

# ADVANCED STRUCTURAL CARBON PRODUCTS: FIBERS, FOAMS & COMPOSITES



**AVM038F**  
**January 2016**

Andrew McWilliams  
***Project Analyst***

ISBN: 1-62296-195-1



**BCC Research**  
**49 Walnut Park, Building 2**  
**Wellesley, MA 02481 USA**  
**866-285-7215 (toll-free within the USA),**  
**or (+1) 781-489-7301**  
**[www.bccresearch.com](http://www.bccresearch.com)**  
**[information@bccresearch.com](mailto:information@bccresearch.com)**

## TABLE OF CONTENTS

TOPIC	PAGE NO.
CHAPTER 1 INTRODUCTION	2
STUDY GOALS AND OBJECTIVES	2
REASONS FOR DOING THE STUDY	2
INTENDED AUDIENCE	2
SCOPE OF REPORT	3
METHODOLOGY AND INFORMATION SOURCES	3
ANALYST'S CREDENTIALS	4
RELATED BCC RESEARCH REPORTS	4
BCC RESEARCH WEBSITE	5
DISCLAIMER	5
CHAPTER 2 SUMMARY	7
<i>SUMMARY TABLE U.S. MARKET FOR ADVANCED STRUCTURAL CARBON PRODUCTS BY USER SEGMENT, THROUGH 2020 (\$ MILLIONS)</i>	7
<i>SUMMARY FIGURE U.S. MARKET FOR ADVANCED STRUCTURAL CARBON PRODUCTS BY USER SEGMENT, 2014-2020 (\$ MILLIONS)</i>	7
CHAPTER 3 INDUSTRY AND MARKETS OVERVIEW	10
UNITED STATES MARKET	10
<i>FIGURE 1 U.S. MARKET FOR ADVANCED STRUCTURAL CARBONS BY TYPE, 2014 (%)</i>	10
<i>FIGURE 2 PROJECTED GROWTH RATE IN U.S. STRUCTURAL CARBONS MARKET, 2014-2020 (CAGR%)</i>	11
GLOBAL MARKETS	12
<i>FIGURE 3 GLOBAL ADVANCED STRUCTURAL CARBON PRODUCTS MARKET BY TYPE, 2014 (%)</i>	12
<i>FIGURE 4 GLOBAL STRUCTURAL CARBON PRODUCTS MARKET SHARE BY REGION, 2014 (%)</i>	12
RESEARCH AND TECHNOLOGY TRENDS	13
INDUSTRY STRUCTURE	14
CHAPTER 4 TECHNICAL OVERVIEW	17
INTRODUCTION TO ADVANCED STRUCTURAL CARBON PRODUCTS	17
IMPORTANCE OF MECHANICAL PROPERTIES	17
CARBON FIBERS	17
RAW MATERIALS FOR CARBON FIBERS	18
Types of Raw Materials	18
Rayon	19
PAN	19
Pitch	19
Raw Material and Fiber Properties Relationship	20
<i>TABLE 1 DEPENDENCE OF CARBON FIBER PROPERTIES ON RAW MATERIALS</i>	20
PAN-Based Fibers	20
Pitch-Based Fibers	21
Rayon-Based Fibers	21
MANUFACTURING PROCESS	21
PAN Carbon Fiber Process	22

<b>TOPIC</b>	<b>PAGE NO.</b>
Precursor Preparation	22
Polymerization	22
Spinning and Stretching	22
Stabilization	23
Carbonization	23
Surface Treatment	24
Sizing	24
Pitch Carbon Fiber Process	24
Precursor Preparation	25
Pitch Refining	25
Isotropic Pitch	25
Anisotropic or Mesophase Pitch	26
Thermal Modifications	26
Solvent Modification	26
Chemical Modification	26
Catalytic Modification	27
Melt Spinning	27
Stabilization	27
Carbonization	27
Graphitization	28
Viscose Rayon Carbon Fiber Process	28
Vapor-Grown Carbon Fibers	29
<b>CHEMICAL AND PHYSICAL PROPERTIES</b>	29
Structural Property Relationship for Carbon Fibers	29
Density	29
Modulus	29
Impact of Fiber Diameter	30
Electrical and Thermal Conductivity	30
Thermal Stability	30
<i>TABLE 2 STRUCTURAL PROPERTY RELATIONSHIPS FOR CARBON FIBERS DERIVED FROM VARIOUS PRECURSORS</i>	30
<b>CARBON FIBER PRODUCT FORMS</b>	31
Carbon Fiber Product Grades	31
PAN-Derived Fibers	31
Pitch-Derived Fibers	31
Tow	32
Carbon Fiber Cloth	32
Prepreg	32
<b>RECENT DEVELOPMENTS IN MANUFACTURING TECHNOLOGIES</b>	32
Microwave-Assisted Plasma (MAP) Process	32
Low-cost Carbon Fiber from Renewable Resources	33
Low-cost Carbon Fiber from Polyolefin	34
Converting Polyethylene into Carbon Fiber	34
Ultraviolet (UV) Stabilization of PAN-based Carbon Fibers	34
Rapid Oxidation Step	35
Surface Modification of Carbon Fibers	35
Carbon Nanotube Reinforcement of Carbon Fibers	36
Continuous Carbon Fiber Produced from Carbon Nanotubes	36

