Low Cost Carbon Fiber Overview

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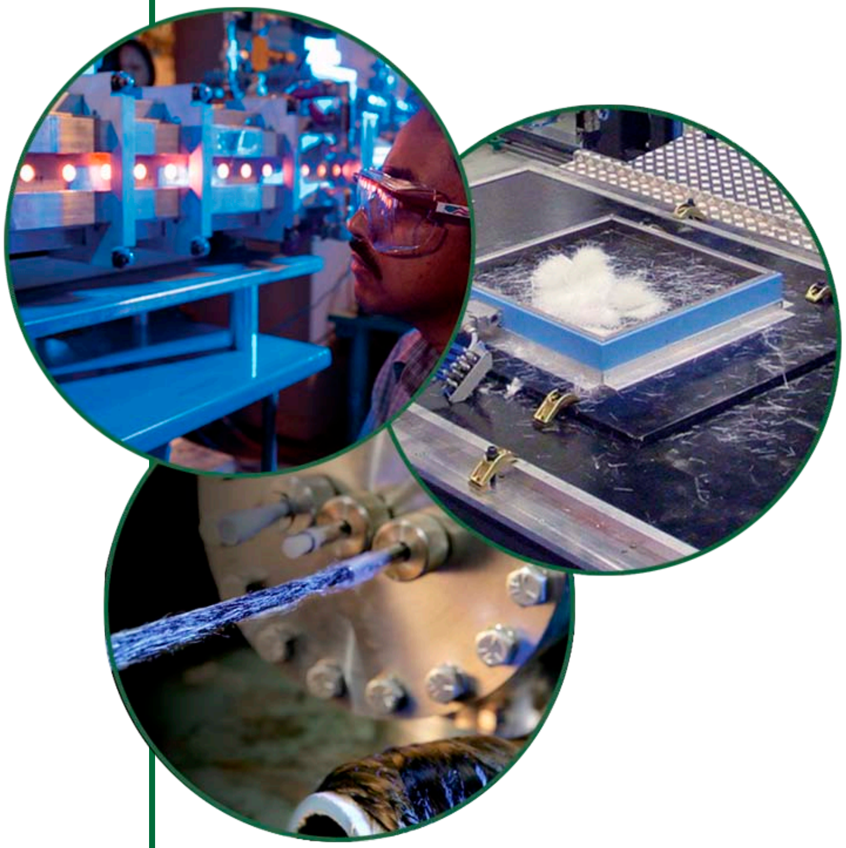

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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CARBON FIBER – Current Research Efforts

LM002

Materials

Full Scale Development of Textile Based Precursors - PAN-VA (VT)

Polyolefin Precursors

- **PE based Polyolefin Based Precursors (VT)**
- Alternative Polyolefin Constituent Precursors and Processing (IT)

Lignin-Based Low-Cost Carbon Fiber Precursors

- **Structural Materials for Vehicles (VT)**
- Graphite Electrodes for Arc Furnaces (IT)
- Nanoporous CF for Super Capacitors (IT)
- Composite Filter for HVAC (IT)
- Filters for HVAC CO_2 and VOC Capture (IT)

Melt Spinnable PAN for H_2 Storage (FCT)

Advanced Oxidative Stabilization of Carbon Fiber Precursors (VT)

Microwave Assisted Plasma Carbonization (IT)

Precursor and Fiber Evaluation (VT)

Carbon Fiber Technology & Demonstration Facility (VT-ARRA)

Conventional Surface Treatment and Sizing (VT)

Carbon Fiber Test Standards (IEA – VT)

Advanced Structural Carbon Fibers (DARPA)

Part of Today's Briefings

CARBON FIBER – Future Research Efforts

Funding Sources - Multiple Agencies

Intermediate Pilot Line Upgrade

Development of Textile Based Precursors – PAN-MA

Advanced Surface Treatment & Sizing

Tow Splitting

Development of Alternative Product Forms

Development of Feedback Process Control

Plasma Modification of Surface Topography

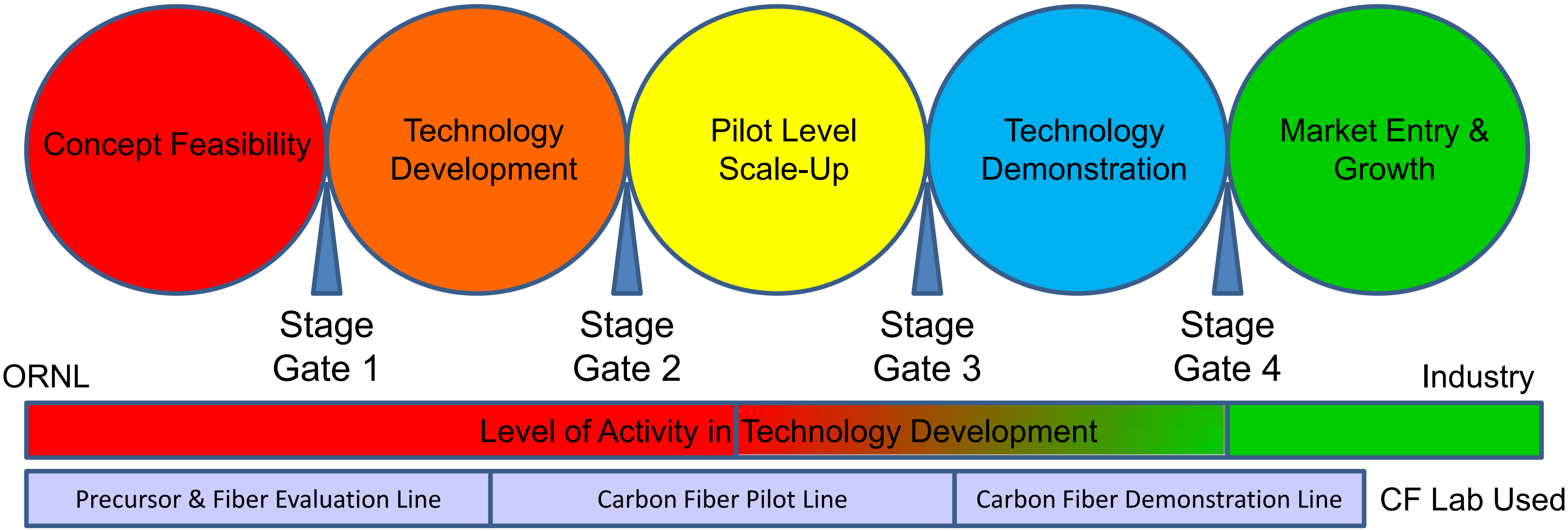
Replacement for Rayon – Ablative Materials

Model for the Conversion of Carbon Fiber Precursors

Recycling – Applications for Recovered Fibers

Process for Carbon Fiber Technology Commercialization

Materials



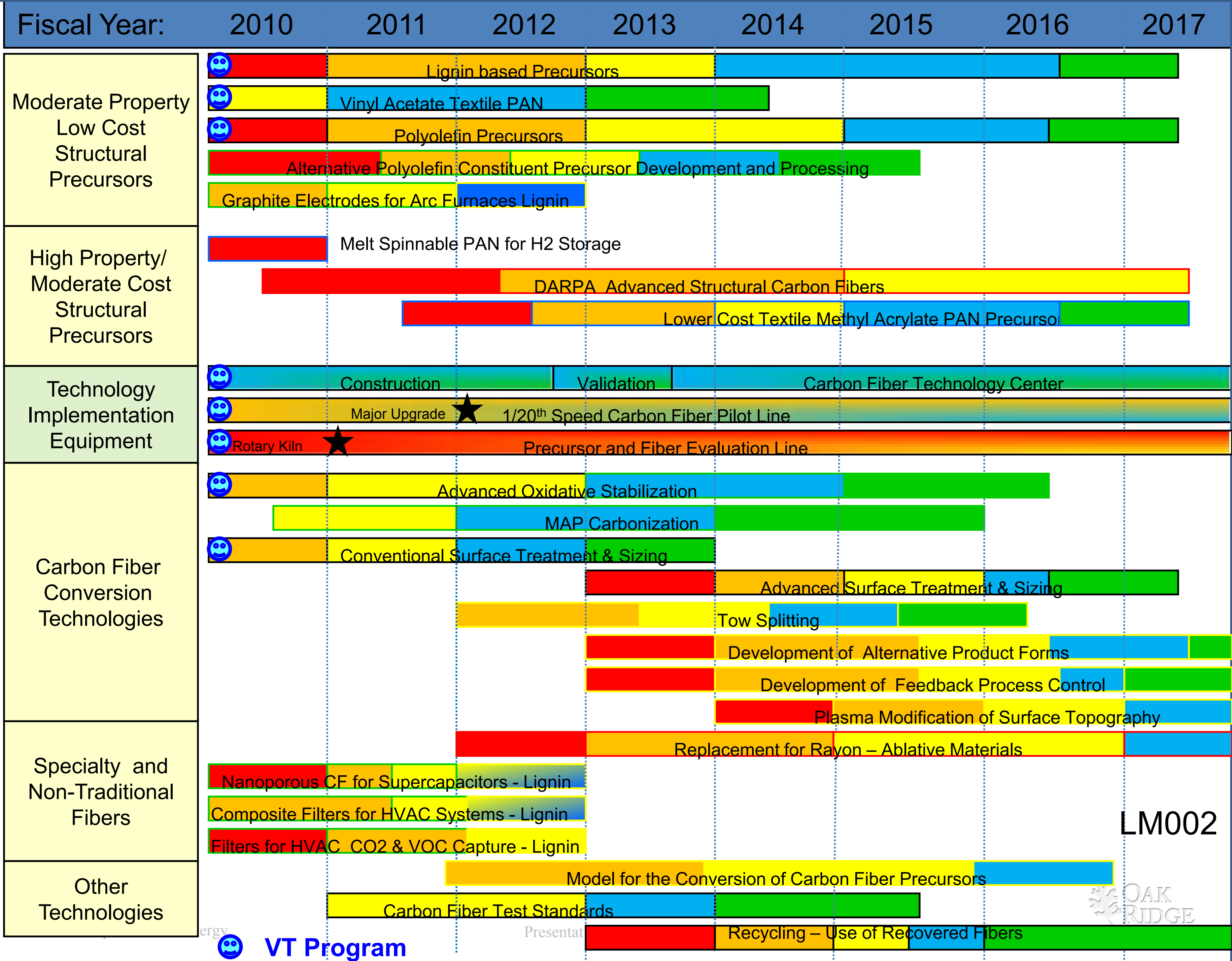
- Demonstrate technical feasibility
- Demonstrate likely cost effectiveness
- Bench scale
- Small material volume
- Batch processes
- Concludes with design of issue resolution plan

