



High Strength CNT Yarn



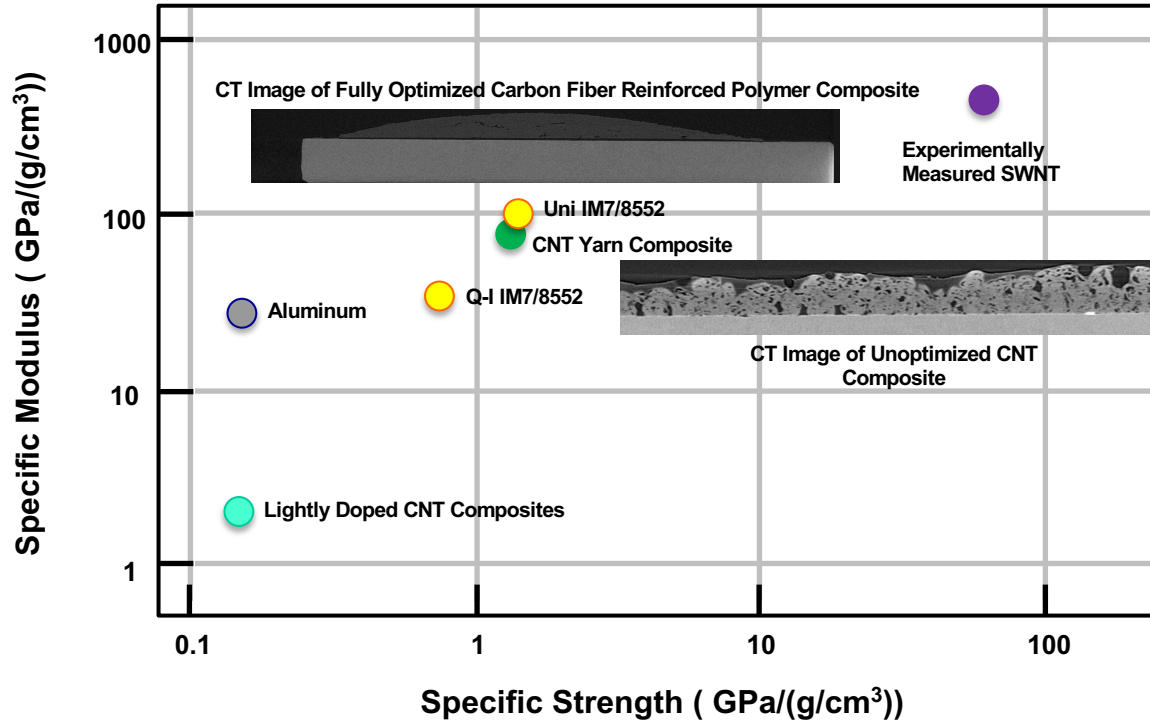
CNT Composite Overwrapped Pressure Vessel Cold Gas Thruster



Sounding Rocket Flight Test



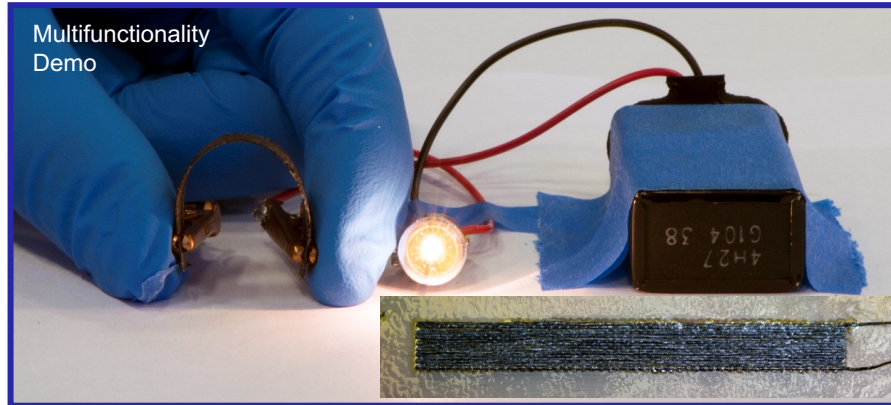
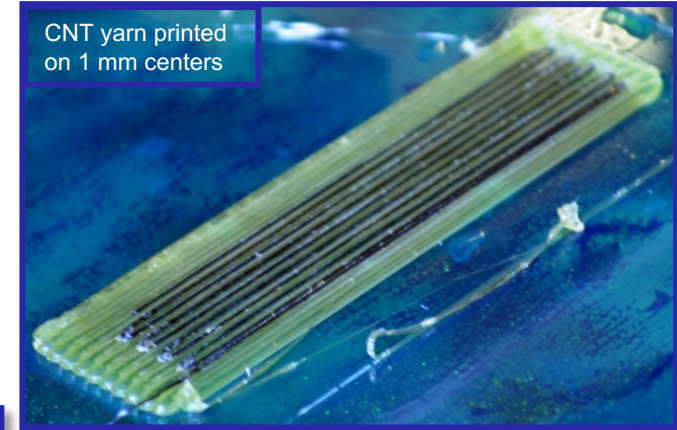
Sounding Rocket Integration



