Lower Cost, Higher Performance Carbon Fiber

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U.S. DEPARTMENT OF ENERGY

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Questions for Today

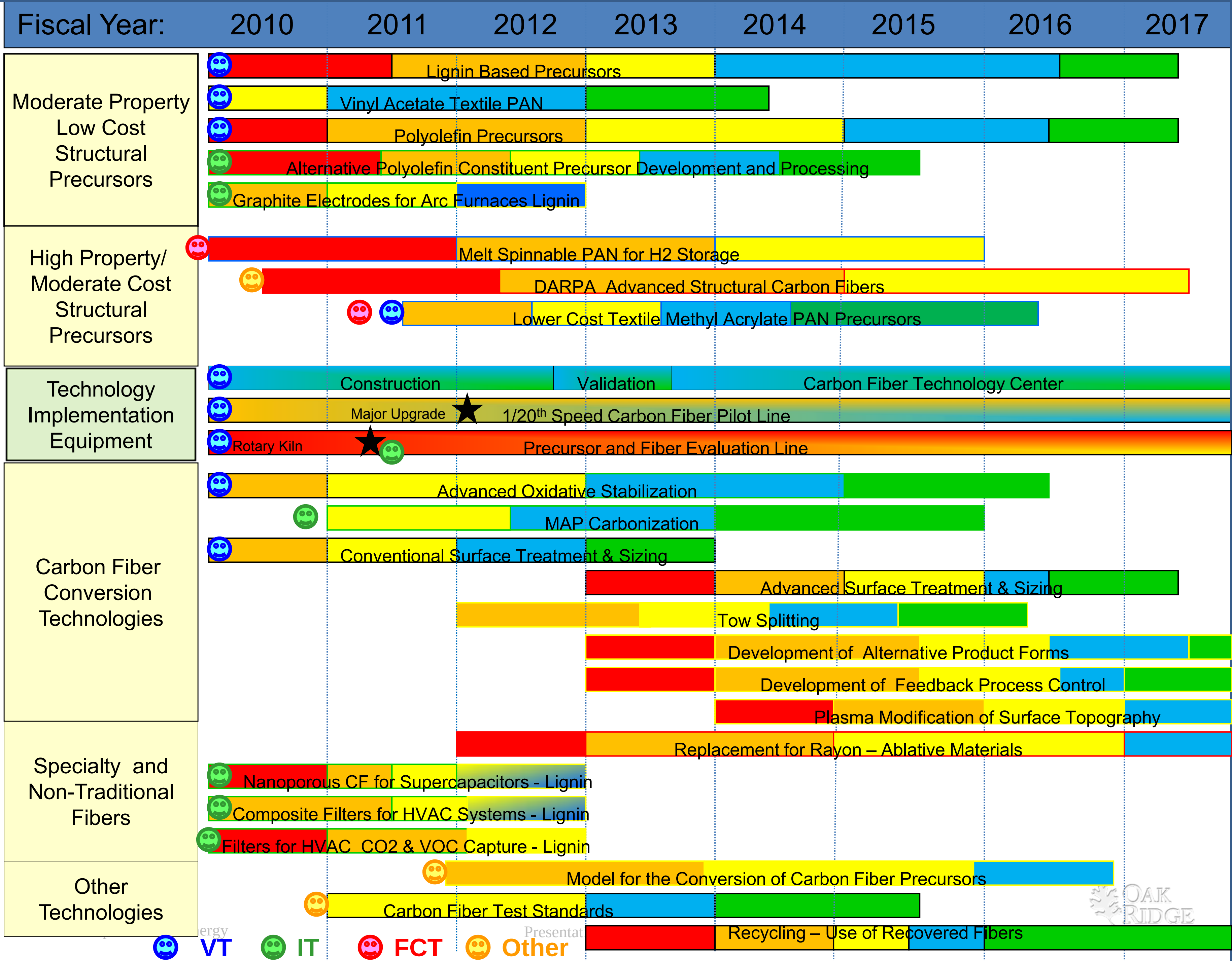
How can the cost of carbon fiber suitable for higher performance applications (H_2 Storage) be developed?

H_2 Storage requirements implies Aerospace grade fibers.

Can we build off of work previously done for more modest structural applications?

To accurately answer: We need to know the **minimum performance** and **maximum cost** requirements of the fiber not simply the properties of current fiber.

Outline:
Technology development & potential industries
The cost of making Carbon Fiber.
The paths taken for structural materials.
Potential paths for higher performance fiber cost reduction.



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 Precursors
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
Other Technologies
Model for the Conversion of Carbon Fiber Precursors
Carbon Fiber Test Standards
Recycling – Use of Recovered Fibers
VT
IT
FCT
Other
OAK RIDGE

Cost Performance Categories

Carbon Fibers can be divided into 4 Broad Cost/Performance Categories:

High Performance	>750 KSI > 35 MSI	Cost is not Limiting Performance Driven
Moderate Grade	500 – 750 KSI 25 – 35 MSI	Cost and Performance Balance
High Volume Grade	250 – 500 KSI < 25 MSI	Cost Sensitive Performance Enabling
Non Structural	Chemical & Physical Properties of Carbon	Usually Low Cost and Chosen for Uniqueness

Most High Volume Industries would require the last 2 Categories

Potential Markets and Needs

Materials

250-500 KSI, 25 MSI Fiber

500 - 750 KSI, 35 - 40 MSI Fiber

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)

Materials

250 - 500 KSI, 25 MSI Fiber

500 - 750 KSI, 35 - 40 MSI Fiber

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
Electrical 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**

So What is the difference between making aerospace and industrial grade carbon fiber?

Attribute	Industrial Grade	Aerospace Grade	Cost Impact
Tow Size	12-80K Filaments	1-12K Filaments	Less material throughput
Precursor Content	< 92% AN, MA or VA	> 92% AN, MA	Little on raw material; slower oxidation
Precursor purity & uniformity	Can tolerate more impurity	Controls UTS and compression strength	Slower spinning speed
Oxidation	Quicker due to lower AN	Slower due to higher AN	Time is money
Carbonization	Lower Temp	Sometimes Higher Temp	Small impact
Surface treatment	Same but utility affected	Same	None but Load Transfer affects amount of fiber needed
Packaging	Spooled	Small Spools	More Handling
Certification	None	Significant	Expensive; Prevents incremental Improvements.

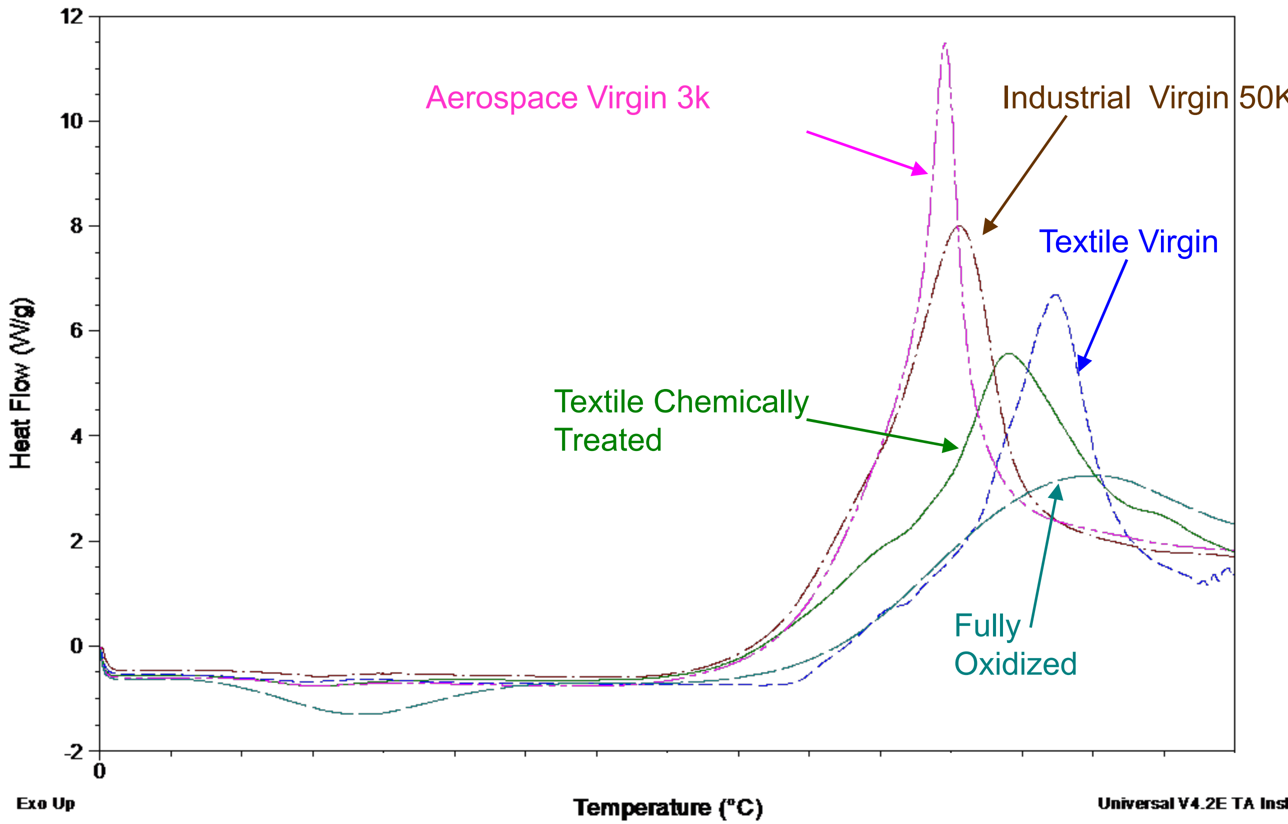
Essentially the same process with slightly different starting materials. Not captured is the fact the CF manufacturers are specialty material makers, not high volume.

