Appendix E

Case Study: The Advanced Composites Industry

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Appendix E

Case Study: The Advanced Composites Industry

NOTE: This study, along with those in Appendixes D and F, is presented in condensed form in chapter 9 of the main report, Holding the Edge

INTRODUCTION

Historians often classify historical eras according to the materials that societies used to build the world around them. The Bronze and Iron Ages gave way to steel and the Industrial Revolution; in the final decades of the twentieth century the world has seen a host of new and powerful engineered materials for which a new age could be named. One such material, polymer matrix composites (PMCs), constructed from two or more separate materials, provides high strength and stiffness and light weight, permitting such remarkable feats as the ‘round-the-world flight of the Voyager and such advances in defense as Stealth aircraft.

The range of possible applications for PMCs is broad, including: aircraft/aerospace, automotive, marine, and biomedical applications; and products such as sporting goods, bridges, reciprocating industrial machinery, and containers for storage and transportation of corrosive materials.

Composites generally consist of strong, stiff, but brittle reinforcements (fibers, whiskers, or particulate) bound together by a surrounding material (a plastic, metal, or ceramic) called the matrix (see figure E-1). Composites are named for their matix material; thus, the composites referred to in this appendix are polymer matrix composites. The polymer matrix is an organic material, usually a thermosetting epoxy that, once formed, cannot be melted and reshaped. It is this matrix material that binds and provides toughness for the brittle fibers.

PMCs are classified according to their strength and stiffness. They can be divided into two categories: reinforced plastics and advanced composites. Reinforced plastics (or engineered plastics) have been used in large volume in corrugated sheet and pipe and in the auto and recreational boat industries. Reinforced plastics are formed using inexpensive, lower-performance glass fibers. They were used to make the composite body of the GM Fiero and the Chevrolet Corvette. These fibers may be chopped into short lengths and oriented randomly in the plastic matrix.

Fibers for advanced composites are made of materials such as boron, aramid, and carbon.[2] Advanced composites comprise only about 2 percent of the total markets for PMCs, selling primarily in the aircraft/aerospace market. Although relatively expensive per pound. they are lightweight and possess excellent strength and stiffness (see figure E-2); according to one industry spokesman, they are “pound for pound, the strongest material known.” Advanced composites are comprised of continuous fibers aligned very carefully within the polymer matrix. Sixty-five to seventy percent of advanced composite structures produced worldwide are reinforced with high-strength carbon fiber.

Used in commercial aircraft, advanced PMCs can currently offer commercial airline companies a savings in fuel of $70 to $100 per pound over the life of an aircraft. Used in military fighter and attack aircraft, advanced PMCs are enabling technologies for high speed and maneuverability, and can be modified for the reduction of radar signatures. This appendix will focus on advanced composites made of carbon and epoxy used in the aircraft and defense aerospace industries.

Advanced PMCs are highly specialized materials; they are not commodity materials, like metals. In contrast to production of metal parts, where material properties are fixed, PMCs used for given applications are tailored to them at the start of the design process. The material cost, and the cost of the process technology used to make an advanced

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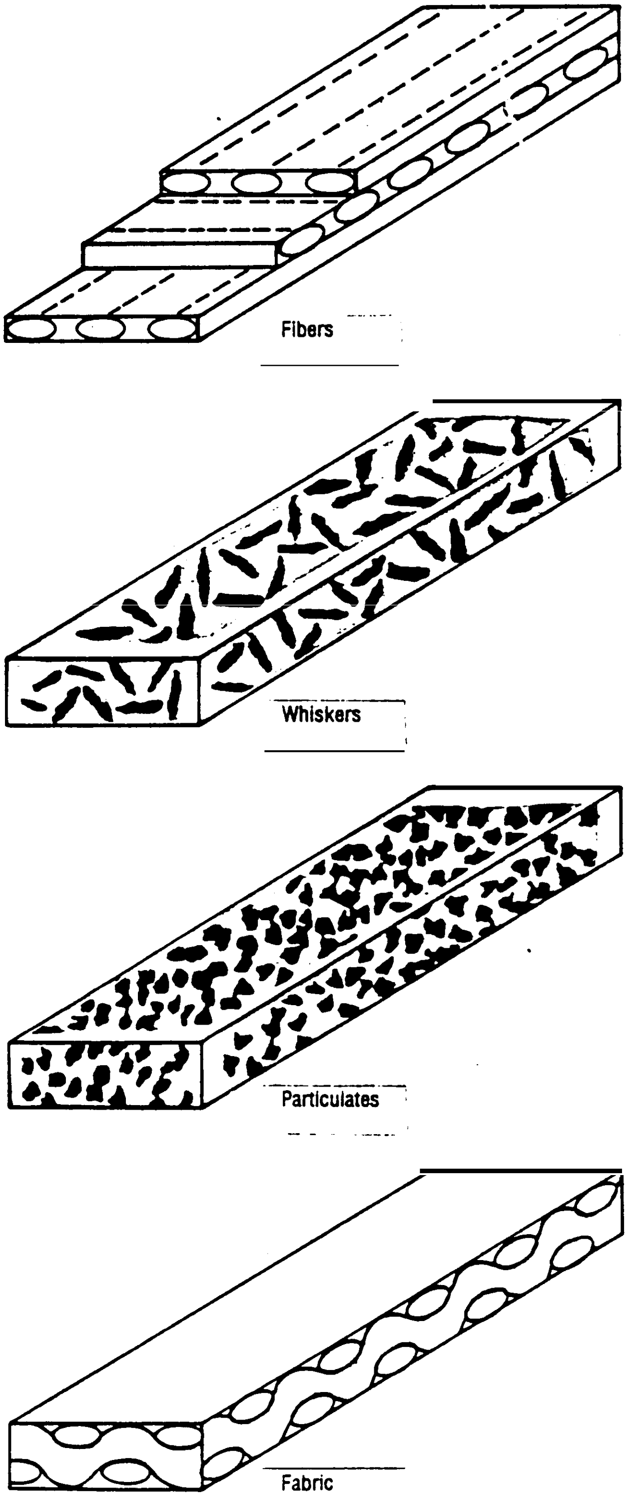
[1] This appendix draws on U.S. Congress, Office of Technology Assessment. *Advanced Materials by Design: New Structural Materials Technologies*, OTA-E351 (Springfield, VA: National Technical Information Service, June 1988).

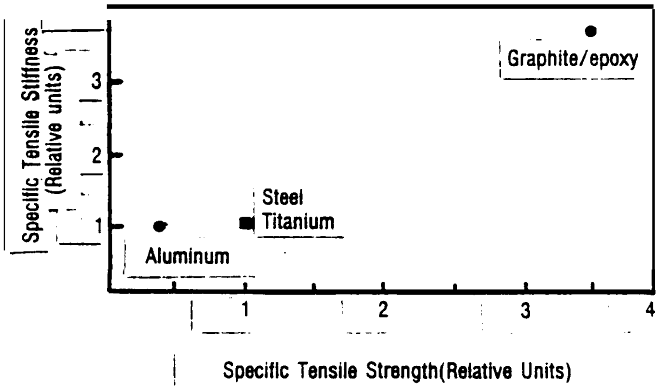
The major type of graphite fiber used comes from polyacrylonitrile (PAN precursor). It is of high strength, but expensive. Many firms, particularly in Japan. have attempted with little success to produce a cheaper high-strength graphite fiber from a pitch precursor. Several Japanese companies (and certain U.S. companies) possess a noteworthy capacity for producing of pitch precursor; but the derivative fibers are not very strong.

