ASSESSING INDUSTRIAL CAPABILITIES FOR CARBON FIBER PRODUCTION

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Analysis and evaluation of requirements and industrial capabilities are an important part of the defense system acquisition process. From providing milestone decision support on industrial and production issues to understanding and managing program risk, assessment of industrial capabilities provides for informed and realistic decision making on major defense acquisition programs. Carbon fiber is a key constituent of advanced composite materials used in many defense and aerospace systems. This paper assesses industrial capabilities for carbon fiber production, a sub-tier industrial sector critical to defense systems.

Carbon fibers are a key constituent in advanced composite materials, which are used in demanding defense aerospace applications. From military aircraft, such as the F–22, F/A–18, AV–8B, and B–2, to strategic missiles such as Trident II D5, to space launch vehicles, such as the Titan IV solid rocket motor upgrade, to satellite structures, carbon fiber composites are widely used for high performance applications because of their high strength, high stiffness, and low density. Because of the performance enhancements attributable to carbon fiber composites, these materials are characterized as militarily critical technology. This analysis was performed to assess the state of the carbon fiber industrial base.

DESCRIPTION OF CARBON FIBERS

Carbon fibers are high-strength, high-stiffness (elastic modulus) materials that are combined with a matrix material, most commonly an epoxy plastic, to form an advanced composite material. It is the combination of high strength, high stiffness, and low density that makes carbon fiber composites so appealing for many demanding aerospace applications, where reduced weight is so important (Table 1) (ASM International, 1987). Some specialized carbon fibers are also useful because of their high thermal conductivity or extreme high-temperature performance. Because of their desirable engineering properties, carbon fiber composites are widely used in defense aerospace systems (Table 2).

Carbon fibers may be manufactured from polyacrylonitrile (PAN), petroleum pitch, or rayon precursor materials by high-temperature (2000 to 3500° F) carbonization or graphitization processes. The PAN-based carbon fibers are the dominant class of structural carbon fibers and are widely used in military aircraft, missile, and spacecraft structures. Pitch-based carbon fibers generally have higher stiffness and thermal conductivities, which make them uniquely useful in satellite structures and thermal management applications, such as space radiators and battery sleeves. Rayon-based carbon fibers used in carbon-phenolic composites have extremely low values of thermal conductivity, making them useful for rocket nozzle and missile reentry vehicle nosecones and heat shields.

CARBON FIBER DEMAND

Carbon fibers are considered dual-use, meaning that they are used in both

Definitions of Terms

Carbon fiber. Fiber produced by carbonizing precursor fibers based on PAN (polyacrylonitrile), pitch, or rayon. The term is often used interchangeably with graphite. Carbon fibers and graphite fibers are made and heat treated at different temperatures, however, and have different carbon contents.

Composite material. Product made by combining two or more dissimilar materials such as fibers and resins to create a product with exceptional structural properties not present in the original materials.

Continuous filament. Carbon fiber of small diameter and indefinite length (as compared to chopped fiber). Each type has different applications.

Modulus of elasticity. The physical measurement of stiffness in a material. A high modulus indicates a stiff material.

PAN (polyacrylonitrile). A polymer which, when spun into fiber, is used as a precursor material in the manufacture of PAN carbon fibers.

Precursor. The PAN, pitch, or rayon fibers from which carbon or graphite fibers are produced.

Tow. An untwisted bundle of continuous filaments, usually designated by a number followed by “k,” indicating multiplication by 1,000 (e.g., 12k tow has 12,000 filaments).

Table 1. Typical Properties of Common Structural Materials

Material	Strength (ksi)[a]	Stiffness (Msi)[b]	Density (g/cm3)[c]
Metals			
Aluminum	80	10	2.76
Titanium	160	16	4.42
Steel	200	30	8.00
Composites			
Glass/epoxy	250	8	1.99
Aramid (Kevlar)/epoxy	190	12	1.38
Carbon (Graphite)/epoxy	215	21	1.55

[a] Thousands of pounds per square inch.
[b] Millions of pounds per square inch.
[c] Grams per cubic centimeter.

Source: ASM International (1987).