Measurable Advancements

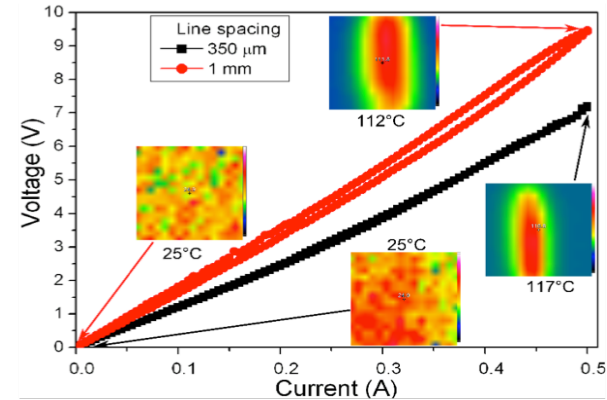
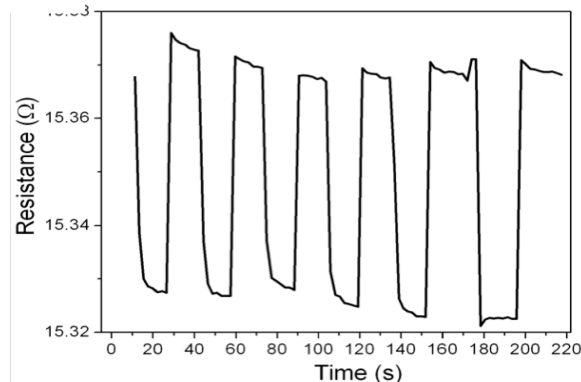
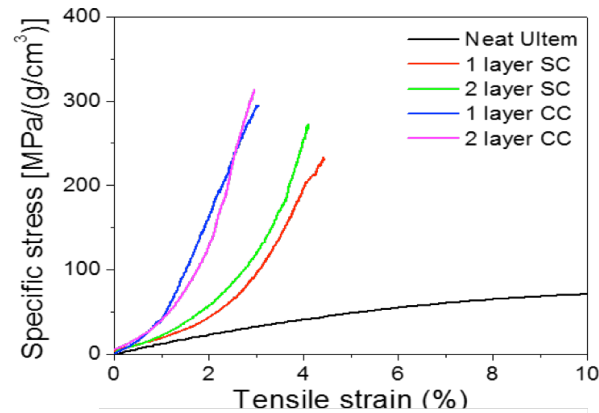
- Improvement in mechanical properties
 - Systems level guided, goal focused research.
 - Project objective provided basis for objective decisions.
- Increase in MRL
 - Volume – material available in spool lengths of hundreds of meters.
 - Consistency – materials met A-basis allowable of at least 20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

3D Printing of CNT Yarns



- CNT compliance allows for high fidelity printing
- Minimum turn radius equal to half the yarn diameter
- Multifunctionality of CNTs retained