<b>TOPIC</b>	<b>PAGE NO.</b>
Carbon Nanofibers	37
Activated Carbon Fibers	37
Diamond Nanofibers	38
MANUFACTURERS OF PAN-BASED FIBERS	38
Small-tow Manufacturers	38
Cytec's Carbon Fiber Production	39
Hexcel's Carbon Fiber Production	39
Other Manufacturers	40
Large-Tow Carbon Fiber Manufacturers	41
Zoltek Companies Inc.	41
Toho Tenax America	42
SGL Carbon Fibers and Composites	42
MANUFACTURERS OF PITCH-BASED CARBON FIBERS	43
CARBON FIBER COMPOSITES	44
Carbon-Fiber-Reinforced Polymer Composites (CFRP)	44
Manufacturing Processes	44
Molding Processes	44
Roving Processes	45
Mechanical Properties	45
<i>TABLE 3 TYPICAL MECHANICAL PROPERTIES OF CARBON-FIBER-REINFORCED POLYMER COMPOSITES</i>	45
Carbon-Fiber-Reinforced Metal Composites (CFRM)	46
Manufacturing Processes	46
Mechanical Properties	46
<i>TABLE 4 TYPICAL MECHANICAL PROPERTIES OF CARBON-FIBER-REINFORCED METAL COMPOSITES</i>	46
CARBON FOAMS	47
RAW MATERIALS	47
<i>TABLE 5 PROPERTIES OF PITCH RAW MATERIALS USED FOR CARBON FOAM MANUFACTURING (°C/%)</i>	48
MANUFACTURING PROCESS	48
Flash Process	48
Blowing Gases	48
Sol-Gel Process	49
CHEMICAL AND PHYSICAL PROPERTIES	49
<i>TABLE 6 PHYSICAL PROPERTIES OF PITCH-DERIVED CARBON FOAMS</i>	49
RECENT TRENDS IN CARBON FOAM TECHNOLOGY	50
Uniform-Density-Gradient Carbon Foams	50
Reinforced Carbon Foams	50
High-Thermal-Conductivity Carbon Foams	51
Magnetic Carbon Nanofoams	52
Low-cost Carbon Foams	52
MANUFACTURERS OF CARBON FOAMS	53
Honeywell	53
POCO Graphite	53
Touchstone Research Laboratory	54
University of Dayton and Wright U.S. Air Force Laboratory Alliance	54
STRUCTURAL GRAPHITE	55

<b>TOPIC</b>	<b>PAGE NO.</b>
TYPES AND MANUFACTURING OF GRAPHITE MATERIALS	55
Natural Graphite	55
Synthetic Graphite	55
<i>FIGURE 5 SCHEMATIC OF MANUFACTURING PROCESS FOR SYNTHETIC GRAPHITE</i>	55
PHYSICAL AND CHEMICAL PROPERTIES	56
Crystalline Structure	56
<i>FIGURE 6 CRYSTALLINE STRUCTURE OF GRAPHITE</i>	56
Lubrication	57
Thermal Properties	57
Oxidation Resistance	58
Chemical Resistance	58
Mechanical Properties	58
<i>TABLE 7 PHYSICAL PROPERTIES OF GRAPHITE MATERIALS</i>	58
EMERGING TECHNOLOGIES	59
Porous Graphite	59
High-Temperature Graphite Process	60
Expandable Graphite	60
CARBON-CARBON STRUCTURAL COMPOSITES	60
TYPES OF STRUCTURAL COMPOSITE MATERIALS	60
CARBON-REINFORCED CARBON MATRIX COMPOSITES	61
<i>TABLE 8 ADVANTAGES AND DISADVANTAGES OF CARBON-CARBON COMPOSITES</i>	62
DIFFERENCES BETWEEN GRAPHITE AND CARBON-CARBON COMPOSITES	63
<i>TABLE 9 COMPARISON OF PHYSICAL PROPERTIES OF GRAPHITE AND CARBON-CARBON COMPOSITES</i>	63
CHEMICAL AND PHYSICAL PROPERTIES	63
REINFORCEMENT ARCHITECTURE	64
One-Dimensional Architecture	65
Two-Dimensional Architecture	65
Three-Dimensional Architecture	65
Multidimensional Architecture	66
Foam Reinforcement	66
MANUFACTURING PROCESSES	66
Infiltration of Matrix Phase	67
Raw Materials for Matrix Phase	67
Chemical Vapor Infiltration Process	67
Temperature Gradient Process	68
Isothermal Process	68
Pressure Gradient Process	68
Liquid Pitch Infiltration Process	69
Raw Materials	69
Manufacturing Process	69
Low-Pressure Process	69
High-Pressure Process	70
Thermosetting Resins as Matrix Precursors	70
<i>FIGURE 7 REPRESENTATION OF CARBON-CARBON COMPOSITE MANUFACTURING PROCESS</i>	70
STRUCTURE AND PROPERTY RELATIONSHIPS	71
Microstructural Features	71

