Carbon Fiber Precursors and Conversion

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All Fibers are Not the Same

Reasons Carbon Fiber is Chosen

- Low Density – Lightweighting
- High Electrical Conductivity – Pitch is Best
- Modulus – Pitch Based is Best
- Near Zero Coefficient of Thermal Expansion
- Strength – PAN Based is Best
- Thermal Conductivity – Pitch is Best
- Cost – PAN Based is Lower
- Filtration Media – Pitch Based is Best
- Design Flexibility of Composites
- Chemical Resistance – Will not Corrode

<table>
<thead>
<tr>
<th>Type</th>
<th>Strength (MPA)</th>
<th>Modulus (GPA)</th>
<th>Strain (%)</th>
<th>Density (g/cc)</th>
<th>Diameter (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-700 CF</td>
<td>4900</td>
<td>230</td>
<td>2.1</td>
<td>1.80</td>
<td>7</td>
</tr>
<tr>
<td>T-300 CF</td>
<td>3530</td>
<td>230</td>
<td>1.5</td>
<td>1.76</td>
<td>7</td>
</tr>
<tr>
<td>Pitch Based</td>
<td>2000</td>
<td>500-800</td>
<td>0.5-1.0</td>
<td>2.1</td>
<td>5-10</td>
</tr>
<tr>
<td>Rayon</td>
<td>580</td>
<td>59</td>
<td>1.0</td>
<td>2.1</td>
<td>6-7</td>
</tr>
<tr>
<td>E-Glass</td>
<td>2000</td>
<td>72-85</td>
<td>2.7</td>
<td>2.55</td>
<td>~20</td>
</tr>
<tr>
<td>S-Glass</td>
<td>4750</td>
<td>89</td>
<td>5.3</td>
<td>2.5</td>
<td>~20</td>
</tr>
<tr>
<td>Spectra 1000</td>
<td>3000</td>
<td>172</td>
<td>1.7</td>
<td>0.97</td>
<td>Varies</td>
</tr>
<tr>
<td>Basalt</td>
<td>2800-4800</td>
<td>86-90</td>
<td>3.2</td>
<td>2.7</td>
<td>Varies</td>
</tr>
<tr>
<td>Kevlar 149</td>
<td>3450</td>
<td>179</td>
<td>1.9</td>
<td>1.5</td>
<td>Varies</td>
</tr>
</tbody>
</table>
Potential Precursors

- **PAN**
  - High Strength, Moderate Modulus
  - Chemical structure

- **Mesophase Pitch**
  - High Modulus, Moderate Strength
  - Chemical structure

- **Rayon**
  - Expensive and use for Ablative
  - Chemical structure

- **Lignins**
  - Strength Properties not yet proven
  - Chemical structure

- **Polyethylene**
  - Properties not yet proven
  - Chemical structure
Fibers are Spun by 3 methods

<table>
<thead>
<tr>
<th>12,000,000 lb/yr Precursor Plant</th>
<th>Wet-Spinning</th>
<th>Melt-Spinning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning Speed</td>
<td>1X</td>
<td>3X</td>
</tr>
<tr>
<td>Capital Required</td>
<td>$77,750,000</td>
<td>$28,000,000</td>
</tr>
<tr>
<td>Raw Material</td>
<td>$0.69</td>
<td>$0.81</td>
</tr>
<tr>
<td>Utilities</td>
<td>$0.77</td>
<td>$0.04</td>
</tr>
<tr>
<td>Labor</td>
<td>$0.52</td>
<td>$0.35</td>
</tr>
<tr>
<td>Other Fixed</td>
<td>$0.36</td>
<td>$0.13</td>
</tr>
<tr>
<td>Depreciation</td>
<td>$0.65</td>
<td>$0.10</td>
</tr>
<tr>
<td>Total Per Pound of Precursor</td>
<td>$2.97</td>
<td>$1.43</td>
</tr>
</tbody>
</table>

It requires 2.1 lbs of PAN Precursor to make 1 lb of carbon fiber.
Precursor Manufacturing

Starts with a large “tank farm” which polymerizes PAN and other co-monomers

Multiple Spinnerettes

Solvent Extraction, Washing and Tensioning

Crimping

Drying with Tension

Spooling or Bailing in Bulk
Prestretch during Fiber Manufacturing

Majority of Carbon Fibers are PAN Based. Stretching occurs below the $T_g$ with H$_2$O as a plasticizer.
Oxygen and/or oxidative species need to diffuse through the oxidized “skin”

Diffusion of oxygen to reactive sites is restricted, sequent reactions follow more slowly

The limiting or controlling factor is diffusion
Conversion - Oxidative Stabilization
Stretching of Fibers during Stabilization

- Stretching of filaments provides high molecular orientation and better mechanical properties.