So What is the difference between making aerospace and industrial grade carbon fiber?

Materials

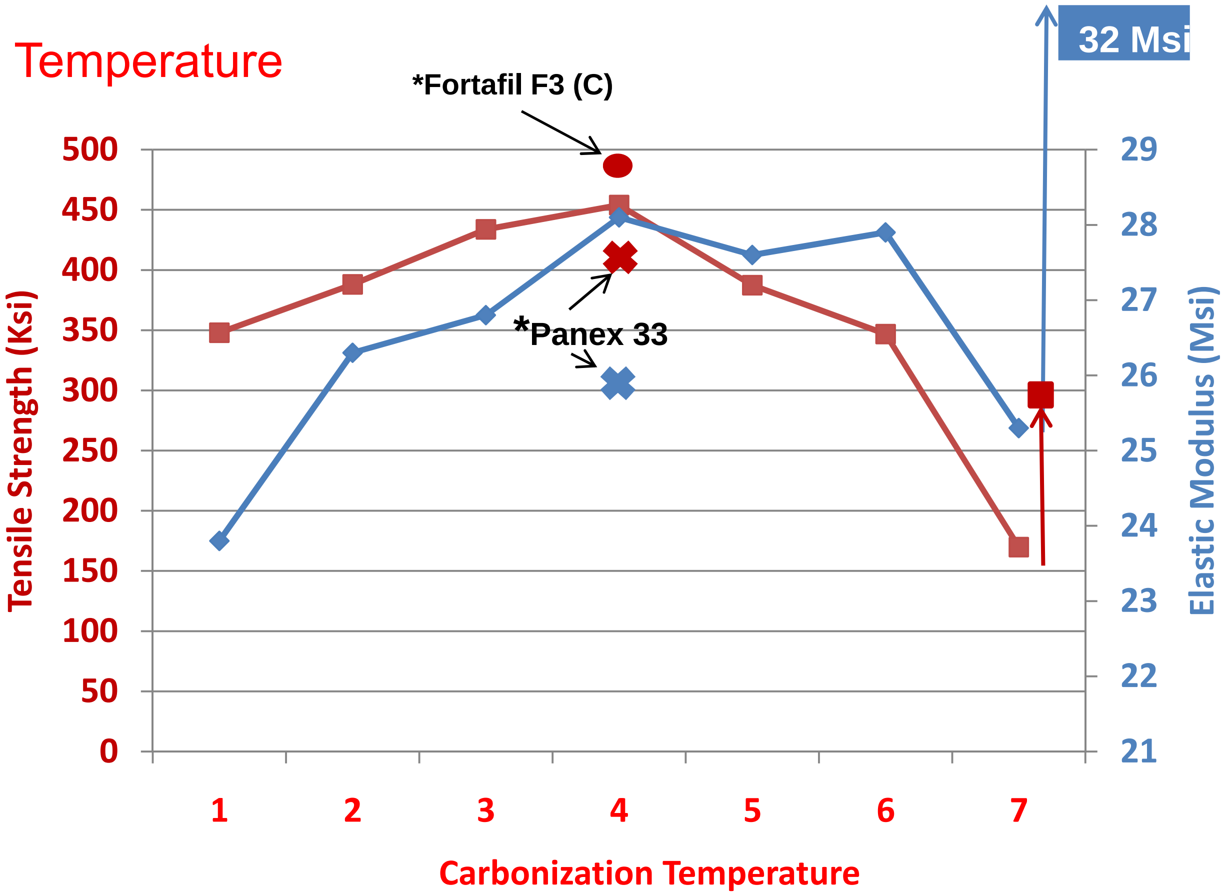
An higher performance fiber during production has:

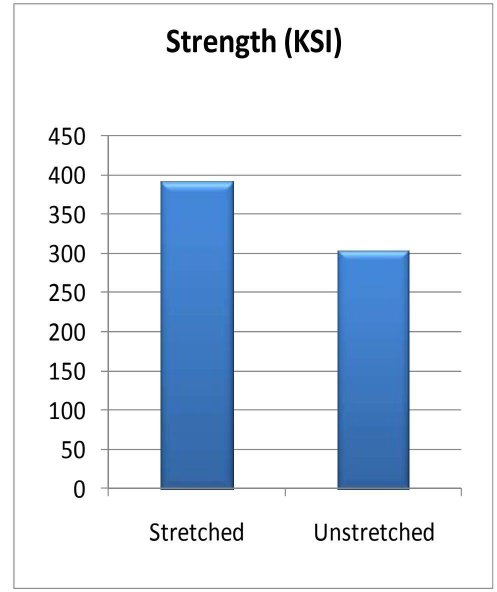
1. Less material throughput (smaller tow size).
2. Requires more care in spinning (to get round fibers).
3. Spends longer in oxidation (affects lbs/hr production).
4. And requires higher temperature carbonization (energy $).



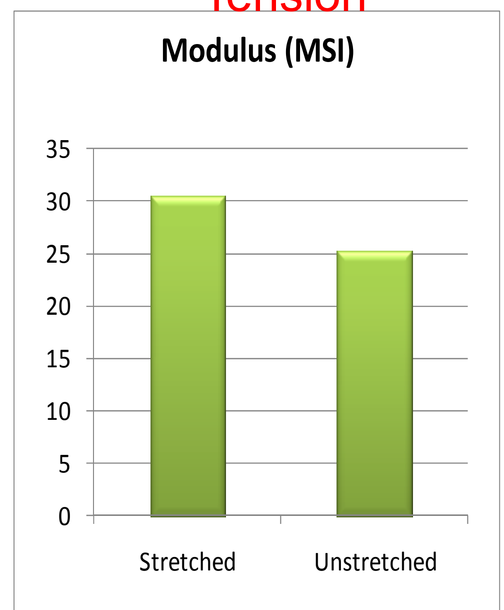
Strength/Modulus vs. Temp

Materials





Tension



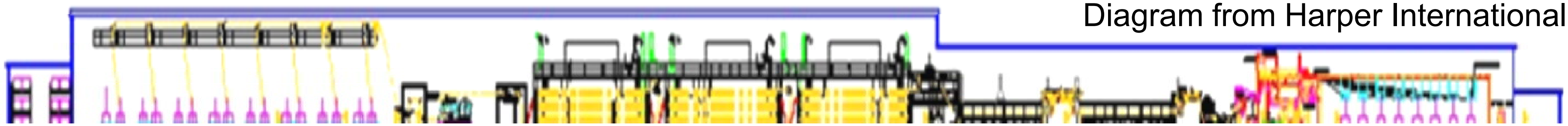
Based on broom straw test method measured in our labs (Not from Co. brochure)

Final Properties Depend upon:

Time – Temperature - Tension

Carbon Fiber Costs (Baseline – 24K)

