

# Carbon Fiber

## Table of Contents

A Report by Nexant's CHEMSYSTEMS  
Process Evaluation/Research Planning (PERP) Program  
PERP 2011S9 - Published May 2012

[www.chemsystems.com](http://www.chemsystems.com)

Section	Page
<b>1 Executive Summary</b> .....	1
1.1 TECHNOLOGY .....	1
1.2 CARBON FIBER COST OF PRODUCTION .....	1
1.3 COMMERCIAL MARKET.....	2
<b>2 Introduction</b> .....	3
2.1 STRUCTURE OF CARBON FIBER .....	3
2.2 KEY PROPERTIES OF CARBON FIBER.....	6
2.2.1 Tensile Strength .....	6
2.2.2 Fatigue Resistance .....	7
2.2.3 Tensile Modulus of Elasticity (Young's Modulus) .....	8
2.2.4 Thermal Conductivity .....	8
2.2.5 Coefficient of Thermal Expansion.....	9
2.2.6 Electrical Conductivity .....	9
2.3 CLASSIFICATION OF CARBON FIBER .....	10
2.3.1 Precursor .....	10
2.3.2 Mechanical Properties.....	13
2.3.3 Tow Size .....	13
2.4 OVERVIEW OF CARBON FIBER PRODUCTION TECHNOLOGY .....	14
2.5 CARBON FIBER PRODUCERS AND TECHNOLOGY LICENSING STATUS .....	16
2.5.1 History.....	16
2.5.2 Licensing and Technology Development .....	17
2.6 HEALTH HAZARDS, STORAGE, AND TRANSPORTATION.....	19
<b>3 Carbon Fiber Production Technologies</b> .....	20
3.1 POLYACRYLONITRILE (PAN)-BASED PROCESS.....	20

3.1.1	PAN Precursor Preparation.....	20
3.1.2	Stabilization .....	23
3.1.3	Carbonization.....	26
3.1.4	Ultrahigh Temperature Treatment .....	28
3.1.5	Surface Treatment.....	29
3.1.6	Sizing .....	29
3.1.7	Take-Up Winding .....	30
3.1.8	Off Gas Processing .....	30
3.1.9	Risks in Commercial PAN- CF Production Process.....	30
3.2	PITCH-BASED PROCESS .....	31
3.2.1	Precursor Preparation.....	33
3.2.2	Melt Spinning.....	36
3.2.3	Stabilization .....	36
3.2.4	Carbonization.....	37
3.2.5	Ultrahigh Temperature Treatment (Graphitization).....	37
3.2.6	Surface Treatment.....	38
3.2.7	Sizing and Take-Up Winding .....	38
3.3	RAYON-BASED PROCESS.....	39
3.3.1	Fiber Preparation.....	39
3.3.2	Stabilization .....	39
3.3.3	Carbonization.....	40
3.3.4	Ultrahigh Temperature Treatment .....	40
3.3.5	Surface Treatment, Sizing, and Winding.....	40
<b>4</b>	<b>Research and Development.....</b>	<b>41</b>
4.1	HARPER INTERNATIONAL (U.S.).....	41
4.1.1	New Developments.....	42
4.1.2	Revamps and Process Optimizations .....	43
4.1.3	Assistance in Developing In-House Carbon Fiber Technology .....	43
4.2	HEXCEL (U.S.).....	43
4.3	INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE (TAIWAN).....	44
4.4	MITSUBISHI RAYON (JAPAN) .....	44
4.4.1	Textile Grade Precursor .....	44

4.4.2	Use of Substituted PAN Precursor to Improve Stabilization Rate .....	44
4.5	OAK RIDGE NATIONAL LABORATORY (U.S.).....	44
4.5.1	FreedomCAR Program .....	45
4.5.2	Lignin-based Carbon Fiber .....	45
4.6	TORAY INDUSTRIES (JAPAN) .....	47
4.6.1	Experimenting with Precursor to Improve Compressive Strength .....	47
4.6.2	Process to Improve Fiber Quality .....	47
4.7	ZOLTEK .....	47
4.8	OTHER .....	48
4.8.1	Post-Spinning Technology.....	48
4.8.2	Coatings .....	48
4.8.3	Catalytic Modification .....	48
4.8.4	PAN Fiber Stretching.....	49
4.8.5	Pyrolysis of PAN Fibers .....	49
<b>5</b>	<b>Downstream Operations</b> .....	<b>51</b>
5.1	FIBER ARCHITECTURE.....	52
5.1.1	Staple Fiber .....	52
5.1.2	Unidirectional .....	53
5.1.3	Two-Dimensional (Planar).....	54
5.1.4	Three Dimensional (3-D).....	59
5.1.5	Summary Comparison of Fiber Structures .....	61
5.2	MATRIX MATERIALS (BINDERS) .....	61
5.2.1	Polymer Resins .....	61
5.2.2	Carbon.....	64
5.2.3	Metals.....	64
5.2.4	Ceramics .....	65
5.3	VALUE CHAIN .....	66
<b>6</b>	<b>Process Economics</b> .....	<b>67</b>
6.1	COSTING BASIS .....	67
6.1.1	Investment Basis .....	67
6.1.2	Pricing Basis .....	67
6.1.3	Cost of Production Basis.....	68

