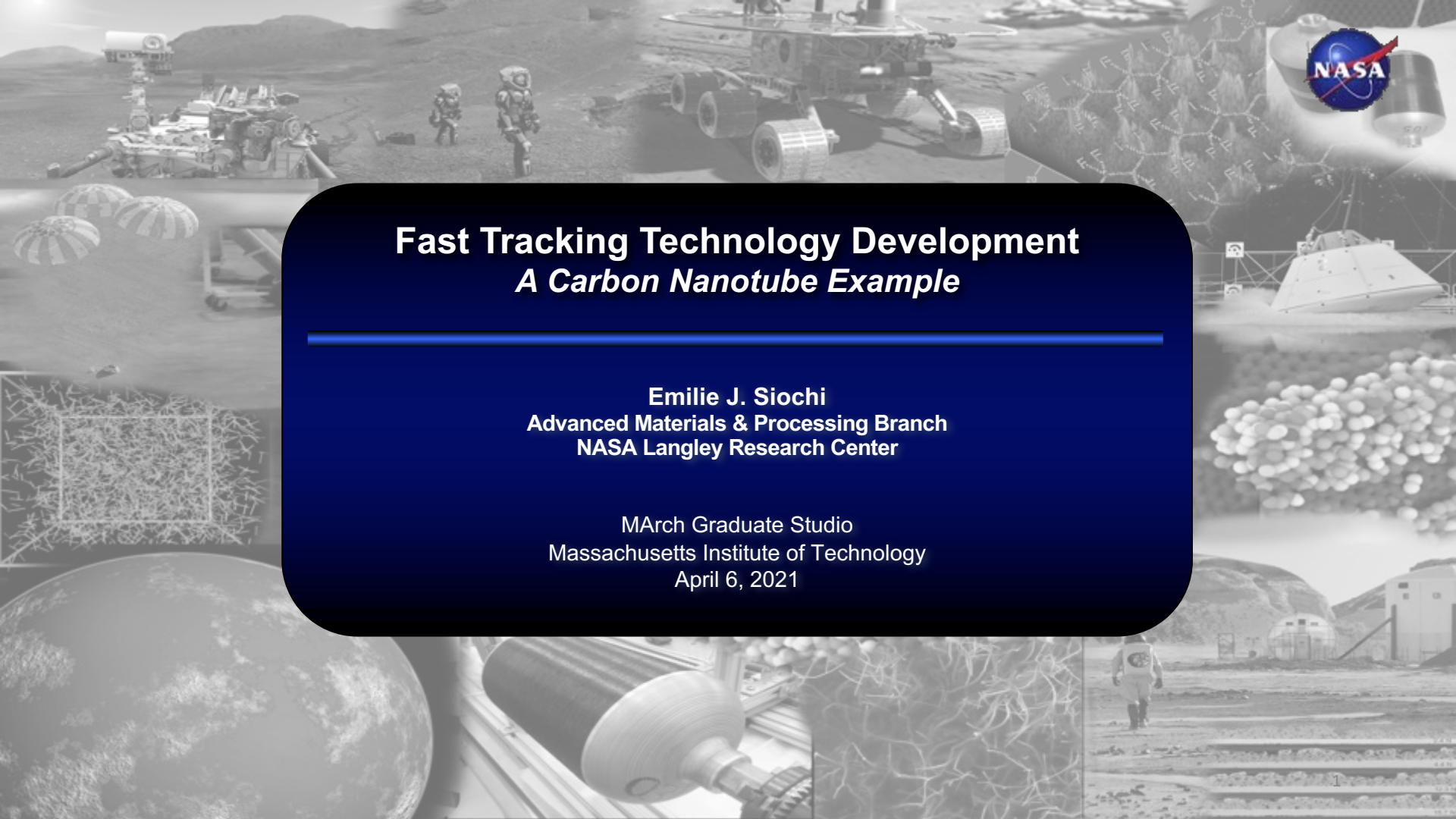

Fast Tracking Technology Development
A Carbon Nanotube Example

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April 6, 2021

Motivation

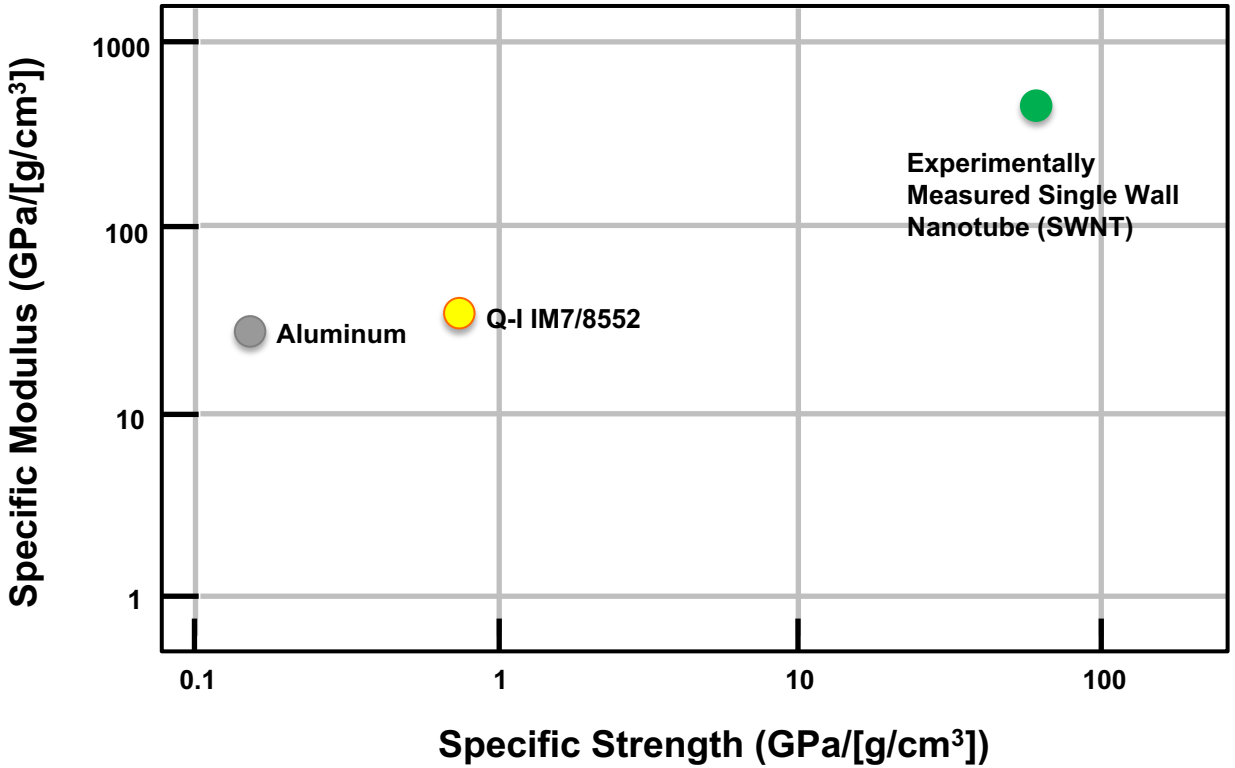
Summary of the Problem

- 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

*Order of magnitude estimates for mass ratios and costs G. Gordon, AIAA SPACE 2007, paper 6278