Diagram from Harper International

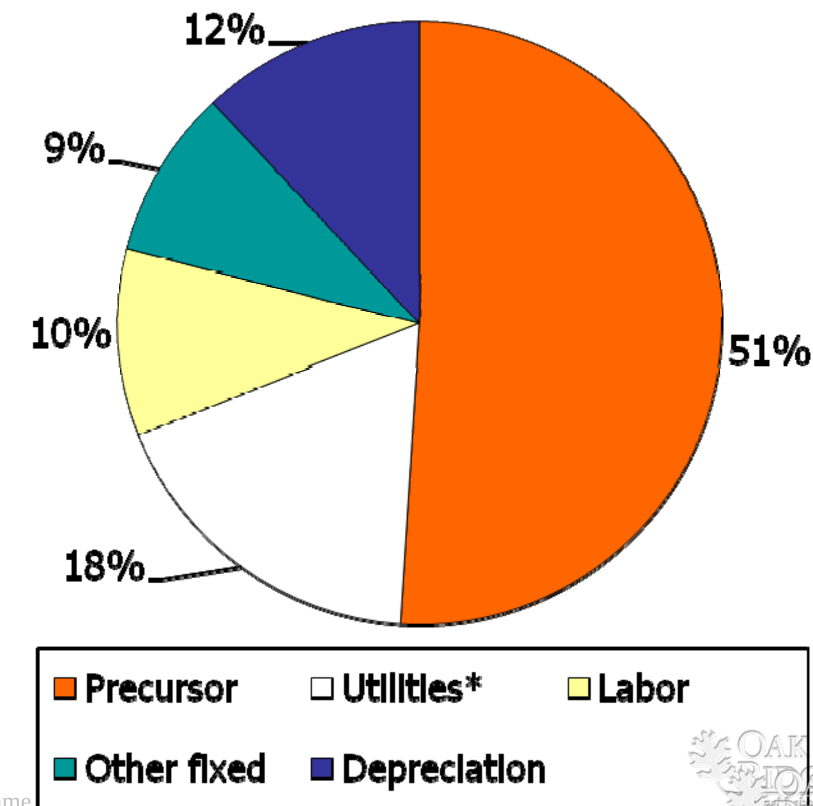


Precursors	Stabilization & Oxidation	Carbonization/ Graphitization	Surface Treatment	Spooling & Packaging
$5.04 (51%)	$1.54 (16%)	$2.32 (23%)	$0.37 (4%)	$0.61 (6%)

Includes Pretreatment and Handling

Baseline - $9.88

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



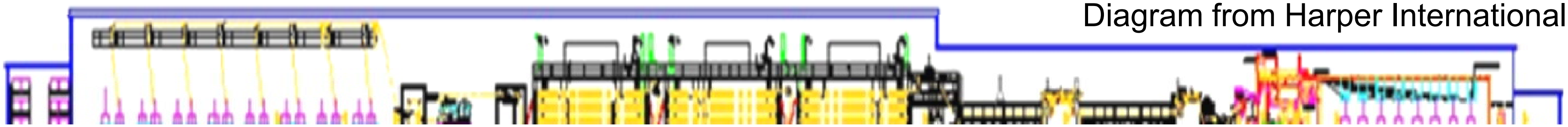
4 Elements of Cost Reduction
1. Scale of Operations
2. Precursors
3. Conversion
4. Manufacturing of Composite

* Data From Kline & Company

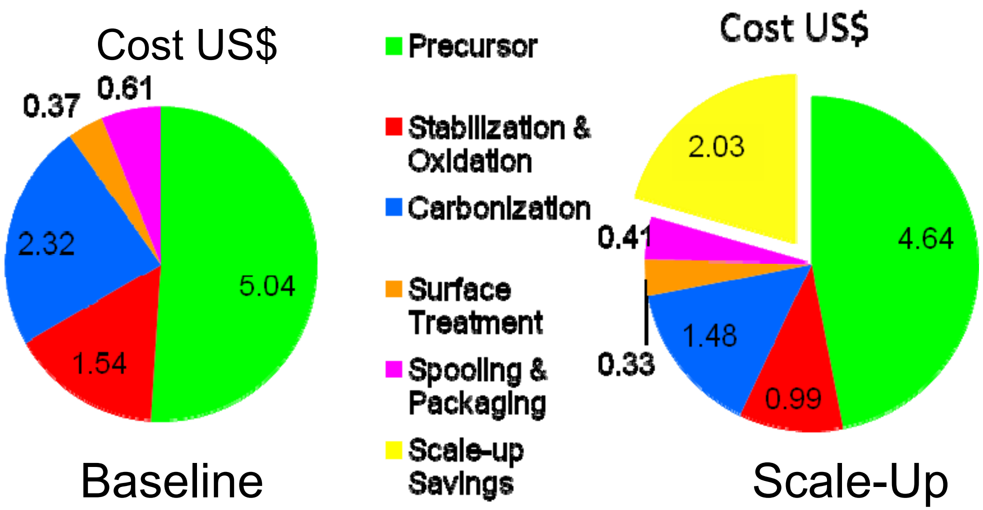
Carbon Fiber Costs (1. Scale of Operations)

Materials

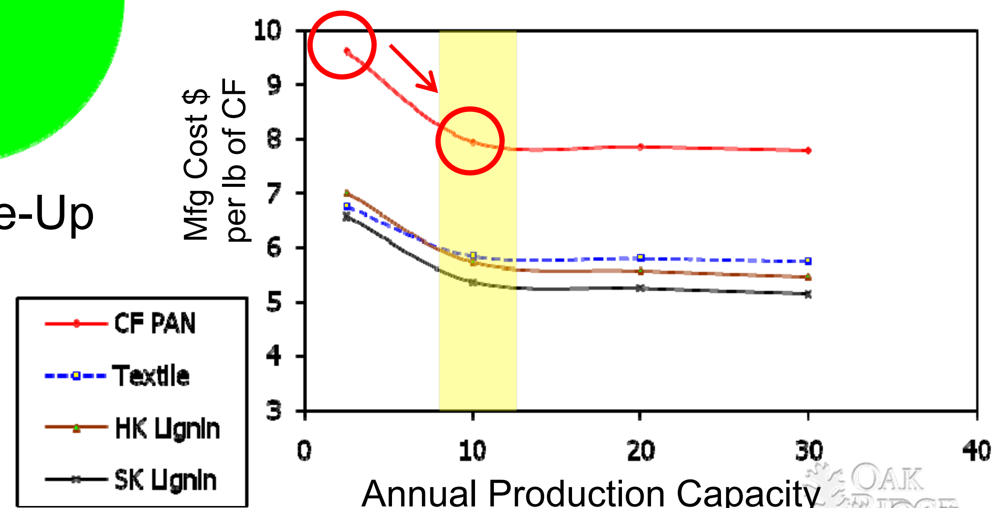
Diagram from Harper International



	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



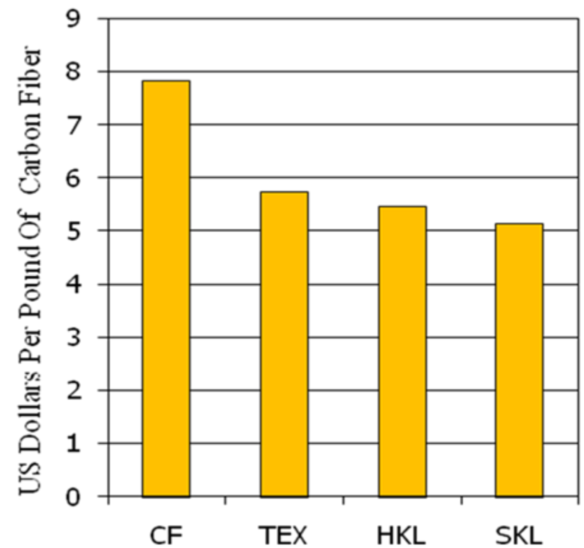
* Baseline Data From Kline & Company

But

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

Carbon Fiber Costs (2. Precursors)

Alternative Precursors and Conventional Processing

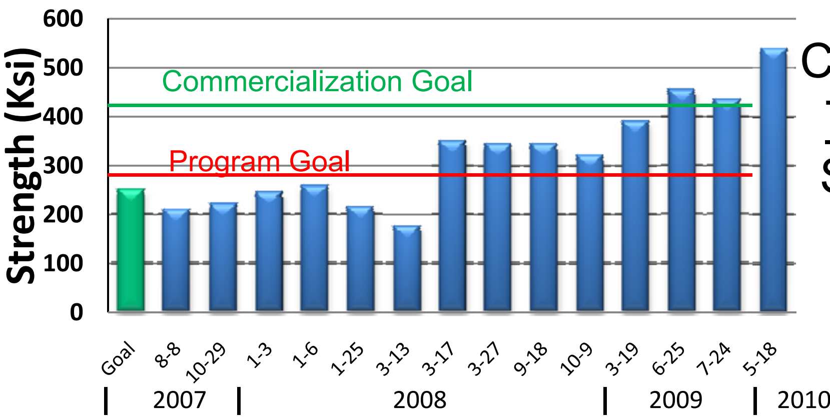


More Affordable Precursors are Needed

3 Current Precursor Options

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

Carbonized Textile Precursor

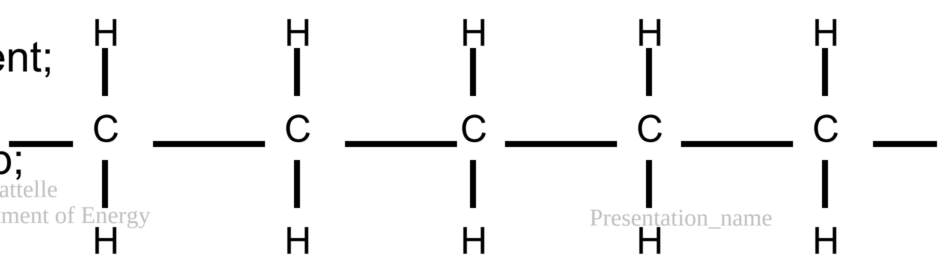


Current Carbonized
Textile Properties:
Strength: 540 KSI
Modulus: 38 MSI

Processed Precursor Fibers from a Hardwood/Softwood Lignin Blend.

