Composites Development for Clean Hydrogen Manufacturing

John Winkel
Technology Manager, U.S. Dept of Energy

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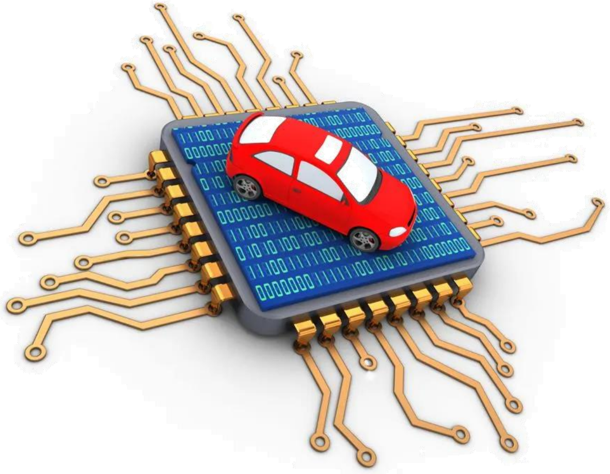
Long Beach, CA

Background & Topics

- Graduate studies under Dr. Don Adams
- Advanced Materials and Manufacturing Technologies Office's Composites R&D portfolio.
- Institute for Advanced Composites Manufacturing Innovation (IACMI), Carbon Fiber Technology Facility (CFTF), other R&D cooperative agreements.
- Topics:
  - About AMMTO
  - On-going / Past Composites H_2-Related R&D
  - Smart Manufacturing – A Possible Future R&D Direction

The World is Changing



Unprecedented Federal Investment in Manufacturing

Bipartisan Infrastructure Law

Inflation Reduction Act

CHIPS And Science Act

AMERICAN MANUFACTURING INDUSTRY

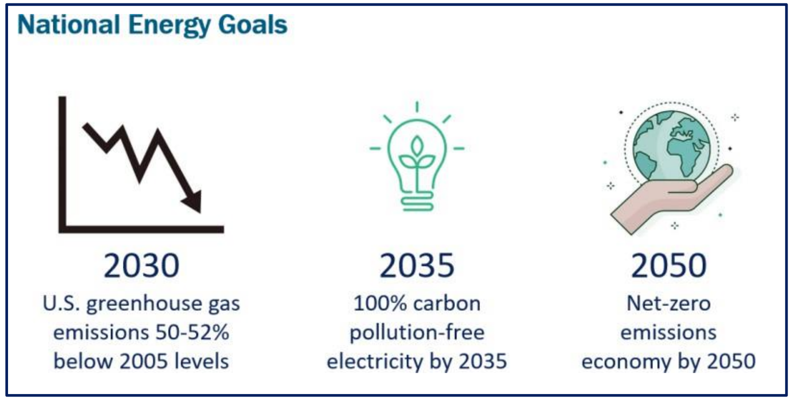
8.5% of U.S. workforce

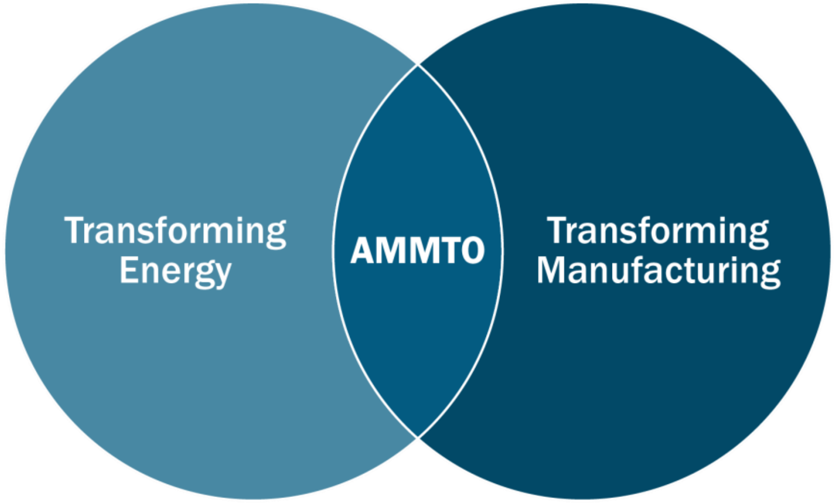
Over 11% of national GDP

Advanced Materials and Manufacturing Technologies Office

- **Vision:** A globally competitive U.S. manufacturing sector that accelerates the adoption of innovative materials and manufacturing technologies in support of a clean, decarbonized economy.

- **Mission:** We inspire people and drive innovation to transform materials and manufacturing for America's energy future.



