DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Carbon Composite Optimization Reducing Tank Cost

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Project objective

Reduce hydrogen storage system costs with newly developed technologies to produce low-cost, high strength CF to accelerate mass deployment of hydrogen fueled vehicles.

- CF cost target < $15/kg, capable of 700 ksi tensile strength (TS) and 35 Msi tensile modulus (TM)
- Additional project goals
  - Demonstrate >25% tank system cost reduction
  - Long-term stretch goal of further CF cost reduction

- Currently, the cost of gas storage tanks is a significant barrier to the mass deployment of cleaner vehicle fuel sources such as hydrogen.
- CF accounts for ~50% of the total hydrogen storage system cost.

- Project and overall DOE targets

	Baseline	Project Target	Ultimate Target
Benchmark CF cost	$26-30/kg	$13-15/kg	
250 bar pressure vessel		10% cost reduction	
Total system cost	$16/kWh		$8/kWh

Collaboration and Coordination

	Key Roles
Hexagon Agility (Prime)	• Program manager and team lead • Pressure vessel modeling, fabrication and testing
Cytec Engineered Materials (CEM)	• Lead development of new low-cost fiber • Lead CF surface modification task
Oak Ridge National Laboratory (ORNL)	• Lead development of new low-cost fiber • Lead CF surface modification task
Pacific Northwest National Laboratory (PNNL)	• Composite material testing and characterization • Lead material modeling • Coordinate the cost model structure
Newhouse Technology	• Composite tank design, modeling support and consulting
Kenworth	• Consulting on tank geometries and packaging • Support of tank/end use cost modeling

Collaboration and Coordination

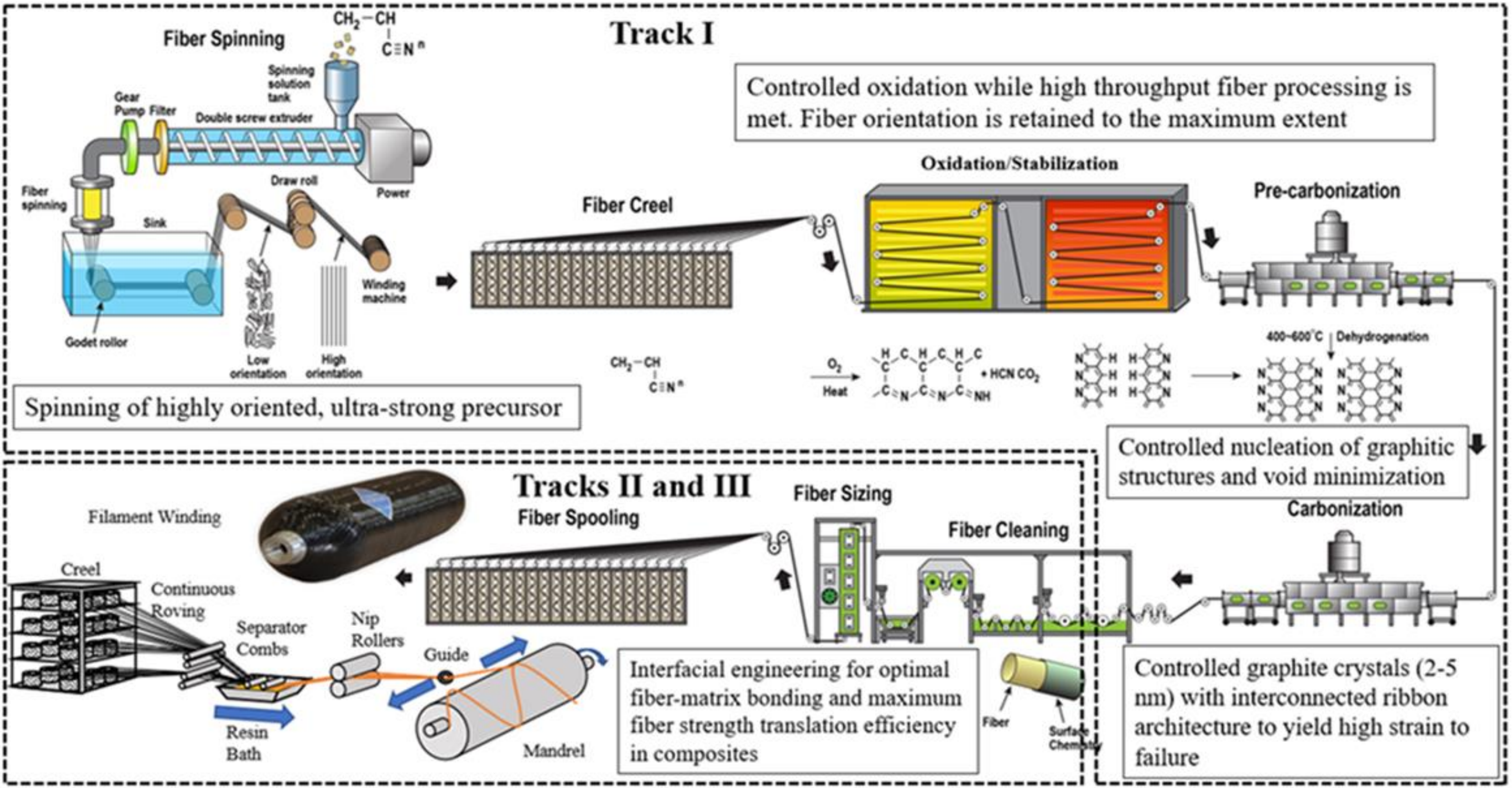
All encompassing team covers full supply chain, raw material → end user

