Developing Advanced Carbon Fiber in India:
Process Technology Advancements for the Future

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Topics

- **Carbon Fiber Composites Market Overview**
  - Automotive, aerospace, construction, energy etc.
- **India's Role**
  - Research & development, engineering services and manufacturing potential
- **Building a Carbon Fiber Ecosystem**
  - The journey from scientific research to production
- **New Technology Innovations**
  - Research Systems - enabling scientific and industrial research through prototyping

Market Overview

- **Key attributes of carbon fiber composites**:
  - High strength & stiffness
  - Lightweight
  - Non-corrosive
  - High temperature tolerance and low thermal expansion
  - High thermal and electrical conductivity
  - High durability and fatigue resistance

Key challenges:

- Lowering production costs for carbon fiber and downstream
- Maximize efficiency of supply chain through greater integration

India's Role:

- Robust scientific research
- Innovative product development
- Scalable manufacturing potential

Aerospace

Automotive

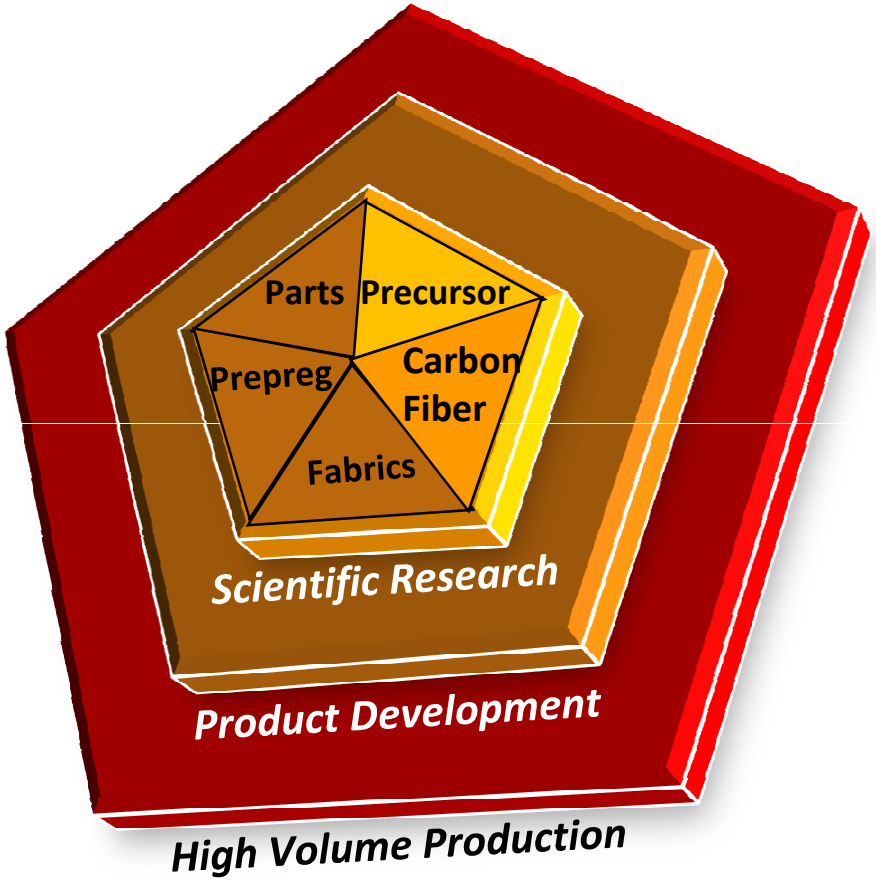
Oil & Gas Exploration

Energy Storage

Wind Energy

Electronics

Building a Carbon Fiber Ecosystem



Stages of Carbon Fiber Development

Scientific Research

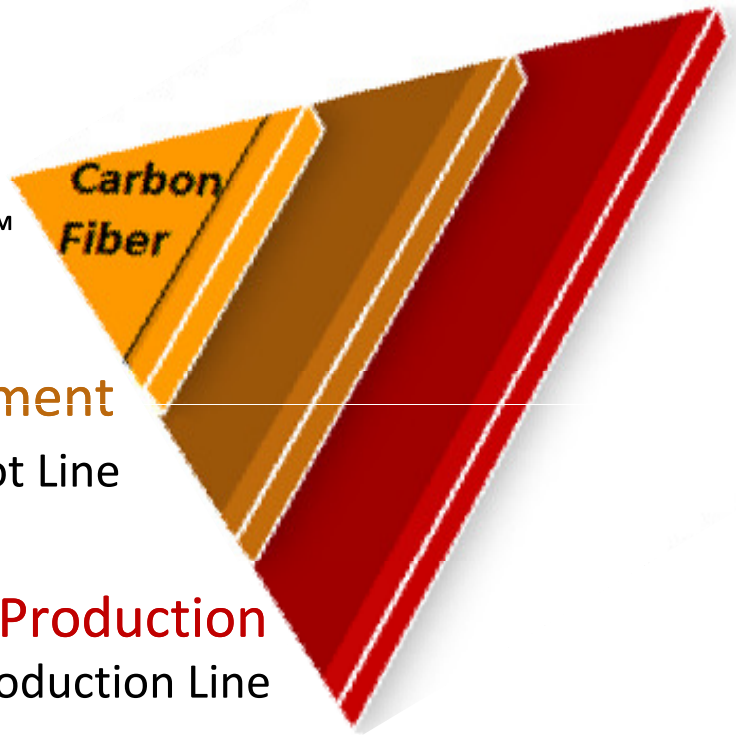
Scientific & Microline™

Product Development

Pilot Line

High Volume Production

Full Production Line



Precursor Fiber

Creel

unwind

Oxidation Ovens

stabilize to 400°C

LT Furnace

HT Furnace

UHT Furnace

carbonize and graphitize @ 1400°C to 2000+°C

Surface Treatment

clean & treat

Winders

re-wind

Carbon Fiber

Carbon Fiber Carbonization Process Scales of Operation

Courtesy of Georgia Institute of Technology

Scale	Size Range (Tow-Band Width)	Capacity
Scientific Line	Fractional tows (<1k or less than 1,000 filaments)	Less than 1 ton/year
Microline™	≤100 mm	Less than 10 ton/year
Pilot Line	300 -1000 mm	20 - 100 ton/year
Commercial Production Line	1000 – 4200 mm	500 - 4000 ton/year

Courtesy of Oak Ridge National Laboratory

New Technology to Enable Innovation: Need for R&D Capabilities

- Recall…

Key challenges:

- Lowering production cost for carbon fiber and downstream
- Maximize efficiency of supply chain through greater integration