Figure E-1—Composite Reinforcement Types



SOURCE: Carl Zweben, General Electric Co.

Figure E-2—Specific Strength and Stiffness of Graphite/epoxy Composites and Selected Metals[a,b]



SOURCE: Carl Zweben, General Electric Co.

composite, depend entirely on the end use and the market. For example, E-glass fiber used in certain automotive applications costs $0.80 per pound and can be formed by processes that produce pounds per minute. Graphite fibers used in aircraft cost $25 to $50 per pound, and are formed by processes that produce pounds per hour.

Processes for making military and commercial aircraft structures from advanced composites are extremely labor-intensive. New, more automated processes are under development at a number of airframe manufacturers. (Table E-1 describes the current range of part-forming techniques in use and under study.) Although PMCs can be competitive with certain metal structures that require complex machining or large numbers of fasteners, more economical processing methods are a key to increasing market interest in advanced PMCs.

This case study is structured to explore three questions: First are the PMC industry and its associated industries eroding in the United States? Second, do military applications of polymer matrix composite technology diverge significantly from their counterparts in the civilian sector of the economy? And third, what are the principal technical and institutional barriers that inhibit civilian access to military PMC technology and vice versa? Each of these questions is refined further and addressed in a separate section below.

Table E-1—Polymer Matrix Composites Part Forming Techniques

Technique	Characteristics	Examples
Compression Molding	Fast, flexible, 1"–2" fiber	Sheet molding compound, auto body panel
njection Molding or Extrusion . .	Fast, high volume very short fibers, thermoplastics, thermosets	Gears, fan blades
Resin Transfer Molding	Fast, complex parts, good control of fiber mat orientation	Auto structural panels
Prepreg tape layup	Slow, labor-intensive, expensive, reliable, automation potential	
Pultrusion	Continuous fiber, constant cross-section parts	-beams, columns
Filament Winding	Moderate speed, continuous fiber, hollow parts, complex geometries	Aircraft fuselage, pipes, drive shafts
Thermal forming*	Reinforced thermoplastic matrices; fast, easy repair, joining	Possibly all of the above

*Future technology

SOURCE: Office of Technology Assessment.

GLOBAL MARKETS AND THE HEALTH OF THE INDUSTRY

Global Nature of Advanced PMC Technology

Although the U.S. Department of Defense drives the development of composite materials technology (historically through its R&D funding and now through its aircraft/aerospace purchases), advanced composites are a global business conducted by companies with broad international interests. Large chemical and petroleum companies are suppliers of fibers and composite parts around the globe; these suppliers are multinationals of varied national origin. BASF, a West German multinational and one of the largest chemical companies in the world, is a supplier of fibers, "prepregs" and fabricated parts. Shell (the Netherlands) and DuPont are also located throughout the world. It has become difficult to determine what is a "U.S. firm."

The PMC industry has been worldwide from its inception. In other technologies, the typical economic scenario has become the successful application and marketing by Japan (or other global economic competitor) of a high technology product invented in the United States. Advanced PMC technology is an exception, in that carbon fiber technology was originally developed in Great Britain and Japan, as well as in the United States by Union Carbide. U.S. firms followed the development of this technology as it occurred, and developed advanced PMC technology for aerospace applications. Since then, the United States has provided the largest market, with U.S. firms having a dominant role.

Joint Ventures and Licensing Agreements

PMC technology spread globally as the Japanese, the Europeans, and the Americans participated in licensing, joint ventures, and acquisitions-a process that continues today. Japan has two main suppliers of carbon fiber, Toray and Toho, each with business and technology ties to European and U.S. companies. Historically, Japanese carbon fiber technology was licensed to U.S. firms to build U.S. production capacity: Union Carbide (facilities now owned by Amoco) and Celanese (facilities now owned by Hoechst). These license agreements are due to expire soon, and Japanese fiber suppliers can be expected to enter U.S. markets. Hercules, another major U.S. carbon fiber supplier, obtained carbon fiber technology from Courtaulds in England.

Roughly 68 percent of the U.S. carbon fiber market is supplied by U.S.-based companies, as indicated in table E-2. The balance of the U.S. market is supplied by Japanese, European, or other firms. Japanese companies are building a strong position worldwide in PMC technology.

U.S. advanced PMC carbon fiber suppliers indicate that their only success in penetrating Japanese markets has been in supplying fiber for fabricating components being built in Japan for American programs. The following discussion of offsets will show that these programs are a significant force both in the development of foreign markets and the transfer of technology to foreign firms. These

Table E-2—World Market Shares In Carbon Fiber for PNCs

	Market Share, percent				
Supplier	Us.	Japan	Europe	Taiwan	Other
United States	68	5	9	3	4
Japan	21	86	68*	81	44
Europe**	8	2	21	10	45
Other	3	7	2	6	7
	100	100	100	100	100

*Via Japan and Japanese—European Joint Venture Facilities

**Non-Japanese

SOURCE: James N. Burns, "Relationship Between Military and Civilian PMC's,"presentation made at an OTA workshop, September 23, 1988.

suppliers feel that it will be very difficult for the United States to participate in Japanese markets.

The Japanese also have a large share of European markets, either by shipping in fiber from Japan or through Japanese joint ventures (there are two in Europe). In Taiwan, the Japanese currently have a very large market share. Although U.S. industry leaders expect Japanese imports to decline as the Taiwanese build their own facilities, Japanese influence will remain high-since many of them will be Japanese-owned.

Offsets

Foreign production of U.S. aircraft components is growing. Manufacturing of composites for commercial aircraft has moved offshore in many cases. As table E-3 shows, a significant number of foreign companies are fabricating parts for U.S. aircraft manufacturers. This is largely the result of economic offsets that are used to secure sales of aircraft by offering portions of the aircraft fabrication to companies from the buying nation. Aircraft sales are of clear economic benefit to the United States in terms of the balance of trade, but the offset agreements associated with the sales enhance technology development and potential future economic competitiveness of foreign-owned advanced composites businesses, possibly at the expense of U.S.-owned firms.

Industry representatives generally believe that the transfer of technology to other firms is necessary and in the best interests of both aircraft manufacturers and materials supplier companies. Access to U.S. technology is provided to sell aircraft and thereby maintain the current competitiveness of the U.S. aircraft industry in international markets. On the other hand, some industry executives privately state that they would rather not use offsets, since they may generate unwanted competition later.

Airbus Industrie (a consortium of European companies) is now offsetting parts to the United States in order to encourage sales to this country. Some PMC industry representatives speculate that Airbus may be concerned that one day poilitical pressure will be applied to U.S. airline companies to avoid buying foreign-made aircraft. The more U. S.-manufactured components there are in the aircraft, the more Airbus will be able to resist that pressure. The dollar exchange rate may also make it more economical to fabricate parts in, for example, Tennessee, than in Europe today.

