AMMTO & IEDO JOINT PEER REVIEW

May 16th-18th, 2023

Washington, D.C.

Low-cost Carbon Fiber Technology| AMMTO or IEDO

Dr. Merlin Theodore Oak Ridge National Laboratory

Contract Number 25349 | Funding Year 2023

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Overview

Scale-up Science Technologies for Advanced Fiber Manufacturing

Mission: AMMTO advance energy-related materials and manufacturing technologies to increase domestic competitiveness and build a clean, decarbonized economy.

ORNL's Carbon Fiber Technology Facility **(CFTF) Ecosystem** provides access to industry, academia, universities and other stakeholders to **co-develop** scale-up advanced fiber manufacturing technologies and best practices from precursor-to-part aiding in the acceleration & adoption of innovative advanced fibers materials (including its composite components) and manufacturing technologies in support of a U.S. supply chain of cost/energy efficient clean energy technologies, decarbonized economy.


FEBRUARY 24, 2021

FACT SHEET: Securing America's Critical Supply Chains

BRIEFING ROOM › STATEMENTS AND RELEASES

First, the order directs an immediate 100-day review across federal agencies to address vulnerabilities in the supply chains of four key products.

1. APIs are the part of a pharmaceutical product that contains the active drug. In recent decades, more than 70 percent of API production facilitators supplying the U.S. have moved offshore. This work will complement the ongoing work to secure supply chains needed to combat the COVID-19 pandemic.
2. Critical minerals are an essential part of defense, high-tech, and other products. From rare earths in our electric motors and generators to the carbon fiber used for airplanes—the United States needs to ensure we are not dependent upon foreign sources or single points of failure in times of national emergency.

- **Semiconductors and Advanced Packaging.** The United States is the birthplace of this technology, and has always been a leader in semiconductor development. However, over the years we have underinvested in production—hurting our innovative edge—while other countries have learned from our example and increased their investments in the industry.
- **Large capacity batteries, such as those used in electric vehicles:** As we take action to tackle the climate crisis, we know that will lead to large demand for new energy technologies like electric vehicle batteries. By identifying supply chain risks, we can meet the President's commitment to accelerate U.S. leadership of clean energy technologies. For example, while the U.S. is a net exporter of electric vehicles, we are not a leader in the supply chain associated with electric battery production. The U.S. could better leverage our sizeable lithium reserves and manufacturing know-how to expand domestic battery production.

<u>Energy, Emissions, & Environment:</u>
CFTF is a critical and necessary enabling advanced fibers technology for the U.S. to achieve its ambitious national energy & decarbonization goals.

<u>Cost & Competitiveness:</u>
CFTF is a national asset and North America's only open-access advanced fiber research and development scale-up (R&D) facility with unmatched capabilities.

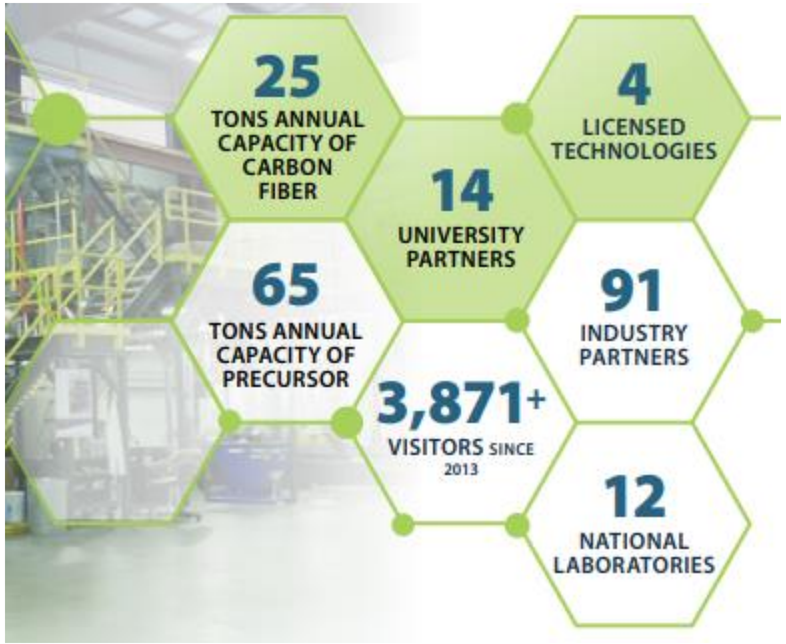
<u>Technical & Scientific:</u>
Advanced fiber manufacturing technology system approach requires full integration of diverse disciplines in materials, modeling, controls, systems, and data science, including partnerships across the supply chain (Consortium). The CFTF Ecosystem allow for seamless technology transfer and accelerating the fruition of manufacturing technology developments maximizing the impact on US economy.

<u>Impacts:</u>
- Development of cost & energy efficient scale-up science and technologies for fiber manufacturing in high volume applications.
- Bridge between R & D proof-of-concept to demonstration, deployment and validation of advanced fiber technologies.
- Enable development of domestic competitive commercial sources of advanced fibers
- Formulate a Workforce
- Development program for
- advanced fiber workforce

Project Outline

Innovation: Scale-up Science Technologies for Advanced Fiber Manufacturing
Project Lead: Merlin Theodore
Project Partners: Over 90 industrial partners, 14 universities, 12 national laboratories
Timeline: Oct 1, 2013 – present
Budget: $5M annually

	FY21 Costs	FY22 Costs	FY23 Costs	Total Planned Funding
DOE Funded	$5M	$5M	$5M	$15M
Project Cost Share	$123K	$231K	$0K	$354K
IACMI (Consortia)	$74K	$69K	$0	$143K
IACMI costs	$42K	$69K	$0	$111K



End Project Goal: Develop and advance scale-up science and technologies for advanced fiber manufacturing from the research and development stage to validation and deployment, enabling domestic commercial sources of these technologies thus enhancing U.S competitiveness in advance fiber manufacturing.

Background – Why Advanced Fibers (Carbon Fibers)?

Carbon fiber (CF) and its composites are recognized "critical materials" and as clean energy technologies due to their positions as enabling materials in many diverse applications with a strong relevance to energy use and essential for DOE initiatives because of the potential life cycle energy savings.

Challenges:

- Pivotal Challenge is "COST"
- Energy intensive process
- Insufficient U.S. owned production capacity - 95% of Carbon Fiber are internationally owned
- Technology scaling
- Process Validation
- Inconsistent quality of raw materials


BRIEFING ROOM

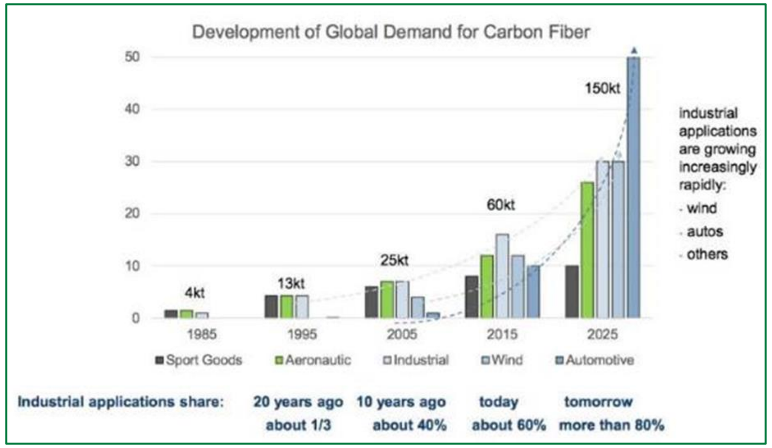
Executive Order on America's Supply Chains

FEBRUARY 24, 2021 • PRESIDENTIAL ACTIONS

2. Critical minerals are an essential part of defense, high-tech, and other products. From rare earths in our electric motors and generators to the carbon fiber used for airplanes—the United States needs to ensure we are not dependent upon foreign sources or single points of failure in times of national emergency.