- Foundational material research
- CF research and commercial manufacturing
- Gas storage tank/system manufacturing, research, and innovation
- End user
- End of life recycling

Approach – Four Tracks of Innovation

Cost reductions achieved through four tracks of innovation:

1. Optimize the CF manufacturing resulting in higher production throughput
2. Increase composite performance efficiency
3. Enhance pressure vessel design and modeling
4. End of life pressure vessel material recycling



Spinning of highly oriented, ultra-strong precursor

Controlled oxidation while high throughput fiber processing is met. Fiber orientation is retained to the maximum extent

Controlled nucleation of graphitic structures and void minimization

Controlled graphite crystals (2-5 nm) with interconnected ribbon architecture to yield high strain to failure

Interfacial engineering for optimal fiber-matrix bonding and maximum fiber strength translation efficiency in composites

Track I – Carbon Fiber Innovation

- Focus is on polyacrylonitrile (PAN) based CF

Precursor spinning and synthesis	Oxidation	Carbonization	Surface treatment and sizing application	Cost modeling
• Increased polymer molecular weight (MW) • Reduced polydispersity	• Oxidation stretch • Zone temperature optimization	• Pre-carbonization stretch • Zone temperature optimization	• Optimized surface for improved strength translation	• Cost reduction achieved through increased yield

Track II –Composite Performance Innovation

- Overall target is enhanced load transfer efficiency
- Benefits of enhanced load transfer efficiency
  - Reduced pressure vessel cost through reduction in material usage
  - Reduced pressure vessel cost through increased throughput
  - Lighter weight tanks and smaller envelope

Track III – Tank Design Innovation and Modeling

- PNNL has developed a modeling approach for H_2 storage pressure vessels incorporating inputs from project partners.
  - Modeling Objectives
    - Burst pressure prediction
    - Guide material selection
    - Tailor layups
    - Meet burst pressure target
    - Perform weight and cost analyses
- PNNL & Hexagon
  - New resin and composite laminate innovation

- CEM & ORNL
  - Low-cost, high-strength CF development, interfacial modification

Track IV – Pressure Vessel Recycling

Mild chemical methods to reclaim CF from pressure vessels

- Depolymerization of the matrix
- Determination of recovered carbon fiber and depolymerized resin properties
- Testing of composite samples using recycled CF and depolymerized resin