Multifunctional 3D Printed Part

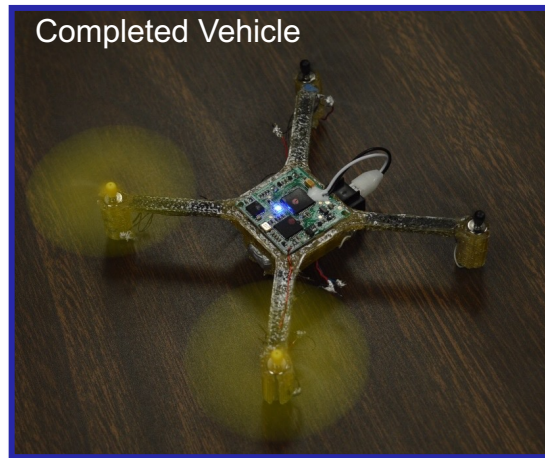
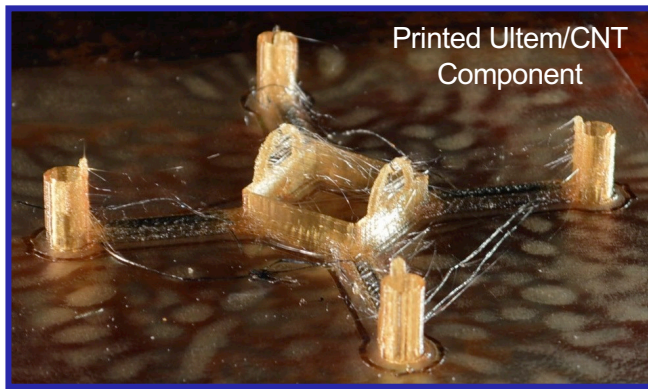
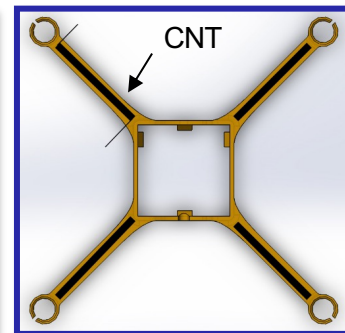
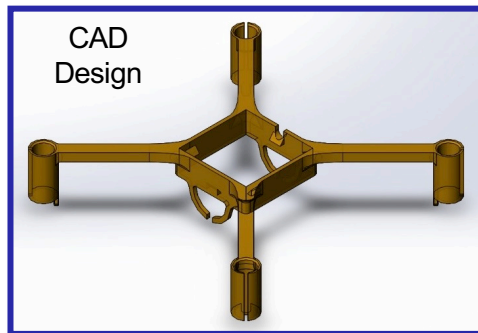


- Selective vs. Continuous
 - Tensile test of one and two-layer samples
- Strain Sensor
 - Cyclical 3-point bending
 - 5 kg load at 5% strain
- Heating Element
 - Current cycled from 0-0.5 A

3D Printed Functional Component

Quadcopter

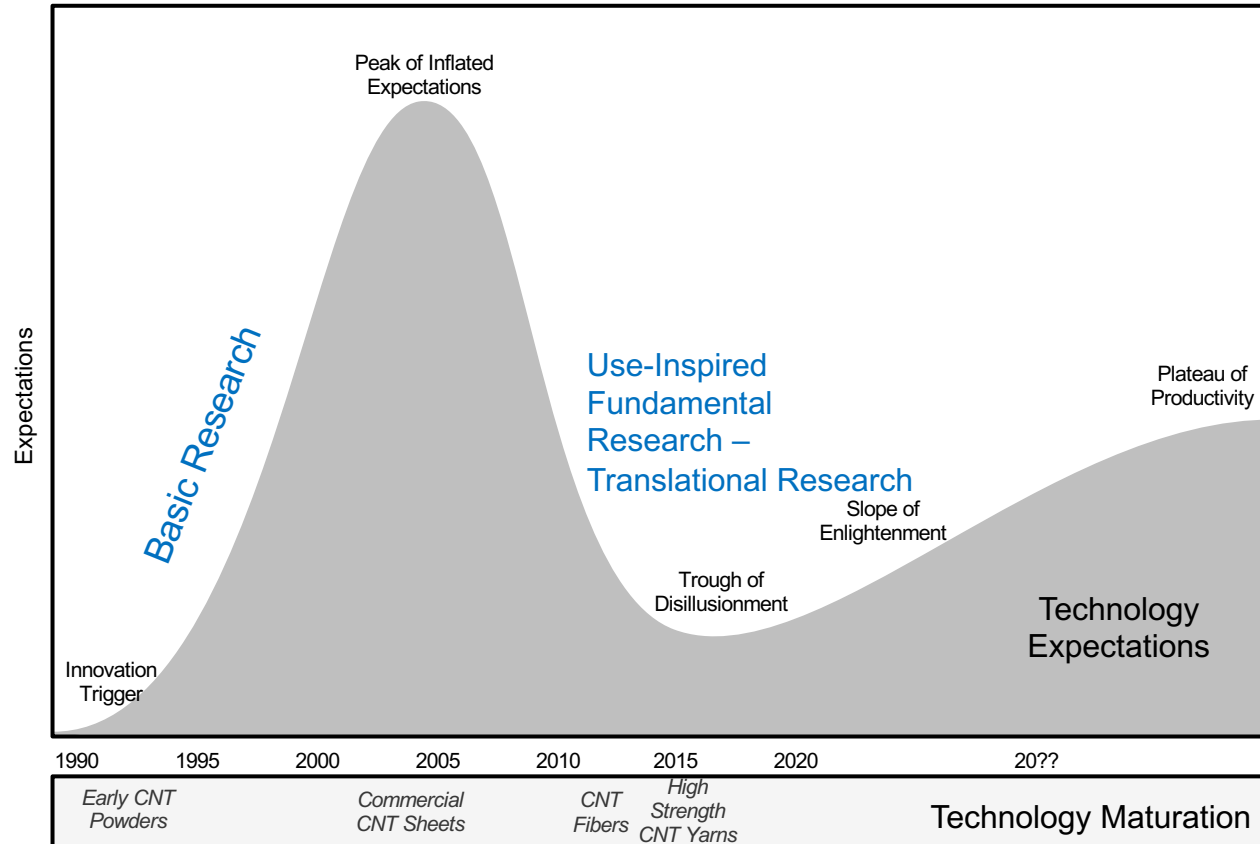
- Dimensions (rotor centers): 75 x 75mm
- Two 9-line CNT raster pattern (structural) depositions in each arm
- CNT yarn used to power motors