[1]FACT SHEET: Securing America's Critical Supply Chains - The White House

Carbon fiber is a "critical material" to our energy future and national security.



www.carbonfibrefutures.com.au/wp-content/uploads/20017/03/20170301-CF-Futures-Deakin-2017-Pichler-v4.pdf

- *Total market in 2022 (PAN-based CF): ~134,000 MT
- Future Market by 2032 (Pan-based CF): ~300,000 MT

*Daniel Pichler Services LLC for ORNL CFTF April 2023

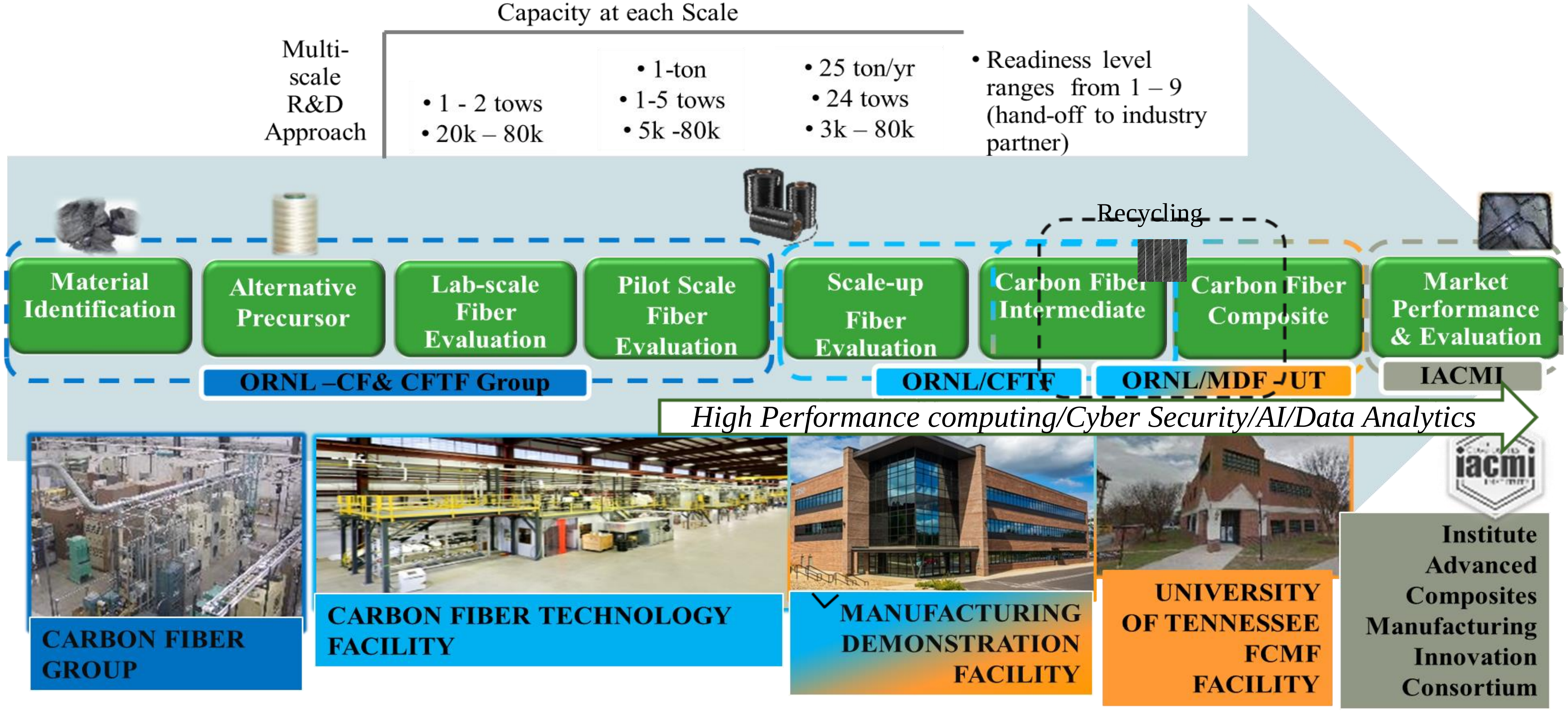
No Investment in Advanced Fibers R&D Impact:

- Transportation – utilize the benefits of lightweight components enabled by advanced fiber materials for one quarter of the U.S. fleet vehicle types/classes which could save more than 5 billion gallons of fuel annually by 2030. https://www.energy.gov/eere/vehicles/lightweight-and-propulsion-materials
- Wind Energy –shortages of fundamental commodity price risks could disrupt supply chain activities, erode U.S. competitiveness, and jeopardize deployment ambitions. https://www.energy.gov/sites/default/files/2022-02/Wind%20Supply%20Chain%20Report%20%20Final%202.25.22.pdf
- Pressure Vessels –roadblock in strides towards sustainability (decarbonization) enabled by advanced fiber materials in transport on land and air. https://www.energy.gov/eere/fuelcells/articles/hydrogen-storage-fact-sheet
- Aerospace/Defense – deficiency of key elements to the electrification of the drivetrain, development, and acceleration of "critical fiber materials" for the Hypersonic supply chain, technology, and National Security.

Strategic Approach - Multi-scale Integrated Precursor-to-Part Approach

- Identify high potential, low-cost alternative precursors
- Multi-scale approach to reduce the uncertainties associated with scaling & develop optimal mechanical properties of resultant carbon fiber from
- Utilize the data analytic framework developed for CF manufacturing
- Provide quantities to industrial partners for testing based on DOE approval
- Address feedback from industrial partners
- Improve carbon fiber manufacturing cost metrics

Scaling of Science



- *Integrator of research initiatives/strategies across the supply chain with unique supporting research facilities and capabilities, projects, technical skills, and established industry partner relationships*