Motivation



Harris, Shuart, Gray, NASA TM 211664, 2002

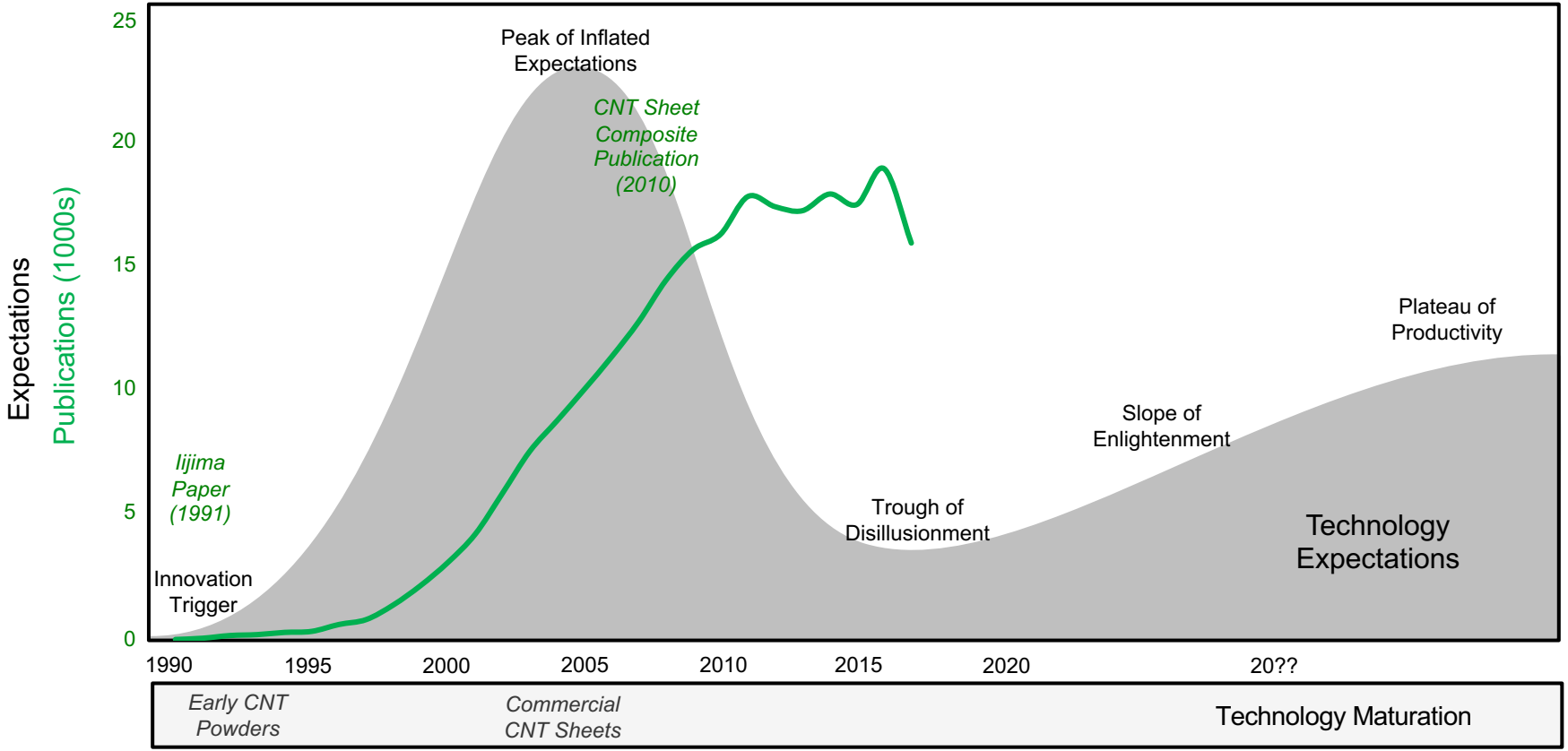
Technology Development Approaches

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

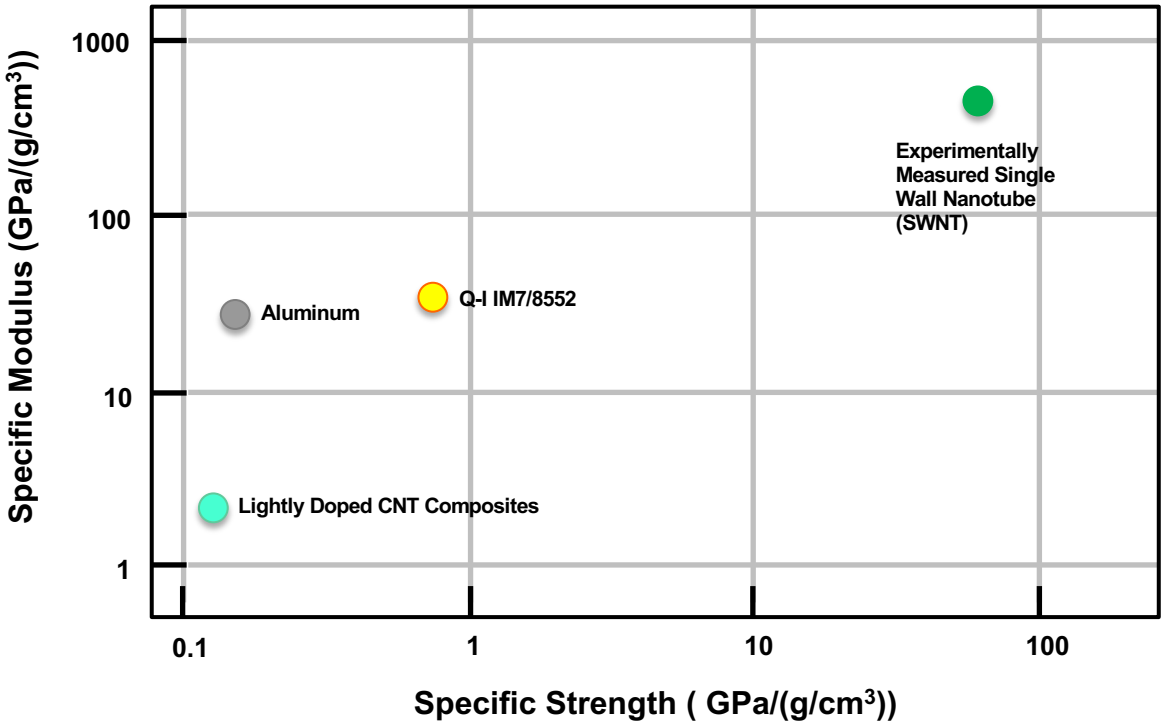
Technology Push

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

Carbon Nanotube (CNT) Gartner Hype Cycle



Outcomes



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