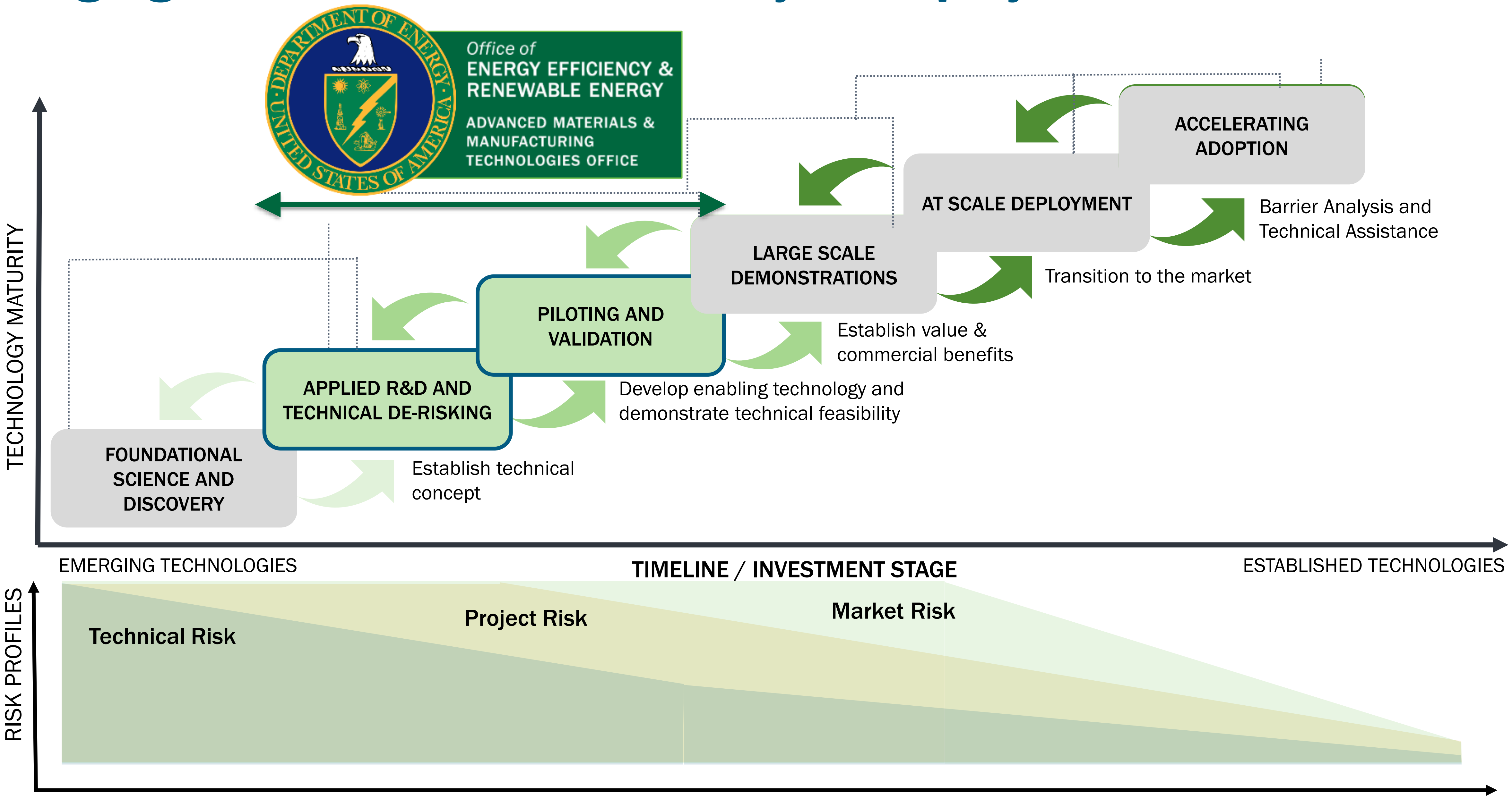


Innovation Ecosystems

Education and Workforce Development

Diversity, Equity, Inclusion, and Accessibility

Bridging Innovation from Discovery to Deployment



Advanced Materials and Manufacturing Technologies Office

Supporting Clean Energy Manufacturing

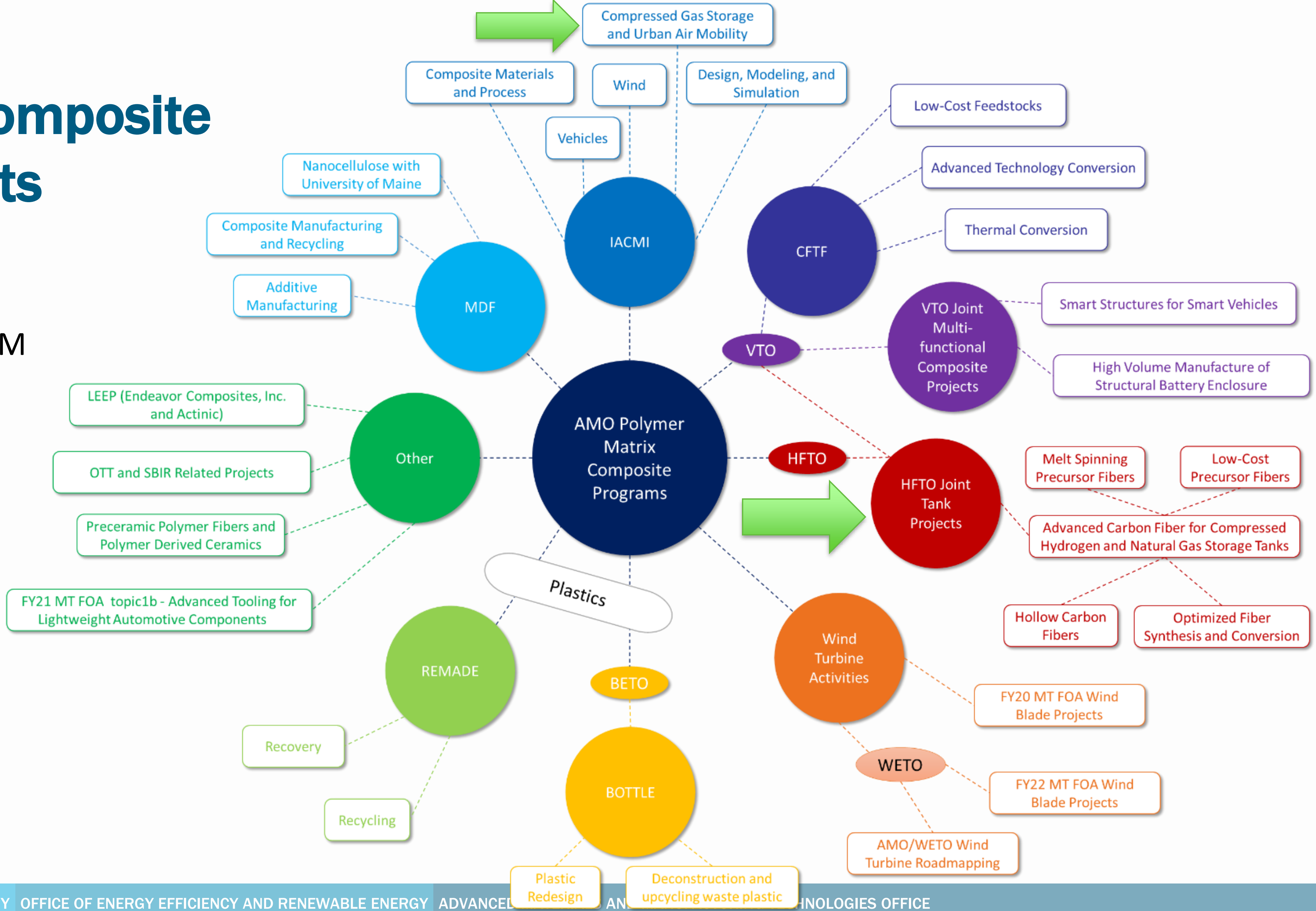
Batteries and long duration storage
Wind turbines and wind blades
Hydropower components
Castings/forgings
Industrial motors
Hydrogen storage
High efficiency conductors
Power electronics
Microelectronics
...

Platform Manufacturing Technologies, Advanced Materials, Workforce

- Manufacturing Technologies: smart manufacturing, AI/ML, cybersecurity, high performance computing, roll-to-roll manufacturing, additive manufacturing, circularity
- Advanced Materials: advanced composites/metals/ceramics, critical materials, high conductivity metals, harsh service condition materials
- Workforce: training programs, curricula development, entrepreneurship

AMMTO Composite Touchpoints

Approx. 100 projects & $180M over last 9 years



AMMTO/HFTO/VTO Joint Tank Projects - Overview

Addresses all stages of carbon fiber processing:

- Precursor materials
- Spinning – solution and melt
- Advanced oxidation and carbonization

Development and Demonstration of Enhanced Carbon Fibers and COPV for Onboard Hydrogen Storage

Technical Goals:

- Full scale carbon fiber and Composite Overwrapped Pressure Vessel (COPV) development for onboard hydrogen storage
- Lower cost carbon fiber and COPV
    - Result in 50% cost reduction for hydrogen storage systems
- Improved carbon fiber properties
- Enhanced carbon fiber composite performance
- Increased gravimetric energy density

Benefits

- Utilizes Carbon Fiber Technology Facility at ORNL
- Collaborations between academia, national labs and industry
- Enables progress towards DOE performance and cost targets

FOA topic: Advanced Carbon Fiber for Compressed Hydrogen and Natural Gas Storage Tanks

- *Project structure:*
    - Phase I: 4 teams, 2 years
    - Phase II: 1 downselected team, 3 years
- *Joint effort:*
    - Hydrogen and Fuel Cell Technologies Office (HFTO)
    - Advanced Manufacturing Office (AMO)
    - Vehicle Technologies Office (VTO)

Teams:

- **University of Kentucky** - hollow carbon fibers
- **University of Virginia** - low-cost precursor fibers
- **Hexagon LLC** - optimized fiber synthesis & conversion
- **Collaborative Composite Solutions Corp.** - melt spinning precursor fibers

IACMI Projects

Completed

5.2	DuPont, Steelhead Composites	Thermoplastic Composite Compressed Gas Storage (CGS) Tanks	Demonstration of a benign failure mode for compressed gas tanks when higher elongation, higher impact thermoplastic resins are used in place of epoxy, which may allow for reduced factors of safety in CGS tanks, lowering costs.