- Dry PAN fibers are difficult to stretch (due to high Tg, strong dipole-dipole interaction)

- Stretching is occurring while oxygen is diffusing in and crosslinking is occurring.
- Crosslinking results in resistance to further stretching and thus molecular alignment.
- A potential path to higher strength fiber would be to achieve the stretch prior to cross linking.

Young’s modulus of precursor fiber vs. resulting carbon fiber

Young’s modulus of precursor fiber vs. precursor stretching

Mathur et al. carbon 1988
PAN fiber is pyrolyzed to carbon fiber

**Process:**
- Inert atmosphere
- \(~ 300 - 1800°C\)
- Tow under tension

**Key Features:**
- Most non-carbon elements are driven from fiber
  - Generates corrosive, toxic, and carcinogenic effluents
- 50-60% of original PAN weight lost
- Carbon yield from PAN = 40-50% (Rayon = 10-30%; Pitch = 80-90%)
- PAN density = 1.2 g/cc - carbon fiber density = 1.8 g/cc
- Carbon fiber diameter \(\approx\) 1/2 PAN fiber diameter
- Carbon content = 80-95%
- Carbon/Graphite fibrils or ribbons with “turbostratic graphite” structure
Graphitization

- Produces graphite fiber with higher carbon yield and more graphitic microstructure than carbonization step
  - Inert atmosphere
  - Tension – promotes correctly oriented morphology
  - 1500-3000° C

- Key features:
  - Carbon content > 99%
  - Density = 1.8 - 2.1 g/cc
  - More graphitic microstructure – increases tensile modulus, decreases tensile strength
  - Diameter = 5 -10 μm
Conventional PAN Conversion - process

Typical processing sequence for PAN –based carbon fibers

Major Cost Elements

- Precursor ~ 50%
- Conversion ~ 40%
- Other ~ 10%

ORNL is developing technological breakthroughs for major cost elements
Typical Carbon Fiber Manufacturing Facility

Staff of 5-8, 2 Lines Side by Side
Unpacking to Spooling Time = 2-3 hours
## Aerospace vs Industrial Grade Carbon Fiber?

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Industrial Grade</th>
<th>Aerospace Grade</th>
<th>Cost Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tow Size</td>
<td>12-80K Filaments</td>
<td>1-12K Filaments</td>
<td>Less material throughput</td>
</tr>
<tr>
<td>Precursor Content</td>
<td>&lt; 92% AN, MA or VA</td>
<td>&gt; 92% AN, MA</td>
<td>Little on raw material; slower oxidation</td>
</tr>
<tr>
<td>Precursor Purity</td>
<td>Can tolerate more impurity</td>
<td>Controls UTS</td>
<td>Slower spinning speed</td>
</tr>
<tr>
<td>Precursor Composition</td>
<td>Moderate MW</td>
<td>Higher MW yields Higher Properties</td>
<td>Significant increase in spinning and polymerization costs</td>
</tr>
<tr>
<td>Oxidation</td>
<td>Quicker due to lower AN</td>
<td>Slower due to higher AN</td>
<td>Time is money</td>
</tr>
<tr>
<td>Carbonization</td>
<td>Lower Temp</td>
<td>Sometimes Higher Temp</td>
<td>Small impact</td>
</tr>
<tr>
<td>Surface treatment</td>
<td>Same but utility affected</td>
<td>Same</td>
<td>None but Load Transfer affects amount of fiber needed</td>
</tr>
<tr>
<td>Packaging</td>
<td>Spooled</td>
<td>Small Spools</td>
<td>More Handling</td>
</tr>
<tr>
<td>Certification</td>
<td>None</td>
<td>Significant</td>
<td>Expensive; Prevents incremental Improvements.</td>
</tr>
</tbody>
</table>