Representative data point from Structural Nanocomposites for Aerospace Applications, Siochi, E. J. & Harrison, J. S., MRS Bulletin, 40, October 2015, pp. 829-835.

Technology Development Approaches

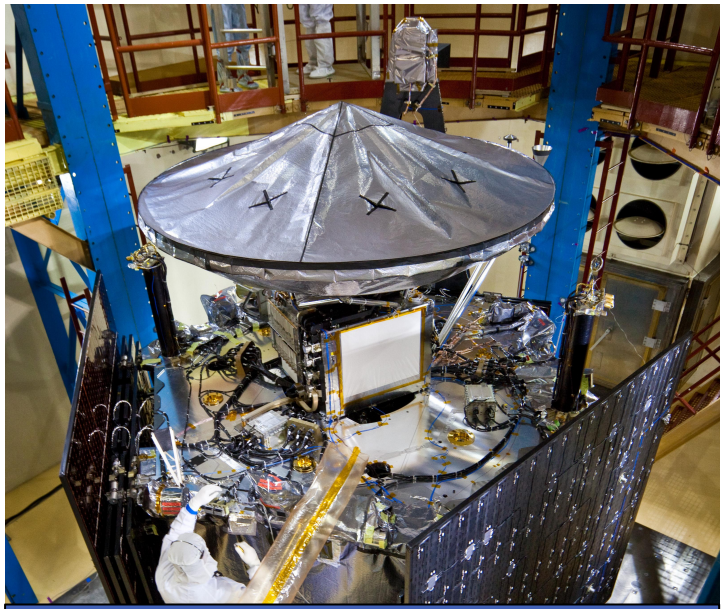
- Technology Push
- **Technology Pull**
- Technology Pull Guided Technology Push

Technology Pull

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

Carbon Nanotubes on Juno Spacecraft

All NASA Images



Carbon nanotubes were used in the engine cover and facesheets of the Juno spacecraft.