6.14	Steelhead Composites, Luna Innovations, Teijin Carbon Fiber	Smart Composite Pressure Vessels (SCPV) with Integrated Health Monitoring	Successful demonstration of embedded fiber optic sensors for live monitoring of carbon fiber overwrapped pressure vessels, allowing for remote monitoring and opening potential for reduction of safety factors, thereby lowering costs for pressurized natural gas and hydrogen tanks in vehicles

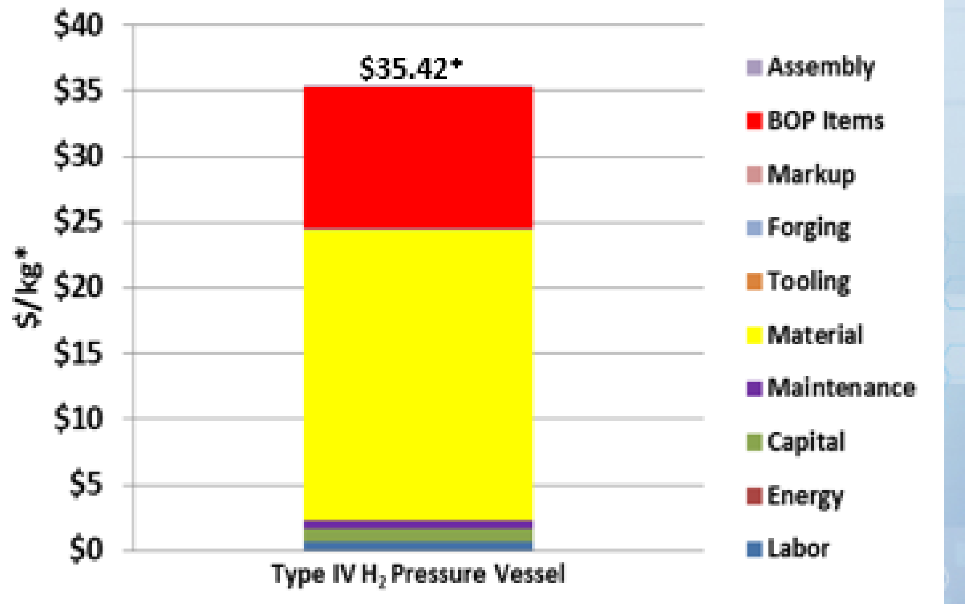
Proposed

- Development of Advanced Composites for Cryogenic Hydrogen Storage

Baseline Metrics – 2015 Technology

Cost

- Material contributes to 62% of total tank cost, of which carbon fiber share is 86.5% -- low cost carbon fiber is one of the major options considered for its economic viability
- Balance-of-Plant (BOP) is another major contributor to tank cost, ~30%
- Other remaining cost components have a less than 5% of total cost share, energy is among one



*Estimated based on a composite mass of 104 kg

Embodied Energy

- With Filament Winding as the baseline process, the embodied energy for a 104 kg H2 tank is 777 MJ/kg

Thermoplastic Composite Compressed Gas Storage (CGS) Tanks

DuPont Performance Materials, Steelhead Composites, Composites Prototyping Center, Univ of Dayton Research Institute

Objectives

- Use DuPont's proprietary thermoplastic / continuous carbon fiber prepreg tape with Automated Fiber Placement to fabricate CGS tanks (e.g., 350 bar CNG, 700 bar H2 gas)

Rationale

- Lower manufacturing costs, lower embodied energy, reduce cycle time and increased recyclability

Approach

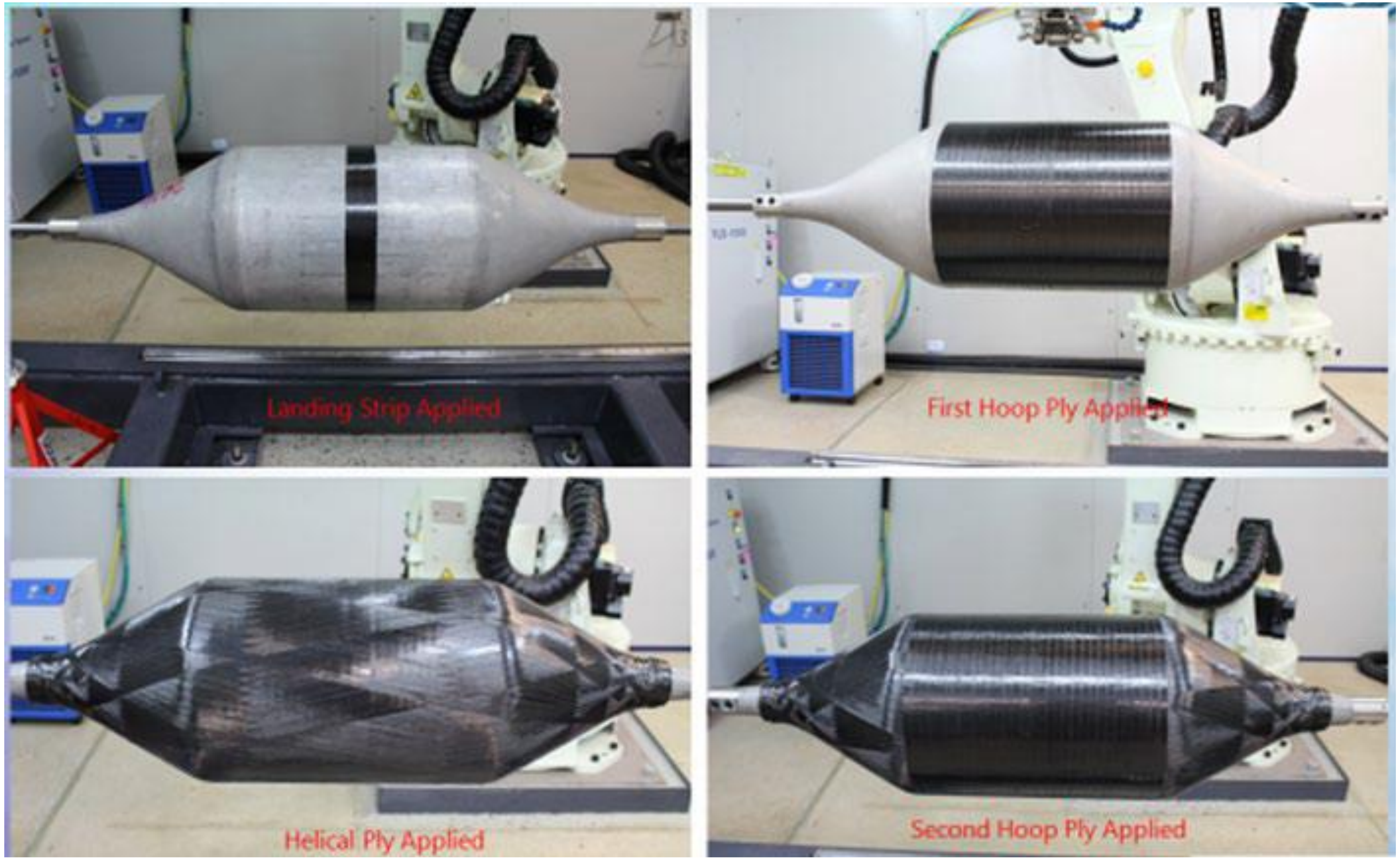
- Proprietary DuPont polyamide blend / carbon fiber composites characterized for mechanical performance and process specific microstructure
- Several iterations of Type III tank articles were fabricated to adapt to and stabilize the process
- High cost of adapting tape laying head design for hemispsherical end domes avoided by using fluted tank ends while demonstrating manufacturing concept
- Final version of the tank was tested to failure at Steelhead Composites

