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Technology Diffusion— The Movement of Technology Between Aerospace and Other Industries

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A project of the Aerospace Research Center
and
the Civil Aviation Advisory Group
Aerospace Technical Council

Consultant
Shriner-Midland Company
Washington, D.C.

A Publication of
THE AEROSPACE RESEARCH CENTER
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AEROSPACE INDUSTRIES ASSOCIATION
OF AMERICA, INC.
1725 DeSales Street, N.W.
Washington, D.C. 20036

October 1985

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The mission of the Aerospace Research Center is to engage in research, analyses and advanced studies designed to bring perspective to the issues, problems and policies which affect the industry and, due to its broad involvement in our society, affect the nation itself. The objectives of the Center's studies are to improve understanding of complex subject matter, to contribute to the search for more effective government-industry relationships and to expand knowledge of aerospace capabilities that contribute to the social, technological and economic well being of the nation.

Table of Contents

Figures

EXECUTIVE SUMMARY

TURBOCHARGER TECHNOLOGY

Foreword

The aerospace industry plays a vital role in the U.S. economy by stimulating the development of technologies that benefit the entire economy. It is for this reason that many other developed countries are actively promoting, and often subsidizing, their aerospace firms. Developing nations such as Spain, Indonesia, and Brazil have established growing niches in aircraft production; major industrialized nations such as England, France, Germany, and Italy actively fund large ventures, often joint ventures, in civil aviation—in part because the industry serves as a technological engine for the rest of the nation. This creates significant competition for U.S. aerospace firms.*

In the United States, the role of aerospace and other key industries as technological pioneers is not generally appreciated. While other countries are promoting their aerospace firms and capturing a growing share of world aerospace markets, the United States pays little heed to the needs and contributions of its "pioneer" industries. These industries develop and perfect new technologies and bring down their costs to the point to which they can be used in many other sectors of the economy. In aerospace, as in other pioneer industries, technology is driven by high performance, reliability and safety requirements.

A century ago the United States recognized that its most important industries at that time were agriculture and the equipment industries that were linked to agriculture including the railroads, the machinery makers, and the food processors. The United States made the commitment to encourage the development and spread of technology in those key industries by the Morrill Act, which established the land grant colleges and led to the Agricultural Extension Service and the Agricultural Research Service. The results have been spectacular. No country today can boast an agriculture industry as efficient or competitive as the United States.

Other U.S. industries which have played the vital role of technological engine in the past have often been taken for granted until they have been eclipsed by foreign competitors, often through the use of government subsidies—among them have been consumer electronics, heavy construction equipment, machine tools and automobiles. Without these technological pioneers, the competitiveness of the entire national economy is weakened.

In order to create a broader awareness of the important role of technology diffusion and of the key industries which advance this process to the benefit of the national economy, the Aerospace Industries Association performed this study. It focuses upon an examination of three representative technologies in whose development the U.S. aerospace industry has been a significant participant: turbochargers, fiber-reinforced plastics, computer-aided design and manufacturing.

Early in the Reagan Administration, an analysis led by the White House Office of Science and Technology Policy of the state of aeronautical research, and the role of the Federal government in supporting that research, led to the conclusion that tremendous advances could yet be achieved as a result of aeronautical research, and that the Federal Government and industry should unite to realize that potential.

An Aeronautical Policy Review Committee has since given direction to the Administration's commitment to aeronautical research and has set specific, major goals. Building on this policy foundation will not only help maintain U.S. leadership in an industry that is an important economic and national security resource, but will serve to sustain and strengthen an important technological resource.

Aerospace is one of several key industries of today and tomorrow—other such industries are electronics, telecommunications, biotechnology, computers and advanced materials. Unless the importance of these pioneering industries is properly understood and valued in the United States, their erosion through loss of market share will have a severe long-term impact on the international strength and competitiveness of the entire U.S. economy.

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*Aerospace Industries Association (AIA), *The Challenge of Foreign Competition to the U.S. Jet Transport Manufacturing Industry* (Washington, D.C., 1981).

AIA, *The U.S. Helicopter Industry—Its Development, World Market and Foreign Competition* (1983).

AIA, *The U.S. Private, Business and Light Transport Aircraft Industry —Its Development, World Market and Foreign Competition* (1984).