Outcomes

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 is flown due to other performance benefits.

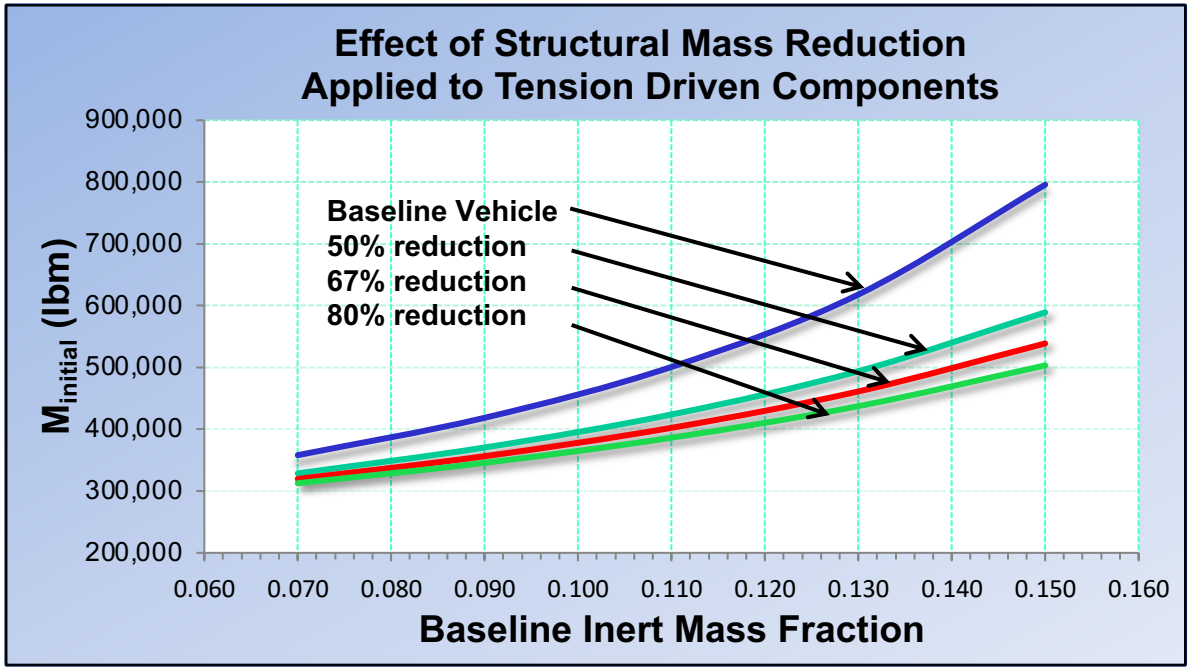
Technology Development Approaches

- 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

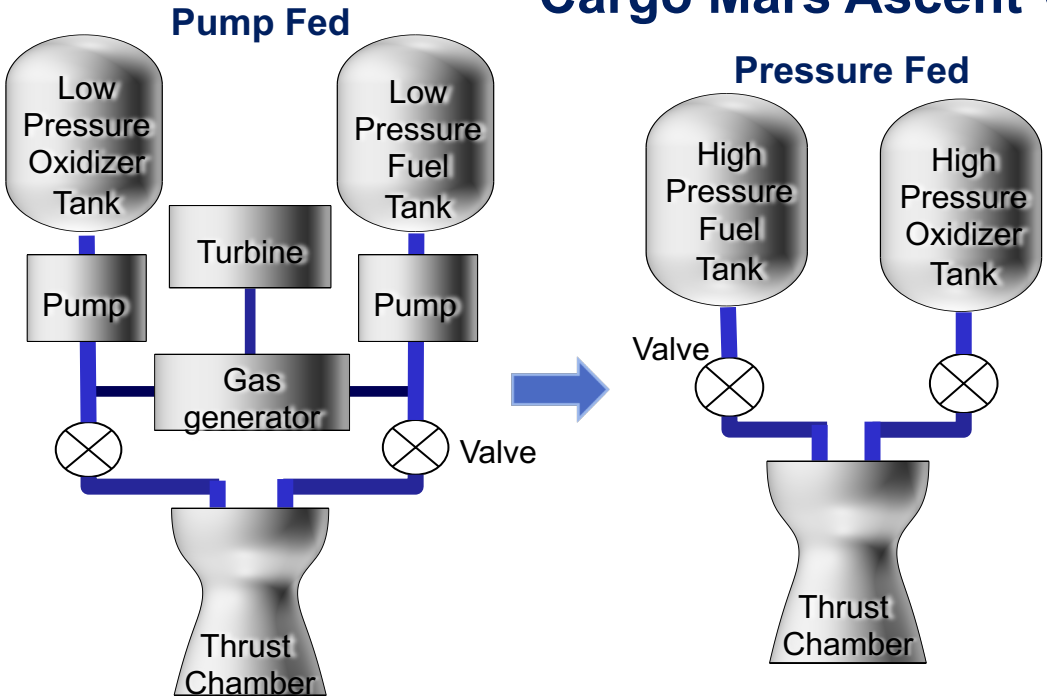


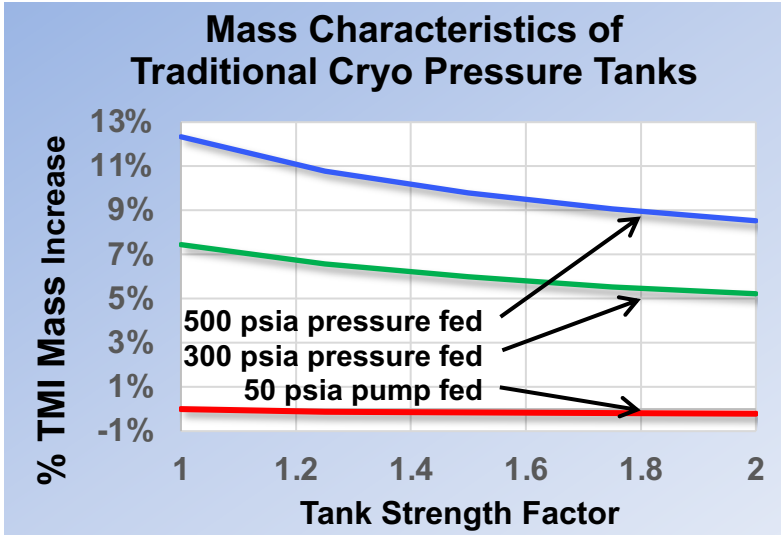
- A 2-3x improvement in specific mechanical properties will permit substantial mass reduction in structural and non-structural components

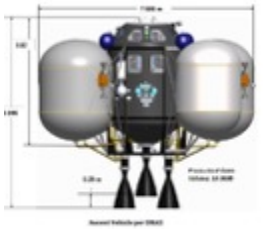
McMillan, M., System Level Impact of High Strength Carbon Nanotube Materials Applied to Launch Vehicle Concepts, White Paper, March, 2013.

Setting Goals using Systems Analysis

Cargo Mars Ascent Vehicle (MAV)