Technoeconomic Conclusion

- Thermoplastic carbon fiber tape composites offer the potential to increase tank structural toughness allowing for reduction of safety factors which in turn can reduce COPV costs by 16%

Thermoplastic Composite Compressed Gas Storage (CGS) Tanks

DuPont Performance Materials, Steelhead Composites, Composites Prototyping Center, Univ of Dayton Research Institute



L: Application of the Landing Ply
R: Application of First Hoop Ply

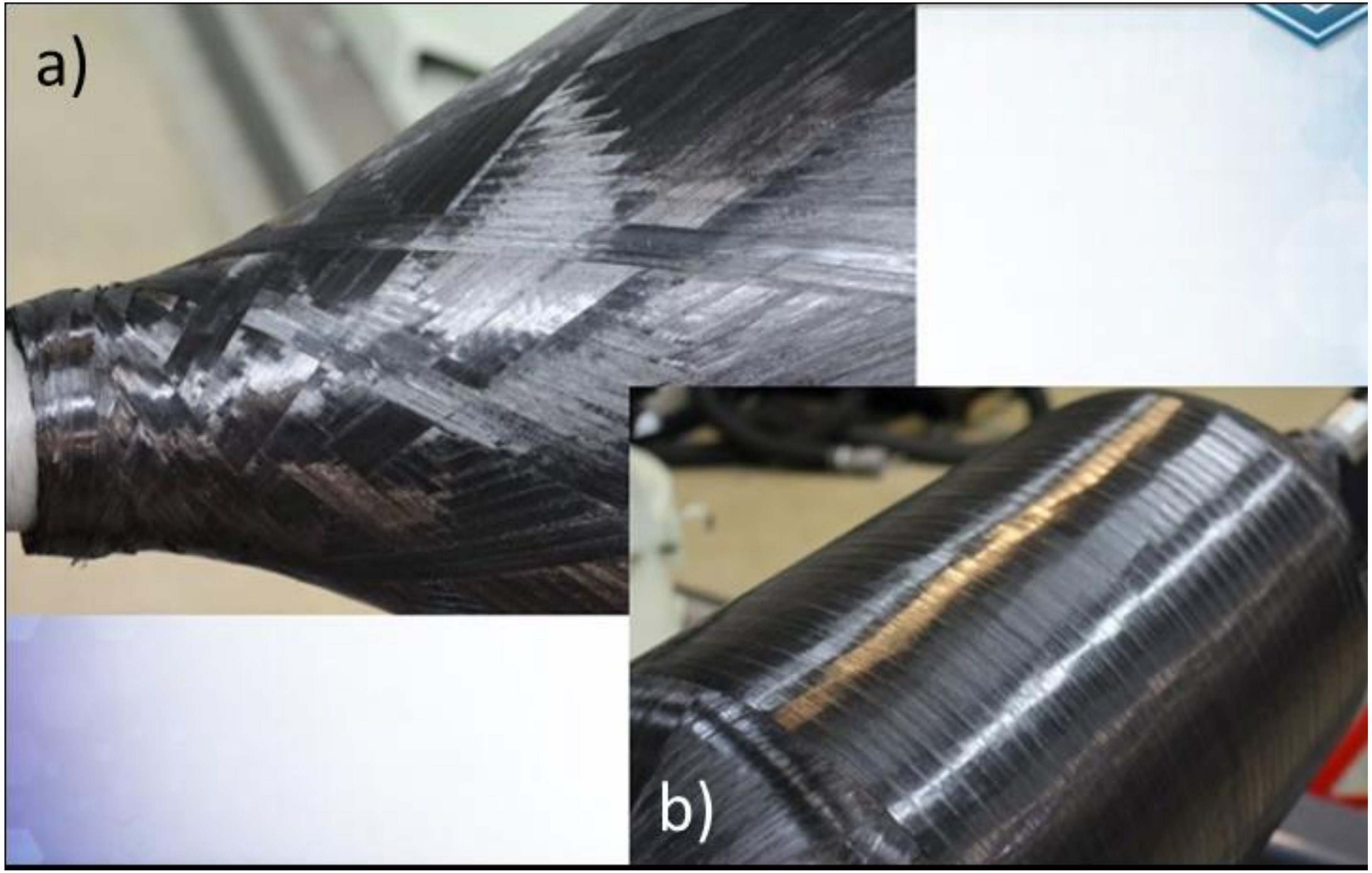
MR Grafil 34-700 12K fiber
Cylinder Dia 12 in
Length 48 in

L: Application of the Helical Ply
R: Application of Second Hoop Ply

Thermoplastic Composite Compressed Gas Storage (CGS) Tanks

DuPont Performance Materials, Steelhead Composites, Composites Prototyping Center, Univ of Dayton Research Institute

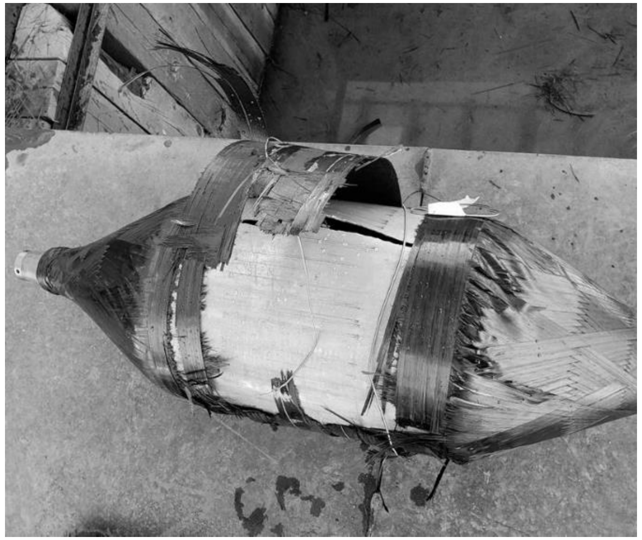
Closeup of wrapped pressure vessel showing (a) helical plies, (b) hoop plies