6.2	COST OF PRODUCING CARBON FIBER FROM POLYACRYLONITRILE (PAN) .....	70
6.2.1	Regional Cost of Production Estimates for PAN-based Carbon Fiber (China, Japan, North-West Europe, USGC).....	73
6.3	COST OF PRODUCING CARBON FIBER FROM MESOPHASE PETROLEUM PITCH .....	75
6.3.1	Regional Cost of Production Estimates for Mesophase Pitch-based Carbon Fiber (China, Japan, North-West Europe, USGC).....	78
6.4	SENSITIVITY ANALYSES .....	79
6.4.1	Sensitivity of PAN-based Carbon Fiber Cost of Production to Acrylonitrile Price (USGC basis) .....	79
6.4.2	Sensitivity of Cost of Production to Plant Scale.....	80
6.4.3	Sensitivity of PAN-based Carbon Fiber Cost of Production to Total Project Investment Cost.....	82
6.5	CONCLUDING REMARKS.....	82
<b>7</b>	<b>Commercial Applications</b> .....	<b>86</b>
7.1	OVERVIEW .....	86
7.1.1	Pitch versus PAN .....	87
7.1.2	Small versus Large Tow .....	88
7.1.3	Staple versus Continuous Fiber .....	89
7.1.4	Main Forms and Applications.....	89
7.1.5	Properties and Applications .....	90
7.2	AEROSPACE AND MILITARY .....	91
7.2.1	Civilian Air Transportation.....	91
7.2.2	Military .....	91
7.2.3	Space .....	92
7.3	CONSUMER GOODS.....	93
7.3.1	Sports and Leisure.....	93
7.3.2	Other Consumer Goods.....	94
7.4	INDUSTRIAL.....	94
7.4.1	Wind Energy .....	94
7.4.2	Ground Transportation.....	94
7.4.3	Civil Engineering Works (Construction).....	97
7.4.4	Pressure Vessels.....	97
7.4.5	Oil and Gas .....	97

7.4.6	Medical .....	97
7.4.7	Other Industrial .....	98
<b>8</b>	<b>Market Analysis</b> .....	<b>100</b>
8.1	GLOBAL OVERVIEW .....	100
8.1.1	Carbon Fiber Recycling .....	100
8.1.2	Global Demand .....	101
8.1.3	Global Supply .....	102
8.1.4	Global Supply and Demand.....	105
8.1.5	Global Trade .....	106
8.2	NORTH AMERICA .....	107
8.3	EUROPE .....	108
8.4	ASIA .....	109
8.5	REST OF THE WORLD .....	111
<b>9</b>	<b>Overview of Strategic/Business Considerations</b> .....	<b>113</b>
<b>10</b>	<b>Glossary</b> .....	<b>115</b>
<b>11</b>	<b>References</b> .....	<b>120</b>
	<b>Appendix</b>	<b>Page</b>
<b>A</b>	<b>Polyacrylonitrile (PAN) Cost of Production Estimate</b> .....	<b>A-1</b>
<b>B</b>	<b>Capital Cost Terms Used in Process Economics Defined</b> .....	<b>B-1</b>
<b>C</b>	<b>Operating Cost Terms Used in Process Economics Defined</b> .....	<b>C-1</b>
<b>D</b>	<b>PERP Program Title Index (2000/2001 - 2011)</b> .....	<b>D-1</b>

Figure	Page
2.1 Carbon Fiber Lattice Structure.....	4
2.2 A Single Filament of Carbon Fiber.....	5
2.3 Example of a Carbon Fiber Tow.....	14
3.1 Carbon Fiber Production from Polyacrylonitrile (PAN) .....	24
3.2 PAN Oxidation Chemistry .....	25
3.3 Carbonization Chemistry .....	26
3.4 Carbonization Chemistry .....	27
3.5 Petroleum Pitch.....	31
3.6 Coal Tar Pitch .....	31
3.7 Petroleum-Derived Mesophase Pitch.....	32
3.8 Carbon Fiber Production via Mesophase Pitch.....	34
4.1 Experimental Setup of Carbonization under imposed Magnetic Field.....	50
5.1 Carbon Fiber Architecture .....	52
5.2 Example of a Carbon Fiber Weave Pattern.....	54
5.3 Plain Weave .....	55
5.4 5-Harness Satin Weave .....	55
5.5 Triaxial Weave.....	56
5.6 Weft-Knitted Fabric .....	56
5.7 Warp-Knitted Fabric .....	57
5.8 Flat Braid .....	57
5.9 Biaxial Braid.....	58
5.10 3-D Autoweave .....	59
5.11 3-D Cylindrical Weave .....	59
5.12 3-D Orthogonal Interlock Weave.....	60
5.13 3-D Through-The-Thickness Braid.....	60
5.14 Carbon Fiber Value Chain .....	66
6.1 Variation of PAN-based Carbon Fiber Production Cost with Price of Acrylonitrile.....	79
6.2 Variation of Production Cost of Carbon Fiber with Plant Scale.....	80
6.3 Variation of Production Cost of Carbon Fiber with PAN Plant Scale.....	81
6.4 Variation of PAN-based Carbon Fiber Production Cost with Project Investment Cost .....	82
7.1 Global Carbon Fibers End-Uses .....	86