Besides securing aircraft sales, airframe companies use offsets to force their suppliers to bear some of the burden of inventory and work-in-progress costs of non-military programs for which there are no progress payments.

Foreign Dependence

A clause contained in the DoD Appropriations Act passed in December 1987, required carbon fiber producers to secure at least 50 percent of their raw materials (PAN precursor) from U.S. sources by 1992.[3] The legislation (H.R. 395, Section 8088) is aimed at assuring the availability of U.S. sources of defense-related carbon fibers, which are used principally to build advanced structural components for military fighters and attack aircraft. The requirement specifically applies to carbon fiber manufactured from polyacrylonitrile. Four major U.S.-based carbon fiber producers are affected by the law: Hercules (by far the major supplier of fiber made from this precursor), Amoco, BASF (West Germany), and Courtaulds-Grafil (United Kingdom).

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[3] In 1985, the Assistant Secretary for Defense Acquisition and Logistics issued a statement expressing concern that there be some domestic source of *production* of PAN fiber precursor. This ultimately led to the legislation described in the text.

Table E-3—Foreign vs. U.S. Production of U.S. Aircraft Components

	Aircraft				
Supplier	767	757	737	F-16	MD-11
Foreign					
Aeritalia, Italy	X	X			X
Casa, Spain	X	X			X
Saab, Sweden	X	X	X		X
Westland, UK					X
Kawasaki, Japan	X	X	X		X
Mitsubishi, Japan					X
Fuji, Japan	X	X	X		X
Fokker, Netherlands				X	
IAI, Israel				X	
Cyclone Aviation, Israel				X	
Korean Air, Korea					X
Fleet, Canada	X				X
Embraer, Brazil					X
Short Brothers, Ireland	X	X	X		
United States					
Heath Tecna			X		X
Rohr Industries			X		X
Rockwell	X				
Grumman	X	X			
Cessna	X	X	X		

SOURCE: James N. Burns, "Relationship Between Military and Civilian PMC's" presentation made at an OTA workshop, September 23,1988.

Until 1987 there were no U.S.-based PAN precursor suppliers to the military. Hercules, the major supplier of carbon fiber for military applications, buys precursor from Japanese suppliers. Industry experts believe that DoD concern for domestic supply on this issue is tied as strongly to breaking up a single-source situation for carbon fiber supply as it is to ensuring that the one production link taking place entirely abroad be brought into the United States. Amoco produced PAN precursor in the United States but was not qualified for military programs. Since 1985 three new plants have been built in the United States, and Amoco's fiber has been qualified for some military aircraft.

Foreign-owned firms may have some difficulty qualifying their products with the DoD, and greater difficulty establishing classified facilities. Some industry analysts cite greater difficulty accessing programs at foreign-owned facilities even after qualification is achieved. However, many companies with U.S. facilities are generally treated as U.S. companies regardless of ownership, once the initial hurdles of classification have been overcome.

Industry Structure

It is difficult to separate foreign and domestic interests in any review of the U.S. advanced composites industry. PMC suppliers are extremely intertwined, whether one considers corporate vertical integration, or integration with major markets, airframe producers, and multinational markets.

In order to grasp the industry's structure, one must understand the process by which PMCs are made. Advanced composites are formed in a series of stages, beginning with raw materials and ending with finished parts sold to (or made by) such end users as the airframe manufacture. Raw materials include: carbon fiber precursor, the carbon fiber made from the precursor. and the epoxy resins forming the matrix. These are used to form prepregs (impregnated woven fabric, impregnated tape, or individual fiber strands coated with epoxy). These prepregs are then formed into shapes, and cured and trimmed to become final parts (see figure E-3 for a schematic of PMC production). For purposes of the following discussion on the industry structure, it is necessary to define three distinct production phases: 1) raw materials, 2) prepregs and shapes, 3) components for end use.

Companies supplying raw materials are generally the large oil companies (Amoco, British Petroleum, Shell) and large chemical companies (BASF, Ciba-Geigy, DuPont, Hercules). There are some compa-

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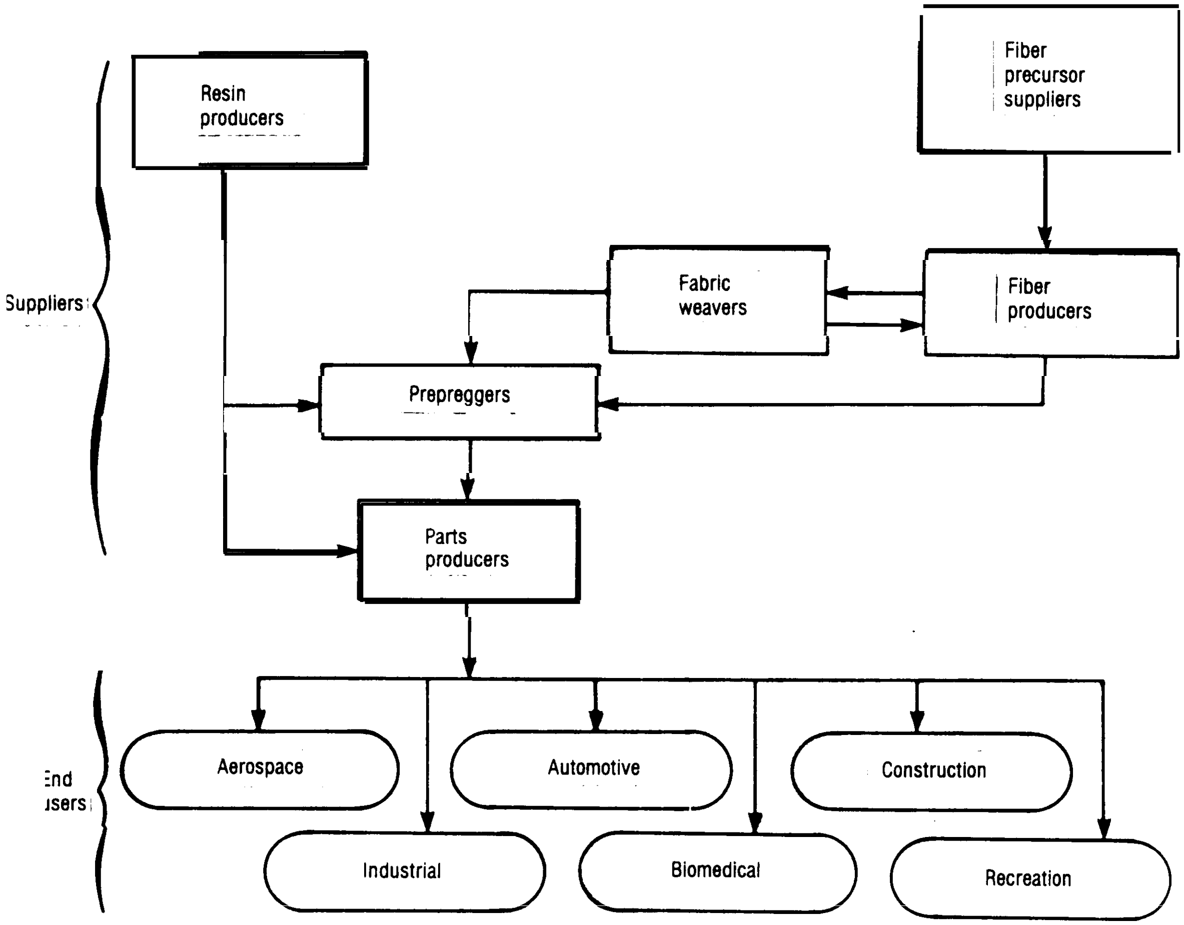
[4] Narmco and Celion Carbon Fiber, owned by BASF of West Germany; Hitco and Standard Oil Advanced Materials,owned by British Petroleum; Fiberite, owned by ICI of the United Kingdom; and Heath Tecna Aerospace, owned by Ciba-Geigy of Switzerland.