Strategic Approach example – Develop, Demonstrate, Validate, Deploy

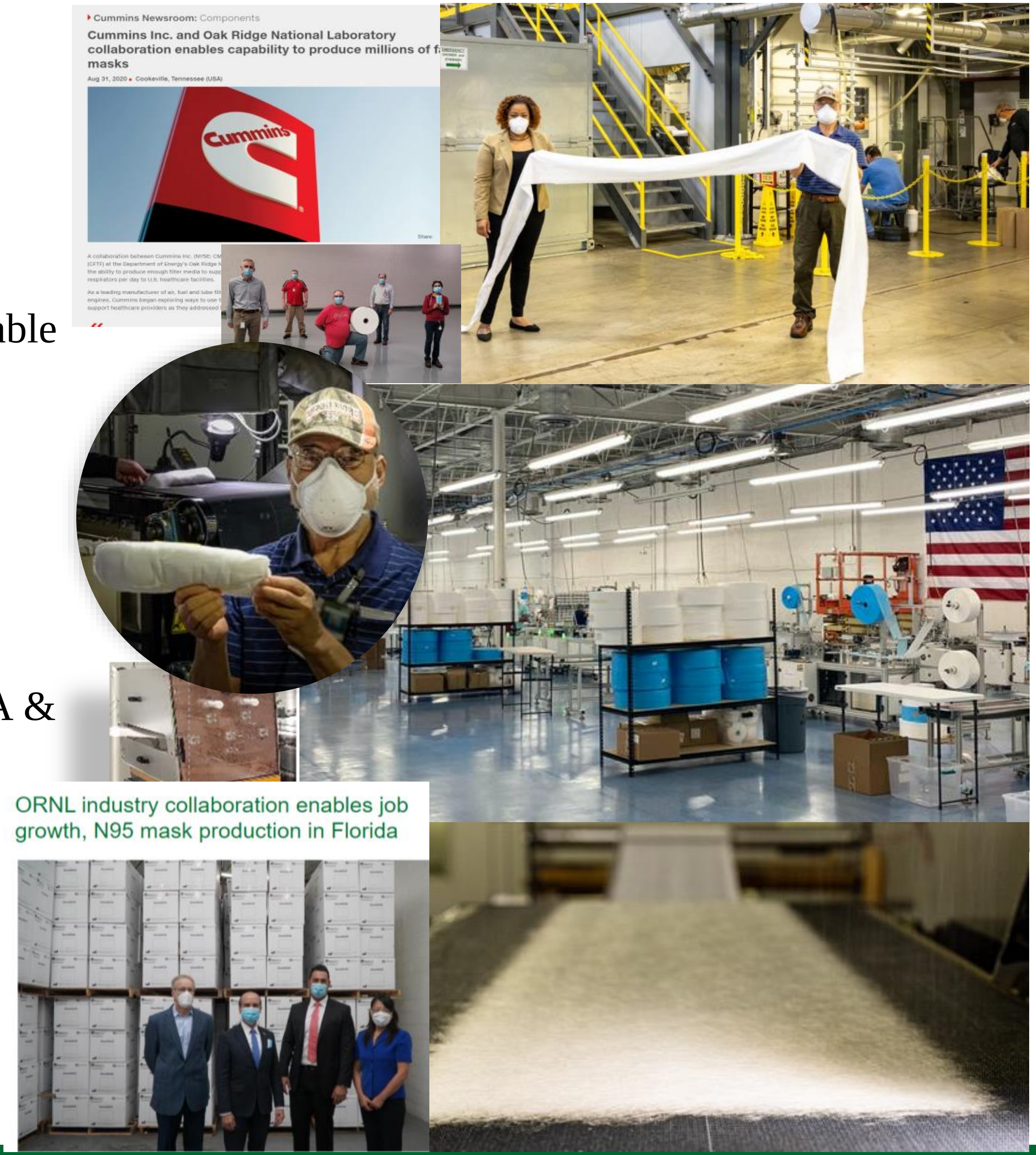
Filter Media Fiber Technology

Research to commercialization in **6 months**

- Develop filter media fibers for PPE and N95 charging device for industrial environment at CFTF
- Transfer Technology to Cummins Filtration – Enable Filter media capacity for 1M masks/day

  Cummins Inc. and Oak Ridge National Laboratory collaboration enables capability to produce millions of face masks | ORNL
- Catalyze relationship with Cummins Filtration & DemeTECH. –
- Enabled PPE capacity to produce millions of FDA & NIOSH approved face masks/day at DemeTECH.
- Created a US PPE supply & economic growth with >1,500 new jobs in medical manufacturing sector

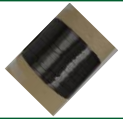
  ORNL industry collaboration enables job growth, N95 mask production in Florida | ORNL



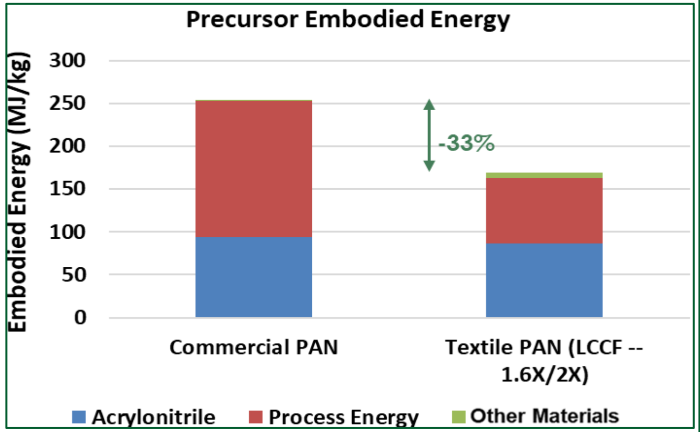
- Critical resource for addressing challenges associated with National Crisis

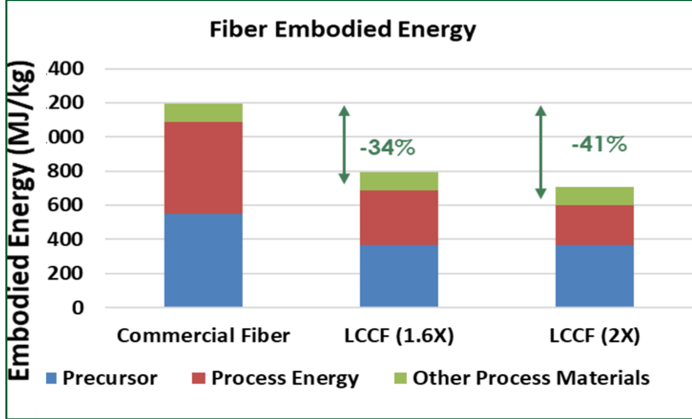
Strategic Approach example – Develop, Demonstrate, Validate, Deploy

Textile Carbon Fiber (TCF) Technology



PARAMETER	BASELINE	HEAVY TEXTILE TOW (Current: 1.6X Capacity)	HEAVY TEXTILE TOW (2X Capacity)
Tow Size	50K	457K	457K
Annual Prodn. Volume	1,500 tonnes/yr	2,400 tonnes/yr	3,000 tonnes/yr
Capital Investment	$58M	$58M	$58M
Final Fiber Cost	$18.11/kg	$11.19/kg	$9.92/kg

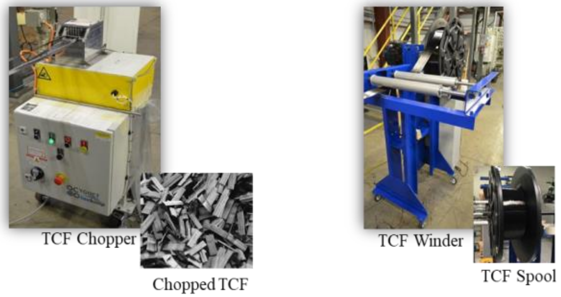




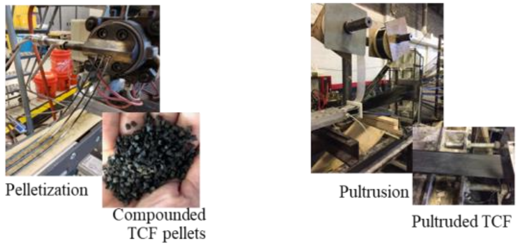
- ✓ Lower precursor cost -- High output textile grade acrylic fiber used for clothing vs. specialty acrylic fiber
- ✓ Lower capital cost – Higher production capacity
- ✓ Lower energy and labor cost – Economies of scale from an increased throughput
- ✓ Estimated heavy textile tow carbon fiber cost reduction potential is *conservative compared to CFTF full potential.*
- ✓ CFTF has demonstrated 2x increase in throughput with the potential of improving throughput even further.