Pressure Vessel Composite Material

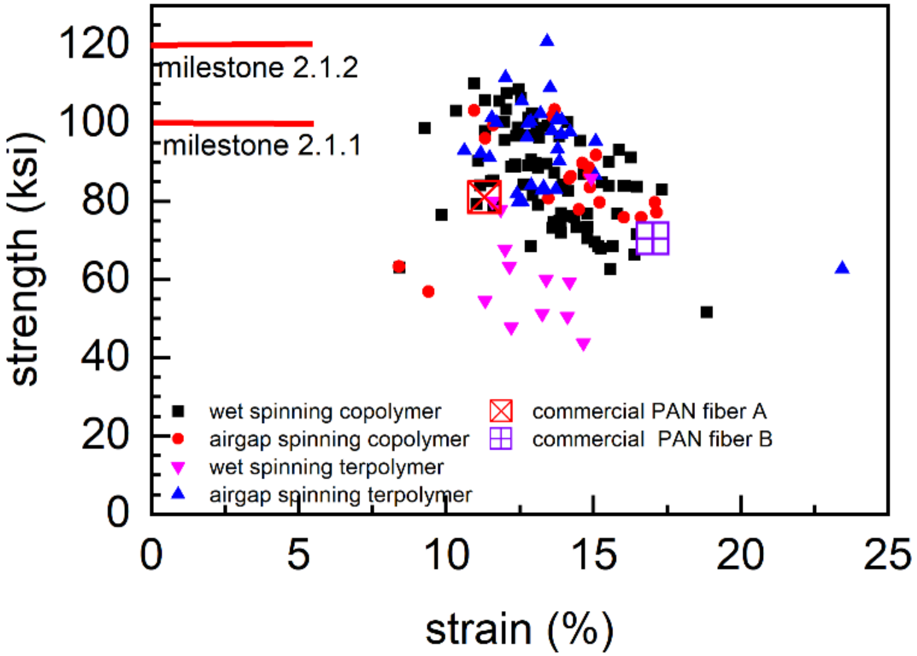
Composite Recycling Process

Fiber Recovery

Resin Recovery

Fiber Spinning Progress

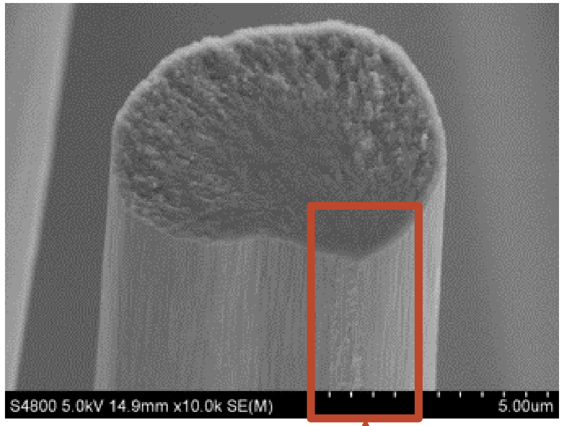
- CEM has converted white fiber from a bench scale 1k to a 24k carbon fiber tow, then achieved a strength > 725 ksi and tensile modulus > 35 Msi at 1.5x conversion line speed
- ORNL produced 1000+ m PAN precursor fibers with 120 ksi tensile strength and 13% elongation, 50%+ increased spinning line with synthesized high MW PAN precursor



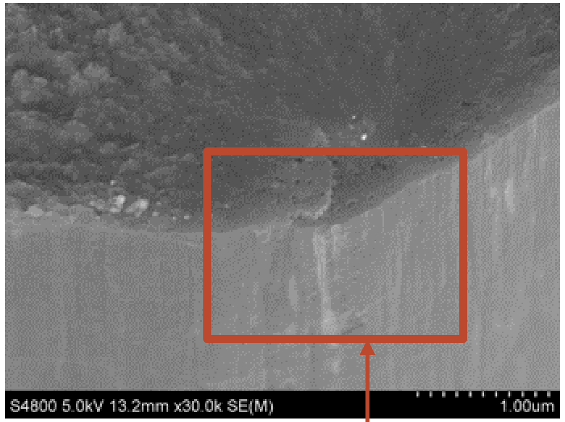
Strength vs. Strain of ORNL PAN fiber showing results exceeding Milestones 2.1.1 and 2.1.2

Progress on Fiber Characterization

- ORNL process shows more uniform distribution of sizing on fiber
- CEM has implemented a new large tow strander to test 24K tow fiber
- CEM fiber defect analysis showed defects stemming from sticking, and unsticking fiber prior to carbonization impacts CF strength