Goal:

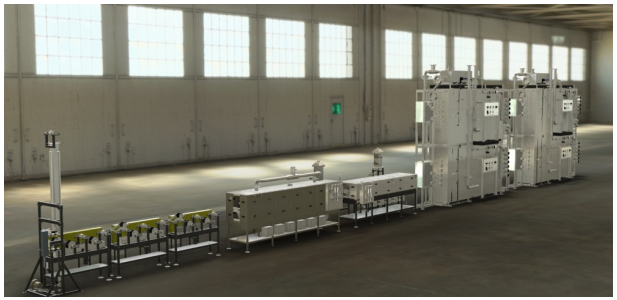
Decrease cost per unit to reach full carbon fiber composites market potential

- Solutions:
  - Energy efficient systems using lower per-unit energy consumption
  - Novel energy recovery techniques by recycling energy inputs
  - Skilled workforce development and job training
  - Innovations in fiber processes and recipes

R&D platforms with manufacturing relevance needed to leapfrog into value generating technology breakthroughs

Research Systems

- Traditional research techniques use batch processing techniques
- However, batch techniques for Carbon Fiber does not yield industry-applicable results



Criteria	Batch Processing Research	Continuous Processing Research
Tensioning	Cannot achieve accuracy with < 500 filaments	Accurate even at very low filament count
Dynamic Tow Effects	Effect on processing techniques and recipe requirements cannot be investigated	Important element of innate capabilities
Carbonization	Difficult to obtain good properties	Properties reflect larger scales for applicability to production
Material Input Required	Grams / sample	At least 1 kg/sample
Material Output	Non-standard format; not usable for repeatable prototyping	Standard package formats
Operation	Lower skill required; flexible to work-day	Higher skill; typically day/night shifts

Continuous Processing R&D = Greater Production Relevance

Key Considerations for Carbon Fiber Research: Precursor Compositions

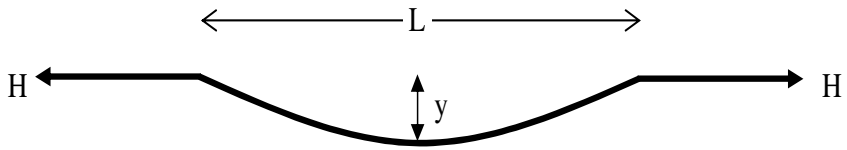
- Polyacrylonitrile (PAN) precursors at commercial production scale for decades
- Alternate chemistries still being converted at micro-scale:
  - Lignin
  - Polyethylene
  - Pitch
  - Carbon nanotube-suffused PAN
- Material form for carbonization:
  - Continuous tow (untwisted)
  - Continuous yarn
  - Non-woven matt
  - Needled felt
  - Loose chopped

Courtesy of Oak Ridge National Laboratory CFTF

- Support of precursor during carbonization and material conveyance:
  - Suspended between rolls
  - Carried on bobbins
  - Carried on belts

Key Considerations for Carbon Fiber Research: Tension & Strain during Conversion

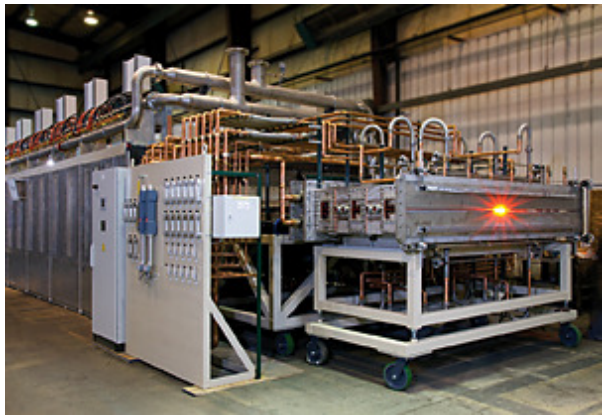
- Any format suspended horizontally will form a catenary shape
- The droop Y depends on the suspended length L, material properties, and the applied tension