PE:

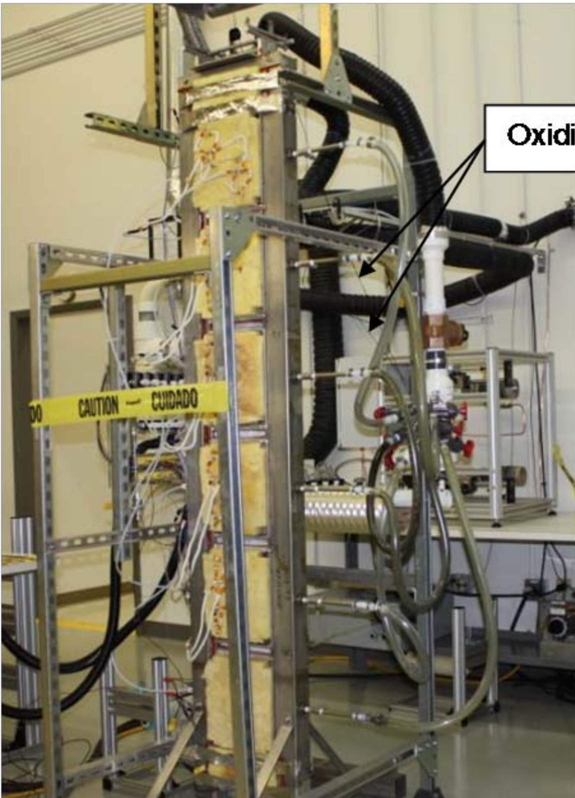
86% C Content;
65-75% Yield
$0.50-$0.75/lb;
Melt Spun



Current Research (3. Conversion)

Materials

Alternative Processing Methods Under Development

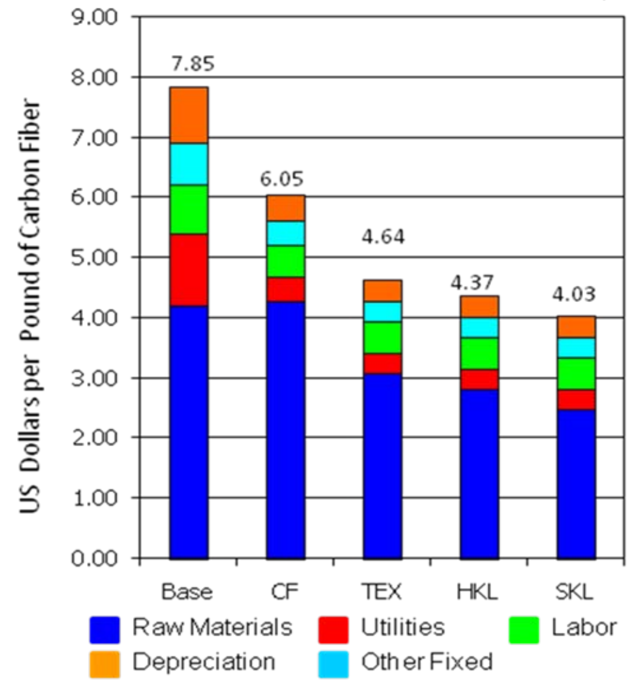


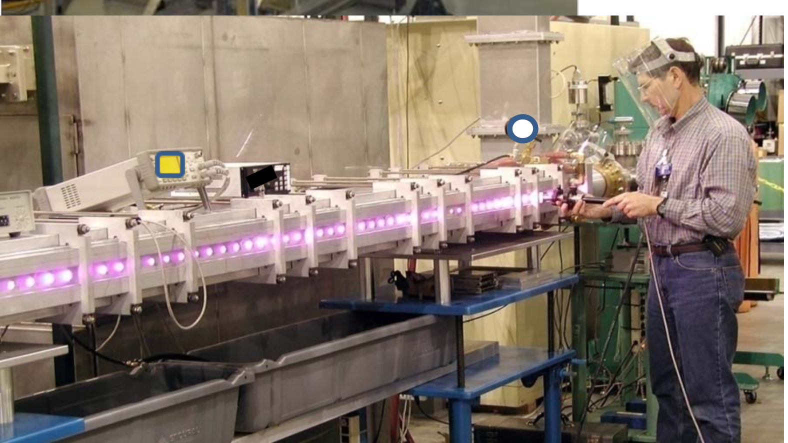
Current Generation of Oxidative Stabilization Equipment

<u>3 Processing Methods</u>

1. Advanced Oxidative Stabilization
2. MAP Carbonization
3. Surface Treatment (Not on graph)

Alternative Processing



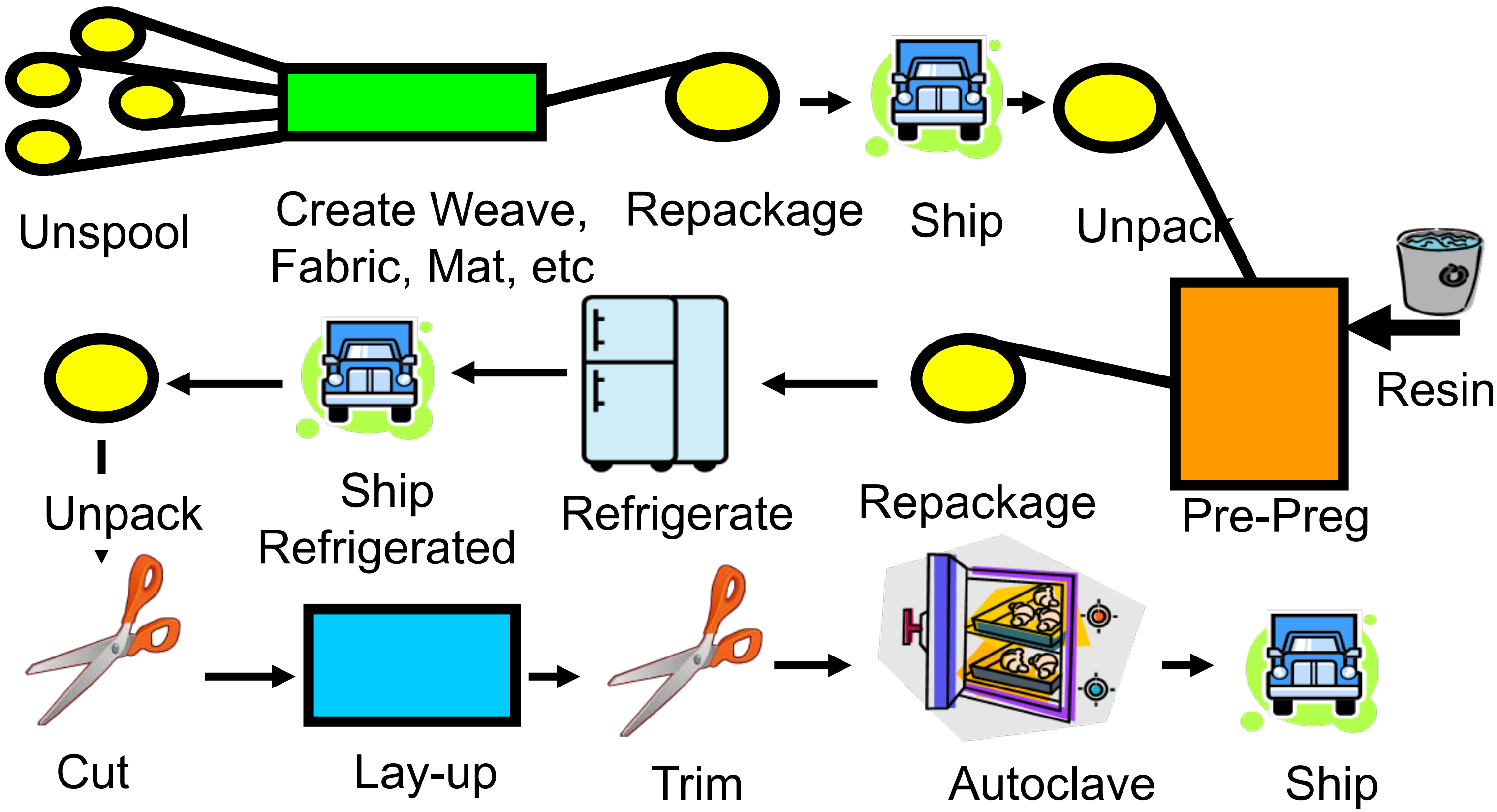


MAP Carbonization/ Graphitization Unit

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.