Sticking damage

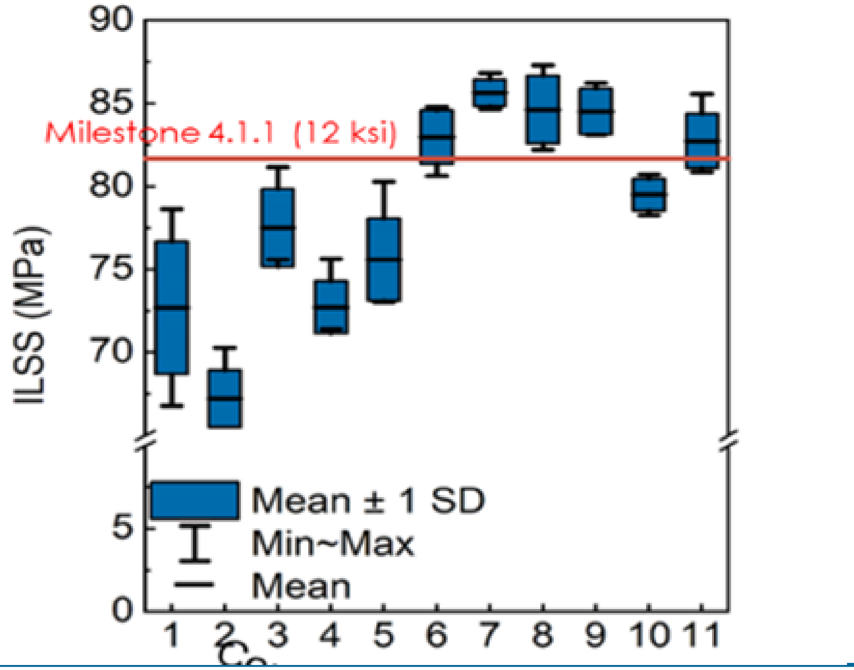


Structural damage or defect

SEM image showing two different types of fiber damage, sticking and structural damage

Progress on Surface Treatment

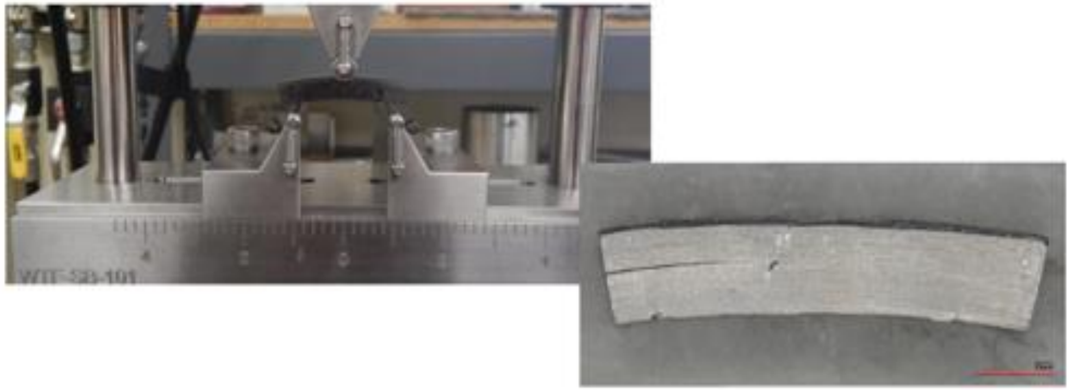
- CEM sizing epoxy formulation trials show reduced fiber width and variability compared to standard epoxy and phenoxy chemistries
- CEM Optimized surface treatment was able to deliver ILSS > 12 ksi
- CEM fiber surface treatment process capable of matching baseline fiber surface functionality
- Progress: ORNL single step electrochemical process replaces two individual surface treatment and sizing processes, achieved an ILSS value greater than 12 ksi with converted commercial PAN

