Future Lower Cost Carbon Fiber for Autos: International Scale-up & What is Needed

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Oak Ridge National Laboratory

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- Nation’s largest energy R&D laboratory
- Nation’s largest concentration of open source materials research
- World-class computing facilities
- Built the $1.2 billion Spallation Neutron Source
- $300 million modernization program in progress
- $1 billion budget
- 4200 employees
- 3000 research guests annually
Office of Energy Efficiency and Renewable Energy

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Light-Duty Vehicle Trends

Adjusted Fuel Economy by Model Year (Three-Year Moving Average)


Weight and Performance by Model Year (Three Year Moving Average)
Key Drivers and Technology Enablers

Product
Annual Model Change
Design Is King

Plant
~300,000 Units/Models

1950
1960
1970
1980
1990
2000

Externalities
“Safety” Focus
“Oil Shock”
“Hyper” Global Competition
Fuel Economy Drives Weight Reduction
Lightweight Material Use Intensifies

Technology Enablers
Increasing Automation
Robots
Lean Mfg.
CAD
CAM
CAE

“Personalized Design and Performance”
Customer Experience

Gas Prices
50,000-100,000 Units/Models
Note: Domestic production includes crude oil, natural gas plant liquids, refinery gain, and other inputs. This is consistent with EIA, MER, Table 3.2. Previous versions of this chart included crude oil and natural gas plant liquids only.
China, with 13 vehicles per 1000 people, is where the U.S. was in 1913.
Materials in a Typical NA Vehicle

- 1906
- 1912
- 1977
- Today
- Future

- Other
- Magnesium
- Aluminum
- Polymer/Composite
- Wood
- Hi/Med Strength Steel
- Low-Carbon Ferrous
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.
1978 Ford LTD

$1M Demonstration Vehicle
Composites in the Automotive Industry

**Ford GT**

- Carbon fiber rear deck lid and seat (4500 units total)

**2006 Z06 Corvette**

Carbon fiber fenders, wheel house, and floorpan (7000 units/year)

**2006 Dodge Viper**

- Carbon fiber LH/RH fender/sill supports, LH/RH door inner reinforcements, windshield surround reinforcement (2000 units/year)
Composites in the Automotive Industry

2005 Mercedes Benz SLR McLaren

Carbon fiber intensive (500 units/year)

BMW M3 CSL

Carbon fiber roof (3000 units/year)

Aston Martin Vanquish

Carbon fiber composite transmission tunnel, braided A-pillar, front end crash structure (400-800 units/year)
Carbon Fiber Demand and Supply

Carbon Fiber Supply and Demand

- **End of the Cold War** 1998
- **2005 Commercial Aircraft build up by Boeing 787 & Airbus A380 & A350**

Source: Cliff Eberle, ORNL and Mohamed Abdullah, MGA Consultants
Carbon Fiber Capacity

North American Vehicle Production > 16 / year
12 pounds of Carbon Fiber per Vehicle: 192M lb/year

2X World Capacity

Carbon Fiber Market History

<table>
<thead>
<tr>
<th>Year</th>
<th>Million Lb/Yr</th>
<th>Demand</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>55</td>
<td></td>
<td></td>
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<tr>
<td>2000</td>
<td>70</td>
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<tr>
<td>2001</td>
<td>80</td>
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<tr>
<td>2002</td>
<td>90</td>
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<tr>
<td>2003</td>
<td>100</td>
<td></td>
<td></td>
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<tr>
<td>2004</td>
<td>110</td>
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<td></td>
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<tr>
<td>2005</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>150</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sources:
- High performance Composites Magazine
- CEH Marketing Research Report: Carbon Fibers, SRI Consulting
- The Market Perspective for PAN-Based Carbon Fiber 1999 - 2005 Kline& Company
Current Carbon Fiber Raw Materials are Tied to Oil
Projected Carbon Fiber Market Demand

The Growth and Challenges are Multi-Industry

90MM lbs Carbon Fiber Produced in 2007

Source: Zoltek Annual Report, February 2007

700% Growth in Next Decade
Carbon fiber is a leading candidate for mass reduction.
- 10% Mass Savings = 6-7% Fuel Savings
- Mass reduction allows earlier introduction of alternative propulsion systems.