Figure E-3--PMC Industry Structure



SOURCE: Office of Technology Assessment, 1990.

nies that are mainly fiber suppliers (Hercules, Courtaulds-Grafil, Toho Rayon, Toray), and one company that is mainly a prepreg and composite shape supplier (Hexcel). Of the 26 companies in the PMC trade association, SACMA[5], 12 are U. S.-owned, 9 are owned by Europeans, and 5 are Japanese-owned.

Corporate Integration

Most of the companies listed above are attempting to integrate vertically (the present degree of industry integration is shown in table E-4). Raw materials suppliers are moving downstream into prepregs and shaping, into more value-added products. The value added in advanced PMC structures, as opposed to commodity fibers, is large: carbon fiber is priced (near cost) at $20 to $25 per pound, prepreg sells for $40 to $55 per pound, but the final structure cost is $250 to $600 per pound.

Airframers, which had relied on shapers and prepreggers for part forming have been moving the making of parts in-house, buying only the raw materials. One company (Hercules) is integrating horizontally, expanding its production to composites other than aircraft that have military applications. Companies throughout the industry buy and sell to each other and compete with each other for business from military prime contractors.

The industry structure plays a very important role in discussions of global movements of technology, civilian versus military needs, and policy objectives.

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[5] Suppliers of Advanced Composite Materials Association.

Table E4-Participation of Key Firms in the U.S. Advanced Composites Industry, 1986

	Advanced material products[a]			
Company	Base resins	Fibers	Prepregs	Shapes
American Cyanamid			X	
Amoco Performance Products	X	X	m	m
Avco		m	m	X
BASF		X	X	m
Boeing				X
Ciba-Geigy	X		m	
Dow Chemical	X			
DuPont	X	X	m	m
Ferro			X	
Grumman				X
Hercules		X	X	X
Hexcel			X	m
HITCO		m	X	X
Hysol Grafil		m	m	
ICI	X			
ICI Fiberite			X	
Lockheed				X
LTV				X
McDonnell Douglas				X
Northrop				X
Phillips 66	X		m	m
Rohr Industries			X	
Shell Chemical	X			
United Technologies				X

[a] X = major product; m = minor product.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

For purposes of this chapter, two stages of integration are defined: materials suppliers (including the intermediate suppliers, the prepreggers), and end users. Fibers, and to a lesser extent prepregs, are sold more as commodity materials, in a standardized fashion; end users and part shapers develop very individually tailored structures for each application.[6] Because of this dichotomy, fiber suppliers' style of business differs markedly, from that of end users. The following discussion of global markets contrasts the market situation of the raw material suppliers with that of the major end users (U.S. airframers and Far East sporting goods manufacturers).

The Carbon Fiber Market

World demand for carbon fiber has grown from a little over 7 million pounds in 1987 to over 8 million pounds in 1988 (as indicated in table E-5) and is predicted to grow to 20 million pounds by 1995. In the United States, the market is a little over 3.5 million pounds, predicted to grow to about 12 million pounds by 1995. About 65 percent of the U.S. carbon fiber market is in aerospace (both military and commercial *aircraft)*, and the market is forecast to remain over 65 percent aerospace during the 1990s. Over half of the U.S. aerospace market for fiber is military; 25-30 percent is commercial. Military applications are projected to grow by as much as 22 percent annually in the next few years.[7]

The U.S. aerospace market is a primary target for foreign companies producing carbon fiber composites because it is the largest, most advanced, and most attractive market (see table E-5) in terms of sales and profitability. The second largest market is the Far East, where carbon fiber products are used in sporting goods (tennis rackets, golf clubs, and the like). The world sporting goods market for carbon fiber is likely to grow at 5 to 10 percent per year.

Based on the assumption that the military market will exhibit the growth projected above, the U.S. market on the whole is likely to grow faster than the world market. Although the number of U.S. military aircraft being built is declining, composites are replacing much of the metal (aluminum) on air-

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[6] There arc a large number of fibers developed to meet different needs, but fibers in general are a commodity product, and will become more so as the technology matures.

[7] From the presentation of James Burns, Hercules, Inc., at the OTA workshop on polymer composite% Sept. 23, 1988, Wash., DC.

Table E-5—World Market for Carbon Fiber, 1888 (pounds, millions)

	Application			
	Aerospace	Industrial	sports	Total
United States	2.44	.90	.35	3.69
Europe	.94	.22	.38	1.54
Far East	.10	.10	2.43	2.63
Other	.10	.15	.20	.45
	3.58	1.37	3.36	8.31

SOURCE: James N. Burns, "Relationship Between Military and Civilian PMC's" prsentation made at an OTA workshop, September 23, 1988.

planes. An older plane, the F-16, has 260 pounds of composite per aircraft; the V-22, which is in the full-scale development stage, has 6,500 pounds (flyaway weight) per aircraft. This represents a tremendous growth in the use of composites. The U.S. market is projected to grow rapidly in the near future, due partly to this continuing replacement of aluminum with advanced PMCs. However, sometime in the mid-1990s this large growth due to substitution should level off, as advanced PMCs move into a high percentage of primary and secondary structures.

Given the large budget deficits with which the Congress must contend, the reluctance of the President to raise taxes, and the current perception of a diminished Soviet threat, the market projections for growth of PMCs in military aircraft may be unrealistic. Advanced composite suppliers are rightly looking toward other markets (commercial aircraft, industrial applications) to support the large production capacity developed in response to new military programs.

Although the major use of advanced composites is in the aircraft industry, carbon fiber materials also play a major role in strategic missile hardware and are forecast to move into weapon systems for all branches of the military. Large amounts of composites would be used in the heavy-lift launch vehicles required to put large payloads into space during the 1990s. A potentially large volume industrial market segment (primarily autos) is forecast for the mid-to-late 1990s.

Overcapacity of Carbon Fiber

At 16 million pounds, worldwide nameplate carbon fiber capacity is twice the current market volume.[8] Japan, with 6.9 million pounds, and the United States, with 5.8 million, have about equal capacity. Japanese companies manufacture carbon fiber precursor which is then sold to U.S.-based carbon fiber suppliers, mainly Hercules and BASF/Celion. Hercules, in turn is the major supplier of fiber for military programs. At present. very little Japanese carbon fiber is supplied directly to U.S. military programs. Most of Japanese carbon fiber goes into U.S. commercial aircraft Japanese programs, and the Far East sporting goods market.