<b>TOPIC</b>	<b>PAGE NO.</b>
<b>TABLE 10 COMPARISON OF CARBON-CARBON COMPOSITES PROPERTIES MANUFACTURED BY VARIOUS PROCESSING ROUTES</b>	72
Mechanical Properties	73
Young's Modulus	73
Strength	73
Fatigue and Creep	74
Effect of Temperature on Mechanical Properties	74
Effect of Oxidation on Mechanical Properties	74
Thermal Properties	74
Friction and Wear Properties	75
<b>OXIDATION PROTECTION FOR CARBON-CARBON COMPOSITES</b>	75
<b>TECHNOLOGY TRENDS</b>	76
Oxidation Inhibition of Carbon-Carbon Composites	76
Rapid-Oxidative-Stabilization Composites	76
High-purity Carbon-Carbon Composites	77
High-density Carbon-Carbon Composites	77
Elimination of Need for Oxidative Stabilization of Carbon Composites	77
High Thermal Conductivity Carbon-Carbon Composites	78
Sequential Deposit of Carbon Matrix and In Situ Polymerization	79
Rapid Processing of Carbon-Carbon Composites	79
Protective Coatings	79
Detecting Flaws in the Carbon Composites	80
Carbon-Carbon Composites from Densified Carbon Foam	80
Low-Temperature Densification Using Sugar Pyrolysis	80
Thick Three-dimensional Preforms for Carbon-Carbon Composites	81
High-Strength Composites Developed by NASA and JPL	81
Carbon-Carbon Frictional Composites for Elevator Brakes	81
Joining Carbon-Carbon Composites	82
Nanotubes in Carbon-Carbon Composites	82
Low-cost Production of Carbon-Carbon Composites	83
<b>GRAPHENE</b>	83
<b>PROPERTIES</b>	83
<b>RAW MATERIALS AND PRODUCTION PROCESSES</b>	84
Established Technologies	84
"Scotch Tape" Method	84
Epitaxial Method	85
Graphite Oxide Reduction Method	85
Experimental Approaches	86
Metal-Carbon Melt Method	86
Pyrolysis of Sodium Ethoxide Method	86
Production of Graphene from Carbon Nanotubes	86
Production of Graphene from Table Sugar	87
Dissolving Graphite in Chlorosulphonic Acid	87
"Molecular Wedge" Method	87
Radio Frequency Catalytic Chemical Vapor Deposition	88
Atmospheric Pressure Chemical Vapor Deposition	88
Carbon Dioxide Reduction	88
Dry Ice-Based Production Processes	88