- Demonstrate technology works
- Demonstrate cost effectiveness if scaled
- Bench scale
- Small material volume
- Batch processes transitioning to continuous
- Concludes with design of prototype unit or materials

- Resolve continuous operation issues
- Develop continuous operation capability for short time periods
- Moderate material volume increasing as issues are resolved
- Concludes with design of continuous unit or final material selection

- Work to resolve full-scale equipment issues
- Develop multi-tow continuous operation capability for long periods of time
- Material volumes for product design and development
- Concludes with industrial adoption

- Industry adoption
- Product development
- Customer base development


Fiscal Year: 2010 2011 2012 2013 2014 2015 2016 2017
Moderate Property Low Cost Structural Precursors
Lignin based Precursors
Vinyl Acetate Textile PAN
Polyolefin Precursors
Alternative Polyolefin Constituent Precursor Development and Processing
Graphite Electrodes for Arc Furnaces Lignin
High Property/ Moderate Cost Structural Precursors
Melt Spinnable PAN for H2 Storage
DARPA Advanced Structural Carbon Fibers
Lower Cost Textile Methyl Acrylate PAN Precursor
Technology Implementation Equipment
Construction
Validation
Carbon Fiber Technology Center
Major Upgrade
1/20th Speed Carbon Fiber Pilot Line
Rotary Kiln
Precursor and Fiber Evaluation Line
Carbon Fiber Conversion Technologies
Advanced Oxidative Stabilization
MAP Carbonization
Conventional Surface Treatment & Sizing
Advanced Surface Treatment & Sizing
Tow Splitting
Development of Alternative Product Forms
Development of Feedback Process Control
Plasma Modification of Surface Topography
Replacement for Rayon – Ablative Materials
Specialty and Non-Traditional Fibers
Nanoporous CF for Supercapacitors - Lignin
Composite Filters for HVAC Systems - Lignin
Filters for HVAC CO2 & VOC Capture - Lignin
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Other Technologies
Model for the Conversion of Carbon Fiber Precursors
Carbon Fiber Test Standards
Recycling – Use of Recovered Fibers
OAK RIDGE
VT Program

Why?

Materials

A 10% mass reduction translates to a 6-7% increase in fuel economy or may be used to offset the increased weight and cost per unit of power of alternative powertrains

Criticality of Challenge (←)

Material Options Impact (↑)

Carbon-fiber Composites	Low-cost fibers	High-volume Mfg.	Recycling	Joining	Predictive Modeling
Aluminum	Feedstock Cost	Manufacturing	Improved Alloys	Recycling	
Magnesium	Feedstock Cost	Improved Alloys	Corrosion Protection	Manufac-ing	Recycling
Advanced High-Strength Steels	Manufacturability	Wt. Red. Concepts	Alloy Development		
Titanium	Low-cost Extraction	Low-cost Production	Forming & Machining	Low-cost PM	Alloy Development
Metal-matrix Composites	Feedstock Cost	Compositing Methods	Powder Handling	Compaction	Machining & Forming
Glazings	Low-cost Lightweight Matls.	Noise, T° struc. models simulations	Noise reduction techniques	UV and IR blockers	
Emerging Materials and Manufacturing	Material Cost	Mfg-ability	Design Concepts	Performance Models	

	Tensile Strength (Mpa)	Tensile Modulus (Gpa)
Aluminum (6000)	**258**	**69**
Mild Steel	**305**	**210**
Glassed Filled Thermoplastic	**45**	**2**
Glass Fiber SMC	**70**	**13**
Carbon Fiber SMC	**215**	**37**

Higher modulus and strength affords thinner composites

Weight saving opportunities

Charts is provided courtesy of Robert McCune and Jim DeVries- Ford Motor Company

ACC Focal Project III Carbon Intensive BIW

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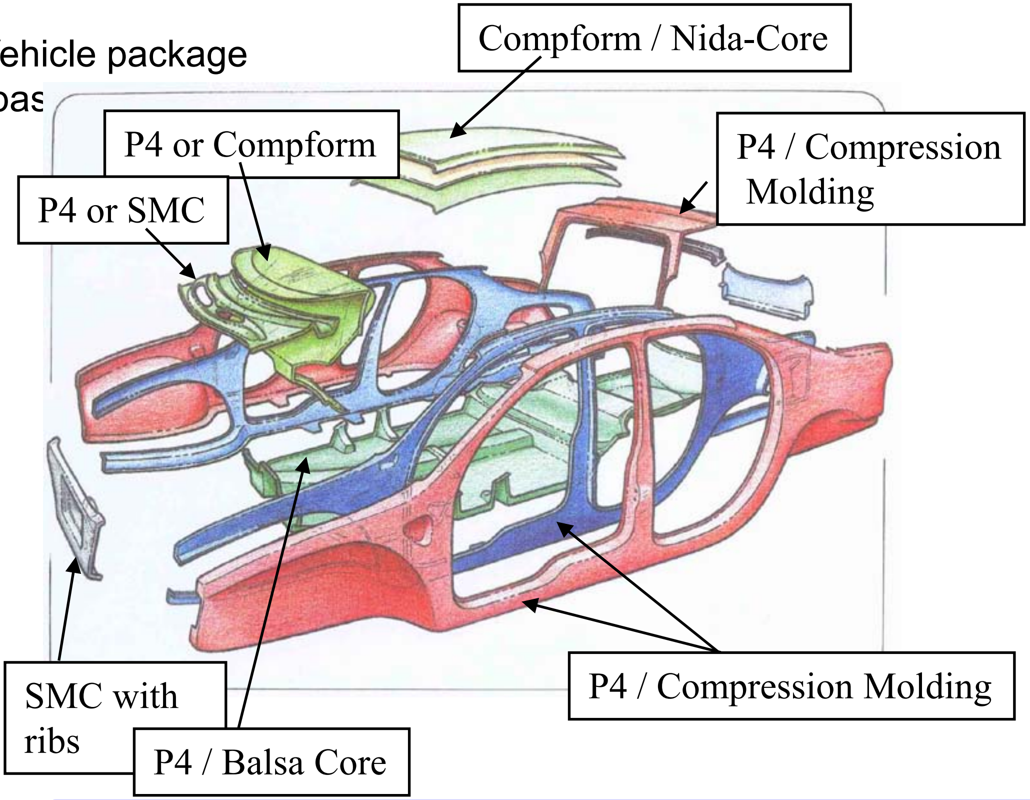
Materials

Vehicle package
(bas



Phase 1 Results:
67% mass savings over baseline
Bending stiffness exceeded 20%
Torsional stiffness exceeded 140%
Durability and abuse load cases satisfied
Manufacturing strategy developed

Materials / Mass Distribution:
Chopped carbon - 54.8 kg
Carbon fabric - 17.7 kg
Core - 3.2 kg
Adhesive - 1.6 kg
Inserts - 8.8 kg

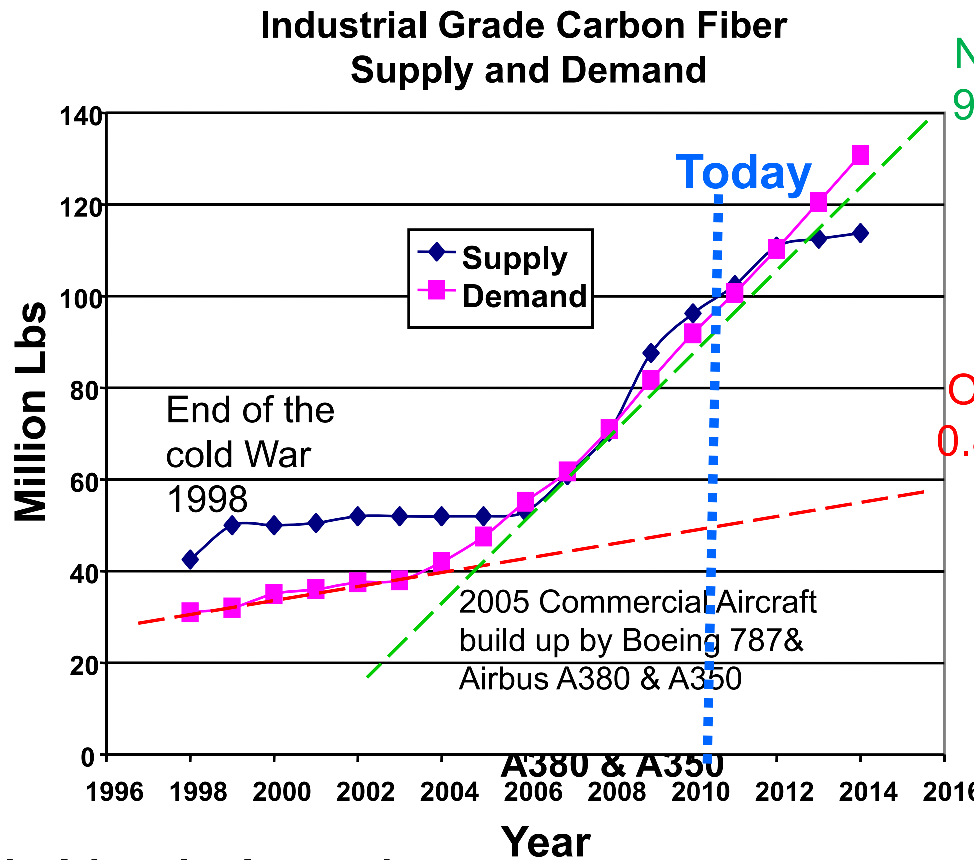
	Density (lb/cu. ft.)	Strength (Kpsi)	Modulus (Mpsi)
Automotive Steel	480	60-200	30
6061 Aluminum	167	30-40	10
Glass Fiber Composite	93	30-100	5-8
Carbon Fiber Composite	79	60-150	10-35