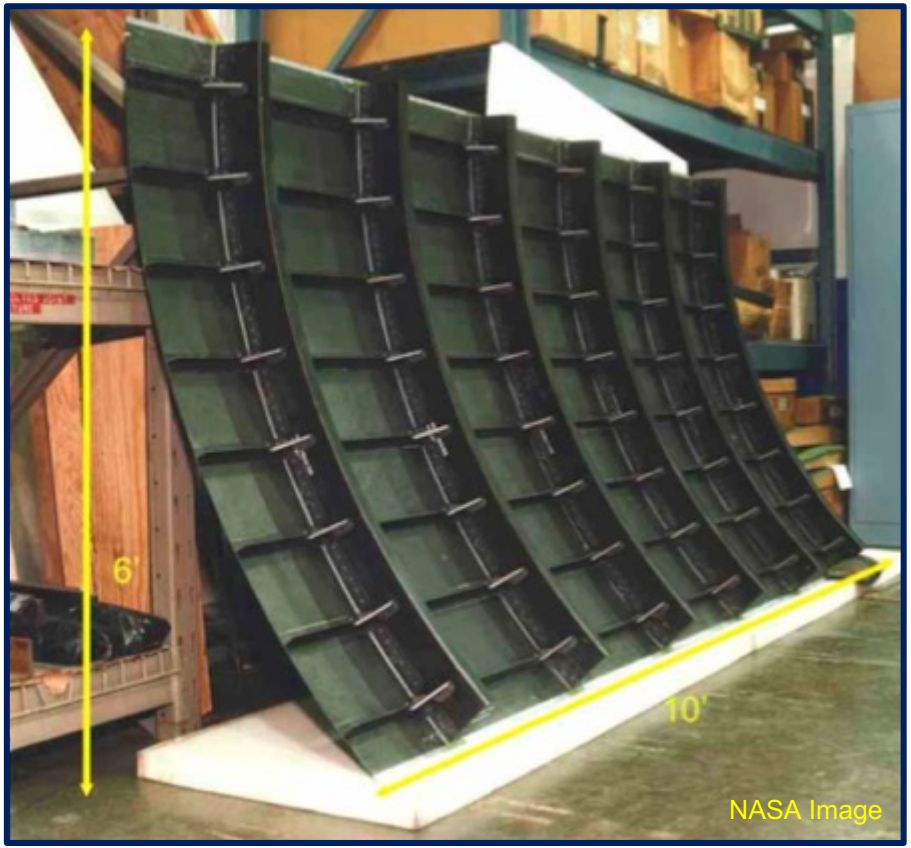




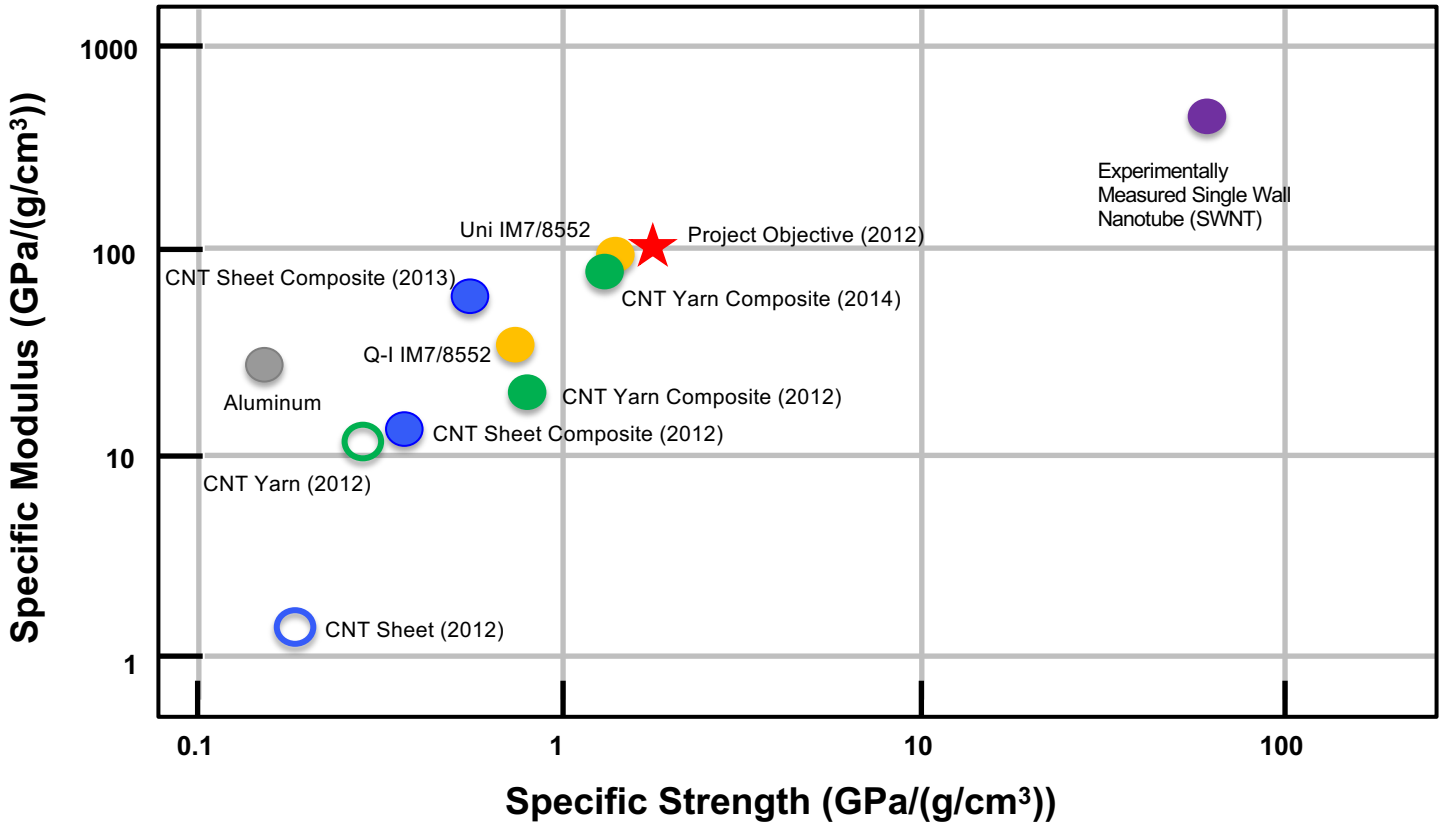
- Mass savings are potentially large enough to change propulsion system design concept.

McMillan, M., System Level Impact of High Strength Carbon Nanotube Materials Applied to Launch Vehicle Concepts, White Paper, March, 2013.

State of the Art Lightweight Structural Material



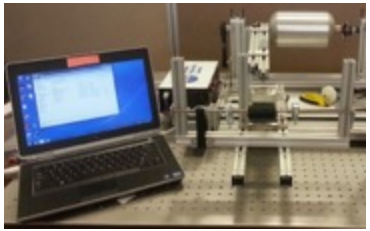
Nano to Macro Challenge



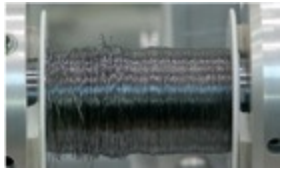
Harris, Shuart, Gray, NASA TM 211664, 2002