<b>TOPIC</b>	<b>PAGE NO.</b>
COMPANIES DEVELOPING GRAPHENE STRUCTURAL MATERIALS	89
Allotropica Technologies	89
General Motors	89
Graftech	89
Graphene Devices Ltd.	89
Graphenea	90
CHAPTER 5 COMMERCIAL APPLICATIONS	92
CARBON FIBER APPLICATIONS	92
<i>TABLE 11 PROPERTIES AND APPLICATIONS OF CARBON FIBERS</i>	92
AEROSPACE AND DEFENSE INDUSTRY	93
Space Vehicles	93
Unmanned Spacecraft	93
Manned Spacecraft	94
Launch Vehicles	94
Total U.S. Space Market	94
<i>TABLE 12 U.S. SPACE VEHICLE MARKET, THROUGH 2020 (\$ BILLIONS)</i>	94
Defense Market	95
Defense Aviation	95
<i>TABLE 13 U.S. MILITARY AIRCRAFT MARKET, THROUGH 2020 (\$ BILLIONS)</i>	96
Missiles	96
<i>TABLE 14 U.S. MISSILE SHIPMENTS, THROUGH- 2020 (\$ BILLIONS)</i>	97
Commercial Aviation	97
Large Aircraft	97
<i>TABLE 15 DELIVERIES OF LARGE U.S.-MADE COMMERCIAL AIRCRAFT BY TYPE, THROUGH 2020 (UNITS)</i>	98
Carbon Fiber Consumption	98
<i>TABLE 16 CONSUMPTION OF CARBON-FIBER-REINFORCED COMPOSITES IN U.S.-MADE COMMERCIAL AIRLINERS (LBS/%)</i>	99
GROUND TRANSPORT	99
Trains and Locomotives	100
Motor Vehicles	100
INDUSTRIAL APPLICATIONS	102
WIND ENERGY	103
<i>TABLE 17 U.S. WIND POWER CAPACITY, THROUGH 2020 (MW)</i>	103
<i>TABLE 18 U.S. PRODUCTION OF WIND TURBINE ROTOR BLADES, THROUGH 2020 (NUMBER OF BLADES)</i>	103
SPORTING GOODS	104
Golf Clubs	104
<i>TABLE 19 U.S. MARKET FOR CARBON FIBER COMPOSITE GOLF CLUBS, THROUGH 2020 (\$ MILLIONS)</i>	105
Bicycles	105
Recreational Boating	105
Sport Fishing	106
<i>TABLE 20 U.S. SHIPMENTS OF CARBON FIBER FISHING RODS, THROUGH-2020 (\$ MILLIONS)</i>	106
Other Applications	106
INFRASTRUCTURE	107

<b>TOPIC</b>	<b>PAGE NO.</b>
New Bridge Construction	108
Bridge Repairs	109
Column Repairs	110
Seismic Retrofit	110
High-Strength Building Construction	111
Engineered Wood Products	112
Deepwater Oil and Gas Structures Made from Carbon Composites	112
Smarter and Stronger Concrete	113
New Manufacturing Process for Reinforced Concrete	114
<b>THERMAL MANAGEMENT</b>	114
Conductive Plastics	115
Carbon Nanotubes	116
<b>OTHER APPLICATIONS</b>	117
Biocompatibility Applications	117
Electrochemical Applications	117
Static Dissipation Applications	117
Lightweight Telescope Mirrors	117
Hollow Carbon Fibers in Molecular Sieve Applications	118
Emerging Energy Systems	118
Turtle Airship Uses Carbon Composites	118
<b>CARBON FIBERS MARKET GROWTH</b>	119
<i>TABLE 21 U.S. CONSUMPTION OF CARBON FIBERS BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)</i>	119
<i>FIGURE 8 U.S. CONSUMPTION SHARE OF CARBON FIBER BY INDUSTRY, 2014 VS. 2020 (%)</i>	120
<i>TABLE 22 U.S. MARKET FOR CARBON FIBERS BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)</i>	121
<i>FIGURE 9 U.S. MARKET SHARE FOR CARBON FIBER BY INDUSTRY, 2014 VS. 2020 (%)</i>	121
<b>CARBON FOAM APPLICATIONS</b>	122
<b>AEROSPACE AND DEFENSE</b>	123
Radiators	123
Fire Barrier Applications	123
Brakes	123
<b>GROUND TRANSPORTATION</b>	123
Automotive Radiators	123
Shock Absorbers and Bumpers	124
Other Automotive Applications	124
<b>INDUSTRIAL APPLICATIONS</b>	124
Sandwich Panels	124
Electronic Heat Sinks	124
Phase-Change Materials	125
<b>ENERGY</b>	125
Batteries	125
Fuel Cells	126
Radiators	126
Humidifiers	127
Bipolar Plates	127