Carbon Fiber Price Goal - Transportation

Vehicle Materials Priority

$5 - $7
Per Pound

Barrier: Price is too High



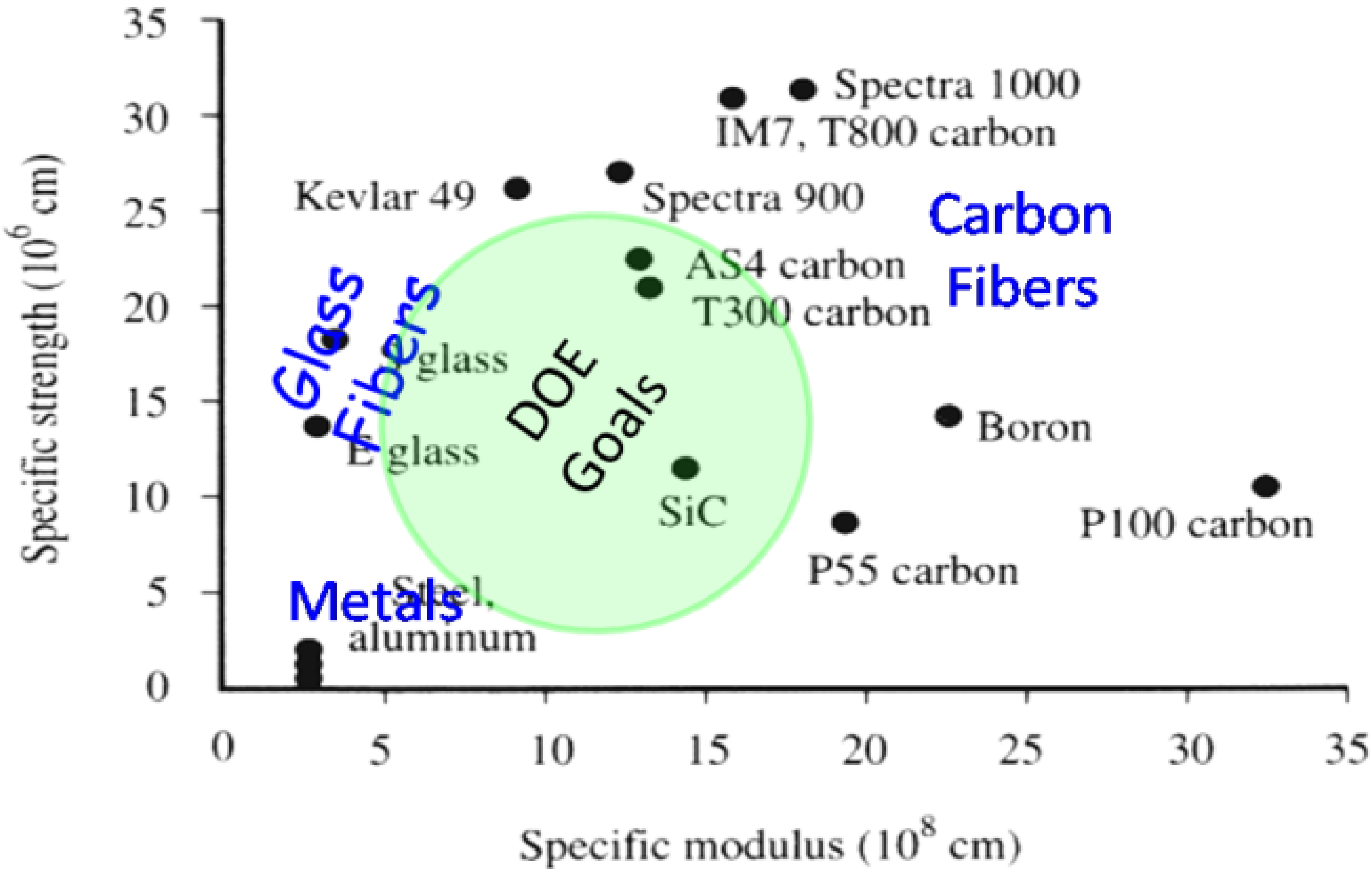
Source: High Performance Composites

Program Minimum:
Strength: ≥ 250 Ksi
Modulus: ≥ 25 Msi
Strain: ≥ 1%

6 lbs of CF on Each North American Vehicle would consume world supply.

Carbon Fiber Property Goal - Transportation

Target Property Ranges for Lower Cost Carbon Fiber Development



Graph provided courtesy of Jose Zayas, Wind Energy Program Manager, SNL

Energy Absorption Capability

Composites can be Successfully Used for Crash Protection

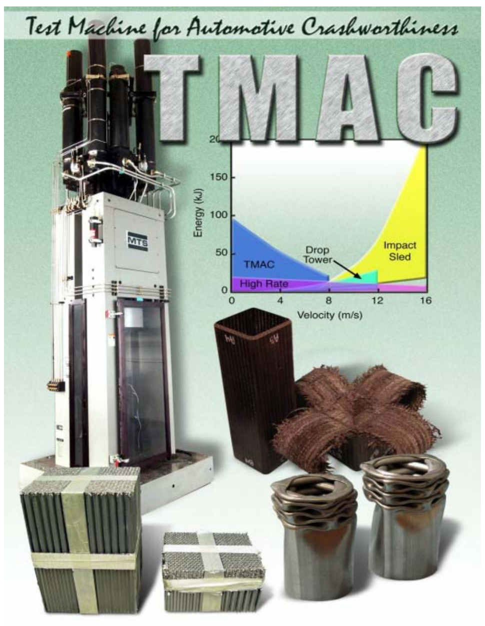
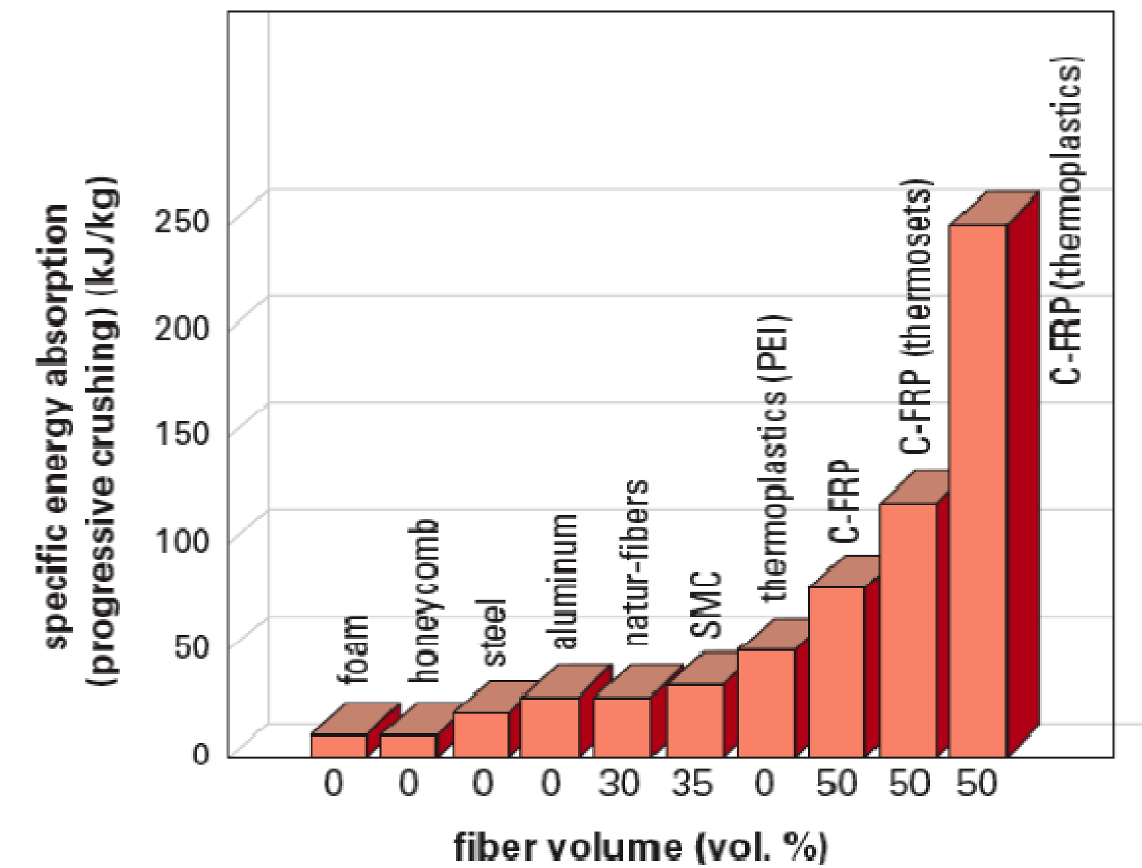


Figure 15: Advanced composites' remarkable crash energy absorption
Carbon-fiber reinforced polymer (C-FRP) crush cones and similar structures can absorb ~120 kJ/kg if made with a thermoset resin like epoxy, or ~250 with a thermoplastic, vs. ~20 for steel.[300] Crush properties can also be optimized by mixing carbon with other fibers.