Essentially the same process with slightly different starting materials. The traditional business model is for CF manufacturers to be specialty material makers, not high volume. That trend is shifting.
North American Carbon Fiber Manufacturers

Worldwide Carbon Fiber Supply and Demand

- Supply
- Demand

1998 End of the Cold War
2005 Commercial Aircraft Boeing 787 & Airbus A380 & A350
50/50 Balance between Small Tow ($\leq 12K$) & Large Tow

Global Market Share by Company

- Toray, 31.0%
- Toho, 19.0%
- Mitsubishi, 19.0%
- Zoltek, 18.0%
- Cytec, 3.4%
- Hexcel, 7.7%
- Others, 5.9%

Competitors are entering the Market from China, Turkey, India and Russia
# Carbon Fiber Production - United States

<table>
<thead>
<tr>
<th>Company</th>
<th>US Facilities</th>
<th>Non-US Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexcel (US)</td>
<td>Decatur, AL; Salt Lake City, UT</td>
<td>Spain</td>
</tr>
<tr>
<td>Cytec (US)</td>
<td>Greenville, SC; Rock Hill, SC</td>
<td>None</td>
</tr>
<tr>
<td>Toray (Japan)</td>
<td>Decatur, AL</td>
<td>Japan</td>
</tr>
<tr>
<td>SGL (Germany)</td>
<td>Evanston, WY, Washington</td>
<td>Scotland, Germany</td>
</tr>
<tr>
<td>Zoltek (US)</td>
<td>Abilene, TX; St. Louis, MO</td>
<td>Mexico, Hungary</td>
</tr>
<tr>
<td></td>
<td>Salt Lake City, UT</td>
<td></td>
</tr>
<tr>
<td>Mistubishi (Japan)</td>
<td>Sacramento, CA</td>
<td>Japan</td>
</tr>
<tr>
<td>Toho Tenax (Japan)</td>
<td>Rockwood, TN</td>
<td>Japan, Germany</td>
</tr>
</tbody>
</table>

Source: Polyacrylonitrile (PAN) Carbon Fibers Industrial Capability Assessment, Department of Defense

**United States Universities with significant research in Carbon Fiber production**
- Clemson University
- University of Kentucky
- Virginia Tech
- Georgia Tech

Note: Large efforts in carbon fiber composite development at many laboratories and universities.
Start with an Understanding of Where the Costs Are

• High Volume is 25,000 Tons/year. All Costs are $/lb

Not Captured is that Oxidation is the rate limiting step and thus mass throughput limiting step.

6 Elements of Cost Reduction
1. Scale of Operations  2. Precursor Materials
2. Precursor Spinning  3. Stabilization
4. Carbonization
5. Surface Treatment
6. Spooling & Packaging

Diagram from Harper International

<table>
<thead>
<tr>
<th></th>
<th>Precursors</th>
<th>Stabilization &amp; Oxidation</th>
<th>Carbonization/Graphitization</th>
<th>Surface Treatment</th>
<th>Spooling &amp; Packaging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Materials</td>
<td>Spinning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial Grade</td>
<td>$2.78</td>
<td>$2.78</td>
<td>$1.78</td>
<td>$1.41</td>
<td>$0.65</td>
</tr>
<tr>
<td>High Volume*</td>
<td>$2.78</td>
<td>$2.45</td>
<td>$1.62</td>
<td>$1.27</td>
<td>$0.49</td>
</tr>
<tr>
<td>Aerospace Grade</td>
<td>$3.21</td>
<td>$3.21</td>
<td>$2.88</td>
<td>$2.45</td>
<td>$0.80</td>
</tr>
<tr>
<td>High Volume*</td>
<td>$3.21</td>
<td>$2.89</td>
<td>$2.54</td>
<td>$1.57</td>
<td>$0.78</td>
</tr>
</tbody>
</table>

Ref:  Brian James Preliminary Cost Model
The precursor and thus CF manufacturing costs are sensitive to oil prices.