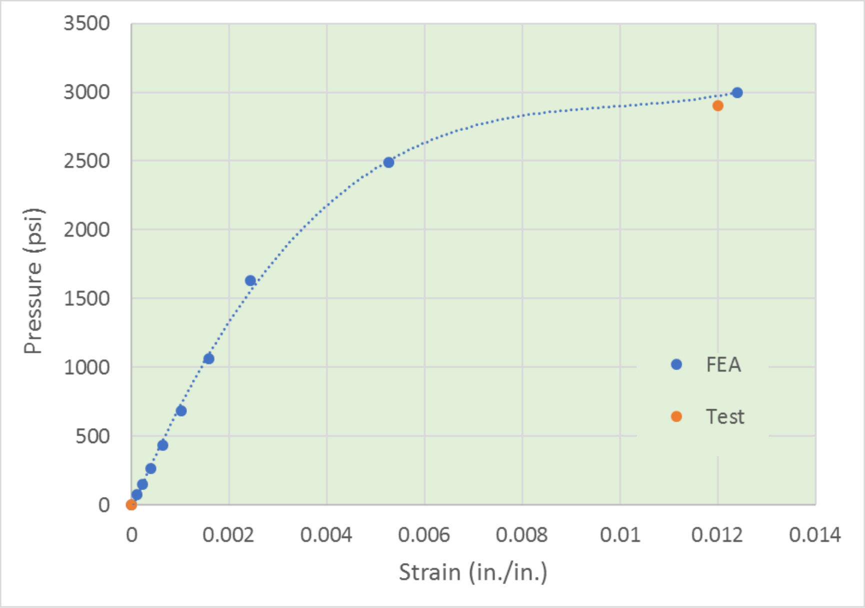
Thermoplastic Composite Compressed Gas Storage (CGS) Tanks

DuPont Performance Materials, Steelhead Composites, Composites Prototyping Center, Univ of Dayton Research Institute

a) Fiber Reinforced thermoplastic composites tank final failure (rupture) mode



b) Fiber Reinforced thermoset composites tank final failure (rupture) mode



Comparison of FEA Predicted Pressure versus hoop strain response with test data up to rupture pressure

Smart Composite Pressure Vessels with Integrated Health Monitoring

Steelhead Composites, Luna Innovations, Teijin America, UTK, ORNL

Objectives

- Demonstrate continuous and predictable health-monitoring of composite pressure vessels, using fiber optic Bragg gratings as sensing elements
- Increase confidence in safety monitoring and thus allow for reduction in regulatory safety factors

Rationale

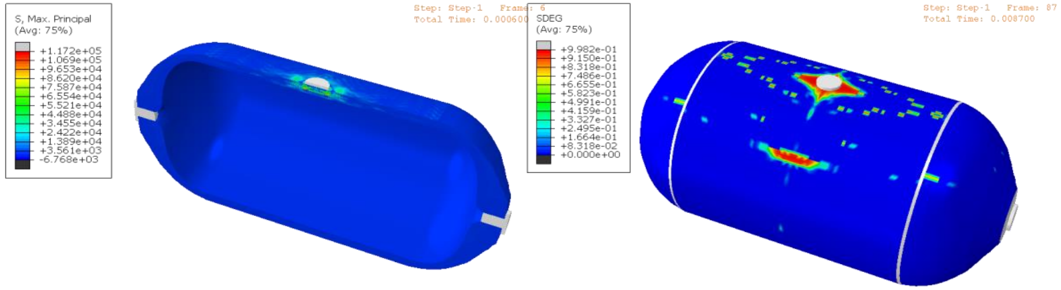
- Reduced safety factor resulting in proportional reduced carbon fiber volume in composite pressure vessels will directly reduce weight of CGS tanks and their cost

Approach

- Develop analytical methods capable of predicting strain response of undamaged composite pressure vessels and the change in response caused by damage from external sources such as foreign object impact
- Develop a fiber optic Bragg grating based strain, pressure, acceleration, temperature etc. sensing system integrated with the pressure vessel and demonstrate wireless transmission and data streaming to enable real time monitoring of pressure vessel health
- Iteratively test coupons, subscale Standard Test and Evaluation Bottle (STEB) vessels, and full-size vessels to validate the analytical capabilities and verify operation of the health monitoring system

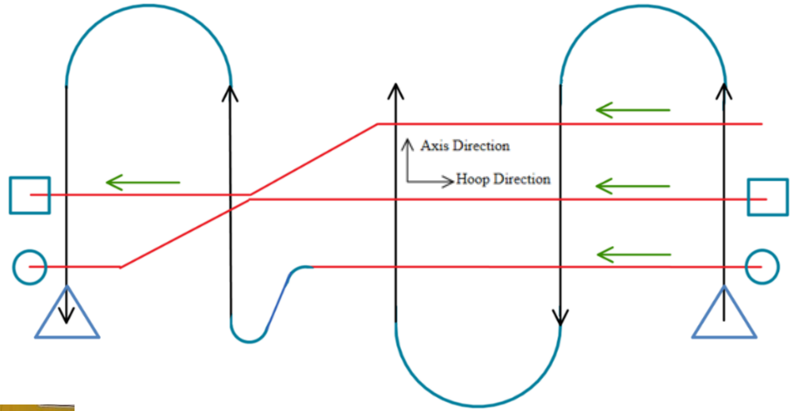
Smart Composite Pressure Vessels with Integrated Health Monitoring

Steelhead Composites, Luna Innovations, Teijin America, UTK, ORNL



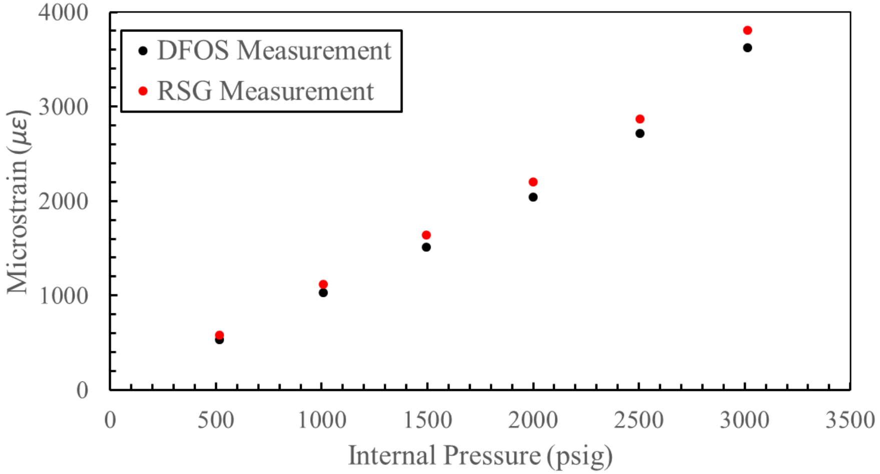
(a) (b)