Source: Herrman, Mohrdeck, & Bjekovic 2002, p. 17.

Potential Markets and Needs

Industry	Benefit	Applications	Drivers	Obstacles	Current Market	Potential Market
Automotive	Mass Reduction: 10% Mass Savings translates to 6-7% Fuel Reduction	Throughout Body and Chassis	Tensile Modulus; Tensile Strength	Cost: Need $5-7/lb; Fiber Format; Compatibility with automotive resins, Processing Technologies	< 1M lbs/yr	> 1B lbs/year
Wind Energy	Enables Longer Blade Designs and More Efficient Blade Designs	Blades and Turbine Components that must be mounted on top of the towers	Tensile Modulus; Tensile Strength to reduce blade deflection	Cost and Fiber Availability; Compression Strength; Fiber Format & Manufacturing Methods	1-10 M lbs/yr	100M - 1B lbs/yr
Oil & Gas	Deep Water Production Enabler	Pipes, Drill Shafts, Off-Shore Structures	Low Mass, High Strength, High Stiffness, Corrosion Resistant	Cost and Fiber Availability; Manufacturing Methods	< 1M lbs/yr	10 - 100M lbs/yr
Electrical Storage and Transmission	Reliability & Energy Storage	Low Mass, Zero CTE transmission cables; Flywheels for Energy Storage	Zero Coeficient of Thermal Expansion; Low Mass; High Strength	Cost; Cable Designs; High Volume Manufacturing Processes; Resin Compatibility	< 1M lbs/yr	10-100M lbs/yr
Pressure Vessels	Affordable Storage Vessels	Hydrogen Storage, Natural Gas Storage	High Strength; Light Weight	Cost; Consistent Mechanical Properties	< 1M lbs/yr	1-10B lbs/yr

Potential Markets and Needs (Continued)

Industry	Benefit	Applications	Drivers	Obstacles	Current Market	Potential Market
Infrastructure	Bridge Design, Bridge Retrofit, Seismic Retrofit, Rapid Build, Hardening against Terrorist Threats	Retrofit and Repair of Aging Bridges and Columns; Pretensioning Cables; Pre-Manufactured Sections; Non-Corrosive Rebar	Tensile Strength & Stiffness; Non-Corrosive; Lightweight; Can be "Pre-Manufactured"	Cost; Fiber Availability; Design Methods; Design Standards; Product Form; Non-Epoxy Resin Compatibility	1-10M lbs/yr	1-100B lbs/yr
Non-Aerospace Defense	Lightweight Ground and Sea Systems; Improved Mobility and Deployability	Ship Structures; Support Equipment; Tanks; Helicopters	Low Mass; High Strength; High Stiffness	Cost; Fiber Availability; Fire Resistance; Design into Armor	1-10M lbs/yr	10-100M lbs/yr
Electronics	EMI Shielding	Consumer Electronics	Low Mass; Electical Conductivity	Cost; Availability	1-10M lbs/yr	10-100M lbs/yr
Aerospace	Secondary Structures	Fairings; seat structures; luggage racks; galley equipment	High Modulus; Low Mass	Cost of lower performance grades; Non-Epoxy Resin Compatibility	1-10M lbs/yr	10-100M lbs/yr
Non-Traditional Energy Applications	Enabler for Geothermal and Ocean Thermal Energy Conversion	Structural Design Members; Thermal Management, Energy Storage	Tensile Strength & Stiffness; Non-Corrosive; Lightweight	Design Concepts; Manufacturing Methods; Fiber Cost; Fiber Availability	1-10M lbs/yr	10M-1B lbs/yr
Electrircal Energy Storage	Key Storage Media	Li-Ion Batteries; Super-capacitors	Electrical and Chemical Properties	Design Concepts; Fiber Cost and Availability	1-5M lbs/yr	10-50M lbs/yr
Total					**11-70M lbs/yr**	**3-114B lbs/yr**

Low Cost Carbon Fiber: Common Issues and Needs

Materials

Civil Infrastructure
Rapid Repair and Installation, Time and Cost Savings

Bio-Mass Materials
Alternative Revenue
Waste Minimization

FUELING OUR FUTURE BIOMASS 2008

Non-Traditional Energy
Geothermal, Solar & Ocean Energy

Non-Aerospace Defense
Light Weight, Higher Mobility

Aerospace
Secondary Structures

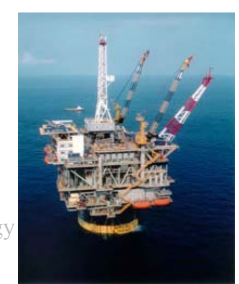
Common Issues:
Fiber Cost
Fiber Availability
Design Methods
Manufacturing Methods
Product Forms

Electronics
Light Weight, EMI Shielding

Energy Storage
Flywheels, Li-Ion Batteries, Supercapacitors

Power Transmission
Less Bulky Structures
Zero CLTE

Oil and Gas
Offshore Structual Components



Vehicle Technologies
Necessary for 50+% Mass Reduction

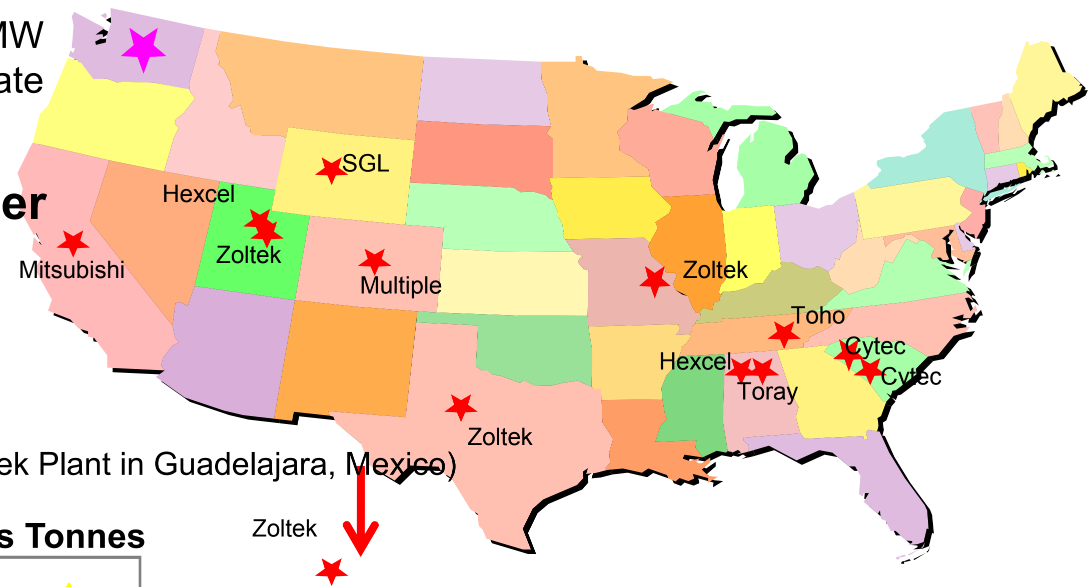
Wind Energy
Needed for Longer Blade Designs

Pressurized Gas Storage
Only Material With Sufficient Strength/Weight

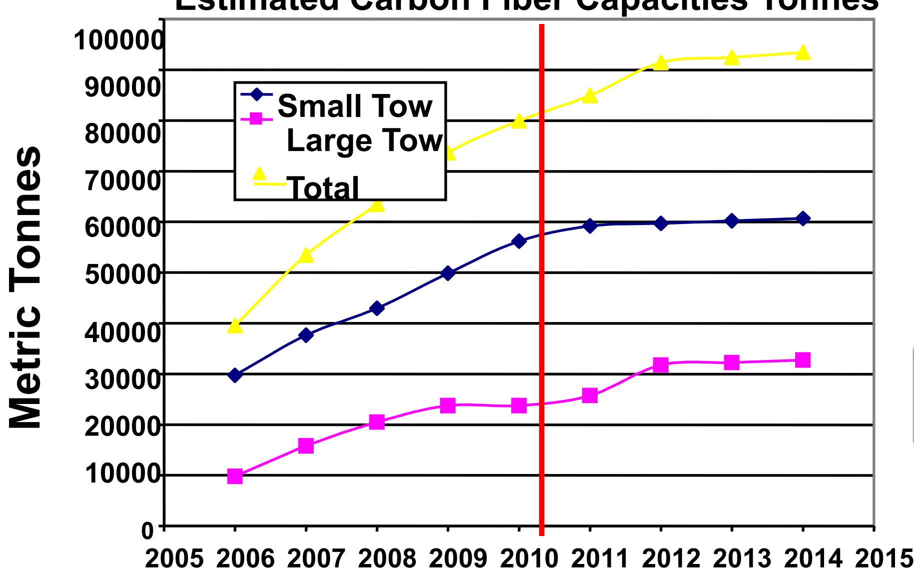
Domestic Carbon Fiber Production & Comparison