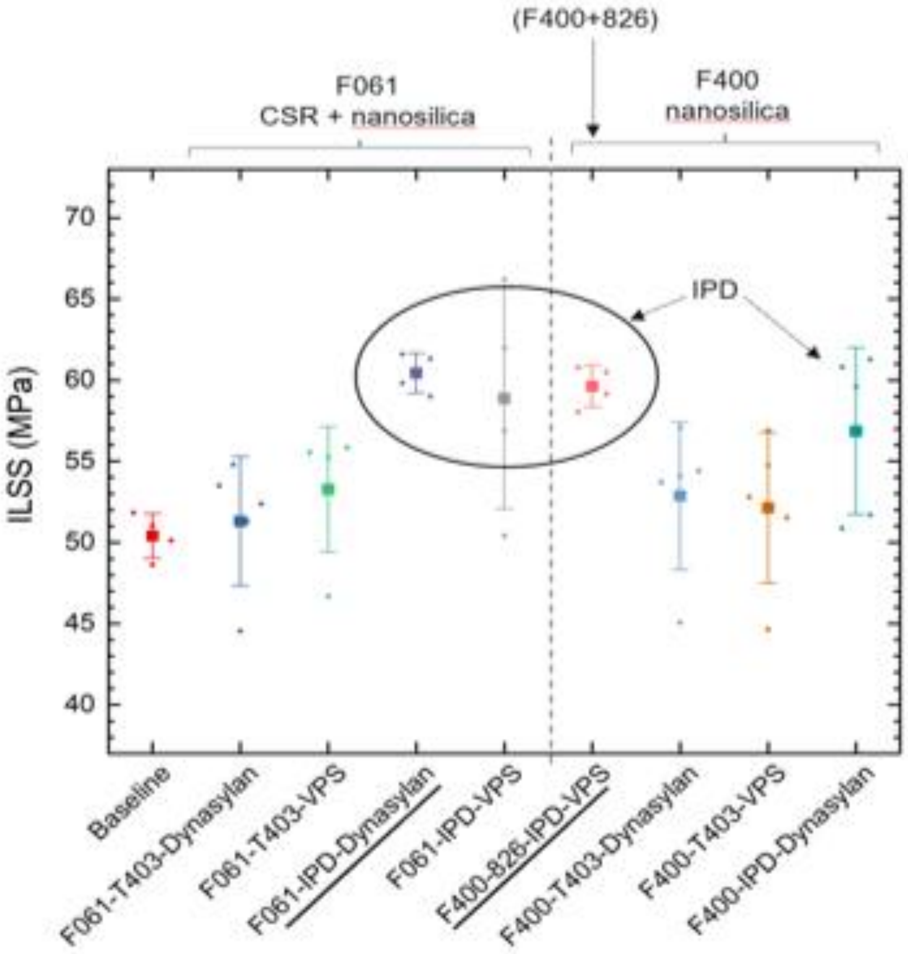


ILSS results from ORNL single step electrochemical process performed on commercial fiber, exceeding Milestone 4.1.1 target

Short beam shear testing

- ASTM D2344 Short beam strength
- Vestamin IPD hardener generally higher strength
- Equivalent performance from F061-IPD-Dynasylan
- F400-826-IPD-VPS 20% increase over baseline





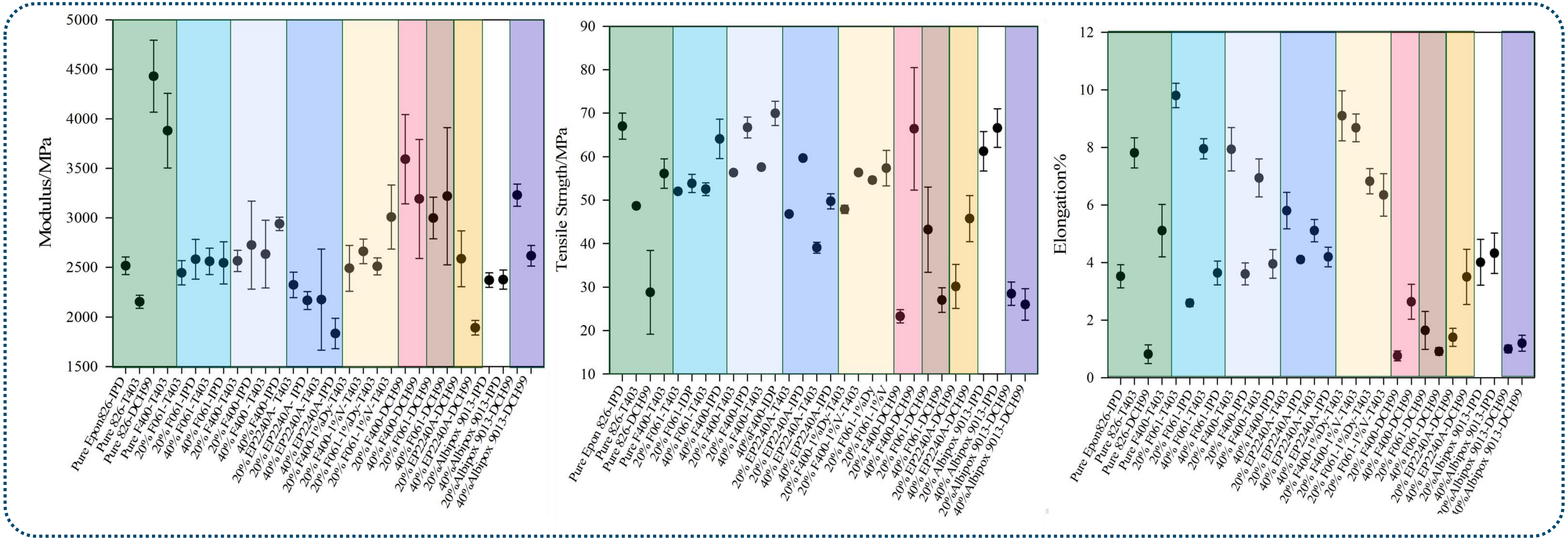
Progress on Fiber Conversion

- ORNL stabilization and carbonization processes for PAN fibers produced > 650 ksi tensile strength and 42 msi tensile modulus measured by single filament tensile test
- CEM further refining oxidation process with increases in fiber stretch/line speeds and implementation of tension control, producing equivalent converted fiber exceeding 700 ksi TS
- Subscale vessels wound with CEM fiber. Burst results match or exceed vessels with baseline fiber

