International Competitiveness in the Advanced Materials Sector: the case of carbon fibre

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INTERNATIONAL COMPETITIVENESS IN THE ADVANCED MATERIALS SECTOR:
THE CASE OF CARBON FIBRE

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ABSTRACT

Carbon fibre is the most commercially significant of the advanced materials, and its development has been driven by both civil and defence interests. With the end of the Cold War, demand from the defence sector virtually collapsed. The data presented in this thesis reveal the consequent global restructuring of the industry. Over the five year period 1990-1995, European market share fell over twenty percentage points, while that of Japan increased markedly. Meanwhile, US production levels faltered and then recovered following government intervention to stabilise this dual-use technology. This thesis examines the subsequent international shift in the location and ownership of carbon fibre production capacity and the variation in corporate response over this turbulent time. It is found that the national business systems in which this particular high technology sector operates have played a fundamental role in shaping the eventual competitive structure of the industry.

DECLARATION

I declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Celia Russell, October, 1996

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Celia Russell holds an honours degree in Physics from the University of Oxford and a Masters Degree in Nuclear and Elementary Particle Physics from the University of London. She subsequently worked at the National Physical Laboratory in the area of radiation science and, concurrent with this, undertook a number of secondments in Whitehall working on R&D management within the electronics industry. Following this experience, the author obtained a Masters Degree in Technical Change and Industrial Strategy at the University of Manchester, where she has continued to study for the degree of Doctor of Philosophy.

For
Robert Heanue, Elisabeth Cardew and Louis Collingwood

CHAPTER ONE:
METHODOLOGY AND CONTEXT

Introduction

For advanced nations, technological competitiveness is a key industrial objective and a significant determinant of economic growth. This thesis examines some of the influences that constrain and stimulate technological competitiveness at an international level, in particular those relating to the ownership and location of a high technology sector. These influences will be explored through a case study of a particular high technology sector, namely, advanced materials, a global business in which international patterns of trade reflect well the technological competencies of the individual nations.

Advanced materials are of particular interest to industrial strategists, economists and policy makers, not least on account of their potential impact across a wide range of future industries (as highlighted by Kodama)[1] and the long time scales involved in their development. They are perceived as an enabling or generic technology, i.e., one that underpins many other manufacturing technology sectors, most particularly the defence, aerospace, electronics, energy, construction, automotive, healthcare and machine tool industries. These sectors in turn are all high ranking in terms of economic performance and, in the case of defence, aerospace, electronics and energy, are also of considerable strategic interest.[2]

It is therefore not surprising that the new materials sector has spawned a wealth of government initiatives and programmes. The OECD publication *Advanced Materials: Policies and Technological Challenges*[3] details the national advanced materials policies of eighteen countries, who collectively spend well over a billion dollars in government funds annually on support for the advanced material sector. Despite this enormous investment of money and effort, and the suggestions in the literature of possible national production capability trends, the data, if it exists at all, is extremely patchy. Consequently, there is a striking absence of robust time series data on actual production capabilities. For example, neither the OECD monograph cited above, nor the UK Collyear report[4] contain such data, while, astonishingly, even the US Department of Commerce report *A Competitive Assessment* *of Selected Reinforced Composite Fibres*[5] is only able to give concrete data for one country, that of the US itself. The lack of quantitative information has been noted by the US DoD which commented in 1996,

> "The competitive standing of the US industry is difficult to pin down because there is very little trade data available for carbon fibre."[6]

Of the advanced materials, carbon fibre is by far the most commercially significant. The purpose of this research therefore is to gather production capacity figures for all the major carbon fibre producers outside the former Soviet Union (FSU). This is then organised by geographical region and ownership over time, to test if national production capacity trends actually exist. It may seem odd that this sort of fundamental data has not already undergone collection but, as we see below, there are many barriers to accurate data acquisition in this particular sector. Carbon fibre produced in the FSU has not, until very recently, been traded on the world markets. Japan, the United States and Western Europe collectively account for 97% of global carbon fibre production (outside the FSU),[7]and are therefore the focus of this research.

The primary data collected in this thesis reveal that there has been an international shift in the global production of carbon fibre. Post 1990, the industry underwent a number of expansions, closures and acquisitions, a restructuring precipitated by a sharp and unexpected fall in demand from the defence sector. Production and consumption data were collected from the individual producer firms and the other sources cited below. These are then organised by geographical location and ownership to reveal a pattern of shifting control and ownership. Japanese firms, it will be shown, took advantage of the difficult market conditions to markedly increase their market share, largely, as we shall see, at the expense of European producers. The market share of US firms first faltered over the period 1990-1993, then recovered as Congress intervened to maintain national competitiveness in this strategic material. Thus, the data collected does reveal significant cross regional variation. The possible underlying causes for this then become the focus of the thesis. Industry respondents questioned during the course of the research cited two explanatory factors as to the regional variations in competitiveness, namely, corporate governance and defence-civil interactions.

There is an extensive literature on international competitiveness, dating back to the work of Adam Smith and David Ricardo. Within the neo-classical economics paradigm, competitiveness is driven by comparative advantage (in labour costs or the availability of natural resources, for example) and macroeconomic variables such as levels of savings and investment. Porter has refined these arguments in his study *The Competitive Advantage of Nations*,[8] uncovering additional contributing factors such as the presence or otherwise of related industries. Porter's work is essentially a very thorough reductionist analysis. By contrast, Whitley[9] and others argue that business systems are culturally specific and it is these broader and more complex factors that most profoundly affect industrial development.

Carbon fibre is a dual use technology and the military has played a fundamental role in its industrial development. Kaldor[10] has, famously, argued that the complexity and cost of weapon systems hinders diversification or creates similarly "baroque" civilian technologies in which high performance is pursued at uncompetitive marginal costs. Authors such as Reppy and Gummett[11] stress the specific organisational features of the defence sector which act as barriers to diffusion. All the arguments cited above are re-examined in the light of the data gathered over the course of this research, including the micro-economic financial ratios for the individual carbon fibre producing firms which are presented along with the production capacities in Chapter Five.

Structure of the Thesis

The first part of the thesis is drawn from the current literature, Firstly, in this chapter we examine the new materials industry as a whole, defining the technology and highlighting the characteristics of the sector. In Chapter Two, we look at the technology characteristics of carbon fibre itself, and its major applications. We will then set the scene for the second part of the thesis by comparing the industrial and financial structures of the major carbon fibre producing regions.

The second part of the thesis is largely based on the information gathered during the course of this research. Before turning to the post-1990 activities of the industry, we first present in Chapter Four a history of the development of the carbon fibre technology, production and markets from its inception in the 1960's, through to its early commercialisation, and finally the period of explosive growth in the industry throughout the 1970's and 80's.

Chapter Five collates much of the individual company data concerning the period 1990-1995. By organising the capacity figures by country, the Tables reveal international shifts in the ownership of production. How and why these shifts occurred then becomes the focus of the chapter. The corporate finance and accounting practices of the producing firms are explored in some detail, as is the military context of the time. Finally, we draw these threads together in the concluding chapter.

Methodology

It is appropriate here to make some brief comments on the methodology of the research and the sources utilised. It is worth noting that there is very little published data regarding the production, shipments, uses, imports and exports of carbon fibre, partly as it is a relatively new industry, but largely due to the proprietary nature of its manufacture. Individual company production, capacity and end use data are virtually non-existent as the companies regard much of the data concerning carbon fibre as company confidential and figures are often reported in basket categories such as speciality chemicals or performance materials.

Hence the bulk of the company information presented here was collected over an 18 month field based study. Concurrently with this ran a secondary source search. Trade press and business intelligence reports were used to identify the key players and build up a preliminary picture of the development of the industry. The Japanese trade journal *Kagaku Kogyo Nippou* publishes industry estimates on market conditions each June, and the English language *Japan Chemical Week* reports the activities of the Japanese producers. The business intelligence journal *Performance Materials* provides many snippets of information on the US scene, whilst trade journals such as *Chemical and Engineering News* have occasional articles surveying the composite and carbon fibre industry as a whole. *Flight International, Aviation Week and Space Technology* and similar publications also provide information concerning composites within the context of the aerospace and defence sectors.

Primary data was collected by contacting the firms directly. For those firms in the UK, France and Japan, an interview was requested. Six months of the research time was spent in Japan at Shizuoka University and three months in Paris, based at the Ecole des Mines. Although it was not practicable to go to the US within the time limits and financial restraints of the research, all the US carbon fibre producers were questioned in writing about their carbon fibre operations. The interviews themselves were semi-structured and lasted around one or two hours. Three of the firms, Toho Rayon, Asahi Kasei and Mitsubishi Rayon, also permitted shopfloor access, enabling the manufacturing processes employed to be seen at first hand. The interviewees were questioned on technical and commercial aspects of carbon fibre production, market histories, end-uses and production forecasts.

In all, during the course of the research, around 20 people were interviewed. The majority of the interviewees were managers and directors from industry. This information was further supplemented by industry observers, academics, government officials and other commentators including the trade associations SACMA (Suppliers of Advanced Composite Materials Association) and the AIA (the Aerospace Industries Association), who were particularly helpful in providing data concerning defence consumptions.

All the firms responded at least in part, with the exception of BASF, who replied that even the most basic information requested concerning production capacities was “proprietary to BASF and cannot be revealed”.[12] Inevitably, then, there is some unevenness within the data collected between companies and there are occasional discrepancies between sources concerning production and consumption.

Context

The introduction of a new material is often considered a radical rather than an incremental innovation in that it may involve the re-definition of the entire architecture of an existing product, or even the creation of a whole new set of markets. The usage of an advanced material will often rely on concepts based on new or relatively untried engineering and scientific principles. These factors often act as barriers to the substitution of traditional materials, barriers that are further reinforced by the traditional reluctance of producers to invest in manufacturing capacity until a market is developed, and conversely, the reluctance of potential users to adopt a new material until supplies are assured and economies of scale reduce costs.[13]

Government support for new material development is widespread across the G7 countries.[14] After the second oil shock and the subsequent increases in energy costs and the price of raw materials, the economic downswing focused policy making on the issue of long term growth and economic sustainability. Concurrently, a consensus emerged that technical innovation *per se* was central to ensuring long term competitiveness, and technology policy gained an increasing role in economic policy planning. Against this background, the G7 nations as a whole were moving toward the development of an R&D intensive, higher value added manufacturing sector, which in turn required constituent materials in possession of a greater sophistication of content.

Governments generally cite a number of reasons to justify their support of advanced materials. Often central to the argument is the role played by advanced materials in stimulating innovation in downstream industries, or, conversely, the lack of an advanced materials base as a possible obstacle to the development of future technological systems. The considerable externalities of advanced materials are also highlighted. These may be direct, when, for example, the introduction of a new material reduces energy consumption or improve safety in automobiles, or indirect in that the wealth creation derived from new materials is generated mainly in the value they add to other industrial sectors. As the UK Foresight report noted,

> "In the UK, as with all advanced industrial countries, new and improved materials underpin the competitiveness of most industries, including automotive, aerospace, construction, electronic, and health care because they are critical to most manufacturing processes. Substantial, well targeted investment in materials research and in its application ... will therefore leverage UK manufacturing to compete successfully in the world markets of the future."[15]

The long time scales involved in bringing a material to market and the difficulties noted above in the establishment of volume production have all contributed toward the rationale for government intervention. There is typically a period of ten years or more between the conception of a new material and its full exploitation in the marketplace. Hence considerable sunk investment is required over a sustained period of time. By way of illustration, as the 1990 DTI High Level Mission to Japan noted, over 80% of new ventures involving new materials technologies were actually unprofitable at the time of the visit.[16] Often, it is believed that progress in materials development would be too slow or even non-existent without substantial government assistance. In particular, in countries without the impetus of ambitious space or defence programmes (such as Germany), direct government support of new materials programmes is seen as necessary to maintain overall manufacturing competitiveness, particularly with respect to R&D.[17]

The Japanese government has demonstrated a sustained interest in advanced materials, not least on account of the lack of indigenous mineral resources. Advanced materials were identified as an industry of the future in the first guidelines issued by the Science and Technology Agency, and along with biotechnology and electronics subsequently under a programme of long term support through MITI's **jisedai** (Future Industries Programme). Composite materials was one of the six major branches of this new materials research.[18] Similarly the French materials mission report of 1983, precipitated the five year materials mobilisation programme (IDMAT)[19] and in 1986 the EC launched EURAM (European research on Advanced Materials), a programme designed to generate a viable pan-European new materials production capacity.[20]

In the UK, the Collyear Committee submitted its report of 1985 recommending a £180 million programme of support of advanced materials research and development in the UK.[21] In the event, however, the findings of the report were largely ignored and government expenditure on the technology areas recommended by Collyear barely totalled £20 million.[22] New materials were again identified as a technology of 'crucial importance' by the UK Technology Foresight initiative in 1995.[23] The reports recommends considerable increases in EPSRC (Engineering and Physical Sciences Research Council) funding for materials research, which stood at £60 million at the time, and a review of the EPSRC portfolio, with greater emphasis of the further development of existing materials and processes. The report further suggests a system of Government supported partnership systems to be initiated by the DTI, MoD and research councils to encourage R&D collaboration between the public and private sectors, and that a new LINK/Foresight scheme be instigated, increasing UK gross expenditure on research and development spending by 5% pa until the year 2000.[24]

Aside from economic concerns, military interests have been fundamental in the government sponsorship of materials research, development and production. The implementation of measures set up to ensure the necessary supply of key materials and to mobilise industry for their production is not new. During the Second World War, the United States authorities established a stockpile for strategic materials (those possessing a unique importance in the manufacture of defence munitions) and critical materials (meaning those imported from countries with potentially unstable regimes).[25] Up until the start of the 1970's, US materials and mineral legislation was simply designed to ensure the physical existence of stockpiles of vulnerable metals and minerals essential for munitions production. Advanced materials were not recognised as such, nor any need for additional policies.

After the oil shocks, however, achieving self sufficiency with regard to strategic resources became an increasingly important objective. By the time of the Reagan Administration, the US was importing $1 billion worth of strategic materials each year,[26] and gradually a new debate emerged calling for a reduction in dependency on the import of raw materials through improvements in the domestic production base and the development of new materials to substitute for critical materials both in their military and non-defence applications. Examples most commonly cited in the literature of the time include cobalt, which was essential for the production of high temperature alloys for jet engines and gas turbines but for which the predominant producer was Zaire, and chromium and manganese, both produced in South Africa and both used in the production of stainless steel.[27]

It was strongly argued that it was neither necessary nor economically sound for the government to increase the existing stockpiles. Instead, the argument ran, the Administration should increase R&D on alternative materials that may both improve performance and lower manufacturing costs.[28] This debate culminated in the passing by Congress of the Stevenson-Wydler Technology Diffusion Act and the National Critical Materials Act of 1984. The former sought in part to improve the industrial manufacture of new materials through the transfer of innovations to the private sector and the latter legislated the creation of an umbrella organisation, the Critical Materials Council which co-ordinated the advanced material R&D efforts of both defence and non-defence departments.[29] Gradually, then, the earlier concepts of stockpiling exclusively for military purposes were realigned into new policies of maintaining defence capabilities through the promotion of materials competitiveness as a whole, a policy change further accelerated by the end of the Cold War. This notion was to be expressed explicitly by the introduction of the Technology Reinvestment Project.

Before turning specifically to carbon fibre itself, we will now briefly survey the new materials sector as a whole, first examining some of the characteristics of advanced materials, then presenting a general survey of the industry.

Defining New Materials

There is no rigid definition of an advanced material. However, we can say that advanced materials generally share the following characteristics:—

1. Advanced materials demonstrate an **improved performance**. Greater strength, or increased operating temperature are typical examples.
2. Advanced materials are highly **knowledge intensive**. The number of employees working in design related jobs is high compared to the numbers working in production. Due to the inter-disciplinary nature of research in advanced materials and the extended time scale involved (15 - 20 years), advanced materials R&D is often expensive. Furthermore, the introduction of a new material may require specialised and expensive equipment and costly testing and certification procedures.[30]
3. The design of advanced materials is largely concerned with the atomic structure. This trend has been accelerated by the widespread use of electron microscopy and the rapid growth in computing capacity. The reliance on microscopic characteristics has entailed the development of many **new manufacturing processes**. Such processes include sol gel chemistry in which a metal is mixed into an organic compound, allowing low temperature processing to create atomic structures that could never have been produced using high temperature methods. Molecular beam epitaxy and ion implantation are examples of techniques that actually build materials atom by atom. To produce materials in bulk, methods such as chemical vapour deposition and plasma deposition are employed. Advanced materials require a great deal of purifying, characterisation and testing. This often adds considerably to their cost. In the case of liquid crystals, for example, processing costs are the major constituent cost of the final material. Unlike many traditional materials, processing is central to the nature of the final product: for example, composites made from identical fibres

and matrices, but under different manufacturing conditions exhibit very different physical properties.[31]

4. Advanced materials show an **increased integration of parts and function**, resulting in a reduced number of parts in the final product. For instance, the use of carbon fibre composite in the vertical fin of the Airbus A310-300 reduced the number of components needed from over 2000 to 100, and eliminated all the rivets.[32] Such use of composites often results in a reduction of cost. The percentage structural weight of composites in the US Navy's new F/A-18E/F fighter/attack aircraft will be twice that of the current F/A-18C/D. This will allow Northorp to drop 20% of the frames used in the C/D version and cut the number of fasteners required by 8000.[33]

5. Although there is an increasing body of knowledge regarding the relationships between atomic structure and bulk capabilities, advanced materials are, more often than not, developed experimentally. The theoretical understanding of the properties of the materials is usually an *ex post* acquisition. Since the development is empirical rather than based on scientific principles, the patenting of advanced materials is effective and the **propensity to patent is high** when compared to other high technology areas such as biotechnology or optoelectronics. First comers are further protected as a consequence of the close links established between the producers and users of a advanced material.

6. The raw materials used to make advanced materials, which include silicon, aluminium, oxygen and nitrogen, are usually **cheap** and **widely available**. At the same time, they allow for the **substitution of strategic materials**.

7. The emergence of **new constellations of producers and users** is yet another feature associated with many advanced materials. Whereas previously a new product was designed according to the properties and behaviour of existing materials, it is now possible to design a material according to the desired features of the final product. In other words, the material is no longer an exogenous variable beyond the control of the user, but one that can be modified according to their needs. Hence increasingly, the material, production and final product are designed and optimised as a system. Moreover, advanced materials often entail a closer integration of manufacturing processes. For example, injection moulding of reinforced plastics involves the simultaneous production of both the final material and the part. Clearly, for this to happen, a high level of co-operation between material supplier, equipment producers and users must exist and often this results in the major players seeking to integrate vertically.[34]

8. As it is now more possible to tailor each material for a specific application, the advanced materials market is highly segmented. Whereas previously a single material was utilised for many applications, now there exists an unprecedented variety of available materials.

9. Finally, advanced materials share the characteristic of a **rapid rate of technological development** and, although they possess relatively limited markets, they demonstrate a **rapid global market growth**.[35]

Materials are classified into two types: functional (or primary) and structural (or secondary).[36] Functional materials are those that possess a physical phenomenon essential for a product to operate and often constitute the active heart of the device. Examples might include the piezoelectric ceramics used in pressure sensors, or liquid crystals, or the optically active crystals found in optoelectronic devices. Functional materials are not easily substituted, for without the material, there is usually no device. Conversely, the development of a new functional material often leads to the creation of radical new products. Functional materials generally command high prices, but only low volume markets.

Structural materials typically form the bulk of a product. They transmit forces, or act as supports, or serve to contain the functional elements, protecting them from shock or environmental attack. Usually, secondary materials are incorporated into existing products after demonstrating an improved performance or lower cost. Rarely does their development lead to the introduction of entirely new devices. Steam engines, for instance, were developed before high strength steels, and aeroplanes predate aluminium alloys. In short, the product typically precedes the material. There are many secondary materials capable of performing similar functions, and they are considered to be readily interchangeable. Examples of structural materials include wood, steel and cement.

Structural materials may be further categorised as either **ceramics, metals** or **polymers.** Each of these classes has its own particular advantages and drawbacks. Ceramics are hard, with high service temperatures, but can catastrophically fail under stress. Metals are strong and tough, but also heavy and reactive. Polymers are light, but restricted to low temperature operation. Ceramics, metals and polymers can be combined to form hybrid materials known as **composites**. Often a composite can be designed to eliminate the undesirable properties of its component materials and combine their advantages. Hence polymers reinforced with ceramic or organic fibres are light, strong and reliable. The most common composites type consists of short fibres of one material embedded in a matrix of a second. It is the matrix phase that denotes the composite type; viz. metal matrix composites, ceramic matrix composites and polymer matrix composites.

The New Materials Industry

Background

The production of new materials is a global business. Trade is shared on a more or less equal basis between the three major economic blocs of Europe, the US and Japan. An international division of labour does exist, however, in that each bloc is steadily developing markets and expertise in specific areas of the industry.

Europe, despite being a net importer of new materials as a whole, is very competitive in advanced plastics through its traditionally strong base of chemical and plastics companies. Hoechst, Bayer and BASF all rank among the world's top five suppliers. Japan, on the other hand, has a relatively weak chemicals industry and ranks third behind Europe in the production of advanced plastics.[37] Nevertheless, Japan has set the development of a new materials industry as a principal industrial objective, not least due to Japan's almost total reliance on imports for raw materials. Four particular areas have been highlighted: fine ceramics, carbon fibres, engineering plastics and amorphous metals. The special emphasis on ceramics reflects the general confidence in Japan that the technical problems associated with these materials can be overcome. As a result, Japan has established a commanding lead in the production of advanced ceramics. In the largest ceramic markets, IC packaging, Kyocera alone fulfil 75% of world demand, and other Japanese companies serve most of the remainder.[38]

The US is strong in virtually all areas of new materials production. According to STI,[39] the US is a major producer of both engineering plastics and ceramics. However, it is in the field of advanced composites that the US predominates, largely as a result of its extensive defence and aerospace activity. The US is particularly noted for its expertise in the design and application of composites, and, through Du Pont, is the only significant producer of aramid fibre.

The advanced materials industry is structured in a manner similar to other high technology industries: a comparatively stable group of major companies predominate, although there is room for a much larger number of specialised firms. In the case of advanced materials, the major players are all large diversified companies. Considerable barriers to entry exist and, although at present there is a high supplier-to-customer ratio in the sector, this situation is expected to reverse as industrial applications are established.

The market share of the established actors is protected by the high costs of R&D, assembling the necessary skill base and the high capital costs of new plant. The relatively high level of user-manufacturer interaction in new materials provides yet another barrier to entry for late entrants. Additionally, producers seek to protect their market share through scale economies, patenting, mergers and acquisition. We now examine each of these elements in more detail below.

Research & Development

Technological competitiveness is core strategy for growth and survival in the new materials industry. Unlike many other innovative sectors, however, several years may pass from the inception of a new material, through its design, early production and arrival in the market place, until significant economic returns are gained. The long lead times and high technical risk mean that despite the good innovation record of the small companies in the new materials sector, the substantial majority of technical developments, whether measured in terms of patenting, new process innovations or new products brought to the market, are realised by the big firms.

Aside from the problem of actual R&D, the creation of a market for a new material is often a lengthy and costly process. Major users are unwilling to adopt a new material until assured supplies exist, whilst producers of new materials are understandably reluctant to invest in a production capacity until a viable market has developed. Additionally, new materials are essentially capital goods, sold to other industrial sectors, who must in turn risk investment in their adoption. For instance, the incorporation of a new composite or ceramic component into a car may require a radical reshaping of the automotive production line, as well as the cost of retraining on the shop floor and acquiring a new design expertise. If the new material is to be integrated into a large technological system (a telecommunications network, for example) the lead time may be as long as ten to fifteen years. This is clearly well beyond the time horizon of a small company.

Patenting

It follows that only large companies have the resources to undertake most new material R&D and create a viable market share. Hence the development of new materials technology, by and large, takes place in big firms. These companies then seek to protect their intellectual property through patenting. Patenting is reasonably effective in that the development of a new material is in general an empirical process. In the case of a structural material, however, patenting rarely results in an effective monopoly, as there is such broad scope for substitution by a material of similar properties. Furthermore, chemical companies have traditionally been wary of publishing information concerning R&D in any form, even that required for a patent. Often a company will patent only the chemical composition of a new compound, but not the details of the temperature, pressure and other critical processing conditions under which it was produced and which bestowed the unique properties for which the material is valued.[40]

Economies of Scale

Increasingly, volume production is the norm for most new materials. Large scale production currently accounts for about 90% by volume of all new material manufacture. However, some specialised technologies are produced only to individual orders (e.g. cermets, which are very hard and extremely difficult to work). This specialised production is of comparatively high value, accounting for 20-22% by value of the total market.

This continuing economic importance means that large firms will remain attracted to certain areas of specialised production, in spite of the drop in volume. However, small innovative companies with a specialist new skill or research expertise can flourish in certain niche markets. In particular, ceramics and some areas of the composite industry are very fragmented with many opportunities for smaller firms to break in.

Mergers and Acquisitions

Small firms that appear to be increasing market share, or hold valuable patents, often become take-over targets for larger predators seeking access to a particular technology base. Farrands has cited the specialised expertise of the workforce of a firm as one of the most effective barriers to entry, arguing that,

> “Knowledge of some of the more important technological innovations is often unique ... associated with that particular combination of machinery, human skills, design expertise, management and marketing which is distinctive to each company.”[41]

Acquisition is also a method of accessing overseas markets. When BP acquired the US firm Hitco, its composites sales increased tenfold.[42] There was a rising stream of take-overs in the new materials sector during the late 1980s. In advanced plastics, 16 cross frontier acquisitions were recorded in Europe in 1988, and 23 in 1989. Similarly, even in the ceramics industry where joint ventures are a popular strategy, there were 11 European take-overs in 1987, 12 in 1988 and 17 in 1989.[43] The steady rate at which take-overs have occurred, despite the collapse of the stock market in 1987, suggests that although clearly financial motives play a part, technological objectives remain a major determinant.

It is rare in manufacturing industries for a single company to be active in every processing step from the manufacture of the basic material to the production of the finished part. Traditional materials are bought 'off the shelf', affording the product manufacturers little opportunity of influencing the design of the materials themselves. In the case of advanced materials, however, both the material and the part may be produced in a single processing step. Furthermore, there is enormous scope for product designers to specify exactly the materials required. Often, a new product and material are developed simultaneously, with the materials manufacturers and their customers working hand-in-glove. Hence the design and manufacture of new materials is necessarily unified into a single integrated process. Joint ventures are also undertaken to pool complementary skills, as is common with many emergent technologies. There is an imperative, then, for collaborative ventures and, indeed, the advanced materials industry has spawned a growing global network of co-operative research agreements, mergers, licensing arrangements and other joint ventures.

Supply and Demand in the New Materials Industry

Growth rate estimates are dependent on several technical and external economic factors. An unforeseen process innovation could cause the price of a particular new material to fall dramatically. Changes in the fortunes of complementary or competing technologies will also affect the growth rate. A rise in metal prices, for example, would accelerate the new material demand. Similarly, a rise in oil prices would cause a switch from plastics and polymers to advanced metals and composites, whilst a world recession would slow the adoption of new materials as a whole.

New materials production suffers long lead times, and, like the chemicals industry as a whole, follows cyclical patterns of growth and recession. Periods of rapid growth for the industry are followed by crises of overcapacity. This in turn leads to price falls which then accelerate substitution rates and regenerate the industry later in the business cycle.

Engineering plastics, especially thermoplastics, which are produced in large volume by major chemical companies, are particularly vulnerable to protracted periods of overcapacity. The ceramics industry, on the other hand, is far less concentrated and far more small scale. The smaller ceramic firms would be unable to sustain losses over a prolonged period and would leave quickly, or would be taken over, if surpluses develop. Hence, any overcapacity in this sector, if it develops at all, would be only temporary. The composites industry is seeing increasing scales of production. Composites are now considered a proven technology in many areas of application and there are few technical barriers to bringing new plant on stream. The late 1980's saw a substantial surge in capacity in the polymer composites sector, followed by severe surpluses in the early 1990's as defence aerospace applications peaked in demand. The consequent industry shakeout and the eventual resurgence of demand is the central topic of this thesis.

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CHAPTER TWO:
THE NATURE AND USE OF CARBON FIBRE

Introduction

In this chapter we consider the technical aspects of carbon fibre, and examine the major applications. A composite material, as we saw in Chapter One is made by combining two or more materials to produce a new material with new capabilities. Generally, a composite consists of a polymer matrix in which short or continuous fibres are embedded. The fibres act to strengthen and stiffen the composite whilst the matrix serves to align the fibres, bond them together and distribute the load.

Advanced composites are distinguished from reinforced plastics chiefly by their superior mechanical properties (usually strength and stiffness) and high concentration of fibre (50-60%). The potential use of carbon fibre reinforced composite (CFRC) as a structural material has been recognised for more than thirty years. Originally developed for the military sector, over 80% of all CFRCs are now used in civil applications. However, CFRCs are relatively expensive and remain restricted to high value added applications in which the advantages of high performance offset the high cost. Worldwide, aerospace applications account for about fifth of the current market and sporting goods over half. Industrial applications account for most of the remainder.[1]

Carbon fibre is commercially produced as either a continuous filament yarn, or tow, as a woven fabric, or as a discontinuous mat or felt. It is then combined with a matrix, usually a synthetic resin or polymer, to produce a composite. Carbon fibre acts as the reinforcer in the composite, giving the required strength and stiffness. Carbon fibre is often traded as **prepreg**, an intermediate form, usually a tape or woven mat that has been preimpregnated with a thermoset resin and partially cured.

Carbon fibres are manufactured by the pyrolysis (chemical decomposition by heat) and stretching of organic precursors, namely **rayon, polyacrylonitrile (PAN)** or **pitch.** The resulting fibres are classified according to the original precursor. The earliest carbon fibres were based on rayon, but PAN derived fibre was found to possess a far greater tensile strength and has largely dominated the dramatic growth of the industry during the 1970's and

1980's. Currently, around 95% of carbon fibre structures are made from PAN based carbon fibre.[2] Pitch based fibres come in two grades. 'General purpose' pitch based fibre is comparatively cheap and is used in applications such as packing and insulation. In contrast, 'high performance' pitch based fibre (a relatively recent product) is very expensive. This type of fibre has demonstrated exceedingly high moduli and thermal conductivities and is expected to be used extensively in spacecraft and critical military applications.

Technical Characteristics.

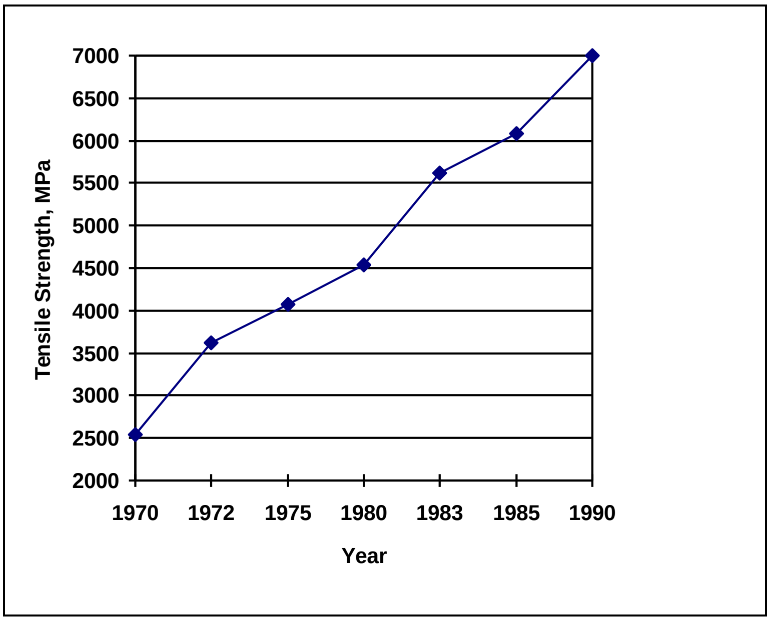
Chief among the advantages of carbon fibre is high **tensile strength**. Carbon fibre is also **light** (with a density of around 1.5 grams per cubic centimetre), and the consequent high strength to weight ratio has been central in its success as a major structural material in the transport and aerospace industries.[3]

A third key characteristic is that of **stiffness**, which is measured in terms of the modulus (the ratio of a given stress to the resultant strain) of a material. This combination of properties make carbon fibre particularly suitable for the manufacture of sporting goods such as tennis rackets, golf club shafts, rowing eight shells, ski poles and racing car bodies.

There is a linear relationship between the tensile strength and modulus of the carbon fibre and those of the final composite. The improvement of tensile strength with time is shown in Figure 2.1.

At present, the tensile strength of commercial fibre is about 7 Giga-Pascals (GPa), which is only around 4% of the theoretical value. This is because carbon fibre is essentially a brittle material and its strength is greatly affected by defects in the microstructure. Such defects can be reduced by improving the quality of manufacture. It is expected then that tensile strength will continue to increase steadily with time as processing techniques improve.[4]

Figure: 2.1 Improvement of tensile strength over time for R&D grade carbon fibre



Source: Odorico[5]

The modulus of carbon fibre, however, is already 60-80% of the theoretical limit of 750 GPa. This is because the modulus is generally immune to defects (it depends mainly on the degree of orientation) and has been comparatively easy to improve.[6]

High performance pitched based carbon fibre, which has the highest modulus of all, possesses a negative coefficient of thermal expansion, i.e. unlike most materials, it shrinks when heated. This means that when combined with an appropriate matrix, a material of exceptional thermal stability is produced, an important property for spacecraft and sensitive electronic systems in which thermal strain and distortion can be critical. Moreover, this sort of fibre exhibits very high values of thermal and electrical conductivity (two to three times that of copper)[7] and oxidation resistance, all of which makes it a particularly appropriate material to be used in demanding aerospace applications such as rocket nozzle throats, missile nose tips and satellite structures.

Pitch based carbon fibre also comes in a so-called ‘general purpose’ grade. This is a cheap form of carbon fibre of comparatively low modulus and strength (but of good flexibility, ductility and wear resistance) which is used in bulk applications such as insulation for furnaces and in the construction industry.

A further beneficial property of carbon fibre is its near transparency to X-rays. The replacement of aluminium X-ray table tops and cassettes by carbon fibre can cut the patient dose by a half.[8] Moreover, its compatibility with living tissue has enabled carbon fibre to be utilised in artificial bones and ligaments.

Finally, carbon fibre also possesses the properties of carbon itself: low friction, good wear, high service temperature and chemical resistance. Electrical and thermal conductivities can be modified over a wide range of values. Tables 2.1 and 2.2 overleaf compare the key properties of carbon fibre and carbon fibre epoxy composite with those of competing materials. It can be seen that high strength carbon fibre ranks among the highest tensile strength fibres of any kind, and high modulus carbon fibre possesses moduli higher than that of any competing material. Moreover, the density of carbon fibre is relatively low, making the specific modulus and strength exceptionally competitive. Kevlar and its sister polymer fibre, polyethylene, are also of low density, but their corresponding melting points are also low, limiting their range of application. The ceramic fibres, SiO_2, Al_2O_3 and SiC have comparatively high densities, and suffer from the additional drawback of high cost. The main mechanical problem of carbon fibre is its low ductility (strain at break) or how far the fibre can stretch before fracture. The low ductility of the early forms of carbon fibre proved a major barrier to their use in civil aerospace applications before the technical improvements of the mid-1980's.[9]

Table 2.1: Properties of Carbon Fibres and Competing Fibres and Whiskers

	Density (g/cm^3)	Tensile Strength (Gpa)	Modulus (Gpa)	Ductility (%)	Melting Temp (^{0}C)$^{.}$	Specific Modulus)
S-glass	2.5	4.5	86.9	5.2	1725	3.56
Carbon (high strength)	1.5	5.7	280	2.0	3700	18.8
Carbon (high modulus)	1.5	1.9	530	0.36	3700	36.3
Kevlar	1.44	4.5	120	3.8	500	8.81
SiO_2	2.19	5.9	72.4	8.1	1728	3.38
Al_2O_3	3.95	2.1	380	0.55	2015	9.86
SiC	3.18	21	480	4.4	2700	15.4

Source: Chung[10]

Table 2.2: Properties of Carbon Fibre Composites and Competing Structural Materials

	Density (g/cm^3)	Modulus (GNm^{-2})	Strength (MNm^{-2})	Ductility (%)	Thermal Expansion (10^{-6} $^0C^{-1}$)	Specific Modulus (GNm^{-2})	Specific Strength (MNm^{-2})
Al alloy	2.8	72	503	11	24	25.7	180
Steel alloy	7.85	207	2050	12-28	11	26.4	270
Carbon fibre/ epoxy	1.62	220	1400	0.8	-0.2	135	865
Glass fibre/ resin	1.93	38	750	1.8	11	19.7	390

Data for composites are values parallel to fibre direction. Source:Hull[11]

Process Characteristics[12]

Fibre Production

Currently, carbon fibre is produced from three organic precursors, polyacrlylonitrile (PAN), rayon and pitch. These precursors all provide a high carbon yield and high degree of molecular orientation, although virtually all commercially produced fibre derives from PAN. Table 2.3 shows the conversion ratio or yield (i.e. the quantity of carbon fibre produced per unit of precursor) derived from these precursors.

Table 2.3: Precursor Conversion Ratios

Precursor	Yield
Pan	50%
Rayon	20%
Pitch	80-90%

Source:Toho Rayon[13]

It can be seen that in fact the use of pitch precursor produces the highest yield. However, in order to make good quality, high performance carbon fibre from pitch, the pitch has to be first refined, a process that greatly increases production costs and reduces the yield to 30%. Some commentators, such as Aotoni, expect that the technical problems of processing pitch will in due course be overcome and high performance carbon fibre from pitch is likely to become cheaper than that based on PAN.[14] Low performance pitch based fibre, such as that which is used in packing and insulation, is indeed already the cheapest to manufacture.[15] PAN-based carbon fibre is both easier and cheaper to make than rayon derived fibre, largely as a result of the higher conversion ratio.

1. Pan based Carbon Fibre As almost all high performance carbon fibre is derived from PAN,[16] hereafter ‘carbon fibre’ means PAN-based carbon fibre unless stated otherwise. A breakdown of production costs for PAN based carbon fibre is shown in Table 2.4.

Table 2.4: PAN Carbon Fibre Breakdown of Production Costs

Precursor	36%
Marketing and Quality Control	17%
Depreciation	16%
Labour Costs	11%
Chemical Costs	11%
Carbonisation and Oxidation	9%

Source: Aotoni[17]

Two important features stand out from Table 2.4. Firstly, we should note that the precursor accounts for a large percentage of the final cost, and secondly, we see that carbon fibre production is a relatively capital intensive industry with depreciation costs accounting for 16% of the cost of the final product.

The PAN itself is manufactured by the polymerisation of mono-acrylonitrile, a process that takes two or three hours in the presence of a catalyst. The properties of the final fibre are closely related to the purity of the precursor itself. One possible way to reduce the final fibre cost is thought to be the development of a technology to produce a higher quality precursor.[18]

The fibres themselves are then commercially produced in three major manufacturing stages; namely; **pre-treatment**, **carbonisation** or **graphisation**, and finally, **surface roughing**.

The first step of **pre-treatment** is the wet spinning of the PAN polymer. During this process, a solution of the polymer is squirted as a fine stream into a coagulating bath from which the fibre precipitates. The fibre is then **mechanically stretched** to between four to eight times its original length while being heated in air at a temperature of about 300^{0}C. After a few hours, the carbon turns black. This oxidation process stabilises the fibres and increases the molecular orientation in preparation for the next stage of either **carbonisation** or **graphisation.**

For **carbonisation,** the fibre is heated to between 1000-1500 ^{o}C in an inert atmosphere. This yields a fibre with a carbon content of over 90%. The conditions under which carbonisation takes place have a profound effect on the mechanical properties of the final fibre. The tensile modulus of the fibre increases as the heat treatment temperature is raised. The tensile strength, however, reaches a maximum at a temperature range between 1000-1500 ^{o}C, and then falls. Hence, for high performance fibres there is an apparent trade off between strength and modulus. Recent research (Matsuhisa et al., to be published) has demonstrated that ion implantation into the fibre may improve both strength and modulus.[19]

If instead the fibre is heated to a very high temperature of between 2000-3000^{o}C, a process known a **graphisation** occurs, resulting in fibres of very high modulus but low tensile strength. This type of fibre is used in the construction of space vehicles and premium sports goods.

Following carbonisation or graphisation, the fibres are then **surface treated** to improve the adhesion between the carbon fibre and matrix resin. This may be achieved chemically, usually by oxidation, or physically by whiskerisation, whereby very thin whiskers are grown onto single filaments, like hairs on a fox's tail. Fibre-resin technology interface technology remains the weakest area of carbon fibre technology.[20]

Carbon fibre is usually produced as a yarn or tow consisting of bundles of single filaments. The diameter of a single filament is between five to ten microns. A bundle is classified by the number of filaments it contains, usually 3000, 6000, or 12000. 12K tow is the standard for the industry and is generally the cheapest. Some typical costs are:

Table 2.5: Typical Carbon Fibre Costs

3K tow	$46-68/kg
6K tow	$48/kg
12K tow	$22-29/kg

Source, Toray[21]

2. Pitch-based Carbon Fibre Carbon fibre compounds can also be produced from petroleum or coal pitch. This comes in two forms. The so-called 'isotropic' general purpose pitch based fibres is used in cheap, bulk applications such as packing and construction. The fibres are fragile and difficult to handle, and the resulting strength and modulus correspondingly low.[22]

In an alternative and relatively recent process, the pitch is first heat treated at about 400^{o}C in an inert atmosphere to form an intermediate ‘mesophase’ structure. This is then melt spun through a multihole spinneret to form the fibres. The fibres are then heat treated to 2000^{o}C, resulting in very high performance, high modulus carbon fibres. However, because of the problems in refining the pitch, this type of fibre is extremely expensive, at around $3300/kg.

Matrix Resins

Carbon fibre reinforced composites are chiefly manufactured using epoxy matrix resins, which possess reasonably good heat resistance, mechanical properties and environmental durability. However, epoxy resins are limited to applications below 300^{o}C and so lack the heat resistance required in more specialised applications, such as break-pads in aircraft and in certain types of engine. Some high temperature composites such as carbon-carbon systems (see below) have already been commercialised. However, these are very expensive and the development of improved resin systems and matrix resin interfaces is now crucial to the future commercial success of carbon fibre reinforced composites. Future possibilities include carbon fibres combined with cement, ceramics or metals.[23] These will access major new markets for carbon fibre, for example in the construction industry, or as parts in gas turbine engines.

Matrix resins are generally categorised as either thermoset or thermoplastic. Thermoset resins are cured slowly at low temperatures. This leads to high dimensional stability, strength at high temperatures and good chemical stability. Thermoplastics are heated and cooled very quickly and are cheaper to fabricate.[24]

At present thermoset resins are generally used as their performance characteristics are on the whole superior. However, recent advances have improved the high temperature strength and heat resistance of thermoplastics and they hold the greater promise for high volume production (as it is quicker to heat up and cool down a material than it is to cure it). It seems likely that thermoplastic will become essential for the production of carbon fibre composites for cost sensitive applications, such as in the automobile or construction sectors. Moreover, thermoplastics resins are more ductile and so are preferred for applications requiring flexibility, such as tennis rackets. Most companies expect epoxy resins to be replaced by high performance thermoplastics such as PEEK from ICI in the production of continuous fibre composites for high volume applications over the next few years. One company, Asahi Kasei, started commercial production as early as 1991.[25]

Carbon-Carbon Composites

Carbon fibres may be embedded in graphite and, indeed, carbon itself is the material most compatible with carbon fibre. Carbon is a low density material and the specific strength, modulus and thermal conductivity of carbon-carbon composites are the highest of any composite material.[26] However, the high cost of fabrication limits its use to specific aerospace applications, with re-entry thermal protection constituting 37% of the market, rocket nozzles 31% and aircraft brakes 31%. Typically, carbon-carbon composites are used in very high temperature applications, for example in the US National Aero-Space Plane, on which surface temperatures may exceed 1,000^o C. Most of the market for carbon-carbon composites resides in the United States (79%), with Europe and the CIS accounting for a further 20% and Japan the 1% remainder.[27] China's recent attempts to import carbon-carbon manufacturing technology from the UK were blocked by COCOM.[28]

Small, thin walled, carbon-carbon composite parts, up to a few centimetres in size, are made by vapour deposition from the gas phase. For larger structures, or higher density parts, the fibre is impregnated with a suitable resin, which is then charred off at very high temperatures.[29]

Production of the Composite

Many different processes may be used to produce a composite part from the component carbon fibres and resin. However, four basic steps are generally involved: impregnation of the fibre with the resin, forming the structure, curing and finishing. Some of the widely used manufacturing proceses are:[30]

Pultrusion, a process used for the production of continuous, constant cross-section parts. In pultrusion, the impregnation, forming and curing take place in a single manufacturing step.