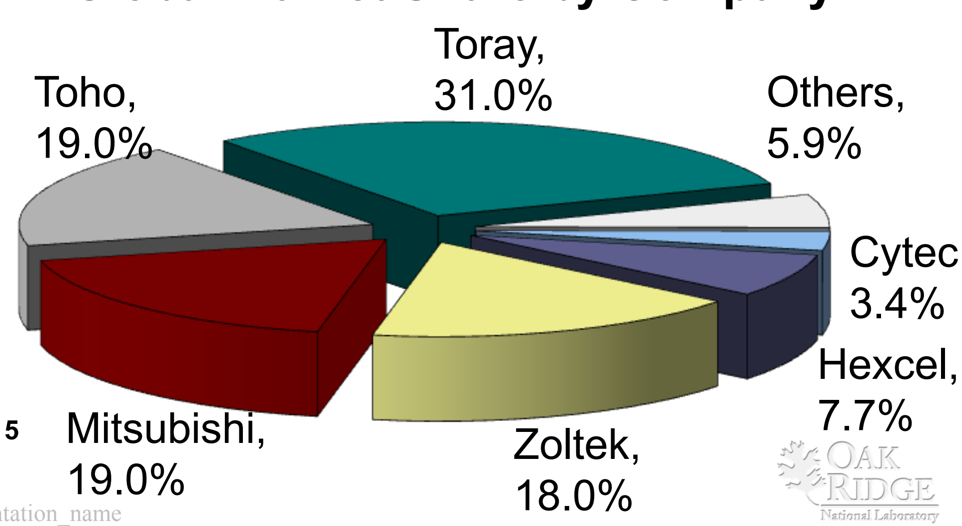
Recently Announced: SGL & BMW Joint Venture in Washington State

North American Carbon Fiber Manufacturers



(One Zoltek Plant in Guadelajara, Mexico)





Source: McConnell, V. "*The Making of Carbon Fiber*", CompositesWorld, 19 December 2008.

Global Carbon Fiber Production

Global Carbon Fiber Production
Estimated Capacity 2010 by manufacturer and type of fiber

Not included is a 40,000,000 lb/year Chinese plant to come on-line after 2010.
*Small Tow is ≤ 24,000 filaments. Large Tow is > 24,000 filaments.

Company	Headquarters	Manufacturing Sites	Small Tow* Production, lbs/year	Large Tow* Production, lbs/year	Total Production, lbs/year
AKSA	Turkey	Turkey	4,000,000		4,000,000
Cytec	US – SC	US-SC	5,000,000		5,000,000
Dalian Xingke	China	China	1,320,000		1,320,000
Grafil - Mitsubishi	US – CA	US - CA	4,400,000		4,400,000
Hexcel	US – UT	US - UT, AL	16,000,000		16,000,000
Kemrock	India	INDIA	1,430,000		1,430,000
Mitsubishi - Rayon	Japan	Japan, US-CA	13,530,000	6,000,000	19,530,000
SGL	Germany	Germany, UK, US-WY		14,300,000	14,300,000
Toho	Japan	Japan, US-TN	29,620,000		29,620,000
Toray	Japan	Japan, US-AL	39,440,000	660,000	40,100,000
Yingyou	China	China	484,000		484,000
Zoltek	US-Mo	US -UT, TX, MO, Mexico		19,300,000	19,300,000
Total			**115,224,000**	**40,260,000**	**155,484,000**

Source: McConnell, V. "*The Making of Carbon Fiber*", CompositesWorld, 19 December 2008.

Carbon Fiber Costs (Baseline)

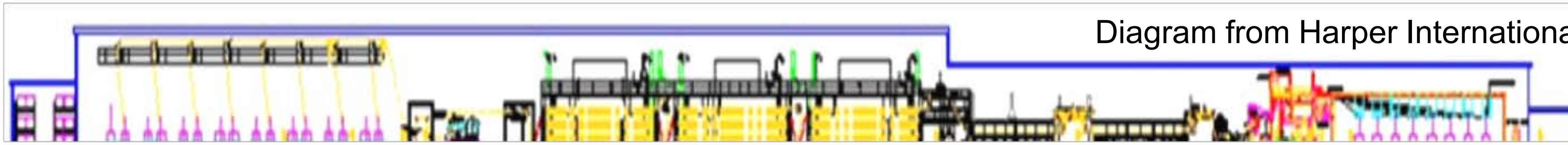
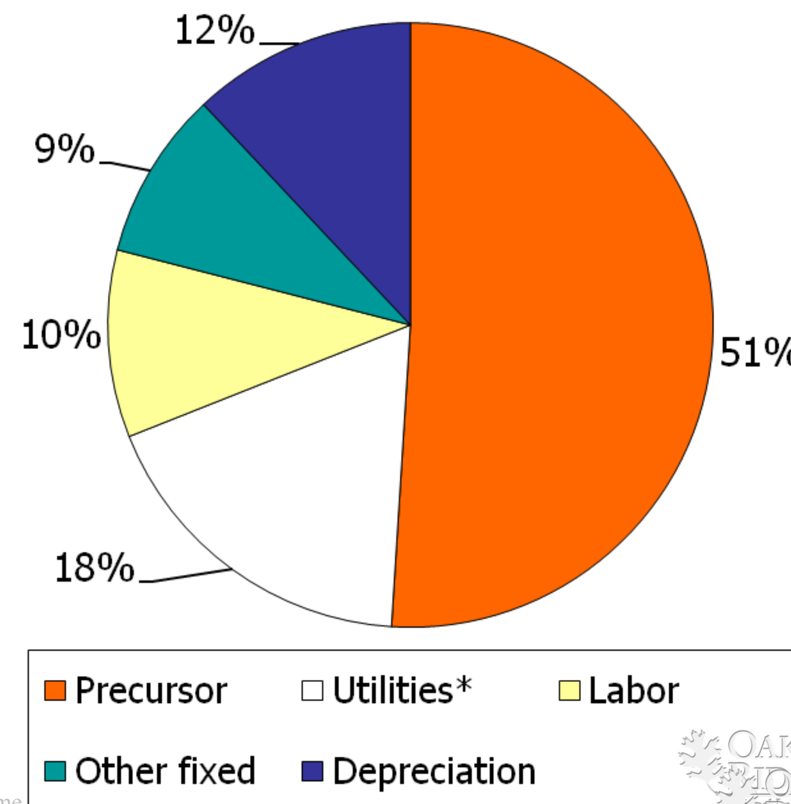


Diagram from Harper International

Precursors	Stabilization & Oxidation	Carbonization/ Graphitization	Surface Treatment	Spooling & Packaging
$5.04 (51%) Includes Pretreatment and Handling	$1.54 (16%)	$2.32 (23%)	$0.37 (4%)	$0.61 (6%)

Baseline - $9.88

- With conventional processing using a carbon fiber-grade (CF) PAN, precursor is over **50%** of the carbon fiber cost



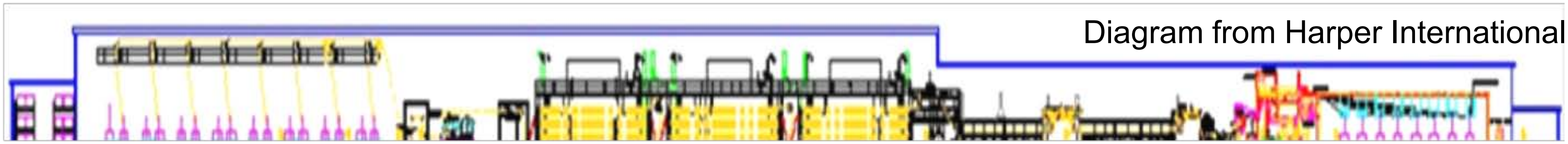
<u>4 Elements of Cost Reduction</u>

1. Scale of Operations
2. Precursors
3. Conversion
4. Manufacturing of Composite

* Data From Kline & Company

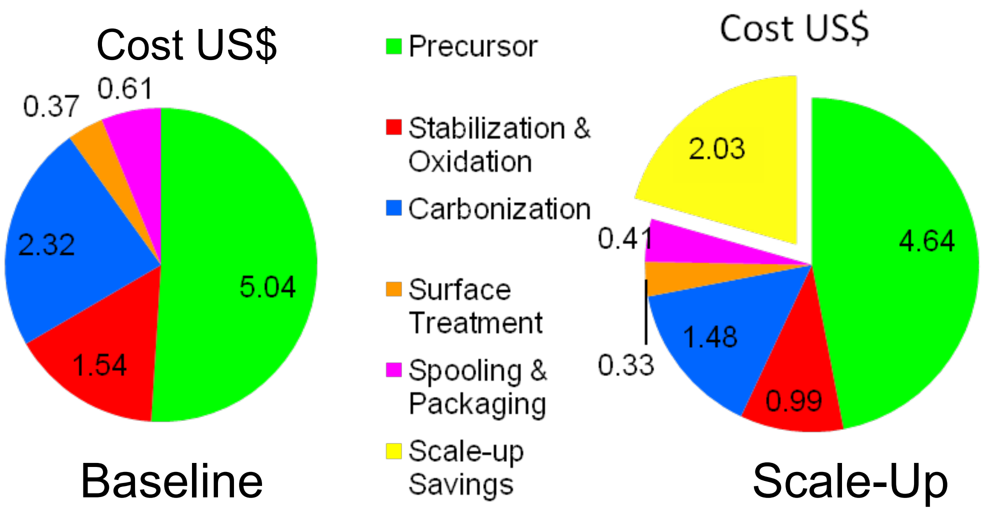
Carbon Fiber Costs (1. Scale of Operations)