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

1. Textile PAN that is MA-based
(Shorter Term)

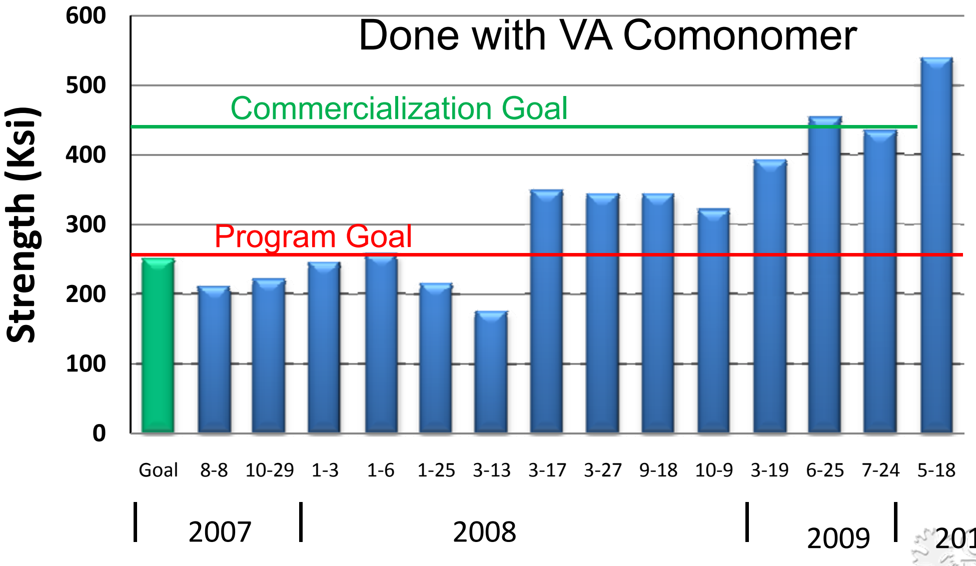
Challenges:

1. Adapting high speed processes for higher AN concentration.
2. Adapting high speed processes to increase precursor purity (minimize defects).
3. Spinning of round fibers (air gap spinning).
4. Improving consistency, fiber to fiber and along fibers without sacrificing speed.

Can be done. Largely a quality control and willingness issue.

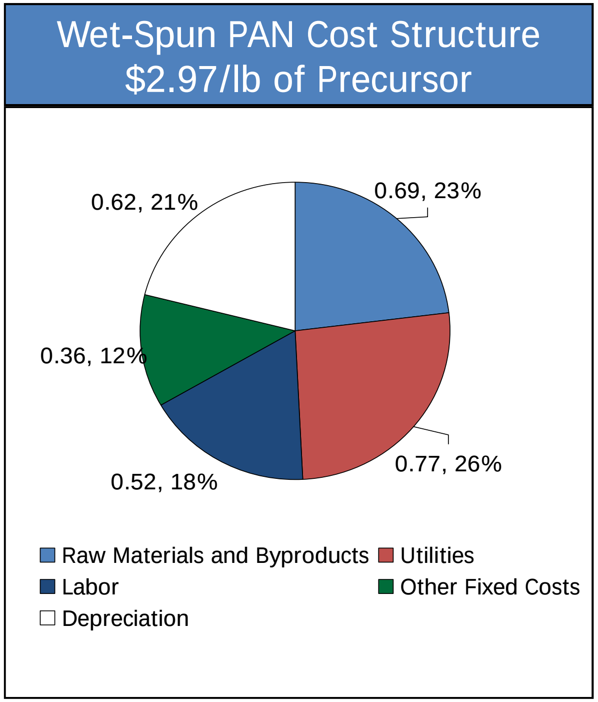
Target Properties:
Strength: 1.72 GPA
(250 KSI)

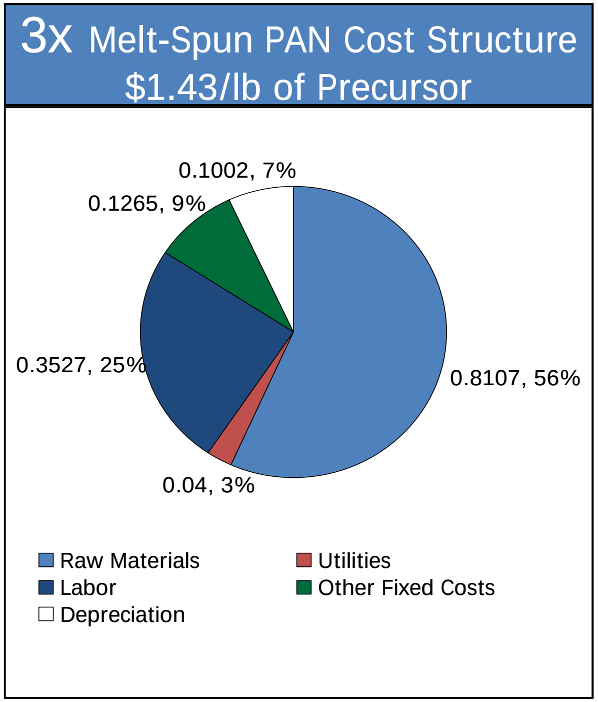
Current Properties:
Strength: 3.72 GPA
(540 KSI)



2. Melt-Spun PAN (Mid-Term)

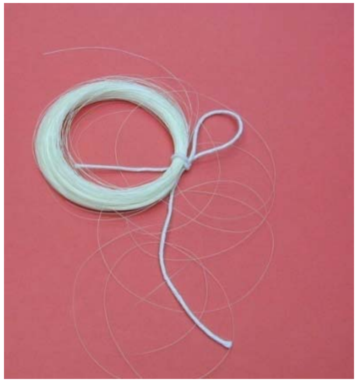
1. 30% lower plant cost and 30% lower operating cost. No current manufacturers.
2. Higher properties must be developed. 400-600 ksi proven.
3. Melt spinning if faster.





BASF developed melt-spun PAN precursor in the 1980's

- Carbon fibers were qualified for B2 bomber
- Demonstrated 400 – 600 ksi fiber strength and 30 – 40 Msi modulus; even better properties were thought to be achievable
- PAN content was 95% - 98% (consistent with high strength)



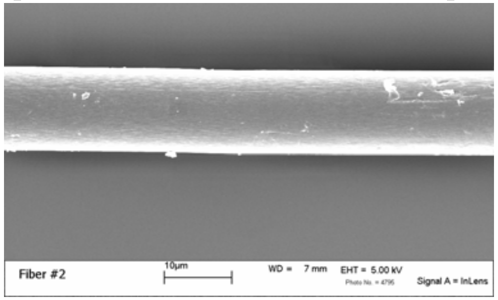
Significantly lower production cost than wet-spun fibers

~ 30% lower precursor plant capital investment

~ 30% lower precursor plant operating cost

Typical precursor line speed increased by ≥ 4X at winders

- **Demonstrated feasibility of using benign plasticizers to melt spin PAN and promote higher degree of drawing**
- **Novel comonomers were successfully incorporated**
  - Initially produced: Foamed PAN fibers and high molecular weight "fibrous" materials (4/08)
- **First (low-quality) fibers were melt spun (2008 to mid 2009)**
- **Actual, produced PAN filaments:**
  - Moderate quality
  - Large diameters
  - Need increase AN contain, > 95%