### Carbon Fiber Raw Material Pricing History

<table>
<thead>
<tr>
<th>Source: Kline (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Oil Price</td>
</tr>
<tr>
<td>$60/barrel</td>
</tr>
<tr>
<td>$75/barrel</td>
</tr>
</tbody>
</table>
The Making of Composites – Fiber is Part of the Cost

Polymer

Spinning

Precursor

Conversion

Surface Treatment

Fiber

$ 

Preform/

Fabric

Resin

C E

Composite Processing

Curing

Finishing

Painting or

Coating

Joining

Crash, Durability

and Performance

Each Step often results in material passing through different hands at different locations – adding $$$

C – Capital Investment Intensive
R – Raw Material Expensive
T – Time Expensive
E – Energy Intensive

Reducing Fiber Cost is a 1st Step. BUT

Composite processing must be more affordable. And

Material Handling Integrated.
## Potential Elements of Cost Reduction for Reinforcement

### Carbon Fiber Cost

1. Non-PAN precursors. (Pitch, Rayon, Lignin, Polyolefins, etc.)
2. Melt or Dry Spun PAN. (Melt spun being pursued, 1 source of dry spun)
3. Higher Molecular Weight Precursors.
4. High Rate Stabilization. (Developed under VTO program, not yet extended to high performance fibers)
5. Higher Volume Conversion Methods (i.e. Fiber Layering)
6. Pre-stretching above the Tg of the polymer to yield better molecular alignment.
7. Alternative Carbonization. (Early work being conducted.)
8. Alternative Surface Treatments and Sizings. (Work is dormant.)

### Other Technologies

1. Full or Partial use of Alternative Reinforcements. (Some characterization or alternate fibers needed under long term operating conditions.)
2. Higher Rate Composite Manufacturing Methods. (IACMI)
3. Alternative Product forms (Tapes, Preimpregnated tow, etc.)
4. Improved Load Transfer (improved fiber/resin bonding)

### Table

<table>
<thead>
<tr>
<th>Precursor Materials:</th>
<th>24%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precursor Spinning:</td>
<td>24%</td>
</tr>
<tr>
<td>Stabilization &amp; Oxidation:</td>
<td>26%</td>
</tr>
<tr>
<td>Carbonization:</td>
<td>14%</td>
</tr>
<tr>
<td>Surface Treatment/Sizing:</td>
<td>6%</td>
</tr>
<tr>
<td>Spooling and Packaging:</td>
<td>5%</td>
</tr>
</tbody>
</table>
Key Challenges – Requires a Multi-Prong Approach

Precursors
- Raw Materials are Commodity (Can we use other materials)
- Melt Spun PAN, Air-Gap Spun PAN, Increased MW of either.

Conversion
- Pre-stretching to achieve molecular alignment (new method)
- Advanced Oxidation to improve throughput (3X)
- Higher rate, lower energy carbonization
- Fiber Layering to increase throughput

Post Treatment
- Improved surface treatment and sizing
- Alternative Product forms

Design
- Alternate Fibers (in part or in whole)
- Higher Rate Manufacturing methods
Thank You   Mahalo   Merci
Dziekuje   Gracias   Achiu
Obrigado   Danke   Spasibo
Grazie   Xie xie   Tesekkür ederim
Arigato   Jag tackar   Toda
Sas efharisto
# History of Carbon Fiber Composites Industry

- **Early Composites:** Wood, Adobe Bricks, Laminated Bow
- **1900-1970:** Fiber glass, man-made fiber, and resin systems

<table>
<thead>
<tr>
<th>Year</th>
<th>Carbon Fiber Market Major Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970’s</td>
<td>Golf Shaft &amp; Fishing Rods</td>
</tr>
<tr>
<td>1974</td>
<td>DoD Filament Winding Rocket Motor Cases</td>
</tr>
<tr>
<td>1975</td>
<td>Satellite Applications</td>
</tr>
<tr>
<td>1976</td>
<td>Aerospace Structures</td>
</tr>
<tr>
<td>1980</td>
<td>Cold War Defense Boom</td>
</tr>
<tr>
<td>1980’s</td>
<td>Boeing 757 &amp; 767, Secondary Structures</td>
</tr>
<tr>
<td>1991</td>
<td>Defense Force Reduction</td>
</tr>
<tr>
<td>2003</td>
<td>Airbus 380</td>
</tr>
<tr>
<td>2004</td>
<td>Boeing 787</td>
</tr>
<tr>
<td>2009</td>
<td>Recession and Slow Down in Economy</td>
</tr>
<tr>
<td>2012</td>
<td>Increases in Wind and Industrial Sector</td>
</tr>
</tbody>
</table>
Current & Growing Applications of CFCs