Prepreg tape lay-up, in which a fibre tape or cloth that has been impregnated with resin and partially cured (prepreg) is placed on the contoured surface that defines the shape of the finished part. This is, at present, a labour intensive process, that is being increasingly automated. Prepreg tape lay-up is expensive and slow and is most commonly used in the manufacture of aerospace structures.

Compression and Injection Moulding are further techniques. Compression moulding, which uses long lengths of filament or pieces of woven carbon fibre cloth, produces a much better quality composite than injection moulding which uses short fibre lengths and yields a lower fibre content. Injection moulding is commonly used in high volume applications producing parts such as fan blades.

Filament winding involves the winding of the carbon fibre tow and resin simultaneously onto a former. Filament wound parts can be of great size, rocket bodies being one example.

The properties of the composite depend not only on the nature of the fibre and the matrix, but also on their relative proportions and geometry. Generally, better quality composites use long lengths of fibre and have a high fibre content. The cheapest form of composite is one produced from short, randomly orientated fibre strands. This can be manufactured relatively inexpensively using technologies such as compression moulding. Sheet moulding compound (SMC) is one such material widely used for making golf club heads.[31]

A stronger form of composite can be produced from continuous fibre reinforcements. This is more expensive to make but is widely used in applications where high strength is critical, for example, golf club shafts. However, continuous fibre composites are inherently anisotropic in character; it is very strong along the direction of the fibres, but up to twenty times weaker when stressed perpendicular to the bundle. In practice, most continuous fibre products use bundles of fibres orientated in different directions in order to optimise the performance for a particular application. The computer design of these sorts of composites is often critical and requires finite element analysis and other complex stress analysis techniques.[32]

In contrast to metal parts, composites are usually produced by moulding rather than matching methods. Composites also carry forward the integration of parts to a large degree, i.e. whereas a metal part may be made from many separate components, its composite counterpart often has few sub-assemblies. For example, in the CFRC ladder structure of the Airbus A320 tail fin, the number of major parts was reduced by 70% (from 17,015 to 4,800) and that for subparts reduced by nearly a half (from 660 to 335).[33]

Applications

The major properties of carbon fibre reinforced composites and the subsequent applications are summarised below.

Table 2.6: Properties and Example Applications of Carbon Fibre

Property	Application
Lightweight, high strength	Aircraft, space vehicles, high speed centrifugal separators
High elastic modulus	Premium sports goods
High X-ray transparency	Medical X-ray diagnostic equipment
Low thermal expansion	Parabolic antenna, e.g. in radio telescopes, Space structures
Electrical conductivity	EMI shielding, anti-static plastics
Good wear	Bearings (made of carbon fibre reinforced plastics)
Compatibility with living tissue	Artificial ligaments and joints

Source: Toray[34]

Carbon fibre is costly for a structural material. The cheapest 'general purpose' grade pitched-based carbon fibre costs around $18 kilo. The bulk purchase price for standard PAN based carbon fibre is approximately $26 per kilo and the cost of high performance mesophase-pitch carbon fibre is estimated at $3300 per kilo or more.[35] Aerospatiale estimate the cost of carbon fibre composite to be over ten times that of competing aluminium alloy.[36] However, as composites are moulded rather than machined, there is far less wastage. The overall cost is measured in the "buy to fly" ratio i.e., the ratio of the quantity bought to the amount actually used in the final product. The buy to fly ratio for aluminium alloys is roughly 4, compared to 1.3 for composites. Hence the price per kilo in the final product is approximately 1,100 francs for carbon fibre composites compared to between 200-230 francs for an aluminium alloy, that is, the net cost of using composites works out at around four times more than that of competing materials.[37] Consequently, the use of carbon fibre is largely concentrated in those applications where performance takes preference over cost.[1] As can be seen below (Table 2.7), the actual cost of the fibre varies widely with the market size and quantity required by specific applications.

Table 2.7: Variations in Carbon Fibre Cost

Application	Approx. Cost (yen/gm)
Space Satellite	20,000
Space Shuttle	10,000
Fighter Plane	1,000
Fishing Rod	100-1,000
Industrial Robot	400
Camera	300
Golf Club	200
Civil Aircraft	150
Tennis Racket	50
Television	7
Automotive	2

Source, Toho Rayon[38]

The cheapest carbon fibre is at present around 5 yen per gram.[39] It can be seen from the Table 2.7 that this would need to fall further to access very large automotive markets. Historically, the cost of fibre has declined dramatically as volume markets have been increased. During the early 1970's, the cost of standard quality carbon fibre was around $330 per kilo. This had fallen to around $44/kg by the mid 1980's and now stands at about $26/kg.[40] Over the last few years the cost of carbon fibre fell again because of the difficult market conditions,[41] but the industry expects prices to remain more or less constant or even recover in the foreseeable future.[42] Carbon fibre production is a capital intensive industry with significant scale economies, and the key to achieving dramatic cost reductions lies in

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[1] There is a range of currencies in this thesis as costs are given in the source currency. September 1996 Sterling exchange rates are (Source: Financial Times, 27th September 1996):

	US$	DM	FFr	Yen
£ Sterling	1.56	2.38	8.04	172

volume production. The most likely future high volume application is in drive shafts and engine parts in the automotive sector. For these, the industry believes, high performance thermoplastic resins first have to be developed.[43]

Table 2.8 shows how carbon fibre markets breakdown by region and end use. As there are no official statistics on carbon fibre demand, the data was obtained from the largest producer, Toray, (upper data) and the Japanese trade journal *Kagaku Kogyo Nippou,* which uses Toho Rayon estimates for carbon fibre consumption (lower data). There are some discrepancies between the two sources, but the overall pattern of usage remains the same.

Table 2.8:Carbon Fibre Consumption, 1994, tons

	Aerospace	*Sports*	*Industrial*	*Total*
USA	1165	925	1060	3150
	780	850	1200	2830
Europe	530	330	460	1320
	435	355	505	1295
Japan	30	910	660	1600
	55	1030	650	1735
Taiwan/	5	1640	5	1650
Korea	0	1550	20	1570
Total	1730	3805	2185	7720
	1270	3785	2375	7430

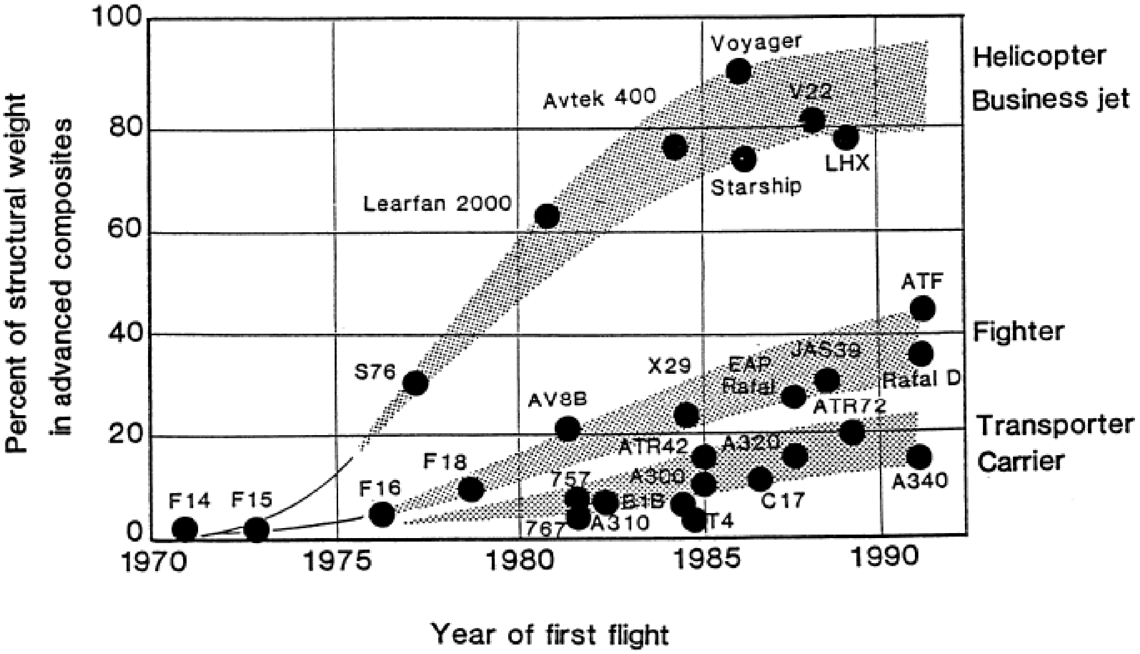
Sources: Toho Rayon (upper data),[44] Toray (lower data)[45]

The US consumes well over a third of the total world carbon fibre production. Aerospace remains a major market in the US, although consumption in this sector has fallen sharply over the last five years, as we shall see later. The United States is also the main producer and consumer of aerospace composites. World-wide, sports goods are the largest single end use, and by far the largest national consumers in this sector are Taiwan and Korea, who between them account for about 40% of the global sports goods total. This is not through any extraordinary national athleticism on the part of these two nations, but rather due to the rapid growth of subcontracted work; Taiwan has manufactured the tennis rackets for virtually all the world's major sports goods producers since 1982. Almost all the carbon fibre used in Korea and Taiwan is imported from Japan. The largest market in Japan itself is for golf clubs. The Japanese golf club market was blessed with, in Toray's words, a kamikaze (Divine Wind) when Gay Brewer won the Japanese Open with a carbon fibre club. This led to enormously increased sales in Japan.[46] The importance of this market is such that Toray provided the author with an additional chart showing the growth of carbon fibre golf club consumption in Japan and the US. Industrial uses account for around 25% of total carbon fibre production. As Table 2.8 shows, the use of carbon fibre in industrial applications is distributed fairly evenly between the US, Europe and Japan. We will now examine the more important applications in more detail.

Aerospace

Aerospace, which accounted for 40% of total carbon fibre consumption throughout the late 1980's, now constitutes a fifth of the carbon fibre market. Composites typically constitute 15-20% by weight of large civil aircraft and carriers, 30-40% for high speed fighter craft and up to 80% of business planes and helicopters (Figure 2.2, see overleaf) The main advantage of the use of composites in aerospace applications is the resultant weight reduction. Kelly estimates that of 40% of an aluminium alloy structure is replaced by CFRC, a weight saving of 12% is achievable.[47] This weight saving may be used to reduce fuel consumption or increase the payload, manoeuvrability and speed. Additional benefits include the superior fatigue and corrosion resistance of composites and their vibration damping properties.

Figure 2.2 Application of Advanced Composites in Aircraft Structures



Source: Matsui[48]

The use of composites in aerospace applications is likely to be accelerated if their strength continues to improve and their costs fall. The precursor PAN accounts for a high proportion of the cost of the fibre (see Table 2.4) and some commentators (such as the Society of British Aerospace Companies) believe that in mid-term techniques will be developed allowing lower cost fibre to be produced from pitch.[49] The development of high performance thermoplastic matrices will also cut the cost of the final composite. Currently available matrices tend to absorb moisture over time and break down at high temperatures. Again, it is thought that these problems will be overcome with the development of improved resins.

One further barrier to substitution in the aerospace sector is need for any new material to first be ‘qualified’, or certified safe, for aerospace use. Aviation authorities obviously have less experience with composites than with traditional metals and alloys, and testing for certification tends to be conservative, adding to the developmental costs. Safety certification is expensive, anyway, involving the supply of historical data on production, visits from audit teams and the production of fibre to make sample parts. It is also a lengthy process as samples of the material have to be submitted for testing, and test flights carried out. Toray estimates that these shop floor trials can cost as much as £5 million for a new composite type. Qualification for commercial aerospace parts takes at least 9 to 12 months, and can take as long as 24 to 36 months. For military aerospace applications, qualification may take several years. Once a material has been qualified, further product and process innovations are not permitted.[50]

Aside from being one of the largest single markets for CFRCs, aviation has been the test bed for many of these materials. Many aerospace end-users such as Boeing, Aerospatiale, British Aerospace and McDonnell Douglas are large, technology intensive companies with correspondingly large research and development facilities. Aside from the benefits of weight saving, carbon fibre composite materials possess radar invisibility, the strength, toughness and fatigue resistance to withstand the rigours of high acceleration manoeuvres and other qualities of interest to the defence sector. It is hardly surprising therefore that government defence ministries have been major sponsors of the development of aerospace applications.

Defence Aviation

Carbon fibre was developed primarily in the aerospace laboratories of the 1960's. With its critical weight saving advantages, it had been introduced into fighters such as the F-14 and F-15 by the early 1970's. Throughout the 1970's and 1980's, military programmes were intensive users of carbon fibre. Figure 2.2 shows the degree of carbon fibre usage by aerospace project. For military aircraft, advanced composite usage has increased from a few percent in the F-14, F-15 and F-16 to 6% in the Mirage 2000 and over 40% in the Advanced Tactical Fighter. Helicopter composite usage is particularly intense. In the tilt rotor V-22, for example, advanced composites account for 70% of the total structural weight.

The US is by far the largest defence buyer in absolute terms ($252,358 million in 1994), with a defence budget seven times that of the UK ($35,055 million) and over eight times that of Japan ($29,877 million).[51] The US can afford several different types of specialised aircraft, whereas the European countries tend to develop a smaller number of multi-role aircraft. Consequently, the Pentagon has been a major impetus behind new materials development. For example, under the Strategic Defense Initiative there was a special programme for new materials development, and Du Pont has made many advances in carbon fibre technology through DoD funding. As a result, the US leads the world in military applications of carbon fibre technology.[52]

With regard to Europe, the French fighter Rafale has composite structures and carbon fibre surfaces throughout. The French airforce plans to buy a total of 235 Rafale aircraft and the French navy 86.[53] The first delivery (to the French navy) is scheduled for 1997, with the first operational aircraft entering service in 2000.[54] The service entry date to the French airforce has been delayed to 2005. The Eurofighter has been described as "the embodiment of cold war requirements that are no longer relevant to the needs of the major partners"[55] and is currently awaiting a series of government decisions on production levels. The present workshares are UK, 35%, Italy, 21%, Spain 13% and Germany 33%, with first deliveries scheduled for 2001-2.[56] The aircraft incorporates carbon fibre composites developed in part under the EUREKA programme. Roskill estimates that 82% of the Eurofighter surface will be made from composite of which 70% will be carbon fibre.[57] In addition, the foreplanes, access panels and cockpit floor panels will all be carbon composite based.

The Japanese aerospace industry was virtually closed down by the Occupation forces after the Second World War. At present, Japan either purchases military aircraft directly from the US, or assembles US military components under licence. Mitsubishi Rayon, for example, makes carbon fibre parts for the F-15.[58]

Helicopters are a special case in that the rotor blades suffer from forced vibrations at particular frequencies and are subject to extreme twisting forces that place severe technical constraints on their constituent materials. Although composites are very strong along a defined plane, multi-directional tensile strength requires the complex deign of both the material and the way it is laid up. As a result, helicopter manufacturers are at the forefront of composite design. By way of illustration, Farrands writes,

> "When United Technologies bought the UK [helicopter] company Westland ... the main goal of the acquisition was to obtain Westland's skilled staff and research expertise in new materials together with some recent patents to pre-empt their use by competitors."[59]

The US holds the technical lead in the design and use of composites in helicopter applications.[60] According to Freedman, while Britain, France and West Germany have between them 2,800 military helicopters, the United States has more than 10,000, largely purchased in a protected market.[61]

Carbon fibre parts are also increasingly used in guided missiles, most commonly in motor casings, which are filament wound on mandrels. It has been estimated that the use of carbon composite rather than metal rocket motor parts can increase a missile range by about 600 miles.[62] Carbon fibre trusses are also used in load bearing structures. The American company Hercules specialises in the production of such parts. The US Trident D-5 missile, for example uses Hercules intermediate modulus fibre in all three stages.[63]

Defence spending as a whole has fallen in the light of the improved relations between the former superpowers and the dissolution of the Soviet Union. Moreover, most Western airforces re-equipped during the military build-up of the 1980’s. Barring another major upheaval in the Middle East, or further crises in Eastern Europe, Western arms spending is expected to continue to decline.[64] Similarly, so long as the Pacific region remains politically secure, the Japanese military market is expected to remain level. In order to amortise their original high investments, those producers and users of CFRCs in military applications are seeking to transfer their technologies into non-defence applications, especially civil aerospace. This will place them in much more direct competition with Japanese carbon fibre producers.[65]

Space Structures

For those structures that are to be used in space, weight saving is particularly crucial and the price of a material is not a primary factor in its selection. It is estimated that every additional kilogram costs an extra $10,000 in a satellite launch, and a further $5,000 in the cheaper (re-usable) US space shuttle.[66] There is a current surge in satellite launches to satisfy the demands of the telecommunications and broadcasting industries. It is estimated that there are currently around 120 working satellites in geostationary orbit, the majority being for civil applications. *The Economist* estimates 214 will be in use by the end of 2000.[67] The cost of a failed satellite launch is around $200 million and so the performance and reliability of structural materials is critical.[68] Even so-called 'cold structures' in satellite launchers can reach temperatures of 250°C. Hence, although this is a small market segment, it is one in which there is a high value element. Furthermore, this application is one at the forefront of composite technology. Ultra high modulus pitch based carbon fibres, for example, were developed by Du Pont through DoD funding partly for use in space structures and Hercules has developed very high performance carbon-carbon composites for use in rocket nose applications.[69]

Civil Aerospace

The commercial aerospace sector has been notably more cautious in the adoption of composite materials than its military counterpart. This is due in part to the differences in certification, liability and reimbursement procedures between the two arms of the industry. The possible financial penalties brought about by equipment failure are far greater for the civil sector, rendering the industry unsurprisingly more conservative in its selection of materials.[70] That said, new materials are expected to represent an increasingly significant proportion of aircraft production. According to Farrands, new material sales for civil aerospace applications during the 1990's were expected to be between $12 billion and $16 billion, broadly averaging $1.5 billion per year,[71] of which, the Society of British Aerospace Companies estimated, CFRCs would constitute around 30%.[72]

Farrands forecasts, made at the start of the 1990s, included orders already placed and were also based on the expectation that prospects for the civil aerospace industry would be strong over the decade. He presumed that airlines would require new planes of all sizes and ranges from airlines to replace ageing aircraft (the Boeing 767 had been launched fifteen years previously). Moreover, Farrands expected passenger volumes in Europe to increase by 25% as a result of industry deregulation.

However, the general economic recession of the early 1990's, and the negative impact of the Gulf War on air traffic precipitated a severe downturn in the civil aerospace sector. The deregulation of the industry in the US also contributed to falls in airline profitability. This in turn slowed the pace of investment within the industry as well as leading to the collapse or acquisition of some of the major players. For example, the cutbacks in Northwest Airlines resulted in the cancellation of $3.8 billion in orders for 50 new Airbus A320s and 24 Airbus

A340s. World airlines reported losses totalling $15.6 billion over the period 1990-1993.[73] The problems of the civil aircraft producers have been compounded by the downturn in their defence business. Military aircraft are manufactured almost exclusively by those companies that also produce civilian planes, or, put another way, the top ten civil aerospace companies all rank amongst the world’s top twenty producers of arms.[74]

Table 2.9: World Civil Jet Aircraft Orders and Deliveries 1981-1995 (aircraft number)

	Orders	**Deliveries**
1981	283	608
1982	260	472
1983	256	427
1984	363	362
1985	674	404
1986	639	466
1987	598	490
1988	1075	583
1989	1305	647
1990	1003	768
1991	446	950
1992	473	893
1993	391	727
1994	361	551
1995	691	499

Source: The European Aerospace Industry[75]

Table 2.9 shows aircraft orders and deliveries throughout the 1980's and early 1990's. Although the period 1990-1993 was difficult for the industry, prospects are looking brighter the for second half of the decade. The industry turned a profit in 1994 for the first time since 1990 and profits on international scheduled services are forecast by IATA at $6 billion this year (1996). However, as the industry has stressed, despite the recent results, the total profit for 1994-1996 represents only 85% of the losses made in the early 1990's.[76] Nevertheless, the recovery looks set to continue, as the 1994 Aerospace Keynote report comments,

> "The resumption of a 5% to 6% annual growth in revenue passenger miles since the Gulf War supports confidence for the medium term. The return of passenger traffic growth to long term trend levels supports expectations for a recovery in aircraft orders, now generally anticipated for 1996."[77]

Table 2.10 gives the world-wide aircraft requirement forecasts.

Table 2.10: Predicted World-wide New Aircraft Requirement, 1994-2013 (Number of Aircraft)

Aircraft Size (Seating Capacity)	1994-1998	1999-2003	2004-2008	2009-2013	1994-2013 Total
70-90	194	184	227	180	785
91-120	419	500	414	443	1776
121-170	1112	974	852	1333	4271
171-240	559	445	684	1016	2704
241-350	298	291	295	366	1250
350+	560	717	937	1054	3268
Total Volume	3142	3111	3409	4392	14054

Source: Keynote Report[78]

Of the civil aeroplane manufacturers, Boeing has by far the largest market share at 77%. Boeing is a fairly extensive user of new materials. Current Boeings have CFRCs in secondary structures and the Boeing 777 incorporates CFRCs into the vertical fin and horizontal stabilisers with a total composite weight of 3600 kg per plane. The Japanese producer Toray has established a prepreg plant at Frederickston in Seattle in order to fulfil Boeing's carbon fibre requirement.[79]

Airbus Industrie is a European consortium in which British Aerospace has a 20% stake, Spain 4% and France and Germany around 38% apiece.[80] It is generally acknowledged that, in terms of new materials, Airbus Industrie makes the most innovative civil aircraft. The A320 was the first large civilian aircraft to incorporate CFRCs into primary structures as well as control surfaces, in the undercarriage and in interior fixtures. Composites are used even more extensively in the new, larger, longer distance A340. Although small compared to Boeing, Airbus has a significant market share, which has resulted in substantial investment in European carbon fibre production.[81]

The use of carbon fibres in civil aircraft is growing steadily and expected to continue to increase incrementally in the foreseeable future. It is the belief of the industry that the civil aerospace applications will become the largest market for carbon fibre in the mid-term.[82]

Finally in this section, we look briefly at carbon fibre applications in leisure and private flying. Private business jets incorporate a very high proportion of carbon fibre and the use of composites in primary (flight critical) structures is widespread. Indeed, the Beech Corporation Starship and the Artek 400 are designed and built with airframes based almost entirely on a carbon composite structure.[83]

Table 2.11: World Deliveries of Light and Business Aircraft

(number of aircraft)

Year	1986	1987	1988	1989	1990	1991	1992	1993	1994
Total	809	819	842	894	879	776	729	698	706

Source: The European Aerospace Industry[84]

Table 2.11 shows the number of number of business aircraft deliveries over the last ten years. The economic affluence of the West during the 1980's resulted in a large increase in private plane ownership and there has been a corresponding decline in the recent recession. Sales of microlights and hang-gliders also grew throughout the 1980's, increasingly steadily at between 8 and 15% per annum throughout the decade. Microlighting is largely concentrated in the US whereas hang-gliding has a greater following in Europe. Both sports rely heavily on small, local, private companies, often established by a leading figure in the sport and continue to grow in popularity. Although small in terms of value, leisure and private flying act as valuable technology demonstrators for the industry.[85]

Sports and Leisure

The sports market for CFRC was largely developed by Japanese companies, and is now the biggest end sector of carbon fibre accounting for almost half of total global consumption. Golf club heads were the first volume application of carbon fibre, and fishing rods, yacht masts, tennis and badminton racquets swiftly followed. According to Asahi Shinbum, golf clubs alone account for one quarter of global carbon fibre consumption.[86] Sports goods made from carbon fibre are comparatively expensive, but obviously users feel that the performance justifies the price they pay. Examples include golf clubs at 50,000 yen, fishing rods at 150,000 and skis at 140,000 yen a pair.[87] A carbon fibre ribbed umbrella can be bought for around 20,000 yen. Needless to say, one of the largest markets for these kinds of goods is Japan, where the high growth economy together with the equable distribution of income (the most equable in the OECD) has ensured a very large domestic consumer market. Golf is a prestigious sport in Japan and it is not uncommon for golfers to upgrade their entire set of clubs each year. Yachting is another prestigious sport and the use of carbon fibre made by Hercules and Mitsubishi Rayon in the America's Cup race was given high profile in their respective annual reports.[88]

Industrial

Industrial applications of carbon fibre account for just over 20% of consumption. These sorts of applications include robot arms, centrifugal rotors, weaving machinery, printing rollers and other high speed industrial machine parts that can exploit the low inertial mass of a lightweight material. The use of CFRCs also offers other advantages such as the tailorable and isotropic stiffness, high strength, dimensional stability, vibration damage and fatigue resistance characteristics we have already seen employed in other applications. Carbon fibre also has a low coefficient of friction, and so is often used in bearings. Robotic applications look particularly fruitful as carbon fibre has a high stiffness to weight ratio, which means that unlike metals, where endpoint accuracy can only be achieved at the cost of higher mass and hence slower response time, a light weight yet accurate arm can be produced. The current growth rate of the robotic sector is estimated at 6%. In line with general growth of the advanced engineering industry in the Far East (and the corresponding decline in Europe and the US), Japanese companies now dominate robotics production.[89]

It is difficult to predict the future growth of industrial applications of carbon fibre as the sector is very fragmented both regionally and sectorally, and the use of new materials often incurs additional re-tooling costs. However, the US Office of Technology Assessment (OTA) forecast a 'slow but steady' increase in this market segment.[90]

If the price of carbon fibre falls further, the very high volume **automotive sector** will be accessed. At present, CFRCs are used in car engines to a small degree. The US company Hercules, for example, supply General Motors with carbon fibre composite for the manufacture of drive shafts. The use of carbon fibre in car body parts would allow manufacturers to reduce weight while increasing strength and stiffness. Additionally, carbon fibre offers superior corrosion resistance over steel or galvanised steel, with the result that the OTA estimate that a polymer matrix composite body might have twice the lifetime of current steel models.[91] However, aside from the cost, there is at present a lack of manufacturing technologies that can compete with the high production rate of the metal stamping industry. In order to compete with standard car parts, a CFRC moulding technology that can produce complex and integrated structural parts quickly and reliably needs to be developed. Over the last few years, a series of environmental and safety related regulations in the US has made the production of carbon fibre natural gas tanks for use in public transport vehicles economically viable. At present, the demand for such tanks is so high, that the market crises of the early 1990's have completely reversed, with the result that most carbon fibre producers are currently working to full capacity.[92]

Other

Although carbon fibre finds its largest markets in aerospace, sports and leisure, in which high strength and modulus are required, other applications are being developed that exploit not only the mechanical properties but also other characteristics such as low thermal expansion, good electrical conductivity and high X-ray transmission. One example of an application that uses a specific property of carbon fibre is the development of **X-ray table tops and cassettes**, which has significantly reduced patient (and radiographer) dosage. The Swedish firm Siemens pioneered the development of this application.[93]

As second example is the use of carbon fibre as a **heat insulator** in high temperature furnaces. General purpose grade pitch based carbon fibre is used in this application, which can withstand temperatures of 3000°C in an inert atmosphere or high vacuum furnaces. The carbon fibre employed in this application is fairly expensive at around 40,000 yen per kilogram. This compared favourable, however, with the cost of competing materials such a molybdenum plate.[94]

Carbon fibre composites are bio-compatible (i.e. are not rejected by the body and have a neutral effect on body chemistry) and are already in use as **artificial ligaments and joint replacements.** Current implant devices are made from metal which can result in allergic reactions to the metal ions, fatigue failure, degeneration due to a lack of mechanical loading and poor matching of mechanical stiffness. CFRCs not only have the capability to overcome these difficulties, but also offer additional benefits. A degradable composite system could be designed to provide initial support to an injury and then be gradually absorbed by the body as the natural tissue repairs. Medical implants is a small volume but high value added sector (with an additional high societal value) in which the advantages of using carbon fibre often outweigh the expense.

The total market world-wide for bio-compatible materials is worth around DM 7.5 billion with the US accounting for 53% of sales, followed by Europe at 29% and Japan at 8%.[95] The current growth rates for implants is said to be between 15 and 20% per annum.[96] This high rate is partly due to the wider diffusion of technologies and partly as a result of the ageing populations in industrialised nations. Market figures do not differentiate the sales of carbon fibre in this sector from those of other materials. However the OTA believe that CFRCs will constitute a 'substantial portion' of the market.[97] This rapid growth rate will ensure a steady investment in research and development and a continuing interest from large companies. Du Pont holds key patents for prosthesis materials and in Europe Bayer is a leading producer of bio-compatible materials.[98]

A potentially large volume application is the **construction industry**. Current applications include actual buildings and bridge parts, such as cables and domes, and in the machinery employed, for example cranes. Again, the benefits of using CFRCs in this sector include high strength to weight ratios (with a density of between two thirds to a half that of conventional concrete), a reduction in the number of subassemblies and corrosion resistance. The ability of carbon fibre composite to withstand chemical attack makes it increasingly relevant in applications where the working environment is particularly tough, such as off-shore oil rigs. The carbon fibre used in construction applications is usually the lower cost general grade fibre made from pitch.

Carbon fibre reinforced concrete curtain walls have a tensile strength and a flexural strength two to five times higher than those of conventional concrete curtain walls.[99] One of the first major building projects to use carbon fibre reinforced concrete was the Al Shaheed monument in Iraq. This consists of a pair of twin domes, each 40 metres high and 45 metres across at the base. The domes were constructed with a galvanised steel skeleton covered in beautiful porcelain tiles backed by carbon fibre reinforced concrete, selected as it is light weight, able to withstand the weather extremes in Baghdad (it is dimensionally stable under extremes of temperature) and strong.[100] However, generally speaking, the cost of competing materials is low and the companies themselves notoriously conservative. These are expected to be major barriers to substitution in this sector. Any increase in the use of carbon fibre in the construction industry is therefore expected to be slow.[101]

We have seen that carbon fibre is a high performance material, mainly limited in application by its high costs. The very large volume automotive market remains a holy grail for carbon fibre producers, and the use of carbon fibre in compressed natural gas tanks, if successful, could prove a useful technology demonstrator that may access large market mainstream automotive applications. For these applications, the manufacturing costs of carbon fibre composites must be reduced, most likely through the improvement of either resin or precursor technology. The cost of PAN accounts for a large percentage of the final cost of the fibre and the development of new precursors, perhaps based on pitch could significantly lower costs. Similarly, the higher performance thermoplastic resins would enable cheaper high volume production of car parts.

In the foreseeable future, however, the use of carbon fibre composites will continue to increase in civil aerospace and Toray believes this will become the largest market for carbon fibre in the mid-term.[102] This view is reinforced by the launch in 1995 of the Boeing 777, the first Boeing civil aircraft to use carbon fibre in primary structures. With the demise of the defence sector, it is now generally acknowledged that the health of the civil airline sector is the main determinant in the growth of the carbon fibre industry in the mid-term.

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CHAPTER THREE:
THE CORPORATE CONTEXT

In this chapter we will seek to compare the business systems and industrial structures of those countries in which carbon fibre is produced. The development of a high technology sector, such as carbon fibre, takes place within a general national industrial and economic environment which, as we shall see in Chapter Five, has had a profound influence on the industry. Every country has its own distinct industrial structure, dependent, for example on the type and mix of corporate governance, patterns of demand, means of finance, range of governmental institutions and regulatory and tax regimes. We examine here those aspects of Japanese industrial structure that have most influenced the development of carbon fibre manufacturing, then, in the second part of this chapter, look at the development of the Anglo-American corporate environment. Firstly, we will look at the major influences in the historical development of Japanese industry from the Meiji restoration to the present day.

Part One: Japan

For People, Mitsui; For Organisation, Mitsubishi; For Unity, Sumitomo

Japanese Saying

Background

Prior to the restoration, Japanese society was typified by rigidly defined social classes based on a system of vertical loyalties and reciprocal obligations. This system was made necessary by the exigencies of rice culture and the pressures of living in an overcrowded land. Even before the restoration took place, however, there was a steady growth in the power of a centralised national government and a rising system of state protection. In 1853, with the arrival of Perry's convoy from the United States and the subsequent threat of foreign invasion and colonisation, all classes perceived the importance of national security and the idea of some form of state cohesion gained massive popularity, culminating in the Meiji Restoration of 1868.

The restoration reinforced the guiding ethos of reciprocal obligations, but these obligations were transferred from specific social classes to the firm and state. Hence a form of paternalism arose between labour and capital, receiving widespread support through its identification with the overriding demands for a national security under the external threat. In this way, despite the rapid political transition of the period, the social order was, by and large, maintained. This stability enabled Japan to enter a period of rapid economic growth and construct the industrial infrastructure necessary to build and sustain a military power. The result was that Japan became the first non-western country to industrialise.[1]

Meanwhile, Japan's system of banking and finance was reorganised along fashionable European lines rather than on the basis of the country's traditional feudal systems. A new decimal currency, the yen, was introduced in 1871, shortly after which the Bank of Japan was established as the country's central bank. The post office savings system was inaugurated in 1874 and the establishment of private savings banks soon followed. During World War II, the Bank of Japan was reorganised to control currency, credit and finance in line with government strategy. The Bank's powers were further strengthened in 1949 to include responsibility in changes in the discount rate. The consequent interest rate regulations (most notably the creation of a stable business environment) resulted in a high rate of industrial indirect finance. This financial system, with the Bank of Japan at the apex of a structure based on commercial and savings banks, and with the post office playing a major role, remains more or less intact today. Similarly, indirect finance (by which companies obtain funds by borrowing from financial institutions as opposed to selling securities) remains a predominant feature of Japanese industry today.[2]

Pre-war origins

Before the war, Japanese industry had been dominated by the **zaibatsu**, semi- monopoly groups of related business enterprises. The zaibatsu were run by family-owned holding companies which maintained their control through majority share ownership. The Big Four zaibatsu were:

1. Mitsui. Mitsui was one of the oldest of the zaibatsu groups with some of its business enterprises dating back to the 17th century. Although it had mining and commodity trading operations, its major business was money lending and by the middle of the 19th century was in all but name acting as a private exchequer to the Japanese government. In 1871, however, the government established its own central bank, the Bank of Japan. Mitsui temporarily floundered, then acted to consolidate its businesses by strengthening its other concerns and diversifying along three new manufacturing lines, namely, silk reeling, cotton spinning and electrical machinery. In 1893 it acquired Tokyo Shibaura Electric (later shortened to Toshiba), an innovative start-up company that made electrical motors, power generators and communication equipment. Demand for such machinery soared during the Russo-Japanese War and Mitsui's reputation as a supplier of defence equipment spread throughout the industrialised world. The outbreak of World War 1 was particularly timely for Mitsui, not only increasing demand for military equipment but also opening new markets in regions now cut off from their former European suppliers. This enabled Mitsui to pursue its vigorous agenda of expansion not only domestically but also overseas. Hence by the mid 1930’s Mitsui was probably the most powerful zaibatsu in Japan.[3]

2. Sumitomo. Sumitomo, like Mitsui, was founded in Tokugawa Japan as a family business. The firm had its origins in mining. In the 1880’s the restoration government privatised virtually all its industrial concerns and Sumitomo acquired a number of new businesses relating to minerals and mines, including the most productive copper mine in Japan. The ensuing profits were reinvested to launch a shipping storage business. Sumitomo consequently became a prime contractor to the government of the day in the supply and transport of raw materials.[4]

3. Yasuda. In contrast to the hoary origins of Mitsui and Sumitomo, Yasuda and Mitsubishi, considered the arrivistes of the zaibatsu world, were both created by pioneering entrepreneurs at the start of the Meiji regime.[5] Yasuda began as a family money lending business but quickly emerged in the decade following the Restoration as a powerful banking and financial zaibatsu. Eight railways and two shipping lines were soon added to the portfolio. These transport related investments burgeoned during the Russo-Japanese war by the end of which Yasuda had virtually doubled its railroad interests.[6]

Yasuda changed its name to Fuyo after the War. Most of its financial institutions, however, continue to bear the Yasuda name.

4. Mitsubishi. Mitsubishi was set up by a group of ex-samurai headed up by Yataro Iwasaki. A small shipping line was the groups first purchase and, in 1874, Mitsubishi was awarded a very profitable government contract to ship troops in Japan’s first modern military venture, the so-called Taiwan Expedition. The group quickly established its own network of domestic and overseas shipping lines and acquired a number of mining interests through the Meiji government privatisation. Mitsubishi grew and diversified into a fully fledged zaibatsu, with interests in banking, brewing, chemicals and, most particularly, heavy industry. The group acquired the Nagasaki shipyard and by the start of World War II, was a major producer of battleships and aircraft (including the Zero fighter). In short, “Mitsubishi put the muscle into Japan’s military advance”.[7]

Post-war Change

Not surprisingly, the zaibatsu were seen by the post-war occupation authority as the driving force behind Japan's militarism; the US Ambassador, Edwin W. Pauley reported:

> "Japan's zaibatsu (literally, financial cliques) are the comparatively small group of persons, closely integrated both as families and in their corporate organisations, who throughout the modern history of Japan have controlled not only finance, industry and commerce, but also the government. They are the greatest war potential of Japan. It was they who made possible all Japan's conquests and aggressions." [8]

Similarly, General MacArthur declared in his New Year Message of 1948:

> "Economically, allied policy has required the breaking up of that system which in the past has permitted the major part of the commerce and industry and natural resources of your country to be owned and controlled by a minority of feudal families and exploited for their exclusive benefit. The world has probably never seen a counterpart to so abnormal an economic system ... The integration of these few with government was complete and their influence upon government policies inordinate, and set the course which ultimately led to war and destruction".[9]

Pauley and MacArthur both had great influence on American policy toward post war Japan.[10] The dissolution of the zaibatsu became a central theme of the occupation reforms and legal measures were quickly introduced to disband the 'abnormal economic system'. Banks were prohibited from holding more than 5% of the stock of any single corporation. Executives were fired, trademarks banned and the "excessive economic concentrations" broken up into independent companies.

The occupation ended in 1951 and by April 1952, when the Peace Treaty came into effect, Japan was formally an independent nation. The **gyoku kosu** or reverse course commenced. Little by little, many of the restrictions of the 1947 Law for the Elimination of Excessive Concentrations of Economic Power were removed (former trade names were resuscitated), moderated (the upper limit of share holding by a financial institution was raised from 5 to 10%), revised or ignored.[11] Mitsui, Sumitomo and Mitsubishi set about reassembling their original zaibatsu partners, while the Fuji, Sanwa and DaiIchi banks picked up the stray firms that had survived the successful occupation demolition of their (smaller) zaibatsu parents. These six banks became the centre of the new big keiretsu.[12]

The new keiretsu differed from the pre-war zaibatsu in three important ways. Firstly, whereas the zaibatsu were commercially specialised (under the **ichi gyoushuu, issha taisei**, or one group, one sector principle) and competed through evolving inter-firm economies of scale, the keiretsu grew through a policy of rapid expansion based on what became known as the "one set" (i.e. one of everything) principle, the result being that each keiretsu built up a diverse range of interests so as to include almost every major field of business endeavour.

Secondly, whereas the ownership of the zaibatsu was largely concentrated in the hands of a single family, consequent to the occupation reforms, the stock of a keiretsu firm was distributed fairly evenly across the keiretsu group. This second feature came about as a direct result of the upper 10% limit on shareholder ownership. The old zaibatsu holding companies were not revived. Instead each keiretsu member brought a small percentage, typically 2 or 3%, of stock in each of the other companies of the former zaibatsu. Although small, every keiretsu member held such a stake in almost every other firm in the group. The cumulative effect was that between 30 and 90% of the shares of each firm were tied up in these stable crossholdings. This strategy was further pursued through an increase in market capitalisation. Mitsubishi, for example, increased its capitalisation 400%, allocating the 20 million new shares to firms within its keiretsu group. As a result the concentration of Mitsubishi share ownership rose from 10.4 to 31.1%.[13]

Despite this, however, the group bank became the primary source of finance for keiretsu firms. This is the third major difference between the pre-war zaibatsu and the keiretsu groups. The zaibatsu were largely directly financed. During the pre-war period shares and retained profits accounted for 80% of total industrial income, with bank loans accounting for the remainder. This state of affairs was largely reversed for the keiretsu. In 1951 for example, loans from banks accounted for 62.8% of keiretsu capital income, while the own capital contribution shrank to 25.9%.[14] Loans from related banks enabled keiretsu firms to raise finance without losing corporate control by issuing large volumes of stock to outside shareholders. Hence commercial banks became the main provider of funds for industry, through a system of indirect finance that remains a central feature of Japanese business today.

In this way, the construction of the new keiretsu system began. The reconstitution of Mitsui, for example, was more or less complete by 1956. Despite running counter to the original Occupation ideals, the economic restructuring met with the tacit approval of the US as since the fall of imperial China, Japan was perceived as a bulwark against the rise of communist East Asia.[15]

The Role of Government

After its shattering defeat in World War II, Japan faced severe economic problems. Material losses were estimated at a quarter of the total national wealth and two thirds of the nation's capital stock were destroyed. Real GNP per capita had fallen to half the pre-war level. Hence the first priority of the occupying forces had been emergency shipments of food and raw materials. However, after 1948 the emphasis of US policy shifted toward economic self reliance for Japan. In order to industrialise as fast as possible, extensive government involvement was required, specifically in the form of industrial policy.[16]

In 1949 the Ministry of International Trade and Industry (MITI) was established. Under its aegis, a Development Bank was created as a source of low interest funds for industrial investment; tax reforms were introduced in the form of investment allowances; sectoral priorities were established; infant industries protected; a system of foreign exchange allocation was developed (which in practice gave officials the ability to direct raw materials to selected companies); and technical co-operation agreements were made with foreign firms, especially American ones. The policy of prohibiting direct foreign investment that had begun under US Occupation continued throughout the next couple of decades. Direct foreign investment was not encouraged and, as a result, the introduction of foreign technology was achieved through technical co-operation agreements rather than turn key factories. Many foreign companies were only too willing to sell their technology as the Japanese market was considered too small to be worth developing. This had a direct impact on carbon fibre manufacture as it encouraged foreign companies to license patents since direct manufacturing in Japan had to ruled out. Furthermore, as Japan was a comparative latecomer to many technologically based industries, it had the advantage of investing directly in more modern facilities than foreign rivals.

Supervision was exercised by means of what was called **gyosei shido** (administrative guidance) which enjoyed semi-legal status, and survived challenge under the antimonopoly laws of 1952. MITI used these powers to improve the competitiveness of Japanese business through actively sponsoring the formation of new keiretsu centred on the big banks, the largest of which were closely related to the pre-war zaibatsu which, as we saw, had been dissolved during the first phase of the occupation. With MITI assistance, however, the major keiretsu such as Mitsubishi and Mitsui were back in full scale operation by 1955.[17]

Hence by the mid-1950s, American assistance and MITI policy had laid the foundations for what was to be an exceptional surge of industrial development. Aside from direct government support, Japanese industry benefited from several exogenous factors. The world economy as a whole was undergoing a period of expansion. During the Korean War (1950-1953), the United States set up a special procurement programme in Japan to buy supplies and repair equipment. Currency earnings on this account were almost $600 million in 1951, over $800 million in 1952 and again in 1953, making possible large new investment in plant and equipment. This greatly aided Japan to achieve a balance of payments throughout an otherwise difficult period. Meanwhile, domestic social changes such as land reform, introduced in part by the Occupation, ensured that gains were widely spread (thus ensuring a large domestic market), and the Japanese population's high propensity to save made capital more readily available for investment.[18]

Although post-war Japan had low wage advantages and lower comparative costs of production, the Japanese government adopted a strategy of concentrating on capital and technology intensive industries. These involved much higher initial risks and costs but offered many longer term advantages, of which the most important was the potential for high income, rapid gains in technological advancement and the prospect of faster improvements in labour productivity.

In short, government industrial policy was targeted primarily at rapid economic growth. And indeed, the result has been a phenomenal increase in wealth; between the years 1950 and 1990, real income per head rose from $1230 (in 1990 prices) to $23,920, a growth rate average of 7.7% per annum.[19] This compares to just 1.9% in the United States. During its period of fastest growth (1955-1970) the Japanese economy achieved a rate of average annual growth of over 10%. Japan was hit badly by the oil crises of the early 1970's and these, combined with the Nixon shock[2] of 1971, slowed the country's economic growth to around 4.5% per annum. (Still higher, however than any other major industrial power throughout the decade.) In response to these crises, MITI's policy shifted away from industries that depended heavily on imported raw materials and towards more technologically intensive, energy efficient, value added sectors[20]. This is reflected in the list of Japan's top fifty industries (in terms of export market share), which uniquely includes no natural resource intensive sectors. [21]

Finally, we should also note that Japanese industry in general is relatively stable, not least of account of the high level of co-operation between management and labour and the comparatively constant political environment. Large firms are additionally stabilised by the copious number of small companies. These bear the burden of adjustment during market fluctuations so muting business cycles.