<b>TOPIC</b>	<b>PAGE NO.</b>
Supercapacitors	127
Nuclear Reactor Cores	127
Gas Storage	127
OTHER APPLICATIONS	128
Air Filtration Devices	128
Personal Cooling Devices	128
Health Care Applications	128
Acoustic Absorber Materials	128
CARBON FOAM MARKET GROWTH	128
<i>TABLE 23 U.S. CONSUMPTION OF CARBON FOAM, THROUGH 2020 (THOUSAND LBS.)</i>	128
<i>FIGURE 10 U.S. CONSUMPTION SHARE OF CARBON FOAM BY INDUSTRY, 2014 VS. 2020 (%)</i>	129
<i>TABLE 24 U.S. CARBON FOAM MARKET BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)</i>	130
STRUCTURAL GRAPHITE APPLICATIONS	130
AEROSPACE AND DEFENSE	131
GROUND TRANSPORTATION	131
INDUSTRIAL APPLICATIONS	132
Chemical Industry Applications	132
Mechanical Applications	133
Bearings and Brushes	133
<i>TABLE 25 TYPICAL APPLICATIONS FOR GRAPHITE BEARINGS</i>	134
Seals	134
Friction Materials	134
Metallurgy	135
Glassware	135
Refractory Applications	136
ENERGY	136
Fuel Cells	136
Nuclear Industry Applications	137
Hydrogen Storage	137
STRUCTURAL GRAPHITE MARKET GROWTH	138
<i>TABLE 26 U.S. CONSUMPTION OF STRUCTURAL GRAPHITE BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)</i>	138
<i>FIGURE 11 U.S. CONSUMPTION SHARE OF STRUCTURAL GRAPHITE BY INDUSTRY, 2014 VS. 2020 (%)</i>	139
<i>TABLE 27 U.S. MARKET FOR STRUCTURAL GRAPHITE BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)</i>	140
CARBON-CARBON COMPOSITES APPLICATIONS	140
AEROSPACE	140
Space Vehicle Thermal Protection Systems	140
Aircraft Engine Components	142
Aircraft Brakes	143
Other Aerospace Applications	144
GROUND TRANSPORTATION	144
INDUSTRIAL APPLICATIONS	145
Refractory Structures	145
Glass Industry	146

<b>TOPIC</b>	<b>PAGE NO.</b>
Corrosion-Resistant Structures	146
Thermal-Management Solutions	147
ENERGY	147
OTHER APPLICATIONS	147
Biocompatible Structures	147
CARBON-CARBON COMPOSITES MARKET GROWTH	148
<i>TABLE 28 U.S. CONSUMPTION OF CARBON-CARBON COMPOSITES BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)</i>	148
<i>FIGURE 12 U.S. CONSUMPTION SHARE OF CARBON-CARBON COMPOSITES BY INDUSTRY, 2014 VS. 2020 (%)</i>	149
<i>TABLE 29 U.S. MARKET FOR CARBON-CARBON COMPOSITES BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)</i>	150
STRUCTURAL GRAPHENE APPLICATIONS	150
INDUSTRIAL APPLICATIONS	150
Thermal Management Solutions	150
ENERGY	151
Hydrogen Storage	151
Oxidized Graphene Sheets	152
Corrugated Graphene	152
Other Developments	152
Batteries	153
OTHER APPLICATIONS	154
<i>TABLE 30 POSSIBLE TYPES OF GRAPHENE COMPOSITES AND THEIR PROPERTIES</i>	154
MARKET GROWTH	155
<i>TABLE 31 U.S. CONSUMPTION OF STRUCTURAL GRAPHENE BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)</i>	155
MARKETS FOR ADVANCED STRUCTURAL CARBONS	156
<i>TABLE 32 U.S. CONSUMPTION OF STRUCTURAL CARBONS BY MATERIAL TYPE, THROUGH 2020 (THOUSAND LBS.)</i>	156
<i>FIGURE 13 U.S. CONSUMPTION SHARE OF STRUCTURAL CARBONS BY MATERIAL TYPE, 2014 VS. 2020 (%)</i>	157
<i>TABLE 33 U.S. MARKET FOR STRUCTURAL CARBON PRODUCTS BY TYPE, THROUGH 2020 (\$ MILLIONS)</i>	158
<i>FIGURE 14 U.S. MARKET SHARE FOR STRUCTURAL CARBON PRODUCTS BY TYPE, 2014 VS. 2020 (%)</i>	158
CHAPTER 6 INDUSTRY STRUCTURE AND MARKET DRIVERS	161
MARKETS FOR STRUCTURAL CARBON MATERIALS	161
MANUFACTURERS OF STRUCTURAL CARBONS	161
Carbon Fibers	161
<i>FIGURE 15 U.S. CONSUMPTION SHARE OF CARBON FIBER BY LEADING SUPPLIERS, 2014 (%)</i>	162
Carbon Foams	162
<i>FIGURE 16 U.S. CONSUMPTION SHARE OF CARBON FOAM BY LEADING SUPPLIERS, 2014 (%)</i>	162
Structural Graphite	163
<i>FIGURE 17 U.S. CONSUMPTION SHARE OF STRUCTURAL GRAPHITE BY LEADING SUPPLIERS, 2014 (%)</i>	163
Carbon-Carbon Composites	164