Executive Summary

In 1984, the U.S. aerospace industry led the nation's industries in R&D investment. This heavy commitment to R&D is important not just to aerospace but to the entire U.S. economy. The aerospace industry remains the nation's leading net exporter of manufactured products largely because of its productivity and technological leadership. Just as important, aerospace serves as a pioneer—helping open up new industrial technologies which ultimately strengthen many other U.S. industries as well. Without a strong aerospace industry, the technological competitiveness of other U.S. industries would suffer.

High Performance Requirements Push Technological Progress

The motivation or driver for technological progress is strongest when performance improvements provide competitive advantage and cost savings. High performance and reliability requirements compel certain industries, including aerospace, to become technological pioneers. These "pioneers" develop and use new technologies at an earlier and more costly stage than most other industries because the potential payoffs are correspondingly greater. In the process, they absorb initially high research and development risks and the high costs of early applications.

As experience with a new technology increases and its total usage rises, costs of using that technology decline, following a "learning curve" which is unique to each technology. Early applications by pioneer industries thus push costs downward along the technology's learning curve until use by other industries becomes economically feasible (see p. 9 for a fuller explanation of the technology learning curve.) Pioneer industries also facilitate the advance of technology in other industries through demonstration of new possibilities and the development of skills which are diffused to other industries through movement of personnel, production contracts, patent licenses, joint projects, and other means. They also often provide early markets for innovations that originate outside the pioneer industry.

Representative Aerospace Case Studies

This study examines three representative technologies in which the U.S. aerospace industry has played a significant pioneering role and attempts to show the important linkages between early aerospace usage and other applications elsewhere in the economy. These representative technologies are:

- *Turbochargers*—a *device* for improving engine efficiency;
- *Fiber-Reinforced Plastics*—a type of composite *material* with improved strength-to-weight and producibility characteristics; and
- *Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM)*—a *process* for improving efficiency in design, analysis and production.

Turbochargers

In the case of turbochargers, the principal manufacturer of turbochargers today attributes their position to experience gained as a subcontractor on aircraft engines in the 1940's, prior to the development of jet aircraft engines. The early turbocharger used to boost the inlet air pressure on piston-powered aircraft is clearly the forerunner of today's compact, lightweight, and simpler auto turbocharger. Turbocharger applications in autos (other than racing), trucks, and earth-moving equipment emerged after turbocharged piston-driven aircraft engines had been replaced by jet engines. Development of jet engines was facilitated by advances in the broad field of turbo-machinery, of which turbochargers were a significant part. Although quantitative data on aircraft turbocharger output is limited, the pioneering role of the aviation industry is evident and well-documented.

Fiber-reinforced Plastics

Experience gained with fiber-reinforced plastics (FRP's) in aviation in the 1940's led directly to the revolution in recreational boating which occurred in the 1950's with the introduction of glass FRP power boats, sailboats, and canoes. Research and experimentation in carbon FRP's during the 1960's set the stage for the explosion of "graphite" racquets, clubs, and other recreation equipment in the 1970's. The cost of high-modulus carbon fibers has declined as usage has increased, from over $600 per pound in the mid-1960's to about $20 today, making its use economically feasible in many industries. Two-thirds or more of carbon FRP usage has occurred in aviation and aerospace, which now accounts for approximately 75–80 percent of annual usage. Without this aerospace usage, carbon fiber and FRP costs would be at a much higher level on the learning curve, and usage by other industries would not have progressed to the stage which currently exists. In addition to the design flexibility which FRP's provide, they also offer the prospect of major savings in production costs as fabrication techniques improve. First, FRP's require less energy to produce than a comparable amount of metal. Second, designs which require an intricate combination of large and small metal parts to achieve the desired shape, strength, and weight can often be replaced by a single large FRP component of complex design. The reduction in number of parts reduces production and assembly time. Third, FRP fabrication reduces material wastage, especially in complex metal components in which 50 percent or more of the original metal must be cut or ground away to create the part. This creates still further energy cost savings.

Until recently, most FRP fabrication was done by hand but many firms, particularly in the aerospace industry, are rapidly increasing the amount of automation in FRP fabrication. As these techniques are developed and used more widely, they will further reduce costs and improve the quality of FRP products.