Price too high for medium to large volumes.
Supplies are insufficient.
Processing technologies undeveloped.
Longer blade design requires use of CF.
- Energy captured is greater with longer blades
- Blades must be both stiff and light.

Insufficient volume of CF at any price.
Lower price needed for more efficient designs.

(Needed now for rapid deployment)
In deeper waters strength/weight and stiffness/weight becomes critical. Pipes, drill shafts and other structures must support their own weight while being constructed.

Carbon fiber could replace steel with Equivalent stiffness - similar “packing factor” of reinforcement
• Increased strength - higher tension permissible
• Low (slightly negative) CTE - less sag compensation needed for low temps
• Reduced weight (~94 lbs vs 344 lbs) - more conductor for equivalent sag

Need ready supply of materials at volume pricing and development of materials and processing technologies.
Strength to weight demands CF for pressurized H2 storage. Could make more compact NG storage with higher pressures. Cost of fiber makes designs prohibitively expensive.

Cost of fiber makes Designs prohibitively expensive. Insufficient volume of CF available.

40 - 80% is carbon fiber cost
Retrofit and new construction in days rather than months. Large structures fabricated in plants rather than on site. High demand for rebar.

Need standard materials.
Standard construction processes.
Affordable materials.
Steady supply of materials.
Rapid Repair
Strong History in Aerospace
Needed for lightweight portable ground and sea systems.
Affordable materials for rapid deployment of ground systems.
non-flying equipment.
Bio-Fuel Refining

1. Oil refinery profitability is in making fuel AND other products from input material.
2. Virtually all input Crude is turned into a value-added product.
3. To be economically viable, a bio-refinery will have to operate in much the same manner.

Lignin Based Carbon Fiber may be one Value-Added Product to make Bio-Refineries economically Attractive

<table>
<thead>
<tr>
<th>Product</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquified Refinery Gases</td>
<td>209.0</td>
<td>229.0</td>
</tr>
<tr>
<td>Motor Gasoline</td>
<td>2225.4</td>
<td>1964.4</td>
</tr>
<tr>
<td>Aviation</td>
<td>570.4</td>
<td>546.7</td>
</tr>
<tr>
<td>Kerosene</td>
<td>23.9</td>
<td>17.3</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>1672.4</td>
<td>1706.6</td>
</tr>
<tr>
<td>Petrochemical Feedstocks</td>
<td>141.9</td>
<td>143.9</td>
</tr>
<tr>
<td>Lubricants</td>
<td>61.2</td>
<td>66.8</td>
</tr>
<tr>
<td>Waxes</td>
<td>5.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>304.7</td>
<td>309.4</td>
</tr>
<tr>
<td>Asphalt and Road Oil</td>
<td>186.7</td>
<td>184.7</td>
</tr>
<tr>
<td>Still Gas</td>
<td>249.5</td>
<td>258.9</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>21.4</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Source: Energy Information Administration
Common Issues and Needs

Civil Infrastructure
- Rapid Repair and Installation, Time and Cost Savings

Power Transmission
- Less Bulky Structures
- Zero CLTE

Bio-Mass Materials
- Alternative Revenue
- Waste Minimization

Fiber Cost
- Fiber Availability
- Design Methods
- Manufacturing Methods
- Product Forms

Oil and Gas
- Offshore Structural Components

Vehicle Technologies
- Necessary for 50+% Mass Reduction

Wind Energy
- Needed for Longer Blade Designs

Hydrogen Storage
- Only Material With Sufficient Strength/Weight

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- Only Material With Sufficient Strength/Weight
If the Demand is so Great, Why Don’t we see more applications in Automotive and other Industries?

#1 Reason

But there are other Reasons
Designers are not comfortable with composites, especially in Crash critical applications. Full system & subsystem demonstration needed.