<b>TOPIC</b>	<b>PAGE NO.</b>
<i>FIGURE 18 U.S. CONSUMPTION SHARE OF CARBON-CARBON COMPOSITES BY LEADING SUPPLIERS, 2014 (%)</i>	164
SWOT ANALYSIS OF STRUCTURAL CARBONS INDUSTRY	165
Strengths	165
Weaknesses	165
Opportunities	165
Threats	166
MARKET DRIVERS	166
ECONOMIC FACTORS	166
LEGAL AND REGULATORY FACTORS	167
Price-Fixing in the Carbon Fibers and Composites Industry	167
Price-Fixing in the Graphite Industry	168
INDUSTRY FACTORS	168
Capacity Trends	168
Price Trends	168
New Technologies and New Entrants to the Business	168
Influence and Leverage	169
Buyers' Influence and Leverage	169
Suppliers' Influence and Leverage	169
Substitute Products	170
COMPETITIVE STRATEGIES IN THE STRUCTURAL CARBONS INDUSTRY	170
NEW BUSINESS DEVELOPMENT	170
COMPETITIVE PRICING	171
VERTICAL INTEGRATION	171
GLOBAL STRATEGIC ALLIANCES	172
SGL-BMW Joint Venture	172
SGL-Mitsubishi Joint Venture	172
Mitsubishi Rayon's Expansion Plans and Alliance with SGL	172
Zoltek-DeWind Supply Agreement	172
Zoltek and Chomarat	173
GrafTech and Ballard Power Systems	173
Zoltek and Leggett & Pratt	173
Hexcel and Airbus Industries	173
Hexcel and Boeing	174
Chinese - Russian Alliance	174
CHAPTER 7 INTELLECTUAL PROPERTY AND TECHNOLOGY TRENDS ANALYSIS	176
INTELLECTUAL PROPERTY ANALYSIS	176
<i>TABLE 34 PATENTS ISSUED TO LEADING MANUFACTURES IN STRUCTURAL CARBON MATERIALS TECHNOLOGY, 1996-SEPTEMBER, 2015</i>	177
TECHNOLOGY DEVELOPMENT TRENDS	177
CHAPTER 8 INTERNATIONAL ASPECTS OF STRUCTURAL CARBONS BUSINESS	180
<i>TABLE 35 GLOBAL MARKET FOR STRUCTURAL CARBON MATERIALS BY TYPE, 2014 (\$ MILLIONS)</i>	180
<i>FIGURE 19 GLOBAL MARKET SHARE FOR STRUCTURAL CARBON MATERIALS BY TYPE, 2014 (%)</i>	180

<b>TOPIC</b>	<b>PAGE NO.</b>
<i>TABLE 36 GLOBAL STRUCTURAL CARBON MATERIALS MARKET BY REGION, THROUGH 2020 (\$ MILLIONS)</i>	182
CHAPTER 9 PROFILES OF MANUFACTURERS	184
U.S. MANUFACTURERS	184
ADVANCED CARBON TECHNOLOGIES INC.	184
ADVANCED COMPOSITES INC.	184
AEROSPACE COMPOSITE PRODUCTS CO.	185
ALBANY ENGINEERED COMPOSITES	185
APPLIED SCIENCES INC.	185
ASBURY CARBONS	186
BOEING CO.	186
CARBON-CARBON ADVANCED TECHNOLOGIES INC.	186
CHOMARAT NORTH AMERICA	187
CYTEC CORP.	187
FIBER MATERIALS INC.	188
GENERAL MOTORS CO.	188
GRAPHITE METALLIZING CORP.	188
GRAPHITE SALES INC.	189
GRAFTECH INTERNATIONAL LTD.	189
GRAPHTEK LLC	189
HELWIG CARBON PRODUCTS INC.	190
HEXCEL CORP.	190
HITCO CARBON COMPOSITES INC.	191
HONEYWELL INTERNATIONAL INC.	191
KIRKWOOD HOLDING INC.	191
MER CORP.	192
MINERALS TECHNOLOGIES INC.	192
MITSUBISHI RAYON CARBON FIBER AND COMPOSITES.	193
MORGAN ADVANCED MATERIALS	193
POCO GRAPHITE INC.	193
ROC CARBON CO.	194
SCHUNK GRAPHITE TECHNOLOGY LLC	194
SGL GROUP - THE CARBON COMPANY	194
SIOUX MANUFACTURING CORP.	195
SPENCER COMPOSITE CORP.	195
ST. MARYS CARBON CO.	195
SUPERIOR GRAPHITE CO.	196
TOHO TENAX AMERICA INC.	196
TORAY CARBON FIBERS AMERICA INC.	197
TOUCHSTONE RESEARCH LABORATORY LTD.	197
TPI COMPOSITES INC.	197
ULTRAMET INC.	198
UTC AEROSPACE SYSTEMS	198
V2 COMPOSITE INC.	198
ZOLTEK COMPANIES INC.	199
INTERNATIONAL MANUFACTURERS	199
ANAORI CARBON CO. LTD.	199