Prototyping to Support Materials Development

CNT Composite Overwrapped Ring



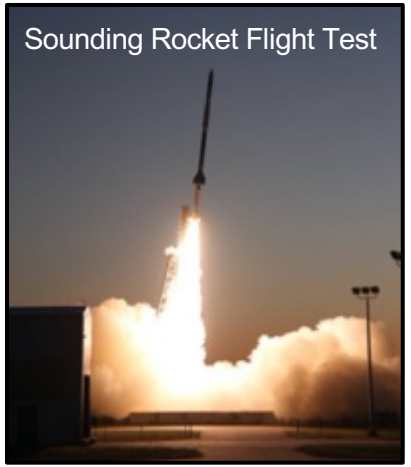
Composite Process Prototyping



High Strength CNT Yarn

Commercial Scale CNT Composite Winding

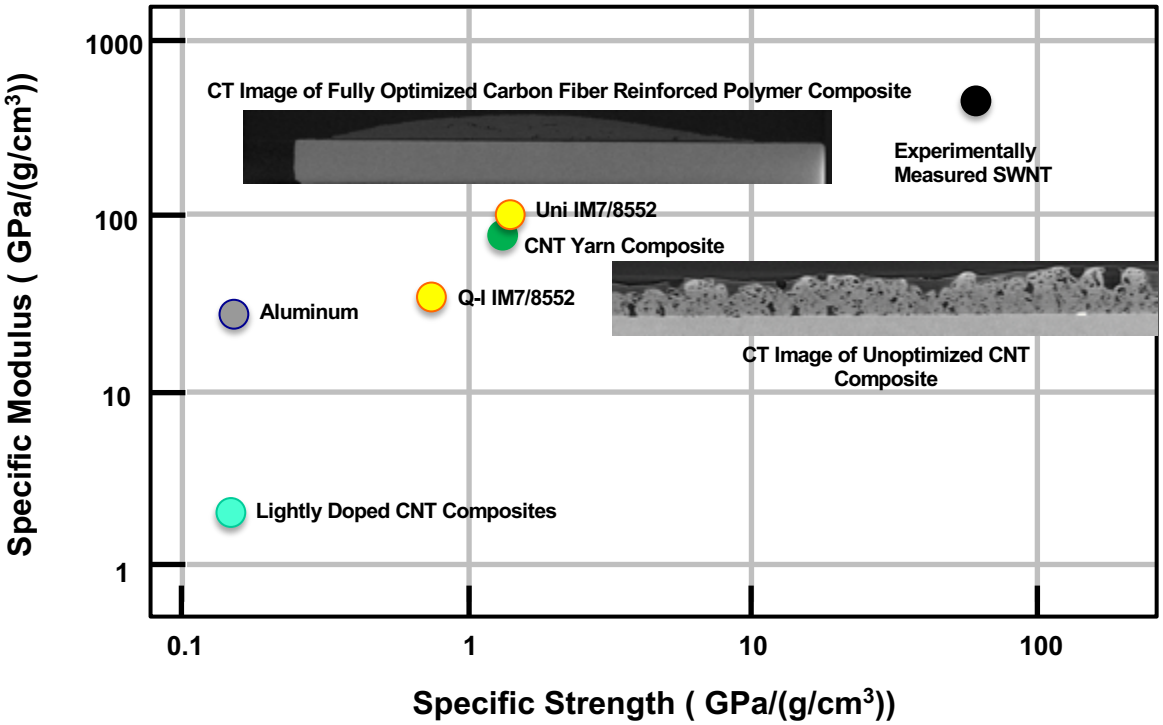
CNT Composite Overwrapped Pressure Vessel Cold Gas Thruster