Corporate Governance

Following the developments described above, present day Japanese industry possesses several distinguishing features. The three most important, for our purposes, are:

- a high rate of savings and investment;

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[2] In August 1971, President Nixon suspended the gold convertibility of the dollar (thus ending the Bretton Woods system of fixed exchange rates), and announced a 10% surcharge on imports into the US. Japan was consequently forced to cut its fast export led growth.

- a high rate of indirect financing; and
- a high number of corporate alliances.

Since the 1950's, Japanese savings rates, according to every measure, have been the highest in the world and have often exceeded those of other major industrial countries by a factor of two or more. This especially held true in the very high growth years before the oil shock. During the period 1970-1972, for example, Japanese households and unincorporated businesses saved 13.5% of GNP. The corresponding figure for the United States was 5.3%. The net savings of Japanese corporations was 5.8% of GNP compared to 1.5% in the States. The Japanese government saved 7.3% net of GNP. The net savings of America's government was 0.6%. Hence Japan's total net savings over the period was 26.6% compared to just 7.4% in the United States.[22]

Household savings are the largest component of Japan's total savings and have been approximately 75% higher than in the West over the last 25 years. Despite a gradual decline in the propensity to save, the Japanese still manage to save at a level some 50-60% higher than the OECD average. The high rate of private savings has been attributed to the importance of educational expectations, high housing costs, a tradition of frugality, and the uncertainty surrounding welfare provision. Probably the major factor, however, is state incentives in the form of tax exemptions (50-60% of personal savings are tax exempt). Japanese post office savings carry additional special privileges and now constitute the largest single collection of retail deposits in the world.[23]

Whatever the reasons, the results have been that every component of Japan's savings has been high by international standards. This exceptionally high savings rate, sustained over many years, has spurred (and financed) a correspondingly high rate of capital investment through indirect finance. This has been noted by many commentators. The OECD, for example, reports that throughout the 1960's, 70's and 80's, the rate of fixed capital investment in Japan was significantly higher than in other G7 countries. As individual Japanese savers have long favoured low risk investments with easy access for withdrawals, bank and post office savings take two thirds of individual deposits. The state has played a pivotal role in transferring these savings into investment in both private and public sectors. The chief mechanism by which this takes place is the state run Fiscal Investment and Loan Program (FILP).

The FILP is run by the Ministry of Finance and effectively acts as a bank within the government. Since its establishment in 1953, the flow of funds through FILP has been considerable. In the 1980s, for example, the FILP budget was equivalent to 30% of total investment or 10% of GNP. BY 1987, FILP funds had reached over 27 billion yen, or half the government's general budget for that year.[24] Around 50% of FILP funds are private savings collected by the state through the post office system. FILP then makes loans at lower than market interest rates to a variety of public agencies. Aside from such bodies as local government and public transport and communication enterprises, around a half of FILP allocations are earmarked for public finance institutions, which in turn provide loans to private companies. Hence, FILP provides a mechanism through which the accumulated savings of households are channelled via a state institution into private sector industry.

Since savings have been in good supply, real interest rates have remained generally lower than those of other major industrial economies. Moreover, since inflation, too, has been relatively low, Japan's nominal interest rates have also been below those of other G7 countries.[25] As we have seen, the bulk of private savings are deposited into banks and post offices, which in turn lend to private industry. Companies are further encouraged to rely on loans as, in contrast to dividends, loan interest is tax deductible. As a result, there is a relatively high level of indirect finance and a consequent low rate of self capitalisation amongst Japanese firms. Okimoto, for example, has demonstrated that, over a given period, marketable securities, such as stocks and bonds, accounted for 35.9% of the total non-monetary assets of US corporations compared to only 12.9% in Japan.[26] Japanese companies instead had a pronounced preference for raising finance through bank loans. In short, the high level of investment in Japan is largely financed indirectly through the banks in contrast to US companies who rely more heavily on internal funds.

The predominance of indirect financing is further strengthened, as we have seen above, by the organisational structure of Japan's private sector, in particular the **keiretsu** system. We should first briefly note that there are two basic keiretsu classifications. These are known as **yoko** (horizontal) and **tate** (vertical). The vertical keiretsu have a pyramid structure with a single large manufacturing company at the apex supported by hundreds of small sub-contractors. Toyota is one example. Horizontal keiretsu are the enormous groups of loosely affiliated companies held together through interlocking share holdings, mutual business transactions and a common main bank. A horizontal keiretsu typically includes a big bank, several large capital intensive manufacturing companies and a trading house. The big six keiretsu are based on the Fuji, Sanwa, DaiIchi, Mitsui, Mitsubishi and Sumitomo Banks - Toyota is a member of Mitsui. All the carbon fibre manufacturers are affiliated to horizontal keiretsu to some degree and hence it is this type which are the focus of this discussion.

Although nominally independent companies, keiretsu companies are linked together through reciprocal share holding, interlocking directorships, and intra-keiretsu trading and credit relations. Increasingly, technological cross-licensing is an additional characteristic. However, keiretsu groups do not act as single corporations and it is quite common for financial corporations from other keiretsu to also hold stock and extend loans (but to a smaller degree). Significant cross keiretsu ties exist through inter-keiretsu stockholdings and business transactions. Within a keiretsu, firms will compete intensely to increase their own market share even at the expense of rivals within the group. Moreover, it is not unusual for a company to belong to more than one keiretsu. Nissho Iwai, for example, belongs to both Sanwa and DaiIchi Kangyo. Hitachi, the **keiretsu no chou** (keiretsu butterfly), belongs to three (Dai-Ichi Kangyo, Sanwa and Fuyo). Here we define a **core firm** of a keiretsu as one that is an official member of the group's presidential council and an **affiliated firm** as one in which core firms collectively hold a minimum 10% stake.

By way of example, Table 3.1 shows a breakdown of the Mitsubishi keiretsu:

Table 3.1: Structure of the Mitsubishi Keiretsu Group

Firm	Percentage of firm owned by keiretsu members
Mitsubishi Corporation	32%
Mitsubishi Bank	26%
Mitsubishi heavy Industries	20%
Mitsubishi Trust and Banking	28%
Tokio Marine & Fire Insurance	24%
Meiji Mutual Life Insurance	0%
Mitsubishi Motors	55%
Nikon Corporation	27%
Kirin Brewery	19%
Mitsubishi Oil	41%
Mitsubishi Electric	17%
Mitsubishi Plastics Industries	57%
Mitsubishi Petrochemical	37%
Mitsubishi Gas Chemical	24%
Mitsubishi Metal	21%
Mitsubishi Aluminium	100%
Mitsubishi Steel Manufacturing	38%
Asahi Glass	28%
Mitsubishi Construction	100%
Mitsubishi Cable Industries	48%
Mitsubishi Paper Mills	32%
Mitsubishi Rayon	26%
Mitsubishi Mining and Cement	37%
Mitsubishi Estate	25%
Mitsubishi Kasei	23%
Mitsubishi Warehouse and Transportation	40%
Mitsubishi Kakoki	37%
Nippon Yusen	25%

Source: Johnson[27]

The keiretsu is composed of 28 core firms which all hold mutual equity and which each have at least one director from another Mitsubishi company. There are an additional 217 affiliated firms i.e. those with 10% or more equity held by core keirestu members. These include the Honda Motor Corporation and Nikko Securities (one of the big four brokers in Japan). Together these firms generate annual sales of $360 billion dollars (fiscal 1990). The three central firms are the Mitsubishi Corporation (a trading company), Mitsubishi Bank and Mitsubishi Heavy Industries. Mitsubishi banks acts as the primary source of funding for the industrial members of the group. Aside from the main bank, there are two insurance firms and a trust company. There are over twenty manufacturing core firms covering a wide range of industries. In almost every case, over 20% of the stock of each core company is held within the keiretsu.

On almost every measure, the big six keiretsu banks are ranked the largest in the world and collectively Japanese banks account for over a third of OECD total banking assets.[28] Table 3.2 lists the world's largest banks by assets and capital.

Table 3.2: World's Biggest Banks, 1995

Bank	*Country*	*Assets $bn*	*Capital$mil*
Tokyo Mitsubishi	Japan	819.0	28,221
Sanwa	Japan	582.2	19,577
Dai-Ichi Kangyo	Japan	581.6	19,360
Fuji	Japan	571.1	19,388
Sumitomo	Japan	566.0	22,120
Sakura	Japan	559.5	18,549
Deutsche	Germany	503.4	-
Industrial Bank of Japan	Japan	433.3	13,596
Norinchukin	Japan	429.3	3,367
Long Term Credit Bank Of Japan	Japan	371.6	-

Sources: Economist[29]

Keiretsu Economics

Under neo-classical economic theory, the objective of a financial corporate grouping is to enhance the profitability of member firms. However, Nakatani, in his seminal examination of the financial and corporate governance of keiretsu firms[30] demonstrates that the rate of business profits over total assets is **negatively** correlated with keiretsu membership. Hence we must look for motivations other than profit maximisation in the formation of these corporate financial groups.

Several authors have noted the comparative stability of the Japanese business environment. In 1990, the Economic Planning Agency compared the sensitivity of Japanese and US stock prices to their short term profit by measuring fluctuations in the price to earning ratio (stock price/current profit after tax). American stock prices were found to follow variations in short term profits very closely. Japanese stock prices, on the other hand, were little influenced by changes in short term profit. As a result, the paper concludes,

> "Japanese stock prices are less sensitive to fluctuations in short term profit and that the shareholders' focus on the short term achievement of the corporation is less pronounced in Japan." [31]

Similarly, Nakatani has shown that, all else being equal, the **variance** over time of business profits over total assets is considerably smaller for group firms. Moreover, even the variance of the growth rates of keiretsu firms is significantly lower than that of independent companies.[32]

This stability enables keiretsu members to more easily pursue new growth sectors. Finance can be raised quickly for new ventures by distributing stock amongst the keiretsu members through the central bank. This reduces the underwriting costs and uncertainties of new issues. Ventures involving, for example, new technology or some other high risk element are often jointly financed by the group. This spreads the risk and the burden of debt should the project fail. It enables a broader range of manufacturing expertise to be exploited and in some cases guarantees a market for the new product. For a business like carbon fibre, the sunk costs are relatively high and production very capital intensive. These factors restrict the possibilities of transferring the burden of adjustment to small subcontractors should the project fail and so increases significantly the importance of the additional protection provided by keirestu membership.

Group membership also has a profound effect on the corporate governance of keiretsu firms. The dividends paid out by keiretsu firms are consistently **lower** than those of similar companies. The system of interlocking shareholders not only cements relationships but protects firms from the dictates of market imperatives. Unlike in the US, where the value of stock may plummet if short term profits fall, hostile acquisition is relatively rare in Japan as group stockholding reduces the availability of stock to outsiders. In 1992, *The Economist* reported,

> "The stockmarket value of no fewer than 234 of 2,045 publicly quoted Japanese companies is less than their net book value, a measure of a firm's assets minus its liabilities. At least theoretically, these firms should be worth more broken up than as going concerns. As a result, many Japanese companies now look seriously underpriced by the stock market. Over the past few months, the market capitalisation of such well known manufacturers as Nissan, JVC, Hitachi Maxell, Fuji Heavy Industries and Minebea has dropped well below the level of their shareholders' equity.
>
> Despite their low prices, many of these firms remain immune to take-over, or at least of the unwelcome variety. The clubby atmosphere of corporate Japan rules out hostile bids for big companies [as] 70% or more of their shares are locked up safely with their banks, corporate cousins and other friendly firms."[33]

Hence, Japanese companies do not feel the same compulsion to yield high dividends so long as the real value of the stock appreciates. Indeed, during the 1980’s the rate of dividend of Japanese manufacturing as a whole was only 11.3% compared to 19.6% in the US.[34] Similarly, Nakatani finds that the rate of dividend over paid in capital is much smaller for keiretsu companies compared to a set of matched independent firms.[35] Low dividends give a company the stability and flexibility to re-invest a higher proportion of profit into longer term market share strategies. Large UK firms, for example, spend on average 2.29% of turnover on R&D, compared to 5.9% for their counterparts in Japan.[36]

The low rate of dividend is brought about by several factors. Firstly, dividend payouts in general are less important for long term shareholders as long as the capital value of the stock appreciates. Moreover, intercorporate dividends are not tax exempt in Japan and so the keirestu as a whole benefits if the dividends arising from reciprocal shareholdings are kept low. Clearly low dividends do not benefit independent, individual shareholders. These shareholders, however, have little say in Japanese corporate affairs. Nearly 90% of all Japanese companies hold their annual meeting on the same day. Hence it is a physical impossibility for a single shareholder to vote in more than a few meetings. This is largely irrelevant anyhow as Japanese annual meetings are *pro forma* events that rarely last more than half an hour.[3] Indeed, it is not unknown for companies to compete to claim the shortest meeting.[37]

Hence the real power base of the firm lies within the board, which, for those firms that fall within a keirestu group, is influenced to an uncertain degree by the **shacho-kai** (presidential council)**.** Each of the big six keiretsu has a committee of core company presidents that meets every month (or every three months in the case of Dai Ichi Kangyo). That is,

> "every month the Sanwa Group must gather its most important 44 top executives in a room; the Mitsubishi and Fuyo Groups must each call the roll for 29 CEOs; Mitsui has 26 and Sumitomo 20. Even without the DKB Group ... that's a total of 148 of the top executives from the most important companies in Japan coming together every four weeks."[38]

The role of the presidential council is to examine group dealings with respect to other keiretsu and the business community as a whole. It mediates intra-group conflicts and discusses the group's interests vis à vis government affairs. According to the Japanese economist Yoshinari Maruyama, however, the council's most important function is to plan company strategies within the context of the group.[39] As an example, in 1990, Ken-Ichi Imai published a study of NEC in which he found that around a third of NEC's huge investments

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[3] As a case in point, the 1996 Sumitomo annual meeting, the first following the revelation that the company had lost $1.8 billion through unauthorised trading by a single employee, lasted just 40 minutes (Economist June 29th 1996).

in semiconductor technology had been funded by fellow firms within the Sumitomo keiretsu. He concludes,

> “Information exchange was the key for innovation and investment. ... This system [of keiretsu grouping] has contributed considerably to innovative financing in Japan.”[40]

Finally, membership of a keiretsu makes it easier for companies to borrow money. Banks clearly have a vested interest in expanding those companies in which they themselves hold stock and may offer preferential terms such as lower interest rates or flexible borrowing limits. A high level of co-operation exists between keiretsu banks and affiliated companies, rooted in their common interests. Companies benefit from the reduced levels of uncertainty concerning their future plans. Banks benefit not only directly from their company customers but also indirectly as company employees deposit their own personal savings with the bank most closely associated with their firm. As keiretsu firms are perceived as low risk borrowers, even banks outside the group will loan money at a discount rate.

Hence keiretsu membership provides a comparatively stable business environment and ease of access to long term capital. The system of interlocking shareholders not only cements relationships but also cushions the impact of market fluctuations, enabling keiretsu companies to adopt longer time horizons when planning future strategies. Planning horizons are clearly set out in Japanese annual reports. "Medium term" is typically defined as five to ten years and "long term" ten years or more. These are approximately twice the corresponding US time-scales.[41] The stable business environment also enables keiretsu members to more easily pursue new growth sectors. Finance can be raised quickly for new ventures by distributing stock amongst keiretsu members through the central bank. Ventures involving, for example, new technology or some other high risk element are often jointly financed by the group. This spreads the risk and the burden of debt should the project fail. The broad industrial base of each keiretsu results in wide range of accessible manufacturing expertise and in some cases guarantees a market for the new product.

Summary

We have seen that tax exemptions have ensured a high level of personal savings in Japan. These are for the most part deposited in banks and post office savings accounts rather than invested directly in shares. The additional privileges afforded to post office savings and the FILP mechanism allows the Japanese government to implement industrial policy by channelling private savings into selected private sector industries. Companies, too, are encouraged to raise money for investment through bank borrowing rather than equity issues. The majority of those shares that are issued are held by related companies and banks through the keiretsu system. As a consequence, Japanese firms are less vulnerable to fluctuations in equity markets and under less pressure to produce profit in the short term.

Part Two: The United States
Sunshine and Due Process: the American Corporate Environment

We will now turn to the American corporate environment and, in the light of the above discussion, will examine those characteristics of the American corporate context most pertinent to the growth of a high technology sector. In particular, we will trace the development of those aspects of the Anglo-American firm that have most influenced the carbon fibre sector, i.e., corporate governance and the capital structure of firms.

Unlike the Japanese firm, the Anglo-American company operates as an “autonomous legal and financial entity facing largely anonymous and impersonal market pressures”.[42] There are few interfirm collective commitments and the bank-firm relationship is conducted through classical arm's length contractual relations. This has been brought about through three structural arrangements:

- a very large and dispersed base of share ownership;
- a heavy reliance on legal formalities;
- and the role of contract and the role of banks and state agencies.

Origins

The Anglo-American firm has its roots in the public stock exchanges of the late nineteenth century. In order to justify its power and acquisitiveness, American business fostered a pragmatic philosophy drawing selectively on religious, biological, and legal elements. Wealth was viewed as a sign of divine favour and so the acquisition of wealth considered a moral obligation. Darwinian notions of natural selection were applied with great enthusiasm to the economic management of the nation. (“The growth of a large business is merely the survival of the fittest” affirmed Rockefeller.[43]) Finally, the libertarian view that those that govern least govern best was vigorously promoted.[44]

The United States also developed a strong, perhaps unique, belief in the sanctity of property. In 1866, the Joint Committee on Reconstruction drew up the Fourteenth Amendment to the Constitution prohibiting any state from depriving 'any person of life, liberty or property without the due process of law'. This was applied with great rigour by the legal system and through a series of rulings it was decided that the word 'person' meant a corporation as well as an individual citizen. In this way, American business came to be protected from state regulation, and corporate holdings such as charters and franchises were accorded virtually the same rights as personal belongings.[45]

In reality, however, state regulation was generally unrestrictive anyhow. A firm could chose to incorporate in any State, irrespective of where it actually operated. States competed directly for companies, the result being that those States with the least regulation attracted the most firms. As Charkham observes,

> "The competition between states is 'not one of diligence but one of laxity' or in Professor L. Cary's words 'a race for the bottom'. If proof of this was needed, the example of New Jersey could be cited. In 1913 its legislature reintroduced a restrictive approach to corporations. The law lasted only four years because by that time most corporations had transferred to Delaware."[46]

Concentration of Wealth

After the Civil War, business had started to concentrate into large pools, trusts, corporations and holding companies. These concentrations of power not only stifled competition, but also enabled economies of scale in manufacture, transportation, marketing and administration. In 1890, Congress enacted the Sherman Anti-Trust Act. However, in case after case, as the legislature failed to amend the Act and the executive failed to enforce it, this particular piece of trust-busting legislation was rendered largely ineffective. After the 1895 ruling in which E.C. Knight and Company successfully contested that its control of 98% of the sugar refining trade did not constitute a restraint of trade, the Act lost all remaining credibility.[47] Not until the Roosevelt administration was the Sherman Act successfully invoked to break up trusts.

And so big business continued to flourish. Although the stock exchanges had existed since the late 1700's, up to the late 19th Century, they had been primarily used for trading government securities and railway company shares. As corporations grew, the demand for capital to finance the rapid industrialisation soared. Firms of all kinds entered the equity market; between 1893 and 1897, the number of industrial companies issuing shares in America increased from 30 to 170; in Britain the rise was from 60 in 1887 to almost 600 in 1907.[48]

In 1932, Adolf Berle and Gardiner Means published *The Modern Corporation and Private Property*[49] a highly influential text in which it was argued that the American corporation, typified by strong managers and fragmented ownership had emerged as an inevitable winner of a Darwinian struggle between the different forms of corporate governance. The American firm was seen as both the driver and the outcome of healthy neo-classical economic activity. In an echo of Adam Smith's invisible hand, Berle and Means concluded that 'self interest ... is the best guarantee of economic efficiency'. This belief became the central tenet of Anglo-American capitalism.

The Role of Regulation

More recent interpretations,[50] however, have averred that the Berle-Means corporation owes its existence to American politics, in particular a series of federal measures that broke up large financial institutions and so forced corporate ownership to remain fragmented. The National Banking Act of 1863 and the later McFadden Act had tied banks to one state. In 1933, the Glass Steagall Act was passed, dividing investment and commercial banks and limiting the ability of both to hold shares. At the same time, the Federal Bank Deposit Insurance Corporation was created to guarantee individual deposits up to $5000. Despite being denounced by the American Bankers Association as "unsound, unscientific, unjust and dangerous"[51] the scheme stemmed the run from small banks and proved to be one of the most effective legislative outcomes of the Roosevelt's New Deal. As a result of these measures, American banks have tended to towards the small and local, a point emphasised by Mark Roe:

> "Large American banks play a role in the American economy equal to only **one quarter** of the role played by large banks in Germany and Japan ... America still lacks a truly national banking system like that of other nations" (original emphasis). [52]

Other providers of finance were also regulated. In 1906, large life insurers had their shareholding restricted and similarly the Investment Company Act of 1940 discouraged mutual funds (unit trusts) from corporate governance and required them to hold diversified portfolios. In this way, the big share holders were effectively ruled out and the Berle-Means firm was left as the best available option.

Ownership and Control

And so the American pattern of share ownership emerged. In comparison with Japan and Germany, share ownership is widespread and fragmented, as illustrated in Table3.3.

Table 3.3: Biggest Shareholders: percent of total shares

General Motors		Toyota		Daimler-Benz	
Mich. St. Treas.	1.42%	Sakura Bank	4.9%	Deutche Bank	41.80%
Bernstein-Stanford.	1.28%	Sanwa Bank	4.9%	Dresdner Bank.	18.78%
Wells Fargo	1.20%	Tokai Bank	4.9%	Commerz-bank	12.24%
CREF	0.96%	Nippon Life	3.8%	Sonst. Kredit	4.41%
Bankers Trust NY	0.88%	LTCB	3.1%	Bayerische L-Bk.	1.16%
Totals	5.74%		21.6%		78.39%

Source: Roe[53]

The Table shows the five largest shareholders in three comparable car producers in Japan, Germany and the US. We can see from the Table that US shareholders own relatively small stakes: the top five institutional shareholders in General Motors own 5.74% of the stock. Toyota's top five own 21.6% and for Daimler-Benz the figure is 78.39%. Moreover, as we see below, over 50% of US shares are in the hands of individuals (Table 3.4), over twice the percentage of Japan and Germany. By contrast, substantial percentages of German and Japanese stock are held by banks and firms with business links to the company.

Table 3.4: Share Ownership in Germany, Japan, the UK and the US

	Germany(%)	Japan(%)	UK(%)	US(%)
Individuals	23	21	21	52.5
Banks	10.5	16		
Pension Funds			35	17.5
Companies	42	28		
Mutual funds Insurance Unit Trusts	3.5	14	23	21
Overseas/ Other	21	21	21	9

Source: Economist[54]

Widespread share ownership is underpinned in America by a liquid and vigorous stock market. Whereas there are restrictions on the exchangeability of shares in Japan and Germany, US stocks are freely traded. Central to the ideal of free trade is the notion of **disclosure** - in an efficient market, the theory goes, the price of shares incorporates all known information about a company. In the US, the Securities and Exchange Commission (SEC) was established to ensure than no one shareholder had better access to information than any other. Under the Sunshine Act, companies were obliged to disclose fairly comprehensive financial data and the SEC empowered to prosecute insider traders. Furthermore, if ten or more shareholders meet, all the other shareholders must be informed and similarly if shareholders who possess 5% or more of a company's stock agree to act together, disclosure is required by law. This is in sharp contrast to the regular Japanese presidential council meetings where companies privately discuss the future of firms in which collectively they may hold 70% or more of stock.

In short, the ownership and control of Anglo-American companies are separated to a high degree. Unlike in Germany or Japan, where shareholders have both influence and a large stake in corporate performance, US shareholders are generally uninvolved in the management of the firm and have little incentive to take a long term view. As *The Economist* has observed,

> "To share holders in a typical public company in America or Britain ... a share is little more than a betting slip. A title deed to a house tells an American or Britain what he knows instinctively: that he owns the place and must care for it. A share certificate tells him nothing more than he has the chance to make some cash."[55]

Any shareholder who wants to exercise ownership rights, for example to improve the long term performance of a company, must undertake all the expense for only a *pro rata* share of the gains. In short, although it may be in the best interest of the firm to be financed by stable long term investors, it is in the best interest of the shareholder to sell at the first sign that a stock may have reached a trading peak. Hence a wide share ownership has a tendency to dissipate the individual responsibilities of the stockholders toward the long term health of the firm.

The impersonal nature of dispersed share ownership, combined with an active market, gives US managers a powerful incentive to worry about share price. We have seen in previous sections that whereas Japanese share prices are relatively stable, US share prices closely follow fluctuations in dividend. If share prices fall, the US firm is left vulnerable to a hostile take-over, in which quite possibly the whole board may be replaced. Hence the Anglo-American corporate board is under a strong compulsion to yield high rates of return and indeed, dividend payouts ratios are much lower in both Japan and Germany. Mayer,[56] for example, has noted that the proportion of earnings paid out as dividends by UK firms were around three times as high those of German firms over the period 1982 to 1989, even though, if anything, retentions are discouraged by the German tax system. Table 3.5 below shows the ratio of dividend payout to income for UK, US and Japanese non-financial corporations.

Table 3.5: A Comparision of Dividend Payout Ratios

Year	*UK(%)*	*USA(%)*	*Japan(%)*
1974		24	17
1975		20	18
1976		20	17
1977	36	19	16
1978	37	20	15
1979	41	20	13
1980	45	23	14
1981	45	22	14
1982	49	25	15
1983	48	23	13
1984	45	21	12
1985	46	20	10
1986	34	22	12
1987	39	22	10
1988	42	21	10
1989	41	28	

Source Charkham[57]

We can see from Table 3.5 that over the period 1974-1990, the ratio of dividend to income has been consistently higher for the UK (at between 35 to 50%) and the US (20 to 30%) than Japan (only 10 to 18%). Theoretically, dividends should simply reflect the balance between residual earnings that are available for distribution and the internal requirements of the firm for investment. However, according to Mayer,

> "US dividends appear to be set according to conventions that include a strong reluctance to cut dividends below those of previous years."[58]

rather than on the actual performance or health of the firm. Although beneficial for the shareholder in the short term, high rates of dividend mean the that firm has lower retained earnings available for future investment.

Due Process

The impersonal nature of US business culture is further illustrated by the comparatively large role played by formal legal agreements and the great reliance placed on legal institutions for the development and policing of agreements. The US consequently has a highly developed legal system, formally separated from the apparatus of the state. Business is largely conducted through detailed formal contracts, and litigation is the chief method of gaining redress. Indeed Charkham asserts that the high recourse to the law is so expensive it affects the price of US goods and services.[59] But for our purposes, the main point to note is that this emphasis on the legal process reinforces the formal nature of business transactions, and that the personal informal agreements between banks and firms that we have seen play a key role in Japanese business are not evident in the United States. As Prevezer and Ricketts summarise,

> "In essence, the Japanese system encourages compliance by establishing accurate flows of information and threatening loss of reputation in the event of opportunistic behaviour. Cheating is less likely where it is understood that the present game is just one in a series stretching into the future, and where there are social as well as financial costs associated with breach of faith. The Anglo-US system encourages compliance by threatening specific penalties in the event of failure to accomplish particular terms of a contract. There may also be an implied threat not to deal again but the lower expectation of repeat dealing combined with the lessor degree of dependency on a particular relationship makes this threat less significant even if more frequently implemented."[60]

The role of contract is particularly vital in the case of a product designed for a highly specific market (that is, one which is designed for a particular application and which is far less valuable on the open market) as this is a high risk option unless the market is assured (as it may be difficult to find alternative applications). Carbon fibre is one such a product, with the additional risks associated with long lead times, high capital requirements and downstream commitments with relatively large complementary investments.

Finally, in this section, we will briefly recap on the US banking system in the context of the transactional relations described above. We have seen that in contrast to the active role played by Japanese banks in their borrowers' affairs, US legislation has actively discouraged corporate governance by financial institutions. Although banks may manage shares on behalf of their customers, the actual holdings of US banks are restricted by law. In addition, the small size of American banks means that their biggest and most profitable potential clients often have credit ratings as good or even better than the bank, and so prefer to borrow money through disintermediation. Bond markets contribute substantial amounts to the finance of the US corporate sector; in every other country, bond markets contribute less than 10%.[61]

What the banking system can provide is finance for leveraged buy outs and other take-overs. In Germany and Japan, the close relations between banks and companies acts as a protective influence against hostile bids. Although mergers do occur, they are generally agreed, and contested take-overs are rare. Between 1980 and 1988, there were ten acquisitions in the US advanced composite industry and none in that of Japan.[62]

In short, restrictive legislation and the widespread ownership of shares has resulted in market orientated relationships between US banks and firms. Banks and other financial institutions allocate funds to a wide portfolio of firms and are more concerned with the immediate attractiveness of competing projects than the long term development of an individual company. The close personal ties we have seen that bind together Japanese banks and firms and that generate long term common interests are uncommon in the United States. The greater stability the Japanese business environment affords is reflected in the financial ratios of its companies. The two empirical measures most commonly used as an indication of firm stability are the self-financing and debt/equity ratios.

The self financing ratio measures the proportion of investment financed by retentions. If a company has no close relationship with an outside source of finance, it is forced to fund those projects perceived as high risk itself. High retentions are regarded as an indication of how banks assess the longer term prospects for a firm. Prevezer and Ricketts have demonstrated that the self financing ratio for Japanese companies was continuously lower by around 40% than that for US firms throughout the period 1977 to 1990.[63]

Companies can raise finance by either issuing stock (equity) or borrowing (debt). The ratio of debt to equity is known as gearing. Debt is generally cheaper, but as the level of interest to be repaid is fixed, irrespective of the profits earned, a high debt can only be undertaken by a firm confident that its prospects are secure. Equity can be more expensive if the firm does well, but as the dividend is decided by the company, the risk is reduced. Hence a firm seeks to strike a balance between the benefits of high gearing (lower cost) and the financial risk it takes if gearing becomes to high. A stable firm can enjoy a higher gearing ratio, because it can accommodate the associated risk. Hence debt/equity ratios are a common measure of longer term stability of a firm.

Table 3.6: A Comparison of Debt Equity Ratios

Year	**Japan**	**USA**	**UK**
1974		0.56	
1975	5.6	0.52	
1976	5.72	0.50	
1977	5.49	0.51	1.06
1978	5.49	0.50	1.08
1979	5.49	0.49	1.06
1980	5.16	0.48	1.06
1981	5.04	0.47	12.10
1982	5.02	0.47	1.13
1983	4.84	0.50	1.10
1984	4.77	0.56	1.09
1985	4.40	0.61	1.04
1986	4.22	0.67	1.04
1987	4.36	0.71	1.03
1988	4.19	0.76	1.03
1989		0.82	1.14

Source Charkham[64]

Table 3.6 compares the debt/equity ratio averages in Japan, US and the UK . It can be seen that the US and UK have a far lower gearing than Japan. Japanese firms have a distinct preference for raising finance though debt rather than equity, and consequently demonstrate much higher gearing ratios. This provides a very strong indication of the comparative stability of Japanese over American firms.

Conclusions

To summarise, we have seen how through a combination of politics, law and economic factors, American industry developed into an approximate free trade economy. We have shown how together these influences have led to contractual, neo-classical bank-industry relations and a system of shareholding that combine to forfeit the long term interests of the American firm.

Japanese industry, in contrast, is characterised by high levels of investment and a system of interlocking shareholding and close bank-industry ties that consolidate common interests and stabilise the manufacturing sector, This stability enables companies to adopt longer time horizons (typically six to ten years as opposed to two or three years in Europe and the US) when planning future investment strategies, a particularly important criteria for the advanced material industries where the time scales between initial investment and turning a profit are particularly long. In short, Japanese companies are more able to perform robustly during difficult trading conditions and ride out short term recessions. We shall now see that this has had a profound influence on the development of the carbon fibre industry.

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CHAPTER FOUR:
"A PARAGON AMONG STRUCTURAL MATERIALS":[1]
THE DEVELOPMENT OF THE INDUSTRY IN THE COLD WAR YEARS

In this chapter we first look at the historical development of the carbon fibre sector from its inception in the 1960's through to 1989. Over this period, carbon fibre markets grew continuously. Carbon fibre production is a capital intensive industry with much scope for scale economies and during this time was characterised by a virtuous circle of increasing production, falling costs and prices and thus the opening of further markets.

The main aim of this chapter is to establish a context for Chapter Five, in which we examine the industrial developments following the end of the Cold War. In Part One, we detail the actions of the carbon fibre producers, and the role of government, in the establishment of the industry. The changing demand side of the industry is examined in Part Two. As almost all carbon fibre produced today is based on polyacrylonitrile (PAN), that is the main focus of this discussion, although we also present a very brief discussion of the commercial production of pitch based carbon fibre. Finally in this chapter, we review resin production and the related downstream industries of prepreg and composite manufacture.

Part One: The Growth and Development of the Industry

The earliest commercial use of carbon fibre was as lamp filaments in the 1880's. Both Edison and Swan patented the carbon filaments designed to exploit the uniformity of electrical resistance carbon exhibits in a vacuum. Bamboo and cotton thread were used as precursors. However, these filaments were quickly displaced as the tungsten drawing process improved, and sixty years passed before any significant further carbon fibre development occurred.

Union Carbide began its own investigations of rayon based carbon fibre during the second World War, and by 1958 carbon fibre, rendered chemically stable by the high temperature process of graphitization, could be manufactured in a useful fabric form. No special stretching was applied during the heat treatment and the mechanical properties of the fibre were poorer than those of the rayon precursor. The fabric was submitted to the US air force for trials and found immediate success as rocket nozzle exit cones and re-entry heat shields.

Commercial applications, however, remained limited by the low strength and modulus of the available fibres.[2]

By the start of the 1960's, research into the possibility of high strength, high modulus carbon was underway independently in Japan, Britain and the US. The earliest patented work (1960) was that of R. Bacon, who succeeded in producing graphite whiskers (long single crystals) by a process known as pressure arcing. Although not a commercially feasible method of production Bacon's research demonstrated the possible mechanical properties of carbon fibre and attracted considerable attention from the US airforce resulting in further R&D programmes into rayon-based fibre at the Airforce Materials Laboratory in Columbia.[3]

In 1960, the Japanese Ministry for International Trade and Industry set up a collaborative research project to explore the production and properties of carbon fibre made from PAN (polyacrylonitrile) precursors. The participants included Toray, a traditional fibre company, Nippon Carbon, a graphite electrode manufacturer with extensive experience in high temperature materials, and the Government Industrial Research Institute in Osaka, headed up by Akio Shindo. The consortium successfully produced the fibres and the results were published by Shindo in December 1961. Despite demonstrating tensile strength and moduli three times those of rayon based carbon fibres, the study was largely ignored by most western workers. The two Japanese firms, Tokai Electrode Company and the Nippon Carbon Company, licensed the processes and started pilot plant operations. The Japanese patent was the first to suggest making carbon fibre from PAN,[4] the material from which around 95% of all high performance carbon fibre is made today.[5] However, these early PAN based fibres still lacked high strength and modulus.

At the same time, researchers at the Royal Aircraft Establishment (RAE) in the UK began work on carbon fibre. RAE had had some experience with the new fibre through its earlier development of impermeable graphite for the Dragon High Temperature Gas Cooled Reactor. As a by-product of this research, it had became apparent that if a feasible method of orientating the graphite crystals could be devised, a low density, high strength material ideal for the aerospace sector would be the result. Accordingly, work started on the new material in the autumn of 1963.[6] The RAE team were at the time unaware of Shindo's work, which was finally brought to their attention at the start of 1964, over two years after it was first published. Knowledge of Shindo's results spurred on the group and the work was increased.

Within six months a process evolved using the same starting material, polyacrylonitrile, but which gave strengths and moduli at least twice that obtained by Shindo.[7]

The RAE researchers had made a major advance in the discovery of a process innovation - the stretching of the PAN polymer during the initial oxidation step - which produced a fibre of much greater strength. This remains the vital step in the manufacture of high modulus, high strength fibre. The research at RAE also clarified the role of heat treatment temperatures and tensions on the resulting fibres. The importance of fibre-resin bonding was recognised and a surface treatment of the fibres based on electrolytic oxidation was consequently developed.[8]

Under the then Treasury rules, the Farnborough process was patented by the National Research Development Corporation (NRDC), a government body formed under the 1948 Development of Inventions Act with the purpose of exploiting inventions made by publicly supported institutions such as hospitals, universities and specialised research laboratories. The NRDC then became responsible for the general industrial exploitation of the fibres and licensed the technology under the Farnborough patents to three UK firms, Courtaulds, Morgan Crucible and Rolls Royce. In accordance with NRDC policy no non-UK firms were directly licensed. The Corporation later explained to the House of Commons Select Committee that,

> "There is not the remotest hope of excluding American firms in the long term from the markets. We should have undoubtedly have been far better off parochially at the NRDC if we had licensed American firms direct. We have quite deliberately said we would not do this because we think it will be in the best national interest to license British firms."[9]

All three British firms had in some way been involved earlier in the RAE research. Courtaulds had been approached by RAE in 1963 and asked to supply polyacrylonitrile (PAN) and other fibre samples suitable for conversion into carbon fibre. PAN had proved by far the most suitable and Courtaulds and RAE consequently collaborated on the production of a more specialised and suitably pure version of the precursor. Courtaulds continued to supply RAE with PAN and by the end of the 1960’s, had built a precursor plant large enough to supply themselves, the other licensees, RAE and Harwell and held 51 patents relating to carbon fibre production.[10] Courtaulds set up their own plant in Coventry to manufacture carbon fibre itself under the brand name Grafil.

Courtaulds sub-licensed the RAE technology to the American explosives company Hercules on the understanding that Hercules would market Grafil, with an option to manufacture at a later date. Under the deal, Courtaulds was excluded from the US market until 1979. This was, as a director of Courtaulds later observed, "a stupid error".[11] Relations between Hercules and Courtaulds broke down and Hercules

> "went their own way, and we [Courtaulds] were out of the market in the US. The others had a field day and we were excluded from the most important market."[12]

Meanwhile Morgan set up a joint venture with the US Whittaker Corporation (later Celanese) to supply the US aerospace industry with carbon fibre under the brand name Modmor. In this way, both Courtaulds and Morgan began pilot plant production of a few tons a year, with the (largely American) aerospace sector envisaged as the primary market.

The carbon fibre facilities at RAE were of a research nature and production was limited to 100 grams a run. By the end of 1965, it had become clear that the demand for carbon fibres for testing and development was far outstripping supply and the RAE team sought out the assistance of other government establishments to help fulfil their own requirement. Harwell was selected for the work as it already had a set of suitable furnaces and some expertise in high temperature graphite technology from its work on graphite piles.[13]

Accordingly, through a formal requirement in the 1965 Science and Technology Act, the then Ministry of Technology instructed Harwell to commence an R&D programme on carbon fibre at a cost of £250,000 a year. A team of seventeen scientists and engineers was assembled and within months production began based on a scaled up version of the Farnborough process. As the importance of the Farnborough work became apparent, further contracts followed and eventually a formal joint research and development programme was established between Harwell, Farnborough, the Ministry of Technology and the NRDC. The programme was controlled by the Ministry and the commercial exploitation became the responsibility of the NRDC. At its peak, the Harwell project was producing 450 tons a year.[14]

The Harwell project was supposedly to explore the technical problems in scaling up carbon fibre production and not a commercial venture in itself. For several years, however, Harwell was selling its fibre to Morgan who then directly sold the fibre on to the American company Whittakers (later Celanese). Morgan later argued that their actions were in fact in the national interest as they enabled Morgans to open up new markets and "maximise its contribution to the dollar earnings of this country before the narrow lead we now hold is eroded by US competition."[15] In fact, the main result of this joint venture was to establish Celanese as one of the major players in the US composite sector.

For many months Harwell also supplied Rolls Royce, who wanted to use the new material in the forward compressor fan of their experimental high thrust engine, the RB211. Rolls Royce had had a materials group researching high performance composites since the late 1950s. They had been in informal contact with the RAE group and were sent a sample of the new carbon fibre in August 1965. The Company Materials Engineer later recounted,

> "We put them in plastic and we made a small beam which was three inches by an eighth by an eighth and measured the Young's modulus of that. When you did this with it, it was obviously as strong as steel. It bent like steel; it resisted bending like steel. This was then shown to the Engineering Director of the day, Mr Lombard, and the excitement was then on ... we were going to go all out to make carbon fibre reinforced blades."[16]

Rolls Royce first made trial sets of compressor blades that were subsequently fitted to VC10 aircraft and run as part of the normal passenger service in West Africa during 1968.[17] These performed well and encouraged by the results, the company decided to incorporate the carbon fibre composite into the more ambitious RB211.

The design was completed in 1966 and Rolls Royce began to negotiate sales agreements with several aircraft manufacturers, most notably Lockheed, who ordered over five hundred engines for the L1011 Tristar. The fact that the RB211 had carbon fibre blades and was thus 300 lbs lighter than rival products was critical in its selection by Lockheed.[18] In August 1966, Rolls Royce set up its own carbon fibre line. Unlike Courtaulds or Morgan, all the carbon fibre produced by Rolls Royce was used captively within the firm. The importance

Rolls Royce was publicly attaching to carbon fibre greatly increased public interest and confidence in the material and Harwell began designs to increase capacity to over 500 tons per annum.

Between late 1968 and early 1969, the UK House of Commons Select Committee on Science and Technology took evidence on the status and future of the carbon fibre industry. Witnesses were called from the NRDC, the Ministry of Technology, RAE, Harwell and the three licensed companies. These meetings took place at a time when the key carbon fibre processing patents were held by the UK government and, moreover, when carbon fibre was attracting world-wide attention, largely through the high profile RB211.

Meanwhile, the US had already made huge investments in its own composite research. Union Carbide's low performance rayon based carbon fibre, Thornel, had already been used in the F111. Epoxy matrix composite parts were made by the laying up of prepreg and filament winding. This work was supported by the US Air Force (AFML) from 1965 to 1970. The company started commercial production in 1964 and the fibres were used in the US, France and Germany for aerospace applications. Research and development focused on the large scale manufacture of high strength and modulus fibres with the consequent introduction of Thornel 40, 50 and 100.[19] The mechanical properties of Thornel are given in Table 4.1.

Table 4.1: Mechanical Properties of Rayon Based Carbon Fibre

Product designation	*Tensile modulus (GPa)*	*Tensile strength (MPa)*
Thornel 25	175	1250
Thornel 40	280	1750
Thornel 50	350	2000
Thornel 100	700	3500

Source: Matsui[20]

Like the other carbon fibres of its day, applications of Thornel were limited by its expense: Thornel 40 cost $720 per kilo and Thornel 50, over $770 per kilo.[21] It was already apparent that the cost of carbon fibre would have to fall considerably before volume markets would be accessed.

Throughout the 1960s, the Americans had sought to improve their composite performance through a series of research programmes developing fibres from boron, silicon and even sapphire.[22] It had been known for many years that a small group of compounds containing elements such as boron, silicon, carbon and other light atoms which formed strong inter-atomic bonds had a spectacular intrinsic strength. (See Driver,[23] for a discussion of the chemistry of structurally useful elements.) The problem was to manufacture these into a usable form, i.e. as a defect-free whisker or fibre.

RAE had chosen to explore carbon, partly because of its existing experience in graphite. The Americans had focused on boron, largely because it was easily deposited by thermal decomposition. By the time of the RAE breakthrough, there had been some success in the production of boron fibres (they were the first high performance composite to be used in military aircraft), but they remained prohibitively expensive to produce.[24] Carbon fibre showed a similar high performance but at a much reduced cost. The House of Commons Committee recognised that carbon fibre would supplant boron in almost all applications, and concern about how best Britain could maintain its competitive advantage was a central theme of the Committee questioning.