Handling capability, Intermediate, Composites, & Applications

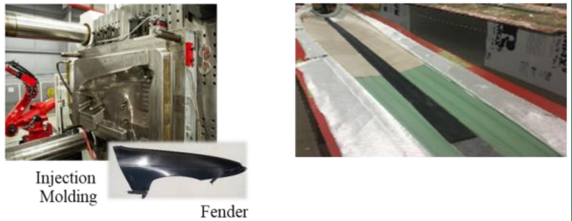
Development of handling processes for TCF



Evaluation of TCF in intermediate processes



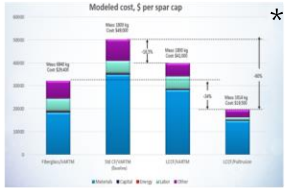
Evaluate TCF Intermediates in Top compositing methods



Automotive application

10% ORNL LCCF / PA66 60 Parts Cycle time: 75s		
Property	Standard CF	CFTF Fiber
Flexural Strength (Psi)	30,000	28,500
Tensile Elongation @ Break (%)	2.4	2.2
Flexural Modulus(Psi)	1,000,000	1,260,000
Notched izod	0.50	0.60

Wind application



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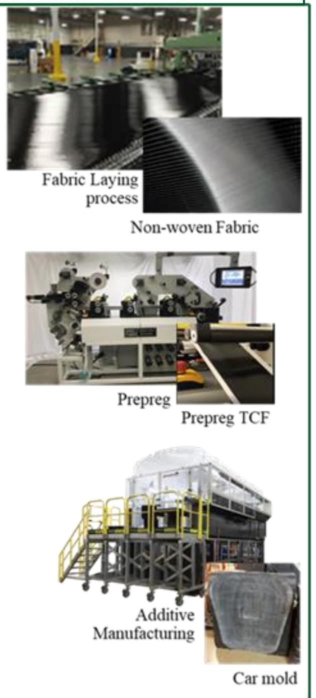


Defense application

Industrial application

Recycled composites

*https://nice.sandia.gov/news/publications/labnews/articles/2021/01-29/carbon_fiber.html

Strategic Approach - for Carbon Fiber Manufacturing - Theoretical Reduction in Cost & Energy for Alternative Precursor Materials/Advanced Conversion Processes

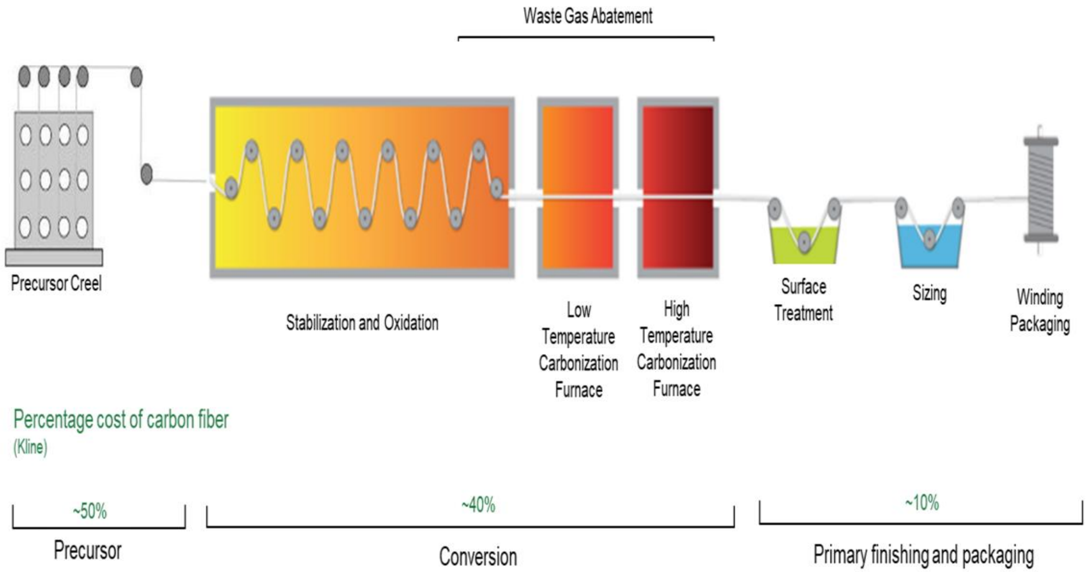
Scale	Precursor/Conversion Process	Cost Δ	Energy Δ
Baseline	**Standard PAN precursor**	0%	0%
Lab	**Melt stable PAN precursor**	- 30%	- 30%
Lab	**Lignin-based precursor**	- 50%	- 40%
Lab	Silicon Carbide Fibers	- 85 %	TBD
Lab	**Advanced conversion processing**	- 25%	- 50%
Lab	**Bio-PAN**	TBD	TBD
Scale-up	**Polyolefin/Polyamide precursor**	- 20%	- 50%
Scale-up	**Pitch-based precursor**	- 70%	- 70%
Scale-up	***Textile PAN precursor >30 variations**	*Theoretical **- 25%** Actual **- 54%**	Theoretical **- 30%** Actual **- 41%**
Scale-up	**Recycled CF**	- 60%	- 90%

*Sources: Das, S. and Warren J., "Cost Modeling of Alternative Carbon Fiber Manufacturing Technologies – Baseline Model Demonstration," presented DOE, Washington, DC, 5 April 2012; Unpublished analysis by Kline and Co, 2007; Suzuki and Takahashi, Japan Int'l SAMPE Symposium, 2005;