U.S.-based industry is continuing to add carbon fiber capacity (about one million pounds in 1988). This fact indicates that, worldwide, there is and will continue to be a great deal of excess capacity. However, while the United States has a large fiber overcapacity compared to domestic market requirements, industry opinion is that most of the worldwide excess capacity is in Japan rather than the United States. Although excessive, the U.S. carbon fiber capacity (5.8 million pounds) is still better matched to the U.S. market size (3.69 million pounds).

Worldwide prices are low mainly due to excess capacity in the Far East; Japanese-made fiber is sold to Taiwan at a loss. While the Far East sporting-goods market is as large as the U.S. aerospace market, its low profitability makes it far less attractive to fiber suppliers than the U.S. aircraft market. It is not known why the Japanese fiber

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[8] Nameplate refers t. an estimate of capacity, rather than actual capacity. Carbon fiber is sold in bunches, called tows, of 3000, 6000, or 12,000 fibers per tow, Mall carbon fibers were sold in tows of 12,000 fibers (the predominant carbon fiber product sold), then nameplate capacity would be equivalent to actual capacity. Real capacity is approximately two-thirds of nameplate capacity.

suppliers are building up such excess capacity. These companies may be overoptimistic about the growth rates of their larger present markets; they may expect to enter U.S. aircraft markets as licensing agreements expire, or to be suppliers to a Japanese aircraft industry as it evolves. The companies may also be gaining production experience in an effort to lower production costs to the point where they can supply these materials in quantity to automobile manufacturers.

There are two possible reasons behind the present U.S. overcapacity. First, the U.S. fiber suppliers misread the military fiber market, adding excess capacity to respond to a military demand that never appeared. While profitable, the military market does not generate high volumes. In continuing to bring new capacity on-line, carbon fiber suppliers exhibit optimism about future use of carbon fiber in civilian and military aircraft. Since the United States is undergoing a budget squeeze, it may be that fiber suppliers are again misreading the market when adding new plant capacity. However, market projections for the carbon fiber market as a whole (including both civilian and military aircraft as well as sporting goods) predict very healthy growth over the next decade: 12 percent annually.[9] Consequently, many companies are continuing to enter the market place.

Second, overcapacity may be endemic: large military projects (like the Titan 4) encourage overcapacity by enticing too many materials suppliers to gear up production. Since the main market is military, and market forces are not allowed to work as they would in the private sector, it may be that overcapacity (which keeps material costs to the primes and the military low) is a direct result of the way that the government and military aircraft prime contractors have structured the market.[10]

Material suppliers feel that overcapacity has created such unprofitability that it is unhealthy for the industry as a whole. Airframe companies, on the other hand, benefit from chronic fiber overcapacity. Assuming that Japanese overcapacity is not affected by U.S. military needs, worldwide overcapacity is not entirely due to the military market structure. Carbon fiber also goes into the sporting goods market at very low prices-at a loss in most cases. Companies manufacturing tennis rackets are making a profit, while companies supplying material to the tennis racket manufacturers are merely dumping excess capacity .11

Intermediate Suppliers

Some material suppliers also see an excess of U.S. part fabrication capacity, with as much as 50 percent underutilization. Airframe manufacturers, though, see a shortage of qualified, economical parts fabricators. Even in the teeth of this oversupply, some airframers see it as less expensive to tool up to fabricate parts in-house than to pay the overhead required to use some of the existing parts fabrication capacity.

End Users of Advanced PMCs

While the U.S. PMC industry is healthy, it is concentrated in the defense/aerospace sector. On the strength of its military aircraft and aerospace programs in advanced PMCs, the United States leads the world in developing and using advanced PMC technology. But according to industry representatives, foreign commercial end users outside the aerospace industry are more active in experimenting with these new materials than are their U.S. counterparts. For example, Western Europe is considered to lead the world in composite medical devices.[12] The European Community (EC) also has several efforts underway to commercialize advanced PMCs in automobiles; outside of the EC in Europe, the EUREKA Carmat 2000 program proposes to spend $60 million through 1990 to develop advanced PMC automobile structures.

Looking at the aircraft industry, Western European commercial aircraft manufacturers use more composites per aircraft (specifically, the A320) than U.S. commercial airframersdo. France is by far the dominant force in advanced PMCs in Western Europe, with sales greater than all other European countries combined. West Germany, the United Kingdom, and Italy make up most of the balance.

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[9] From the presentation of James Burns, Hercules, Inc., op. cit., footnote 7.

[10] The structure of the government market in the absence of private sector market forces is discussed further at the end of the appendix, in the section on teaming and second source requirements.

[11] A carbon fiber production facility needs to be operated near capacity. A fiber line operates at very high temperature, and once the line is up and stabilized, it needs to be run continuously.

[12] The regulatory environment controlling the use of new materials in the human body is currently less restricted in Europe than the U.S.

Airbus is the single largest consumer of advanced PMCs in Western Europe.

In the past few years, the increase in participation of Western European-owned companies in the U.S. advanced PMC market has been dramatic. This has occurred mainly in the form of acquisitions of U.S.-owned companies. Industry analysts indicate that U.S. carbon fiber facilities have been sold due to corporate "impatience" resulting from the need to report favorable quarterly earnings. In general, foreign corporations tend to be more patient; despite excess worldwide capacity and profitability problems, for example, the Japanese have not sold any carbon fiber facilities. Foreign companies want to participate in the U.S. market for carbon fiber, prepregs, and parts. Materials suppliers feel that the foreign interest in U.S. firms reflects a desire to enter the U.S. aerospace market and share the technology leadership that participants enjoy.

Although Japan is the largest manufacturer of carbon fiber in the world, it has been only a minor participant to date in the advanced composites business. Japanese companies have been limited by licensing agreements from participating directly in the U.S. market. Japan also does not have a domestic aircraft industry to which companies can sell advanced PMCs, although it is trying to establish one as it did with automobiles.

Foreign-Owned Firms

The U.S. PMC industry is healthy because U.S. aircraft industries are healthy. The largest, most profitable, and fastest growing market for PMCs in the world is U.S. aircraft (mostly military aircraft). U.S. overcapacity of carbon fibers exists in large part because of PMC market analyze (and general optimism) projecting strong growth in U.S. PMC production for aircraft-civilian as well as military.

Players in the PMC structure market must be U.S.-located for two reasons: 1) coordination of production and technology development with co-suppliers and customers, and 2) DoD regulations and Congressional legislation on domestic sourcing. However, neither of these factors requires that companies be U.S.-owned. New developments by foreign companies in PMC technology flow naturally and swiftly toward the U.S. aircraft market, end users want the latest technology regardless of source, and suppliers will go where the market is. No decapitalization is occurring; in fact, the opposite holds since foreign firms are putting long-term investment into new and acquired U.S.-based facilities. Production of fibers and resins need not even be U.S.-located, since these are commodity products: standardized, relatively high volume, and low value--added.