FEA Model Predicting Impact Damage Response in ABAQUS

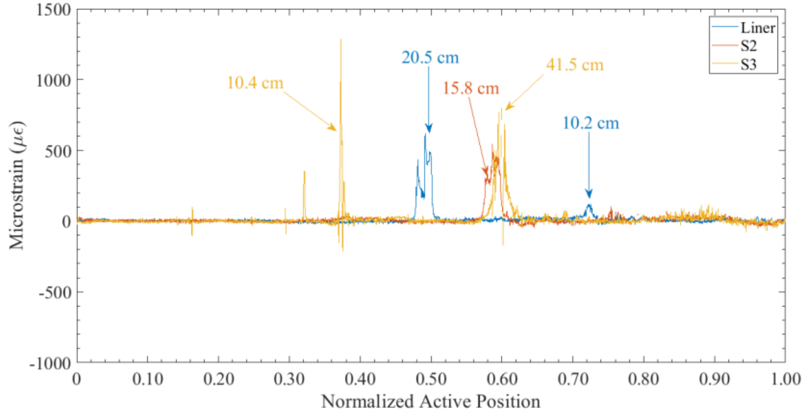


Fiber Optic Bragg Grating Layout, Black~ Axial, Red~ Hoop, Blue~Helical

Fiber Optic Bragg Grating as applied to a pressure vessel



Fiber Optic (DFOS) Hoop Strain Comparison with Resistance Strain Gage Data

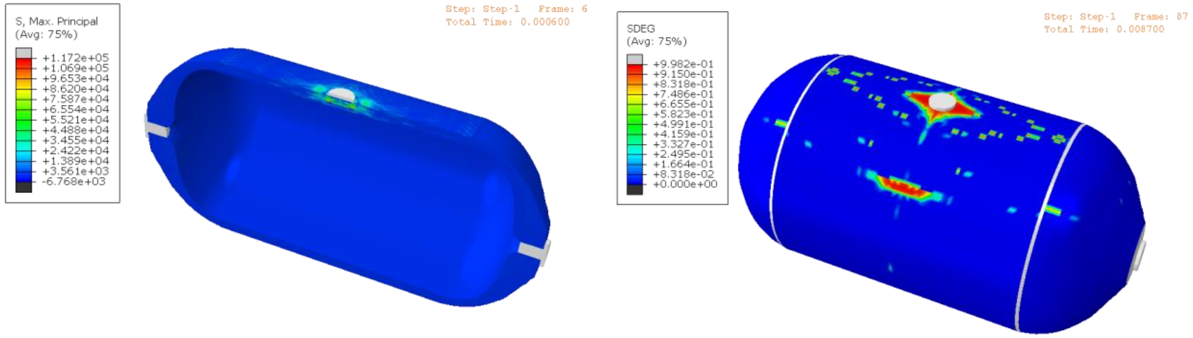


Impact Event Detection by Fiber Optic (DFOS) System

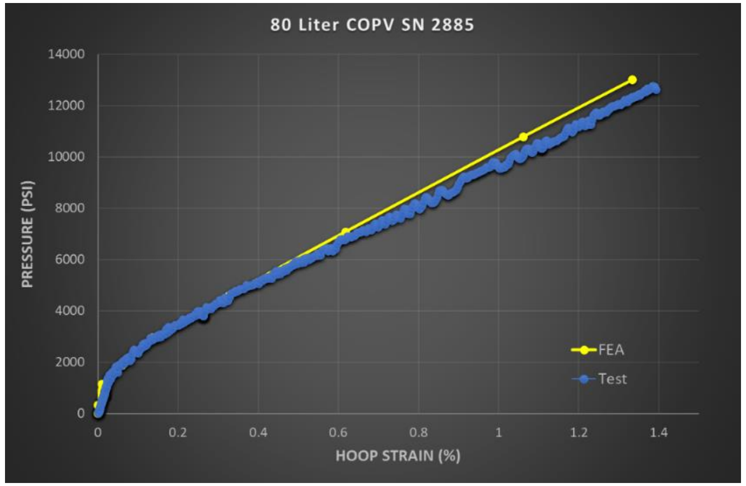
Smart Composite Pressure Vessels with Integrated Health Monitoring

Steelhead Composites, Luna Innovations, Teijin America, UTK, ORNL

Heavy Impactor Frame, 5 ft drop; 72 lb weight; 360 ft lb or 488 J

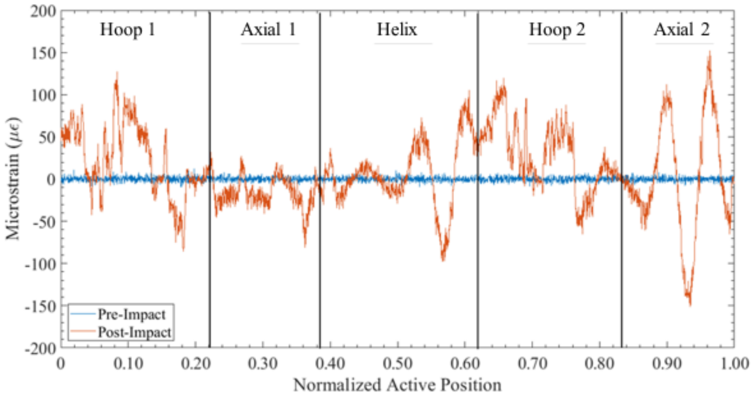


FEA Model Predicting Impact Damage Response in ABAQUS

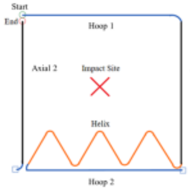


Correlation of FEA Prediction and Strain Gage Data for Burst Testing of 80L Vessel

Heavy Impact Test Set Up



Strain Profile Before and After Impact



Fiber Optic Bragg Grating Layout

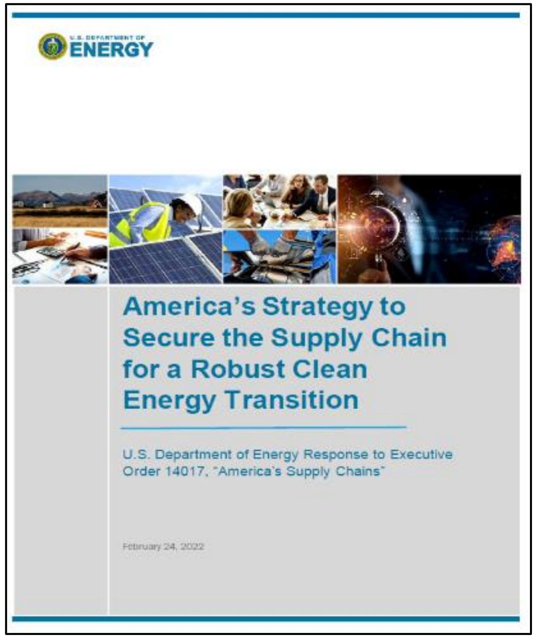
Smart Composite Pressure Vessels with Integrated Health Monitoring

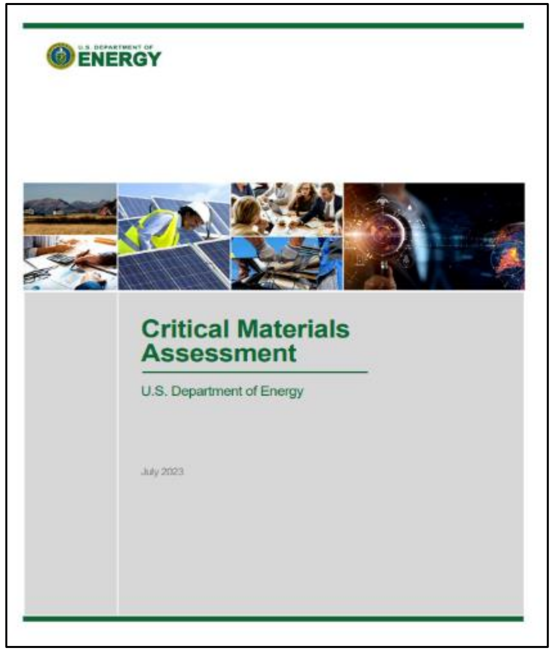
Steelhead Composites, Luna Innovations, Teijin America, UTK, ORNL