The Select Committee perceived the US to be the major, indeed only, serious competitive threat to British carbon fibre interests. Morgan submitted that

> "The use of advanced fibres is receiving major impetus from the enormous materials engineering effort generated by the American aerospace and defence programmes ... there is no comparable scale of engineering effort or established resources in the [UK] aerospace and defence area."[25]

The Director of Harwell, Dr Walter Marshall also sought to impress upon the committee the US competitive position, and dismissed that from other countries:

> “ [Ques] ‘Is there any serious rivalry from other nations that might be well developed in this field?’ —
> [Ans] ‘Not that I know of ... we have no knowledge of any significant competition.’”[26]

The witnesses had good reason for this. They were unaware of the extent of Japanese industrial development in the material, although in fact both Toray and Nippon Carbon had commenced the commercial production of PAN based carbon fibre the previous year.[27] The markets in Japan were considered too small to be of any commercial importance to the UK firms and a licensing exchange agreement was later set up between NRDC and the Tokai Electrode Company, giving the latter the rights to manufacture and sell carbon fibre made by the RAE technique in Japan.[28] The US, on the other hand, had by far the largest aerospace industry and aerospace was considered the only truly significant market for carbon fibre, as we can see from contemporaneous forecasts. For example, in the late 1960's, commentators such as Fleck[29] perceived the prospective markets to be:

> "**1968**: Graphite-reinforced compressor blades competing for application in advanced turbine engines. Small prime aircraft structures in test and evaluation. Current experimental F-111 composite tail assembly in flight test.
> **1970**: Further experimental use in primary aircraft structures, including helicopter blades; limited production. Promising missile applications in preproduction.
> **1975**: Prime structure application for $50/lb composite in commercial aircraft; competition for turbine blade applications favouring composites.
> **1980**: Nominal demand for filamentary composites in non-aerospace structural applications."

The main point to note about these projections is the absence of what came to be the largest market for carbon fibre, sporting applications. These were raised as an esoteric possibility by the Select Committee, but still the main, indeed virtually only, market envisaged at the time by the US and UK was aerospace. In contrast, as we shall see, the Japanese firms had other markets in mind.

The optimism of the consequent Select Committee Report was profoundly influential to the industry - Toray later claimed that it was on the strength of the Report that they first undertook carbon fibre production[30] and referred to Britain as "the mother country of carbon fibre".[31] The report comes close to predicting a second industrial revolution based on carbon fibre, comparing the introduction of carbon fibre to that of iron as a structural material and concluded:

> "Because of their unique combination of physical properties, carbon fibre reinforced composites might well in time replace most conventional materials, not only in aerospace applications, but in general engineering and indeed in nearly all industrial activities, except those involving high temperature oxidising conditions. This is the significance of carbon fibres ... it is of the utmost national importance that a large scale plant for producing carbon fibre is built in this country without delay."[32]

The central recommendation of the committee was that the UK industrial producers should consider collaborating on a single, large scale plant. These conclusions, however, were shortly to be overtaken by events. When the first RB211s were tested in the summer of 1969, the carbon fibre blades failed catastrophically under bird strike. In particular, the root (where the blade joined the hub) was unable to absorb the tremendous twisting force the impact of a bird imposes. As a result, costs on the RB211 project began to escalate.[33] The original programme for the RB211-06 (on which the contracts with Lockheed had been negotiated) committed Rolls Royce to expenditure amounting to 30% of its net worth at the time. The RB211-22 increased this commitment to around 60%. The costs continued to rise and by November 1970, it became clear that the company would not have sufficient funds to complete the project.[34]

In addition to the direct costs of development, Rolls Royce was liable to compensate Lockheed and its other customers through the penalty clauses written into its contracts.[35] A receiver was appointed and shortly afterwards Rolls Royce was nationalised. The RB211 eventually entered production with solid forged titanium compressor blades.[36] As a result of this very public failure, UK confidence in carbon fibre was severely curtailed. Harwell abandoned its plans for scaling up production to 500 tons per annum and Morganite dropped out of the business completely leaving Courtaulds as the only large UK producer. Rolls Royce attempted to divest itself of its carbon fibre plant and in 1970 approached ICI as a potential buyer. The offer was turned down on the grounds that "the development costs would have been enormous and the market wasn't there".[37] Rolls Royce itself had been the primary user of carbon fibre in the UK and they themselves had just abandoned the business. Alternative markets were not immediately clear and, moreover, carbon fibre production involved technologies in which ICI had little experience. Production of Hyfil eventually passed to Bristol Composite UK, who planned to sell the fibre on the open market.

Courtaulds, perceiving a rival, refused to supply the firm with precursor at an acceptable price and Bristol Composites was forced to import the raw material from Toray in Japan. In its day, the company supplied aerospace firms including Shorts and Fokker, but growth was limited and in 1979, Bristol was acquired by BP.[38] By this time, the markets for carbon fibre were much more evident.

Once the key steps in the RAE process became known, the determinant factor in the production of superior carbon fibre became the development of improved precursors. It was in this endeavour that the Japanese company Toray excelled.[39] In the late 1960's, Toray used the results of Shindo's research and the newly developed stretching process to produce carbon fibre based on polyacrylonitrile (PAN). This proved far superior to rayon fibre in terms of both mechanical performance and manufacturing cost. Despite a lack of demand from potential end users, Toray persevered and set up research activities of their own to develop not only carbon fibre and prepreg, but also possible end products and applications. In 1971, the company introduced the 'Torayca' carbon fibre T300, which became the base line for the first generation of composite structural materials.

The PAN based process was offered to Union Carbide under a technical exchange agreement and the resultant fibre became the world best seller for the next dozen years.[40] (Union Carbide subsequently ceased production of the rayon derived Thornel series in 1974.[41]) A second Japanese company, Sumitomo, which also produced an excellent quality precursor, went into partnership with Hercules to produce a series of fibres widely used in the US. In 1973, Toho Rayon began production. It was the development and commercialisation of these PAN-derived, high strength, high modulus carbon fibres which led to the explosive growth of the carbon fibre industry between the years 1970 to 1988. Throughout this period carbon fibre industry was characterised by increases in production combined with developments in process technologies, reducing costs and prices and thus opening further markets. Table 4.2 gives the data for carbon fibre market growth for this period.

In the early 1970's, fuel costs accounted for 25% of airline direct operating costs, a figure that rose to 50% after the oil crises.[42] It had been estimated that a decrease of one pound in weight would save 400 gallons of fuel over the lifetime of a civil airliner.[43] Around the same time, a technical advance in the production of matrix resins took place, vastly increasing resistance to moisture absorption (a problem that had dogged composite use at altitude), and together these factors accelerated the use of composites in aerospace applications.[44]

During the 1970's US carbon fibres were mainly used in military applications such as the F-14 and F-15 fighter aircraft and rocket motor casings. This was in sharp contrast to the first market targeted by Japanese firms, that of sports goods, most notably that of golf club shafts. By the late 1970's, composites made from carbon fibre reinforced epoxy resins began to be incorporated into the secondary (non flight-critical) structures of large civil aircraft such as the Boeing 767.

NASA was heavily involved in the diffusion of carbon fibre technology through the US aerospace industry. By the start of the 1980’s, NASA had spent more than $60 million on fin and tail plane programmes at Lockheed, Boeing and McDonnell Douglas.[45] Around $22 million of the NASA funding went to Lockheed in composite fin project for the TriStar. The first of these fins failed under testing and by the time the second had been completed, Lockheed had withdrawn from civilian aircraft manufacture. NASA had slightly more success with McDonnell Douglas, whose first fin also failed but whose second was successfully tested, failing at 167% of the design limit load. This was a load carrying margin of almost 17% of that required at the time. (Airframes were designed to a safety factor of 150% of the load limit). Of the three projects, that of Boeing was considered the most successful in that a Boeing 737 was the first civil aircraft to fly with a carbon fibre reinforced tailpiece, winning FAA certification for the new part in August 1982.[46] It was Airbus Industrie, however, that first went into production. Work began on the carbon composite tail fin in 1976 under a R&D programme financed by the West German government and by the late 1980's carbon fibres were finding applications in primary structures such as in the construction of the Airbus A310 and A320 vertical tail fin.

By 1983, Hercules and Union Carbide dominated US production, accounting for 350 tons and 250 tons each. Japanese carbon fibre production was already dominated by Toray and Toho Rayon, with 1000 tons and 500 tons of capacity respectively.[47] Meanwhile in Europe, Courtaulds continued as the dominant player in the carbon fibre industry, supplying 13% of the world market for carbon fibres and accounting for 90% of European production. Over the period 1978 to 1983, Courtaulds carbon fibre division grew at an astonishing 50% a year and by 1983 had a turnover of £6 million (1983 prices).[48] At the time, Courtaulds had 15% of the

Japanese market and 20% of that of Taiwan, which was already emerging as a primary producer of sports goods. The company was also a leading producer of the vital PAN precursor, fulfilling 20% of the global demand.

In 1979, the Hercules agreement excluding Courtaulds from the US market expired and Courtaulds immediately set about developing its US carbon fibre operations - the US was by far the largest national market for composite materials. In 1983, a 50/50 joint venture was set up with Dextor Hysol, a Connecticut aerospace adhesives company that had the technology to manufacture matrix resins.[49] This effectively forward integrated Courtaulds into the higher profit composite market.

These further investments required more capital than Dexter was prepared to invest and Courtaulds subsequently increased it share in Dexter-Hysol joint venture to 80%. It reorganised its composite activities into a new division, Courtaulds Advanced Materials and acquired the UK composites producer, Fothergill and Harvey. In this way, with regard to its carbon fibre business, Courtaulds ended the 1980's in a buoyant market position.

In 1982 a new European player entered the arena in the form of the Société des Fibres de Carbone (Soficar), a joint venture between the Japanese firm Toray and the French state owned oil company, Elf Aquitaine,[50] in which the French state had a 13.4% stake.[51] That the French particularly wanted a domestic supply of the material for their own aircraft and space industry was a key consideration.[52] The Dutch chemical company Akzo began carbon fibre production in 1985 with a 450 ton capacity plant in Oberbruch, Germany and in 1987, acquired the US carbon fibre producer Fortafil Inc.[53] The US market for composites at the time was estimated to be in the region of 2,000 tpy, compared to a European market of 750. Industry forecasts at the time were predicting annual growth rates of almost 15%.[54]

By the mid-1980's, the industry was in a state of international interdependence, i.e., some operations were performed mainly or solely in certain countries.[55] For example, Japan and the US were the principal suppliers of PAN, and the US was the primary source of prepreg and led the world in the development of applications. There was very little vertical integration from raw materials through to finished product. As a result, many international joint ventures began to emerge. Toray had established a joint venture with the French company Elf Aquitaine and had a technical exchange agreement in place with Union Carbide, to whom it supplied precursor. Toho Rayon had a similar global stretch, with technical co-operation agreements with Akzo in Germany and Celanese (later BASF) in the US. Other key joint ventures were Sumitomo/Hercules (which single handedly fulfilled a third of the US requirement) and Mitsubishi/Courtaulds.[56] According to Gregory, such strategies were designed to avert trade friction between partner firms and ease technical exchange.[57] In retrospect however, it seems more likely that as well as enabling fuller integration of manufacture, these consortia allowed Japanese companies access to the large overseas markets in Europe and the US. The US was by far the largest national market for composite parts and Europe, too, had a substantial aerospace demand. Figure 4.1 (produced by author) depicts the consequent structure of the industry at this time. It can be seen that most of the marketing agreements involved the exchange of both materials and technology.

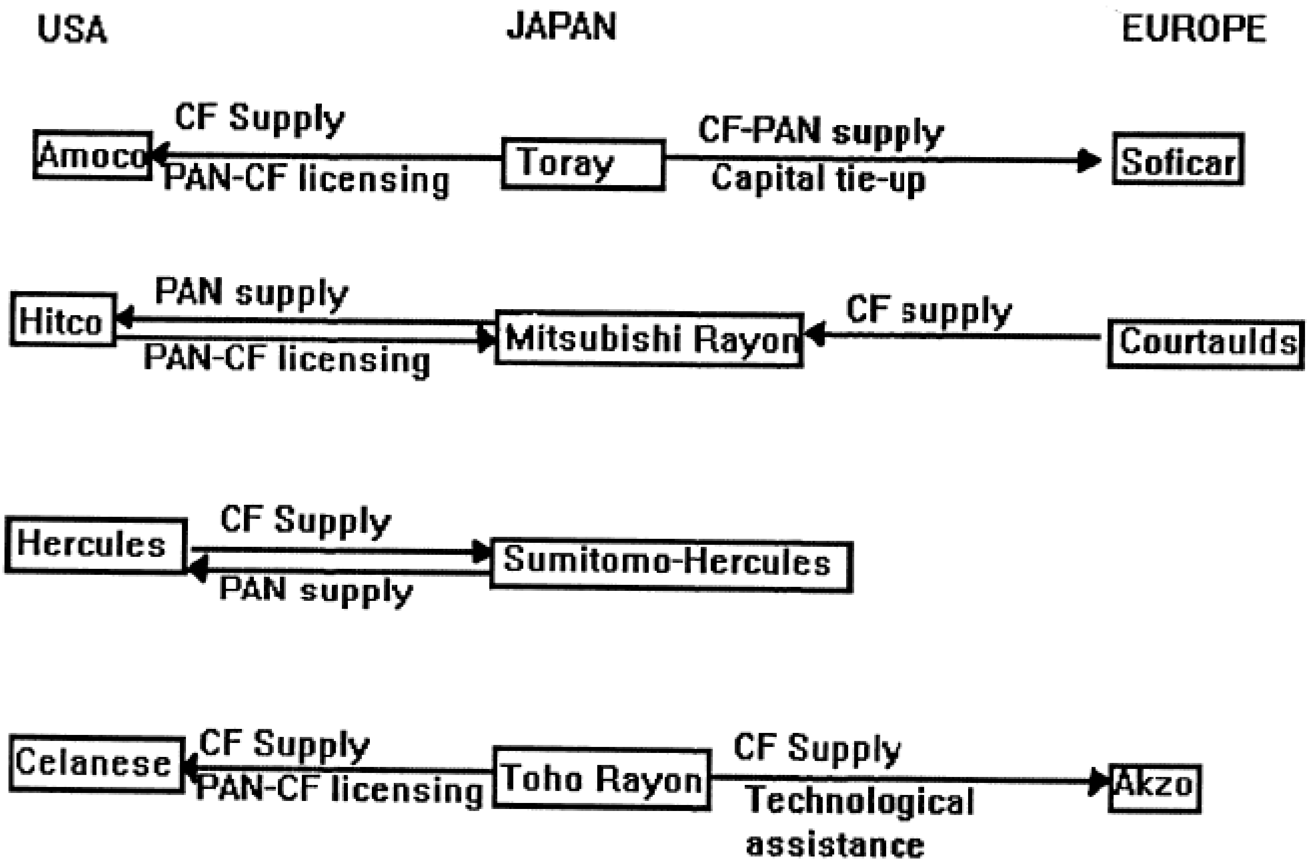


Figure 4.1: International Tie-ups among PAN-based Carbon Fibre Producers, late 1980's

Throughout the 1980's, the composites market consistently grew ahead of GNP. Indeed a growth rate that fell below 10% was seen as a recession. By the end of the 1980's, countries other than Japan, Britain and the US had entered the field. The original patent position was weak in both Japan and the UK: as with many advanced materials, patents relating to particular processing innovations were difficult to enforce and relatively easy to circumnavigate. Production had already begun in Germany and France (to supply Aerospatiale), albeit on a much smaller scale and approval was granted to Israel to acquire US technology (for military applications). Toward the end of the decade, then, carbon fibre was being produced and traded world-wide. Courtaulds in the UK, for example, sold 75% of its production to Taiwan and South Korea (for the production of sporting goods). Competition, especially for the large aerospace markets, became severe as companies fought to gain technological expertise and exploit the benefits of scale economies.[58]

In 1987, the US DoD brought in a stipulation that 50% of all the carbon fibre used in any single system purchased by the Pentagon had to be produced domestically and similarly 50% of all PAN precursor used in DoD projects had to be manufactured in the US. At the time, the DoD accounted for half of the total world market for carbon fibre composites, and Pentagon demand was forecast to rise to $500 billion by the mid 1990's.[59] Furthermore, this stipulation was mandated at a time when the rising value of the yen was making it harder for carbon fibre produced in Japan to compete in US markets.[60] We discuss the impact of the DoD directive and the consequent activities of the individual firms at this time in more detail in Chapter Five. The net result, however, was a wave of investment in capacity, both by US firms and, as any production on US soil was deemed 'domestic' regardless of ownership nationality, by overseas players seeking to establish carbon fibre production sites within the US. Courtaulds, for example, set up its own plant in Sacramento, California and the German firm BASF acquired Celanese in a deal that also included Narmco, one of the biggest US prepreggers. As the US Office of Technology Assessment commented,

> "The past several years have seen a dramatic increase in the activity of European firms in the United States. Courtaulds, BASF, ICI and Ciba Geigy, for instance, now rank among the major participants in the US market as a result of joint venture and acquisition activity. ... The US market is the largest such market in the world, and is likely to grow rapidly, particularly on the military side. As military use grows, so will the emphasis on US-based suppliers. Many of the

> acquisitions of US firms by large European conglomerates are evidence of a faith in the long term viability of the industry." [61]

Hence in the late 1980's, the industry underwent a transition period of consolidation and acquisition, most notably in Europe and the United States. In general, the acquisitions were made by large, diversified chemical and industrial firms, for whom long term investments were relatively affordable. Although the primary motivation for these take-overs was to gain access and distribution rights in the large US markets, there were additional benefits. Carbon fibre production *per se* was not a particularly profitable sector and many of the acquisitions were with a view to forward integration into prepregs and composite parts. For example, when BASF bought Celion from Celanese and added Narmco and Quantum it enabled BASF to move downstream into prepreg and shapes.[62] As a result, though the foreign share of the finished composite structure remained small, by the end of 1988, non-US owned firms controlled 50% of the US prepreg market, 25% of that of resins (largely through the efforts of Ciba-Geigy) and accounted for over 20% of US carbon fibre sales.[63]

At the same time, the larger American firms were expanding their range of operations through increased integration. Du Pont, for instance, added pitch based carbon fibres from to its portfolio of reinforced fibres, and other firms such as Amoco and Hercules integrated vertically into the production of prepregs and parts. The general strategy of the time was to integrate the whole process from the transformation of the raw materials to the production of final products within each single company. All in all, the US share of world carbon fibre production increased from around a quarter in 1981[64] to over a third by the end of the decade.[65]

Pitch based carbon fibre

Finally in this section we will briefly describe the history of pitch based carbon fibre. Pitch has a very high carbon content, higher than that of PAN, and for many years has been mooted as a possible commercial precursor for carbon fibre. The problem with pitch is that although cheap and easily available, it is extremely expensive to produce in a purified form, and as the properties of the final fibre are closely related to those of the precursor almost all current commercially produced pitch based carbon fibre is classified as low performance 'general purpose grade'.

In the early 1960's, Ohtani of Gunma University in Japan developed a method of pyrolysing pitch into carbon fibre. The technology was first exploited by Kureha, a large Japanese chemical company that was producing pitch in large amounts as a by-product of cracking crude oil.[66] In 1970, commercial production of carbon fibre from pitch began.[67] Most pitch derived fibre has a comparatively low strength and modulus and is mainly used as packing, heat insulation, and in the construction industry. The Alshaseed monument in Baghdad and the Ark Hills building in Tokyo are two examples that have exploited this technology.[68] Kureha remains by far the largest global producer of general grade pitch, with a current capacity of around 900 tons.[69]

In the 1960's, Union Carbide began a research programme, funded by the US Air Force (AFML) and the US Navy (NSSC), to develop ultra high modulus fibres based on mesophase pitch and, in 1975, started production of the Thornel P series, which were at the time the highest modulus fibres available.[70] In the late 1980s, Du Pont acquired Conoco,[71] giving the firm access to high grade pitch precursor and proceeded to produce a new range of very high performance pitch fibres which had among their qualities a negative coefficient of thermal expansion. This meant that combined with an appropriate matrix, the overall composite was very dimensionally stable, a valuable property for space applications. Amoco and Ashland Petroleum now manufacture the fibres on a small scale. However, the cost of refining the pitch to a suitable degree remains expensive and high performance pitch derived fibres are limited to very high value added applications such as space structures. Amoco is the dominant supplier of this speciality market. The firm manufactures two fibres types: the P120 which costs between $1800 and $2000 per kilo and the K1100, which sells for $3900 per kilo.[72] Virtually all Amoco's output is purchased by the US DoD which has also

> "supported all aspects of the technology from the development of Amoco's ultra high thermal conductivity fiber to fabrication of demonstration components for test and evaluation."[73]

Research interest in commercial applications of pitch fibres remained and in the mid 1980s, over twenty Japanese companies collaborated on a project to examine petroleum pitch and coal tar pitch precursors. Unlike PAN based carbon fibre, where textile companies had been the driving force, most of the firms in this venture were oil or steel companies hoping to diversify their portfolios and use up a plentiful by-product.

At first, 'the cost of producing such fibres seemed prohibitive and offer[ed] no advantage over PAN based fibres'.[74] However, through a series of incremental process innovations, the prospective price of the final fibre began to fall and one of the firms, Mitsubishi Kasei [Chemical] built a 500 ton per annum capacity plant in 1988. Another project member, Nippon Oil set up a 50 ton pilot plant in Yokohama. This was later scaled up to 120 tons and in 1995 it was announced that the facility would be bodily moved to Hirohata and leased to Nippon Steel in an equally owned joint venture between the two companies to be named the Nippon Graphite Fiber Corporation.[75] According to the Nikkei Weekly,[76] the initial capitalisation is Y500 million ($5.1 million). The venture aims to produce high modulus fibre for premium sporting goods. It remains to be seen how the pitched based carbon fibre variety will compete against PAN-based rivals, but its very existence is a sign that the fallow years of carbon fibre production may be over.

Part Two: Carbon Fibre Markets 1970-1989

Carbon fibre was originally developed as a structural material for aerospace applications. As we have seen, much of the early development took place under the auspices of UK government research institutions and by the end of the 1960’s was seen essentially as a technology in which Britain possessed the patents and the US the market. US companies quickly accessed the technology by setting up licensing agreements with the UK firms Courtaulds and Morgan Crucible. The NRDC licensed Japanese firms directly, largely because the Japanese aerospace market was perceived (rightly) to be too small to be of immediate commercial interest and non-aerospace applications were (wrongly) not considered to be of commercial interest at all.

Sporting goods were the first market targeted by Japanese firms.[77] In 1971, Toray produced its first carbon fibre fishing rod, and golf club shafts quickly followed.[78] Unlike the US and UK firms, who produced the material to fulfil an existing demand, Toray essentially created a new market for carbon fibre, performing the end product research and development in house.[79] Consumption of carbon fibre grew at a rapid rate throughout the 1970s, albeit from a low base, as Table 4.2 shows:

Table 4.2: Carbon Fibre Consumption 1971 to 1988 (tons)

Year	*World*	*U.S.*	*Europe*	*Japan*	*Others*
1971	2	—	—	—	—
1972	10	—	—	—	—
1973	100	—	—	—	—
1974	150	—	—	—	—
1975	180	—	—	—	—
1976	210	—	—	—	—
1977	260	120	60	80	0
1978	360	160	80	120	0
1979	560	260	110	190	0
1980	850	450	130	270	0
1981	1030	550	140	290	50
1982	1440	600	220	470	150
1983	1920	800	270	500	350
1984	2820	1200	450	560	560
1985	3230	1650	580	600	400
1986	3730	1920	690	620	500
1987	4380	2300	830	650	600
1988	5500	2650	900	950	1000

Source: Matsui[80],

Scale economies were difficult to achieve in the early 1970’s (capacities under around 150 tons are considered pilot plants) and prices remained high. Over the decade, however, as production increased, costs and prices fell from £200 per kilogram in 1970 to around £20-80 per kilogram in 1980 (1980 prices).[81] Carbon fibre costs were finally within the same league as competing materials and by the start of the 1980’s, potential markets were much more visible.

At the start of the 1980's, carbon fibre was produced by the following firms:

Table 4.3: Carbon Fibre Production 1981

Company	Country	Capacity (tons)
Toray	Japan	480
Hercules	U.S.	330
Toho Rayon	Japan	250
Courtaulds	U.K.	150
Celanese	U.S.	150
Nippon	Japan	40
Others		50
Total		1250

Source: Financial Times[82]

Other companies were poised to enter the field: within two years Union Carbide (whose carbon fibre interests were later acquired by Amoco) had opened a 1000 ton capacity PAN precursor plant and a 500 ton per year carbon fibre facility. Mitsubishi Rayon also began manufacture, Soficar was established and Toray, Hercules and Toho Rayon had all substantially increased capacity. Carbon fibre production and consumption began to grow at an astonishing rate: 20% in 1981, 40% in 1982, 30% in 1983 and over 45% in 1984. In 1980, the American aircraft industry had identified a need for carbon fibre with a high elongation at break point. These fibres became available in 1982, and a major new market was accessed: civilian aircraft. Production began on the new Boeing 757 and 767 models, which each used over 680 kilos of carbon fibre composite per aircraft, saving 450 kilos of structural weight.[83]

By 1984, carbon fibre production was already dominated by Japanese firms, with Toray and Toho Rayon possessing capacities of 1000 tons and 500 tons respectively. Throughout the decade, with successive leaps in capacity, one or the other of these two firms led the world in carbon fibre capacity. Hercules and Union Carbide dominated US production, accounting for 350 tons and 250 tons apiece.[84] The Japanese companies quickly built up in-house capacity. Between the years 1980 to 1982, Japanese PAN based carbon fibre capacity increased a remarkable five fold and by 1984, Japanese production exceeded that of the US (Japanese total production capacity stood at 2500 tons per annum, the US 1800 tons and the UK 500 tons). The largest market, however, remained the US which consumed over 50% of production, 60% of which was for aerospace applications, as we can see from Table 4.4:

Table 4.4: Carbon Fibre Consumption, 1984, by Application, tons

	Europe	*US*	*Japan*
Aerospace	330	1110	50
Sports	200	400	500
Industrial	180	300	350

Source: US Dept of Commerce[85]

European consumption was also largely concentrated on aerospace. Courtaulds was the only carbon fibre producer of any significant size, but in 1984 Toray, in conjunction with the French government set up a joint venture to produce fibre in Abidos (France alone accounted for a third of European carbon fibre consumption).[86] Production in the Federal Republic of Germany began in 1986, when Akzo, under license from Toho Rayon, set up a carbon fibre plant with a 360 ton capacity.

Toho Rayon increased capacity every year between 1979 and 1987. Toray doubled capacity both in 1981 and 1983 and further increased production in 1985.[87] By the mid-1980's, Japan was the primary producer of carbon fibre and the US the largest consumer. Virtually all US produced carbon fibre was used within America. This was due in no small part to US security restrictions. Carbon fibre, prepregs and composites were freely traded in Europe and Asia but US companies shipping overseas had to apply for export licences both for the technology and the product. According to the OTA,

> "Export licensing requirements place US companies at a disadvantage in foreign markets. A European aircraft manufacturer that buys carbon fiber prepreg material from a U.S. company must get permission from the U.S. Government to export the finished airplane. If the same European company buys from another supplier in Europe or Japan, the paperwork and US restrictions can be avoided."[88]

In contrast, most Japanese firms exported the bulk of their carbon fibre production, as Table 4.5 shows:

Table 4.5: The Export of Japanese Carbon Fibre, %

Company	*Percent Exported*	*Destination*
Toray	55%	Korea, Taiwan, US
Toho Rayon	70%	Korea, Taiwan
Asahi Kasei	65%	Korea, Taiwan

Source Pierrick Rollet[89]

Mitsubishi Rayon was the exception to the rule, with around 90% of its carbon fibre production going to other Mitsubishi keiretsu members.[90] Virtually, all the carbon fibre exported by Japanese companies to Taiwan and Korea was used in the production of sporting goods - Toray has a 70% share in the major Taiwanese sports producer, Taiwan Kawasaki.[91] It is the downstream industries of prepreg and composite production that we will now briefly survey in the final section of this chapter.

An Aside on Related Industries

The carbon fibre industry *per se* is closely interwoven with the related sectors of resin production, prepreg manufacture, composite makers and end users. As we have seen, over the late 1980's, there was a general trend toward greater consolidation and integration within the industry with the result that most companies integrated over two or more processing steps to some degree.

It is the manufacture of prepregs, end shapes and composites that produces the greatest returns in the advanced composite sector and many carbon fibre producers have forward integrated into these areas. For example, Amoco, a fibre and resin producer started production of prepregs and BASF acquired Fiberlite partly as a way into downstream sectors - at the time Fiberlite fulfilled a third of US prepreg consumption and was the largest prepregger in the world. Fiberlite was later acquired by ICI when BASF abandoned its carbon fibre interests. Narmco, too, was a major producer of shapes and end products when it was acquired by ICI in 1985 and it was generally acknowledged by the industry that BP purchased Hitco largely to acquire the prepreg activities of its subsidiary US Polymeric.[92] All the major Japanese companies, (except Mitsubishi Rayon, which has always been an end shape producer) have forward integrated from fibre production. Hence we will now look briefly at resin, prepreg and composite part production.

Resin Suppliers

The market for speciality resins for use in composites amounted to around \$96 million (for 16 million kilos weight) in 1993. Of this thermoset resins comprise 95% and thermoplastics, 5%. Sales of very specialised high temperature resins, which find application mainly in the aerospace sector totalled roughly \$20 million (for 230,000 kilos). Growth was flat through 1995, but is expected to rise to 5 or 6% from 1996 through to 2000.[93] The demand for speciality resins by region is shown in Table 4.6:

Table 4.6: Demand for High Performance Resins, %

Region	$Share	Weight
North America	45%	46%
Europe	25%	24%
Japan	18%	18%
Other	13%	12%

Source: US Department of Defense[94]

Resin suppliers are, by and large, big, diversified chemical companies for whom the production of resin for carbon fibre composites typically constitutes only a tiny proportion of total resin and plastic sales. The Swiss company Ciba-Geigy is the largest global producer with a market share of around 10% Ciba is a qualified supplier for a number of military and civilian aerospace programmes, including Airbus.[95] ICI and the Shell Oil Company are also major producers. For all these firms speciality resins represent only a tiny fraction of their overall business base. Essentially the industry is a spinoff of the much larger chemical sector.

Despite the extensive European ownership of production facilities, the manufacture of resins is widely dispersed geographically. Ciba Geigy has plant in a number of countries, including a \$100 million facility in Alabama, built in 1989. Shell too has production facilities in the USA and France, and owns the German resin producer Technochemie. The major suppliers in the US, (which is the largest national producer of composite parts) are Ciba Geigy, Shell and Dow Chemical, whom together account for almost two thirds of US advanced composite resin sales. These suppliers are in the main producers of thermoset epoxy resins and are also the leading suppliers of thermoset resins in Europe (Ciba Geigy alone holds over half the

European resin market). The major US suppliers of thermoplastic resins include ICI (which produces polyetheretherketone [PEEK], a high performance thermoplastic) Amoco and Phillips. ICI (in the UK), Phillips (in Belgium), BASF (in West Germany) and Amoco (who sell resin imported from the US) are the largest suppliers of thermoplastic resins in Europe.

In Japan, resin producers are again all large leading chemical companies. Yuka Shell Epoxy, Mitsui Petroleum and Asahi Kasei together serve around 70% of the Japanese advanced composite resin market. Nippon Steel Chemical and Sumitomo also supply the Japanese market. Japanese interest in high temperature resins has been accelerated by their aerospace programmes. A number of carbon fibre producers also manufacture their own resins, most particularly Hercules, Mitsubishi Rayon and Toray, which makes the resin used in the Boeing 777 composite parts in-house.

Prepregs

Prepreg (short for preimpregnation) is a partially cured intermediate product made up of resin and fibre, usually in the form of a tape of unidirectional fibre or woven like a textile. As a rule of thumb, the value of prepreg is roughly twice that of its constituent materials and the value of a composite ten times that of the prepreg (although the value of the composite can vary widely depending on the process by which it is produced). Prepregs are the principle starting material for the manufacture of composite parts (over 70% of all carbon fibre is processed into prepreg) and the merchant market for prepregs is large. There was a steady increase in prepreg shipments world-wide throughout the 1980's as the following SACMA data shows (Table 4.7):

Table 4.7: World-wide Carbon Fibre Prepreg Shipments (million kilos)

1985	1986	1987	1988	1989	1990
2.4	2.7	3.5	3.9	5.6	6.0

Source: SACMA[96]

Prepregs are produced and sold in many forms, of which the most common are woven fabrics, unidirectional tapes and filament tows. Both prepregs and fabricated components may be made and used captively for corporation into other products or sold on the merchant market for other end users. Most carbon fibre producing firms have moved into prepreg production through internal integration or the acquisition small firms. As a result the current ranking of prepreg suppliers roughly corresponds to that of the carbon fibre producers themselves.

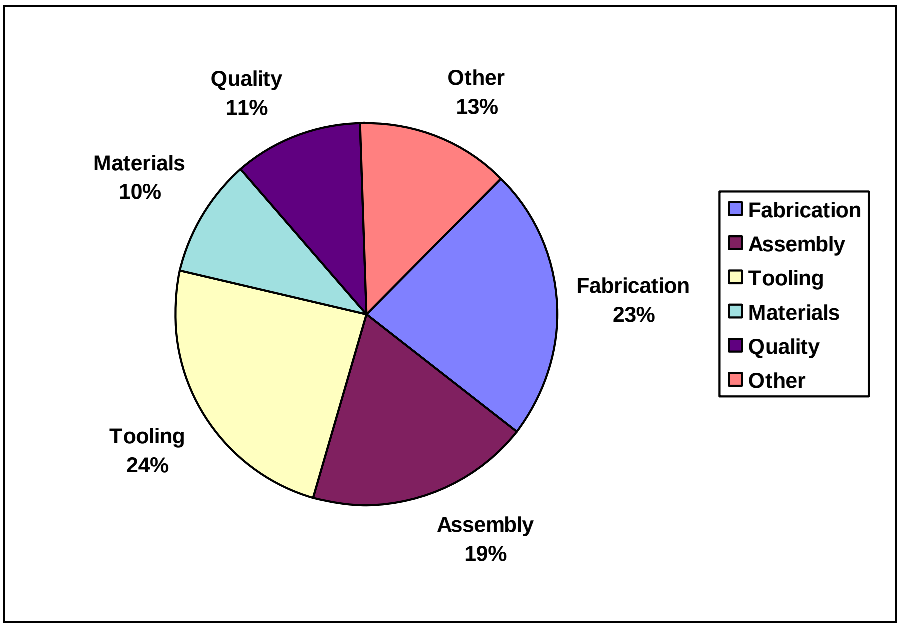
In Europe, a number of aerospace companies produce their own prepreg in-house. These include Aerospatiale (France), Airbus Industrie and British Aerospace.

Composites

At the end of the 1980's, a large number of companies, known as fabricators or moulders, specialised in making components from composites based on carbon fibre. These were generally very small firms specialising in a particular product range, such as racing cars. Some specialised in producing prepreg. In the UK, many of these companies were based in the North-West of England as the manipulation of long carbon fibre filaments utilised the traditional textile skills of knotting, weaving and braiding. Fiberforce is one example. However, in the early 1990's, a time of difficult trading conditions for the carbon fibre industry as a whole, a restructuring of the industry occurred, with the larger corporations tending toward increased integration, and many of these smaller companies were acquired or gave up the business.

The production of the final composite is very much the value added part of the manufacturing chain, especially for aerospace parts. The US Airforce has produced the following cost data (Figure 4.2) for direct cost elements in the manufacture of composite materials: It can be seen that in fact the cost of the fibre and resin amount to only 10% of the final cost. Ninety percent of the total cost is due to processing, assembly and quality control, all functions of the component fabricator.

Figure 4.2: A Breakdown of Final Composite Cost



Source: US Department of Defense[97]

Table 4.8 below shows the production of advanced composites by region.

Table 4.8: World Production of Advanced Composites (1992)

Region	*Quantity (tons)*	*Value ($million)*
Pacific Rim	2.7	817
North America	7.5	2,236
Western Europe	3.4	1,247
Total	13.7	4,300

Source: US Department of Defense[98]

The US remains the biggest producer (about 55% of the global total) and consumer of carbon fibre composites in the world. This is largely as a result of its strong aerospace sector, which accounts for over half of all composite consumption.[99] For many aerospace parts, prepreg lay-up is the preferred method of manufacture. Lay-up is still largely a labour intensive (although increasingly automated) technique that is very expensive. Hence, aerospace is not only the largest market for advanced composites in the US, but also has the highest added value. Once again, this sector has historically shown a general trend toward increased integration. Aerospace companies such as Boeing, Lockheed and McDonnell Douglas all manufacture composite parts for commercial and military use in-house. The major military companies in particular tend to manufacture composite parts captively: the defence orientated company Hercules, for example, is fully integrated from the production of fibre through to the manufacture of shapes and parts. Each prime contractor typically possesses a number of autoclaves (the speciality ovens used for curing composites). The other manufacturing processes for the production of composites such as compression moulding, pultrusion and stamping are often subcontracted out. Since the start of the 1990's there has been an excess of fabrication facilities for composites in the US.[100]

European production of composite parts, although far smaller in scale, has a similar orientation toward aerospace end-uses and defence applications. The industry is largely concentrated in four countries, namely, France, the UK, Germany and Italy, of which France alone, through its Grands Programmes in aerospace and energy production, accounts for around 50% of the advanced composite business. The total UK market for carbon fibre is around 100 tons of which about 80% are used in aerospace applications via the prepregger Ciba-Geigy. (Almost all of Ciba-Geigy's European prepreg goes to Deutsche Airbus in Germany to make horizontal stabilisers for Airbus Industrie in Toulouse.)[101] As in the US, many of the leading aerospace companies manufacture finished parts captively, including British Aerospace, Airbus Industrie, Aerospatiale, Dassault and Aeritalia. Airbus, in particular uses substantial amounts of carbon fibre composite parts in the Airbus 320 and 340.

Recreational markets have dominated Japanese domestic growth and remain the largest consumers of carbon fibre in Japan, accounting for nearly 60% of total carbon fibre usage. Many recreation products are manufactured by the Japanese carbon fibre companies themselves. However, the manufacture of sports goods is fairly labour intensive, and the majority of recreational products are manufactured in Taiwan or South Korea, both of which are enjoying an increasing market share. Production in East Asia is expected to continue with the opening of further labour markets in China.

Summary and Conclusions:

Carbon Fibre Production at the Turn of the Decade

By the start of the 1990's the major producers of carbon fibre in Europe and the US were generally large chemical companies. In contrast, the Japanese carbon fibre producers were companies whose major business is the production of manmade fibres for use in textiles. Indeed, Asahi Kasei, Mitsubishi Rayon, Toray and Toho Rayon all rank in the top five producers of acrylic fibre in Japan (the acrylic monomer is the building block for PAN).[102] All the Japanese producers began carbon fibre production partly as a way to use up spare acrylic fibre capacity.[103] Carbon fibre quality is very sensitive to the quality of the PAN precursor. It is undisputed that the Japanese carbon fibre producers manufacture the best quality precursor and, prior to the DoD directive, almost all the US producers imported PAN from Japan.

As we have seen, it was the US companies that first began to manufacture carbon fibre on a commercial scale in the 1950's. At that time carbon fibre was produced from rayon precursor. Japanese companies and the UK firm Courtaulds started production in the early 1970's, investing directly in PAN precursor technology and so became the first major producers to manufacture carbon fibre from PAN. Rayon based technology proved relatively uncompetitive and gradually the US firms were forced to reinvest (although a very small quantity of rayon based carbon fibre is still produced in the US as it was qualified as a aerospace material in the 1950's).

The production of carbon fibres is a capital intensive (many companies employ a 24 hour shift system), labour extensive (at Toho Rayon, for example, 100 employees produce 2020 tonnes per annum) industry with much scope for scale economies.[104] It is also a high technology industry in which it is generally acknowledged that the large manufacturers hold the best production facilities. The manufacturers of carbon fibre tend to be technology intensive firms generally, ranking high in terms of R&D expenditure within their respective sectors.[105] Company profiles of the key players in the carbon fibre business are presented in **Appendix I**.

By the end of the 1980's, the US was the largest national consumer of PAN and Japan the largest national producer. Four major firms supplied carbon fibre in Japan, of which the top two, Toray and Toho Rayon together accounted for about 80% of Japanese production. For both companies the percentage of export production was, and is, high. Toho Rayon, Toray and Asahi Kasei all exported large quantities of carbon fibre to south East Asian countries including Taiwan, Korea and Hong Kong for the manufacture of sporting goods. Toray in addition exported significant amounts to the US, and has a particularly close relationship with Boeing; before the construction of the Toray plant in Seattle, virtually all the prepreg produced at Ehime was sold to Boeing.[106]

The third largest Japanese producer, Mitsubishi Rayon, marketed around 90% of its Japanese carbon fibre production domestically. The company specialised in the production of 24 modulus fibre of which it claimed 70% of the world market.[107] Finally, Asahi Kasei, a big chemical company (and textile firm) specialised in producing many different kinds of resin systems for its carbon fibre prepregs and composite parts. It was one of the few companies that had started the commercial production of thermoplastic resins. About a quarter of Asahi Kasei's carbon fibre production was used in-house, the majority being exported to South Korea and Taiwan for the manufacture of sporting goods.[108]

Six companies supplied PAN based carbon fibre in the US, of which the top three, Hercules, BASF and Amoco supplied almost 80% of the market. In contrast to the industry in Japan, most US carbon fibre was sold on the domestic market, partly due to the large domestic demand and partly due to export restrictions. Hercules was the largest supplier with a market share of over a third, mostly in defence applications. Amoco, which acquired the carbon fibre business of Union Carbide in 1986, was the second largest producer and prior to the DoD directive, was the only US company capable of producing its own PAN precursor. The third largest US supplier was BASF, a West German company that purchased the Celion carbon fibre business from Celanese in 1985.

Carbon fibre production capacity in Europe totalled over 1000 tons. One of the major European players was Courtaulds in the UK. Other important suppliers of carbon fibre in Europe were Azko in Germany, and Soficar in France (a joint venture between Toray and Elf Aquitaine).[iv]

[iv] For completeness we will also note that other countries with carbon fibre capacities include Israel (the Israeli firm Afikim produces around 100 ton a year for military applications), Taiwan (Taiwan Plastic)and South Korea (Korea Steel Chemical). The latter two countries concentrate on the production of inexpensive, lower performance fibre for cost sensitive applications such as sports goods, construction automotive industries. Production capacities in the former Soviet Union and China are unknown. Up until 1995 carbon fibre produced

Table 4.9: Percentage Growth Rate in Carbon Fibre Demand, 1983 Base

	1983	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*
USA	100	133	146	166	188	208	223
Japan	100	120	137	151	164	168	185
Europe	100	133	171	207	227	227	240
Others	100	129	129	140	160	232	244
Total	100	129	144	164	183	203	217

Source: Rollet[109]

To conclude, then, in the latter half of the eighties, carbon fibre consumption grew by around 17% each year. The markets overall had grown consistently throughout the decade at double digit rates. If we look at the data for the consumption of carbon fibre over the period 1983 to 1989, Table 4.9, we see growth rates of up to 30% and totalling 217% over the six year period. Every year during this time saw double digit growth. Prices stabilised at around $33 per kilo.[110] Forecasts for the 1990's looked good, with the defence outlook particularly strong.

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in these countries was not traded on the world markets However, the Kaiser Aerospace and Electronics Corporation of Houston has recently announced plans to sell carbon fibre produced by the (former Soviet) All Union Advanced Aviation Materials Institute on the world market.

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CHAPTER FIVE:
PROBLEMS AND POSSIBILITIES IN THE 1990's

By 1990, it was becoming clear that the series of shock political changes in Eastern Europe were likely to be sustained, and the Cold War was coming to an end. This realisation bought with it profound changes to the defence outlook and, in turn, the carbon fibre industry. As we saw in Chapter Four, in 1987 the US Department of Defense had mandated that 50% of all carbon fibre used in future systems bought by the Pentagon was to be produced in the US. Similarly the PAN precursor for making the fibre was to be sourced domestically. The net result of these directives, in conjunction with the very optimistic forecasts of the late 1980's (the industry was expecting double digit growth throughout the 1990's[1]), was a period of massive investment with a consequent huge jump in capacity that came on line over the years 1989 to 1991. Unfortunately for the industry, the arrival of this new capacity almost exactly coincided with the end of the Cold War and the start of the defence cuts. The consequent shake out of the sector is the focus of this chapter. Most particularly, we present data collected during the course of this research that reveal the regional patterns and variations in the industry response to the new post Cold War environment.[v]

The main purpose of this chapter is to examine the disparate strategies of the carbon fibre producing firms since 1990. Firstly, we chart the course of the industry 1990-1995. The impact of the changing defence market is then detailed, as is the Technology Reinvestment Project, which was to have a decisive influence on the US producers. Finally, we compare and contrast the corporate and financial governance of the individual carbon fibre producers.

The Carbon Fibre Industry 1990-1995

There are no official statistics on the production and consumption of carbon fibre and as it is a comparatively new industry, there is little published data. Carbon fibre is not classified as a distinct product under the US Harmonic System of trade definitions, even under the most detailed 10 digit level. Hence, most of the data presented below was obtained directly from

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[v] A chronology of the political events leading up the the end of the Cold War is presented in Appendix IV

firms and industrial associations, such as the US based SACMA (Suppliers of Advanced Composite Materials Association) the AIA (Aerospace Industries Association).