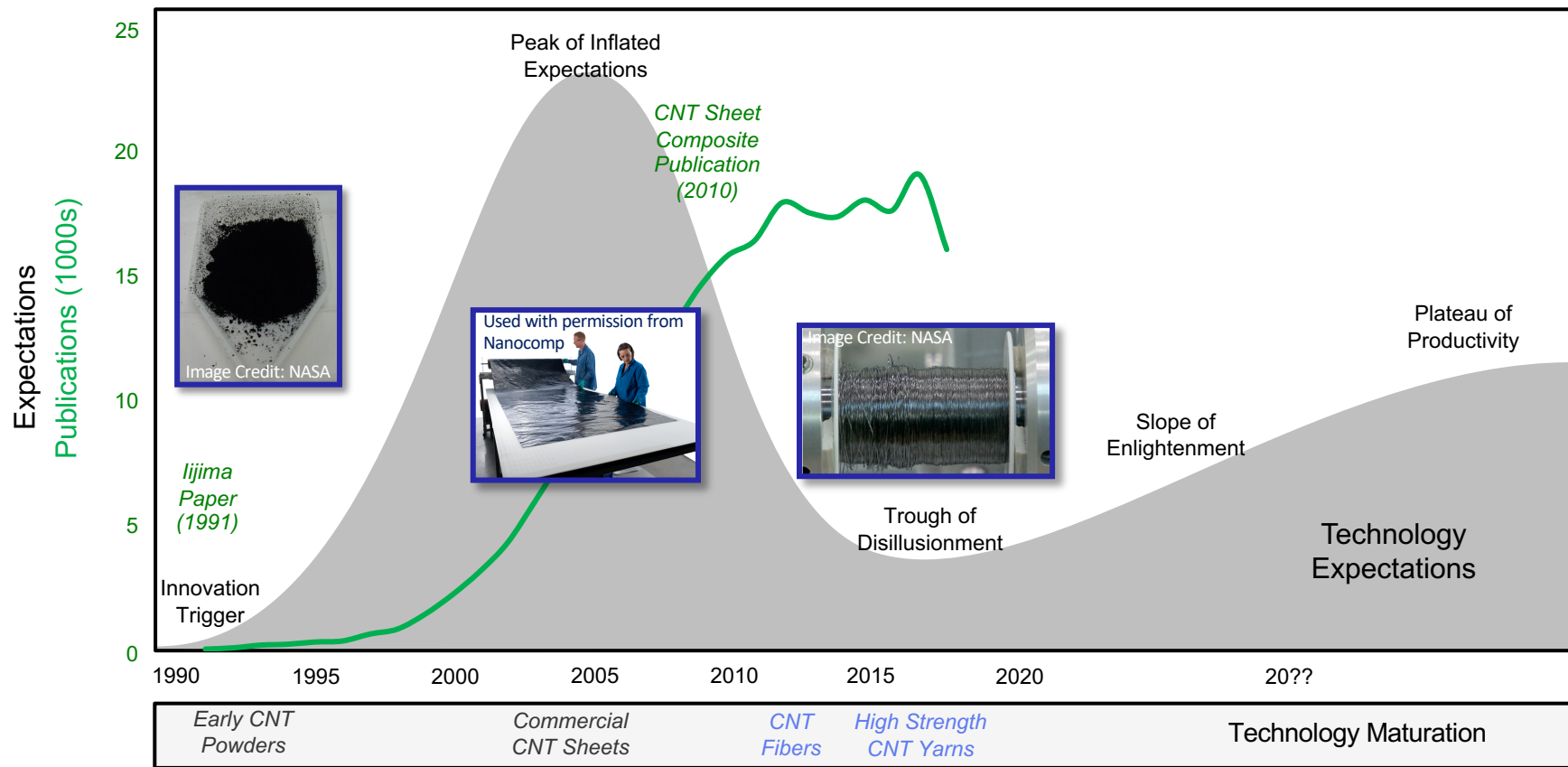
- Displacement of state of the art (SOA) technologies
 - Performance
 - Scale
 - Schedule
 - Risk
 - Cost