LM002
Materials

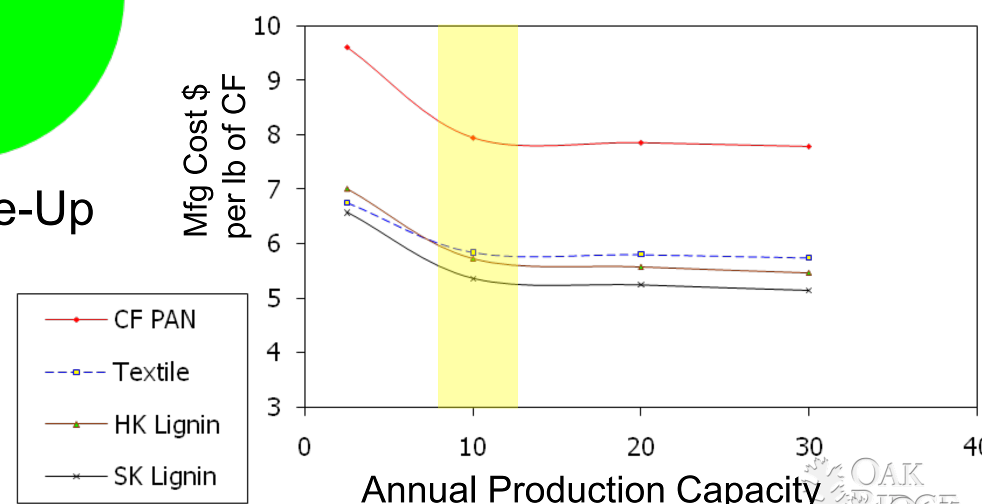


Precursors	Stabilization & Oxidation	Carbonization/ Graphitization	Surface Treatment	Spooling & Packaging

Baseline Today - $9.88	$5.04	$1.54	$2.32	$0.37	$0.61
High Volume - $7.85	$4.64	$0.99	$1.48	$0.33	$0.41



Significant Cost Reduction can be achieved by increased Scale-up of Plant and Line Size

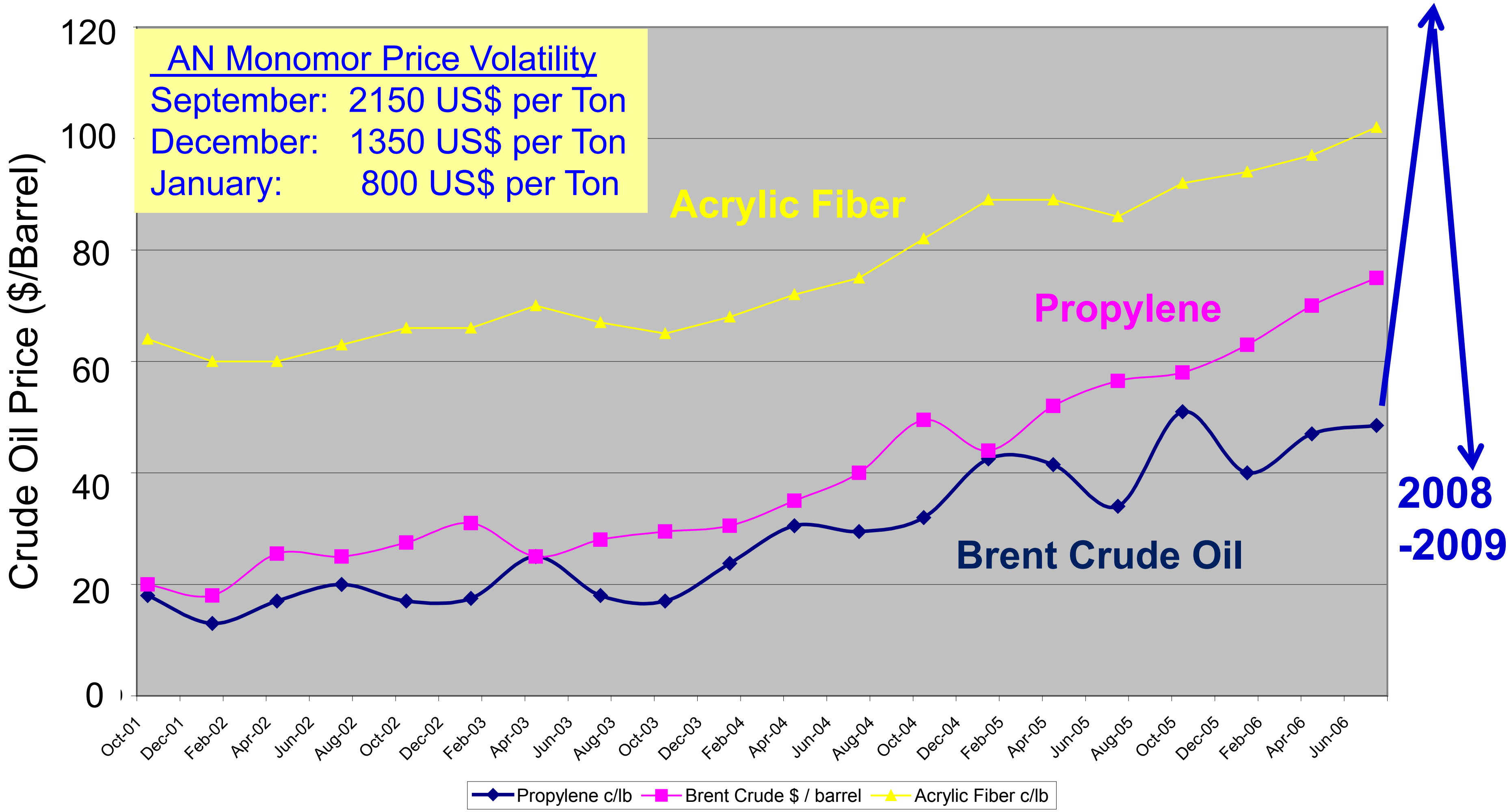


* Baseline Data From Kline & Company

But

<u>Not All the Needed Cost Reduction</u>

PAN Dependence on Oil Price



Current Carbon Fiber Raw Materials are Tied to Oil

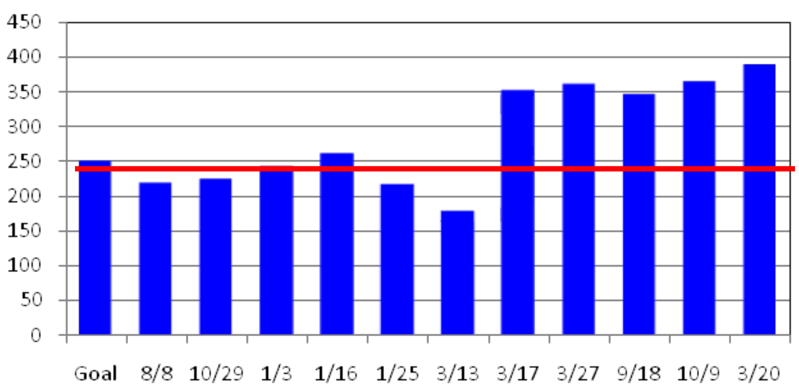
Carbon Fiber Costs (2. Precursors)

More Affordable Precursors are Needed

<u>3 Current Precursor Options</u>

1. Textile Grade PAN (MA or VA formulations)
2. Lignin Based Precursor (Hardwood or Softwood)
3. Polyolefins (not shown on chart)

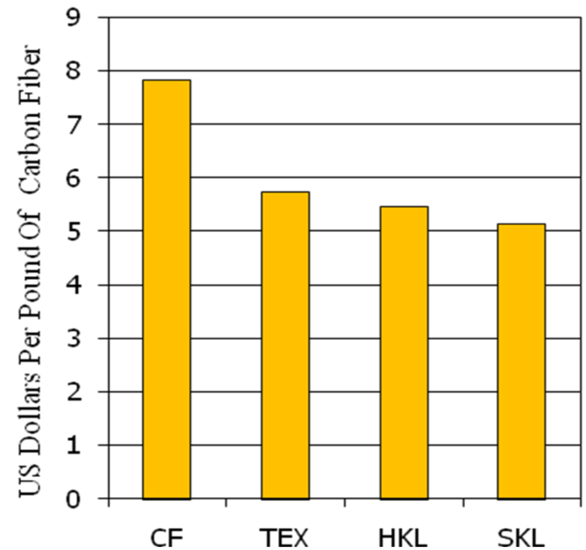
Carbonized Textile Precursor



Tensile Strength (KSI)

Current Carbonized
<u>Textile Properties:</u>
Strength: 400 KSI
Modulus: 35 MSI

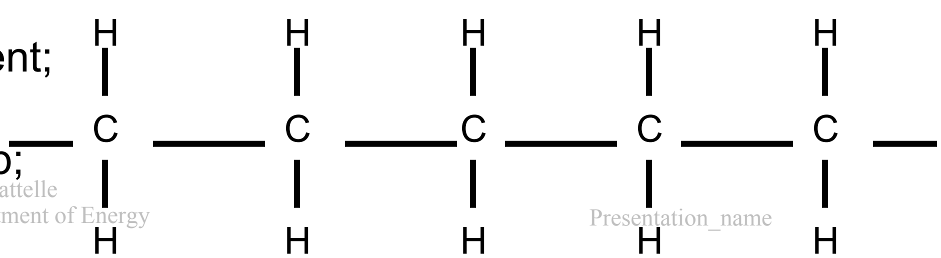
Alternative Precursors and Conventional Processing



Processed Precursor Fibers from a Hardwood/Softwood Lignin Blend.