CEM fiber burst results

Fiber	Burst Difference From baseline
Baseline	-
CEM	+0.7%
CEM	-6%

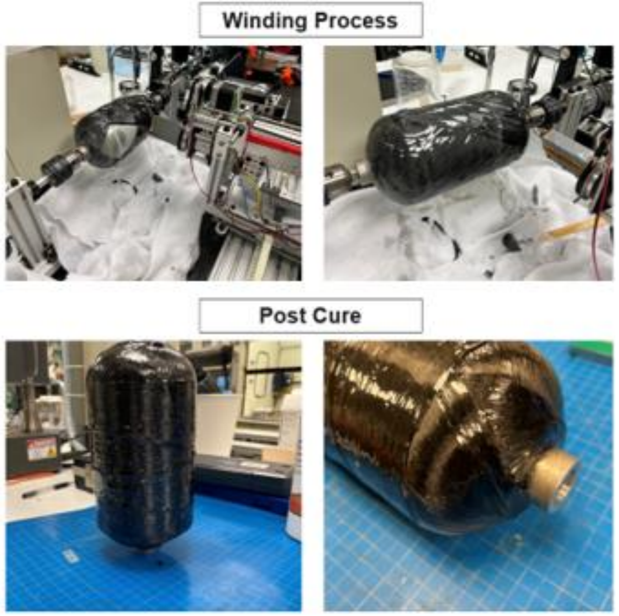
Epoxy resin properties – high performance formulations



- Resins formulations will be selected, and filament wound with new fibers to define optimum composite properties
- Composite performance will be further evaluated in the system cost model