Carbon fibre sales worldwide total approximately 8000 tons per annum.[2] With a median price of between 70 to 80 DM per kilogram,[3] we can estimate the total global market to be between $380 million and $435 million (August 1995 exchange rates). The changing values of advanced carbon fibre composite shipments worldwide, according to the industrial association SACMA are given in Table 5.1 below:

Table 5.1: World-wide Carbon Fibre Shipments

Year	kilograms	U.S. Dollars
1991	51901179	$298,800,000
1992	58980755	$374,100,000
1993	66218995	$384,900,000
Midyear(Jan June)1994	3270988	$225,100,000

Source: SACMA[4]

SACMA draws its figures from member data and estimates that its statistics represent 90 percent of carbon fibre composite shipments within North America, Western Europe and the Far East.[5] According to the Japanese producer, Toho Rayon, the market worldwide for PAN carbon fibre increased by 23% in 1988, 15% in 1989, 7% in 1990 and 7% in 1991.[6]

The modern history of the carbon fibre industry dates from the 1987 DoD requirement that 50% of PAN-based graphite fibre for US defence applications be made from domestic PAN by 1992 and furthermore that 50% of the carbon fibre itself should be domestically sourced. If we examine the carbon fibre market of the time, we find:

Table 5.2:World-wide Carbon Fibre Consumption, 1987, tons

	Aerospace	*Sports*	*Industrial*	*Total*
USA	1500	320	450	2270
Europe	430	150	190	770
Japan	40	650	160	850
Others	40	630	120	790
Total	2020	1750	920	4690

Source, Financial Times[7][vi]

The market showed significant geographical variations. Aerospace was the predominant market in the US and Western Europe, accounting for almost 75% of the US market and half that of Western Europe. In sharp contrast, over 70% of the Asian market was represented by sports goods. These regional markets were also reflected in the variation of local production. Japanese manufacturers, for example, had largely concentrated on the development of consumer goods and markets, whilst in the US military applications consumed a large portion of annual domestic production.

The DoD Directive and its Consequences

As we have seen, in the late 1980's the United States was by far the largest national consumer of carbon fibre, and within the US market, the aerospace sector predominated demand. The DoD accounted for over 45 percent by weight[8] of all carbon fibre consumed by the US and the percentage by value was even higher as military aerospace applications employed very high performance fibre costing over five times that used in sports and civil aerospace applications.[9] Furthermore the DoD was perceived as a good customer offering a reliable demand, and DoD contracts were hotly contested.

[vi] According to the *Japan Economic Almanac*, the figures are:

	Aerospace	*Sports*	*Industrial*	*Total*
US	1720	180	140	2040
Europe	400	160	160	720
Japan	20	540	300	860
Other	-	730	20	750
Total	2140	1610	620	4370

Source: Hisako Yano, Japan Economic Almanac, 1990

Although there is some variation in the figures, the point remains. According to this data set, aerospace accounts for 84% of total US consumption and 56% of that of Europe, Sports goods are by far the largest market in East Asia

Despite the high level of DoD use, all the critical polyacrylonitrile (PAN) precursor qualified for military use was imported from the UK and Japan. US defence companies were also largely reliant on Japan for the carbon fibre itself. Figure 4.1 shows the tie-ups in place at the time. By the mid 1980's, carbon fibre had been placed on the US Commodity Control List (which prevents exports to proscribed countries) and military interest in the material was such that over 70% of US federal composite R&D was funded by the DoD.[10] Through the F-15 and F-16 programmes, carbon fibre had gained a reputation for high performance and reliability and was rapidly becoming a baseline material for the military aerospace industry.

US concerns about the reliance on Japan for a material of such strategic importance began to be voiced. The issue of the falling market share of US firms in the carbon fibre commodity trade was first raised under the 1984 General Tariff Act. In 1985, the then Under Secretary of Defense for Research and Engineering issued a statement proposing that a domestic source of PAN precursor be assured and a policy directive to achieve this end was subsequently developed. This was pursued further by Congress appropriation committees, with the result that in the budget for the 1987 DoD appropriations, the US Congress mandated that PAN production bases be established in the US. The directive timetables incremental increases in the PAN production base: 15% of all PAN to be used in military systems was to be domestically produced by 1989, 20% by 1990, 25% by 1991 and 50% by 1992.[11] The cost of putting in a PAN plant is almost the same as building the equivalent carbon fibre facility.[12]

Legislation governing the production of carbon fibre itself swiftly followed; the 1988 DoD Appropriations Act "directs the Secretary [for Defense] to ensure that at least 50% of the polyacrylonitrile carbon fibre requirement be procured from domestic sources by 1992”.[13] The requirement was reiterated in the appropriations acts of 1989 (HR4781), 1990 (HR3072) and 1991 (HR5803) and developed further in 1992 when the House of Representatives directed "the Secretary [for Defense] to ensure that a minimum of 75% of the coal and petroleum pitch carbon fiber requirement be procured from domestic sources by 1994".[14]

The industry had been expecting the DoD requirement and responded rapidly.[15] Prior to the establishment of the Congressional requirement, Amoco was the only firm producing PAN precursor in the US. At the time, Amoco could fulfil only 15% of the US demand,[16] and was not qualified for use by the military. 100% of the PAN precursor used in the manufacture of DoD systems was imported from Japan. In order to fulfil the directive, therefore, American-based production facilities for both carbon fibre and its precursor, PAN, were expanded. Amoco announced plans to expand its carbon fibre capacity by 600 tons by 1990.[17] Hercules began construction of a 1700 ton per year precursor plant in Decatur, Alabama and a year later completed an expansion project to increase its carbon fibre capacity at its Magna plant to 1400, with further increases planned for 1990.[18] BASF started production of PAN precursor in late 1987, the same year as the DoD directive, and announced plans to increase precursor production further with a $30 million expansion project.[19] The firm also announced it would put in plant to increase its carbon fibre capacity threefold from 450 tons to 1350 tons. Courtaulds, too, was no exception, announcing it would build a precursor plant in the US based on its UK manufacturing technology[20] and BP's Californian based subsidiary Hitco increased its carbon fibre production from 25 to 250 tons. However, neither Toray, Toho Rayon, Mitsubishi Rayon nor Asahi Kasei put in US-based plant during this period, the result being that the Japanese firms became the only global producers of any significant size **not** to respond to the DoD directive.

The net result of this wave of investment was a substantial increase both in carbon fibre and carbon fibre precursor capacity in the US. Over $100 million dollars was invested in new PAN precursor facilities. Table 5.3 below summarises the changes in PAN-precursor capacity of the three big USA producers over this period.

Table 5.3: Changes in US PAN-precursor Supply, tons

Company	Location	Capacity	On-stream
Amoco	Greenville, S.C.	500	1982
		500	1990
Hercules	Decatur, Al	1700	1989
BASF	Williamsburg	3000	1990

Source Roskill[21]

On top of that, as can be seen from capacity data shown later in Table 5.6, within three years of the DoD directive, US carbon fibre capacity had increased by over 60% percent. In 1988, the market research firm Business Communications Co had estimated that 1993 US consumption of carbon fibre would total 5500 tons, of which aerospace would constitute 75%

of consumption and sports goods only 5%.[22] Demand and growth rate expectations were so high that world-wide shortages were forecast.[23]

In 1990, however, carbon fibre aerospace sales in the United States fell, in a drop so sharp that despite growth in every other application, the overall U.S. market fell for the first time since the commercial production of carbon fibre had begun. Industry forecasts were hastily revised downwards. By 1991, the 1993 forecast had fallen to 3850 tons and by 1992 had dropped again to 3370 tons.[24] All these forecasts proved to be overestimates. In the event, the actual 1993 US consumption was only 2820 tons, of which aerospace constituted 40% and sports goods almost 30%.[25] In short, consumption in our example year, 1993, was almost half the 1988 forecast, and fell short of the 1991 and 1992 forecasts by 1030 and 550 tons respectively. In additional there was a large and unforeseen shift away from aerospace applications.[vii] US demand fell again in 1991. If we examine the market data for that year we see:

[vii] **Toray 1991 Carbon Fibre Forecast (tons/year)**

	1991	**1992**	**1993**	**1994**	**1995**
USA	2200	2300	2800	3400	4000
Europe	1260	1400	1550	1750	2000
Japan	1360	1400	1500	1600	1700
Others	1350	1400	1450	1550	1650
Totals	**6170**	**6500**	**7300**	**8300**	**9350**

(Source: Toray, personal communication, February 1992)

Toho Rayon 1991 Carbon Fibre Forecast (tons/year)

	1991	**1992**	**1993**
USA	3000 (3400)	3150 (3600)	3370 (3850)
Europe	1200 (1250)	1300 (1400)	1450 (1550)
Japan	1400 (1400)	1550 (1500)	1680 (1750)
Others	1200 (1200)	1300 (1300)	1400 (1400)
Totals	**6800 (7250)**	**7300 (7850)**	**7900 (8550)**

Source: Kagaku Kogyo Nippou, June 1992
The unbracketed data is the revised 1992 estimate and the data in brackets is the original 1991 estimate.
(Source: Toho Rayon, June 1992)
Overall, Toho Rayon estimated (in 1991) that the 1992 market would increase approximately by 7% over that in 1991. In fact, the 1992 market fell short by 550 tons of the original 1991 estimate. It can be seen that although the 1992 and 1991 estimates for USA vary widely, the estimates for Europe, Japan and other countries have remained relatively unchanged. It is also apparent that even the 1991 US market data differs significantly in the Toray and Toho Rayon estimates. This was a reflection of the huge uncertainty hanging over the US defence industry at the time, following the relaxation of military tension between East and West.

Table 5.4: World-wide Markets for PAN-based Carbon in 1991 (tons)

	Aerospace	*Sports*	*Industrial*	*Total*
USA	1080	530	590	2200
Europe	645	325	290	1260
Japan	60	810	490	1360
Korea/Taiwan		1350		1350
Total	**1785**	**3015**	**1370**	**6170**

Source, Toray[26]

A comparison of Table 5.2 with Table 5.4 reveals that one of the most significant changes between 1987 and 1991 is the large **drop** in the demand from the US aerospace sector, a fall so large that although world-wide carbon fibre demand rose significantly, US consumption failed to increase at all. We shall see exactly why the US aerospace demand for carbon fibre fell in this dramatic manner later in this chapter, but we shall first examine the impact this market dislocation had on the industry.

By 1991, the previously overwhelming position of the US as the largest national consumer of carbon fibre had faltered. Demand by the US aerospace sector fell in absolute terms by 500 tons. Moreover, this fall took place against a background of rapidly increasing capacity in the US in particular as industry responded to the US DoD mandate.

The most immediate result for the industry was a period of overcapacity. In 1991, carbon fibre nameplate capacity worldwide totalled around 11,500 tons, compared to a total consumption of 6170 tons. [viii] Because of the adverse market conditions, the cost of carbon fibre began to fall. The price of 12K tow fibre (the standard for the industry), fell by approximately 20% between the years 1989 to 1992 (with slight variations in price in the different countries depending on local market conditions).[27] Many carbon fibre manufacturers were selling at cost.[28] Indeed, it was alleged that Japanese firms were selling

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[viii] It should be noted that carbon fibre capacities are quoted in terms of their so-called nominal value or "nameplate" capacity. This is the capacity based on the production of 12K tow fibre (the standard for the industry) only. Most companies, however, manufacture a production mix of different tows which reduces the actual output. Hence the real capacity is about three quarters of the nameplate capacities quoted by the companies. In short, although the total world nameplate capacity is over 11,500 tons, the actual total global capacity is only around 8,500 tons, but the point remains.

at dumping prices.[29] In 1991, no US producer turned a profit from their carbon fibre operations[30] and a shakeout of the industry began.

Courtaulds was the first casualty. In June 1991, its plant in Sacramento, California was sold to Mitsubishi Rayon and in November of the same year, Courtaulds abandoned carbon fibre production at its UK plant in Coventry.[31] Gordon Campbell, the Director responsible for carbon fibre told the in-house paper, Courtaulds News,

> "In the last 12 months, the world recession has significantly reduced demand for sporting goods carbon fibre, which is our major market. Demand has also fallen in the defence related industries. On top of this nearly 40 percent additional capacity has come on line from other manufacturers. The combined effect has been devastating."[32]

Sporting goods were indeed Courtaulds major market accounting for 60% of sales. However, the market for sporting goods had in fact **increased** over the period 1990-1991, as it had every year, showing growth in every geographical area:

Table 5.5: Sports Market for Carbon Fibre, tons

	1990	*1991*
US	380	530
Europe	325	370
Japan	750	810
Taiwan/Korea	1200	1350
Total	3015	2700

Sources, Toray [33]

Toray's UK office assert that Courtaulds was in fact adversely affected by the downturn in the UK defence spending. The sector constituted only 7% of Grafil sales[34] but the falling defence demand did colour Courtaulds' view of the future of the industry.[35] Courtaulds' immediate problems centred on several factors. The first was that they were unable to produce fibre of a consistently high quality,[36] a fact that rendered them uncompetitive when the industry faltered. Secondly, it was generally believed throughout the industry that the sector would recover through growth in non military sectors (world-wide, consumption had continued to grow) but that real profitability would not return until the mid 1990's. Courtaulds operated a two to three year return on investment strategy[37] and the projected time scale for recovery was beyond the firm's planning horizon. The company had made its first cutbacks within months of the downturn of the industry and in the summer of 1991, described itself as "simply overwhelmed by external events" and not "able to live with any short term problems."[38]

The unexpected nature of the crash is illustrated by Courtaulds in-house literature, which printed positive forecasts as late as December 1990,

> "[carbon fibre] demand will grow at around 10% per annum ... Grafil is well placed to take advantage of this future growth with a strong international market coverage and an efficient manufacturing operation strategically positioned in Europe and the US ... Toray and Toho [Rayon] will always be tough competition but we have built up a strong position in the Far East which we intend to keep."[39]

Twelve months later, the carbon fibre plant was closed, with 107 redundancies. The company then commented,

> "Carbon fibre is very capital intensive, very heavy on fixed costs, both in terms of manufacturing and in terms of support from research, marketing, sales and so on. A business with these characteristics is very exposed if capacity exceeds demand."[40]

Mitsubishi Rayon had been eyeing the American market for some time. In the summer of 1990, the firm had acquired the Californian companies Newport Composites and Newport Adhesives for $20 million.[41] The two firms were consolidated into one, and used by Mitsubishi Rayon to produce golf clubs from carbon fibre prepreg. With its acquisition of the Courtaulds' carbon fibre plant, the firm was able to establish a well integrated production base in the States.

Another UK owned firm, Hitco, was the next to close. Hitco was a BP subsidiary based in California and, since the DoD mandate, had been steadily increasing capacity. In August 1991, it was announced that Hitco would discontinue its carbon fibre line due to "over crowding of the marketplace".[42] Hitco was a comparatively small producer. As the Japanese trade paper *Kagaku Kogyo Nippou* had observed two months earlier, the most vulnerable firms were smaller companies with capacities under 1000 tons per year.[43]

The large US producers, however, were not left unscathed. By the spring of 1992, reports concerning problems at BASF began to appear in the European press.[44] The company had expanded rapidly in the US and had only a year before opened a major new carbon fibre plant in Rock Hill, South Carolina. By June of that year, the company had made it clear that its carbon fibre operations were for sale. Its downstream structural materials operations were sold to the European firm Hexcel. The sale included BASF's composites division which supplied composite structures to the Eurofighter 2000. The US carbon fibre plant remained unsold. The major Japanese producers were approached but were wary of the sale and there was no attempt by the Japanese producers to take over the plant.[45] BASF had been a major supplier of fibre to the military and specialised in the aerospace sector[46] and investment in such a sensitive, high technology activity was seen as too risky by the Japanese,[47] especially as a particularly bloody trade war was raging between the two countries at the time. Eventually, BASF abandoned the plant, idling 1360 tons of capacity.

Amoco and Hercules also floundered. Amoco announced a downsizing of its composites operations[48] and shut down carbon fibre production completely for ninety days[49] at the end of 1991, just twelve months after the firm's new 540 ton capacity plant began production. According to industry sources, by the spring of 1992 Amoco had withdrawn from carbon fibre sporting goods production due the severe competition[50] and was planning to decrease capacity.[51] Even Hercules, the largest supplier of carbon fibre to the military was caught unawares. In 1990, the company had been forced to write off over three million dollars in aerospace expenses and consequently sell off a number of businesses. It chose to retain only the most profitable. Carbon fibre was described as one of "those with a future",[52] and, despite its financial difficulties, Hercules invested even further in the sector, setting up a 13.5 billion lire joint venture to manufacture carbon fibre and composites in Italy.[53] Just two years later, however, by the spring of 1992, the company had begun approaching possible Japanese buyers in a effort to sell off its carbon fibre interests.[54]

Meanwhile, the Japanese producers themselves were steadily expanding capacity. Toray, Toho Rayon, Mitsubishi Rayon and Asahi Kasei all substantially increased domestic capacity in 1991. Asahi Kasei again increased capacity in 1993. The domestic markets in Japan, Taiwan and Korea all continued to grow at the rates predicted in earlier forecasts. However, the expansion of the Japanese companies was not limited to Japan itself. Throughout the late 1980's, as we have seen, Japanese carbon fibre activities in the US were largely confined to licensing and technology agreements with American firms. Provisions within these agreements limited direct participation by Japanese firms in US markets and no Japanese firm had invested in US-based plant in response to the DoD mandate. As a result, the major carbon fibre producers had only a limited role in the largest market for carbon fibre. The crisis in the industry gave Japanese companies the opportunity for a more active role in US markets. Mitsubishi Rayon acquired the Californian based company Courtaulds Grafil Inc. in 1991. Both Toray and Toho Rayon began selling carbon fibre directly in the US and, in 1992, Toray acquired the US firm Composite Horizon as well as announcing plans to establish a subsidiary prepreg plant in Washington State.[55]

Aside from accessing new markets, these overseas investments offered Japanese firms comparatively cheap land, utilities and labour. Production overseas was one way of avoiding the extra costs incurred through the rising yen. From the viewpoint of the US firms, the businesses were sold at a good price, especially considering the flat market. In yen terms, however, they were relatively cheap. (The yen had been at an all time high since 1989[56]) Europe, too, was seen as a opportunity. Toray completed a second line at Soficar, essentially doubling production, and in April 1993 Toho Rayon increased its stake in Akzo's German carbon fibre business (Tenax Fibers GmbH) to a controlling 51%[57] and immediately increased capacity to 700 tons.[58] In January 1995, Toho once again raised its stockholding in Tenax, this time to 90%.[59] The result of this flurry of activity, along with the closure of Courtaulds UK plant, was that by the mid 1990's, no European based carbon fibre facility remained under European control.

The first half of 1993 proved a low point for the US industry. After BASF decided to withdraw from the business in March, surplus capacity tightened. In the autumn of the same year, the first awards of the Technology Reinvestment Project (a Clinton Administration initiative designed to aid stricken defence sector industries to develop dual use technologies - see below) were announced. The TRP awards essentially secured the immediate future of Hercules and Amoco's carbon fibre business for the following 18 months. Other firms, however, continued to struggle. Finally, after accumulating losses of 1.2 billion yen ($11.5

million), Asahi Kasei announced it was closing down its carbon fibre operations.[60] It is now rumoured that the carbon fibre business will be sold to Mitsubishi Rayon.[61]

The industry remained in a state of over capacity throughout the early 1990's, but as consumption had continued to grow world-wide since 1990 (albeit at a lower rate than expected), gradually the excess capacity was whittled away. "The early '90s slump is over ... most carbon fiber producers are now operating at full capacity" reported the Chemical and Engineering News in late 1994.[62] Within a month, Amoco had announced plans to buy up BASF's 2million pound idled line in Rock Hill[63] and, by the spring of 1995, Toho Rayon, Toray and Fortafil were all reportedly planning major capacity increases.[64]

In Tables 5.6 and 5.7, we group together carbon fibre capacities by company location and ownership for the period 1988 to 1995. In Figure 5.1 we present the changing ownership of the total global capacity of carbon fibre, grouped by geographical ownership (pre-1988 data calculated from Blumberg,[65] 1988 onwards from the data calculations in Table 5.7), and in Figure 5.2, the percentage change in capacity ownership. It can be seen that Japan has remained the largest producer of capacity of carbon fibre throughout the period and that collectively throughout the 1980's, all the producers pursued similar strategies of rapid growth with the result that up until 1987, the percentage ownership of capacity of the respective regional groups stayed more or less constant. The ownership capacities of USA and Western Europe are virtually identical over this period. The most striking feature of Figure 5.1, however, is the divergence of strategy post 1990. Japanese firms rapidly increased capacity domestically and overseas, largely at the expense of the European producers. Meanwhile the volume of US-owned capacity levelled off up until the start of government intervention in late 1993, then resumed growth. Hence, post 1990, we see a startling dislocation in the pattern of market share.

Table 5.6 Carbon Fibre Capacities by Geographical Location [tons]

	May-88	1989	Feb-90	Dec-91	Jun-92	Jun-93	Jun-94	Jun-95
JAPAN								
Toray	1,500	1,500	1,500	2,250	2,250	2,250	2,250	2,550
Toho Rayon	1,420	1,420	1,420	2,020	2,020	2,020	2,020	2,600
Asahi Kasei	300	300	350	450	450	450	-	-
Mitsubishi Rayon	120	150	150	500	500	500	500	500
Total	**3,340**	**3,370**	**3,420**	**5,220**	**5,220**	**5,220**	**4,770**	**5,650**
PERCENT	46.0	43.5	41.6	48.0	45.8	52.0	48.3	46.6
USA								
Hercules	1,050	1,400	1,400	1,715	1,715	1,715	1,715	1,715
BASF	450	450	450	1,350	1,350	-	-	-
Amoco	450	450	450	850	1,000	1,000	1,000	1,750
Fortafil	450	450	450	350	350	350	650	770
Courtaulds	400	400	450	-	-	-	-	-
BP	25	120	250	-	-	-	-	-
Mitsubishi Rayon	-	-	-	450	450	450	450	700
Total	**2,825**	**3,270**	**3,450**	**4,715**	**4,865**	**3,515**	**3,815**	**4,935**
PERCENT	38.9	42.2	42.0	43.4	42.7	35.0	38.6	40.7
EUROPE								
Courtaulds	350	350	450	-	-	-	-	-
Soficar	300	300	300	340	700	700	700	700
Akzo	350	350	500	500	500	500	500	740
Sigri	100	100	100	100	100	100	100	100
Total	**1,100**	**1,100**	**1,350**	**940**	**1,300**	**1,300**	**1,300**	**1,540**
PERCENT	15.1	14.2	16.4	8.6	11.4	13.0	13.2	12.7
GLOBAL TOTAL	**7,265**	**7,740**	**8,220**	**10,875**	**11,385**	**10,035**	**9,885**	**12,125**

Sources: 1988, Hiramatsu and Nishimura;[66] 1989, Matsui;[67] 1990, Asahi Kasei;[68] 1991, Toray;[69] 1992, Kagaku Kogyo Nippou;[70] 1993, Kagaku Kogyo Nippou;[71] 1994, Kagaku Kogyo Nippou;[72] 1995, Kagaku Kyogo Nippou.[73]

Table 5.7: Carbon Fibre Capacities by Company Ownership [tons]

	May-88	1989	Feb-90	Dec-91	Jun-92	Jun-93	Jun-94	Jun-95
JAPANESE OWNED								
Toray	1,710	1,710	1,710	2,488	2,740	2,740	2,740	3040
Toho Rayon	1,420	1,420	1,420	2,020	2,020	2,020	2,270	3266
Asahi Kasei	300	300	350	450	450	450	-	-
Mitsubishi Rayon	120	150	150	950	950	950	950	1,200
Total	**3,550**	**3,580**	**3,630**	**5,908**	**6,160**	**6,160**	**5,960**	**7,506**
PERCENT	48.9	46.3	44.2	54.3	54.1	61.4	60.3	61.9
USA OWNED								
Hercules	1,050	1,400	1,400	1,715	1,715	1,715	1,715	1,715
Amoco	450	450	450	850	1,000	1,000	1,000	1,750
Fortafil	450	450	450	350	350	350	650	770
Total	**1,950**	**2,300**	**2,300**	**2,915**	**3,065**	**3,065**	**3,365**	**4,235**
PERCENT	26.8	29.7	28.0	26.8	26.9	30.5	34.0	34.9
EUROPEAN OWNED								
Courtaulds	350	350	450	Ceased	-	-	-	-
BASF	450	450	450	1,350	1,350	-	-	-
Courtaulds (USA)	400	400	450	Sold	-	-	-	-
BP	25	120	250	Ceased	-	-	-	-
Soficar	90	90	90	102	210	210	210	210
Akzo	350	350	500	500	500	500	250	74
Sigri	100	100	100	100	100	100	100	100
Total	**1,765**	**1,860**	**2,290**	**2,052**	**2,160**	**810**	**560**	**384**
PERCENT	24.3	24.0	27.9	18.9	19.0	8.1	5.7	3.2
GLOBAL TOTAL	**7,265**	**7,740**	**8,220**	**10,875**	**11,385**	**10,035**	**9,885**	**12,125**

Sources: derived from Table 5.6, with additional information from Toray,[74] Europe Chemie,[75] and Japan Chemical Week.[76]

Figure 5.1: Carbon Fibre Capacity by Ownership

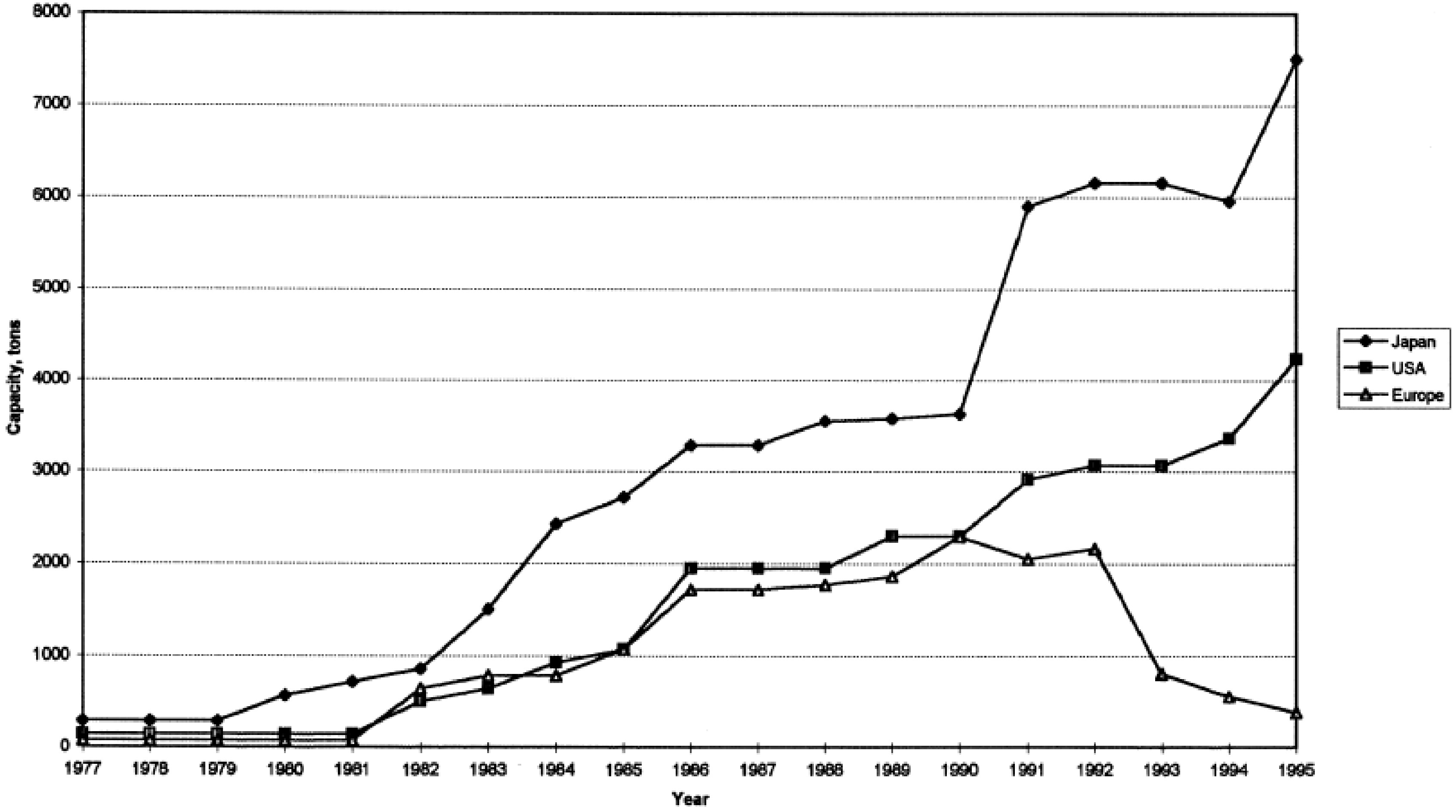
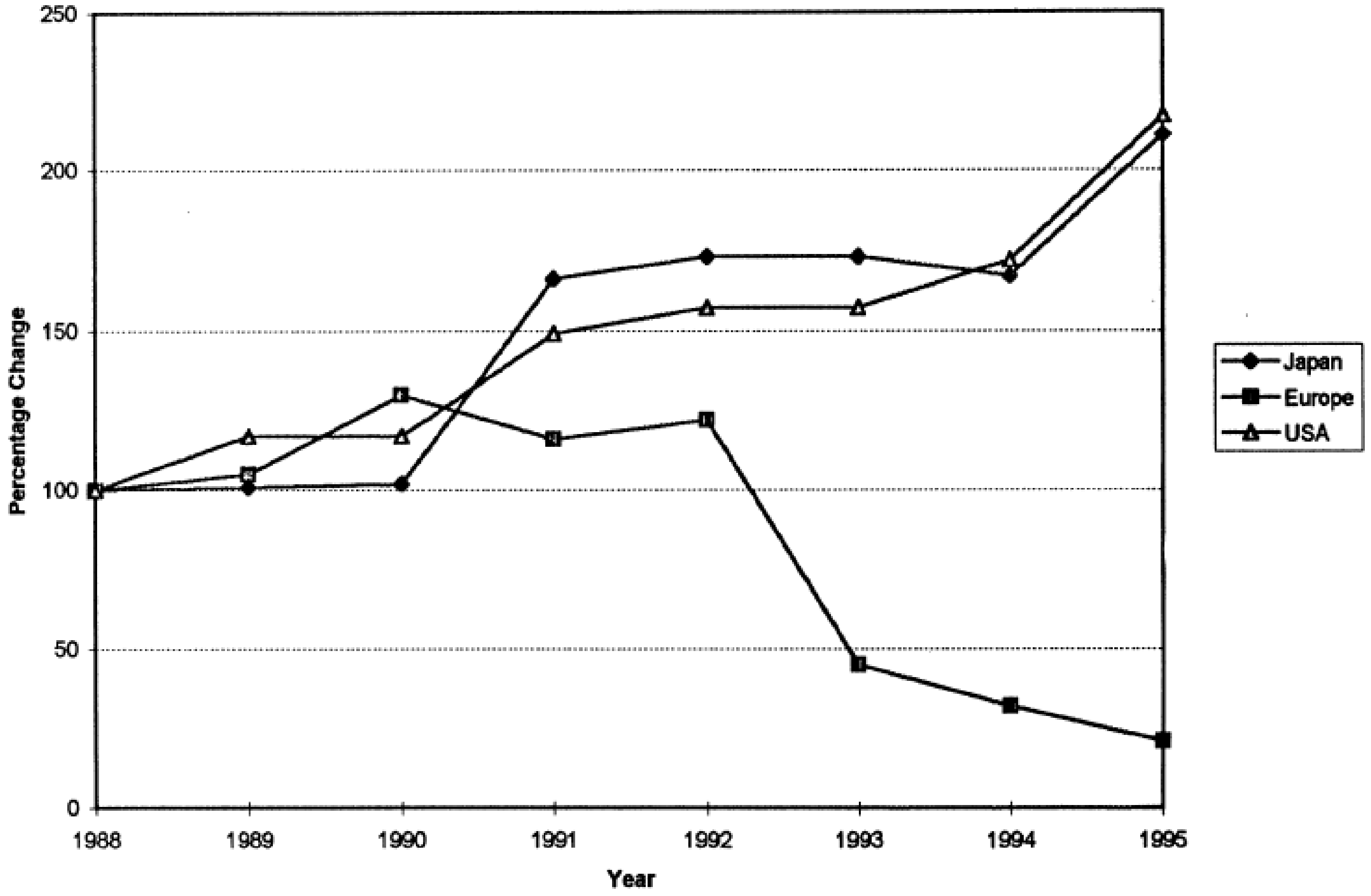


Figure 5.2: Percentage Change in Carbon Fibre Ownership, 1988 base



The period 1990-1993 had been a difficult time for the industry, due to the fall in the demand from the US DoD in combination with the large jump in global capacity. European-owned firms responded to the changing market conditions with a series of closures and sales of stock, with the result that over the four year period 1990-1994, the total capacity within European ownership tumbled from 2290 to 560 tons, at an average annual drop of almost 20%. Meanwhile, the total capacity of US-owned facilities remained flat, temporarily, with a corresponding fall in market share as the Japanese producers increased capacity. US-owned capacity begins to grow again post 1993, the year, as we shall see, that the US government stepped into stabilise the industry. At the same time, the Japanese companies dramatically increased capacity, despite the over-investment generally in the industry, and the excess capacity worldwide. Overall, the capacity share of Japanese companies and their overseas subsidiaries increased from approximately 44% of global production in 1990 to just over 60% by the start of 1993 (see Table 5.7).

The data raise the question as to why firms of different countries demonstrated such radically different responses to the same changing market conditions. It may be argued that these different responses reflect differences in changes at a local level, in local markets. However, trading in carbon fibre has always taken place on a global basis. Moreover the Japanese firms have not only expanded capacity at home but also overseas. As we have seen, Soficar, which is based in France but is 80% owned by Toray, doubled its capacity in 1992, Mitsubishi Rayon acquired Courtaulds Grafil plant in Sacramento in 1991 and Toho Rayon increased its carbon fibre activities in Germany. Toray plans to open a 100% owned subsidiary prepreg plant in Seattle. These investments, moreover, occurred at a time when Japanese investments overseas were falling overall.[77]

This would suggest that the differences in approach between Japanese and Western countries are largely a result of corporate strategy factors and the market type (as opposed to location) on which firms chose to focus. Indeed, all the managers questioned as to why Japanese companies increased carbon fibre production at a time when other firms of G7 countries were currently cutting capacity, cited the same two reasons. These were:

- the over-reliance of US companies on defence markets, and
- the ability of Japanese companies to operate with comparatively long time horizons.

In the following sections we will seek to explore these hypotheses.

The Defence Base; its Collapse and Consequences

We saw above that the changing market for carbon fibre elicited a quite different corporate response from the Japanese produces compared to those in the United States. One of the key explanations cited by the managers interviewed during the course of this research was the relatively heavy reliance on defence markets in the United States. In this section we will examine this claim in more detail.

US Department of Defense usage of carbon fibre had grown steadily throughout the second half of the 1980's. DoD consumption alone had accounted for 53% of the total US carbon fibre market in 1985, and over the period 1985 to 1989 the volume of DoD demand rose by almost 60%, increasing by 5% in 1986, 2.7% in 1987, 15% in 1988 and over 28% in 1989.[78]

Forecasts for military usage were also very strong. By the mid 1980's, all the major carbon fibre producers had developed intermediate modulus fibres to a commercial stage. This had been a critical requirement for further aerospace applications. At the same time, the 'hot wet' problem (that is, the absorption of moisture at ground level by matrix resins heated at high altitude), was overcome. The problems of low modulus and moisture absorption had previously limited the use of composites in supersonic military aircraft to small parts but post-1985, as a result of these technological improvements in matrix resins and stiffer fibre, large carbon fibre composite structures began to be rapidly incorporated into the developmental programmes for military aircraft construction in the 1990's.

In 1986, Mike Bowman, head of the advanced composites group at Du Pont listed the potential carbon fibre projects at the time,

> "The Advanced Tactical Fighter for the Airforce, and a version of that for the Navy a couple of years later. Missiles - almost anything is a carbon fibre opportunity. Helicopters - the LHX, the army's all composite lightweight to replace the Black Hawk. On land, the Hummer series of vehicles - very light, high speed troop and weapon carriers. The whole space industry - space stations, Star Wars and so on. Ships - high speed patrol boats with above water ballistic protection, usually composites. That all adds up to $500bn ... and its all available

> in the mid-1990’s, and that’s what everyone is positioning to take advantage of."[79]

And by way of illustration, when ICI bought the prepregger Fiberite in the mid-1980’s, the Financial Times commented,

> “It may be thought that $750 million is pretty steep for one small company. But Fiberite has a major asset - the necessary security clearance for Pentagon work ..[and].. there are some colossal Pentagon contracts up for grabs.”[80]

Overall, then, the defence outlook was particularly promising. Predictions saw carbon fibre use in military aircraft increasing to 50 or 60 percent of total aircraft weight and Japanese sources began expressing concern over their possible exclusion from the lucrative military contracts. There seemed few doubts about the "increasing demands of the military aviation sector in the 1990s".[81]

The forecasts coincided with the Congressional mandate and further informal assurances from the DoD. As David Forrest, the then president of BASF Structural Materials commented at the time,

> “everyone [has] been pressurised by the Department of Defense to increase capacity."[82]

And as the Chemical and Engineering News observed,

> “The pressures are on to do more ... The US Department of Defense is now pressing for domestic sources of precursors, a strategic decision, to be implemented by 1990. ‘So we will be doing that’ Huismans [a Courtaulds director of the time] says.”[83]

In anticipation of the new markets, and as a result of consequent investments, carbon fibre capacity in the United States increased by around 70% between 1988 and 1992, with the three largest firms, Amoco, Hercules and BASF increasing capacity by **108%** over the four year period.[84]

As we saw in the above section, however, US carbon fibre markets actually fell below the 1989 level in 1990, 1991, and 1992. If we look at the market breakdown in more detail, we see:

Table: 5.8 US Carbon Fibre Markets, (pounds weight, million)

	1985	***1986***	***1987***	***1988***	***1989***	***1990***	***1991***	***1992***	***1993***	***1994***	***1995***
Auto	0.15	0.17	0.20	0.30	0.40	0.34	0.26	0.33	0.54	0.65	0.78
Sports	0.27	0.30	0.50	0.77	0.92	1.08	1.16	1.23	1.29	1.34	1.40
Industry	0.43	0.51	0.60	0.70	0.85	1.13	1.03	1.17	1.38	1.82	2.18
Civil aero	0.39	0.46	0.54	0.64	0.75	0.83	0.92	1.17	1.40	1.70	2.05
DoD	1.41	1.48	1.52	1.75	2.25	1.50	0.95	1.12	1.49	1.86	2.21
Total	2.65	2.95	3.36	4.16	5.17	4.88	4.32	5.02	6.10	7.37	8.62

Source, SACMA[85]

Table 5.8 reveals two main points. Firstly, it illustrates the comparatively heavy dependence of the US carbon fibre market on US military agencies: throughout the period 1985 to 1989, the DoD accounted for around half the total US demand.

The Table also shows that the three year slippage commencing in 1989 was entirely due to the falls in the defence sector. Between the years 1989 and 1991, DoD usage of carbon fibre fell nearly 60%. In 1990 alone the demand for carbon fibre from the DoD fell by over 30%. The DoD market share of the total US carbon fibre market had fallen during 1987, 1988 and 1989. However this was a result of the vigorous growth in the use of carbon fibre in non-military sectors. The demand from the defence sector had continued to increase over this period. The 1989-1990 fall, in contrast, was so severe that despite growth in all other sectors, the total US carbon fibre market also markedly decreased.

The fall in DoD carbon fibre demand came about through the overall cuts in defence spending. The US defence budget had began an enforced, albeit slow, decline in FY1986 in response to the $2 trillion budget deficit and the Reagan Administration Gramm-Rudmann amendment, which mandated that Congress should start presenting balanced budgets. These cuts were accelerated post 1990, as the perceived threat from the former Soviet Bloc subsided, and the purpose and function of military capabilities became less clearly defined. The new security environment, in conjunction with the huge US budget deficit, resulted in military budgets being fixed on almost an ad hoc basis in which economic and short-term political factors played the decisive role.

Procurement was one area of spending where the reduction of military expenditure was, and is, particularly severe. The US military procurement budget authority average during the cold war (1975 to 1990, in constant 1997 prices) was $95.9 billion. This figure is forecast to fall to $63.1 by 1997, a 34.2% drop. Reflecting the demise of the USSR, the maximum cuts are in strategic bombers and tactical wing fighters[86].[ix] In 1992, General Colin Powell, the former Chairman of the Joint Chiefs of Staff remarked,

> "That F-15 of ours is good enough for a long time to come. We only go up to the next family, the F-22, if the threat to justify it really exists at the time or if the F-15s are falling out of the sky."[87]

Tables 5.9 and 5.10 show the US aerospace industry sales by product group in terms of number and value in both real and constant dollars and further confirm the impact of the defence cuts. Throughout the 1980’s, the US DoD was the largest customer for the entire US aerospace industry. In 1991, 1992 and 1993, however, defence sales fell to such an extent that civil sales outstripped military purchases for the first time in over a decade.

[ix] In 1990, the US had 36 tactical fighter wings and 268 strategic bombers. The projected capabilities for 1997 are 26 and 180 respectively, representing percentage drops of 27.8% and 32.8% (Sipri Yearbook, 1993).

Table 5.9: Aerospace Industry Sales by Product Group (current dollars/million)

Year	*Total Sales*	*Total Aircraft*	*Civil Aircraft*	*Military Aircraft*	*Missiles*	*Space*
1979	45,420	26,382	13,227	13,155	4,778	6,545
1980	54,697	31,464	16,285	15,179	6,469	7,945
1981	63,974	36,062	16,427	19,635	7,640	9,388
1982	67,756	35,484	10,982	24,502	10,368	10,514
1983	79,975	42,431	12,373	30,058	10,269	13,946
1984	83,486	41,905	10,690	31,215	11,335	16,332
1985	96,571	50,482	13,730	36,752	11,438	18,556
1986	106,183	56,405	15,718	40,687	11,964	20,117
1987	110,008	59,188	15,465	43,723	10,219	22,266
1988	114,562	60,886	19,019	41,867	10,270	24,312
1989	120,534	61,550	21,903	39,646	13,622	25,274
1990	134,375	71,353	31,362	40,091	14,180	26,446
1991	139,248	73,905	39,897	34,008	11,757	29,831
1992	138,591	73,905	39,897	34,008	11,757	29,831
1993	124,205	66,534	33,750	32,784	8,072	28,898
1994	112,763	58,214	26,263	31,951	7,274	28,481
1995	109,387	56,742	25,817	30,925	6,577	27,837

Source: Aerospace Industries Association[88]

Table 5.10:Aerospace Industry Sales by Product Group (constant dollars/million)

Year	*Total Sales*	*Total Aircraft*	*Civil Aircraft*	*Military Aircraft*	*Missiles*	*Space*
1979	71,528	41,546	20,830	20,717	7,524	10,307
1980	77,475	44,567	23,067	21,500	9,163	11,254
1981	80,470	45,361	20,663	24,698	9,610	11,809
1982	77,083	40,369	12,494	27,875	11,795	11,961
1983	86,741	46,021	13,420	32,601	11,138	15,126
1984	83,653	41,989	10,711	31,278	11,358	16,365
1985	97,843	51,147	13,911	37,236	11,589	18,800
1986	106,396	56,518	15,749	40,769	11,988	20,157
1987	110,008	59,188	15,465	43,723	10,219	22,266
1988	112,426	59,751	18,664	41,086	10,079	23,859
1989	113,604	58,011	20,644	37,367	12,839	23,821
1990	121,606	64,573	28,382	36,281	12,833	23,821
1991	121,508	66,246	32,673	33,573	9,572	25,438
1992	118,050	62,951	33,984	28,968	10,014	25,410
1993	102,819	55,078	27,939	27,139	6,682	23,922
1994	92,353	47,677	21,509	26,168	5,957	23,326
1995	86,884	45,069	20,506	24,563	5,224	22,110

Source: Aerospace Industries Association[89].