Sounding Rocket Integration

All NASA Images

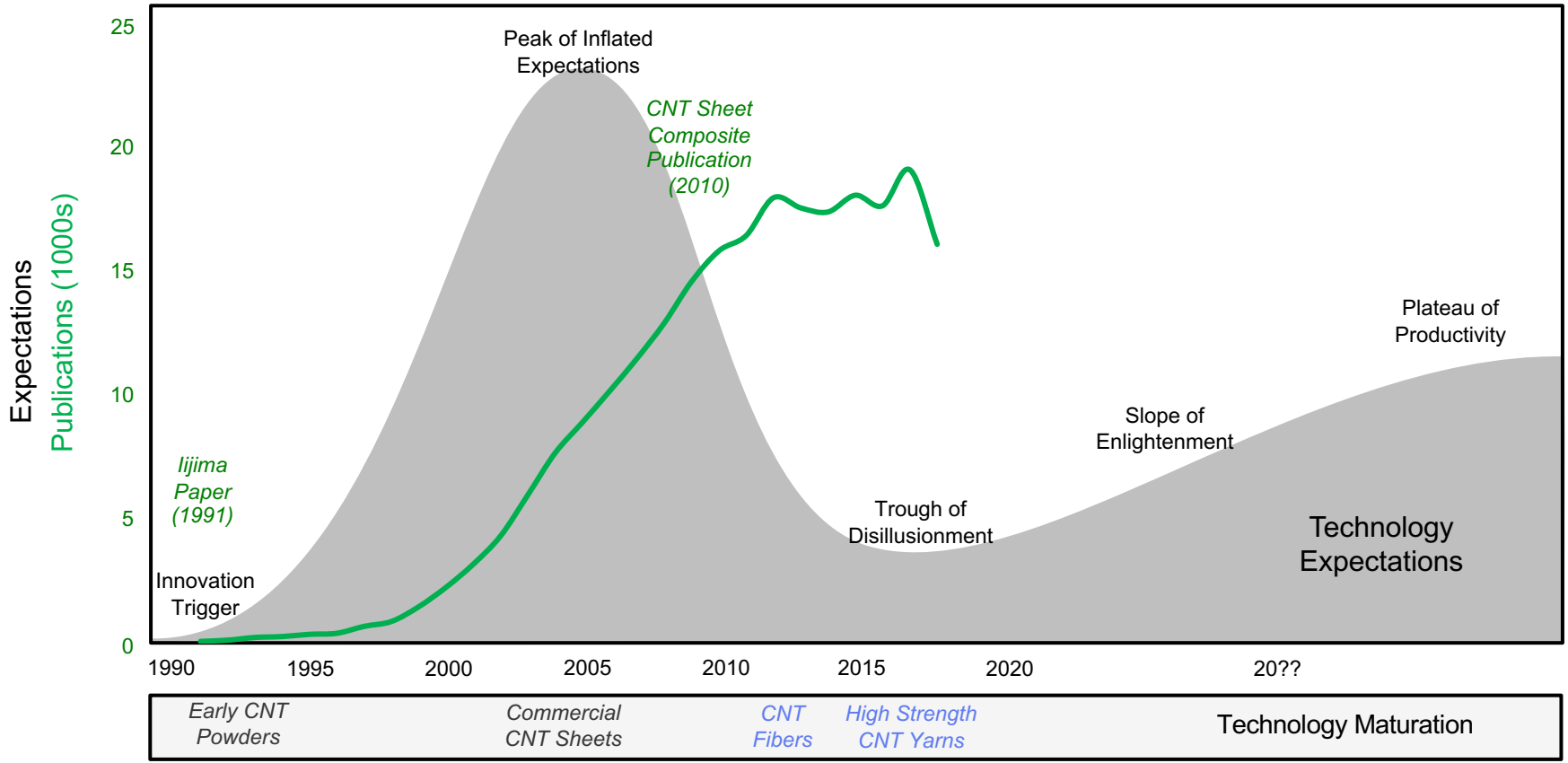
Outcomes



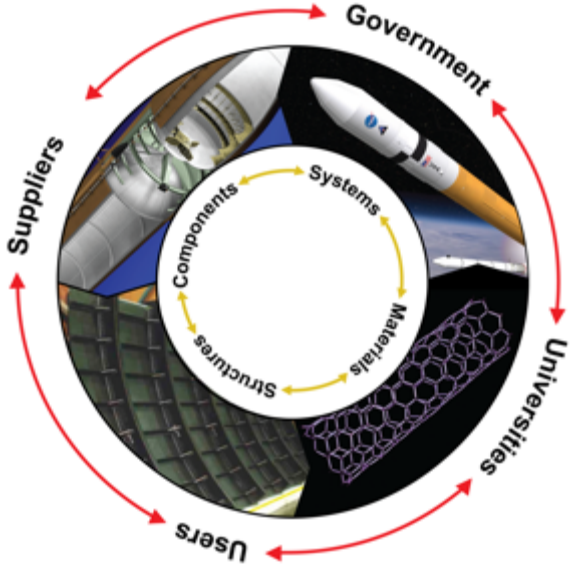
Measurable Advancements

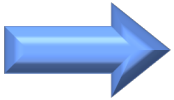
- Improvement in mechanical properties
  - Systems level guided, goal focused research.
  - Project objective provided basis for objective decisions.
- Increase in MRL
  - Volume – material available in spool lengths of hundreds of meters