Many specific examples of spinoffs of specific advances in composite technology from aerospace to other industries are listed in Appendix D. Most of these examples represent directly traceable usages that occurred within a period of 1–5 years after the new technology was created. Even in that relatively short time interval, the impact of these spinoffs on costs and quality were significant.

Many materials experts suggest that FRP's may largely displace metals and other monolithic materials within the next 30 years, because of their ability to be adapted to a wide range of performance requirements and low maintenance costs. Also, less energy is required to produce FRP's than is the case for most metals. Much of what is known about the economical production and use of FRP's and other advanced composites has been the result of efforts in a few pioneering industries, most notably aerospace. Unquestionably, however, many major advances in FRP materials today are occurring outside the United States, principally in Japan. Our ability to develop and use these materials will play an important role in the competitiveness of U.S. firms in world markets in the years ahead. The increasing use of FRP's may also reduce U.S. vulnerability to shortages of critical metals which are not mined in the United States.

Computer-aided Design and Manufacture

Computer-aided design and manufacture (CAD/CAM) were first applied by the aerospace industry in the 1950's to reduce time spent on system design and testing and to reduce production defects. In some cases, CAD/CAM has permitted design, analysis, production and testing which could not otherwise be accomplished without it. In the aerospace industry, the number of parts built from a particular design is relatively small—often fewer than 1,000 units—and engineering changes continue to occur throughout the production life of the aircraft, space system, or sub-system. The share of final cost attributable to design is, thus, considerably larger in the aerospace industry than in most mass-production industries, and the motivation to reduce the cost and improve the productivity of design effort is correspondingly higher.

Acting through the Aerospace Industries Association, a group of aerospace firms in 1957 created a research and development consortium to develop common standards and software for automatic programmed tools (APT). Later, firms from many other industries were invited to join the consortium, and today the APT language for tool control is widely used throughout U.S. industry.

Experience gained in aerospace in the development of custom-built CAD/CAM systems led in the early 1970's to the creation of a totally new industry of firms providing "turn-key" CAD/CAM systems tailored to various industries. One of the largest firms in this new industry gained much of its initial experience in aerospace. It designs, manufactures, markets and services CAE, CAD and CAM products and systems for a wide range of industries. Its systems assist in mechanical analysis, design, drafting, and automated manufacturing.

In the 1980's, CAD/CAM systems were created to operate on low-cost personal computers, making many elements of the technology available to even very small firms. Costs for hardware and software for a basic CAD/CAM system declined from more than a million dollars in 1960 to under $10,000 in 1984. A significant share of that reduced cost and expanded usage is attributable to pioneering usage in the aerospace industry.

The aerospace industry will form an important part of future CAD/CAM markets and will also continue to contribute substantially to CAD/CAM technology development and productivity gains. Major aerospace firms recently announced their intention to form a joint R&D software productivity consortium to devise software tools and techniques for computer-aided design and engineering. Productivity and quality improvements resulting from use of CAD/CAM will play an important role in the international competitiveness of U.S. firms in the future.

Cross Linkages

Cross-linkages among the three technologies also emerge. For example, CAD/CAM systems are being increasingly used in the design and fabrication of FRP's; FRP's and other composite materials are being used to make lighter, stronger turbocharger components, increasingly designed with CAD systems; and the combined use of turbochargers and light-weight FRP materials reduces fuel consumption in today's automobiles by 15 percent or more.

The combined effect of these three technologies in the late 1990's, at presently projected rates of utilization, will be to reduce U.S. per capita energy needs by some 15 percent or more, compared to 1980. More important, they will open up new opportunities for U.S. industry as yet undreamed of, including new products, new processes, and new ways of organizing production.

The three case studies developed in this report were chosen from among numerous possible candidate cases. Appendix B, which recounts the process of case selection, provides other examples. Appendix A—an extensive catalog of spinoff cases documented by NASA—illustrates the wide range of technology spinoff applications resulting from aerospace R&D with attribution to source and an indication of economic impact. Applications abound in the areas of health and medicine, capital equipment production, energy, industrial productivity, safety and the environment, transportation, construction, consumer/home/ recreational products, computer processing and technology, and communications. Outstanding examples of aerospace technology applications include: the wide use of composite materials (see Appendix D); NASA Structural Analysis (NASTRAN) software with a wide range of non-aerospace applications (see Appendix F); image processing used in business graphics/cad/cam/automation and mapping; flame resistant foam; high temperature lubricants; ferrofluid technology employed in various commercial-industrial areas; protective coatings used in the equipment industry; improved inorganic paint with corrosive/resistant properties used in bridge construction and elsewhere; and heat recovery devices for housing and a variety of other commercial and industrial applications.