Textile Pan-precursor

Petro. & coal-based pitch material

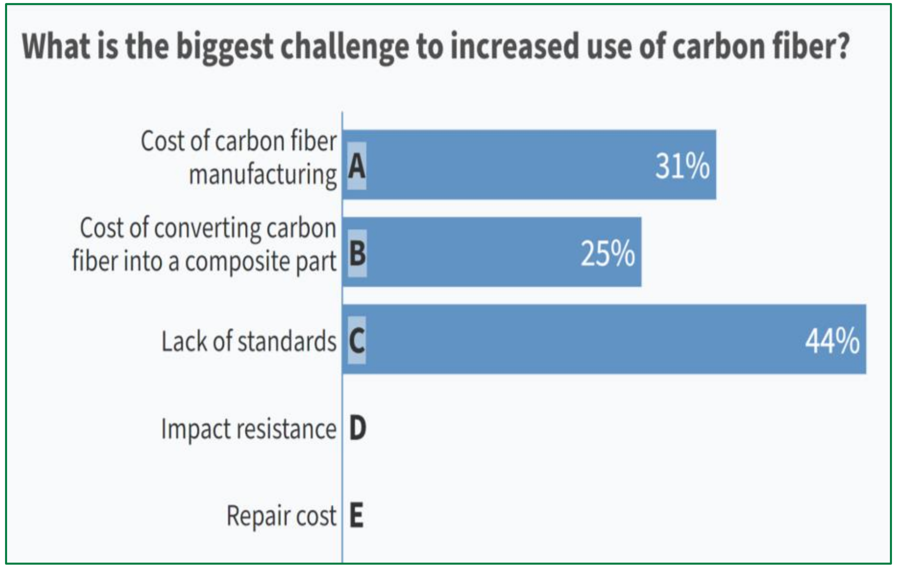
Nvlon 6

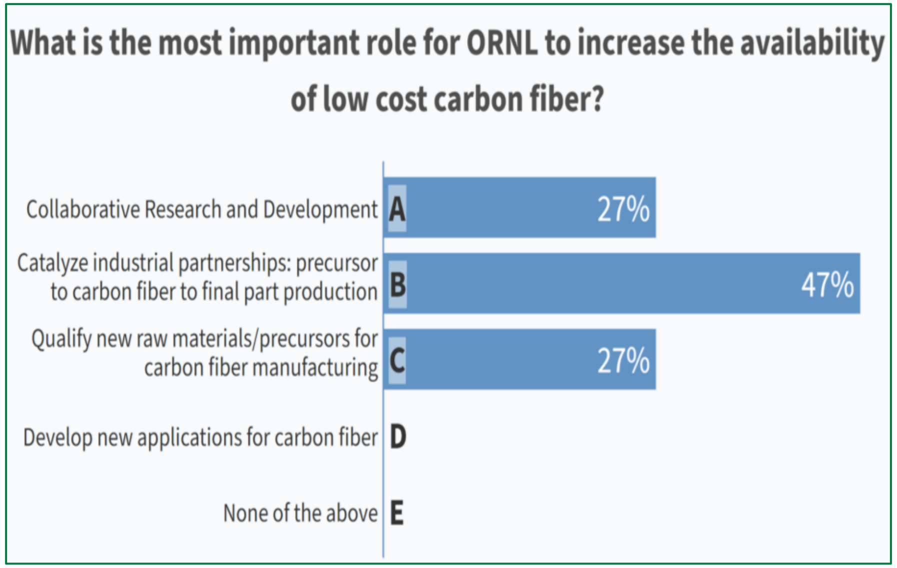


FY 23 Results and Achievements - Carbon Fiber Mini Workshop

Summary of Mini-Carbon Fiber Workshop SAMPE Seattle 4/17 – 4/21

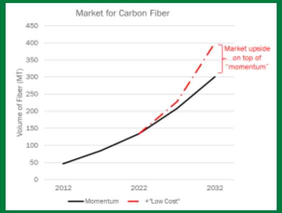
- Industry Panel established with manufacturers across the supply chain
- Extensive market study completed
- 30 attendees – high performance end users & aerospace focused
- Top responses to poll questions
  - Low-cost carbon is important to the future of my business – 100% agree
  - Low-cost carbon fiber is important in the US to reduce energy usage – 79% agree
  - Carbon fiber production in the US is important because – technological leadership – 48%
  - The position that the US holds in carbon fiber manufacturing is – a lost opportunity – 71%
- JEC industry interviews **Seattle 4/17 – 4/21**
  - 34/36 Companies interviewed
- Full workshop June 19-20th 2023 Knoxville, TN





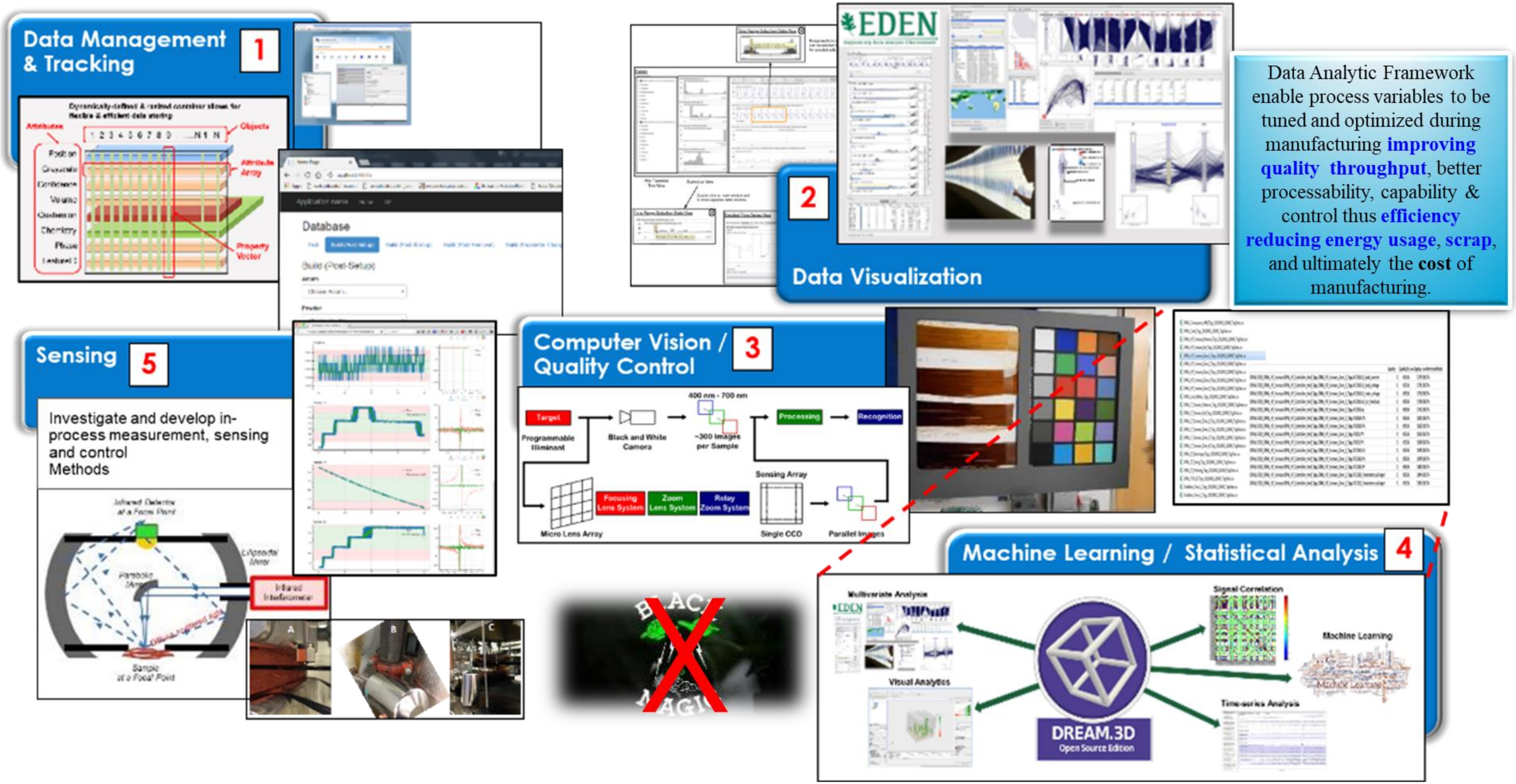
<u>Potential Impact</u>

- Up to 80% reduction in embodied energy from low-cost feedstocks & hi-throughput processes



- Cost & quality improvements from AI & HPC modeling & simulation
- Additional Domestic supply of CF
  - 50-100 kt additional new market for carbon fiber
  - $2 billion investment - Assemble and support the value chain to develop it
  - $1 billion / year in additional production and sales
  - A cluster of complementary downstream enterprises created
  - $20-50 billion in additional economic value created over 10-20 years
  - +5,000 direct jobs; +>10,000 indirect, knock-on jobs