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

From Publications to Economic Payoff



Use Driven Technology Maturation



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

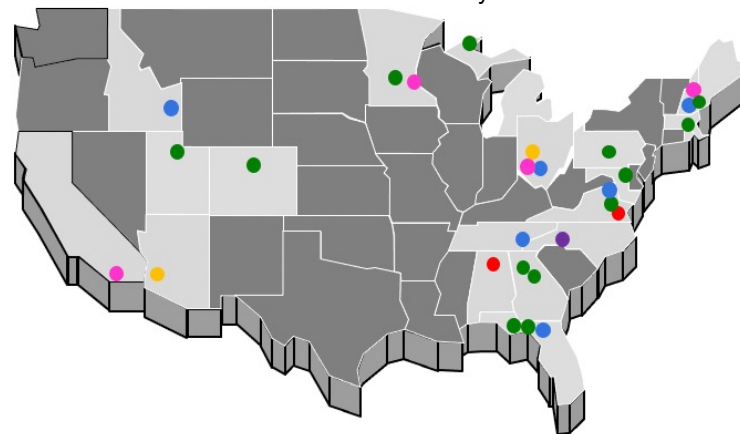
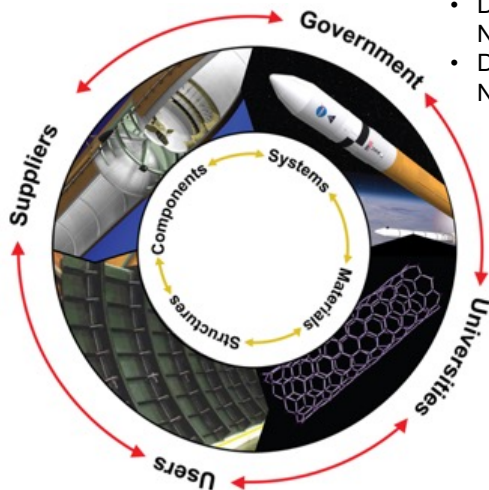
- Textum, Inc.

SBIR/STTR

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

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
- Nanocomp



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

Evolution of Role of NASA in the Nanotechnology Landscape

- Early
 - Basic research
 - From structural materials to multifunctional materials
- Current – Technology Transition
 - Evaluating payoff from investments
 - Metrics from systems level benefits
 - Define structural applications
 - Acknowledge realities of technology insertion
 - Integration of new tools – computational materials, 3D printing, machine learning
 - Bridging academia and industry
 - Publications are not a sufficient measure of payoff.
- Lessons learned and steps forward
 - Challenges of collaborations between academia and industry for national benefit
 - Collaboration and coordination efforts across funding agencies would benefit from opportunities for technology transition pull, including from major industry users.
 - Technology insertion is based on performance and value.

Provide technology pull as a means of demonstrating measurable technology maturation



Acknowledgements

LaRC Team

➤ Composite Processing

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

➤ Characterization/Testing

- Russell Wincheski
- Jae-Woo Kim
- Godfrey Sauti

➤ Polymer Synthesis

- Joseph Smith
- Scott Zavada

➤ Financial Analyst

- Damon Sheaffer

➤ Computational Modeling

- Benjamin Jensen
- Kristopher Wise
- Jacob Gissinger

➤ Systems Analysis

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



Technology pull can guide accelerated maturation of emerging technologies.