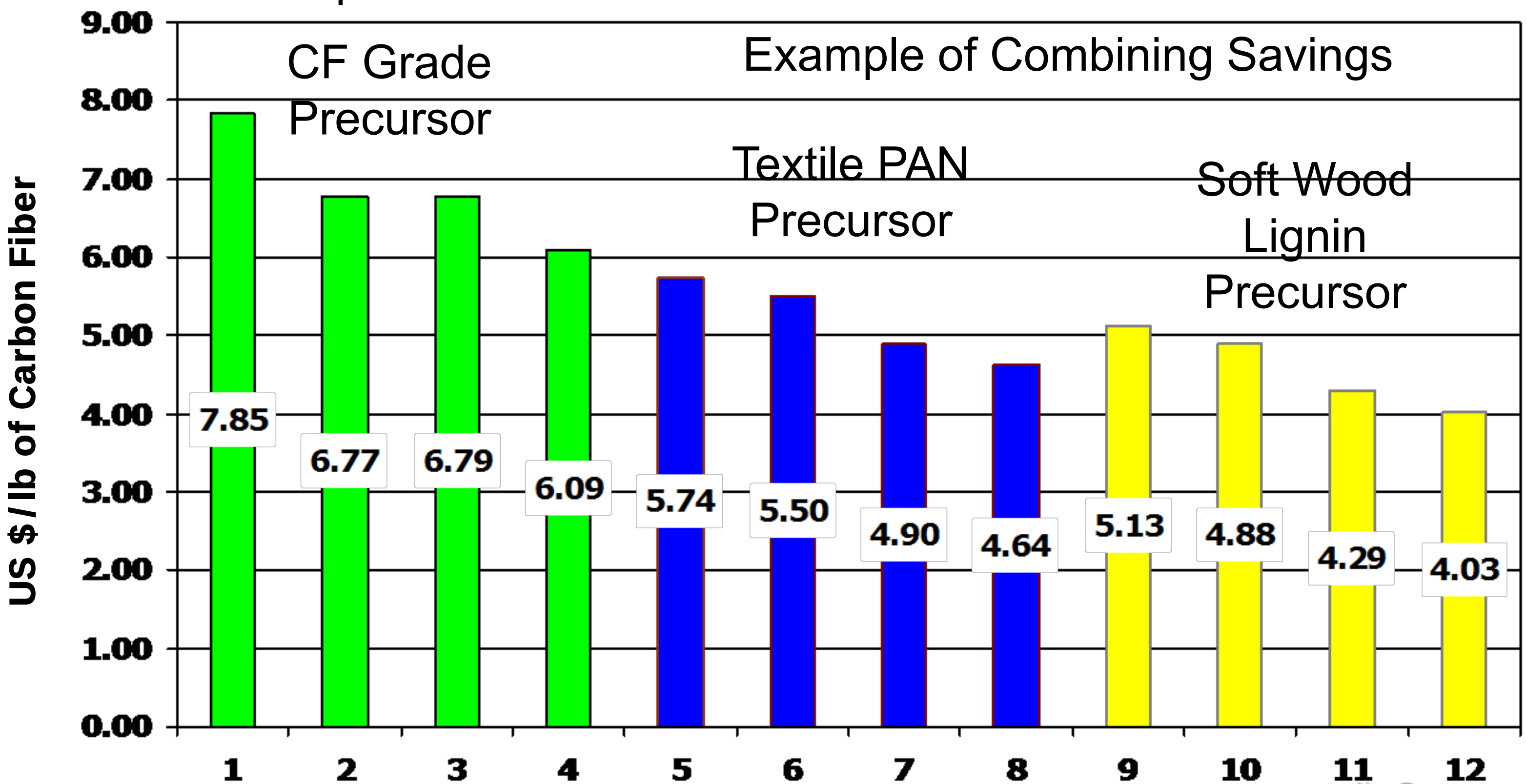
3. Develop a New Precursor (Longer-Term)

1. Polyolefins are the leading candidate, however, technology very premature.
2. Lignin achieving that level of properties unlikely due to inhomogenity.
3. Any other suitable precursor candidates would be even more suitable for lower performance fibers.
4. **Micro/Nano-Doped Precursors** (strength & seeding) [My #1 alternative]
5. New precursors must be proven at lower strength levels before obtaining higher strengths.

4. Couple New Precursor with Advanced Processing (Mid to Long -Term)

1. Cost reduction can be a function of both a lower cost precursor and less expensive processing methods.
2. Would result in a critical path of activities.

Key
1- Baseline
2- Plasma oxidation (PO)
3- MAP carbon-ization (MAP)
4- PO & MAP
5- Textile PAN (TP)
6- TP & PO
7- TP & MAP
8- TP, PO, & MAP
9- Softwood Kraft Lignin (SKL)
10- SKL & PO
11- SKL & MAP
12- SKL, PO, & MAP



Potential Paths for Higher Performance CF cost reduction

5. Increase Competition and Suppliers

Part of the multi-industry approach being pursued.

Global Carbon Fiber Production - Estimated Capacity 2010

Not included is a 40,000,000 lb/year Chinese plant to come on-line after 2010 and a large Russian plant under Contruction.

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.

Comparison of Impact

Materials

Comparison of Technologies	Energy kBTU/lb	CO2 Emitted /lb of CF	Plant Cost $/lb CF	Operating Cost $/lb CF	Precursor Cost $/lb CF	Total Mfg Cost $/lb CF	Best Properties Achieved
Conventional Precursors (CC)	389	49.2	8.72	2.71	4.02	7.85	Baseline
Conventional Precursors (AC)	272	34.4	4.28	1.34	4.02	6.05	Baseline
Textile PAN – MA (CC)	389	49.2	5.56	2.06	2.90	5.74	Should exceed 450 KSI
Textile PAN-MA (AC)	272	34.4	3.57	1.20	2.90	4.64	Should exceed 450 KSI
Melt-Spun PAN (CC)			18.04	3.36	1.62	8.34	400-600 KSI
Melt-Spun PAN (AC)	138	19.4			1.62		Should match Conventional
Polyolefins (CC)	167	22.6					
Polyolefins (AC)	96	13.4					

CC – Conventional Conversion AC – Advanced Conversion

LM002

Questions?

The Carbon Fiber Team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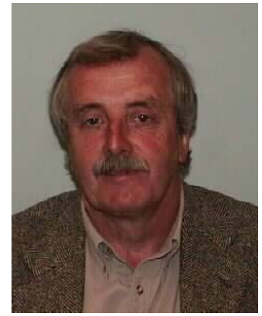
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Soydan Ozcan


Nidia Gallego


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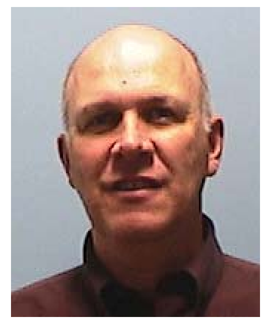
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Rebecca Brown

Daniel Webb

The entire team contributed to this presentation!!!!

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Tomonori Saito

Future Staff

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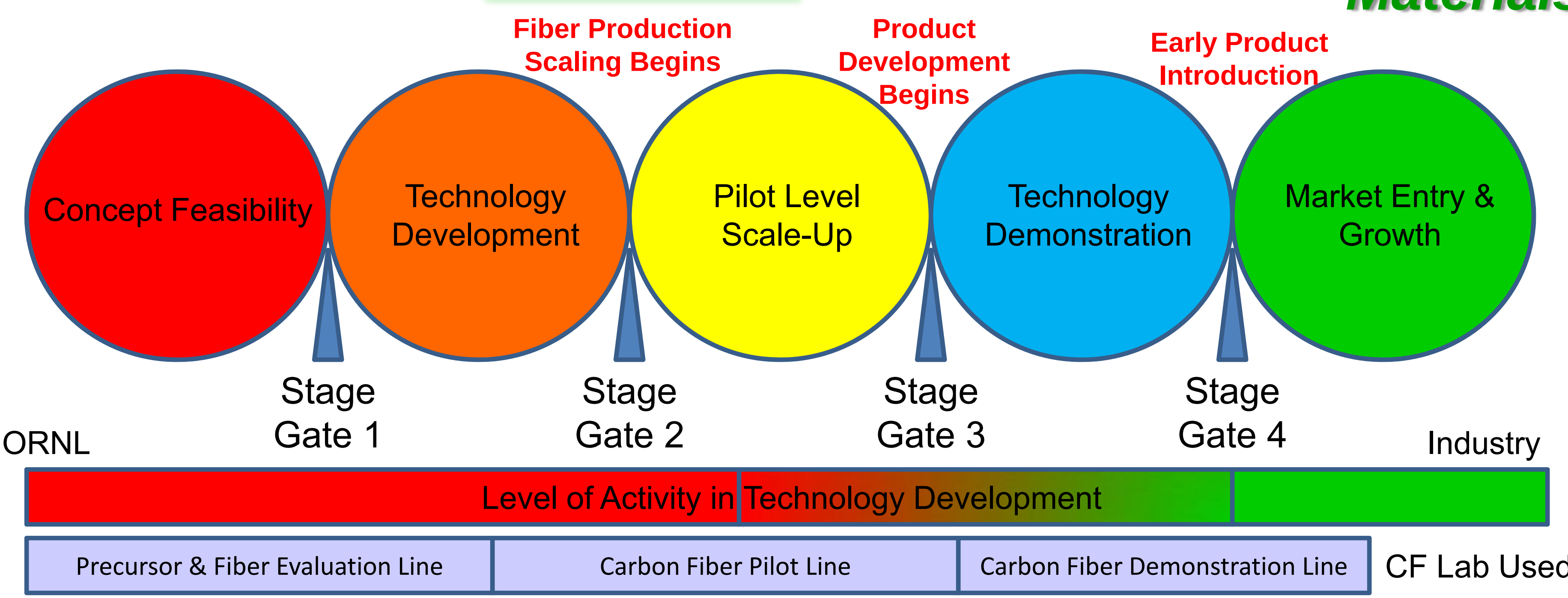
Kelby Cassity