FY 23 Results and Achievements – Data Analytics Framework for CF Manufacturing

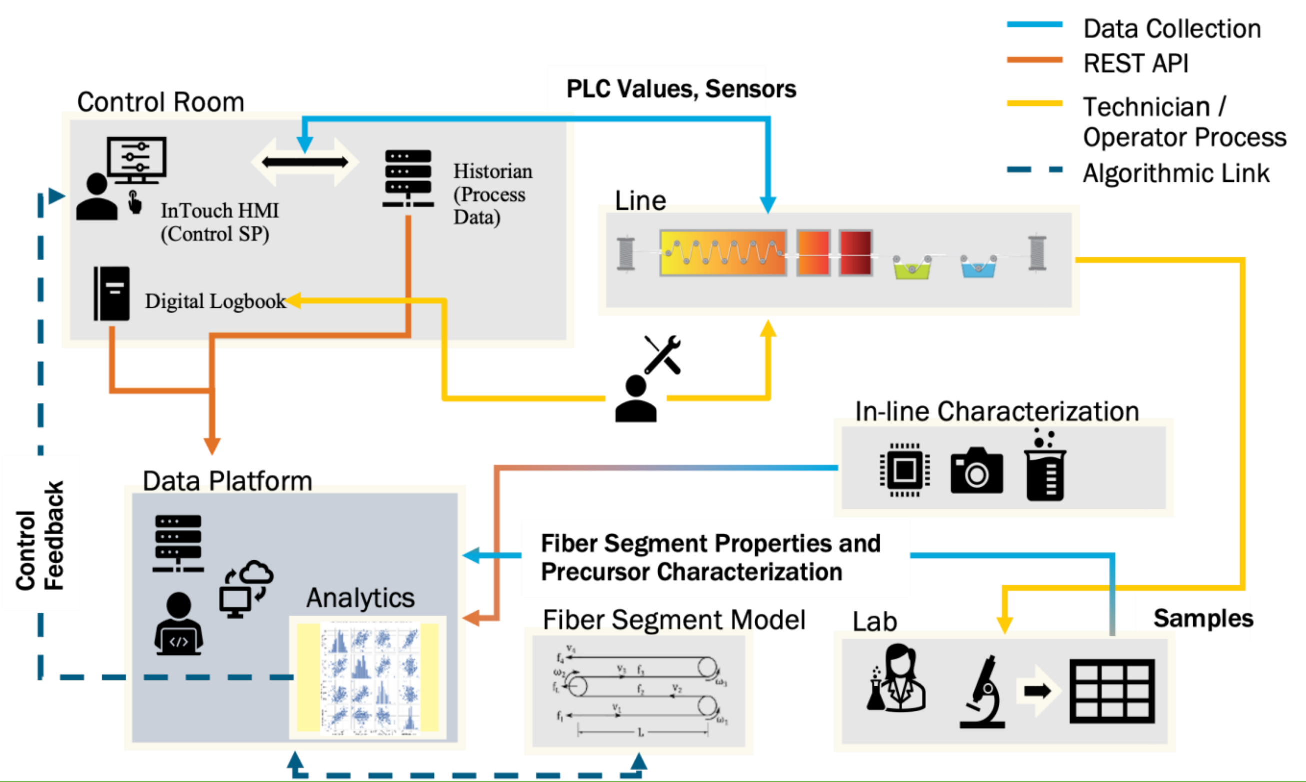


Data Analytic Framework enable process variables to be tuned and optimized during manufacturing **improving quality throughput**, better processability, capability & control thus **efficiency reducing energy usage**, **scrap**, and ultimately the **cost** of manufacturing.

FY 23 Results and Achievements - CF Digital Data Platform Highlights

- **Challenge**: Current "off the shelf" solutions do not efficiently serve CF research and production environments, leading to data being siloed and difficult to fully utilize for optimization tasks (energy reduction or quality improvements).
- **Approach:** Create a custom digital data platform to enable efficient data input and retrieval at the CFTF.
- **Solution:** Designed and built a software API with supporting server code and database backends that allow for:
    1. digital twin modeling,
    2. characterization and process monitoring,
    3. data analytics.
- **Result**: Our current understanding of carbon fiber specific needs and best principles of design for a data platform are being described in a software requirements specification document.

Recording a fiber segment's history allows us to attribute characterizations to process parameters and materials and understand where energy can be saved.



Artifacts:
- Platform software requirements specifications
- Custom designed database schemas
- Data server software creating connections between facility data collection points
- OpenAPI specifications

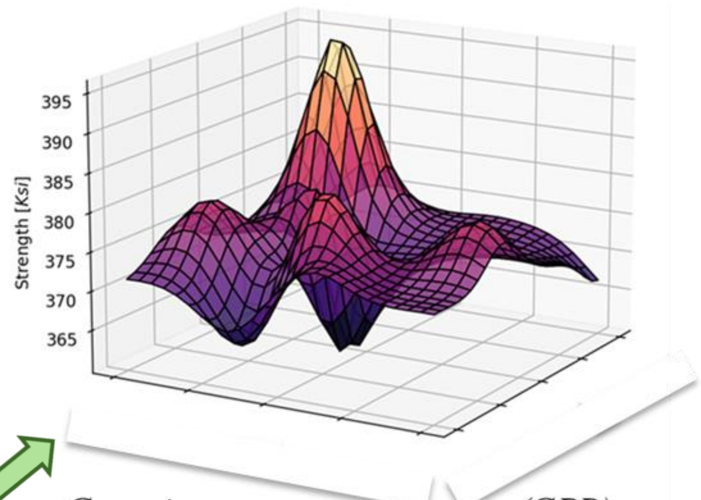
FY 23 Results and Achievements – Control Algorithm for Fiber Manufacturing

Challenge:

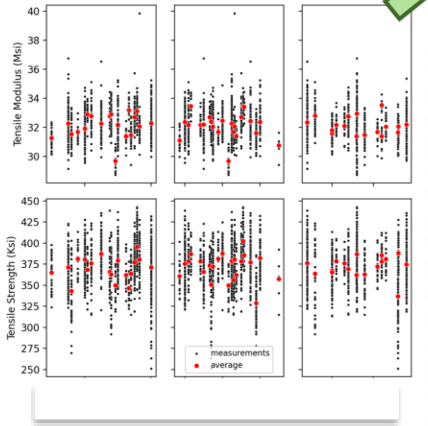
- First principles / mechanistic understanding limited
- Experimental tests at full scale are expensive and tedious. E.g., 12h of operation for one data point

Approach:

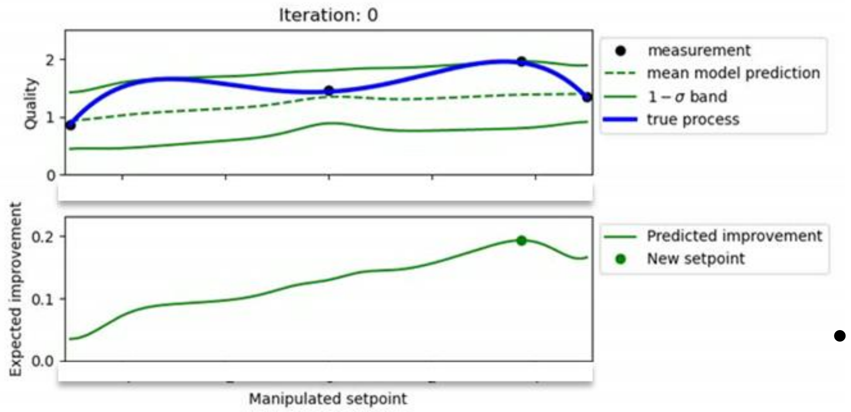
- Data-driven optimization
- Practical aspects
  - Batch mode: multiple tests scheduled at once (e.g., whole week of operation)
  - Multi-input multiple variables available for manipulation
  - Multi-output: multiple metrics of interest (e.g., density, tensile strength/modulus, resource efficiency)



Gaussian process regression (GPR) model implemented in Python/Pytorch



Chaotic Data Set



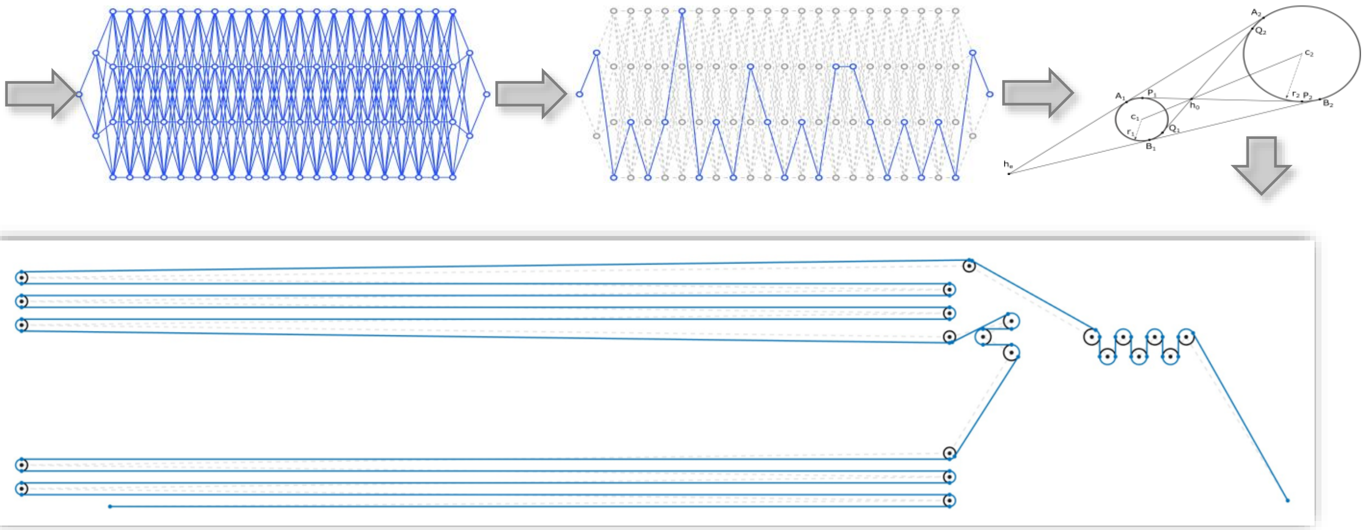
Demo Bayesian Model (simulated example)