Many composite processing methods are optimized for performance not production rate efficiency. Cost optimization of production methods needed.
Capital investment already sunk into metal forming equipment. Must be ready for the next generation.

Size of the carbon fiber industry cannot support large scale utilization. Must choose applications and ramp up capacity.

Boom or bust nature of the market. Automotive industry needs long term pricing and stable long term partners.

The secret art of sizing. Collaborative development efforts are needed.

The lack of resin targeted systems. Need sizings optimized for specific classes of resins that are of interest to the automotive companies.
## Companies with US Facilities

<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</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</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>Mitsubishi (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

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**Universities with significant research in Carbon Fiber production**

Clemson University  
University of Kentucky  
Virginia Tech  

Note: Large efforts in carbon fiber composite development and many laboratories and universities.
• Aircraft orders straining Capacity Worldwide – Boeing (787), Airbus (380)

• Current Carbon Fiber manufacturers replicating Capacity. Announcements from all manufacturers regarding expanded capacity.

• Japanese moving into automotive by vertically integrating into Tier I supply chain. Announcements made by large teams from fiber supplier through OEMs.

• Attempts to entice development of capacity in Middle East in at least 2 different countries.

• EU developing automotive, infrastructure & wind applications but only with existing business models for fiber production.

• UB Koltrefjar ehf in Iceland investigating the development of a carbon fiber plant to be located there due to the reduced cost of energy and potential homeland applications.
- Chinese quietly developing a 40 Million lb/year plant for industrial grade fiber
  - Claimed applications are wind, power transmission and automotive

- Russia, China and Japan have increase R&D efforts significantly

- United States – Expanded interest on all fronts
  - Strong interest from end user communities
  - Growing interest from potential new carbon fiber producers
  - R&D for Carbon Fiber Production focused on high volume
# Carbon Fiber Industry

## To Rapidly Expand the Carbon Fiber Industry

<table>
<thead>
<tr>
<th>Carbon Fiber Obstacles to High Volume, Affordable Supplies</th>
<th>What can be done?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry Age &lt; 50 years</td>
<td>Accelerate Learning Curve</td>
</tr>
<tr>
<td>Limited Precursors – Pitch, PAN, Rayon</td>
<td>Develop Lower Cost Precursors</td>
</tr>
<tr>
<td>Aerospace Mind-Set – High Margin, Low Volume</td>
<td>Develop New Applications</td>
</tr>
<tr>
<td>Limited Technical Advances</td>
<td>Investment by High Vol Industry</td>
</tr>
<tr>
<td>Prohibition against process changes</td>
<td>Involve other R&amp;D Organizations</td>
</tr>
<tr>
<td>Bound to epoxy chemistry</td>
<td>Develop New Processing Methods</td>
</tr>
<tr>
<td>Small Industry and Company Size – 100M lb/yr</td>
<td>Develop Non-Epoxy Chemistry</td>
</tr>
<tr>
<td>Limited resources</td>
<td>Large Manufacturers Enter the Market</td>
</tr>
<tr>
<td>Specialty material mentality</td>
<td>Invest in high volume plants</td>
</tr>
<tr>
<td>Few Scientists (handful worldwide)</td>
<td>Develop commodity mat’l forms</td>
</tr>
<tr>
<td>Limited Research Community</td>
<td>Industry Standards</td>
</tr>
<tr>
<td></td>
<td>Bring together toward 1 Goal</td>
</tr>
<tr>
<td></td>
<td>Sponsor graduate degrees in US</td>
</tr>
</tbody>
</table>
To Rapidly Expand the Carbon Fiber Industry

1. Develop a multiple End Use sector approach.

2. Large investment in NEW production methods required.


4. Product forms amenable to High Volume industries needed.

5. Development of a larger EXPERT base required.

6. Industry Standards
#1 Priority
$5 - $7 Per Pound
$11 - $15.50 Per Kilogram

Strength: ≥ 250 Ksi (1.73 GPa)
Modulus: ≥ 25 Msi (173 GPa)
Strain: ≥ 1%

[Walsh, Zoltek 8/2000]
All time low $5.25/lbs std grade (mid-grade) 2003
Thermal reduction of a limited number of precursors by pyrolysis of all but the carbon followed by heat treatment of the carbon to obtain desired structure.