Like U.S.-owned plants, foreign-owned plants employ U.S. skilled and unskilled labor, and much of the research is conducted in the United States, with the attendant high-paying positions. Foreign-owned companies are as willing as U.S.-owned companies are to comply with Congressional legislation, DoD and FAA regulations, DoD policy goals, and military program requirements. Very telling is the fact that U.S.-owned PMC firms do not have the complaints against foreign-owned firms commonly heard in other industries, and industry representatives are quite comfortable with the international orientation of their industry.

What would be the possible reactions of foreign-owned companies if the U.S. aircraft industry were to become "unhealthy" in a relative sense? Although the United States is still the dominant aircraft supplier worldwide, Airbus is making significant inroads on U.S. market share.[13] Japan's pursuit of a commercial aircraft industry through offsets and joint venture arrangements with U.S. and European airframers will lead to a formidable commercial aircraft industry in Japan at some point however distant that might be. If Airbus Industrie, other European airframers, or Japanese aircraft manufacturers capture enough of the world market share for aircraft, it could profoundly affect the U.S. PMC industry.

If these trends hurt the domestic aviation industry, U.S. airframers might feel it necessary to engage in less PMC development and use as profits fall. Alternatively, they may increase use of PMCs, seeing this as away to gain a competitive advantage, particularly if rising fuel costs are a factor. Airframers might choose to move significant levels of production abroad if planes could be assembled

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[13] Airbus Saks still represent a small fraction of the North American fleet, but the consortium is expanding its North American presence rapidly: 70 percent of all Airbus sales to North America over the past ten years occurred in 1987-88 and, if all options arc exercised, there will be more than 450 Airbus aircraft in service on the Continent by 199S. Total Airbus sales in North America for 1988 were $20 billion for 348 aircraft, according to "Canadian Orders Strengthen Airbus' Role in North America", *Aviation Week and Space Technology, Aug. 8,1988, p.68.*

more cheaply offshore, thus hurting U.S.-based PMC suppliers.

PMC manufacturers might follow the airframers by moving fiber, resin, or prepregging facilities from the United States to the countries with the largest pool of end users. This sort of movement would be attractive to both U. S.- and foreign-owned firms of large size and with currently established international interests. PMC manufacturers maintainingg the majority of their facilities in the United States (most likely U.S.-owned firms of small size) would have to choose one of several options: 1) bank on other potentially sizable markets (such as automotive applications); 2) become entirely military in orientation, while integrating further up- or down-stream; or 3) restructure (shrink) to rely on niche markets in biomedical, sporting goods, or industrial applications.

If the United States were to depend entirely on foreign-owned firms at a point when U.S. aircraft manufacturers were seriously losing market share, and if these foreign-owned firms moved offshore at this point, the U.S. military could find itself in a bind: Without the latest in PMC technology, the military would be forced to choose between buying foreign-developed aircraft or propping up a domestic aircraft industry, spending money now spent by commercial industry on PMC development, or buying significant types and amounts of strategic raw materials from foreign-based suppliers. For good reason, no industry or DoD representative has expressed so pessimistic a view, since the United States currently has the world's strongest aircraft industry—whether one considers innovations in PMC technology, new product technologies, or the use of PMCs in military aircraft. The point, though, is that Japanese and West European aircraft communities are not standing still; DoD will have to have face this issue of dependence on foreign suppliers, whether in 10 or 30 years.

CONVERGENCE/DIVERGENCE OF CIVILIAN AND MILITARY TECHNOLOGY

Military and civilian applications of advanced PMC technology both converge and diverge. It is difficult to know how much of the divergence is due to the nature of the military environments in which the technology must function, and how much to the regulations, government standards, military specifications, and contracting procedures that have accumulated over time. Most of this section considers technical and economic issues of convergence and divergence, with the remainder devoted to "artificially induced" differences between the military and commercial advanced PMC sectors.

Although military and civilian markets have different technical and cost criteria for selecting materials and process technology, both kinds of applications aim to meet the necessary performance criteria at the minimum cost. As will be seen, the particular application, not its military or commercial purchaser, is the strongest determinant of the material used. Convergence and divergence occur simultaneously in different aspects of the PMC industry and its markets.

Cost vs. Performance

Various segments of civilian and military markets place different emphases on performance and cost. In commercial aerospace, military non-aerospace, automotive, and construction markets, for instance, acquisition costs and operating expenses are the major purchase criteria, with a progressively lower premium placed on high material performance. In military aerospace, biomedical, and space markets, on the other hand, functional capabilities and performance characteristics are the primary purchase criteria.

The sales potential of advanced composites is greatest in the automobile and commercial aircraft markets. Construction materials are used in high volume, but must have a low cost; biomedical materials can have high allowable costs, but are used in very low volume.

cost

In the automotive and industrial markets, the major factor determining the value of advanced composites is the reduction of production costs, although in some cases, a performance premium may be passed on to those car buyers interested in high performance or fuel economy.

In commercial aircraft, composites have to earn their way in economic terms. Commercial airframers base the choice of advanced PMCs on the purchase criteria of the customers, the commercial airlines. Airlines weigh the balance of initial cost with the cost over the lifetime of the aircraft, including maintenance and fuel cost.

At a time of rising fuel costs, a composite empennage may have been necessary for U.S. aircraft manufacturers to compete in the commercial aircraft market. Today's relatively "stable" energy costs have minimized the value of weight savings for the present.. In 1978, one airframe manufacturer estimated that at a jet fuel cost of $2 per gallon a single pound of aircraft weight saved was worth approximately $300; today, fuel costs $.80 per gallon and weight savings is valued at roughly $70 per pound. (This measure of the importance of fuel costs is generally valid for new aircraft designs, but would not be a determining factor in changing established production of aircraft.)

Competing vs. Enabling Materials

Despite the ability of advanced composites to provide the same strength and integrity with fewer pounds as high-strength aluminum alloys, other economic benefits are needed to justify their much higher costs. Polymer composites in these markets are just one of a number of competing materials.

Although military and commercial functional requirements (low weight, high strength for primary structures, lower strength for secondary and nonstructural parts) converge, it is their stringent mission requirements that drive the use of advanced composites in military aircraft. For space applications and fighter aircraft, advanced PMCs are more than just one of many competing materials; they can be the enabling technology for mission requirements because of their high stiffness and strength-to-weight ratio.

The use of lower-cost materials (such as glass-reinforced composites) in general means more weight and lower performance (lower stiffness) in the traditional aerospace sense. Industry experts feel that to get the edge on the battlefield, weapons systems must weigh less. That is why composites, particularly carbon-reinforced composites, were attractive at their inception. Lower costs are needed in the military aerospace sector, but performance remains the major driver.

Processing

Seventy to eighty percent of the cost of a finished advanced PMC part is due to fabrication. As discussed previously, developing production technology to reduce fabrication costs is critical to commercial industrial, automotive, or marine applications. Several composite part-forming technologies are more advanced in the industrial/automotive world than in military applications. Table E-6 indicates the status of various low-cost composite material technologies in terms of meeting military application requirements.