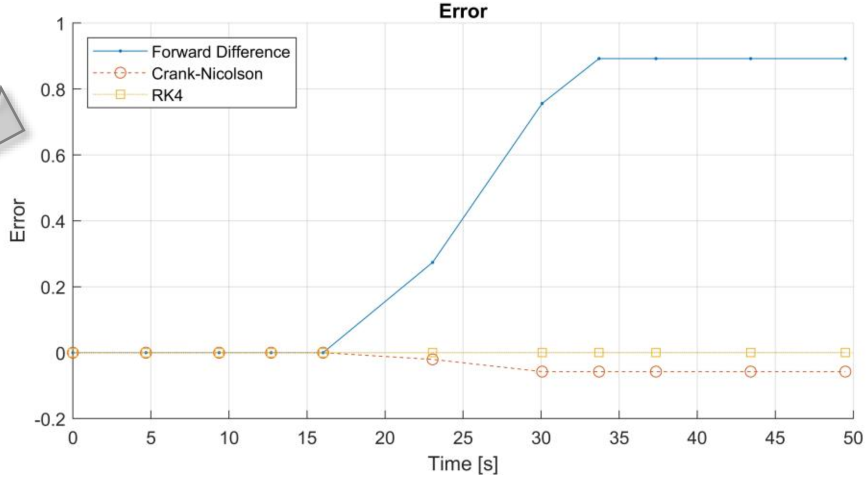
Our solution

- Bayesian models
- Provide optimal trade-off between
  - Expected cost of test
  - Improvement in resource efficiency
  - Joint achievement of:
    - Fiber quality maximization
    - Specific energy minimization
  - Multi-input multi-output (MIMO) batch optimization
  - Developed/tested at CFTF through 2021-2023
  - Toolbox: *Bayesian Optimization for Optimal Test Selection*
    - Software copyright request filed March 2023: https://code-int.ornl.gov/cftf-data/analytics/boots
- Results:
  - Expect 40% reduction in energy requirements
  - For same quality of fiber

FY 23 Results and Achievements - Transport Model for CF- Manufacturing

- Derived a method to automatically find the fiber path through the processing line using dual graphs, roller locations and diameters.
  - Simplifies geometry modeling
  - Generates fiber path geometry automatically
- Derived transport model to simulate carbon fiber tow motion through the processing line.
- Developed a numerical integration method to solve the transport model that has sufficient accuracy for data analytics. Transport model and data analytics are being implemented as an open-source Python library
  - Allows a complete analysis of any fiber segment's process history.
  - Provides a framework for real-time control and optimization.
  - Focus is on ease of use, accuracy, and flexibility.





Accuracy comparison (error in meters) of numerical solutions to the transport model over a short 16-meter-long processing line test geometry.

Algorithm 2 Modified Runge-Kutta 4^{th} order position estimation for a single time step.

function RK4(t,x_0,x_i,v_i)
 $x[0] \leftarrow x_0$
 for $k = 0$ **to** $N-1$ **do**
  Δt_k gets $t[k+1] - t[k]$

  $i \leftarrow \text{Segment}(x[k], X, \varepsilon)$
  $m_i[k] \leftarrow (v_{i+1}[k] - v_i[k])/(x_{i+1} - x_i)$
  $k_1 \leftarrow \Delta t_k\big(v_i[k] + m_i[k](x[k] - x_i)\big)$
  $x_1 \leftarrow x[k] + k_1/2$

  $i \leftarrow \text{Segment}(x_1, X, \varepsilon)$
  $m_i[k] \leftarrow (v_{i+1}[k] - v_i[k])/(x_{i+1} - x_i)$
  $k_2 \leftarrow \Delta t_k\big(v_i[k] + m_i[k](x[k] + k_1/2 - x_i)\big)$
  $x_2 \leftarrow x[k] + k_2/2$

  $i \leftarrow \text{Segment}(x_2, X, \varepsilon)$
  $m_i[k] \leftarrow (v_{i+1}[k] - v_i[k])/(x_{i+1} - x_i)$
  $k_3 \leftarrow \Delta t_k\big(v_i[k] + m_i[k](x[k] + k_2/2 - x_i)\big)$
  $x_3 \leftarrow x[k] + k_3$

  $i \leftarrow \text{Segment}(x, X, \varepsilon)$
  $m_i[k] \leftarrow (v_{i+1}[k] - v_i[k])/(x_{i+1} - x_i)$
  $k_4 \leftarrow \Delta t_k\big(v_i[k] + m_i[k](x[k] + k_3 - x_i)\big)$

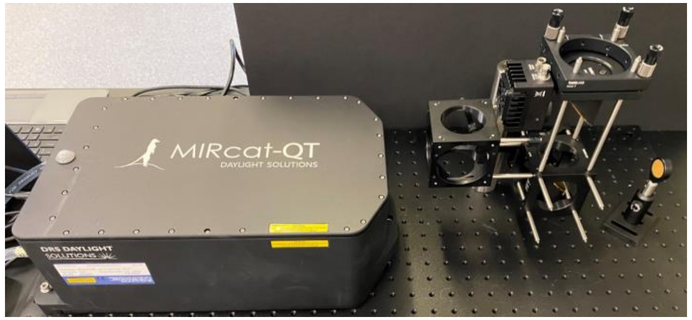
  $x[k+1] \leftarrow x[k] + (1/6)(k_1 + 2k_2 + 2k_3 + k_4)$
 end for
end function

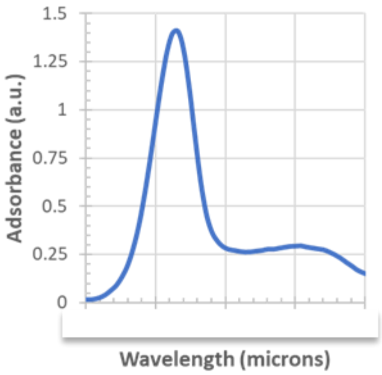
FY 23 Results and Achievements - Insitu-Mearurement Concepts

- **Challenge**: Predictability of CF process is limited in part by a lack of in-situ / in-line measurements of tow properties during production.
- **Approach:** Use on-contact sensors to infer key property values (e.g. conductivity) of the tow on the line.