- Quality and safety concerns require attention to preventing any carbon fiber drag on solid surfaces during processing

Key Considerations for Carbon Fiber Research: Off-Gas Emissions & Residuals

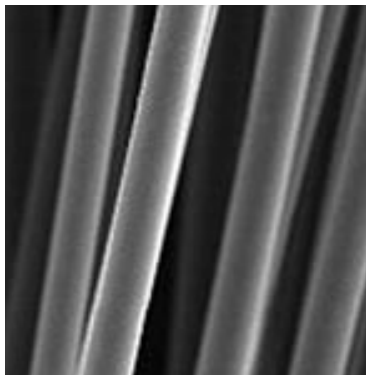
- Residuals from manufacturing process can cause problems for production, (e.g. buildup of sodium and sulfur compounds)
  - Metal dusting or other process corrosion system failures and fiber degradation
  - Formation of toxic byproducts can cause health and safety hazards
  - Not commonly observed as a topic for focused scientific research

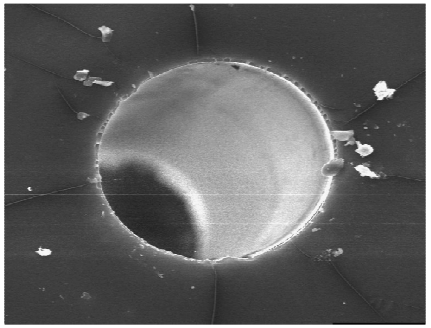


Necessary to test effects at small scale to better understand potential issues for scale up

Key Considerations for Carbon Fiber Research: Post Surface Treatment

- After carbonization fiber surface is smooth and relatively inert
  - Will not adhere well into a polymer matrix → poor composite properties
- Electrolysis
  - Electrochemical process – typically ammonium bicarbonate or dilute acid
  - Chemically activate fiber surface → introduce oxygen functional groups
  - Increase surface area by mechanically roughen surface on microscopic level → enhances mechanical bonding and wettability with polymer matrix
- Lowers mechanical strength of fiber → introducing surface defects
  - Do not want to electrolyze too little or too much, "want it just right"



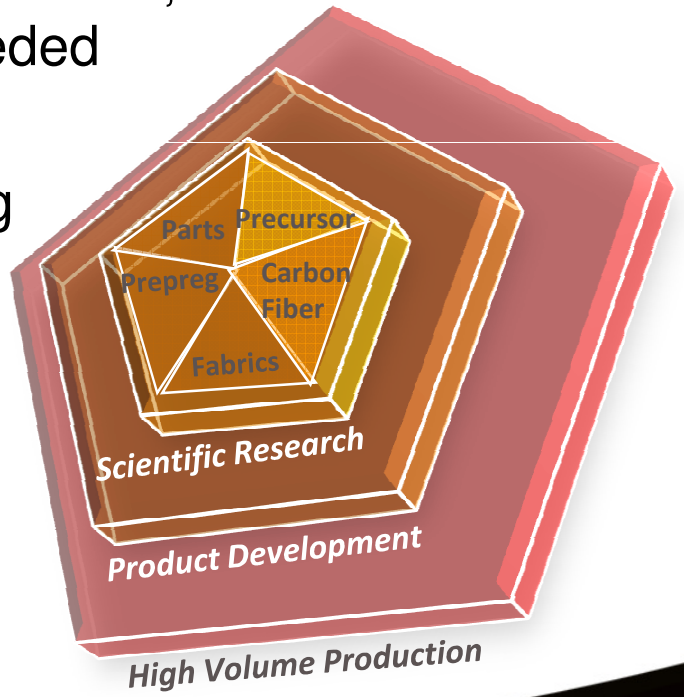


Considerations for the Future: Ease of Scale Up to Production

- Start with an R&D system that closely mimics production scale to decrease recipe development cycle time
  - Expensive and time consuming to redevelop recipe from one scale up to another
  - Easier to make go/no go decisions
  - Better conceptualize scaled up equipment specifications and modifications
  - Fewer assumptions required because will develop process recipe for particular precursors → every precursor is different
- Reduce down time for learning how to maintain equipment – significant savings potential on production scale systems

Conclusions

- Goal is to design and build better composites that will meet the growing demand in aerospace, automotive, construction, power generation and energy storage
- For composites to reach their full potential, innovations and developments in carbon fiber is needed
  - → Start with State-of-Art R&D capability
- India has many of the basic building blocks today to be a big player in carbon fiber composites
- Still requires common vision and collaboration to build a carbon fiber ecosystem



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