Table 2. Carbon Fiber Usage on Aerospace Systems

Weapon System	Carbon Fiber Type		
	PAN	Pitch	Rayon
Missiles			
Strategic	X	X	X
Tactical	X		X
Space			
Launch vehicles	X		X
Satellites	X	X	
Aircraft			
Fixed-wing	X	X	
Rotary-wing	X		

commercial and military applications. Demand varies significantly for PAN-, pitch-, and rayon-type carbon fibers because of the fibers' different physical properties, their use in different applications, and the manufacturing processes used in their production.

Recent figures (Table 3) released by the Suppliers of Advanced Composite Materials Association (SACMA, 1997) indicate that PAN carbon fiber demand has increased annually from 11 million pounds in 1991 to 26 million pounds in 1997. Commercial demand in the industrial, sports, and commercial aerospace sectors are the major market drivers, and have sustained this industry's growth in recent years. A major commercial application is the use of carbon fiber for the tail fin composite structure for the Boeing 777. In contrast, defense demand for PAN carbon fibers was estimated in 1995 to be about 1 million pounds, or about 5 percent of the overall market.

"The Department of Defense (DoD) continues to foster competition and innovation in carbon fiber development."

The Department of Defense (DoD) continues to foster competition and innovation in carbon fiber development. For example, the Naval Air Systems Command is developing an acquisition strategy for naval aircraft (e.g., the F/A–18E/F and the V–22) to qualify two sources of PAN carbon fiber for a broad array of structural applications. As of the end of 1997, the PAN carbon fiber industry had grown to a $600 million-per-year business.

Official figures for pitch-based carbon fiber usage are not available, but it is estimated that demand for these specialized materials is much less and is measured in the thousands as opposed to millions of pounds. The major market for pitch carbon fibers is for aircraft brake discs and other carbon-carbon composite applications. Satellite manufacturers also use pitch-based fibers for their high modulus and high thermal conductivity for heat dissipation in space radiators or electronic enclosures. Engineers at satellite manufacturers have reported typical lot buys of a few thousand or several hundred pounds.

Although demand for pitch-based carbon fibers is much less than for PAN carbon fibers, there will likely be increased use of pitch-based carbon fibers in thermal structural applications. In general, pitch fibers are much more expensive (Table 4) because of the energy-intensive, higher temperatures required in their manufacture and their lower demand ("Update: New Carbon Fiber," 1998; Amoco, 1998). In consequence they are only used where lower-cost PAN or other fibers do not meet a particular application's engineering requirements.

Carbon fibers produced from rayon precursor are used almost exclusively in ablative applications, such as reentry vehicle nosetips, heat shields, and solid-rocket motor nozzles and exit cones. Rayon-based carbon fiber-phenolic composites can withstand the high temperature and erosive gases of solid-rocket motor operation and the high temperatures generated by aerodynamic heating on missile reentry systems. During the past 10 years, demand for annual production of aerospace-grade rayon has varied from 100,000 pounds to more than 1 million pounds due to DoD and National Aeronautics and Space Administration

Table 3. Worldwide PAN Carbon Fiber Shipments, 1991-1997

Year	Pounds	U.S. (millions of $)*
1991	11,442,059	298.80
1992	13,002,812	374.10
1993	14,598,544	384.90
1994	17,425,452	461.40
1995	19,714,671	464.80
1996	20,672,741	489.24
1997	25,964,530	621.41

* Dollars are current year and have not been adjusted for inflation.

Source: Suppliers of Advanced Composite Materials Association (1997).

Table 4. Cost of Carbon Fibers

Fiber	Tensile Modulus (Msi)	Thermal Conductivity (W/mK)	Cost ($/lb)
PAN-based carbon fiber[a]			
Heavy tow (48–320K)	33–35		8–11
Aerospace grade			
Standard modulus (12K)	33–35		18–20
Intermediate modulus (12K)	40–50		31–33
High modulus (12K0	50–70		60–65
Ultrahigh modulus (3K, 6K, 12K)	70–140		120–900
Pitch-based carbon fiber[b]			
P–55	55	120	55–80
P–120	120	640	800
K–1100		1100	1,750

[a] Source: High Performance Composites 1999 Sourcebook.
[b] Source: Amoco (1998).