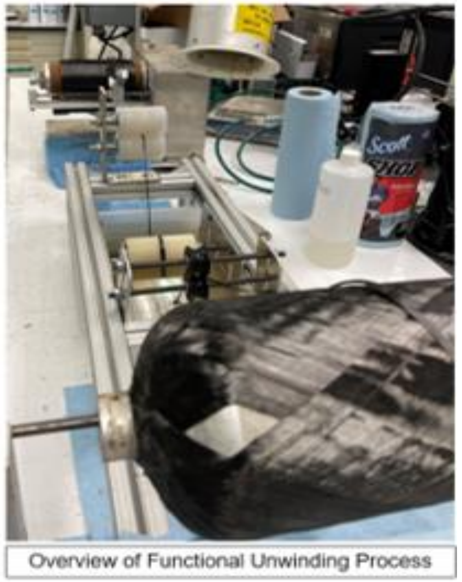
End-of-Life Recycling Progress

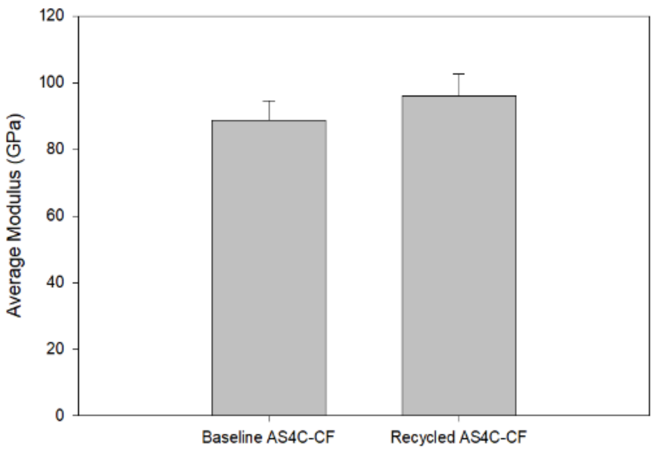
Tank winding using X-winder

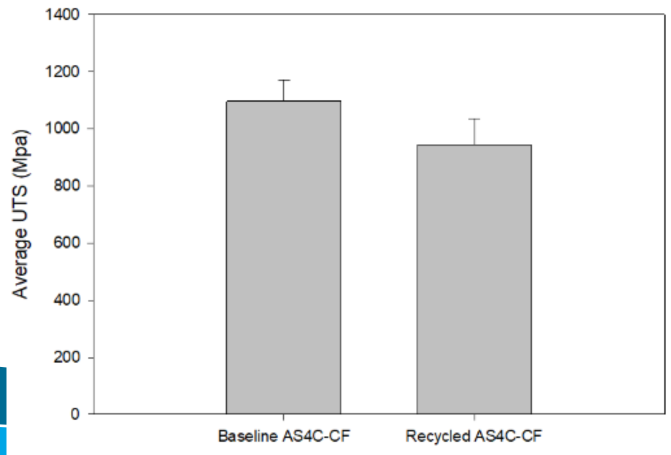


Solvolysis process to depolymerize resin

Unwind and reclaim CF







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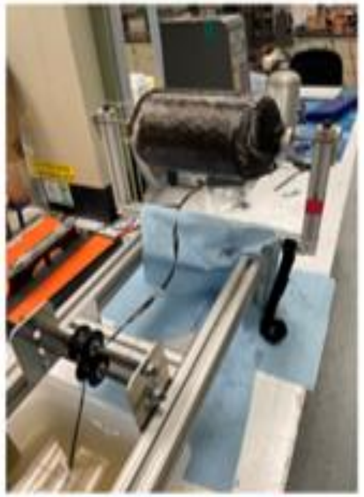
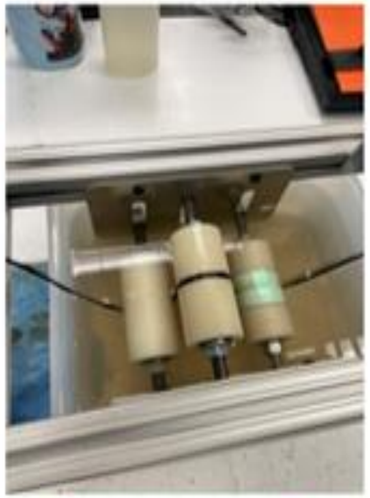
End-of-Life Recycling of Carbon Fiber – unwinding process

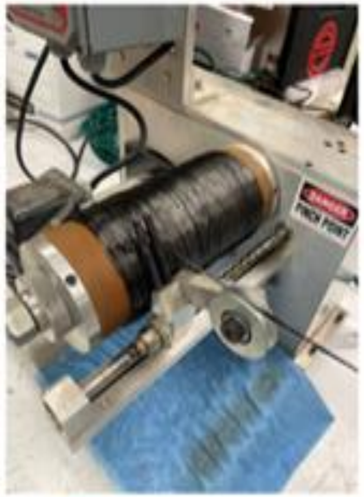


Pressure Vessel Mounted

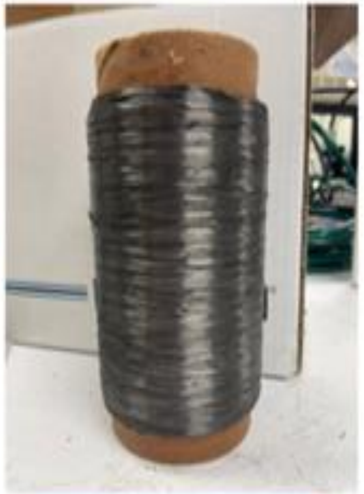


Resin Wash

Nip Rollers



Rewound Recycled Fibers



Recycled Carbon Fiber Spool

Phase II progress successfully demonstrated reclaiming long, continuous CF and polymer matrix from overwrapped pressure vessels!

Cost Modeling

Cost Model Parameters (100,000 Units)	**Units**	**Program Record**		**CORTC**	
		Cost	**Mass (kg)**	**Cost**	**Mass (kg)**
Composite Tank Total Cost and Mass	$	1926	99	1382	81.6
Balance of Plant (BOP) $486 (15.4 kg) + $219 (3 kg) + $288 (3.6 kg)	$	993	22	993	22
Assembly	$	11		11	
Total Tank Cost =	$	2930	121	2386	103.6
Tank Cost =	$/kWh	15.71		**12.79**	
Tank Mass =	kg/kWh		0.65		0.58
Gravimetric Effic. = kWhr/kg (5.6kgH2, 33.31kWh/kg)	kWh/kg		1.47		**1.71**
Gravimetric Effic. = kgH2/kg system	kgH2/kg Syst		0.046		0.054
Composite Contribution to System Cost	$ Comp/kWh	9.99		7.08	