8.1 Carbon Fiber Consumption by Region .....	100
8.2 Carbon Fiber Main Players .....	103
8.3 Carbon Fiber Name Plate Capacity Distribution by Region.....	104

Table	Page
2.1 Mechanical Properties of Typical Grades of Carbon Fiber .....	6
2.2 Specific Tensile Strength Compared .....	7
2.3 Specific Modulus of Elasticity Compared .....	8
2.4 Thermal Conductivity Compared .....	9
2.5 Typical Properties of High Strength PAN-based Carbon Fibers .....	10
2.6 Typical Properties of Pitch-based Carbon Fibers .....	12
2.7 Typical Properties of Rayon-based Carbon Fibers .....	12
2.8 Carbon Fiber Producers .....	18
5.1 Comparison of Selected Fiber Structures .....	61
5.2 Overview of Selected Fabrication Technologies for Carbon Fiber Reinforced Thermoset Matrix Composites.....	63
6.1 Prices of Raw Materials, Products, Utilities and Labor.....	68
6.2 List of Major Equipment used in PAN-based Carbon Fiber Production .....	71
6.3 Cost of Production Estimate for: Carbon Fiber Process: PAN Stabilization, Carbonization, Surface Treatment, Sizing, Winding .....	72
6.4 PAN-based Carbon Fiber Regional Cost of Production Estimates.....	73
6.5 List of Major Equipment used in Mesophase Pitch-based Carbon Fiber Production.....	76
6.6 Cost of Production Estimate for: Carbon Fiber Process: Pitch Preparation (Mesophase), Stabilization, Carbonization, Graphitization, Surface Treatment, Sizing, Winding .....	77
6.7 Mesophase Pitch-based Carbon Fiber Regional Cost of Production Estimates .....	78
6.8 Comparison of PAN and Pitch-based Carbon Fiber .....	83
7.1 Main Forms of Carbon Fiber and Properties/Application .....	90
7.2 Carbon Fiber Properties and Examples of Applications.....	90
8.1 Global Carbon Fiber Demand by Segment.....	102
8.2 Firm Capacity Additions.....	105
8.3 Speculative Capacity Additions.....	105
8.4 Global Carbon Fiber Supply, Demand, and Trade .....	106
8.5 North America Carbon Fiber Capacity .....	107
8.6 North America Carbon Fiber Supply, Demand, and Trade .....	108
8.7 Europe Carbon Fiber Capacity.....	108
8.8 Europe Carbon Fiber Supply, Demand, and Trade.....	109
8.9 Asia Carbon Fiber Capacity.....	110

---

8.10 Asia Carbon Fiber Supply, Demand, and Trade .....	111
8.11 Middle East Carbon Fiber Capacity.....	111
8.12 Rest of the World Carbon Fiber Supply, Demand, and Trade.....	112
9.1 Summary of Advantageous/Limiting Factors .....	114

# CHEMSYSTEMS

## PERP PROGRAM



[www.chemsystems.com](http://www.chemsystems.com)

The ChemSystems Process Evaluation/Research Planning (PERP) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. PERP reports are available as a subscription program or on a single report basis.

### Contact Details:

**London:** Dr. Alexander Coker, Manager, PERP Program  
Phone: + 44-(20)-7950-1570, e-mail: [acoker@nexant.com](mailto:acoker@nexant.com)

**New York:** Heidi Junker Coleman, Global Programs Support Manager  
Phone: + 1-914-609-0381, e-mail: [hcoleman@nexant.com](mailto:hcoleman@nexant.com)

**Shanghai:** Dr. Y. Larry Song, General Manager, Nexant China  
Phone: +86 21 6182 6791, e-mail: [ylsong@nexant.com](mailto:ylsong@nexant.com)

Nexant, Inc. ([www.nexant.com](http://www.nexant.com)) is a leading management consultancy to the global energy, chemical, and related industries. For over 38 years, ChemSystems has helped clients increase business value through assistance in all aspects of business strategy, including business intelligence, project feasibility and implementation, operational improvement, portfolio planning, and growth through M&A activities. Nexant has its main offices in San Francisco (California), White Plains (New York), and London (UK), and satellite offices worldwide.

Copyright © by Nexant Inc. 2012. All Rights Reserved.