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

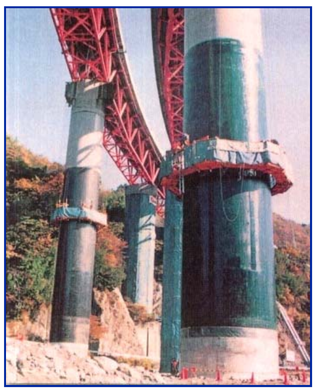
- Resolve continuous operation issues
- Develop continuous operation capability for short time periods
- Moderate material volume increasing as issues are resolved
- Concludes with design of continuous unit or final material selection

- Work to resolve scale –up 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

Common Issues and Needs: Multi-Industry Approach

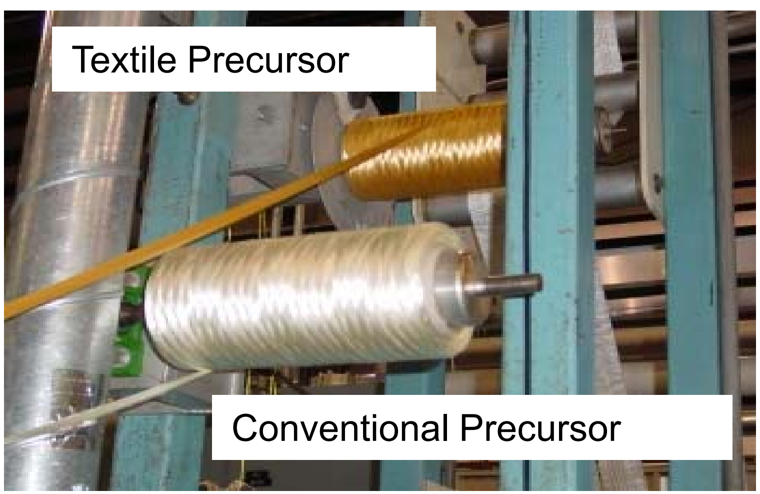
Materials

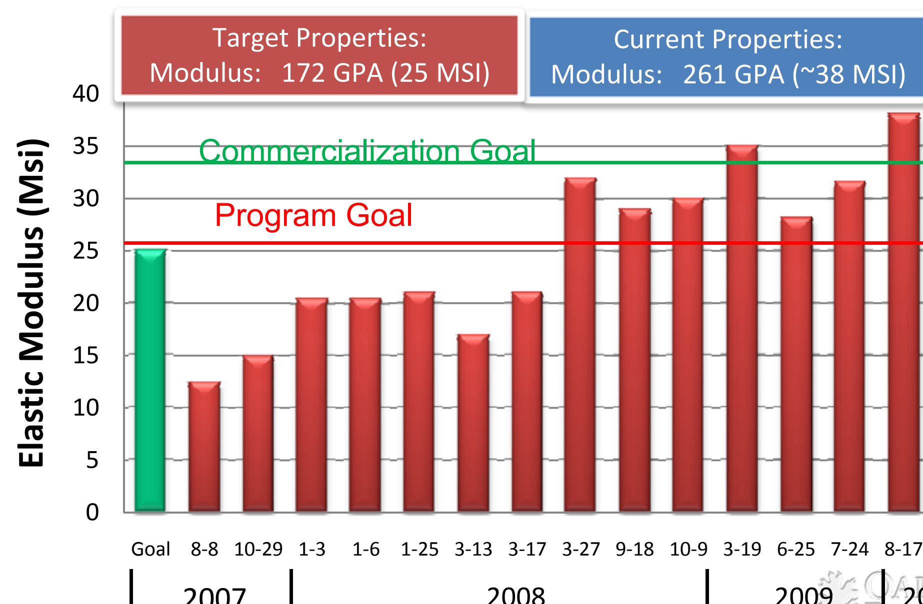


Low, stable price
Assured supply
Design methods
Product forms
Product consistency
Manufacturing methods
Recovery and reuse

Textile PAN – Strength & Modulus

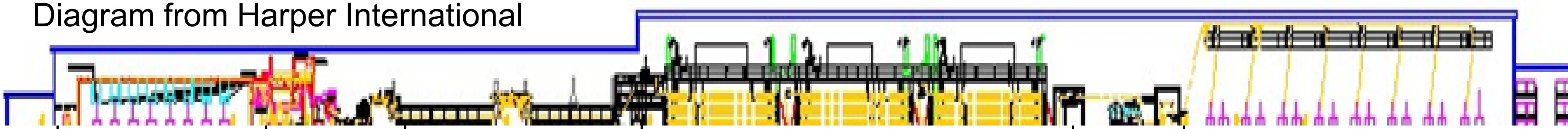
Materials





Polyolefin Precursors

Diagram from Harper International



Spooling & Packaging	Surface Treatment	Carbonization/ Graphitization	Stabilization & Oxidation		Precursors
$0.61	$0.37	$2.32	$1.54	Baseline Today - $9.88	$5.04
$0.41	$0.33	$1.48	$0.99	High Volume - $7.85	$4.64

Precursor type	Yield (%)		$/lb (as-spun)	Melt-spinnable	Best achieved properties		Problem
	Theoretical	Practical			Strength (KSI)	Modulus (MSI)	
Conventional PAN	68	45-50	>4	No	500-900	30-65	High cost
Textile PAN*	~ 68	45-50	1-3	No	300-400+	30	High variation in properties
Lignin*	62-67	40-50	0.40 - 0.70	Yes	160	15	Fiber handling, low strength & slow stabilization step
Polyolefin**	86	65-80	0.35 - 0.5	Yes	380	30	Slow stabilization (sulfonation) step

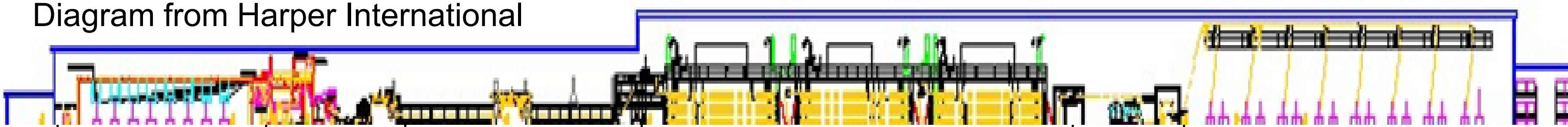
* Ongoing work
** Hexcel work (2004)

↑ High ↑ Yield ↑ Inexpensive ↑ ↑ Properties Proven At Small Scale ↑ Obstacle Addressed