<b>TOPIC</b>	<b>PAGE NO.</b>
ATLAS COMPOSITES LTD.	199
GRAPHENEA	200
GRUPO ANTOLIN INGENIERIA S.A	200
MERSEN GROUP	200
MITSUBISHI CHEMICAL CORP.	201
MITSUBISHI RAYON CO. LTD.	201
NIPPON GRAPHITE FIBER CORP	201
TAIWAN CARBON TECHNOLOGY CO. LTD.	202
TOHO TENAX CO. LTD.	202
TORAY INDUSTRIES INC.	203

**LIST OF TABLES**

<b>TABLE HEADING</b>	<b>PAGE NO.</b>
SUMMARY TABLE U.S. MARKET FOR ADVANCED STRUCTURAL CARBON PRODUCTS BY USER SEGMENT, THROUGH 2020 (\$ MILLIONS)	7
TABLE 1 DEPENDENCE OF CARBON FIBER PROPERTIES ON RAW MATERIALS	20
TABLE 2 STRUCTURAL PROPERTY RELATIONSHIPS FOR CARBON FIBERS DERIVED FROM VARIOUS PRECURSORS	30
TABLE 3 TYPICAL MECHANICAL PROPERTIES OF CARBON-FIBER-REINFORCED POLYMER COMPOSITES	45
TABLE 4 TYPICAL MECHANICAL PROPERTIES OF CARBON-FIBER-REINFORCED METAL COMPOSITES	46
TABLE 5 PROPERTIES OF PITCH RAW MATERIALS USED FOR CARBON FOAM MANUFACTURING (°C/%)	48
TABLE 6 PHYSICAL PROPERTIES OF PITCH-DERIVED CARBON FOAMS	49
TABLE 7 PHYSICAL PROPERTIES OF GRAPHITE MATERIALS	58
TABLE 8 ADVANTAGES AND DISADVANTAGES OF CARBON-CARBON COMPOSITES	62
TABLE 9 COMPARISON OF PHYSICAL PROPERTIES OF GRAPHITE AND CARBON-CARBON COMPOSITES	63
TABLE 10 COMPARISON OF CARBON-CARBON COMPOSITES PROPERTIES MANUFACTURED BY VARIOUS PROCESSING ROUTES	72
TABLE 11 PROPERTIES AND APPLICATIONS OF CARBON FIBERS	92
TABLE 12 U.S. SPACE VEHICLE MARKET, THROUGH 2020 (\$ BILLIONS)	94
TABLE 13 U.S. MILITARY AIRCRAFT MARKET, THROUGH 2020 (\$ BILLIONS)	96
TABLE 14 U.S. MISSILE SHIPMENTS, THROUGH- 2020 (\$ BILLIONS)	97
TABLE 15 DELIVERIES OF LARGE U.S.-MADE COMMERCIAL AIRCRAFT BY TYPE, THROUGH 2020 (UNITS)	98
TABLE 16 CONSUMPTION OF CARBON-FIBER-REINFORCED COMPOSITES IN U.S.-MADE COMMERCIAL AIRLINERS (LBS/%)	99
TABLE 17 U.S. WIND POWER CAPACITY, THROUGH 2020 (MW)	103
TABLE 18 U.S. PRODUCTION OF WIND TURBINE ROTOR BLADES, THROUGH 2020 (NUMBER OF BLADES)	103
TABLE 19 U.S. MARKET FOR CARBON FIBER COMPOSITE GOLF CLUBS, THROUGH 2020 (\$ MILLIONS)	105
TABLE 20 U.S. SHIPMENTS OF CARBON FIBER FISHING RODS, THROUGH-2020 (\$ MILLIONS)	106
TABLE 21 U.S. CONSUMPTION OF CARBON FIBERS BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)	119
TABLE 22 U.S. MARKET FOR CARBON FIBERS BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)	121
TABLE 23 U.S. CONSUMPTION OF CARBON FOAM, THROUGH 2020 (THOUSAND LBS.)	128
TABLE 24 U.S. CARBON FOAM MARKET BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)	130
TABLE 25 TYPICAL APPLICATIONS FOR GRAPHITE BEARINGS	134
TABLE 26 U.S. CONSUMPTION OF STRUCTURAL GRAPHITE BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)	138
TABLE 27 U.S. MARKET FOR STRUCTURAL GRAPHITE BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)	140
TABLE 28 U.S. CONSUMPTION OF CARBON-CARBON COMPOSITES BY INDUSTRY, THROUGH 2020 (THOUSAND LBS.)	148
TABLE 29 U.S. MARKET FOR CARBON-CARBON COMPOSITES BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)	150
TABLE 30 POSSIBLE TYPES OF GRAPHENE COMPOSITES AND THEIR PROPERTIES	154