  - Consistency – materials met A-basis allowable of at least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

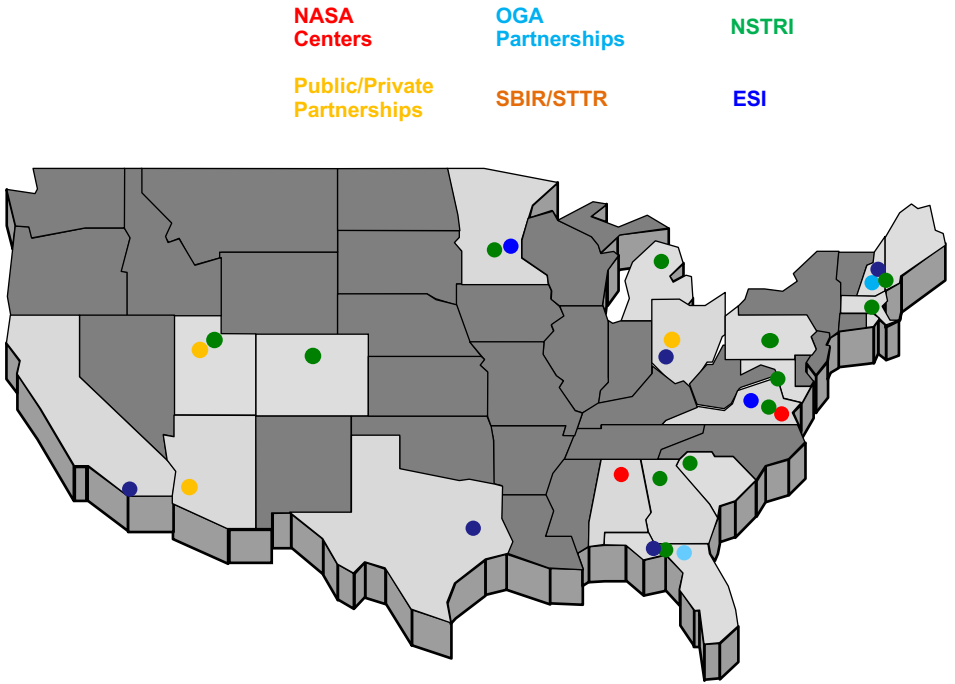
Use Driven Technology Maturation



Systems Defined Goal Provides Common Objective







Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise

Technology pull can guide accelerated maturation of emerging technologies.