Eliminating Oxidative Stabilization Reduced conversion time to 15 – 30 minutes

Polyolefin Precursors – Cost Potential

Diagram from Harper International



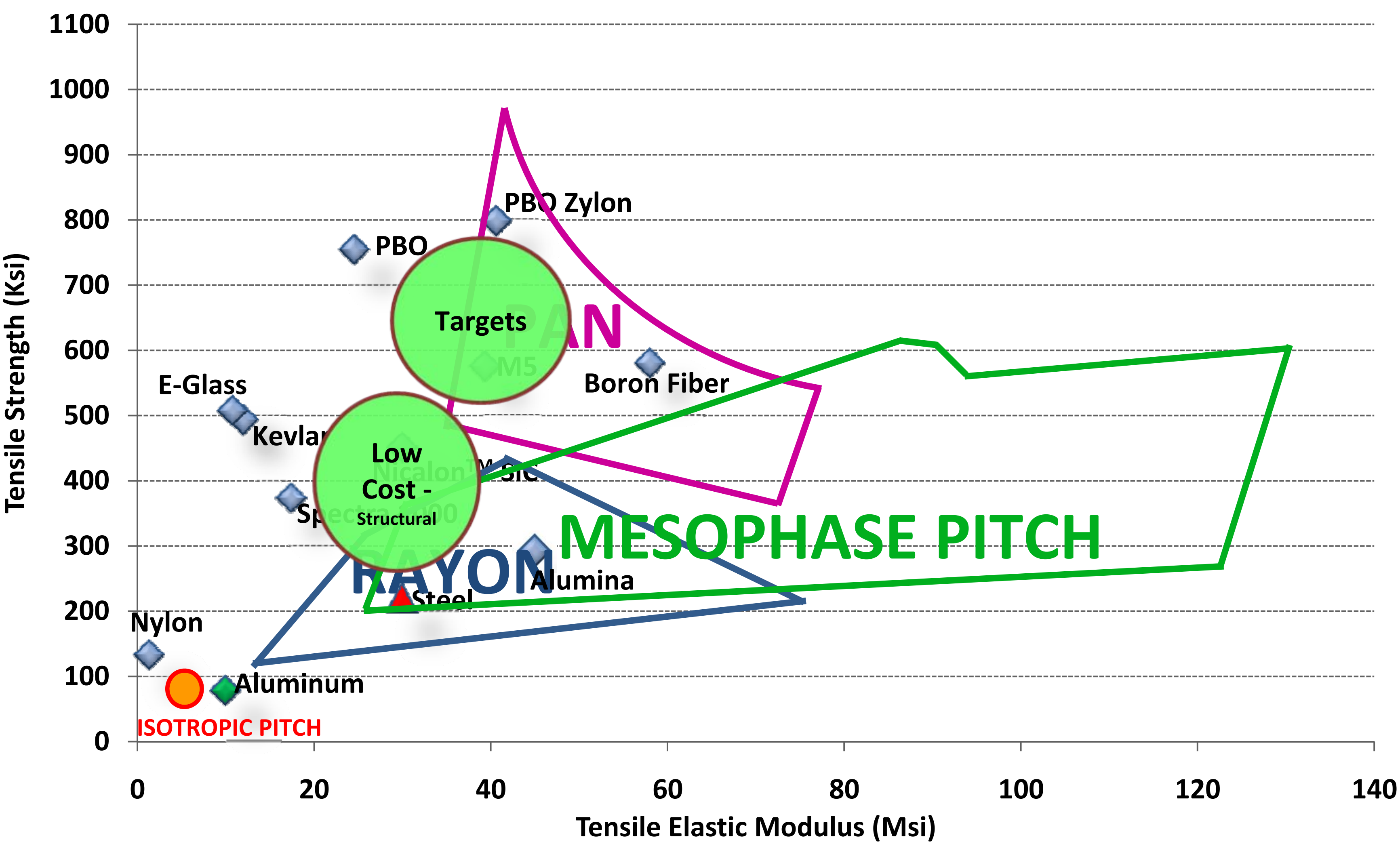
	Spooling & Packaging	Surface Treatment	Carbonization/ Graphitization	Stabilization & Oxidation		Precursors
	$0.61	$0.37	$2.32	$1.54	Baseline Today - $9.88	$5.04
	$0.41	$0.33	$1.48	$0.99	High Volume - $7.85	$4.64
High	$0.41	$0.33	$1.48	$0.20	$3.32	$0.90
Low	$0.41	$0.33	$1.25	$0.10	$2.74	$0.65

Less Effluents
Faster throughput
Less Incineration

	Large tow CF Precursor	Small tow (<24k) CF Precursor	Textile Precursor	Polyolefin Precursor
As-Spun Fiber ($/lb)	$ 3-5	$ 4-6	$ 2-3	$ 0.50 - $ 0.60
Carbon Yield	~45%	~50%	~50%	65 - 80%
Precursor Cost ($ /lb CF)	$ 6.5-11	$ 8-12	$ 4-6	$ 0.65 - $ 0.90
Stabilization	85 - 120 min	75 -100 min	75 - 100 min	60 min **
Carbonization	Same	Same	Same	Same

Carbon Fiber Property Goal

Materials

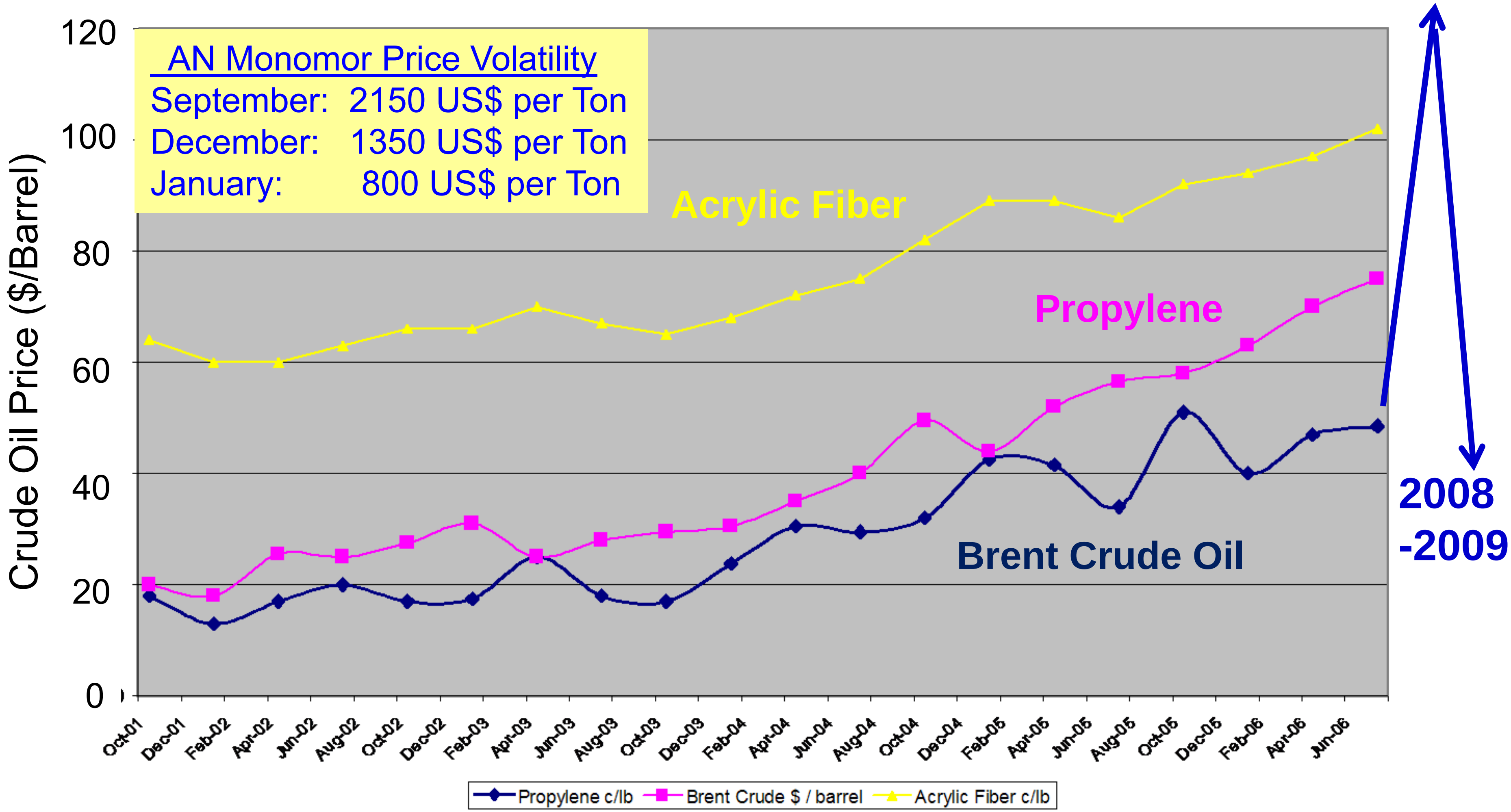


Source: 1) Modified from J.G. Lavin, 'High Performance Fibers', Ed John Hearle, Chapter 5, Woodhead Publishing, 2001, 2) Peter Morgan, Carbon Fibers and Their Composites, Taylor &Francis 2005, 3) A.R.Bunsell, Fibre reinforcements for composite materials, Elsevier, 1987

Courtesy: Soydan Ozcan

PAN Dependence on Oil Price

Materials



Current Carbon Fiber Raw Materials are Tied to Oil