<b>TABLE HEADING</b>	<b>PAGE NO.</b>
TABLE 31 U.S. CONSUMPTION OF STRUCTURAL GRAPHENE BY INDUSTRY, THROUGH 2020 (\$ MILLIONS)	155
TABLE 32 U.S. CONSUMPTION OF STRUCTURAL CARBONS BY MATERIAL TYPE, THROUGH 2020 (THOUSAND LBS.)	156
TABLE 33 U.S. MARKET FOR STRUCTURAL CARBON PRODUCTS BY TYPE, THROUGH 2020 (\$ MILLIONS)	158
TABLE 34 PATENTS ISSUED TO LEADING MANUFACTURES IN STRUCTURAL CARBON MATERIALS TECHNOLOGY, 1996-SEPTEMBER, 2015	177
TABLE 35 GLOBAL MARKET FOR STRUCTURAL CARBON MATERIALS BY TYPE, 2014 (\$ MILLIONS)	180
TABLE 36 GLOBAL STRUCTURAL CARBON MATERIALS MARKET BY REGION, THROUGH 2020 (\$ MILLIONS)	182

**LIST OF FIGURES**

<b>FIGURE TITLE</b>	<b>PAGE NO.</b>
SUMMARY FIGURE U.S. MARKET FOR ADVANCED STRUCTURAL CARBON PRODUCTS BY USER SEGMENT, 2014-2020 (\$ MILLIONS)	7
FIGURE 1 U.S. MARKET FOR ADVANCED STRUCTURAL CARBONS BY TYPE, 2014 (%)	10
FIGURE 2 PROJECTED GROWTH RATE IN U.S. STRUCTURAL CARBONS MARKET, 2014-2020 (CAGR%)	11
FIGURE 3 GLOBAL ADVANCED STRUCTURAL CARBON PRODUCTS MARKET BY TYPE, 2014 (%)	12
FIGURE 4 GLOBAL STRUCTURAL CARBON PRODUCTS MARKET SHARE BY REGION, 2014 (%)	12
FIGURE 5 SCHEMATIC OF MANUFACTURING PROCESS FOR SYNTHETIC GRAPHITE	55
FIGURE 6 CRYSTALLINE STRUCTURE OF GRAPHITE	56
FIGURE 7 REPRESENTATION OF CARBON-CARBON COMPOSITE MANUFACTURING PROCESS	70
FIGURE 8 U.S. CONSUMPTION SHARE OF CARBON FIBER BY INDUSTRY, 2014 VS. 2020 (%)	120
FIGURE 9 U.S. MARKET SHARE FOR CARBON FIBER BY INDUSTRY, 2014 VS. 2020 (%)	121
FIGURE 10 U.S. CONSUMPTION SHARE OF CARBON FOAM BY INDUSTRY, 2014 VS. 2020 (%)	129
FIGURE 11 U.S. CONSUMPTION SHARE OF STRUCTURAL GRAPHITE BY INDUSTRY, 2014 VS. 2020 (%)	139
FIGURE 12 U.S. CONSUMPTION SHARE OF CARBON-CARBON COMPOSITES BY INDUSTRY, 2014 VS. 2020 (%)	149
FIGURE 13 U.S. CONSUMPTION SHARE OF STRUCTURAL CARBONS BY MATERIAL TYPE, 2014 VS. 2020 (%)	157
FIGURE 14 U.S. MARKET SHARE FOR STRUCTURAL CARBON PRODUCTS BY TYPE, 2014 VS. 2020 (%)	158
FIGURE 15 U.S. CONSUMPTION SHARE OF CARBON FIBER BY LEADING SUPPLIERS, 2014 (%)	162
FIGURE 16 U.S. CONSUMPTION SHARE OF CARBON FOAM BY LEADING SUPPLIERS, 2014 (%)	162
FIGURE 17 U.S. CONSUMPTION SHARE OF STRUCTURAL GRAPHITE BY LEADING SUPPLIERS, 2014 (%)	163
FIGURE 18 U.S. CONSUMPTION SHARE OF CARBON-CARBON COMPOSITES BY LEADING SUPPLIERS, 2014 (%)	164
FIGURE 19 GLOBAL MARKET SHARE FOR STRUCTURAL CARBON MATERIALS BY TYPE, 2014 (%)	180