For military and commercial aircraft, the structures made from composites (e.g., wings, fuselage, and empennage) are similarly complex to fabricate. The basic method of production of aircraft parts is also similar: coating of continuous fibers with resin, careful placement of fibers, and application of heat and pressure to form the structure. Many developments have wide applicability across both the civilian and military arenas. There is synergism between military and commercial aircraft produc-

Table E-6—Status of Emerging Low-Cost Composite Material Technologies

		Development Status		
Process	Application/Potential Benefit	New Techn.	Developing Techn.	Production Ready
Filament Winding (Thermosets)	Near cylindrical parts			●
	Complex shaped parts		●	
Filament Winding (Thermoplastics)	Near cylindrical parts		●	
Resin Transfer Molding	Complex thermoset parts with continuous fibers		●	
Compression Molding	Complex thermoset and thermoplastic parts with chopped fibers			●
Pultrusion (Thermosets)	Constant cross-section parts		●	
Pultrusion (Thermoplastics)	Constant cross section parts		●	
Injection Molding	High production rate process for thermosets		●	
Reaction Injection Molding	High production rate and quick cure of thermoplastics	●		
Thermal Forming	Complex thermoplastic parts with continuous fibers	●		
Superplastic Forming Of Thermoplastics	Complex parts		●	

SOURCE: McDonnell Douglas Astronautics Company, Missile and Defense Electronics Division.

tion in resins and fibers, the way materials are stitched together, and the way they are used.

However, military applications have requirements that may force a modification of the fabrication process. For example, a process called pultrusion is typically used in producing beams for industrial applications. Military applications need superior load-carrying properties, so that for military applications pultrusion must be modified to impart different properties to the fabricated part.

Lower-cost processing technologies are being evaluated in the Low Cost Composite Weapon Program (located at Eglin AFB). This program looked at three different low-cost commercial approaches for building an interdiction missile airframe:

- Compression molding (from the automotive industry),
- Pultrusion processing, and
- Resin transfer molding.

The goal of the Low Cost Composite Weapon Program is an order-of-magnitude reduction in cost lowering airframe costs to the $10,000 to $20,000 range. It was developed to examine the civilian market and assess the application to defense systems of materials and technology used in automotive and other commercial enterprises.

The initial objectives were to save weight, reduce costs, and make materials capable of traveling at higher speeds and operating at higher temperatures. In actuality, the fret-round demonstration of the application of commercial technology and materials sacrificed performance to achieve lower cost. The final design did not include carbon fiber advanced composites; low-cost materials (viz., glass fiber) were required to meet the program cost goals.

Production Volumes

Put simply, the military community often demands custom-made hardware, while commercial industries seek off-the-shelf products combining low cost and high quality. Many military and space hardware applications are very specialized and require low production volumes. The automotive industry, on the other hand, is driven by low costs and high production rates. Between the aerospace and automotive advanced PMC markets, a variety of other market applications (including the non-aerospace military market) have production rates higher than military aerospace, cost objectives similar to automotive applications, and moderate performance requirements.

Structural aircraft components may initially cost $1,000 per pound and fall to $230 per pound after production of 500 units. The DoD fiscal year 1989 budget forecast procurement of only four aircraft at these volume levels for fiscal years 1989-93:

Aircraft	*6-year total*	*Average production*
UH-60A helicopters	432 units	72 units/year
AH-64A helicopters	432 units	72 units/year
F/A-18A	504 units	84 unit/year
F-16 fighters	930 units	155 unit/year

Typical commercial production rates range from 130 per year (MD-80s) to 300-400 per year for Boeing commercial aircraft (all models).

Material quantities required for small missiles are significantly greater. Thousands of missiles such as the Stinger (6,750 units in fiscal year 1989) and the laser Hellfire (5,000 units in fiscal year 1989) are built annually. For these and similar weapon systems, materials requirements for casings and fins approach automotive composite part production levels. In the automotive industry, production of 100,000 structurally identical vehicles *is* not unusual, although special units may be built at "low" production levels of 20,000 units. (Composites have a cost advantage over steel for these specialty low volume automotive applications, mainly because composite tooling costs are lower.)

Specific Technical Performance Criteria

Military and commercial aircraft experience some similar environmental conditions, and because of this require similar lightning protection, corrosion resistance, fatigue resistance, and material toughness. While the technical requirements for PMCs in commercial aircraft are comparable to those for fighter aircraft, the major differences include:

- Military fighter aircraft are designed to technical criteria based on peak g-loading and maneuverability, while commercial aircraft are designed to meet high duty cycle and fatigue stress.
- Repair strategies for military aircraft emphasize rapid turnaround, while repair strategies for commercial aircraft emphasize lifetime durability.

- Military aircraft design and material selection must consider battlefield issues; stealth, repair of battle damage, and radiation hardening have no relevance in the commercial sector.
- Design temperatures for very high speed military aircraft are more severe than for commercial subsonic aircraft

Maintenance

Military and commercial aircraft have inherently different duty cycles. Military aircraft are on the ground a significant amount of the time, while commercial airplanes spend much more time in the air. Commercial aircraft designers are concerned with structural fatigue and takeoff-and-landing duty cycles. The dominant factors for maintenance of military aircraft are ground temperature, corrosion, and exposure.

Quality Assurance

Before a material can be used in a military or FAA-certified system, it must be "qualified" for use. Advanced composite materials are produced in the same facilities for both the military and commercial aerospace markets. For example, the same composite material is used in the production of components for the military C-17 and the civilian MD-11 aircraft by McDonnell Douglas; in fact, both aircraft use the same material specification. While the costs may be the same for FAA and military qualification of a material, the military can pay more to qualify a material. The entire cost of qualifying a material for a civilian aircraft is borne by the airframer and passed onto the customer; for a military aircraft the government is the customer. For any man-rated (e.g., piloted or passenger-carrying) application at least, materials will need to be qualified for use in either sector.

In the aircraft industry, material property databases are continually being developed to qualify new materials and combinations of materials. Each airframer, military or civilian, must conduct extensive tests on potentially useful materials to avoid any possibility of structural failure; thus, a certain amount of overtesting between materials supplier and user will always be necessary because of this issue of liability.

It can cost up to $10 million apiece to develop databases on individual new materials, and doing so can involve up to *3,000* individual tests by the prime contractor and a similar number by the material supplier. Much of the materials qualification expense for a military aircraft is borne by the Federal Government, either in the form of independent research and development (IR&D) overhead, or through specific program/contract charges paid to the prime contractor. Each prime contractor maintains expensive test facilities in order to develop its materials databases. Airframers consider these databases proprietary information.

Various groups are trying to reduce testing costs, among them: the airframers' Composite Materials Characterization, Inc.; the Suppliers of Advanced Composite Materials Association; DoD's Standardization Program (Composite Technology Program Area); and the American Society for the Testing of Materials.

Partly because of these expensive, time-consuming, and overly duplicative qualification procedures, the same material supplied for military use will cost a third more than for commercial use.[14] This may just be paying for a certain amount of necessary overqualification up front, rather than buying liability protection as commercial companies must do.

Government Regulations

Aircraft manufacturers, parts fabricators that subcontract to the aircraft manufacturers, and materials companies that contract directly with the DoD often must set up separate divisions to comply with government regulations and procedures. Although personnel can be transferred from the commercial

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[14] Contractor report by Technology Management Associates, summarizing a workshop entitled "The Relationship Between Military and Civilian PMC Technology," held at OTA, Sept. 23, 1988, Wash., DC.

divisions or hired from other defense contractors, industry analysts state that everybody in the defense division eventually thinks "government contracting." Due to accounting costs, the overhead charged by that division is much higher than that charged by the rest of the company.