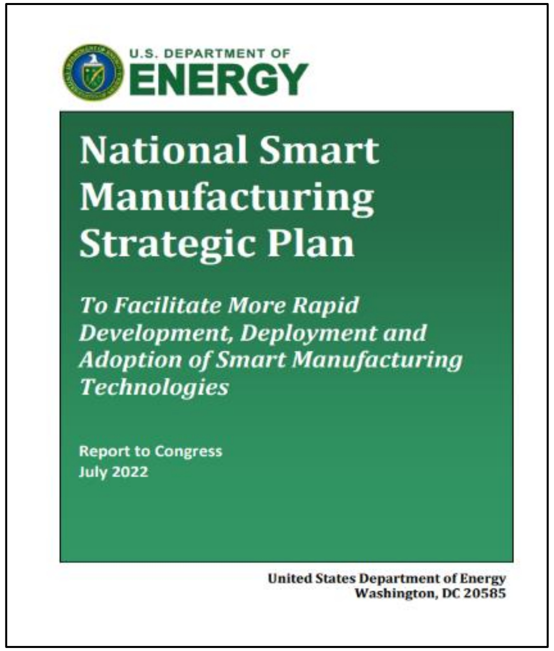
Conclusions

- Successfully Integrated material characterization, design and analysis, process development, information systems, testing and data analysis towards a technology that can make composite pressure vessels safe by enabling health monitoring
- Embedding fiber optics sensor elements during filament winding of the pressure vessels is challenging, more an art that needs development into techniques that can be used repeatedly
- Termination of the sensors due to the frangibility of the fiber optics is a challenge and requires significant development to ensure repeatable implementation
- Granularity of the fiber optic sensors is particularly useful for detecting sub-surface damage within the overwrap of the COPVs. Particularly for small delaminations resulting from low energy impacts
- Modeling to predict impact damage in the composite overwrap needs further development

Technology Analysis and Strategy





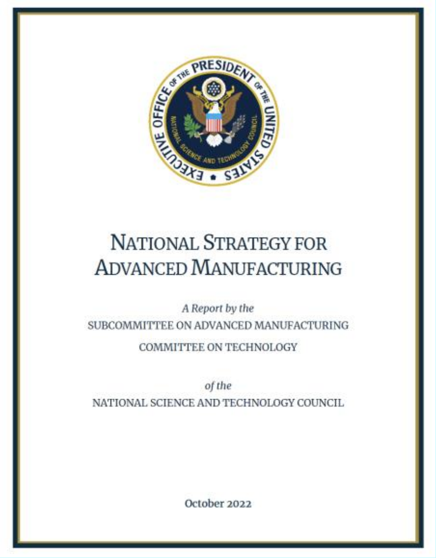


- Analysis guided research to drive impact of manufacturing innovation for supply chain resiliency and industrial decarbonization goals
- Technology roadmapping for key manufacturing and materials technologies
- Strategy development for manufacturing innovation in multiple areas including critical materials, smart manufacturing, circular economy, power electronics, microelectronics, harsh environment materials

National Strategy For Advanced Manufacturing

Vision: United States Leadership in Advanced Manufacturing

Grow the economy, create jobs, enhance environmental sustainability, address climate change, strengthen supply chains, ensure national security, and improve healthcare.


NATIONAL STRATEGY FOR ADVANCED MANUFACTURING

A Report by the
SUBCOMMITTEE ON ADVANCED MANUFACTURING
COMMITTEE ON TECHNOLOGY

of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

October 2022

National Goals:

1. Develop and implement **advanced manufacturing technologies**
2. Grow the advanced manufacturing **workforce**
3. Build resilience into manufacturing **supply chains** and ecosystems

Recommendation 1.1.2. Clean Energy Manufacturing Technologies:

Manufacturing advances that produce cost-competitive technologies for clean energy production, storage, and utilization domestically position the United States to lead the global energy transition. Innovations such as advanced composite materials for wind turbine blades and efficient power electronics for charging and grid integration are needed to meet growing demands driven by the electrification of multiple sectors.

Recommendation 1.4.1. High-Performance Materials Design and Processing:

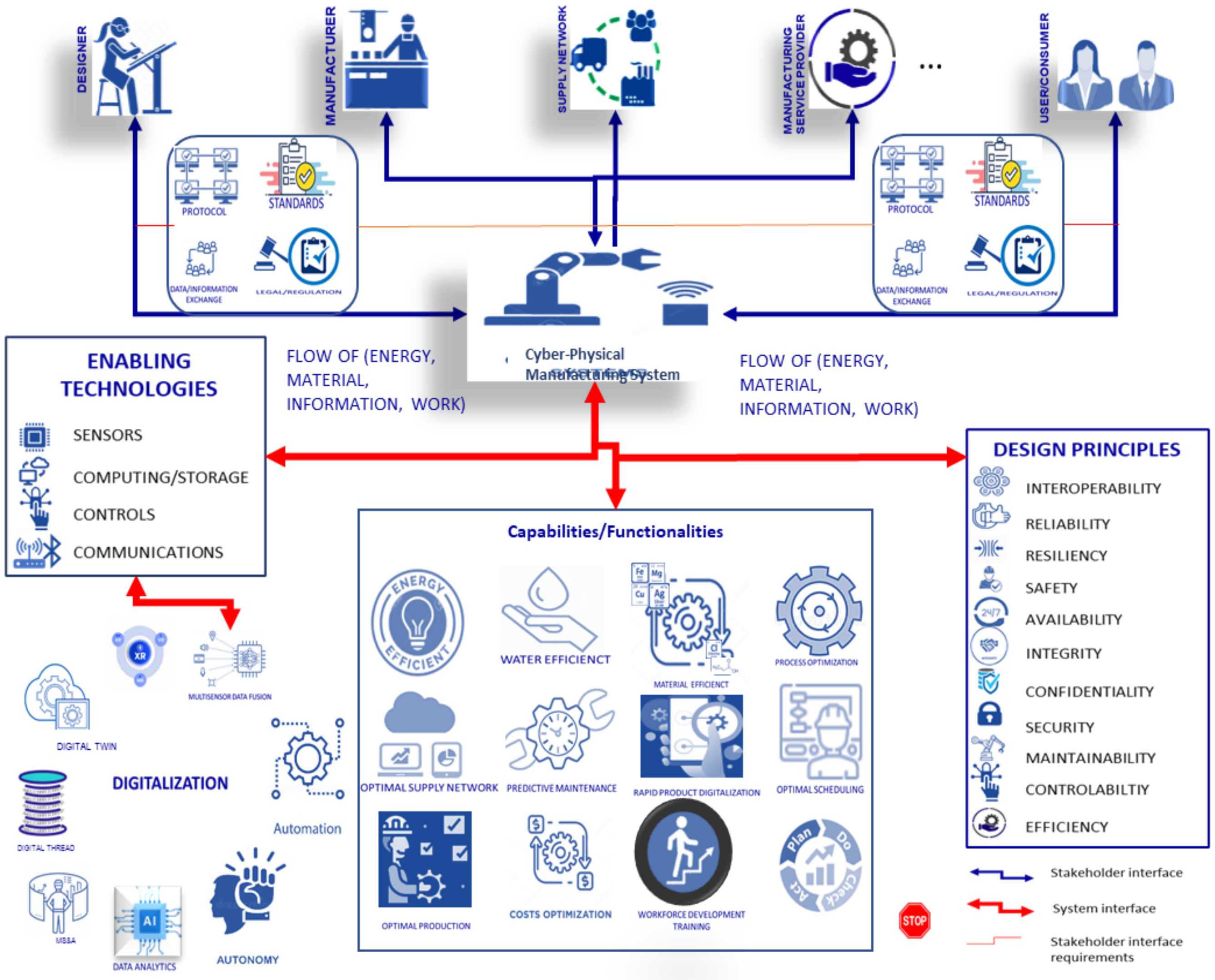
Accelerate testing, qualification and process validation of high-performance materials to streamline entry into market. Develop predictive capabilities for materials behavior and performance under harsh service conditions….Systems that…have profound national security or economic impact,…typically involve operation under harsh service conditions….The development and adoption of lightweight, high strength, high conductivity, corrosion-resistant metals, composites, and other classes of advanced materials are important enablers for emerging manufacturing capabilities.