Notes: Constant dollar data based on AIA’s composite price deflator (1987=100), 1994 data preliminary, 1995 data estimated

Table 5.11: Military Aircraft Accepted By US Military Agencies (number)

Year	Total	Bomber/ Control/ Command/ control	Fighter/ attack	Transport/ Tanker	Trainer	Helicopter
1979	734	17	529	16	-	158
1980	819	16	551	15	18	189
1981	918	19	649	17	60	158
1982	758	26	478	14	60	172
1983	836	34	421	22	120	233
1984	632	34	298	18	30	240
1985	777	34	409	25	-	306
1986	818	52	424	76	-	266
1987	858	74	483	36	-	265
1988	842	55	509	31	-	247
1989	706	24	408	21	-	253
1990	763	24	454	25	-	260
1991	650	17	395	23	-	215
1992	544	10	312	30	37	155
1993	528	11	293	25	56	143

Source: Aerospace Industries Association[90]

Table 5.12: Military Aircraft Accepted By US Military Agencies

(flyaway value, $million)

Year	Total	Bomber/ patrol/ command/ control	Fighter/ attack	Transport/ tanker	Trainer	Helicopter
1979	5,470	442	4,660	136	-	219
1980	6,514	475	5,282	178	32	516
1981	8,446	526	6,518	509	32	825
1982	8,605	886	6,383	410	42	872
1983	9,640	1,259	6,708	575	79	1,009
1984	9,308	1,270	5,774	627	18	1,597
1985	14,122	3,640	7,923	838	-	1,715
1986	20,903	8,177	8,004	2,665	-	2,057
1987	21,459	8,569	8,900	2,218	-	1,772
1988	16,031	2,911	8,953	2,314	-	1,853
1989	11,968	1,423	7,735	743	-	2,067
1990	13,036	1,499	8,731	605	-	2,201
1991	11,754	1,023	8,517	437	-	1,777
1992	11,482	613	7,673	1,346	267	1,583
1993	11,277	1,530	6,360	1,332	565	1,490

Source: Aerospace Industries Association[91]

Fighter/attack procurement increased apace throughout the Cold War but fell in 1989, increased slightly in 1990, the year of the Gulf War and has since fallen sharply from 454 in to 293 in 19, a drop of over 35%. Over the five year period 1988-93, the total flyaway value of fighter/attack aircraft accepted by military agencies fell from 8,953 million dollars to 6,360 million. Helicopter procurement shows a similar pattern: aside from a increase of 7 to 260 in 1990, helicopter procurement fell in 1991, 1992 and 1993 after steady growth since the start of the AIA figures in 1979. Missile sales, according to the industry estimates, were most severely affected. In 1994, missile sales dropped to the lowest level since 1980 and are projected to fall a further 10% in 1995.[92] Overall, in real (constant dollar) terms, the value of aircraft sales to the military has fallen by 40% from an all times high in 1987.

Serious though these procurement cuts were, it was the cuts in the authorisation budget that most profoundly affected the industry. The then current procurement aircraft had a relatively low degree of carbon fibre usage. The proposed replacements, however, were very intensive users of composite materials, with a substantially higher fraction of their structural weight composed of carbon fibre. For example, as we see from Figure 2.2, carbon fibre constituted only a few percent of the total structural weight of the F-15 and F-16. In contrast, the figure for their replacement, the next generation F-22 (the Advanced Tactical Fighter, or ATF), is close to 40%.

In 1987, essentially the year in which the industry's investment strategies following the DoD mandate were decided upon by the US carbon fibre producers, the industrial association, SACMA identified five very high intensity use projects. These were:

- the V-22 Osprey (Bell/Boeing), a tilt rotor, medium lift aircraft, the first to be developed from the outset for use by all four US armed forces.
- the B-2 stealth bomber (Northrop), a high subsonic 'flying wing' with a carbon fibre radar absorbent skin.
- the ATF (Advanced Tactical Fighter), the replacement for the F-15. Two teams were competing for the ATF contract at the time, McDonnell Douglas/Northrop and Lockheed/Boeing/General Dynamics.
- the A-12, (General Dynamics/McDonnell Douglas) a high subsonic, high payload attack platform commissioned by the US Navy.
- the LHX (two competing teams were awarded initial $158 million developmental contracts - Boeing/Sikorsky and Bell/McDonnell). The LHX was to be a virtually all composite helicopter originally envisaged to fulfil the Army's light helicopter requirement.

In terms of total estimated cost, the V-22, ATF, A-12 and LHX all ranked amongst the top six conventional weapon systems under development at the time, and at an estimated total cost of $69 billion the B-2 bomber was the single most expensive DoD weapon project, strategic or conventional.[93] In the late 1980’s, the projected carbon fibre usage for these five systems, described by industry journals as "the major programmes that suppliers [are] counting on",[94] had been:

Table 5.13: Carbon Fibre Usage Forecasts, 1987, by DoD project

(pounds weight, million)

	1991	*1992*	*1993*	*1994*	*1995*	*CUM*
V-22	0.79	1.26	1.26	1.26	1.26	**5.83**
B-2	1.25	1.57	1.57	0.26	0.0	**4.65**
ATF	0.01	0.07	0.14	0.21	0.43	**0.86**
A-12	0.01	0.01	0.70	0.14	0.21	**0.44**
LHX	0.01	0.01	0.0	0.50	0.10	**0.17**
Total	**2.07**	**2.92**	**3.04**	**1.92**	**2.00**	**11.95**

Source: SACMA[95]

The forecast shows that collectively the total carbon fibre demand from these five projects alone was expected to be close to 6000 tons, or about **three times** the total US consumption both civil and military at the time, and over **twice** the then total US production capacity.

It is pertinent here to query here why the forecasts for future projects were so optimistic despite the declining defence budgets of the time. As we have seen, the defence budget had begun to decline in fiscal year 1986, two years before the fall of the Berlin Wall, in light of the $2 trillion national debt. Up until 1989, the budget deficit had been the primary driver for the defence cuts, and the military tensions of the Cold War security environment remained. Throughout the period 1986 to 1989, the DoD, in its internal Future Years Defence Programme (FYDP) continued to project **increases** in future defence spending. In every year during this period, the FYDP assumed that the defence budget would start growing again the following year and continue growing for the five years subsequent. "This optimistic outlook" the Bulletin of Atomic Scientists comments, "allowed the Defense Department to continue to research and develop more weapons than it could ever afford."[96]

Post-1990, however, with the collapse of the Berlin Wall and the start of the dissolution of the Soviet Union, it was clear to even the most ardent hawk that the defence budgets of the 1990s would not only be lower but also qualitatively different from their predecessors. In the last Cold War budget, (FY1990), 60% of spending, or roughly $200 billion, had been targeted at the perceived Soviet-Warsaw Pact threat, a threat that, by 1991, had largely evaporated. Within the year, the Office of Technology Assessment had recommended a cut in defence spending of 50 percent as "a justifiable response to the end of the Cold War".[97]

Hence, the then Secretary of Defense, Dick Cheney, announced his intention of making a series of far deeper cuts in defence spending in light of the changing security environment. For the first time, defence authorisations for **future** projects were severely affected. The V-22 tilt rotor helicopter[x], the B-2 bomber[xi], the Advanced Tactical Fighter[xii] and the LHX were all markedly cut back. The A-12 became the largest programme ever cancelled outright by the Pentagon.

By 1991, the 1987 DoD demand forecast we detailed above (Table 5.13) had radically changed:

Table 5.14: Carbon Fibre Usage Forecasts, 1991 (1993)(pounds, million)

	1991	*1992*	*1993*	*1994*	*1995*	*CUM*
V-22	0.00	0.00	0.00	0.00	0.00	**0.00**
	(0.00)	(0.03)	(0.00)	(0.00)	(0.00)	**(0.03)**
B-2	0.11	0.22	0.38	0.38	0.59	**1.68**
	(0.11)	(0.00)	(0.00)	(0.00)	(0.00)	**(0.11)**
ATF	0.00	0.02	0.04	0.04	0.04	**0.14**
	(0.00)	(0.02)	(0.04)	().04)	(0.04)	**(0.14)**
A-12	0.00	0.00	0.00	0.00	0.00	**0.00**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	**(0.00)**
LHX	0.00	0.01	0.01	0.00	0.00	**0.02**
	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)	**(0.02)**
Total	**0.11**	**0.25**	**0.43**	**0.42**	**0.63**	**1.84**

Sources, SACMA, Composite Market Reports[98]

Although the detail in the project cuts changes each year, the key point remains the same: **by the time the new capacity came on line, the original market had apparently disappeared.** DoD cuts occurred over the same two year period in which as all the major carbon fibre producers had increased production and world capacity as a whole increased almost 40%. If the 1987 US carbon fibre forecast for the early 1990's is compared with the

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[x] Low rate production scheduled to begin FY 1997. Decision on full rate production will be made in FY 2001. Current plans are for the procurement of 523 aircraft through FY 2021, with initial operational capability anticipated in FY 2001.(Source: Annual Report to the President and the Congress, William J. Perry, March 1996)

[xi] Current B-2 procurement plans: 1995, 7 aircraft; 1997, 13 aircraft; 1999, 17 aircraft; 2001, 20 aircraft.(Source: Perry, ibid.))

[xii] Production deliveries planned to begin in FY 2000, initial operational capability slated for FY2005. (Source, Perry, ibid.)

actual consumption, the degree of error in the military demand outlook estimates is revealed (Table 5.15):

Table 5.15: US DoD Carbon Fibre Consumption, (Pounds, million)

	1991	**1992**	**1993**	**1994**	**1995**	**Total**
1987 Forecast	4.84	6.09	7.09	6.97	6.67	31.66
Actual Demand	0.95	1.10	1.30	1.64	1.86	6.85

Source, SACMA[99]

The table sums up the large overestimate in the 1987 DoD forecasts. The actual DoD carbon fibre consumption is down **78%** on the 1987 industry forecast. For such a capital intensive industry, this is a very severe change in a major market segment. By 1992, military orders had fallen to 15% of total consumption and 50% of US carbon fibre capacity was idle.

The industry was in crisis. The Clinton Administration, however, was keen to preserve those industries considered vital to the defence interest. As a result, and, as part of its commitment to the diversification of dual use technologies following the defence base collapse, Technology Reinvestment Project (TRP) was established. TRP in effect secured the carbon fibre capabilities of Amoco and Hercules, the two largest indigenous American producers, and both key suppliers to the Department of Defense. We therefore offer here a brief description of the TRP, particularly with respect to its impact on the survival of the US carbon fibre sector.

The Technology Reinvestment Project

“The DoD has a clear role to play in the economic defense of the country”

Les Aspin, December 1993

Throughout the Cold War period, the need to maintain a military technology base was the central justification for US public R&D investment. Post 1989, sharp cuts were made in military procurement and research and development with a consequent downsizing in federal military technology spending. This raised fears concerning not only the future of the military technology base itself, but also, since defence R&D had previously been a mainstay of US federal research, the potential erosion of the national technology base as a whole. In an attempt to address these issues, and the additional problems of a shrinking defence industry, in March 1993, the Clinton administration launched the Defense Reinvestment Conversion Initiative.

The centrepiece of the new legislation was the Technology Reinvestment Project (TRP), formed to execute the eight statutory programmes enacted by Congress in the Defense Technology Conversion, Reinvestment and Transition Act of 1992. In its early days, TRP was promoted as a sort of rescue package for the struggling defence industry, an enabling device whereby defence companies and their workforce could diversify into new, commercial markets:

“I've given it another name - Operation Restore Jobs” said President Clinton,[100] although it was also made clear that,

> “[TRP] is not a foaming of the runway for a crash landing of the Defense Department.”[101]

With the advent of a Republican congress, however, the focus of the TRP was changed. Funds were cut, programmes related to retraining and regional development were axed and applicants urged to demonstrate their proposals “present a compelling Defense benefit.”[102]

TRP is a six agency technology investment effort, headed up by ARPA but including the Army, Navy and Airforce as well as the Departments of Commerce, Energy and Transportation, the National Science Foundation and the National Aeronautics and Space Administration. Through the selective funding of dual-use technologies, TRP is designed to leverage commercial technological progress for the benefit of the US military. TRP proponents argue that the encouragement of dual use innovation would maintain a strong defence base despite the constrained fiscal resources by several avenues.

Firstly, it recognises that “more and more of the best technology is being developed in the commercial, not the defence, sector ... overall, R&D expenditures by business in the United States are now more than double those by the DoD and continue to increase”. TRP aimed to ensure that part of this research would be conducted with “a direct regard for military need.”[103]

Secondly, it is argued, by developing cheaper, market driven but defence related technologies, military and commercial components could be produced within the same production facilities. The production of military parts from commercially derived military upgrades could avoid the high unit costs of strictly military production and so substantially increase the affordability of acquiring a weapon system. Finally, a strong civil technology base would be more capable of responding to a surge in demand for military products should the need arise.

All the TRP projects are based on cost sharing, with non-federal sources matching federal funds on at least a dollar to dollar basis. Almost all are organised around teams in which industrial firms form the bedrock but which may include Universities or, occasionally, other organisations such as hospitals. As TRP is not a direct procurement programme (it is funded through co-operative agreement or ARPA's 'other transactions' budget), TRP contracts are not governed by Federal Acquisition Regulations (the restrictive government - only rules and requirements concerning secrecy and intellectual property rights usually attendant on DoD contracts). "These instruments" claims the TRP literature "give TRP more flexibility in dealing with intellectual property rights, and this helps attract firms that might not otherwise deal with government." Indeed, roughly 75% of the technology development projects selected in the first round included both a commercial and a defence firm.[104]

The TRP itself was originally split into four programme elements. These were:

- *technology development projects*, i.e. programmes of applied and early developmental research designed to develop new products or manufacturing techniques that possess both defence and commercial applications;

- *small business innovation and research*, a specific programme to develop dual use technologies within smaller companies;
- *technology deployment*, an area which sought to improve the diffusion of technology through organisational changes in defence serving sectors;
- *manufacturing education and training*, the smallest programme area and one that sought to "redress the classic US weaknesses in critical technical skills like product design and manufacturing" by the establishment of vocational engineering courses in schools, colleges and universities.[105]

The first TRP winning proposals were announced in the autumn of 1993. In total, $605 million was awarded to 212 projects involving 1,600 firms, universities and other participating institutions. A further $15 million was later awarded in the small business innovation research project competition area. The second round of awards, bringing the total TRP spending to $820 million, was announced by President Clinton in autumn 1994.

> "Today, commercial firms are the source of many of the advanced technologies that are needed to keep our military the most powerful in the world," the President said. "The winning projects I am announcing today link commercial and defense needs, to keep America strong, militarily and economically."[106]

TRP literature describes composite materials as an "especially critical area"[107] and argues that,

> "Defense's reduced demand for advanced materials and structural systems, without some compensating growth in civilian demand, threatens the existence of the U.S. advanced materials industries as they apply to the military. Through several activities, the TRP is addressing this shortfall to ensure that advanced materials are available for essential Defense uses, such as high-performance aircraft and bridging equipment. If advanced materials for the military can be put to civilian use, then the military will always be able to access these materials through commercial producers ... the commercial market for such materials must grow so that the much smaller Defense market can access a reliable source of advanced materials as needed."[108]

Essentially the TRP sought to find ways of reducing manufacturing costs of advanced materials and stimulate high volume commercial markets, in order to ensure a continued DoD access to an advanced material production base. The Annual Report continues,

> "The high cost of composite materials restricts their use, especially in the commercial sector. And the production that does exist today, primarily in the military sector, has been threatened by Defense downsizing, which has reduced industry's capacity for competitive production."[109]

Two of the largest awards went to carbon fibre composite related projects, **Advanced Composites for Bridge Infrastructure Renewal** (announced 22nd October 1993) and **Affordable Composites for Propulsion** (announced the following spring on 23rd February 1994). Both these projects fell into the Technology Development competition area. We will now look at each of these two projects in more detail.

Advanced Composites for Bridge Infrastructure Renewal, a continuation of an earlier DARPA project, was awarded $21 million under the first round of TRP awards. At eighteen months long, the project aimed to find a lighter weight but low cost alternative to the portable bridges used by the US Army Corp of Engineers in combat situations or in the wake of natural disasters. The consortium, including Amoco and Hercules, were awarded $21 million in an 18 month programme to develop polymer composite materials for use in bridge construction. "This technology" claimed the proposal, emphasising the dual use nature, "can generate mobile, lightweight bridges for use by the US Army Corp of Engineers in combat situations or after natural disasters"[110]. The project members were:

- University of California, San Diego, La Jolla, CA.
- Amoco Performance Products, Inc., Alpharetta, GA.
- Hercules, Inc., Magna, UT.
- Muller International, Inc., San Diego, CA.
- Trans-Science Corporation, La Jolla, CA.
- University of Delaware, Newark, DE.

The project largely succeeded in demonstrating the use of composites in construction applications. Ferrous bridges corrode, a particular problem in marine industrial environments where there may be high levels of salt or carbon, nitrogen or sulphur dioxide. In autumn of 1995, Toray told the author of the new markets emerging through government research programmes including TRP, and the smaller EU Euroconcrete programme and the DTI Robust initiative in bridge infrastructure renewal. These applications (composite reinforced columns, high strength fibre cables and composite wear surfaces) in bridge construction have an "enormous potential ... there are 10,000 bridges in the UK requiring upgrading [to the new European 44 tons weight standard]."[111])

Under Round 4 of the following year, a second large award was made to a composite related proposal. *Affordable Composites for Propulsion* is a five year project aimed at developing reliable, low cost manufacturing techniques to replacing metal engine parts with polymer composites in advanced aircraft propulsion systems. The total project cost is estimated to be $370 million, of which the US government will contribute $130 million.[112] Hercules was also a member of this consortium. Again the dual nature of the project was made clear. "This project" reads the proposal "will enhance US competitiveness in aircraft production as well as preserve a critical capability for DoD weapon systems". The consortium members are:

- Pratt and Whitney, West Palm Beach, FL.
- Boeing Commercial Airplane Group, Renton WA.
- Dow—United Technologies Composite Products Inc., Wallinford, CT.
- Du Pont, Wilmington, DE.
- Hercules, Inc., Magna, UT.
- Martin Marietta Technologies Inc. Baltimore MD.
- Vought Aircraft, Dallas TX.

Collectively, the consortium represents half the aerospace composite component manufacturing capacity in the United States.[113] The project goal is the development of automated techniques for the manufacture of composite parts on a large scale i.e., it is directed at the low cost, high volume manufacture of high performance carbon fibre composites. Automation, it is argued, will reduce costs and access markets in commercial aerospace engines. The programme also has an immediate defence use as it is also directly applicable to the new generation of engines, which increase the range of military aircraft by up to 20%, extend the on-station time of Airborne Warning and Control Systems (AWACS) by 2 hours and reduce the level of noise. These sorts of engines are a key feature of the future Advanced Tactical Transport Aircraft and could also be used in the F-22.[114]

On April the 5th, 1995, the by then Republican Congress cut the 1995 TRP funding by $300 million in order "to help pay for recent military operations in the Persian Gulf, Somalia, Rwanda and Haiti".[115] Only those projects considered to possess an immediate or considerable defence benefit were retained. The Manufacturing Education and Training Competition was cancelled outright. Major reductions were made in the Technology Deployment and Small Business Innovation Research. A number of Technology Focus areas were eliminated from the Technology Development competitions, including those for ceramic materials, cryogenic coolers and speciality metals. Composite programmes, however, were left unscathed.

One of the largest project areas proposed by ARPA for TRP 1996 is the Affordable Composite Primary Aircraft Structure, for which, according to Jon Devault of ARPA's Defense Science Office "all the major airframe companies have formed teams and are busy preparing proposals".[116] Proposed funding totalled $160 million over the lifetime of the project, with $30 million available for the first year. However, in the event, no submissions were actually made by the deadline.[117] Firms were reportedly nervous about the future funding of the programme and the increasingly defence orientated nature of the project. Funding for the 1996 TRP, for which President Clinton had requested $415 million, had at one point been actually eliminated from the House Version of the Defense Authorisation bill by the House National Security Committee.[118] As the Composite Market Reports commented,

> "Originally in keeping with the ground rules set up for ARPA's Technology Reinvestment Project this [the affordable composites primary aircraft structure project] was to be a dual use (commercial and military) aircraft composite wing program, but with strong and continued pressure from Congress, it subsequently became clear that the primary emphasis would be on developing the technology for future military rather than commercial-military use. This was probably the main reason the Bell-Boeing team [previously considered the main contender] decided to no-bid ... with Congress threatening to sharply cut or eliminate

> ARPA's TRP funding, there is too much risk in starting a major program during a period when all budget items are being so carefully scrutinised."[119]

Whatever the outcome, the carbon fibre industry will not be directly affected by TRP 1996. By the summer of 1995, for the first time in five years, all the major carbon fibre producers still in the business were working flat out.[120] Order books had been filling up as the incremental US legislation mandating that compressed natural gas tanks be made from carbon fibre composites took shape. Hercules announced in the spring that it was "fully booked through to September" and trying to find ways of increasing output from current facilities without incurring the cost of building a whole new line.[121] Amoco and Grafil were also reportedly running close to capacity and Akzo was having a "great year".[122] What the TRP initiative succeeded in creating for the industry was a breathing space that enabled Hercules and Amoco to ride out the difficult trading conditions of the early 1990's, conditions that had already driven out four non-TRP firms. The TRP had sought to "stabilise the U.S. composites industry and ensure the DoD can access an affordable supplier base."[123] By acting as a temporary expedient or stopgap, the Project achieved these stated objectives.

The Role of Corporate Strategy

We have seen earlier in this chapter that the Japanese producers were insulated in part from the full impact of the defence cut backs as they had focused in non-military markets. We now examine the second strand of argument raised by those questioned i.e., the relative stability of the Japanese carbon fibre producers.

At the start of the 1990's, while the firms of the US and Europe were trimming capacity or seeking to withdraw from the industry, the Japanese producers rapidly increased capacity against the background of falling demand. At face value this is an astonishing move. The industry is very capital intensive with high sunk costs. Furthermore, a carbon fibre line, once built, cannot be easily converted for other uses. This type of strategic investment in over-capacity was what is known in game theory literature as pre-commitment, or a **credible threat**.[124] The market had contracted to such an extent that a certain number of participants would be forced to leave. By making a sizeable sunk investment the Japanese companies were signalling that it would not be them.[125] A precommitment strategy at this time was a risky but a high reward option which, if successful would result in a very large market share, control of price and trade and a strong manufacturing base overseas.[126] This is an essentially long term strategy, however, requiring the backing of patient capital as initial losses are high, and may be sustained over several years. In Chapter Three we saw that for large firms, especially those in keiretsu groups, the accounting practices in Japan, in conjunction with the lower interest rates generally, allow for this type of investment. We now look at the evidence for this type of financial governance in the case of the carbon fibre sector.

In **Appendix III,** we examine the keiretsu status of each of the Japanese carbon fibre producers. A core keiretsu company is traditionally defined as one that has a seat on the presidential council. All our companies fall within this definition. However if we look closer, we find we can differentiate on the degree of their membership. Toray, Mitsubishi Rayon and Toho Rayon possess all the key characteristics, namely interlocking shareholdings, close creditor relations, interlocking directorships as well as seats on their respective councils. In addition, Mitsubishi Rayon sells almost all its carbon fibre to related Mitsubishi firms. It is interesting to note that this is the firm least affected by the recession in the industry, and as a result has increased its market share in Japan by several percent at the expense of the other players.[127]

Mitsubishi Rayon bought up plant in the US at a time when the yen was strong against the dollar. However, it was primarily a strategic investment, made at a time when Japanese investment overseas was falling as a whole, and resulting in Mitsubishi Rayon gaining full integration in the carbon fibre composite industry in the US. Toray and Toho Rayon have pursued similar strategies in Europe, both establishing a business base through joint ventures with large European chemical companies and moving quickly in the shake out of the early 1990's to acquire majority stakes. Toray was hit hardest by the recession in the industry as the (previously military) US suppliers sought to enter new markets in the civil sector, competing directly with Toray's US civil aerospace interests. Toray responded aggressively by continued investment in the sector, even in the face of heavy losses, establishing value added downstream production facilities in the US. This strategy appears to be proving successful in that competing firms left the industry, and new growth is now apparent in the civil sector.

Asahi Kasei was the one Japanese producer to cease carbon fibre production. Keiretsu membership aside, the firm was perhaps slightly more predisposed than other Japanese producers to close its carbon fibre business. Despite increasing its capacity to 600 tons the previous year, the firm still lacked the economies of scale possessed by Toray and Toho Rayon. Moreover, Asahi Kasei was the only Japanese producer to organise its carbon fibre activities as a separate business. Toray, Toho Rayon and Mitsubishi Rayon all produce carbon fibre from divisions within the firm. Asahi Kasei, however, produced from a wholly owned subsidiary. This made it much harder for the firm to write off its carbon fibre losses against more profitable operations. It also made it much easier to close down its carbon fibre business with minimum financial repercussions for the main group.

However, the central distinction between Asahi Kasei and the other Japanese producer is its minimal keiretsu standing. Of all the carbon fibre producers, Asahi Kasei is the least tied either financially or informally to a keiretsu group. As we have seen, Asahi Kasei officially sits on the presidential council of DaiIchi Kangyo. However, it has close financial ties with Sumitomo, a different keiretsu group. DIK is the 'loosest' of the big keiretsu, with an average cross shareholding of only 12%. The presidential council meets infrequently, just four times a year, and the companies are relatively independent. The company stated in interview that it was not a keiretsu member, unlike the other firms, and described this as a distinct 'disadvantage' in a high risk, high technology sector.[128] In short, when compared to rival producers in Japan, the Asahi Kasei’s relatively independent status left the firm exposed to a far greater degree to the sharp downturn and consequent recession of the industry.

With the exception of Asahi Kasei, all the Japanese carbon fibre producer firms are classic core keiretsu firms. Keiretsu membership is a sensitive, not to say confidential, topic amongst the companies, as they are perceived as cartels in the West. Direct questions relating to specific keiretsu mechanisms by the author resulted in either pleas of confidentiality, or a conflicting response ("Toray are quite independent of Mitsui influence" [Toray London office[129].], "Toray has a good relationship with Mitsui Corporation" [Toray Tokyo Head Office[130]]).

We have shown, suggestively, that keiretsu membership and the ability of the Japanese carbon fibre producers to maintain their operations in times of difficult trading appear to be linked. To go further would require detailed information on financial transfers and orders within each keiretsu. As this is not available, we will try an indirect approach to add weight to the argument. This is based on a analysis of accounting practices of all the carbon fibre producers for indications of variance in corporate governance. In particular, we will develop the argument on the basis of a direct comparison of key financial ratios for all the major carbon fibre producers. These are given in Tables 5.16 and 5.17. Any use of financial data requires first the consideration of a number of caveats and some explanation is also needed of the ratios themselves. We therefore turn to these preliminaries before considering the ratios directly.

Firstly, in comparing ratios between firms, especially those of different countries of origin, we must ensure as far as possible that the ratios have been prepared on a consistent basis. Secondly, the data totals appearing in financial statements usually summarise a whole series of transactions, the nature and mixture of which may vary from one year to the next. Thirdly, a particular extraordinary item or other exceptional circumstances may distort the figures for a particular accounting period.

In order to mitigate these effects as far as possible and ensure some consistency in preparation and uniformity in accounting principles (such as in the definition of profit), we have taken all our ratios from the same source, Datastream. Those definitions that vary from country to country due to different accounting or tax regimes have been avoided. Secondly, we have taken data from five consecutive years. This ensures that we have a spread of data to average out any particular rogue year and will hopefully circumvent financial 'window dressing' by the firms (wherein capital and profit positions are manipulated through the acceleration or delay of transactions close to the end of the financial year). Thirdly, where appropriate we present more than one measure in order that we may as far as possible counteract any odd variation in any particular financial item. Finally, all the ratios presented here are dimensionless and so independent of currency and exchange rate.

We will first consider data ratios relating to the **capital structure** of the firm, that is, the borrowing, capital gearing and loan capital ratios. The **borrowing ratio** (also known as the debt equity ratio) used here is defined as:

$$\frac{\text{subordinated debt + total loan capital + short term borrowings}}{\text{equity capital and reserves + deferred tax - total intangibles}}$$

and is a measure of the reliance of a firm on bank borrowings as opposed to raising funds through equity. A similar measure is **capital gearing**, defined as:

$$\frac{\text{preference capital + subordinated debt + total loan capital + short term borrowings}}{\text{total capital employed + short term borrowings - total intangibles - future tax benefits}}$$

Capital gearing measures the fraction of the total capital employed by the firm that is raised by bank borrowings and preference shares (which normally entitle the holder to a fixed rate of dividend). For completeness, we will also examine the ratio of **loan capital to equity and reserves**, calculated here as :

$$\frac{\text{subordinated debt + total loan capital}}{\text{equity capital and reserves + deferred tax - total intangibles}}$$

The loan capital to equity and reserves ratio, measures gearing while omitting short term borrowing which in reality may be renewed each year. All three of these ratios are measures of **gearing**, that is, the degree to which a company raises finance through borrowing rather than equity.

Table 5.16: Measures of Gearing

Borrowing	**Ratio**						
	1990	1991	1992	1993	1994	MEAN	ST DEV
BASF	0.26	0.29	0.39	0.39	0.25	0.32	0.062
Hercules	0.42	0.32	0.29	0.32	0.35	0.34	0.044
Amoco	0.32	0.32	0.34	0.31	0.27	0.312	0.023
BP	0.71	0.84	1.12	0.91	0.65	0.846	0.165
Courtaulds	0.78	0.67	0.64	0.47	0.55	0.622	0.106
Toray	0.73	0.87	0.98	1	0.97	0.91	0.101
Toho Rayon	1.4	1.69	1.86	1.7	2.06	1.742	0.217
Asahi Kasei	1.1	1.08	1.01	1.07	1.05	1.062	0.0306
Mitsubishi Rayon	1.53	1.63	1.6	1.5	1.49	1.55	0.0555
Capital	**Gearing**						
	1990	1991	1992	1993	1994	MEAN	ST DEV
BASF	13.15	14.97	18.45	19.11	13.66	15.87	2.46
Hercules	28.46	23.18	21.06	19.69	20.98	22.67	3.10
Amoco	22.81	22.76	22.66	21.06	18.89	21.64	1.520
BP	33.24	36.47	41.51	36.56	30.08	35.57	3.82
Courtaulds	41.28	38.1	37.13	29.31	32.19	35.6	4.29
Toray	39	43.08	45.46	45.87	45.13	43.7	2.54
Toho Rayon	55.42	60.21	63.21	60.88	64.88	60.9	3.21
Asahi Kasei	47.1	46.92	46.75	48.4	47.83	47.4	0.621
Mitsubishi Rayon	56.45	58.1	57.72	56.06	55.78	56.8	0.921
Loan Capital/Equity and Reserves							
	1990	1991	1992	1993	1994	MEAN	ST DEV
BASF	0.17	0.16	0.21	0.16	0.15	0.17	0.020
Hercules	0.29	0.23	0.23	0.21	0.22	0.236	0.028
Amoco	0.28	0.25	0.32	0.24	0.25	0.268	0.029
BP	0.54	0.67	0.85	0.78	0.55	0.678	0.123
Courtaulds	0.6	0.53	0.48	0.29	0.26	0.432	0.134
Toray	0.36	0.35	0.45	0.41	0.5	0.414	0.056
Toho Rayon	0.56	0.9	0.45	0.48	0.2	0.518	0.228
Asahi Kasei	0.7	0.6	0.66	0.62	0.68	0.652	0.0371
Mitsubishi Rayon	1.03	1.06	1.08	0.79	0.85	0.962	0.119
N/A = data not available		Ratio Source : Datastream					

Table 5.17 Selected Financial Ratios

Working Capital Ratio							
	1990	**1991**	**1992**	**1993**	**1994**	**MEAN**	**ST DEV**
Hercules	1.76	1.85	1.63	1.39	1.5	1.63	0.17
Amoco	1.21	0.97	1.16	1.14	1.32	1.16	0.11
BASF	1.88	1.71	1.64	1.39	1.61	1.64	0.19
BP	0.99	0.97	0.87	0.89	0.91	0.93	0.045
Courtaulds	1.16	1.15	1.2	1.14	1.07	1.14	0.042
Toray	1.33	1.28	1.28	1.18	1.29	1.27	0.049
Toho Rayon	1.22	1.45	1.06	1.08	1.84	1.33	0.29
Asahi Kasei	1.31	1.22	1.36	1.26	1.31	1.29	0.048
Mitsubishi Rayon	1.47	1.41	1.42	1.24	1.37	1.38	0.078
Operating Profit Margin							
	1990	**1991**	**1992**	**1993**	**1994**	**MEAN**	**ST DEV**
Hercules	7.36	9.01	9.98	12.97	15.25	10.91	2.83
Amoco	10.02	8.75	4.15	9.37	7.31	7.92	2.09
BASF	6.57	N/A	N/A	N/A	N/A	6.57	N/A
BP	6.98	3.33	2.79	3.67	5.19	4.392	1.52
Courtaulds	9.8	10.63	10.04	8.84	7.83	9.428	0.986
Toray	8.55	8.83	7.82	6.92	4.64	7.352	1.51
Toho Rayon	2.7	3.21	0.24	-0.35	-0.71	1.02	1.62
Asahi Kasei	8.37	7.38	5.58	3.95	2.15	5.49	2.25
Mitsubishi Rayon	6.1	5.47	5.12	3.61	2.08	4.48	1.45
Return on Shareholder Equity							
	1990	1991	1992	1993	1994	MEAN	ST DEV
BASF	10.25	N/A	N/A	N/A	N/A	10.25	0
Hercules	6.68	8.27	9.75	11.55	18.69	10.99	4.17
Amoco	10.18	6.48	5.35	10.92	10.32	8.65	2.28
BP	17.24	4.25	4.73	9.16	14.75	10.03	5.23
Courtaulds	33.49	31	27.64	16.72	14.68	24.71	7.61
Toray	9.75	8.82	6.26	5.97	2.79	6.72	2.44
Toho Rayon	3.37	4.51	-1.06	-1.6	-25.04	-3.96	10.81
Asahi Kasei	12.24	11.22	7.29	4.29	2.09	7.43	3.90
Mitsubishi Rayon	5.38	3.18	4.38	1.8	0.13	2.97	1.86

Table 5.17 (continued)

Tax Ratio							
	1990	**1991**	**1992**	**1993**	**1994**	**MEAN**	**ST DEV**
Hercules	41.19	42.72	34.47	31.73	32.85	36.59	4.49
Amoco	43.9	42.36	15.25	27.4	28.18	31.49	10.62
BASF	59.56	49.95	50.53	28.01	44.57	46.52	10.43
BP	37.64	68.16	50.46	52.61	30.34	47.84	13.06
Courtaulds	21.31	22.99	21.33	27.88	23.49	23.4	2.404
Toray	47.66	45.34	50.68	46.72	58.94	49.89	4.863
Toho Rayon	46.36	36	-3.2	-70.72	-5.31	0.63	41.19
Asahi Kasei	50.14	47.99	47.51	49.6	43.95	47.84	2.17
Mitsubishi Rayon	46.85	54.34	48.66	55.69	123.13	65.73	28.89

Return on Capital Employed							
	1991	**1992**	**1993**	**1994**	**1995**	**MEAN**	**STDEV**
Hercules	9.58	10.78	12.37	12.75	18.47	12.80	3.06
Amoco	15.35	10.2	5.35	11.75	11.45	10.82	3.23
BASF	13.89					13.89	0
BP	16.49	8.6	7.26	9.66	12.4	10.88	3.27
Courtaulds	28.25	28.14	26.59	21.61	16.7	24.26	4.49
Toray	9.63	8.85	7.35	6.05	3.54	7.08	2.16
Toho Rayon	2.41	2.71	-0.89	-5.63	-4.07	-1.09	3.35
Asahi Kasei	11.39	10.43	6.94	4.31	1.88	7.00	3.59
Mitsubishi Rayon	4.37	3.72	1.99	0.63	1.55	2.45	1.39

N/A = data not available Ratio Source : Datastream

Analysis

Gearing (Table 5.16) is the single most important measure of the company's own perception of risk and stability. A company raises finance partly from (comparatively long term) bank loans and partly from shareholder equity. These two sources of finance possess different characteristics in that the providers of bank loan require a fixed amount of interest to be paid each year whereas the dividend repaid to equity holders is set by the residual profits won each year. Debt is usually cheaper than equity but a high debt equity ratio increases the financial risk of a company. If a company is otherwise financially stable, it will set its debt equity ratio at a high level. Hence the debt equity measure is the basic financial measure used for the long term stability of a firm. Table 5.16 illustrate that, averaged over the five year period, **by every measure**, **the gearing ratio is significantly lower for every non-Japanese carbon fibre producer than that of any of the Japanese companies**. In other words, the Japanese carbon fibre manufacturers raise finance in a way that indicates a greater confidence in the future stability of the firm.

We also present here a number of other key ratios in order to gain a perspective of the overall health of otherwise of all the firms. These are:

- the **working capital ratio:**

$$\frac{\text{total current assets}}{\text{total current liabilities}}$$

- the **return on shareholder equity**, defined here as:

$$\frac{\text{Earnings for ordinary shares}}{\text{Equity capital and reserves — total intangibles + deferred tax}}$$

- the **return on capital employed**, or:

$$\frac{\text{total interest charges + pre-tax profit}}{\text{total capital employed + short term borrowings - total intangibles - future tax benefits}}$$

- the **operating profit margin:**

$$\frac{\text{operating profit}}{\text{total sales}}$$

- and the **tax ratio:**

$$\frac{\text{published tax}}{\text{pre tax profit.}}$$

The first of these, the *working capital ratio* (Table 5.17) is a broad indicator of a company's immediate financial position. It significance is as a measure of the immediate funds available to cover short term crises. Generally speaking, the working capital ratio is a reflection of the major business sector of the company rather than its corporate governance, especially when considering established firms. All the carbon fibre producers are broadly diversified companies and, unsurprisingly, the working capital aggregate means for the Japanese and non-Japanese firms are virtually identical, at value of 1.3.

The *tax ratio* (Table 5.17) is simply the total tax paid, including that paid overseas, as a proportion of the pre-tax profit. We use it here to check there are no major differences in levels of tax paid that may seriously affect other ratios. From the table we can deduce that the aggregate mean for the Japanese and non-Japanese companies differ slightly at 37.1 and 32.8 respectively, but that both fall within the standard deviation of the overall group.

The *rates of return* and *operating profit margin* are all measures of firm profitability and collectively they tell us that over the five year period, the Japanese firms were on the whole less profitable, with Toho Rayon sustaining losses throughout 1993, 1994 and 1995. This is consistent with Nakatani's assertion that keiretsu firms are not profit maximisers, but rather sacrifice short term profit for long term stability. The *return on capital employed* (ROCE) is probably the most important measure of profitability, being very sensitive to downturns in the industry. Over the five year period 1991-1995, the Japanese firms have sustained a significantly lower ROCE than their non-Japanese counterparts.

For all these firms, carbon fibre production represents only a tiny fraction of business, typically only a few percent of turnover.[xiii] Moreover, it is not a core business for any of the companies. For these reasons, combined with commercial sensitivities, financial data for carbon fibre operations is not published. However, according to industry sources, every major producer made losses on its carbon fibre operations over the period 1990 to 1994.[131] These losses are exacerbated by the high total capital employed by the sector. The fact that for many major producers, carbon fibre is not a core product combined with the negative or consistently low ROCE made carbon fibre a prime business for disposal throughout this period. However, despite being less profitable over the period generally, Japanese producers, with the exception of Asahi Kasei, chose to maintain or even expand their carbon fibre operations. We shall seek to explain this by looking at in greater detail at a further financial indicator, the price - earnings ratio.

[xiii] For example, Toray's carbon fibre sales are estimated to be around $180 million, out of total sales of $7.3 billion, or just over 2% (Source, Performance Materials, 17th May 1993)

The *price earnings ratio* (PER), Table 5.18, is calculated by dividing the market price of ordinary shares by the earnings per share (the total amount of earnings available to ordinary shareholder divided by the number of shares). By including the market price of the shares, the PER contains a subjective element that reflects the expectations of the market concerning the future earnings and viability of the company. All else being equal, a company with a high ratio is one expected by investors to have good earning potential and/or good prospects for capital appreciation. Table 5.18 presents the variation in price earnings ratio over time of all the major carbon fibre producers. The data is shown figuratively in Figure 5.3, and in Figure 5.4 the data averages by geographical region are presented.

The first point to note is the relatively high level of PER for the Japanese firms, on average almost **four times** that of the aggregate mean for their non-Japanese counterparts. This indicates that despite the low level of dividend paid out by the firms, the price paid for their shares is high, and has been consistently so over the five year period. In other words, the shareholders of these firms are tolerant of low dividend and keep hold of the shares even in times of low profit. In this way, so long as the capital value of the stock appreciates the share prices is maintained regardless of the return on equity.