PE:

86% C Content;
65-75% Yield
$0.50-$0.75/lb;
Melt Spun

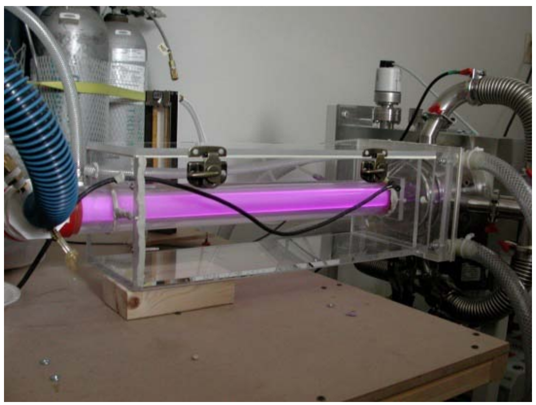


Current Research (3. Conversion)

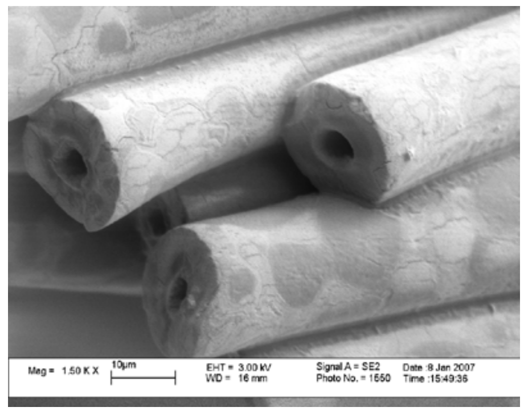
Alternative Processing Methods Under Development

<u>4 Processing Options</u>

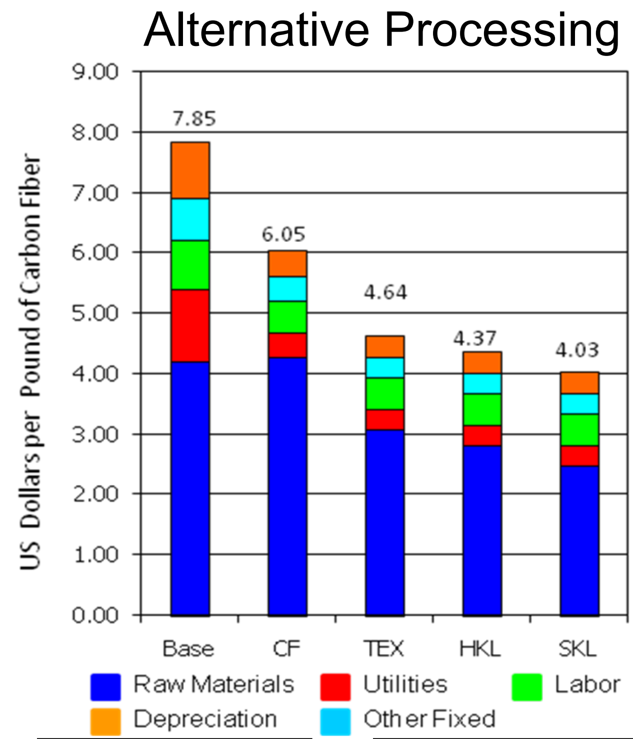
1. Advanced Stabilization
2. Plasma Oxidation
3. MAP Carbonization
4. Surface Treatment (Not on graph)

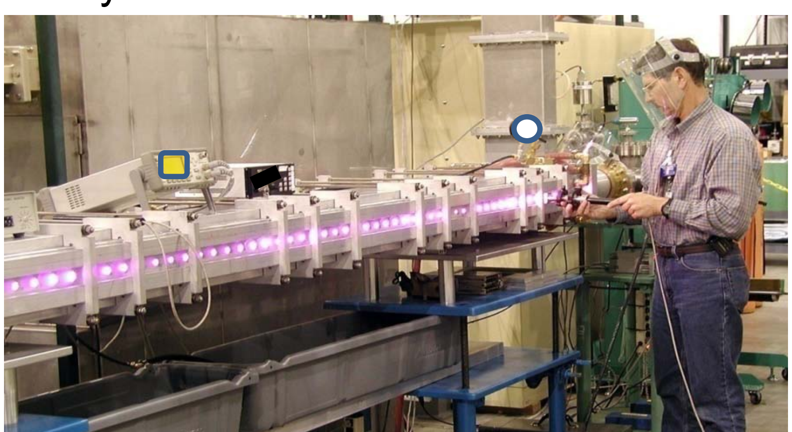


Early Generation Oxidation Module



Advanced Stabilization



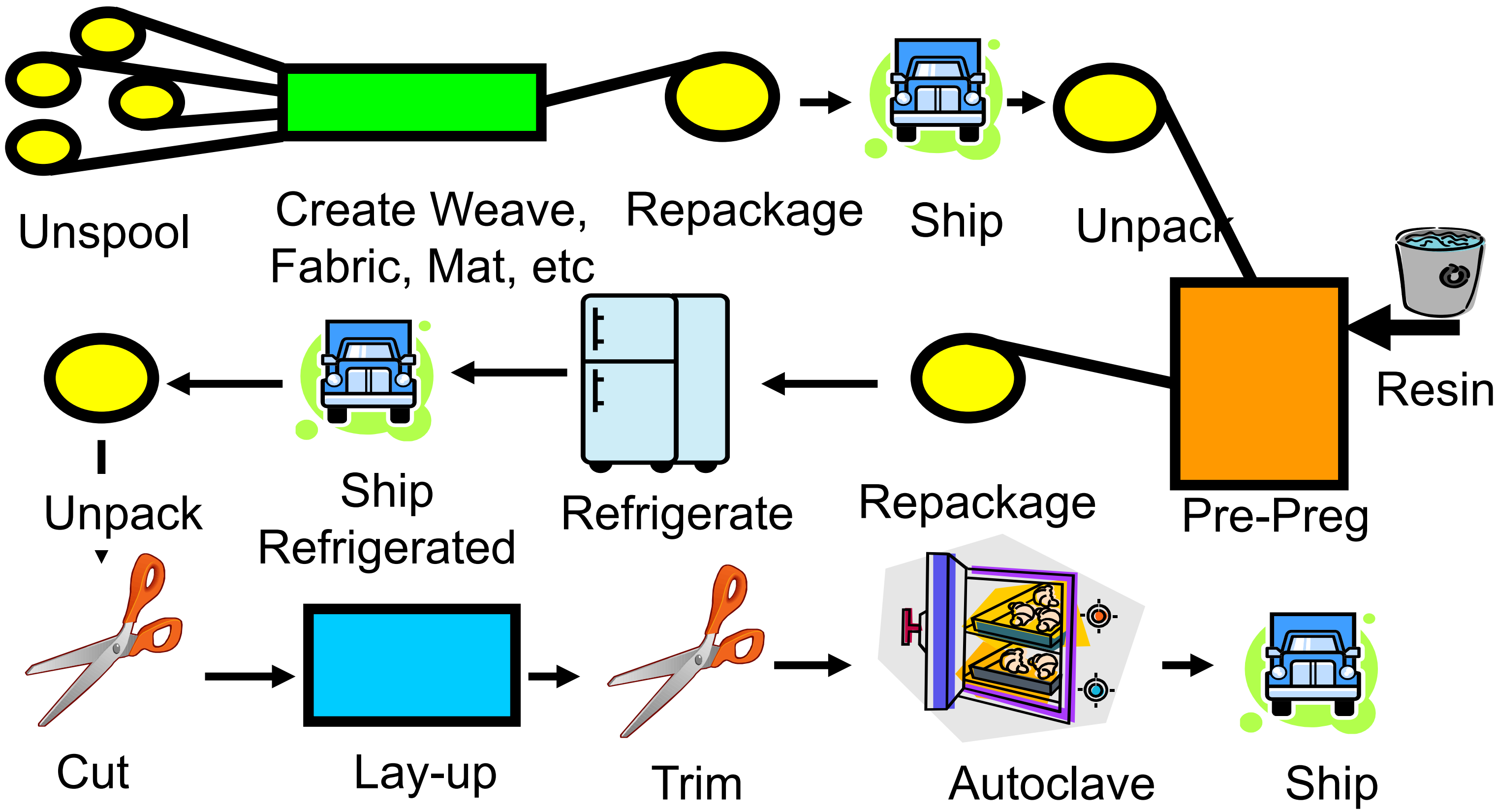


MAP Carbonization/ Graphitization Unit

Advanced Surface Treatment

Cost Reduction (4. Processing)

Composite Down Stream Processing



System designed for Epoxy based, Aerospace parts

The composite development and production process is very fragmented and expensive for typical carbon fiber composites.