Smart Manufacturing for Hydrogen Industry

Some initial thoughts

Proposed Activities:

1. **Digitalization of a science-based and data-driven model for hydrogen electrolysis and fuel cells manufacturing and assembly (process and fuel emissions) from unit operations/processes to the supply chain - Digital Thread and Twin, Cyber-Physical System**
2. **Process optimization for electrolysis and fuel cells and re-use across sectors using smart manufacturing – Smart Manufacturing Platform**
3. **Digitalization of integrated energy-material system to enable feedstock substitution for electrolyzers and fuel cells, reducing material intensity, and increasing supply chain resiliency.**
4. **Automation, Prediction, and Control of processes for electrolysis and fuel cell manufacturing and automation (advanced DAQ, AI/ML, HPC) – Enabling Technologies, Advanced sensors, Control interfaces, Hardware innovation**
5. **Model the reverse value chain and supply network implications**
6. **Identify the class of products, components, and materials that are well suited for Re-X (reduce, recycle (upcycle/down cycle), recover, repair, reuse, remanufacture, retire) – Bring in the different industry sectors**
7. **System thinking for Design for X with Re-X**
8. **Impacts of digitalization at a scale of process technologies, domestic supply chain, skills and workforce development, and DEI - WFD, Skills, Training, DEI**



Smart Manufacturing FOA Overview

Projects funded under this FOA will develop and demonstrate technologies to **accelerate the adoption of smart manufacturing technologies and processes**, helping domestic manufacturers create new, integrated systems and support their competitiveness around the world. Collaborative teams partnering with industry will de-risk innovations and mature smart manufacturing technologies in four areas: **circular economy, tooling and equipment, high performance materials, and sustainable US mining**.

Goals:

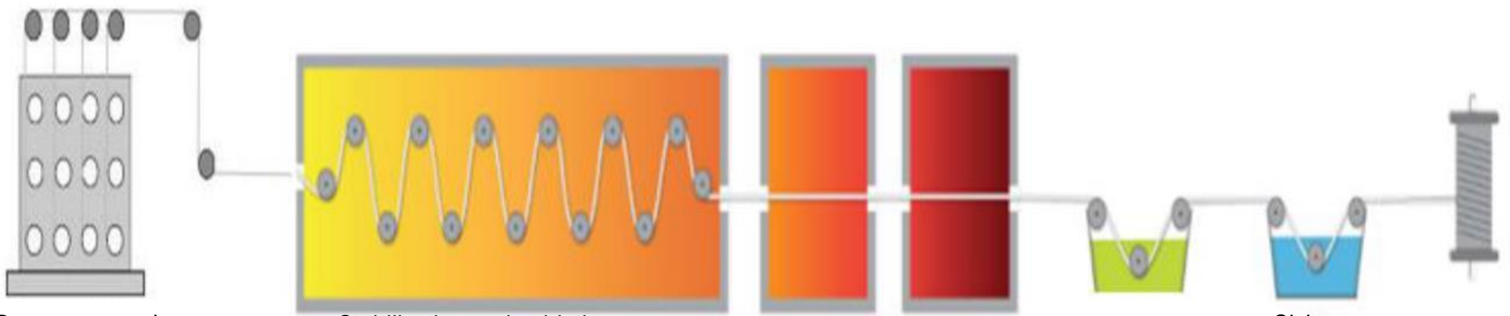
- Foster partnerships across supply chains to accelerate the adoption of smart manufacturing technologies and processes for more efficient, resilient, and responsive US manufacturing;
- De-risk technologies through collaboration with industry to advance smart manufacturing technologies and processes;
- Demonstrate innovations that can be deployed to multiple applications across the clean energy manufacturing sector to improve US competitiveness.

Funding: $33M

Planned as yearly FOA
Fiscal Year: 2024
Office: AMMTO
Programs: Next Generation Materials & Processes; Secure & Sustainable Materials
Subprograms: Tooling, High Performance Materials, Digital Manufacturing, Circular Economy, Critical Materials
TRL Range: 3 to 7
Project Duration: 12 to 36 months
Estimated Release Date: June 2024
Cost-Share: 20%

FOA Managers: John Winkel, Allison Robinson

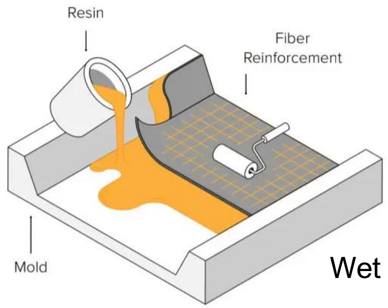
SM application: Carbon Fiber Production - CFTF



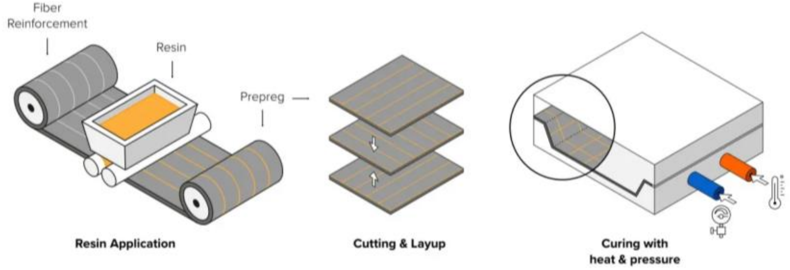
Smart Manufacturing Platform
Monitor Predict Control

Increase fiber quality
Reduce variability
Reduce cost
Increase energy efficiency
Zero-defect fibers
Improve Process safety and health issues

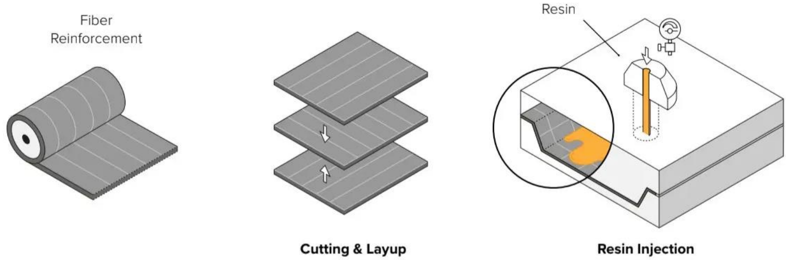
Composite parts manufacturing



Wet Lay-Up



Prepreg Lamination



Resin Transfer Molding

Smart Manufacturing Platform
Monitor Predict Control

Increase part quality
Zero-defect parts
Reduce cost
Increase Energy Efficiency

AMMTO is Already Busy…and Looking to the Future!

- **Smart Manufacturing FOA coming soon**

Recent:

- Domestic Near Net Shape Manufacturing to Enable a Clean and Competitive Economy
- Materials and Manufacturing to Lower Costs of Large Wind Turbines

As we look for the future, we want to hear from YOU!

- Manufacturing USA Institute Renewed, **Project Calls**

- **Vehicles/other Workshops & Analysis -** to align AMMTO's composites R&D portfolio/strategy with most impactful needs.

Thanks For Your Attention
Questions?