Table 5. Carbon Fiber Producers for Aerospace Systems

Manufacturer	Carbon Fiber Type	Principal Fibers Used on Aerospace Systems
Amoco	PAN	T300,T650
Amoco	Pitch	P120, K1100, K800X
Hexcel	PAN	AS4, IM6, IM7, UHM
Toray	PAN	T300, MJ series
Toho	PAN	G30, G40, G50 series
Mitsubishi	Pitch	K13C2U
Nippon	Pitch	XN and YSH series
NARC	Rayon	No longer produced

(NASA) stockpiling and usage fluctuation. After assessing rayon fiber industrial capabilities in 1997, DoD and NASA made a deliberate policy decision to buy out and stockpile their rayon fiber needs for the next five years. As of this writing, there is no immediate demand for new aerospace-grade rayon production.

CARBON FIBER PRODUCERS

Major producers of carbon fibers for aerospace systems are identified in Table 5, along with the fiber designations of their products. The list is limited to fibers that are widely used in military and aerospace applications. As mentioned above, PAN carbon fibers are the most widely used and deserve closer analysis.

To assess the trend in industrial capabilities for PAN carbon fiber production, one must look back at worldwide carbon fiber production capacities in 1989 and 1991 (for which data were available) to make a comparison to current production capacity (1998). Table 6 lists the major carbon producers in 1989 and 1991 and their reported production capacities (Hercules, 1991; Lin, S-S., 1992). Table 7 documents results of a recent survey of current PAN carbon fiber producers (Traceski, 1998), including plant locations and current annual capacities. The table also groups producers into two categories based upon what form of product (i.e., small or large tow) they produce. (A tow is an untwisted bundle of continuous filaments.) Generally speaking, the smaller tows have been qualified for military aerospace applications.

In 1989 worldwide production capacity for PAN-based carbon fibers was 19 million pounds. By 1991 capacity had increased to 26 million pounds. In 1998 production capacity is 65 million pounds, having more than tripled since 1989. The table comparisons also reveal some name

Table 6.
Worldwide Production Capacity for PAN-Based Carbon Fibers, 1989 and 1991

Producer	Production Capacity (1989, lbs per year[a])	Production Capacity (1991, lbs per year[b])
United States		
Hercules	3,000,000	3,850,000
BASF (Celanese)	990,000	3,267,000
Amoco (UCC)	880,000	2,200,000
Courtaulds-Grafil	660,000	792,000
Akzo	990,000	792,000
Stackpole (Zoltek)	130,000	242,000
BP	260,000	88,000
Avco	150,000	44,000
Asia		
Toray	3,300,000	4,950,000
Toho	3,100,000	4,444,000
Asahi Nippon Carbon	990,000	990,000
Mitsubishi	350,000	1,100,000
Nikkisso	130,000	
Taiwan Plastics		506,000
Korea Steel		330,000
Europe		
Courtaulds-Grafil	790,000	770,000
Soficar	990,000	660,000
Enka/Akzo	1,100,000	770,000
R.K. Carbon	220,000	506,000
Sigri	220,000	55,000
Other	770,000	
Total	**19,020,000**	**26,356,000**

[a] Hercules (1991).
[b] Lin, S-S. (1992).

Table 7.
Worldwide Production Capacity for PAN-Based Carbon Fibers (1998)

Manufacturer	Facility	Capacity (lb)
Aerospace Grade Carbon Fiber (small tow)		
Amoco	Greenville, SC	2,200,000
Amoco (BASF, 1993)	Rockhill, SC	2,000,000
Hexcel (Hercules, 1996)	Magna, UT	4,500,000
Toho	Mishima, Japan	7,400,000
Toho	Oberbruch, Germany	3,900,000
Toray	Ehime, Japan	9,400,000
Toray	Abidos, France (SOFICAR)	1,600,000
Toray	Decatur, AL (Monsanto)	3,600,000
Mitsubishi-Grafil	Toyohashi, Japan	5,500,000
Formosa Plastics	Taiwan (Tairylan)	4,000,000
Commercial Grade Carbon Fiber (large tow)		
Zoltek	St. Louis, MO	3,500,000
Zoltek	Abilene, TX	3,000,000
Zoltek	Nyergesujfalu, Hungary	2,000,000
Akzo Fortafil	Rockwood, TN	5,000,000
Mitsubishi-Grafil	Sacramento, CA	2,000,000
SGL Carbon (RK Carbon)	Inverness, Scotland	3,000,000
SGL Carbon	Meitingen, Germany	600,000
Aldila	Evanston, WY	2,500,000
Total		**65,700,000**

All capacities are nameplate capacities (i.e., the optimum amount for which a line is designed).