Table 5.18: PERs, all producers

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	Mean	Sd Dev
BASF	8.2	4.6	7.6	8.9	17.9	7.8	7.4	9.2	8.8	8.8	7.2	6.6	13.7	19.1	14.2	11.2	10.08	3.97
Hercules	6.3	6.8	8.8	13.8	12	9.6	16.4	12.6	3.2	15.3	13.3	N/A	37.2	18.4	25	19.5	14.55	8.13
Amoco	8.2	14.7	6.6	6.3	8.1	7	8.1	9.4	15.4	9.3	17	15.8	15.8	64.1	15.1	16	14.81	13.30
BP	8.8	5.7	5.8	9.5	10.7	7.9	6.5	18.6	10.5	11.5	11.3	12.1	16.1	28.5	25.5	14.1	12.69	6.41
Courtaulds	7.7	11.3		11.5	10.9	8.2	10.1	12.3	9.3	7.3	12.5	11.6	15.8	15.1	17	18.8	11.96	3.30
Toray	18.3	23.3	45.2	38.3	36.1	34.7	41.6	52.4	102.5	70	61.2	25.1	29.6	36.5	36	63.6	44.65	20.62
Toho Rayon	9.3	20.2	265.5	52.9	111.1	32.1	28.3	87.8	56	68.3	242.9	84.2	79.9	75.5	N/A	N/A	86.71	73.86
Mitsubishi Rayon	11.8	15.3	38.2	42.6	48.1	53.3	42.4	53.8	72.7	100	110.2	41.8	54.5	65.9	242.5	164.2	72.33	57.03
Asahi Kasei	16.5	14.9	36.6	22	41.9	65.4	65.4	66.2	75.6	54.6	51	29.4	24.4	41	65.2	104.7	48.425	23.90

Ratio source: Data Stream

Figure 5.3: Price-earning ratios, all producers

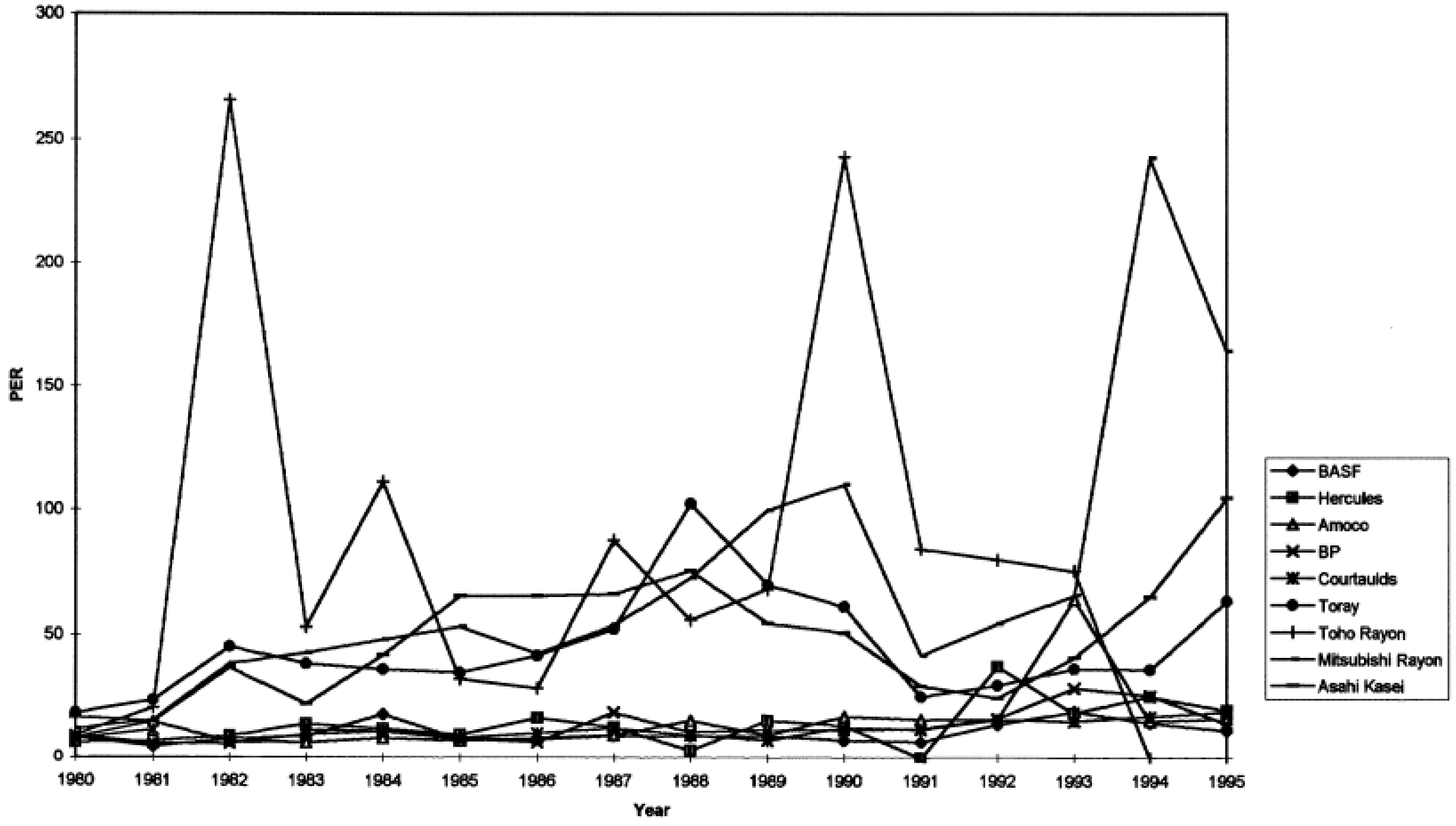
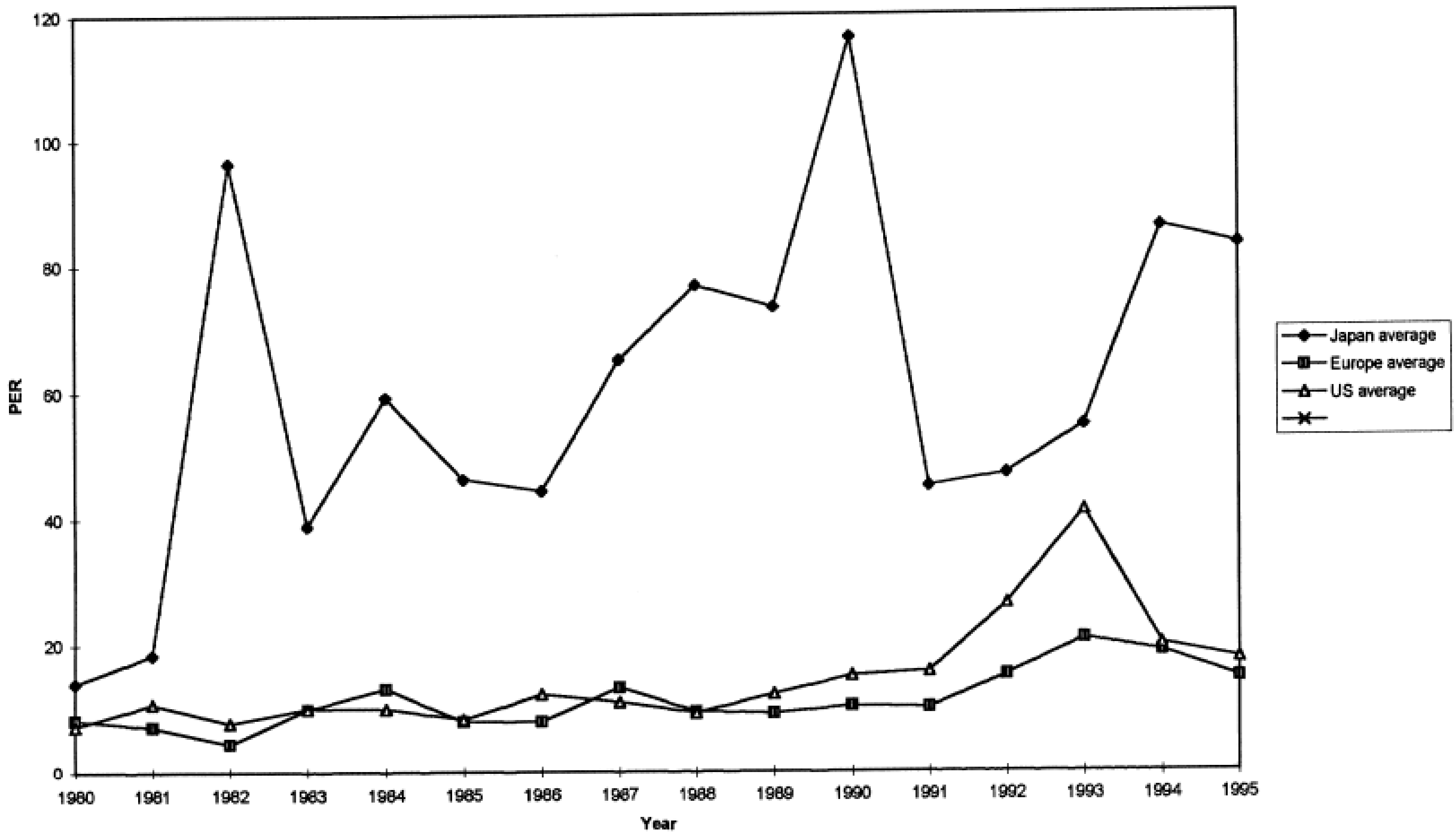


Figure 5.4: PER AVERAGES



Secondly, if we examine the variance of PER over time for each firm we see the PER shows significant **less** fluctuation in time for US and European corporations compared to those of Japan. The variance of the PER is essentially a measure of the sensibility of stock prices to short term profit, as reflected in the earnings per share. The low variance for the non-Japanese producers indicates that in Europe and the US, **short-term profit largely governs stock price**. The high variance for the Japanese firms suggests that for these firms, stock prices are less sensitive to fluctuation in short term profit.

In short, we have seen from the gearing ratios and variance in PER that the non-Japanese producers of carbon fibre have a **significantly higher dependence on equity** and a **compulsion to yield high dividends** in order to maintain share price. For the Japanese producer, the reverse holds true on both counts.

Summary and Conclusions

Overall, then, the period 1989 to 1995 has been one of transition and restructuring of the carbon fibre industry, and one dominated by a surplus capacity world-wide. We have seen a variety of industrial responses to the changing market conditions. US-based subsidiaries of European firms were the most badly affected. Although carbon fibre produced in any US-based plant technically counts as US production, the Pentagon had been reportedly "unhappy" with the number of European takeovers in such a strategic industry[132] and, when times got tough and US government agencies acted to prevent key closures, no non-US firm received government aid. Only the US-owned Hercules and Amoco were awarded the critical DARPA and ARPA awards that enabled them to continue production, in a process the trade press dubbed the 're-Americanisation' of the industry.[133] BASF, Courtaulds and the BP subsidiary Hitco all ceased production despite the substantial investment each had undertaken in response the 1987 DoD mandate.

In Europe itself, there was no direct government intervention to aid the industry and although carbon fibre capacity increased from 1300 to 1500 tons over the period, Japanese inward investment, along with the closure of Courtaulds UK plant, resulted in the percentage of European capacity actually owned by European firms falling from 80% to 25%.[134]

Meanwhile, the Japanese firms themselves pursued longer term strategies design to increase market share. Capacity was increased domestically, despite the losses incurred throughout the period, and expansion took place in both Europe and the United States.

In this chapter, we have sought to explore how and why these disparate industry responses occurred, through an examination of the forces that have driven and shaped the industry since 1990, most particularly the defence sector, the Technology Reinvestment Project and the financial governance of the carbon fibre producing firms. We have seen that throughout the 1980's, the US carbon fibre industry had had a high dependency on defence contracts, a reliance that was expected to increase in the 1990's. In conjunction with the DoD's encouraging 1987 mandate, the strong defence outlook prompted US and European producers to increase capacity in the US to met a burgeoning demand. Over the two year period 1989-1991, the three largest US-based producers, Hercules, BASF and Amoco all made substantial capacity increases (of 25, 200 and 130% respectively). Total US capacity increased by almost 50%. Over the same short period, changes in the defence environment radically affected both demand and outlook. The defence cuts dealt the carbon fibre industry a double blow with profound cuts both in immediate aircraft procurement and in future project authorisation. Extensive cuts were made in the highest intensity users of carbon fibre, that is aircraft, helicopters and missiles. More importantly, the future weapon systems for which the new capacity had been put in place were cut back, deferred, or cancelled. In short, by the time the investments of the late 1980's came into operation, the military market for which they were designed to fulfil had largely disappeared.

Keiretsu membership, as we have seen in earlier chapters, is characterised by reciprocal shareholding and close lender borrower relationships. Although it has proved not possible to uncover the exact keiretsu mechanisms, if any, employed in the carbon fibre sector, what we can say is that the ratios represented above show that empirically the Japanese carbon fibre producers possess greater long term stability and a certain immunity to market imperatives. The firms of the US and Western Europe were far more vulnerable to the dictates of the equity markets and left exposed when short term profits fell. For the carbon fibre industry, and its recent period of sustained loss and uncertainty, these factors have proved decisive.

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CHAPTER SIX:
CARBON FIBRE AND THE CONDITIONS FOR SURVIVAL IN THE ADVANCED MATERIALS SECTOR

"Any invention or discovery is a great thing, but to put it to practical use is even more important"

Masara Ibuka, founder of Sony.[1]

In the late 1970's, as John Zysman has noted,[2] economists discovered Japan. There has since existed a growing body of comparative literature examining the distinct modes of capitalism in Japan, Western Europe and the United States. Running parallel with this discussion has been the increasing interest in the relations between defence and civil technologies. In this thesis we have focussed on these themes though the lens of an advanced material, namely, carbon fibre.

Advanced materials are a seedcorn technology, described by J. Michael Bowman, the Vice President of Du Pont, as one that "feeds and enables all the large system integrators such as aerospace, construction, automotive, electronics and defense ... these are multi-billion dollar markets critical to our GNP and societal growth."[3] Advanced materials are also a classic generic dual-use technology, one whose development and fortunes have been driven by an intricate compulsion of both civilian and military interests. Finally, advanced materials is a capital-intensive industry involving long lead times, high investment requirements and uniquely close customer-supplier relations that forcibly illuminate the industrial structures in which it has evolved. Of the advanced materials, carbon fibre is by far the most commercially significant and is traded more or less world-wide. It is the carbon fibre industry, therefore, that has been the focus of this research.

Carbon fibre is a high technology sector that has undergone something of a convulsion over the period 1990-1995, as the evidence collected during the course of this research has shown. This convulsion was precipitated by a large drop in demand from the defence sector as the Cold War cessated. We have seen that this shifting macroeconomic landscape brought about marked differences in microeconomic response from the carbon fibre producers of Japan, United States and Western Europe, and have attempted to elucidate the reasons underlying these diverse corporate strategies.

In Chapters Two and Three of this thesis, we examined the technical characteristics of carbon fibre and gave an overview of its applications and markets. We also discussed the secondary literature, contrasting Anglo-American industrial structures with those of Japan. In Chapter 4, we presented the historical development of the industry up to 1989, and then, in Chapter Five, charted in some detail the turmoil of the industry over the period 1990-1995. During this time a major restructuring of the industry took place, the result being an industrial shift of carbon fibre manufacture, with capacity increases in Japan and growing Japanese control of production facilities in Europe and the United States. In Chapter Five, we also sought out the possible determinants that precipitated and shaped the consequent industrial shakeout and examined the evidence and relative weight of each. In effect, Chapter Five bridges the gap between the broader macroeconomic structures discussed earlier in the thesis and the micro-economic performance of the carbon fibre producing firms themselves.

The managers questioned during the course of this research offered two explanations as to the cross national variations in corporate response. These were the relatively high dependence of the US producers on the defence sector and the higher stability generally of Japanese firms. The empirical evidence collected during the course of this research and presented in Chapter Five supports both these claims.

Throughout its history, as we saw in Chapter Four, the development of the carbon fibre industry has been driven by a complex mixture of commercial and military interests. All the carbon fibre manufacturers reported this as a major influence on the development of the industry. At its inception, the two most significant advances in the actual creation of the new material originated in government research laboratories. It was the Japanese Industrial Research Institute that first developed fibre based on PAN, while in the UK, RAE discovered the critical processing step for the production of high strength high modulus fibre. The production technology for the manufacture of a commercial viable fibre was then pioneered at Harwell. It is worth noting that none of these laboratories was either strictly civil or strictly military in their operations.[4] The Japanese research was a collaborative venture conducted under the auspices of MITI, and the RAE already had a long tradition in civil aerospace research. When the technology was first licensed to Rolls Royce, in the mid-

1960's, UK defence spending was in a downturn while civil aerospace was booming, and Rolls Royce was primarily a civil aviation contractor. Only in the United States was development of aerospace applications almost entirely sponsored by government military research establishments. The Air Force Materials Laboratory, for example, underwrote much of Union Carbide's work on rayon, pitch and PAN based fibres.

Defence-sponsored R&D doubtless accelerated the development of applications in the US and Western Europe, but the role of the defence sector as end user was of far greater value to the industry. The defence sector was critical in nurturing and sustaining the infant manufacturing base by undertaking the higher risks and costs as first major customer. This was particularly apparent in the US, but in the UK, too, the Fellowship of Engineering describes the role of the Ministry of Defence as crucial in the early support of a indigenous carbon fibre industry,

> "Courtaulds are the principal audited supplier of carbon fibres for British military aircraft and this favoured position has certainly been of great benefit to them ... without MoD orders, Courtaulds would certainly have given up."[5]

Although we have not gone into the French case in this thesis, the position there was in fact similar. The Délégation Générale de L'Armement (the procurement arm of the Ministry for Defence) and the Ministère de la Recherche et de la Technologie (MRT) centralised French government new materials research under a joint programme. Largely through the intervention of these ministries, the then nationalised firm ELF set up a joint venture with Toray in the south of France to produce 300 tons a year, essentially granting the country self sufficiency in carbon fibre production. It is a measure of the degree of proprietary knowledge required in the management of new materials that when a national champion plant actually came to be built, the expertise of an overseas firm, Toray, was still a prerequisite, despite a decade of internal research by the French Government and aerospace sector. The MRT claims that it was in France that the first major product to be conceived in terms of the properties of carbon fibre (a helicopter rotor blade, in 1970) was developed and produced.[6]

The United States, with its uniquely large defence budget, has provided a first market for many advanced goods and industries. In the early days of carbon fibre development, the US, through its military aerospace interests, created a demand for carbon fibre far larger than that of any other national market. There is little doubt that this demand was decisive in the establishment of the US as the dominant player in the end-use advanced composite industry. The demand factor for carbon fibre in the United States was so strong it overcame the fact that the key processing patents for the technology were held by Japan and the United Kingdom.

In the early days of the industry, Japan and the UK were actually in remarkable similar positions. Each held a key patent; neither had a large immediate domestic market and for both the only significant existing market at the time was in the US. In Britain, the US aerospace industry was seen as the only serious market and there was little discussion of alternative applications. Two of the three UK RAE licensees consequently set up joint ventures with US firms (Courtaulds-Hercules and Morganite-Celanese). These tie-ups benefited the US partners enormously and served to establish a strong production base in America.

By contrast, the Japanese firms sought to create new markets for the material in sporting goods. This was a longer term strategy that resulted in the companies carrying large losses over a long period. Toray in particular was noted for its aggressive 'missionary marketing' of the new material. The result of these disparate corporate strategies was a wide geographical variation in the markets for carbon fibre that persisted throughout the history of the industry. Sports goods became the dominant application for Japanese produced carbon fibre, for which the military market was barely a few percent of total production. In Western Europe and the United States, aerospace markets predominated, of which around 50 percent were in military applications. In this way, the carbon fibre civil-military dichotomy was mirrored by distinct geographical variations in production, or, put another way, there arose a civil-military division of labour across the sector that served to differentiate not companies but continents.

The concentration on defence applications would have had a far from detrimental effect on the strength of the industry in the United States had the Department of Defense expectations of the late 1980's come to fruition. In 1987, the DoD forecast that it alone would require almost 3600 tons of carbon fibre a year by 1995.[7] At the time, US companies had the capacity to produce just half that amount. The same year, the DoD mandated that it would preferentially buy systems built from domestically sourced fibre. Once the mandate was established, Amoco, Hercules, Courtaulds and BASF all announced plans to expand or build new PAN precursor plant and all, with the addition of BP, substantially expanded their American carbon fibre production facilities. It is worth noting here that, despite the apparent market opportunity, none of the Japanese firms invested in plant in the US as a result of the Department of Defense mandate.

Hence the DoD mandate resulted in a flurry of investment and a huge jump in US-based capacity that would have paid off had the Pentagon forecasts been fulfilled and would have left the United States as not only the largest consumer but also the largest producer of carbon fibre. In fact, peak DoD usage - just over 900 tons - was recorded in 1989. The actual usage in 1995 now estimated to be just 450 tons:[8] the DoD procured 408 aircraft in 1989 but only 155 in 1995, with similar drops occurring in ship, missile and helicopter numbers.[9] The fact that carbon fibre consumption had grown at an exponential rate throughout the 1980's only served to compound the shock when, in 1990, markets fell, and fell sharply, for the first time in the history of the industry. Hence the very large excess production capacity of the early 1990's was created through a combination of overestimation of market demand and a US policy decision to create a national supplier base. The arrival on stream of the new plant coincident with the end of the Cold War left the industry in a state of severe overcapacity. Prices fell world-wide, but although the immediate outlook was bleak, midterm prospects were promising. The civil aerospace industry, in a mid-cycle downturn at the time, was set to pick up post-1995, the year in which the Boeing 777, with its high composite usage, was due its first delivery. There was little question that if companies could weather the immediate storm, there would, eventually, be a return to profit and the opportunity to amortise the recent large investments.

In the short term, however, the problems were severe. Demand was so low that half of all US plant was idled. Malaman has argued that,

> "first comers are highly protected in the supply of advanced materials, because of both technological factors and market structure. As a consequence, the shake out processes following the creation of excessive production capacity does not usually push the first-comer out of the market, because they are capable of imitating incremental innovations originated by the followers. The first-comer's general culture and experience about the materials and the processes allows such

> imitation phenomena, which was observed during the development of synthetic materials".[10]

In fact, however, in the case of carbon fibre, the industrial structure factors described above, along with the US government interventions described below, played the greater role, with the result that Courtaulds, one of the pioneer firms in carbon fibre production, was the first to abandon the industry.

Meanwhile, Japanese producers saw the troubles of the industry as an opportunity to pursue market share strategies. Despite the flat market, the Japanese firms were able to access capital for investment and thereby expand into both the US and Western Europe. Although Courtaulds was not able to support the losses of its carbon fibre operations, Mitsubishi Rayon could, allowing it to purchase the Courtaulds plant in US. The other Japanese producers also continued to invest in their domestic plant, despite the downturn in the market. Meanwhile, BP and BASF also withdrew from the industry. Courtaulds, BP and BASF all had production facilities in the US, facilities which all three firms had substantially expanded following the 1987 DoD mandate.

By 1993, the industry had reached an all time low. Prices had fallen for the third year running and no profit had been turned since 1989. “We’re in a fight for survival” remarked Jim Burns of Hercules in 1993,[11] and in the words of Charles Toyer of Toray, "Everyone had their back to the wall ... everyone was watching to see who would go".[12] The build up in capacity in anticipation of Pentagon demands and the then evaporation of this market had left the United States with a large volume of brand new and suddenly unwanted plant. The unforeseen and rather dramatic end to the Cold War had resulted in a downsizing of the defence sector that caught the entire industry off guard. Rumours began to circulate that even Hercules, the biggest defence supplier, was seeking a partner for its carbon fibre operations.

The only likely candidates for partnership with Hercules were Japanese. It was at this point that the US government acted to stabilise its domestic carbon fibre sector. The Technology Reinvestment Project was the first measure to be announced, and the one that proved to have the most immediate impact. As we saw in Chapter Five, TRP was an inter-agency programme designed to aid conversion to commercial sectors for previously defence orientated firms. Hercules and Amoco were the two most likely contenders for the big TRP composite award. Both were US-owned, US-based companies; the Pentagon had been reported earlier as unhappy over the volume of non-US owned carbon fibre production set up in the US following its mandate and had made no move to prevent the closures of Courtaulds and BP's carbon fibre operations in the United States. Hercules and Amoco did indeed win the award, amidst much discussion on the 're-Americanization' of the industry. Shortly after the award announcement, BASF abandoned the business, writing off of its new carbon fibre plant. It had been the largest line in the world and represented a huge loss for the company. With the departure of BASF, US carbon fibre supply tightened. In this way, TRP secured the immediate future of Amoco and Hercules, the two largest US-owned carbon fibre producers.

The beating of swords into plough-shares has been a topic of much discussion, largely within the literature on the interdiffusion of military and civil technologies and the debate on the general economic benefits or otherwise of defence spending. These arguments have grown particularly pertinent in the fiscal constraints and reduced threat of the early 1990’s military environment. Chesnais has argued that a large defence demand, although central to the establishment of an industry and the driver of early industrial growth can disadvantage firms later in the product cycle. In general terms, he avers, military interest in a technology leads to high levels of research investment but to short product cycles and high levels of technical and financial risk.[13] This may in fact be true, but in the case of carbon fibre the events that led up to the sharp curtailing of the defence market far outweighed considerations of business cycles and technical risk. Put another way, had the DoD expectations come to pass, the United States would by now probably possess the largest and most vigorous carbon fibre industry in the world.

Kaldor has argued that military emphasis on performance over cost inhibits technological conversion from the military to the civil sector.[14] These arguments, too, have limited application in this particular case study, chiefly because carbon fibre is an upstream, generic technology far removed from the final end product and in fact the technical changes required to convert a plant producing carbon fibre ostensibly for military aircraft to one making carbon fibre for tennis racquets is minimal. A carbon fibre line is, as we saw in Chapter Two, either high tensile or high modulus. By far the largest percentage of carbon fibre production in Europe and the United States is high tensile, including the US plants of Amoco, Hercules and BASF.[15] High tensile fibre is the type used in almost all the major applications, including most sports goods and almost all military aircraft. In Chapter Two, we saw that the strength and modulus of the final fibre are determined directly by the temperature at which the precursor is processed (if the heat treatment step takes place at 1500^{o}C, a high tensile fibre results, while 2500^{O}C degrees produces a high modulus fibre). Therefore, conversion requires at most the alteration of furnace temperature, which takes around a month to stabilise. High modulus fibre is used in space structures and high performance golf clubs. At a cost of £500/kg, this fibre type is "too expensive for fighter aircraft",[16] which is the reverse in fact of the Kaldor argument.

Alic, et al., have detailed the limits of the spin-off model as a basis for US technology policy, arguing that although US defence R&D spending is high, the diffusion of military technologies into the commercial sector has been less than the spin-off model would suggest.[17] Samuels, too, argues that the secrecy and specificity associated with military R&D impedes the interchange of commercial and defence technology.[18] Japan, in contrast to the US, is not only a leader in the design and manufacture of dual use technologies but also fully integrates civil and military industrial production. Samuels further argues that the Japanese perception of technological capability as central to national security has driven Japan to a programme of "commercial technonationalism"[19] Similarly, according to Reppy, many barriers to diversification from military into commercial markets are organisational rather than technical have their origin in culture specific features of the defence sector.[20]

We find these arguments have a very strong relevance in the carbon fibre sector. For example, the development of a civilian carbon fibre base in the United States has been hampered by the many controls and restrictions placed on the industry. Carbon fibre is on both the Commodity Control List of the Department of Commerce and the DoD's critical technology list. This makes it subject to a complex regime of export control legislation and has limited the development of non-defence applications. As Thomas R. Goldberg observed at an international advanced composite conference in 1991,

> "Because much of the US investment in advanced materials is in military research and hardware, export controls limit the availability of data to US firms engaged in the development of commercial applications. By contrast, our allies enjoy greater freedoms to market advanced products around the globe that in some cases are comparable or superior to those developed in the US. The result

> of these circumstances is one we are witnessing today - the loss of the US technological-industrial lead in advanced materials."[21]

As we saw in Chapter One, close producer-user relations are characteristic of new materials, and carbon fibre is no exception. The first Boeing 777 rolled off the production line more or less on schedule in the summer of 1995, Boeing having first started work with Toray on carbon composites for the project five years ago in 1990. In order to work still closer with Boeing, Toray built an entire new plant in Washington State to service the Boeing contract. Such relationships, so characteristic of the advanced materials sector, can take years to establish and can hinder the entry of new players into a sub-sector of the industry. It is these types of organisational features, in conjunction with the general overcapacity of the industry, that restricted the movement of the defence suppliers of carbon fibre into civilian markets.

The second strand of argument raised by the managers, that is, Japanese firms are more stable generally, was examined in Chapter Three at a macroeconomic level, and in Chapter Five, at the level of the firm. Early neo-classical discussions of economic growth and change assumed that, economically speaking, nations shared fundamental similarities of market structure. Differing market modes, it was argued, could not co-exist as eventually free market efficiency would drive out less successful economic systems. International competitiveness was discussed only in terms of comparative advantage, exchange rates and basic cost and price indicators.

Porter argues that the competitive advantage of a nation is determined by four broadly based attributes; namely factor conditions (such as the skill mix of the labour pool and available existing natural resources), domestic demand conditions, the existence or otherwise of related and support industries and firm strategy, structure and rivalry.[22] Similarly the OECD Technology-Economy programme attempts to bridge the gap between competitiveness at the level of the firm and the macroeconomic competitiveness of national economies. Although the OECD examines the failure of "classical" competitiveness theories concerning price, costs and exchange rates and argues that "factors related to technology [such as national systems of innovation and military R&D] ... are empirically found to have played more important roles than cost or price",[23] it offers no further explanations other than those rooted in Porter.

However, despite the globalisation of capital markets, national rates of saving and investment and internal capital market structures continue to differ widely between nations and, as technological competitiveness becomes the *sine qua non* of the industrial strategies of advanced countries, notions of capital and labour costs are no longer capable of fully explaining shifts in market share and the changing patterns of international trade.

Porter's set of analytical techniques to describe and assess competitive ability (and similar approaches such as that of Dicken[24]) are thought by some (Toshiro Hirota, for example[25]) to be reductive to the extent that the more qualitative factors such as culture or ideology that may also create or impede competitive advantage are overlooked. These factors are especially pertinent to non Anglo-American corporate systems, such as that of Japan. In the US and UK, legal institutions are formally separate from the official apparatus of the state and the firm may be described as an autonomous legal and financial entity facing largely anonymous and impersonal market pressures.[26] In East Asia, however, these separations are not evident (and never were historically). The result is that business transactions in these countries are far more personal and the role of formal contract relatively unimportant.

East Asian nations commonly refer to themselves as post-Confucian economies[27] and do appear to possess a common set of basic business axioms. Strategy and planning, for instance, forms one of the great departments of post-Confucian thought as is the notion of '**ie'** or 'the group'. We have seen these broader themes expressed explicitly in the case of carbon fibre through the structured and committed policies adopted by the Japanese carbon fibre producers and the influence of the keiretsu group.

Nishida[28] and others argue that such concepts of 'economic culture' have had a profound influence on the industrial development of nations[xiv]. Recent studies have revealed the routes by which business strategies and systems follow country specific patterns, and suggest that the structural characteristics of the domestic economy exert a profound influence on corporate behaviour. In capital intensive and technologically advanced sectors in particular, the extent and manner in which firms compete, and their strategic preferences, vary considerably between national business systems.[29]

[xiv] For example, in Japan the 1947 Law for the Elimination of Excessive Concentrations of Economic Power was introduced by the Occupation as a sort of Japanese version of the Glass-Steagall Act, designed to trust-bust the zaibatsu. In fact it had virtually the reverse effect in that it precipitated the formation of the keiretsu group system.

Carbon fibre is a primary example of such a sector, and in many ways antithesis of the classic free market product. Its production requires a high degree of proprietary knowledge, close and long term user - producer co-operation. a large technological input, few natural resources, long lead times and considerable sunk investment. There are high barriers to entry, it is capital intensive and possesses great economies of scale. (The minimum size for a commercially viable carbon fibre plant is 350 tons, and under 1000 tons is considered small.[30] New plant takes around three years and several million dollars to construct.[31]) Defence interest in the sector is intense.

As we saw above, both Japan and the UK were strong in the early technical development of carbon fibre. However, the subsequent implementation of this innovation followed quite divergent paths. UK firms and, to an even greater extent those of the US, concentrated on meeting military requirements. This became their key market. In contrast, Japanese firms actively pursued and developed new market sectors and worked vigorously to maintain a highly competitive technological edge. With the end of the Cold War, the defence market contracted and the consequent industrial shift has been the focus of this thesis.

In Chapter Three, we outlined the differences in industrial structure at a macro-economic level in Japan and the United States.[32] One of the most striking contrasts is the variation in rates of saving and investment. The US saving rate has rarely exceeded 10% of the Gross National Product but may reach over 25% in Japan.[33] Furthermore, would - be American borrowers must compete for capital with an enormous government debt for capital. The US budget deficit drives up interest rates for the private sector in the capital markets and consequently US rates of investment had been consistently lower than those of Japan.

Japanese industrial structure was also closely contrasted with that of the United States at a microeconomic level. In our examination of the financial structure of corporations, we saw that Japanese firms have a relatively high debt-equity ratio, that is, they have a pronounced preference for raising finance through borrowing rather than through the issuing of shares. All else being equal, the more stable the firm, the higher the optimal debt-equity ratio. We also saw that Japanese firms pay out far less of their profit in dividend, but despite this the price-earnings ratio (which is the key measure of investor confidence in a firm) remains far higher in Japan than virtually any other country. (In late 1995, the Japanese price-earnings ratio average stood at around 120, compared to 20 in the United States and just 15 in the UK.[34])

We have also seen how the line between bank and firm is often blurred in Japan and that, through the keiretsu system, companies are locked into a complex lattice of cross-shareholding and implicit agreements orchestrated by the main bank. Although there is a negative correlation between keiretsu membership and profit, keiretsu firms show a lower variance in profit fluctuation, that is, high profit is sacrificed in favour of company stability. As Nakatani has observed the keiretsu system acts as a sort of mutual insurance scheme, insulating firms from fluctuations in the exogenous environment.[35]

In the US, the financial markets are comparatively fluid. Theoretically, this increases the efficient allocation of finance in that scarce available capital is distributed to those projects, be they long or short term, that provide the highest return measured in terms of the present discounted value.[36] Porter,[37] however, has argued that this argument is flawed as in practice a 'credibility' gap exists, creating pockets of underinvestment. An underinvested project typically possesses high technological costs, a slow to mature return, illiquid investments, and benefits that are diffuse or difficult to evaluate. Advanced materials fit Porter’s criteria on every point.

In Chapter Five, we looked at the financial ratios and capital structure of all the major carbon fibre producers to see how well they fitted the macroeconomic financial models presented above. The Japanese firms all demonstrated significantly higher levels of gearing than the other carbon fibre producers and slightly lower levels of profitability. The non-Japanese producers also possess far lower price-earnings ratios; this means they are under a greater compulsion to deliver short term profit in order to maintain share price. Finally, and perhaps most significantly, the variation in price-earnings ratio was over three times greater for the Japanese firms. If share price closely follows profit, the variation is low. This is the case for the non-Japanese producers. For the Japanese producers, in contrast, profits have little influence on share price, giving the firms a far greater flexibility to retain earnings for investment and enables firms to plan long term even in times of financial distress.

Drawing on various sources, the keiretsu affiliation of the Japanese producers was examined in Chapter Five and Appendix III. Mitsubishi Rayon, Toho Rayon and Toray were all found to be core keiretsu firms, with seats on the presidential councils and very close financial ties to their respective groups. Asahi Kasei proved to be more of a rogue element, with personal ties to one keiretsu, DKB, but financial relations with another, Sumitomo. Dodwells, the definitive English-language source on the subject, does not classify Asahi Kasei as a keiretsu firm at all and Asahi Kasei itself specifically told the author that it had no keiretsu affiliation.[38]

Keiretsu membership is a problematic subject in Japan and despite many discussions with the companies, it was not possible to uncover the specific keiretsu mechanisms that came into play during the upheavals in the carbon fibre industry. However, the data collected for each firm indicate that all the Japanese firms possess financial ratios geared toward long term stability rather than short term profit. It is not unlikely that the keiretsu standing of Mitsubishi Rayon, Toray and Toho Rayon, in conjunction with the national financial environment in Japan, did enable these firms to survive the turbulence of the early 1990's and, indeed, by buying up plant when cheap, to turn the problems of the industry to their advantage. Asahi Kasei was able stay with the industry through almost four years of losses and world-wide overcapacity, outlasting the British firms BP and Courtaulds and the US-based German producer BASF. However, in 1994, after the TRP awards had been announced and it was clear that Amoco and Hercules would thus be able to continue production, there were no other likely capacity reductions on the cards and Asahi Kasei announced plans to withdraw. Despite the troubles of the sector, the industry still described itself as 'a little surprised' at the Asahi decision.[39] It is currently believed that Mitsubishi Rayon plan to buy up the Asahi plant, which will thus remain under Japanese control.[40] In short, the core keiretsu producers were best able to ride out the trading conditions of the early 1990’s, and even the non-keiretsu Japanese firm, Asahi Kasei fared better than its European counterparts.

Finally, while all the industry respondents put forward the two explanatory factors raised above, none invoked a third factor which has become evident during the course of this thesis; that is, the role of direct US government intervention in the preservation of a US-owned composite industry. While the US government actively intervened to maintain an industrial capacity in the US, there was no equivalent government intervention to benefit either Japanese or European firms.

The Technology Reinvestment Project was a stop-gap measure that tided over the US-owned firms while other steps could be brought into play. The Clinton Administration employed two subsequent policy instruments to bring the new commercial carbon fibre sector into equilibrium. On the same day as the TRP announcement, the President unveiled a second programme that was to dramatically improve the fortunes of the sector in the mid-term.[41] This was The Clean Car Initiative, a new inter-agency project led by the Environmental Protection Agency and the Departments of Energy and Transportation. The Clean Car was to be powered by compressed natural gas, contained in an aluminium lined container overwrapped by one of three competing materials, steel, glass fibre or carbon fibre The industry was at first bemused. "I don't know what the hell it means"[42] said one carbon fibre representative and business press, initially sceptical, charged that,

> "The people in charge of developing this technology have no clue as to how to design a product to use this technology." [43]

However, the clean car was to develop into a surprisingly high volume market. The Los Angeles South Coast Air Quality Management District, concerned about its smog, placed a $16 million order and other US public transport systems quickly followed suit.[44] In 1994, however, after two rather unfortunate explosive failures of trial vehicles, the Highway Traffic Safety Administration regulated that carbon fibre cylinders should fulfil additional safety standards on the grounds that carbon fibre was an 'unproven technology'. Had this regulation come into force, the increased cost would have effectively ruled out carbon fibre as a contending material.[45] The industry appealed the ruling which was overturned the following December,[46] and carbon fibre became the material of choice. There are currently 40,000 (mostly fleet) vehicles running on compressed natural gas in the US, and over a million world-wide.[47] The demand for carbon fibre for these cylinders is currently so high that every carbon fibre producer is now working flat out and shortages have been reported world-wide in almost every sub-sector of the industry. Forecasts also strong, with exponential growth expected over the next few years (Table 6.1). Furthermore, in sharp contrast to the early 1990’s, forecasts are now revised upwards rather than down.[xv] Virtually all this new growth is to fulfil the emergent demand for carbon fibre from the manufacturers of natural gas.

[xv] For example, in 1994, Toray estimated that total global consumption would be 7,815 in 1996, 8,640 in 1997, and 9,510 in 1998. In 1995 the corresponding figures were increased to 9,780, 11,640 and 13,340 respectively.

Table 6.1: Pan-Based Carbon Fibre Consumption Forecast, 1995 (tons/year)

		1995	*1996*	*1997*	*1998*
USA	**Total**	**3605**	**4180**	**5460**	**6590**
	Aerospace	970	100	1210	1220
	Sports	880	910	930	950
	Industrial	1755	2270	3320	4420
Europe	**Total**	**1440**	**1580**	**1730**	**1900**
	Aerospace	445	470	520	570
	Sports	370	390	410	430
	Industrial	625	720	800	900
Korea/ Taiwan	**Total**	**1680**	**1800**	**1920**	**2060**
	Aerospace	10	20	20	20
	Sports	1630	1710	1800	1890
	Industrial	40	70	100	150
Japan	**Total**	**1880**	**2220**	**2530**	**2790**
	Aerospace	70	100	120	130
	Sports	1060	1090	1120	1150
	Industrial	750	1030	1290	1510
Global	**Total**	**8605**	**9780**	**11640**	**13340**
	Aerospace	1495	1590	1870	1960
	Sports	3940	4100	4260	4420
	Industrial	3170	4090	5510	6980

Source: Toray[48]

The military-civil conversion of the industry was further aided by a third government initiative. In summer of 1994, the Defense Secretary Bill Perry announced plans to overhaul the DoD's 31,000 military specifications and standards. The Pentagon document, entitled Blueprint for Change states, "The military specification and standards process is obsolete. It was not structured to deal with technology cycles that are measured in months rather than years or decades".[49] The Department of Defense estimates that just 17 percent of US military purchases are based on commercial standards. The administration now plans to reverse the situation such that 17 percent of future contracts will be based upon military specifications.[50] Formerly, a waiver was required for DoD to use commercial standards. Under the Perry plan, a waiver will be required for military specifications to be employed. It is widely believed that this measure will gradually but profoundly aid the establishment of a more robust commercial carbon fibre sector in the US. As John Banisaukas of Amoco products commented on the announcement,

> "The lack of standardisation in the aerospace industry has been a major barrier to the increased use of composites ... in some cases designers have actually foregone the advantages of composites and continue to use other materials because of qualifications difficulties."[51]

In these ways, US government policies of removing barriers to conversion and actively creating new markets through the legislative process, have enabled the American carbon fibre industry, at least, to survive more or less intact. Indeed, the DoD recently announced that although,

> “the [polymer matrix composite] industrial base is restructuring because of declines in defense spending, ... increasing commercial applications will soon offset military sales declines ...[and]... the technology industrial base is, as of now [January 1996], adequate for future military requirements.”[52]

To conclude, over the period 1990-1995, the entire carbon fibre industry was running at a loss. The coincidental arrival of new plant and onset of disappearing markets in 1990 had left the entire industry in a rather precarious position. The earlier certainties of the military markets had evaporated, and there was no hope of recovery in the short term. In the midterm, however, prospects, though still uncertain, were fairly bright with civil aerospace looking set for a upturn post 1995. In short, for those companies able to ride out the short-term upheavals and five years of losses, the outlook was promising. The Japanese producers had the stability and financial ratios to ride out the storm, and indeed, turn the troubles of the industry to their advantage. The firms of the US were directly aided by intervention by a government concerned about the stability of a strategic material industrial base. The European producers, however, had neither the direct government support nor the industrial environment to continue trading in the turbulent market conditions. Consequently, these were the firms that lost market share.

This thesis demonstrates that both the Japanese and US firms succeeded in maintaining market share throughout an unstable and volatile macroeconomic environment. However, a close examination of the data has revealed that while the Japanese producers pursued consistent, proactive, expansionist investment strategies throughout the period, those of the US manufacturers were, in contrast, incremental, episodic and continuously reactive to market dictates and government interventions. This is the central difference distinguishing the investment decisions of the carbon fibre producers of Japan and the US.

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APPENDIX I
Company Profiles

We present in this appendix profiles of the major extant carbon fibre producers, plus BASF and Asahi Kasei, who both abandoned production in 1994. For each firm, we will first examine the development and current status of their respective carbon fibre activities. All the firms are large, diversified companies and carbon fibre production typically represents just a few percent of total sales. For this reason, although carbon fibre is perceived as a high technology product, its production is not quantified in annual reports and scarcely merits more than a sentence. Hence, most of the information in these sections was gathered through visits to the carbon fibre divisions and subsequent correspondence. Further information relating to the carbon fibre industry is derived from the trade press, including *Japan Chemical Week*, *Chemical Week*, *American Metal Markets, Plastics Industry News* and the *Nikkei Weekly*.

Hercules, USA

Background

Total Assets: 3653.2 million dollars
Net sales: 3091.7 million dollars
Sales composition: Chemicals 66.5% (paper, textiles, resins, food gums)
Aerospace 27.2% (solid propellant rocket motors, electronic equipment, ordnance and powders)
Carbon fibre produced at Bacchus, Utah, under the brand name Magnamite

Source: Hercules Annual Report, 1993

In 1912, a Delaware judge ordered that E.I. du Pont de Nemours, a firm that controlled two thirds of all explosives production in the United States, be broken up. Hercules was one of the two new companies thus formed. The new business was set up complete with a number of explosives factories and a $5 million government "loan" and turned a profit in its very first year. Hercules grew quickly, its early years marred only by the loss of its Hazardville plant, which exploded in its first month of operation. Between 1915 and 1917, Hercules exported 46 million pounds of powder to Britain and, by the Second World War, was the largest producer of naval stores in the US, the third largest producer of explosives and managing six ordnance plants for the US government.[1]

Although there was some diversification into petroleum products after World War II, Hercules' defence interests were regenerated by the Korean War and the DoD Cold War aerospace programme. Between 1955 and 1963, Hercules sales doubled, largely due to a series of government contracts, and throughout the Vietnam War, the firm supplied the US government with rocket fuels, anti-personnel devices, Agent Orange and napalm. These products accounted for 25% of Hercules' profits at that time.[2] All in all, the company estimates it has sold over a million rocket motors for tactical missile systems, including motors for the Minuteman, Honest John, Polaris and Trident[3]

Hercules expanded rapidly through both domestic and overseas acquisition throughout the 1960's, but its petro-chemical interests left it vulnerable to the oil shocks of the early 1970's. The company subsequently reduced its dependence on commodity chemicals and became a supplier of higher value added chemical products, such as films and other speciality plastics.

It maintained its defence interests and in 1984 was reorganised into three separate divisions, the Hercules Speciality Chemicals Company, Hercules Aerospace and Hercules Engineered Polymers.[4]

Carbon Fibre Activities

We now detail the key points in the development of Hercules' carbon fibre operations. In **1988,** within a year of the new DoD regulations on the domestic sourcing of PAN (the chemical precusor for carbon fibre), Hercules and the Japanese firm Sumitomo Chemical began construction of a $70 million, 1700 ton per year PAN precursor plant in Decatur, AL. to be named Hispan.[5] Previously, Hercules had imported all its PAN from Sumika-Hercules, a Hercules/Sumitomo joint venture in Japan. The company also completed an expansion project to increase its carbon fibre capacity at Magna to 1400 tons a year and demonstrated a prototype multi axis computer controlled fibre placement machine to NASA, DARPA and other government bodies. Essentially, the machine automated the moulding of composites for aerospace applications and cut (the very high) costs previously associated with the manufacture of complex composites shapes. The new process cut the process time in half and required only one operator to make a composite aircraft wing compared to the twenty operators required previously. The demonstration project was a prototype military aircraft. It was announced that the machines would be scaled up for the commercial production of volume shapes.[6]

In **1990** Hercules wrote off $323 million in aerospace expenses, of which around $100 million was non-recoverable, after under-bidding a series of missile contracts. All in all, the aerospace division reported a $256 million loss. The company decided to commit to a number of core businesses and sell several others. Carbon fibre was one of those “with a future” kept by the company. "The object now is to get business back to a 10% return," said the CEO, David Hollings, predicting that Hercules would recover its historical 13 to 14% return on equity by 1993.[7] In June 1990, Hercules and Sumitomo Chemical opened the 50/50 joint venture Hispan, giving Hercules and Sumitomo a combined PAN precursor capacity of 5000 tons per year.[8] In a bid to access EC markets, Hercules set up a joint venture in **1991** to manufacture carbon fibre and composite materials in Southern Italy. The new firm, Technologie d'Avanguardia e Materili Avanzati or TAEMA, was a collaboration of Hercules (25%), the Italian engineering firm Bat (45%) and the Dutch holding company HNR Investments (30%). The initial capitalisation was 13.5 billion lire.[9]

The same year, the company began to approach possible buyers, including Japanese carbon fibre producers with a view to selling its US carbon fibre operations[10] and in **1992** Hercules officially announced it was seeking a partner for its carbon fibre business.[11] In August 1992 the *Chemical and Engineering News* reported that Hercules had come close to finalising a deal to sell part of its carbon fibre and composite business.[12] However, in October **1993** Hercules was named as part of a consortium, funded by the Technology Reinvestment Project to adapt advanced materials for use in bridge construction and rehabilitation.[13] The same year, *America*, a yacht manufactured from Hercules carbon fibre, and a high profile project for the company, won the America's cup.