- **Solution:** Demonstrated **Quantum Cascade Laser (QCL)** Infrared Spectroscopy technique for fiber density measurement

- **Results:** Improvements over FTIR-based technique include:
  - Increased signal-to-noise by >100x
  - Increased scan speed by 20x
- Next step: on-line measurement R&D

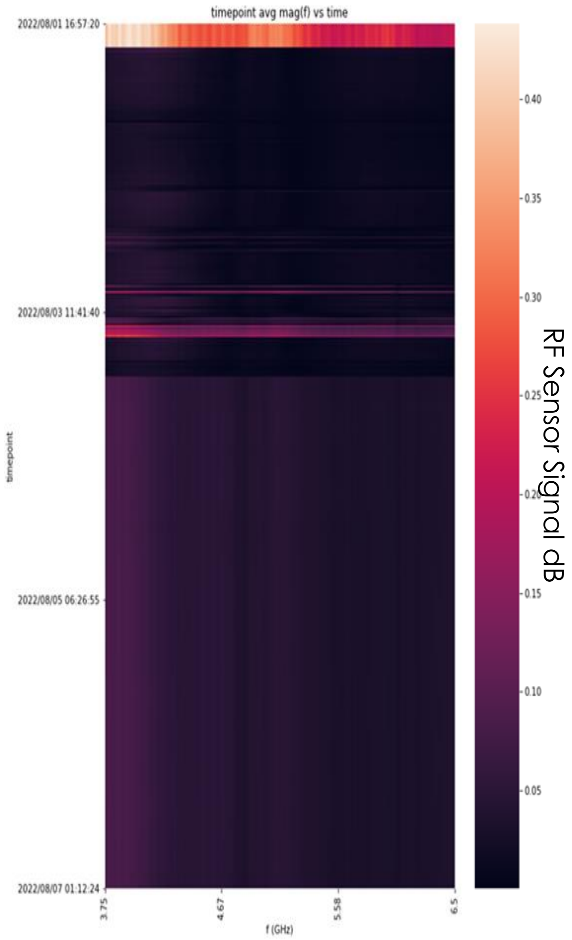




Invention Disclosure 202305265 [Method for on-line measurement of fiber density with infrared diffuse reflectance spectroscopy]

- **Solution:** Designed and built a platform for acquiring sensor data from two types of sensors – radio frequency (GHz) and magnetic susceptibility sensors.

- **Result**: The developed sensor fusion technique may be capable of inferring useful property variables if experimental artifacts can be overcome. Present efforts include image-based monitoring of the experimental sensors



Invention Disclosure 202305341 [RF and B-Sus CFTF Tow Sensing]

FY 23 Results and Achievements – New Alternative Precursors/Capabilities

Proof of concept ideas focused on advanced fiber manufacturing and/or materials technologies for advanced fiber manufacturing.

First Low-cost Silicon Carbide Fiber line – expect ~85% reduction in SiC fiber manufacturing costs

- Development of new low-cost precursor materials using more environmentally friendly lower cost materials, cost-efficient precursor spinning processes (ex. melt-spinning), and cost-efficient conversion processes.

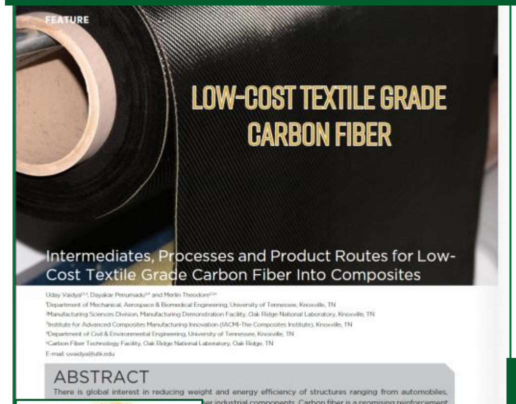
Development of Silicon Carbide fiber precursor

Development of cellulosic biodegradable fibers for film & packaging

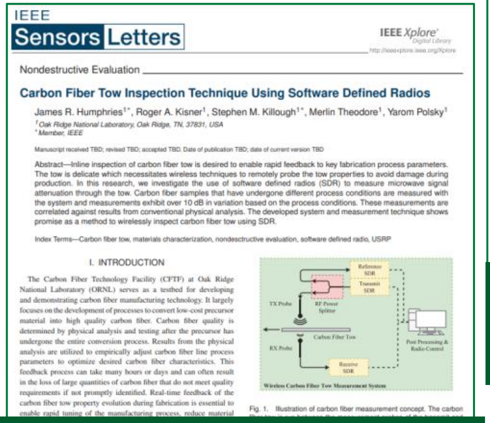
Development of Silicon Nitride Fibers

Results and Achievements - Publications & Intellectual Property

SAMPE Journal Feature March/April 2022 & 2023

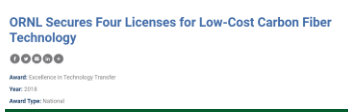


2023

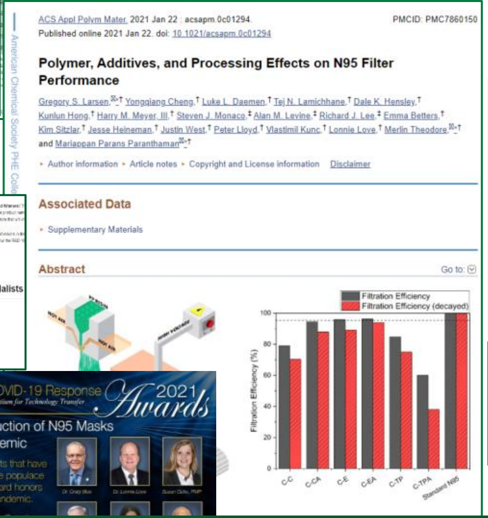


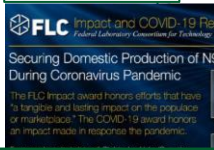
In-situ measurement concept

TCF in Wind & automotive

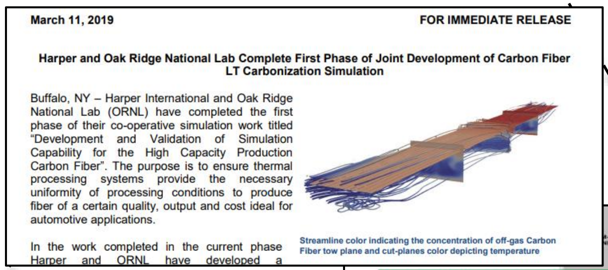


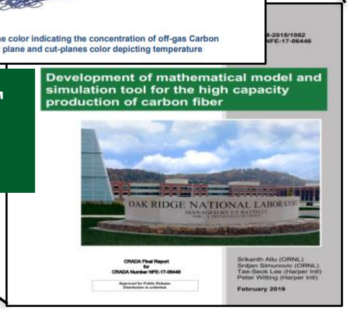
FLC TCF Licensed Technology award





Filter Media Technology & Awards





Modeling for CF manufacturing

Achievements

- Market Study completed
- API Best Practices
- > 20 publications
- Carbon Fiber Market Study/Industry Panel Identified
- 2 Copyrights1 Mathematical model and 1 Simulation tool:
  - Bayesian Model Software copyright: https://code-int.ornl.gov/cftf-data/analytics/boots
  - Transport Model Software copyright
  - Mathematical Model & Simulation Tool
- >10 Invention Disclosures/Patents:
- Workforce Development - 77% Students/Interns landed jobs
  - Students – 33% Current, 40% Academia, 20 % Industry, 7% Government
  - Tech Interns - 16% Industry, 66% Government

Future Work, Technology Transfer, & Impact

Future Work:

- Carbon Fiber Workshop
- Develop business case for Textile Carbon Fiber
- Demonstrate Textile Carbon Fiber performance in Demonstration Projects
- Upgrade of Melt-spinning equipment for processing pitch material from various sources of coal and petroleum
- Further Development and scaling of new advanced precursors, fibers, and conversion processes
- Continue integration of AI, computational models, science and understanding at the CFTF to drive commercialization of low-cost precursor-based Carbon Fiber
- Work with DOE program offices to integrate research strategy for significant impact to energy applications

Technology Transfer:

- Complete Full-scale workshop to generate interested licensees', CRADA, and other forms of joint collaborative work for ORNL Carbon Fiber IP packages to market to interested parties

Potential Impact:

- A Domestic supply of carbon fiber subsequently resulting in an additional new market for carbon fiber and a cluster of complementary downstream enterprises created, $20-50 billion in additional economic value created over 10-20 years, +5,000 direct jobs; +>10,000 indirect, knock-on jobs

Questions?

Low-cost Carbon Fiber Technology| AMMTO

Dr. Merlin Theodore

Email:theodorem@ornl.gov

Office: 865-576-6569