It will be necessary for the military to relax regulations to meet the goal of low-cost composite weapons; however, some materials vendors have encountered great resistance to a straight military adoption of a commercial material in a military procurement

Diverging Business Approaches

Most of the points of convergence and divergence described above centered on technical or economic factors. There is also a certain divergence of business approaches in the PMC industry between the military and civilian sectors.

Approach To R&D

Managers of civilian aircraft companies do not understand the extent to which company money must be spent to participate in government research programs. The general view among military airframers seems to be that R&D contracting is a "loss leader." That is, although companies invest in product and technology development leveraged with government contract R&D money, these R&D projects do not turn a profit or break even. From the standpoint of companies that do business primarily in the commercial world (particularly small materials suppliers), R&D costs seem a substantial barrier to entering the military market.

Managements in the commercial sector are also unfamiliar with the government's way of doing business. Note that while commercial airframers are used to "betting the company" during the development of a new aircraft, and materials suppliers are used to putting in a great deal of development money on a new material, they expect large payoffs from these investments within a given time.

Auditing Procedures

One civilian aircraft manufacturer indicated concern over contracts that require monthly tracking of costs and schedule status of every part. It is estimated that using military specification accounting would have added $13 million to a $200 million contract. The accounting costs for fixed price programs were considered by some industry representatives to be unnecessarily burdensome. For example, in a subcontract for a secondary structural part for a military aircraft, more money is involved in accounting and reporting than in engineering.

BARRIERS TO ACCESSING PMC TECHNOLOGY

The military sector was the first to apply advanced composite technology. Although the PMC industry envisions a very large commercial market for advanced composites in the future, it sees limited commercial opportunities today. PMC suppliers feel that commercial development is the key to profitability in advanced composites, and that sustaining a presence in the military marketplace is a way to pursue it. However, companies (even the large ones) that do not currently participate in the defense arena have reservations about entering the military market.

Military contracting and accounting procedures, and the potential loss of proprietary rights and patentability, are distinct drawbacks to participating in the military composites market. This last factor is considered by some commercial sector companies as a threat to their survival in a competitive marketplace. Forfeiting proprietary rights goes against the "corporate culture" in many non-defense companies, and fear of such loss inhibits the flow of technology between the defense and commercial sectors. Due to proprietary concerns, technology developed in the commercial half of the company will not be shared with the military half.

These barriers inhibit, but do not prohibit, the transfer of technology between the civilian and military sectors. Participation by commercially oriented companies in recent defense programs such as the Low Cost Composite Weapon Program and C-17 subcontracts indicates that such companies are willing to engage in military programs. One factor frequently cited as significant in its effect on technology transfer is classification, which is discussed below.

Government Business Practices

Government business rules and regulations have inhibited the transfer of PMC technologies from commercial to military applications. For example, in 1978 ACF Industries had successfully developed an inexpensive glass fiber composite railroad car based on aerospace technology (filament winding of large shapes). DoD repeatedly approached ACF to use this technology in an ongoing defense program. ACF management declined to work with the government because putting up with the government audit procedures was more trouble for the company than it was worth.

Similarly, the teaming arrangement for the Low Cost Composite Weapon program was designed to augment a military aircraft manufacturer's capabilities with the lower-cost commercial technology of nonmilitary subcontractors. The lack of simple purchase orders for commercial sector contractors and complying with government accounting requirements met with stiff resistance. Commercial sector subcontractors expressed reluctance to participate because of the forms, audits, and justification of overheads.

According to an industry spokesman, small commercial companies fear working with a military prime contractor in this environment. One subcontractor on the Low Cost Composite Weapon team is under criminal investigation because of purported irregularities; apparently technical errors were made and the subcontractor did not comply with every detail of the specifications.

Military Contract Specifications

According to one military aircraft manufacturer, the process that generates "red tape" starts when Congress tries to solve a problem by creating legislation that implies action but does not specify exactly what needs to be done, then interprets Congressional action and creates a number of regulations. In a mirroring of DoD action, the prime contractors then impose more requirements on the subcontractors.

Classification of Programs

Personnel working on highly classified programs sometimes cannot obtain clearance from their program monitors to share what PMC industry representatives believe to be nonsensitive information, such as generic materials and process technology data. This generic information is often embedded in classified reports. It is costly for the military or the contractor to employ personnel to extract generic types of information from classified reports, even though it would benefit them in the long run to avoid duplication of effort. There is no tangible reward for either the military or the contractor to undertake the effort Even in cases where a military contractor has a commercial side that could benefit, and proprietary concerns are few, unsensitive information is not available outside the classified regime.

DoD has similar internal problems. There maybe technology under development in the "black world" that the rest of DoD could build on but does not know about. PMC industry representatives have indicated that more attention should be placed on the transfer of "black" technology into a "white" technology base.

One militaryairframe manufacturer reports difficulty finding people to work on classified programs, citing the fact that they get "lost" in a professional sense. Considering the cost of secure areas, monitoring, and clearances, industry representatives estimate that a classified program may cost two to three times as much as a similar unclassified program.

Unwillingness To Share Data

Some sharing of materials databases is necessary to reduce current costs, which are expensive. U.S. companies also need to share advanced materials databases if they are to compete effectively in global markets.

As an indication of this concern, seven U.S. aircraft manufacturers have created a consortium, Composite Materials Corporation (CMC), for materials database development.[15] CMC does not specify particular designs (i.e., provide design allowable); instead, it screens new composite materials for subsequent testing by the individual companies. CMC is funded only by the participating companies, and the data developed by CMC are proprietary to them as a group.

According to one U.S. aircraft manufacturer, these companies really do not want to cooperate with each other, but cannot afford to pay to evaluate all the new materials being developed. Some companies feel that information disclosed to the government would become public and might be used by their competitor in a different market.

Teaming and Second Sourcing Requirements

Forced teaming is a response to DoD's industrial preparedness concerns: without a significant commercial business base in advanced composites,

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[15] Several major airframers have not joined in this effort.

maintenance of the PMC industrial base has been taken to be the responsibility of DoD. For example, under the current teaming philosophy, DoD selected two teams from multiple competitor to develop the Advanced Tactical Fighter. Military aircraft manufacturers and DOD personnel contend that the team members, who normally are competitors, are willing to share technology to improve the chances that their team will eventually win procurement contracts large enough to benefit all the team members.

From the viewpoint of one military airframe manufacturer, military second source programs do not enhance the health of the industry; they drive down the price of a particular weapon system at the expense of industry. For example, in some instances contractors are awarded 70 percent of production one year and a competitor is awarded 30 percent. PMC industry representatives feel that a new DoD procurement is offered only when the smaller supplier will bid anything just to keep from shutting down production. The second sourcing approach exacerbates the competitive nature of the business and inhibits the willingness of competitors to share data and team naturally on other programs. Competition is heightened further in programs for which the lead prime contractor (with 70 percent of the procurement) is required to provide assistance, including materials technology, to the second source contractor.