Are these the only materials and the only way?

*Historically: No cost driver for lower cost. Only better Performance.*
Carbon Fiber Costs
(Production Costs)

Baseline $9-10/lb

- Precursor: $2.32 (18%)
- Surface Treatment: $0.37 (9%)
- Stabilization & Oxidation: $1.54 (12%)
- Spooling & Packaging: $0.61 (10%)
- Textile: $0.33 (9%)
- HK Lignin: $1.48 (12%)
- SK Lignin: $0.99 (9%)
- Depreciation: $0.61 (18%)
- Utilities: $0.37 (9%)
- Other fixed: $0.33 (9%)

Effect of Large Volume and Alternate Precursors

- Baseline Today: $9.88
- High Volume: $7.85
- HK Lignin: $5.04
- SK Lignin: $4.64

Cost versus Volume for Conventional Technology
3 Precursor Options
1. Textile Grade PAN (MA or VA formulations)
2. Lignin Based Precursor (Hardwood or Softwood)
3. Polyolefins (not shown on charts)

Other Important Precursor Technologies:
1. Melt-Spun PAN
2. Scaling to Pilot Plant
3. Cost Studies
3 Processing Options
1. Advanced Stabilization
2. Plasma Oxidation
3. MAP Carbonization

Other Important Processing Technologies:
1. Tow Splitting
2. On-line Feedback
3. Scaling to Pilot Plant
4. Development of carbon fiber SMC
5. Plasma Modification of Surfaces
6. Cost Studies

Carbon Fiber Costs (Production Costs)
Program Integration

Precursor Production

Baseline

Options

Textile Grade PAN
$2.33

or

Hardwood Kraft Lignin
$2.07

or

Softwood Kraft Lignin
$1.73

Processing Precursor to Fiber

Conventional Thermal

Oxidation
$1.34

Carbonization
$1.00

Graphitization
$1.19

ST
$0.82

Advanced Stabilization
and
Plasma Oxidation

and/or

Microwave-Assisted
Plasma

MAP
$1.34
Lignin Precursors

Future Biorefinery

Thermo-chemical enzymatic hydrolysis, hybrid systems

Cellulose and Hemi-cellulose

Ethanol at $1.07/gal

Lignin energy value: about $60/ton

Other value-added products

PAN $3.53 (44.8%)
Oxidation $1.34 (17.0%)
Carbonization $1.00 (12.7%)
Graphitization $1.19 (15.1%)
ST $0.82 (10%)

FCVT Low-cost Carbon Fiber R&D

Low-cost Carbon Fiber Target

Melt Spinning, and Thermal Processing, etc.

ITP R&D
OBP R&D
OFCVT R&D

Washed Hardwood Kraft Lignin Lignin content (%)
100% 95% 87.5% 75%

What is this cost?

= $5-7/lb
• Demonstrated that solvent-extracted, purified hardwood lignin (provided by MeadWestvaco) can be continuously melt-spun into fiber form

• Successfully Spun 12 filament tows with no additives and no problems using lignin from MeadWestvaco’s “Organosolv” process

• Lignin fiber diameters were successfully varied under controlled conditions from 20 down to 10 microns.
Achieved Excellent Structural Characteristics in Melt Spun Lignin Fiber:

12-filament fiber spun from solvent-extracted hardwood lignin (HWL-SE1)
Processed carbon fibers from a Hardwood/Softwood lignin blend.

A Hardwood lignin was used as the plasticizer for the softwood lignin.
**Chemical Modification** of textile acrylic fibers reduces stabilization time and increases CF mechanical properties.