In November **1994**, Hercules divested its structural materials business to Alliant Technology Systems in Minnesota, but retained its carbon fibre production facilities in Utah. Group director, Robert C. Eixenberger noted that 'Hercules is working on more non-aerospace projects now [than a few years ago]'.[14] By **1995** Hercules had completed the sale of its Aerospace business to Alliant Technological Systems Incorporated for $300 million plus 3.86 million shares of newly issued Alliant stock. It still has partial control over the business through its 30% stake in Alliant.[15] In February **1995**, the carbon fibre precursor joint venture Sumika-Hercules that had “relied on US military business” was dissolved.[16]

Commentary

Hercules has had a long history in composite production. In the 1950’s it became something of a pioneer in composite manufacture with the opening of its Youngs Development Laboratories. This was a research centre which specialised in the manufacture of glass fibre reinforced rocket case motors. Hercules was responsible for the first filament wound composite cases for space booster use. These cases were also subsequently used in strategic and some tactical missile systems such as Polaris. In 1969, the UK firm Courtaulds announced an agreement whereby Hercules was guaranteed an exclusive right to sell Courtaulds carbon fibre.[17] (The two companies had previously collaborated on a joint venture to manufacture cellulose acetate.) By the mid-1970’s, Hercules had its own small plant manufacturing carbon fibre itself.

By the late 1980's Hercules' carbon fibre operations were very strongly orientated toward defence. Historically, it had very close links with the DoD and at the time operated two US government owned ammunitions plants. 100% of Hercules' aerospace carbon fibre needs were supplied by the composite division, which also directly supplied NASA, the DoD and prime contractors. Hercules' aerospace activities were themselves largely military. The table below shows the breakdown of the division's sales:

Hercules Aerospace Sales By Market Segment

	1989	***1988***	***1987***	***1986***
Defence	83%	84%	86%	83%
Civil	6%	7%	6%	6%
NASA	1%	1%	2%	2%
All Other	10%	8%	6%	9%

Source: Hercules Annual Report, 1989

In response the 1987 DoD directive, Hercules invested heavily in its carbon fibre operations, building a new PAN precursor plant and considerably increasing its carbon fibre capacity. In 1989, the company commentated,

> "Hercules has carefully evaluated its programs in light of the decreasing defence budget environment, and believes that our programmes are well positioned and that earnings growth will occur as the programs enter the productive stage."[18]

Things were looking bleaker by 1992. Material segment sales had been in decline for three years. Hercules tried to sell its carbon fibre operations but the global overcapacity made it impossible for the company to sell outright. The aerospace division reported a further $3 million dollar loss. Even the company report was struggling to find a positive tone,

> "Composite products continues to feel the impact of cutbacks by the US DoD and industry overcapacity ... Net sales [of the materials segment] decreased $21,079 in 1992, principally due to the termination of a carbon fiber supply contract in April 1992 ... composites were adversely affected by DoD cutbacks [and] continue to generate losses from operations. Net sales in 1991 were negatively

> affected by the disposition or closure of several operations and DoD reductions and stretch-outs."[19]

It was at this point that DARPA stepped in, creating a series of federally funded consortia under the Technology Reinvestment Project to encourage dual use applications for advanced composites. This interventionist measure safeguarded Hercules' composite operations over the short term. In 1993, Hercules' second largest American rival, BASF closed its carbon fibre operations, reducing the global overcapacity by 14% and US capacity by 30%. Prospects began to look much brighter for Hercules. Although composite products was still "under performing", the company declared that "in three to five years, carbon fiber is going to be a major industry in the United States and on a global basis."[20] The attempts to divest the company of its carbon fibre operations ceased and the selloffs that had looked so likely the previous year called off. Indeed, when Hercules eventually sold most of its Aerospace division in 1995, its carbon fibre operations were actually retained.

Amoco, USA

Background

Total Assets: 28,486 million dollars

Total sales: 28,617 million dollars

Sales composition: Crude oil and oil and gas products 88%

Commodity Chemicals 8%

Speciality Chemicals 4%

Carbon fibre produced at Greenville, South Carolina under the brand name Thornel.

Amoco is a large US petroleum company, with over 80% of its revenues won from oil and gas production. It is the largest private owner of North American natural gas reserves and the leading North American natural gas producer. The remainder of Amoco's revenue comes from its chemical activities, which are split into two divisions, commodity speciality chemicals. Amoco is the world's largest producer of purified terephthalic acid (PTA), the polyester precursor and is also a major producer of polypropylene, paraxylene (the feedstock for making PTA), polypropylene and olefins. These sorts of commodity chemicals are closely tied to the general chemical business cycle and Amoco's chemical earnings have been low since the beginning of the 1990's. Amoco is a relative newcomer to carbon fibre production. Carbon fibres are produced within the firm's speciality chemicals division.

Carbon Fibre Activities

In **1985** Amoco entered negotiations with Union Carbide to acquire their engineering polymers and advanced composite business. The acquisition included Union Carbide's carbon fibre plant in Greenville, South Carolina.[21] The acquisition was completed in **1986** at an approximate cost of $200 million[22] and a new subsidiary established, Amoco Performance Products Incorporated, to manage the company's engineering polymers, carbon fibres and advanced composite business.

The following year, the company introduced two high strength, high modulus fibres of the sort used in aerospace applications. Prior to the 1987 DoD directive, Amoco was the only US company capable of manufacturing PAN precursor. However it was not at the time a qualified military supplier (although it had started the process of gaining qualification).[23] As a result of the directive, in **1988**, construction of a second carbon fibre plant began. The company announced an increase of 13% in sales of carbon fibre and advanced composites.[24]

The same year, Amoco transferred its pitch-based carbon fibre production from a developmental facility to a newly installed full scale commercial production plant. This type of carbon fibre is extremely expensive and designed for use in very high value added military aerospace applications.

In **1989,** production capacity of high performance pitched based carbon fibre was further expanded "to meet demand ... in aerospace and defence applications".[25] Amoco's sales of carbon fibre and composites increased a further 8%. Construction of the second PAN carbon fibre plant was completed, increasing capacity by 540 tons.[26] Production started at the new plant in **1990**. The company announced that the carbon fibre and composite "business is expected to achieve substantial growth in the 1990s".[27]

In **1991** Amoco Performance Products was "realigned" to reflect the new, lower expectations for military demand. The company reported

> "The carbon fibre composites business was downsized ... we are continuing to incur significant development costs."[28]

In addition to the downsizing, the company ceased production of carbon fibre entirely for several months at the end of 1991. In **1992,** Amoco described the defence industry as a,

> "major customer for carbon fibres, but at significantly lower levels than anticipated when we entered the field. Consequently, we are cutting costs and seeking profits from civilian applications such as commercial aircraft."[29]

In its annual report of **1993** Amoco commented that is had,

> "refocused this [carbon fibre] product line through cost cutting and divestment of our advanced composite business"[30]

The business prospects of Amoco carbon fibre were hugely improved the same year through the Technology Reinvestment Project and the decision by BASF, Amoco's second largest rival to close its carbon fibre operations and in **1994** Amoco announced plans to purchase BASF’s idled 900 ton a year carbon fibre line at Rock Hill, South Carolina by the end of the year. The deal did not include the two other BASF fibre production lines. The Rock Hill line "will be operated as a satellite facility at a relatively low cost".[31] The company increased PAN precursor production in Greenville and trucked the additional PAN to Rock Hill for processing to maintain the high proportion of US produced PAN based fibres required by the DoD guidelines.

Commentary

Amoco was the last of the big three American carbon fibre producers to start production and the last to gain qualification from the military. As a result of the 1987 DoD mandate, and in anticipation of the increased defence demand, Amoco built a second carbon fibre plant in 1988, which it expanded the following year. Amoco supplied the DoD with carbon fibre brake pads for the F-16, the skin of the B-2 bomber and was in the process of being evaluated as one of suppliers of carbon fibre for the primary airplane structure of the Advanced Tactical Fighter. As we have seen earlier, by 1991 it was clear that this project would be cut back, a decision that hit the primary supplier, BASF very hard. The B-2 bomber programme has been limited to 20 operational craft and one test aircraft.[32]

BASF's decision to abandon the carbon fibre business effectively cut US capacity by almost a third and Asahi Kasei's withdrawal from the industry further tightened the global overcapacity. As we have seen, Amoco's carbon fibre operations were struggling during 1991, 1992 and 1993. However the TRP awards reawakened Amoco's interest in the sector. There is a general belief in the industry that market for structural composite may start to recovery with the new applications in the automotive sector. It would appear that with its current investments in its domestic capacity of PAN precursor and its purchase of the BASF line, Amoco shares that belief.

Toray, Japan

Background

Sales 599,160 million yen

Total Assets 821,814 million yen

Sales Composition: Polyester fibres 31%
Nylon 15%
Other Fibres 10%
Plastics 27%
Chemicals 6%
New operations 12%

Carbon fibre produced at Ehime, under the brand name Torayca

Toray was established as a rayon manufacturer in 1926 by Mitsui and Co. The company has since grown into a large business conglomerate with a extensive scope of sales including synthetic fibres, plastics, chemicals, electronics, medical products and pharmaceuticals. The company remains one of Japan's largest synthetic fibre manufacturers, with fibres and textiles accounting for just under half its total sales. The company began production of acrylic fibre in 1964, and began carbon fibre production (which uses the same monomer) in 1971.[33]

Carbon Fibre Activities

Carbon fibre is produced at the company's Ehime plant under the brand name *Torayca*. Commercial scale production of carbon fibre started at Ehime in **1971.** In **1973,** at the inception of 'carbon boom' in sports applications, Toray began exporting carbon fibre, mainly to the US and in **1977** Torayca carbon fibre became the first to be qualified by Boeing (for use in secondary structures).

Capacity at Ehime increased to 1250 tons/year in **1982** and in **1984** Soficar was established in the south of France, with an annual capacity of 300 tons. Toray assumed managerial control of Soficar in **1988**.[34] In **1990** Boeing qualified a Toray prepreg for use in primary aircraft structures[35] and placed 80 billion yen worth of orders.[36] The same year, Toray doubled carbon fibre capacity in Japan to 2250 tons per annum.

In **1992** Toray transferred its Shiga operations to Ehime, thus consolidating its Japanese prepreg activities in preparation for volume production.[37] Toray also acquired Composite Horizon, a carbon fibre end product manufacturer for $5.5 million.[38] Later that year, a 360 ton second line was completed at Soficar. Production began the following January.[39]

Commentary

In 1979, Toray licensed its carbon fibre production technology to Union Carbide in the US. Union Carbide subsequently sold its carbon fibre interests to Amoco to raise cash after Bhopal. Toray also sought to gain a foothold in Europe by setting up a joint venture with Elf Aquitaine, named Société des Fibres de Carbone (Soficar), to produce T300 in Abidos in the south of France. In December 1988, Toray assumed managerial control with a 70% stake and in 1992 completed a 7.5 billion yen production unit that essentially doubled Soficar's capacity to 700 tons. The new line makes T800, a high strength fibre qualified for use in the EFA, the ATR42 and ATR72.[40] Other applications will include premium sporting goods such a golf club shafts.

In April 1990, a Toray prepreg of T800 and 3900-2 was qualified by Boeing for use in primary structural components. Toray increased its carbon fibre capacity at Ehime by 50% the same year. However, Toray suffered badly from the world wide fall in carbon fibre prices during 1991-92, losing over 6% of its market share.[41] In 1993 the company's carbon fibre sales slipped from 23 to 19 billion yen[42] and fell again to 9 billion yen in 1994.[43] In November 1993, Soficar implemented 30,000 hours of temporary layoffs to avoid redundancies.[44]

Nevertheless, the company continued to invest in its composite operations. In May 1992, Toray announced that a 100% owned subsidiary - Toray Composites America Inc - would be set up in Frederickson, Washington for the production and sales of prepreg, primarily for the nearby Boeing Company Commercial Airplane Group.[45] Toray already supplied carbon fibre for use a secondary structures in the Boeing 737, 747, 757 and 767 and the in the Boeing 777 carbon fibre composites are used in the vertical fin and horizontal stabilisers, as well as the floor beams, trailing edge flaps, rudder, nacelle and cowling, with a total composite weight of 8000 tons per plane.[46] According to Boeing, around 120 777 are on order, including orders from launch customer United Airlines (34 craft with an option on 34 more) All Nippon Airways (which has placed orders totalling 25 of the aircraft).[47]

Toray originally supplied Boeing with prepreg from its Ehime plant. It is now expected that almost all the prepreg now supplied to the US from Toray will be replaced with production from the new plant. Toray's investment is expected to total 4.5 billion yen (US$35 million) and projected sales are US$38 million by FY1996.[48] Toray is currently the sole qualified supplier, however the possibility that Boeing will consider second sourcing its prepreg supply, although unlikely, cannot be ruled out.

Toray for many years was the world's largest producer of carbon fibre (its current capacity is 2250 tons a year) and the company's baseline product, T300, has become a standard for the industry. Around 60% of Toray's carbon fibre output is exported (mainly to the US).[49] However, the company is now seeking to expand its production of final carbon composite products for sale in the Japanese domestic market. Toray is strong in the production of composites for aerospace applications (although it is not a direct DoD supplier) and sees aerospace as the major area of growth for carbon fibre composites.[50] Toray’s main centre of production of carbon fibre remains at the company's Ehime plant in Japan.

Toho Rayon, Japan

Background

Total Assets: 81,172 million yen

Total Sales: 75,500 million yen

Sales Composition:	Acrylic Fibres 32%
	Rayon 21%
	Cotton Yarns 27%
	Raw Silk 2%
	Chemicals and others 17%

Carbon fibre produced at Mishima, under the brand name Besfight

Toho Rayon is a medium sized spinner of acrylic, rayon and cotton yarns.[51] Like Toray, carbon fibre activities began as a way of using excess acrylic fibre capacity. Carbon fibre is produced under the brand name Besfight at Toho's Mishima plant which also produces acrylic fibre, carbon fibre precursor, activated carbon fibre and carbon fibre composites.

Carbon Fibre Activities

Toho Rayon commenced carbon fibre production in the early 1970's. In **1982** the firm's carbon fibre technology production technology was licensed to Akzo in the Netherlands and in **1986** Akzo completed plant in Wuppertal, Germany to manufacture carbon fibre under license from Toho. Toho Rayon also set up a licensing agreement with Celanese (US) (later acquired by BASF) and in **1987** Toho Badische was established as a joint venture between Toho and Narmco (US). (Narmco was also later acquired by BASF.)[52]

By **1990** Toho Rayon had a production capacity of 1420 tons/years and had announced plans to increase this capacity by 600 tons. In **1993** the firm completed a $3.8 million plant for the manufacture of carbon fibre reinforced composites. Resins are bought in from other suppliers.[53] The same year, Toho acquired a majority (51%) stake in Akzo's carbon fibre business. The company was renamed Tenax Fibres (after the Akzo brand name) and the capacity of the plant raised to 700 tons per year.[54] The same year, a wholly owned carbon fibre composite plant was completed at Toho's Tokushima site.[55]

In **1994** BASF withdrew from the carbon fibre industry. Toho Rayon's former US joint venture with the company, Toho Badische was renamed Toho Cytec and reorganised as an equally owned joint venture between Toho Rayon and Cytec Industries (US).[56] Finally, in **1995,** Toho announced it was increasing its stockholding in Tenax to 90%.[57]

Commentary

The company exports around 70% of its carbon fibre to South East Asian countries, most notably Taiwan, Hong Kong and South Korea for the manufacture of sporting goods. Toho Rayon current carbon fibre capacity stands at 2600 tons, ranking it the largest global producer. Although, there is some forward integration into prepregs and shapes, and the company produces a range of resins (20 or 30 quoted by the company), Toho's strength lies in the range of carbon fibres it offers.

In 1982, the company licensed its carbon fibre production technology to Akzo, the Dutch chemical firm, which then built a plant in Oberbruch and commenced carbon fibre production in 1986. Concurrently, Akzo and Toho set up a number of joint ventures for the manufacture of end shapes in Europe. Similarly in the States, Toho set up a licensing agreement with Celanese (which was acquired in 1985 by BASF) and in 1987 formed a joint venture with Narmco (also part of the BASF group). The joint venture, Toho Badische, quickly became established as a prepreg and shapes company. Hence by the mid 1980's, Toho had established manufacturing agreements in its main export markets and had successfully forward integrated into the more value added prepregs and composite operations.

Although not a direct military supplier, Toho was hit by the general overcapacity in the global market as defence sales fell. The company lost around 10% of its carbon fibre business in financial year 1992, dropping over a percentage point in terms of market share.[58] In FY1993 Toho's Kaseihin [chemical division] which mainly handles the carbon fibre business reported a loss of 100 million yen.[59] The company announced that "due to a large expansion in carbon fibre production capacity in 1990 and an abatement in demand from space and aircraft markets, a worldwide recession has set in, making it necessary to restructure the carbon fibre business".[60] A three year plan was implemented, aiming to restructure the firm's carbon fibre and textile operations and put them back in the black by FY1996. In fact, Toho's carbon fibre business realised its set goal in FY 1995. As part of this restructuring, Toho completed an agreement on Jan 1st 1993 to acquire a 51% majority share in Akzo's carbon fibre business, Tenax fibres. In the summer of the same year, it was announced that Tenax would increase its capacity from 500 to 700 tons per annum "in expectation of an increase in demand for the fibres by the aeronautical industry from around 1995".[61] Toho has since increased its stockholding in Tenax to 90%. Hence in a similar manner to Toray, Toho has established a stable business network within the European Union.

Mitsubishi Rayon, Japan

Background

Total Assets 399,908 million yen
Total Sales 300,000 million yen
Sales Composition: Acrylic Fibres 18%
Acetate 14%
Polyester Filaments and others 14%
Plastics and Resins 44%
Other 10%
Carbon fibre produced at Otake and Toyohashi, under the brand name Pyrofil

Mitsubishi Rayon was established as a synthetic fibre producer in 1950. It continues to be a leading manufacturer of acrylic fibres but is now better known for as one of the world's largest producers of moulding and coating resins, most notably MMA.

Carbon Fibre Activities

Research and development activities relating to carbon fibre and its composites began at Mitsubishi Rayon's Central Research Laboratories in Otake in **1965**. In **1976** the firm started production of carbon fibre prepreg at the Toyohashi plant using carbon fibre imported from Courtaulds in the UK and the following year, PAN precursor production started at Otake.[62] The US firm Hitco licensed its carbon fibre production technology to Mitsubishi Rayon in **1981**. Carbon fibre production started at the Otake pilot plant the following year and an autoclave and filament winder installed at Toyohashi. Hitco and Mitsubishi Rayon established the composites shapes producer Dai-Hitco Composites as a joint venture in **1983**.[63]

In **1989** carbon fibre production started at Toyohashi on a commercial scale and in **1990,** Mitsubishi Rayon acquired Newport Adhesives and Newport Composites Inc., at a reported cost of 6 billion yen. It consolidated the two companies under the new name Newport Composite and Adhesives Inc and began the manufacture of prepreg in the US.[64]

Mitsubishi Rayon acquired the carbon fibre producer Grafil in the US from the British company Courtaulds in **1991**. By then, Mitsubishi Rayon had a 150 ton carbon fibre capacity at Otake and a further 350 tons at Toyohashi. It was producing around 760 tons of prepreg each year in Japan and had announced plans to expand its Advanced Composite Materials plant further at Toyohashi.[65]

Commentary

Unlike Toray, Toho Rayon or Asahi Kasei, Mitsubishi Rayon first began its carbon fibre interests through the production of prepreg and final products, integrating backwards to the manufacture of carbon fibre itself. The company acquired its prepreg technology from Courtaulds and began prepreg tape production at its Toyohashi plant in 1976, importing the carbon fibre itself from Courtaulds. In 1982, Mitsubishi Rayon began the manufacture of its own carbon fibre at its Otake plant, licensing the production technology from the American firm Hitco (which was acquired by BP in 1986). Seven years later a second line was opened at the Toyohashi plant, where an autoclave and filament winder had earlier been installed. Mitsubishi Rayon is the only Japanese carbon fibre producer with a significant defence interest; around 5% of its output is for Japanese F-15s.[66] It is also qualified for the NASA training plane the T-4 S-B and Japan’s next generation fighter, the FS-X.[67]

In 1983, Mitsubishi Rayon set up a joint venture, the Dia-Hitco Composite Company, with Hitco in the US and further expanded its downstream American operations with the acquisition of Newport Adhesives and Composites, a US prepregger in 1989. These acquisitions resulted in Mitsubishi Rayon possessing a fully integrated production capacity from carbon fibre production through to finished shapes in the US.

In 1991, the UK company Courtaulds decided to sell Grafil, a 400 ton capacity carbon fibre plant in Sacramento, California it had set up in 1984. Mitsubishi Rayon purchased the entire business. Grafil had a 8% market share in US carbon fibre and annual sales of around $15 million. The purchase price was variously reported as between $14.3 million[68] and $22 million.[69] Mitsubishi Rayon later announced plans to increasing Grafil's capacity to 600 tons.

Mitsubishi Rayon currently produces 500 tons of carbon fibre a year in Japan and 710 in the US.[70] Of all the Japanese firms, the company suffered the least during the early 1990's. Its market share in Japan increased 3.4% to 26.1% in 1992, at the expense of both Toray and Toho Rayon.[71] Net sales of carbon fibre actually increased between 1992-93 from 10.7 to 12 billion yen, but slipped back slightly in 1994 to 11 billion yen.[72] Mitsubishi Rayon sells around 90% of its Japanese output to other members of the Mitsubishi group.

Asahi Kasei (Asahi Chemical), Japan

Background

Total Assets 975,677 million yen
Total Sales 1,000,000 million yen
Sales Composition: Acrylic Fibres 4%
Nylon 6%
Other Fibres 8%
Chemicals and Plastics 46%
Building Materials and Housing 33%
Others 3%
Carbon fibre was produced at Fuji, under the brand name Hi-Carbolon

Asahi Kasei is one of Japan's leading synthetic fibre producers. Its principal textile product is acrylic fibre and it is largest producer of mono-acrylonitrile , which is used to make acrylic. This is the monomer that is also used to make PAN, the precusor used in the manufacture of carbon fibre. However, the company is essentially a large chemical firm producing plastics, industrial chemicals and petrochemicals, synthetic rubber, pharmaceuticals and medical equipment, electronics, housing materials and food products. (Asahi Kasei is the firm that blessed us with the discovery of monosodium glutamate). The non textile divisions account for nearly 80% of total sales.

Throughout the over 50 years since its founding as a synthetic fibre producer, Asahi Kasei has expanded its operations by vertical integration from raw materials to finished product and the full utilisation of by-products and derivatives. Full self-sufficiency in basic production materials was established in the early 1970's with the completion of the Mizushima petrochemical complex in Okayama prefecture.[73]

Carbon Fibre Activities

In **1980** Asahi Kasei and Nippon Carbon established a joint venture for the manufacture of carbon fibre. Production began a year later. In 1986, Asahi Kasei bought the company 100% and changed the name to Asahi Kasei Carbon Fibre.[74] Capacity was subsequently increased from 360 to 450 tons in 1989 and Asahi Kasei Carbon Fibre and Asahi Kasei Composites consolidated into a single company and re-named Shin [new] Asahi Kasei Carbon Fibre.[75]

1990 saw the development of the WIP prepreg, the first major commercial prepreg based on a thermoplastic resin. WIP found its major market in the manufacture of tennis rackets and in **1992** the firm announced plans to increase capacity from 480 to 600 tons per year.[76] Originally, the company had planned to increase production to 1000 tons per year and build a new plant. However, these plans were dropped as the global over capacity became evident. The increase in capacity to 600 tons was completed by **1994,** (by increasing the composition of feedstock to the line rather than introducing more production lines) and Asahi Kasei became the world's sixth largest producer of carbon fibre.

In April 1994, however, Asahi reported accumulated losses of 1.2 billion yen on carbon fibre operations. The company announced it would abandon the carbon fibre business.[77] Asahi Kasei posted extraordinary losses of 600 million yen for the financial year through to March **1995.**

Commentary

Carbon fibre production at Asahi Kasei started relatively recently with the establishment of a joint venture with Nippon Carbon. Toray, Toho Rayon and Hercules were the only major producers at the time and carbon fibre markets were increasing at double figure rates, sometimes exceeding over 20% a year. Asahi Kasei was already producing the PAN monomer in huge quantities through its acrylic fibre operations. Nippon Carbon, a big producer of electrodes for melting iron, provided the high temperature technology required for carbonisation. In 1986 Asahi Kasei bought out Nippon Carbon and reorganised its carbon fibre operations as a 100% owned subsidiary.

Asahi Kasei established itself as a producer of standard 12K modulus fibre. This was produced mainly at the firm's Fuji plant, from where around a quarter was sent to Asahi's Moriyama plant for the manufacture of prepreg. The Moriyama plant also brought higher modulus fibre from Toray and Toho Rayon. The bulk of Asahi Kasei's carbon fibre production was sold to Taiwan and South Korea for the manufacture of sporting goods.[78] Asahi Kasei's main strength was its ability as a major chemical company to offer dozens of different kinds of resin for the manufacture of composites. It was the first major producer to manufacture thermoplastics resins (which possess the potential for fast, high volume production) for carbon composites on a commercial basis. Its thermoplastic prepreg WIP was submitted to Boeing as a possible contender for primary structure qualification. The carbon fibre division did not forward integrate to a large degree, however, each resin division had its own downstream activities.[79]

Asahi Kasei's carbon fibre operations were about a fifth the size of its major competitors Toray and Toho Rayon and the company lost out to some degree on the benefits of scale economies. It completed its plans to increase capacity to 600 tons a year, but by early 1994, the subsidiary had accumulated losses of some 1.2 billion yen and in April the company announced plans to cease carbon fibre activities.

BASF, Germany

Background

Total Assets: 39,859 million DM

Net Sales: 46,565 million DM

Sales Composition: Oil and Gas: 9%
Plastics and Fibers:26%
Chemicals: 15%
Dyestuffs and Finishing products: 19%
Other: 31%

Carbon fibre was produced at Rock Hill, South Carolina, under the brand name Celion.

BASF is one of the world's largest chemical companies and holds a significant fraction of the international trade in gas, plastics, petroleum products, nitrogen compounds and dyes. All considered, since its inception in 1865 as the Badische Analin und Soda Fabrik AG, BASF has had a profound influence on the global chemical industry.

The roots of the company lie in the manufacture of artificial dyes following William Perkins' discoveries at the end of the nineteenth century. The new dyes proved cheap, bright and, (unlike their natural counterparts), reliable and by the beginning of the twentieth century, journalists were referring to BASF as "The World's Greatest Chemical Works". [80] The firm's profitability lay in part in the organisation of the German chemical industry into two major cartels, one centred on Hoechst and the other on BASF and Bayer. Within the cartels, the firms fixed prices, set quotas and even shared profits. In 1925 the cartels merged and hundreds of smaller chemical companies formally incorporated to form the huge conglomerate Interessen Gemeinschaft Fabenwerke, better known as I.G. Fabern.[81] At its peak during World War II, I.G. Fabern had a controlling interest in 379 German firms and 460 foreign companies. Primo Levi's autobiographical work, If This Is A Man gives a personal account of I.G. Fabern's wartime activities.[82] At the end of the war, the then director of BASF was consequently tried for war crimes and I.G. Fabern was broken up by the Allies into its three component large firms, Hoechst, Bayer and BASF, and nine smaller ones.

BASF grew steadily throughout the 1950's and 60's becoming the world's largest producer of plastics and fulfilling over 10% of the international requirement for synthetic fibres. After the oil shock, the growth of the company slowed and, in a bid to reverse the trend, the company began an active expansion into foreign markets. The establishment of a US manufacturing base became the cornerstone for BASF's strategy for growth; at the time, the US consumed a third of the world's chemical products.[83]

Carbon Fibre Activities

In **1985** BASF began carbon fibre production with the acquisition of the Celion carbon fibre business from the US firm Celanese[84] and in December **1987**, the same year as the DoD directive, PAN precursor production started at Rock Hill. In **1989**, BASF announced that it would increase its carbon fibre capacity to 1500 tons a year. It was later announced in April **1990** that BASF would go ahead with a $30 million expansion project at its carbon fibre precursor plant in Rock Hill, South Carolina.[85]

In **1991,** the new carbon fibre plant at Rock Hill commenced operations. The *Metal Working News* had reported that by the third quarter of 1991, when the expansion of the then 136,000 kilogram carbon fibre precursor plant would be complete, BASF had estimated that it would be able to produce in excess of 900 tons annually of the US domestic PAN requirement.[86] However, in March, the French journal *L'usine Nouvelle* reported a BASF spokesperson as saying,

> "BASF ne juge pas opportun de continuer à supporter les charges resultant de cette activité", [BASF does not think it opportune to continue to bear the costs of this area of business]

and in June reported that,

> "BASF à clairement fait savoir que son unité de Rock Hill (Etats Unis) était à vendre" [BASF has made it clearly known that its (carbon fibre) plant at Rock Hill is for sale].

In September of the same year, the *Rubber and Plastics Weekly* reported that BASF would sell its structural materials operations to the European firm Hexcel.[87] The sale included BASF’s composites division in Lugwigshaven, which was moved to Welkenraedt in Belgium, and was completed in the fourth quarter of 1992. The carbon fibre plant at Rock

Hill was closed down at the end of 1992. (Hexcel now supplies composite systems to the Eurofighter).[88] BASF planned to sell its Rock Hill plant and the whole of its composites division once a buyer was found. By **1993,** BASF had shut down its carbon fibre plant, idling 1360 tons of capacity and by May **1994**, BASF had made it clear it would abandoning carbon fibre production.[89] In November of the same year, Amoco signalled an interest in buying 900 tons of BASF's idled carbon fibre capacity in Rock Hill.[90] The two other BASF production lines were not included in the deal.

Commentary

BASF entered carbon fibre production by the acquisition of Celanese's carbon fibre plant in Rock Hill, South Carolina. Celanese itself had been manufacturing carbon fibre since 1982 under a technology licensing agreement with the Japanese firm Toho Rayon, from which it was supplied with PAN precursor. At the same time, BASF built a prepreg factory in Ludwigshafen, created a daughter firm (Hybrid Yarns) to specialise in the production of thermoplastic composites and bought the Connecticut firm Quantum, which produced aerospace composite parts. BASF's US acquisitions took place at a time when investment in the US was a central theme of the company's strategy for growth. Moreover, as contemporaneous sources observed, it was believed at the time that the US military markets were set for rapid growth and that the DoD would preferentially buy from domestic sources.[91]

Up until 1987, all BASF carbon fibre was produced from Japanese precursor manufactured by Toho Rayon. After the 1987 DoD directives, which mandated that by 1992 at least 50% of both the carbon fibre and its PAN precursor used by the military be produced domestically, BASF rapidly increased its capacity for both. In 1987, it started up PAN precursor production and increased its PAN capacity further in 1990. In 1989, BASF announced plans to increase carbon fibre capacity by opening a new line in Rock Hill, which it did in 1991. By this time, BASF had became the main supplier of composite prepreg for the US air force's Advanced Tactical Fighter.[92] However, it was soon clear that this project would be severely cut back and within a year, BASF was trying to sell its composite businesses. "We are discontinuing our line of advanced composites" said the company "The drop in demand from the aerospace industry increased competition considerably and ... we were unable to attain our original goals."[93] For two years, the carbon fibre plants remained idle. Eventually Amoco bought the 900 ton capacity line in 1994. BASF remains the owner of the remaining carbon fibre capacity, but has made it clear it has abandoned the business.[94]

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APPENDIX II
Interviewees

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Bourgeois, J.L., Ministère de la Recherche et de la Technologie, Paris, June 1991

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Sample Interview Questions

Background

What range of carbon fibre composite materials do you use/produce?

How much do they cost?

What alternative materials do you make/consider?

What are you main products currently using carbon fibre?

What processes are used to produce them?

What manpower and costs are being invested in this technology? How does this compare with your investment in competing technologies?

What are your future plans for investment?

What is the history of your carbon fibre operations, over, say, the last 20 years? How did you get into carbon fibre and why? What R&D has been performed by the firm? What were the major applications?

What are your current carbon fibre R&D programmes? What factors do you believe are most likely to inhibit the development of the sector?

Markets

How big are the markets in which your carbon fibre products compete? What are the products that they have displaced? How do carbon fibre products compare, in terms of cost and performance, with competing technologies? How is this likely to change over the next 5 or 10 years? What are the likely market projections?

What are the major barriers to substitution?

What are the main national markets? How do these compare with overseas markets in terms of scale, quality and level of civil/military demand?

Who are your main suppliers and customers? Who are your major competitors?

Civil/Military Interactions

How distinct are your civil and military activities? By what mechanisms, if any, does civil/military conversion take place? What is the evidence for their success?

In ongoing programmes, what are the expectations for civil/military technology transfer?

Other Institutions

What institutions do you consider important in the generation of knowledge/expertise underlying this technology?

What are your links with government and/or other companies?

Current Activities

The latest figure I have for your current carbon fibre capacity is XXX tons. Is this correct and, if not, what is the correct figure?

Do your current plans for carbon fibre production capacity include any increase or decrease in output? If so, by how much and over what period?

What are your total carbon fibre sales in terms of value?

What percentage does carbon fibre constitute of your total company sales?

What percentage by value and by weight is exported?

Are any of your carbon fibre products qualified and if so, by whom?

Approximately what percentage (by value and weight) of your carbon fibre output is used in defence applications?

Has the downturn in defence expenditures affected your carbon fibre activities and, if so, how?

From my research it would appear that over the last couple of years, Japanese owned carbon fibre capacity has markedly increased, in contrast to that owned by US and European firms. Given that carbon fibre is a commodity that is traded on world markets, why do you think this is so?

Financial governance

How does the operating profit on your carbon fibre operations compare to that of the group as a whole?

Who are your major stockholders and what percentage of the total stock holding do they each hold?

Who are your major creditors and what percentage of your total borrowing do they each extend?

Has membership of XX keiretsu affected your carbon fibre interests in any way (for example, initial and subsequent investment, initial and subsequent markets)? What percentage of your current fibre output is sold to other companies within the keiretsu?

Other

Company history

Synopsis of carbon fibre operations

Annual Reports

APPENDIX III
Keiretsu Status

We examine here the keiretsu status of each of the Japanese carbon fibre producers. As we saw in Chapter Three, a keiretsu company will:

- depend on same-group institutions for a high proportion of its borrowing;
- collectively, this same group will hold a large number of shares in the firm;
- have a seat on the influential presidential council and perhaps further councils of the same group;
- have one or more interlocking directorships with other same-group firms.

Measures of keiretsu affiliation of firms are listed in Dodwells, the English language translation of **Keiretsu no Kenkyu**, a Tokyo based annual publication of individual company data on company directorships, reciprocal shareholding and intra-group borrowings. The companies themselves were also asked by the author to provide more detailed data on their main debtors and creditors. Finally Professor Yoshiteru Takei of Shizuoka University provided the author with much background data on the keiretsu groups. We will now consider the keiretsu standing or otherwise of each of the Japanese carbon fibre producers in the light of these criteria. Turning first to the largest producer **Toray**, we find the major shareholders to be:

Dai Ichi Mutual Life Insurance	5.4%
Nippon Life Insurance	5.2%
Mitsui Mutual Life Insurance	4.6%
Mitsui Taiyo Kobe Bank	4.5%
Mitsui Trust and Banking	3.9%
Sumitomo Trust and Banking	2.4%
Toyo Trust and Banking	2.2%
Long Term Credit Bank of Japan	2.0%
Daiwa Bank	1.9%

Source: Dodwell[1]

Of the major shareholders, Mitsui related institutions hold 40% of Toray's stock. The Mitsui Kobe Bank and Mitsui Trust and Banking are also Toray's major creditor banks and, as a whole, Mitsui related financial institutions extend 25.7% of Toray's total borrowings, over three times that of any other lender group. Hence Toray's major shareholders and lenders are all members of a single keiretsu group (a central characteristic of a keiretsu firm).

Historically, Toray is a core firm of the **Mitsui keiretsu**. Toray sits on the Nimoku-kai (the presidential council of the Mitsui Group) and the Getsuyo-kai (a group of 76 executive directors of Mitsui firms).[2] The Fellowship of Engineering assert that Toray was greatly aided by its membership of the Mitsui keiretsu at the time Toray started up their carbon fibre production. Keiretsu membership minimised the financial risk Toray took in laying down plant before demand was evident as close contacts already existed with potential end users. It also helped Toray weather the storm when their original targeted market (a uranium enrichment centrifuge) fell through by quickly providing alternative applications such as golf clubs and fishing rods.[3]

*

Turning next to **Toho Rayon**, we see the largest shareholders are:

Nisshinbo Industries	24.4%
Yasuda Trust and Banking	5.6%
Fuji Bank	4.9%
Toyo Trust and Banking	4.9%
Mitsui Trust and Banking	4.1%
Mitsubishi Trust and Banking	4.0%
Mitsubishi Bank	1.9%
Sumitomo Trust and Banking	1.9%
Yasuda Mutual Life Insurance	1.8%
Showa Denko	1.5%

[xvi] Source: Dodwell[4]

Of the major shareholders, Fuyo related financial institutions hold 69.5% of Toho's stock. Fuyo related financial institutions also extend 21.3% of Fuyo's loans, compared to 11.8% from the next largest creditor group, Mitsubishi.

[xvi] Nisshinbo Industries is the textile branch of the Fuyo keiretsu; Yasuda Trust and Banking and Yasuda Mutual Life Insurance are financial institutions within the Fuyo keiretsu. With thanks to Professor Takei.

Toho Rayon is a textile firm within the **Fuyo keiretsu**. Toho sits on the presidential council and on the Fuyo Kondan-kai, a group of 67 Fuyo companies that aims to raise product awareness amongst member firms.[5] It has five concurrent directorships, one with Fuji Bank and four with another Fuyo member.[6]

*

The third largest producer, **Mitsubishi Rayon** is part of the **Mitsubishi** keiretsu on every count. If we examine the data for the major stockholders, we find the percentage stock they hold to be:

Meiji Mutual Life Insurance	6.2%
Mitsubishi Trust and Banking	4.9%
Mitsubishi Bank	4.7%
Nippon Life Insurance	3.3%
Dai-Ichi Kangyo Bank	3.1%
Sumitomo Trust and Banking	2.1%
Industrial Bank of Japan	2.0%
Long Term Credit Bank of Japan	2.0%
Dai-Ichi Mutual Life Insurance	1.7%
Mitsubishi Heavy Industries	1.6%

[xvii] Source: Dodwells[7]

We can see from the above that within the major shareholders, Mitsubishi related institutions hold 55.1% of the stock. Mitsubishi related financial institutions also extend 40.4% of Mitsubishi's credit, and represent the largest group of creditors. Hence not only does Mitsubishi Rayon rely on the Mitsubishi group for long term loans, but that Mitsubishi group firms hold a large proportion of the total stock.

Mitsubishi Rayon has a seat on the Mitsubishi presidential council and also sits on the Kingo-kai, a group of 76 executive directors and presidents of Mitsubishi member companies.[8] The company also possesses the third keiretsu fingerprint; it has two interlocking directorships, one with Mitsubishi Bank and one with Mitsubishi Trust and Banking.[9]

*

[xvii] Meiji Mutual is a financial institution within the Mitsubishi group.

Finally, if we examine the stock holding data for **Asahi Kasei**, we find the major shareholders to be:

Nippon Life Insurance	4.5%
Sumitomo Bank	4.0%
Sumitomo Life Insurance	3.9%
Dai-Ichi Life Insurance	3.8%
Asahi Life Insurance	3.4%
Mitsui Life Insurance	3.3
Dai-Ichi Kangyo Bank	3.2%
Sumitomo Trust	2.8%
Meiji Life Insurance	2.3%
Tokyo Marine and Fire Insurance	2.2%

[xviii]Source: Takei[10]

Asahi Kasei does appear to have a close relationship with its primary creditor Sumitomo in that Sumitomo related financial institutions hold 10.7% of Asahi Kasei stocks. However, and as a most important difference from our other cases, Asahi Kasei sits on the presidential council of another keiretsu group, Dai-chi Kangyo. The company does not see itself as part of a keiretsu grouping and non-financial ties and support are minimal.[11]

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[6] Dodwells, op. cit
[7] Dodwells, op. cit
[8] Miyashita and Russell, op. cit.
[9] Dodwells, op. cit.
[10] Professor Yoshiteru Takei, personal communication, May 1992
[11] Akitaka Kikuchi, Asahi Kasei, in interview, May 1992

[xviii] Nippon Life Insurance is a financial institution within the Sanwa keiretsu; Meiji Life Insurance and Tokyo Marine and Fire Insurance are part of the Mitsubishi keiretsu.

APPENDIX IV
The End of the Cold War: a chronology

1970-1984

"The Soviet Union is the focus of evil in the Modern World"

Ronald Reagan, March 1983

Throughout the 1970's and early 80's, there is a steady increase in weapon numbers, although the **rate** of increase is controlled though SALT (the Strategic Arms Limitation Talks). SALT I and SALT II are signed in 1972 and 1978 respectively.

In **1980** Reagan comes to power. Relations with the Soviet Union, which have steadily deteriorated over the last years of the Carter administration, grow still colder. Reagan denounces the USSR as the 'evil empire' and defence expenditures are sharply increased. The Strategic Arms Initiative further accelerates the arms race. The arms industry becomes the leading growth industry in the United States and worldwide, military spending reaches \$550 billion.[1]

1985

Gorbachev comes to power and Reagan begins his second term of office. In November 1985, Reagan and Gorbachev meet for the first time at the Geneva summit. No agreements are reached.

1986

The US budget deficit reaches \$221 billion and the national debt almost \$3 trillion.[2] In response to the growing fiscal crisis in the US, the Gramm-Rudman-Hollings Act is passed, mandating major deficit reductions over the following five years.

At the Reykjavik summit in Iceland, Gorbachev and Reagan meet each other for a second time. Arms reductions are discussed but stall on the issue of the Strategic Defence Initiative.

1987

The INF (Intermediate Range Nuclear Force) Treaty eventually follows from the Iceland Summit. The treaty calls for the dismantling and destruction of all short and medium range missiles, with provisions for on-site inspection and verification.

The Soviet Union removes its SS-20 missiles from Eastern Europe and the USA removes cruise and Pershing missiles from Germany, Italy and the UK.[3]

1988

Bush wins the US presidential elections

1989

Gorbachev reduces Soviet weapon spending by 20 percent. In Poland, the trade union Solidarity wins a decisive victory over the communist party in the summer parliamentary elections. Hungary opens its borders and thousands of East Germans pour into the country en route for the West.

Following massive pro-democracy demonstrations in October, Czechoslovakia undergoes its ‘velvet revolution’. Violent revolutions oust the communist regime in Romania. Bulgaria and Albania remain under communist control.

On the afternoon of November the 9th, the East German government, now completely unable to stem the tide of exodus of its people through Hungary announces that it will open West German crossing points. Within hours of the announcement, tens of thousands of East Germans have crossed into West Berlin. The Berlin Wall itself is breached and subsequently torn down.

1990

After the fall of the Berlin Wall, the East German government attempts independence, but fails as populist demands for a united Germany grow. Kohl and Gorbachev negotiate and agree a formula for re-unification. The East German army is completely erased and the West German army reduced. Russia begins the withdrawal of its troops from Germany - a manoeuvre that takes four years to complete. In October, East and West Germany are re-unified.

The Paris Treaty is signed. The treaty is a bilateral agreement on conventional weapon reduction, also known as CFE (conventional forces in Europe). This marks the end of 15 years of negotiations that had begun in Vienna under the banner MBFR (Mutual Balanced Forces Reduction); negotiations that had borne no fruit until the fall of the Berlin Wall. Progress is then accelerated by the settlement of the Paris Treaty. Under the CFE agreement, reductions are made in tanks, aircraft, artillery, personnel transport and armed vehicles throughout the European arena. For example, Germany is now limited to a total of 350,000 army, navy and airforce personnel.[4] The Paris Treaty has been described as a “foundation for military security in Europe ...[and] the most comprehensive arms control agreement in history.”[5]

In August, Iraq invades Kuwait. The UN votes to authorise military action. On the 16th of January 1991, the United States and allied forces begin a massive bombardment of Iraq, which surrenders within 6 weeks. There are small increases in DoD aircraft procurement during this period.[6]

1991

Following the collapse of communism in Central Europe, the Warsaw Pact disintegrates. In August, a military coup by hard-line communists takes place in Moscow. The coup fails, precipitating the collapse of communist power in the Soviet Union. In December, Gorbachev is removed and forced to resign. Yeltsin comes to power and effectively outlaws the communist party. Following the Moscow coup, the Soviet Union breaks up. By the end of 1991, led by the Baltic States, every republic has declared independence. On the 31st December 1991, the Soviet Union formally ceases to exist.

1993

The START (Strategic Arms Limitation Talks) are signed by the USA and USSR/Russia (the other nuclear powers did not take part). SALT and START are concerned with cuts in nuclear forces, including ICBMs (intercontinental ballistic missiles) and SLBMs (submarine launched missiles), and result in considerable cuts in these weapon systems.

1995

Problems arise with the Paris (CFE) treaty as Russia wishes to deploy greater numbers of troops and weapons in Chechnya and the rest of the Caucas region. The CFE agreement was concerned with total weapon and division numbers and where they could be stationed. Russia decides to adjust its flank limits within the overall CFE ceiling in order to maintain control of its southern regions.[7]

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