Current Traditional Applications

• Aerospace: Space, Military and Commercial (~30%)
• Industrial use (55%)
• Sport (15%)
• Energy Wind Blades
• Energy Storage: Flywheels, Pressure Vessels
• Medical implants (prostheses), x-ray and MRI equipment
• Space Travel

Growing Applications

• Unmanned Vehicles
• Wind Generator Blades
• Automotive, transportation and marine
• Batteries; EMI/RF, Ablative Applications
• Civil engineering: Bridges and bridge columns
• Offshore oil exploration and production
• Thermal Radiators
• Cell Phone and Computer Casings
Approach:
1. Develop the Technologies at Lab Scale
2. Scale to Pilot Line
4. Work with OEMs & Suppliers to incorporate in composite material systems. Reduce their risk.
To Reach Technical Targets, All Five Barriers Must Be Overcome

A Gap in the above decreases chances for success.
**Critical Cost Reduction Pathways**

The cost reduction goal can be accomplished by combining technologies. Savings from $10.20 baseline. $0.85/lb additional savings available from volume scale-up. Current Cost Model did not evaluate savings of combining technologies.

### Precursors
- High PE Polyolefins ($5.65/lb)
- Polyolefin Blends ($2-$5/lb)
- **Kaltex Textile*** ($2.35/lb)
- PAN-VA Textile ($2.61/lb)
- Alternate Textile Precursor $?
- Lignin Blends ($0.60-1.20/lb)
- High Content Lignin ($2.68-$5.98/lb)
- Bio-Mimicked Spider $?

### Stabilization & Oxidation
- Conductive Oxidation $?
- Disassociated Pre-Stretching $?

### Carbonization/Graphitization
- Low Temperature Alternative Carbonization* ($0.50-2.00)
- Microwave Assisted Plasma ($1.31)

### ST/Sizing
- All ($0.07-2.50/lb)
- Interfacial Optimization

### Spooling & Packaging
- Thermochemical Surface Treatment
- Plasma Surface Treatment

### Current Technology Status
1. Early Stage Development (PFE Facility)
2. Initial Integration of Technologies (Pilot Scale)
3. Pre-Production Demonstration (Pre-Production Scale)
Advanced Oxidation

- Phase I: Develop the technologies to reduce oxidation time by 2-3X (Lab Scale)
- Phase II: Demonstrate Phase I capability at Pilot Scale. Large tows and multiple tows. (Current)
- Future Phase III: Scale to Preproduction Level (CFTF)

Currently Processing 2-24K tows with properties over 300 KSI.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Technology</th>
<th>Advanced Oxidation</th>
<th>Savings*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 t/y Scale</td>
<td>$10.20</td>
<td>$7.51</td>
<td>$2.69 (26%)</td>
</tr>
</tbody>
</table>
Advanced Carbonization Using MAP

- Microwave Assisted Plasma (MAP) Carbon Fiber Manufacturing is a technology for carbonizing carbon fibers at higher speeds and significantly lower costs than those achievable by present industrial practice.

Substantial advances with MAP demonstrated:

- Demonstrated stable system in 8 hour continuous operation
- Successfully scaled from 3 to 5 tows meeting all property requirements
- Reduced effluents to enhance economic feasibility
- Low thermal inertia – rapid turnaround for maintenance, repair, and production set-up:
  - 20 min for MAP vs. 12-40 hrs for conventional.
  - Lower residence time enhances output and reduces energy consumption (smaller footprint)
  - Lower temperature operation versus conventional process with equivalent fiber mechanical properties
- Cost savings driven by substantially reduced carbonization, abatement, and surface treatment processing costs

<table>
<thead>
<tr>
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<th>Conventional Technology</th>
<th>Advanced Carbonization</th>
<th>Savings*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 t/y Scale</td>
<td>$10.20</td>
<td>$8.89</td>
<td>$1.31 (13%)</td>
</tr>
</tbody>
</table>