Established recommended “recipes” to produce carbon fiber from chemically modified or radiated commodity textile acrylic tow

Reduced Oxidation time from 85 min down to 50 minutes

Data from Hexcel Development Project

<table>
<thead>
<tr>
<th></th>
<th>TEXTILE</th>
<th>CONVENTIONAL</th>
<th>Program Goals GPA</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Spool 1</td>
<td>Spool 2</td>
<td>Zoltek Panex 33</td>
</tr>
<tr>
<td>Production Line Speed (in/min)</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>212</td>
<td>208</td>
<td>180</td>
</tr>
<tr>
<td>Ultimate Strength (GPa)</td>
<td>2.75</td>
<td>2.71</td>
<td>2.81</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>1.30</td>
<td>1.30</td>
<td>1.56</td>
</tr>
</tbody>
</table>

**Project Impact**

- PAN $3.53 (44.8%)
- Oxidation $1.34 (17.0%)
- Carbonization $1.00 (12.7%)
- Graphitization $1.19 (15.1%)
- ST $0.82 (10%)
Steepest part of slope determines speed of stabilization. Location of ramp up start & peak determine oxidative stabilization temp range.

Chemically treated textile could be undergo oxidative stabilization in less time but a slightly higher temperature.
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

Slightly Modified versions of polymer selected

Gathering during Crimping will Be Deleted

Chemical Pretreatment
Current Properties:

- Strength: 2.41 GPA (350 ± 27 KSI)
- Modulus: 218 GPA (31.7 ± 1.0 MSI)

Target Properties:

- Strength: 1.72 GPA (250 KSI)
- Modulus: 172 GPA (25 MSI)

Textile Precursors

- PAN: $3.53 (44.8%)
- Oxidation: $1.34 (17.0%)
- Carbonization: $1.00 (12.7%)
- Graphitization: $1.19 (15.1%)
- ST: $0.82 (10%)
Transforms PAN from a thermoplastic linear polymer structure to an infusible, highly condensed cyclized structure (thermoset) capable of further processing at high temperatures

- Conducted in an oxidizing medium (e.g., air) at ~ 200 - 250°C
Oxidative Stabilization

Oxidative Stabilization represents 75-80% of fiber residence time and 18-20% of cost.

Project Impact

<table>
<thead>
<tr>
<th></th>
<th>Oxidation</th>
<th>Carbonization</th>
<th>Graphitization</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAN</td>
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<td>Oxidation</td>
<td>$1.34 (17.0%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Oxygen needs to diffuse through the stabilized “skin”

Mainly stabilized region

Stabilized and oxidized region

Before stretching. Right: Entry end of 1st oxidation oven.
Acid Digestion Removes Unstabilized Material

Poorly Stabilized but Typical for Many Lower Cost Fibers

Project Impact

- PAN: $3.53 (44.8%)
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Two Early Generation Oxidation Modules

Proprietary Oxidation Process Developed based on Non-Thermal Atmospheric Plasma

Process able to replace later 3/4 of conventional oxidation but requires the use of slightly pre-stabilized precursor.

Effort began to develop a rapid Pre-Stabilization Technique

Project Impact

<table>
<thead>
<tr>
<th>Process</th>
<th>Cost (Total %)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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</table>
Oxidative Stabilization

- Objective is to stabilize (cross-link) the precursor sufficiently that it can subsequently be plasma oxidized
- Needs to be fast (high throughput) and Inexpensive (<$0.05/lb)
- Three routes investigated

<table>
<thead>
<tr>
<th>Stabilization Method</th>
<th>Time ReQ’d</th>
<th>Thermal Post Treatment</th>
<th>Plasma Oxidation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A E-Beam</td>
<td>Secs</td>
<td>20-26 min</td>
<td>20-24 min</td>
<td>40-50 min</td>
</tr>
<tr>
<td>B ultraviolet</td>
<td>6-7 min</td>
<td>None</td>
<td>20-24 min</td>
<td>26-31 min</td>
</tr>
<tr>
<td>C Thermo-Chemical</td>
<td>5-10 min</td>
<td>None</td>
<td>20-24 min</td>
<td>25-34 min</td>
</tr>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td>100-120 min</td>
</tr>
</tbody>
</table>

A Post Treatment believed to be due to over processing. Potentially may be eliminated.
B 6-7 minutes would require a huge amount of lamps at textile line speeds.
C By far the easiest to implement in existing plants

Down Select – Thermochemical (E-Beam)

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</tbody>
</table>
VFME was discarded as primary energy source for this process.