Carbon fiber cost, reported directly to DOE, between $15/kg and $20/kg

Cost model assumptions

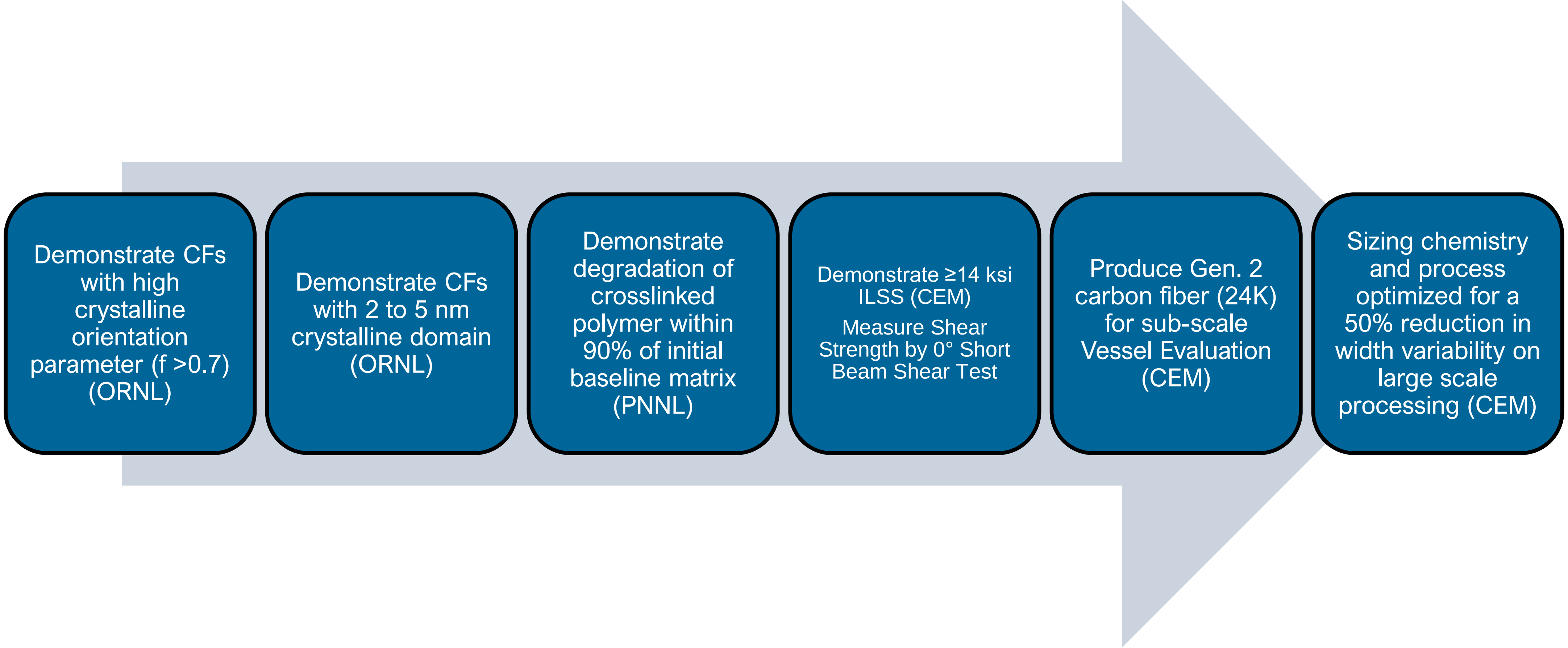
- CSA HGV2 Standard
- 100,000 units/year factory
- Vessel - carbon fiber and GP epoxy resin
- PA Liner, aluminum bosses, and foam domes derived from Program Record
- 10% ROI on composite tank processing
- DOE supplied values:
  - BoP, valve, and regulator data
  - Labor rate of $59,000/year
  - Hydro testing and Helium leak testing

- **Projected tank cost: $12.79/kWh**
- **Gravimetric capacity: 1.71 kg/kWh**

Remaining Challenges and Barriers

Spinning	• Reduce airgap spun, terpolymer PAN fiber diameter variation at ORNL • Reduce variability between spinning trials at CEM
Conversion	• Lower costs through line speed increase at oxidation and carbonization at CEM • Develop advanced stabilization and carbonization processes from ORNL PAN fiber to CF with 700-750 ksi tensile strength and 35 msi tensile modulus, reduce cost in stabilization and sizing processes
Scale-Up	• Simulate scenarios for commercial carbon fiber plant
Composite Innovation	• Span gap between High Performance (HP) resin and carbon fiber development • Potential benefits of HP resin could enhance cost savings of the fiber
Testing	• Scale-up testing from single filament fiber to carbon fiber tow
Modeling	• Refine cost modeling through analysis of cylinder packaging on vehicle and decreased fiber costs

Planned Future Work



Demonstrate CFs with high crystalline orientation parameter (f >0.7) (ORNL)

Demonstrate CFs with 2 to 5 nm crystalline domain (ORNL)

Demonstrate degradation of crosslinked polymer within 90% of initial baseline matrix (PNNL)

Demonstrate ≥14 ksi ILSS (CEM)

Measure Shear Strength by 0° Short Beam Shear Test

Produce Gen. 2 carbon fiber (24K) for sub-scale Vessel Evaluation (CEM)

Sizing chemistry and process optimized for a 50% reduction in width variability on large scale processing (CEM)