* From cost model
Thermo-chemical and Plasma Surface Treatment + New Sizings

THERMOCHEMICAL

- Double the oxygen concentration on the carbon fiber surface as compared to Electrochemical industrial practice
- Very high volume of OH (15%) and COOH (5%) groups and no carbonyl,
- 20% higher short beam shear compared to industrial practice with VE

* Allows for the use of far less fiber in the composite which yields a significant per part cost reduction. 10-20% fiber use reduction possible reducing overall composite part cost. Example: 50% fiber / 50% resin part made of $12/lb CF and $1/lb resin would have $6.50 in material costs. A 20% reduction in fiber use would yield a 40% fiber / 60% resin part which would have $5.40 in material cost.
Critical Pathways for Achieving $5-7/lb Goal

The goal can be accomplished by combining technologies.

Savings from $10.20 baseline. $0.85/lb additional savings available from volume scale-up.

Current Cost Model did not evaluate savings of combining technologies.

- **Precursors**
  - High PE Polyolefins (Savings: $5.65/lb)
  - Polyolefin Blends (Savings: $2.00-$5.00/lb)
  - PAN-VA Textile (Savings: $2.61/lb)
  - Kaltex Textile $2.35
  - Alternative Textile $?.??
  - High Content Lignin (Savings: $2.68-$5.98/lb)
  - Lignin Blends (Savings: 11-25%/lb $1.12-$2.55/lb)
  - Bio-Mimicked Spider $?.??

- **Stabilization & Oxidation**
  - Advanced Oxidative Stabilization (Savings: $2.69 – Mass Throughput Increase)
  - Disassociated Pre-Stretching
  - Conductive Oxidation

- **Carbonization/Graphitization**

- **ST/Sizing**

- **Spooling & Packaging**

- **Multi-Tow Processing**
  - Microwave Assisted Plasma (Savings: $1.31)
  - Alternative Carbonization
  - and/or
    - Interfacial Optimization (Savings: $0.07)*
    - Thermochemical Surface Treatment*
    - Plasma Surface Treatment*

- **VT/AMO Projects**
  - VT Projects
  - AMO Projects
  - Not Current
Integrating Multiple Technologies

Savings from $10.20 baseline. $0.85/lb additional savings available from volume scale-up.

<table>
<thead>
<tr>
<th>CF Manufacturing Costs – Various Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Costs ($/lb)</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>Baseline*</td>
</tr>
<tr>
<td>10.2</td>
</tr>
<tr>
<td>PO*</td>
</tr>
<tr>
<td>8.12</td>
</tr>
<tr>
<td>MAP*</td>
</tr>
<tr>
<td>8.67</td>
</tr>
<tr>
<td>PO + MAP*</td>
</tr>
<tr>
<td>7.19</td>
</tr>
<tr>
<td>T-PAN*</td>
</tr>
<tr>
<td>7.85</td>
</tr>
<tr>
<td>TP + PO*</td>
</tr>
<tr>
<td>7.19</td>
</tr>
<tr>
<td>TP + MAP*</td>
</tr>
<tr>
<td>6.75</td>
</tr>
<tr>
<td>TP + PO + MAP*</td>
</tr>
<tr>
<td>6.19</td>
</tr>
</tbody>
</table>

Note: Results for combined technologies from an Earlier cost Model (circa 2009) but the baseline, PO, MAP and T-PAN numbers were reconfirmed in the 2012 cost model.*

PO – Plasma Oxidation  
T-PAN – Textile PAN  
MAP – Microwave Assisted Plasma Carbonization
Savings from $10.20 baseline. $0.85/lb additional savings available from volume scale-up.

**Current Technology Status**

1. Early Stage Development
2. Initial Integration of Technologies
3. Pre-Production Demonstration
Other Industries have Interest. CF Manufacturers who adopt new technologies will do so only if they can sell into multiple markets with minimal risk.
Carbon Fiber Research Facilities

Precursor & Fiber Evaluation Lab

1:20 speed of a commercial grade production line
Capacity for 1-5 tows, 5000-80,000 filaments
Preferred tow size ≥ 3k

15 in/min
1-2 tows, 20-80,000 filament
Small Volume

Full Speed Line
25 Tons/year Capacity, 3,000 – 620,000 Filaments/Tow
Fully integrated, Multi-format design

Pilot Line

3 Scales of Development Lines
+ Analytical Labs

Carbon Fiber Technology Facility