Effective capacity, which takes into account downtime and product mix factors, etc., is generally proprietary.

A “tow” is an untwisted bundle of continuous filaments, usually designated by a number followed by “k,” indicating multiplication by 1,000 (e.g., 12k tow has 12,000 filaments).

Standard aerospace-grade structural carbon fiber tows are 3k, 6k and 12k.

Larger tow products are generally used in commercial, nonaerospace type applications.

Zoltek produces 48k, 160k and 320k tows.

Akzo Fortafil produces 50k tow. An additional 3.3 million lb capacity to be on-line by December 1998.

Grafil produces 1k, 3k, 6k, 12k and 24k tow in Japan and 12k, 24k and 48k tow at Sacramento.

SGL Carbon produces 60k and 320k tow. An additional 3 million lb capacity to be on-line by December 1998.
Aldila produces 50k tow, primarily for golf shafts.

Source: Traceski, F. (1998).

Table 8.
Worldwide Production Capacity for Pitch-Based Carbon Fibers (1991)

Manufacturer	Trade Name of Fibers	Capacity (ton/year)	Capacity (lb/year)
Amoco	Thornel	230	506,000
Kureha Chemical	Kureha	900	1,980,000
Mitsubishi Chemical	Dialead	50	110,000
Nippon Oil	Granoc	50	110,000
Nippon Steel		12	26,400
Osaka Gas	Donacarbo	300	660,000
Petoca	Cabonic	12	2,400
Tonen	Forca	12	2,400

Notes:
Kureha and Osaka Gas produce short fibers, which have different applications than do continuous fibers.
In 1991 total capacity for continuous pitch fibers only was 366 metric tons or 805,200 pounds.
Petoca and Tonen halted pitch fiber production in 1992 and 1993, respectively.
Data Source: Lin, S-S. (1992).

changes due to various consolidations, acquisitions, and restructurings in the carbon fiber industry that took place between 1989 and 1998. Notably, Japanese Toray and Toho are the world's leading producers of PAN carbon fibers, with annual production capacities of 14.6 and 11.3 million pounds, respectively. U.S. companies Hexcel and Amoco each have annual capacities of more than 4 million pounds.

Worldwide annual production capacity for continuous pitch-based carbon fibers has been and continues to be significantly less than that for PAN carbon fiber. In 1991 there were six companies producing continuous pitch-based carbon fibers (Table 8) (Lin, S-S., 1992). In 1998 there were only three companies (Table 9) (Traceski, 1998). Amoco remains the only U.S. company producing pitch-based carbon fibers, with a current annual nameplate capacity of approximately one million pounds. Mitsubishi and Nippon are the two principal Japanese competitors. The Mitsubishi Chemical plant in Sakaide, Japan, has a capacity of approximately 1.1 million pounds per year. Nippon Graphite Fiber Corporation has a plant in Hirohata, Japan, that has a nameplate capacity of 264,000 pounds.

Production capacity for aerospace-qualified rayon fiber is virtually nonexistent. Up until October 1997, the sole

Table 9.
Worldwide Production Capacity for Pitch-Based Carbon Fibers (1998)

Principal Supplier	Facility	Capacity (lb/year)	Tow Sizes
Amoco	Greenville, SC	1,000,000	2k
Mitsubishi Chemical	Sakaide, Japan	1,100,000	2k, 10k
Nippon Graphite Fiber	Hirohata, Japan	264,000	0.5k, 1k, 2k, 3k, 6k
		2,364,000	

Notes:

All capacities are nameplate capacities (i.e., the optimum amount for which a line is designed).