Single frequency microwave energy became a major player.

Hand processed samples

**Generation A**

**Generation B**

Microwave direct heating of carbon fiber using a long, tunable, resonant cavity.

Capability to monitor fiber temperature.

Pre-heating of fiber with nitrogen/air to enhance microwave coupling.

Line speed 2-4 inches/minute.

---

**Project Impact**

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Project paused While other Technologies Catch-up

- Produced fibers for ACC testing
- Ran 3 large tows at 44in/min for > 1 hr in August 2006 with satisfactory mechanical properties

### Fiber Modulus
- Fiber Type: Fortafil, Zoltek, MAP 1@35, MAP 1@110, MAP 1@160, MAP 3@12
- Design Basis: 3 std dev
- Data from ORNL mechanical tests

### Fiber Ultimate Strain
- UTS, ksi
- Design Basis: 3 std dev
- Data from ORNL mechanical tests

### Fiber Ultimate Strength
- UTS, ksi
- Design Basis: 3 std dev
- Data from ORNL mechanical tests

#### Project Impact
- PAN: $3.53 (44.8%)
- Oxidation: $1.34 (17.0%)
- Carbonization: $1.00 (12.7%)
- Graphitization: $1.19 (15.1%)
- ST: $0.82 (10%)
• Fiber surface chemistry, due mainly to treatment and sizing, is important to adhesion-sensitive mechanical properties
  – Oxygen concentration on fiber surface is very important

• Preliminary ORNL plasma surface treatment results far superior to conventional treatment results

<table>
<thead>
<tr>
<th>Condition</th>
<th>O</th>
<th>O/C</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated commercial fiber</td>
<td>4.7%</td>
<td>0.051</td>
<td>0.21</td>
</tr>
<tr>
<td>O$_3$ treated commercial fiber</td>
<td>6.2%</td>
<td>0.069</td>
<td>0.26</td>
</tr>
<tr>
<td>AP-A</td>
<td>24%</td>
<td>0.42</td>
<td>0.38</td>
</tr>
<tr>
<td>AP-B</td>
<td>30%</td>
<td>0.55</td>
<td>0.22</td>
</tr>
<tr>
<td>AP-C</td>
<td>29%</td>
<td>0.52</td>
<td>0.40</td>
</tr>
<tr>
<td>AP-D</td>
<td>21%</td>
<td>0.35</td>
<td>0.80</td>
</tr>
<tr>
<td>AP-E</td>
<td>28%</td>
<td>0.54</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Data from XPS analysis

Project Impact

- PAN
  - $3.53 (44.8%)
- Oxidation
  - $1.34 (17.0%)
- Carbonization
  - $1.00 (12.7%)
- Graphitization
  - $1.19 (15.1%)
- ST
  - $0.82 (10%)
Pitch:

Isotropic Liquid Pitch → Liquid Crystals (mesophase)

PAN:

\[
\begin{align*}
\text{C} & \equiv \text{N} \\
\text{H} & \quad \text{H} \\
\text{C} & \equiv \text{N}
\end{align*}
\]

PE:

\[
\begin{align*}
\text{C} & \quad \text{C} \\
\text{H} & \quad \text{H} \\
\text{C} & \quad \text{C} \\
\text{H} & \quad \text{H}
\end{align*}
\]

63% C Content
48-49% Yield
Mono: $2150/MT
$1.09/lb
$1.31 - $2.43/lb
Solution Spun

86% C Content
65-75% Yield
Fiber: $0.50-$0.75/lb
Melt Spun
Thank You