21 Managed by UT-Battelle for the U.S. Department of Energy

Carbon Fiber Portfolio (Current)

Production Costs for Current Technology in High Volume

Surface Treatment

Spooling & Packaging

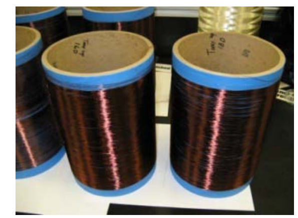
Carbonization/ Graphitization

Stabilization & Oxidation

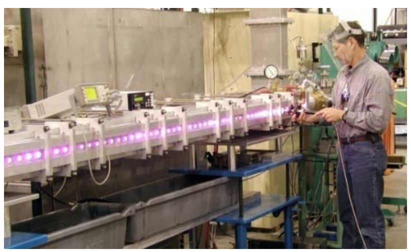
Precursors

Textile Precursor

Lignin Based Precursors



Microwave Assisted Plasma (MAP)

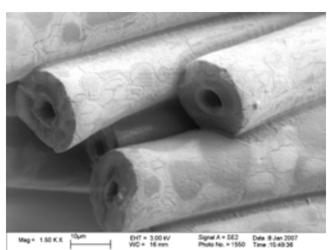


Advanced Stabilization

Commercialization (All Projects)

Advanced Precursors (ORNL Internal)

Advanced Oxidation



Conventional Surface Treatment

Precursor and Fiber Evaluation (All Projects)

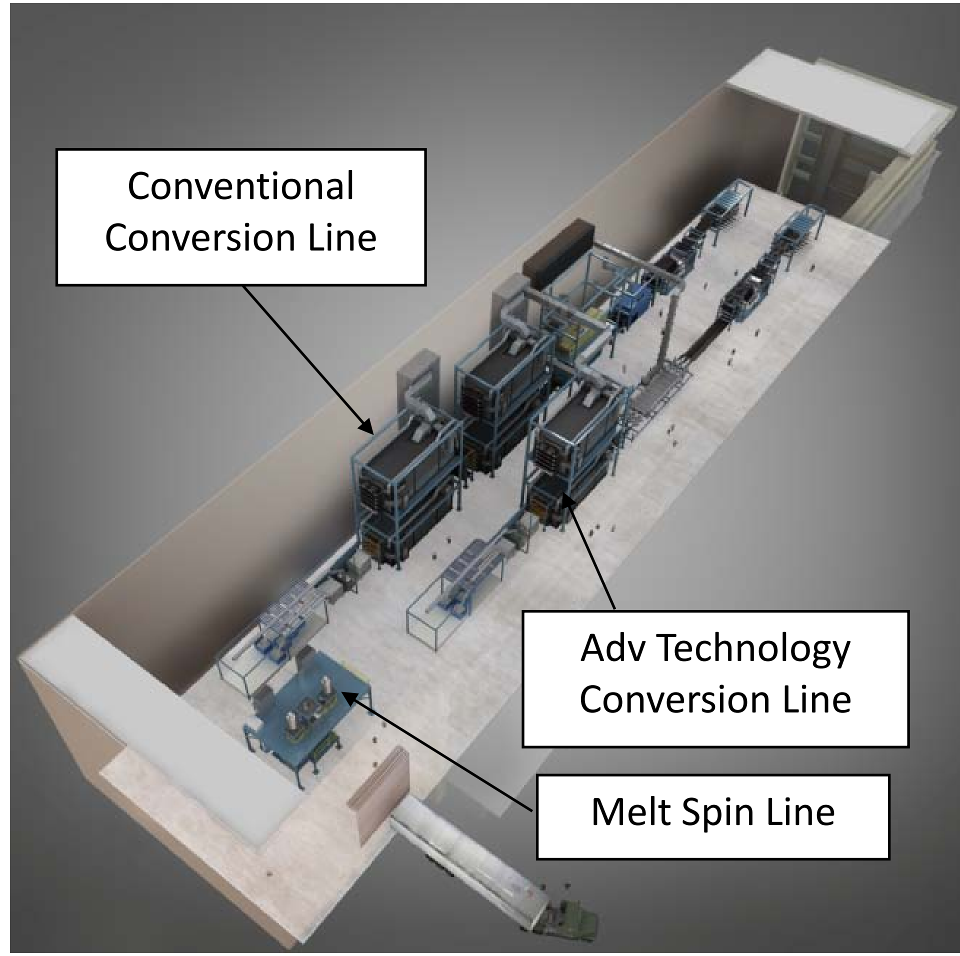
COMPARISON OF CASES - High Volume

Cost Model Output Example Comparing Technologies

Factor	CF-GRADE PAN				TEXTILE-GRADE PAN			
	Con. Tech	PO	MAP	PO and MAP	Con. Tech.	PO	MAP	PO and MAP
Capacity, MM lb/yr	24.0	31.0	24.0	31	27.5	31.0	27.5	31.0
Number of lines	14	6	14	6	8	6	8	6
Line speed, Ft/hr	1,064	3,192	1,064	3,192	2.128	3,192	2,128	3,192
Investment, $ Million	209.4	166.0	174.1	132.5	152.9	144.1	126.0	110.5
Investment, $ per lb of CF	8.72	5.36	7.23	4.28	5.56	4.66	4.58	3.57
Total Head count	372	320	372	320	300	320	300	320

Con Tech – Conventional Technology PO – Plasma Oxidation
MAP – Microwave Assisted Plasma

Carbon Fiber Technology Center



Facility and equipment perspective.

- North America's most comprehensive carbon fiber material and process development capabilities
- Development of carbon fiber technology for energy and national security applications
- Low-cost and high-performance fibers
- Fast, energy efficient processing
- Capability to evaluate micrograms and produce up to 25 tonnes/year
- Produce fibers for material and process evaluations by composite manufacturers
- Train and educate workers
- Grow partnerships with US industry

Required Program Partnerships

Carbon Fiber Technology Deployment Line Partnerships

<u>Government Agencies</u>
DOE (National Laboratories)
(VT/IT/FE/Wind/Solar/Power)
DOD (AFRL, AFML, NRL, TARDEC)
DOC (NIST)
DOT (VOLPE, FHWA)

<u>Academia</u>
Graduate Programs
Undergraduate Programs

<u>Carbon Fiber Manufacturers</u>
Current Industrial Grade
Precursor Manufacturers
Potential Aerospace Grade
Future Industrial Grade

<u>Polymer Industry</u>
Sizing Suppliers
Resin Suppliers
Molders
Product Developers

<u>Industrial Product Mfrs</u>
Wind Blades
Automotive (OEM & Tier I)
Power Transmission
Military Land & Sea Based
Gas Storage Vessels
Oil and Gas
Bridges & Retrofit
Buildings & Concrete
Electronics
Other Industrial

<u>Trade Groups</u>
SAMPE
ACMA
SPE
SAE
Etc.

<u>US Equipment Manufacturers</u>
Oxidation/Stabilization Ovens
Carbonization Equipment
Fiber Handling Equipment
Post Treatment Equipment
Composite Processing

Technology Deployment Line to be Built as Part of Stimulus Funding

Significant Awards and Presentations

Significant Recognitions:

- ORNL Team Invited to Conduct Pre-Conference Workshop on Carbon Fiber
- SPE Leadership Award
- Chaired 2008 Carbon Fibre Conference Hamburg, Germany
- American Carbon Society Fellow and Graffin Lecturer, Fred Baker - 7 Lectures

Conference Keynote and Plenary Presentations:

- Baker: Keynote - Carbon 2008 conference in Nagano, Japan.
- Warren: Keynote - 2009 Composites and Polycon Conference in Tampa, Florida.
- Warren: Keynote - 2009 SAMPE Spring Conference in Baltimore.
- Warren: Keynote - Carbon Fibre Conference in Hamburg, Germany.
- Warren: Plenary - Composites and Polycon Conference in Tampa, Florida.
- Warren: Keynote - ICCE-17 Conference, July 2009, Honolulu, HI.
- Eberle: Plenary - *2009 Regional ASM/TMS Annual Symposium on Materials Challenges for Alternative Energy*, 11-12 May 2009.
- Baker: Plenary - 6th World Congress on Industrial Biotechnology and Bioprocessing

Other (Too many to List):

34 Published Technical papers.

Significant Awards and Presentations

Chairing Paper Sessions at Conferences:

- Das: Chaired three technical Sustainable Program Development Committee sessions at the *SAE 2009 Annual Congress* held in Detroit .
- Baker: Chaired paper session: "Carbon-based composites, nanocomposites, and components (fibres, nanotubes, matrices) for mechanical properties," at the *CARBON 2009* Conference, Biarritz, France.
- Eberle: Selected to chair a session at the *SAMPE 2010 Composites Conference.*

Patents & Invention Disclosures:

ID / Patent #	Inventor	Title
7,534,854 B1	Paulauskas, White, & Sherman	Apparatus and method for oxidation and stabilization of polymeric materials
7,649,078 B1	Paulauskas,	Apparatus and Method for Stabilization or Oxidation of Polymeric Materials
1973	Naskar, Paulauskas, Janke, & Eberle	Novel compositions for PAN based carbon fiber precursors
2060	Menchhofer, Baker, & Montgomery	Carbon Nanotubes Grown on Bulk Materials and Methods for Fabrication
2187	Baker	Production of Composite Cellulose/Carbon Fiber Filters for HVAC Systems
2212	Several	Carbon Fiber Composites with Enhanced Compression Strength
2239	Several	Polyolefin-based flame retardant material
2241	Paulauskas & Naskar	Extremely Flame Retardant Material from PAN Fibers via Advanced Oxidation
2293	Baker et. al.	Genetically-Modified Lignin-Derived Bio-Thermoplastics for Polymer Matrix Composites

The Carbon Fiber Team

Materials


Felix Paulauskas


Frederick Baker


Soydan Ozcan


Nidia Gallego


Mohamed Abdallah


Fue Xiong


Amit Naskar


DaveWarren


Rebecca H. Brown


Ken Yarborough


Cliff Eberle

Questions?