Effective Capacity, which takes into account downtime and product mix factors, etc., is generally proprietary.

Nippon Graphite Fiber Corp is a joint venture company wholly owned by Nippon Oil and Nippon Steel, having undertaken their pitch fiber businesses in 1995.

Source: Traceski, F. (1998).

qualified source for aerospace-grade rayon fiber was North American Rayon Corporation (NARC) of Elizabethton, TN. The NARC ceased production because it had no current orders or promises for future orders. NARC had an annual capacity of approximately 2.5 million pounds of rayon fiber. Other unqualified sources of aerospace-grade rayon are Grupo-Cydsa (Monterrey, Mexico), Akzo (Obernburg Plant, Germany), Lenzing (Lowland Plant, TN), and Courtaulds (Axis Plant, AL). There is no current qualified U.S. producer of rayon fibers for aerospace use. Any new rocket or missile system will be faced with either qualification of a new rayon fiber or the use of some alternative material (such as PAN fiber) or an alternative design able to meet the requirements of extreme high-temperature performance for nozzle applications. Qualification of PAN fiber appears to be the preferred program approach at present.

Industry Consolidation and Restructuring

In recent years, the carbon fiber industry has undergone its share of consolidation and restructuring through various acquisitions. In the PAN carbon fiber industry, Amoco purchased BASF's manufacturing plant and equipment at Rock Hill, SC, in 1993. Hexcel acquired the Hercules PAN carbon fiber business at Salt Lake City, UT, in 1993. Zoltek bought equipment from Stackpole and Courtaulds, and RK Carbon was sold to Sigri Great Lakes Carbon (SGL).

Significant changes have also taken place in the pitch carbon fiber industry. Japanese producers Petoca and Tonen exited the pitch fiber business in 1992 and 1993, respectively. In 1995 Nippon Oil and Nippon Steel formed a joint venture company, known as Nippon Graphite Fiber Corporation, wholly owned by these two parent companies.

Industrial Capabilities Assessment

From an assessment of worldwide industrial capabilities for carbon fiber production, one can make the following observations:

PAN-based carbon fibers. Annual worldwide demand for these fibers increased from 1991 to 1997 and reached 26 million pounds. Annual worldwide production capacity now exceeds 65 million pounds, with Japanese Toray and Toho the leading producers. Defense needs make up only a small percentage of the annual demand for carbon fibers; commercial applications are the principal market.

Pitch-based carbon fibers. Research and development of pitch-based carbon fibers is resulting in their increased use in spacecraft structural and thermal management applications. There is only one U.S. supplier (Amoco) of these fibers. Mitsubishi and Nippon are the leading Japanese suppliers.

Rayon-based carbon fibers. There is no current U.S. supplier of rayon fibers for aerospace applications. Future systems will be forced to qualify alternative materials or new rayon fibers to meet their needs.

Summary

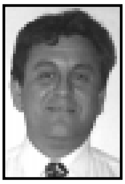
Assessment and evaluation of carbon fiber industrial capabilities reveal that this critical sub-tier industry (with the exception of rayon) is growing despite reductions in defense aircraft and missile procurements in the 1990s. Analysis of the worldwide carbon fiber industry indicates that demand for carbon fibers has increased over the past several years, as did production capacities. Carbon fiber production is one example of dual-use production where commercial products and processes have not only sustained the industry, but also are now driving new development, despite defense cutbacks.

Specifically, the PAN carbon fiber industry has grown into a $600 million-per-year business. Worldwide competition between major producers (Hexcel, Amoco, Toray, and Toho) continues to push innovation and new fiber development.

The pitch carbon fiber industry, although much smaller, maintains markets in aircraft brakes and satellite applications. Competition between producers (Amoco, Nippon, and Mitsubishi) is spurring new fiber development. Satellite manufacturers are exploiting these fibers for increased system performance.

"Research and development of pitch-based carbon fibers is resulting in their increased use in spacecraft structural and thermal management applications."

There is no current U.S. producer of carbonizable rayon fiber. New systems requiring high thermal performance will be faced with qualifying new rayon precursor materials or designs, or reconstituting a domestic industrial capability to manufacture aerospace-grade rayon.



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