Aerospace Needs Help Diffuse Technology

These examples of direct technology spinoff—in concert with the case studies which show how aerospace needs prompt, advance and help diffuse technology throughout the economy—demonstrate the important role pioneer industries such as aerospace play in the overall pace of technical progress. Technical progress in turn directly affects national economic competitiveness in domestic and international markets. The value of the aerospace industry as a technological pioneer paving the way for the advancement of many other industries is recognized today in most industrialized nations. The governments of many of the developed and developing nations whose firms are key competitors of traditional U.S. industries view aerospace as a vital national resource, to be actively developed and nurtured because of its ability to stimulate technical competitiveness throughout the national economy. Several countries have made major national commitments to create and maintain a successful foothold in the aerospace industry; and others have targeted aerospace as a developmental goal. The number of nations with significant aerospace production capabilities has risen sharply in the last two decades, increasing competition throughout the industry.

In the United States, the federal government is traditionally less concerned than other national governments with the nurturing of particular industries. Nevertheless, it is important to recognize the important role that pioneer industries such as aerospace play in the long-term competitiveness of U.S. industry.

For the future, the United States must be concerned with maintaining a leading share of the international aerospace market. Since 1970, the U.S. share of the free-world aerospace market has declined in every major market segment: airframes, engines, equipment, and space. If present trends continue, the U.S. share of free-world output will soon fall below 50 percent in every area except space (Appendix G). The United States still retains a significant lead in space technology; however, other countries are making a concerted effort to capture a significant share of the rapidly expanding market for space systems. To the extent that the United States continues to lose its share of this critical technologically pioneering industry, it will be losing part of an important stimulus for development in many other U.S. industries.

The Study—Perspective and Methodology

Each of the three representative technologies studied in this report—turbochargers, fiber-reinforced plastics, and CAD/CAM—represents a somewhat different stage of development, diffusion and maturity. Pioneering applications of turbochargers in aviation occurred in the 1910–20's, fiber-reinforced plastics in the 1930–40's, and CAD/CAM in the 1950–60's. Turbocharger technology is relatively mature, whereas the other two technologies are still developing at a rapid pace.

The perspective of this study is considerably longer and broader than previous efforts, and the methodology is different. Earlier studies, such as the National Aeronautics and Space Administration (NASA) "spin-off" studies, have attempted to measure benefits of specific inventions or applications by intensive tracking from origin to application during a period of one to ten years. Other studies by Chase Econometrics and Mathematica attempted to estimate direct and indirect economic impacts based on econometric analysis of productivity shifts and other measure. Both groups of studies have been criticized for giving NASA or the aerospace industry credit for technologies which had possibly been originated elsewhere. This criticism was largely irrelevant, since where the idea originated is less significant than where the pioneering development efforts occurred, but it still undermined the credibility of the studies in the eyes of some critics.

This study emphasizes the role of aerospace and other pioneer industries in moving technologies along the learning curve, regardless of the original source of the technology. This approach eliminates debates over who gets credit for the "first" invention or innovation. Credit for "pioneering" is shared among all whose early production and usage helps move the technology down the learning curve, in proportion to their share of production along the way.

Cross-linkages among the three technologies also appear when a longer and broader perspective is taken. The significance of these cross-linkages is not quantifiable, but their existence is no less important.

Wherever possible in this study, an effort has been made to quantify costs and benefits, although this has not always been possible because of lack of data and of rigorous statistical techniques for quantifying linkages and down-stream effects. The emphasis has been to view each technology as part of a larger technological context, and to add to the general understanding of the technology diffusion process insofar as the aerospace industry is concerned.

The process by which these representative technologies were selected is discussed in Appendix B.

Technological Learning Curves Reveal the Contribution of Pioneer Industries

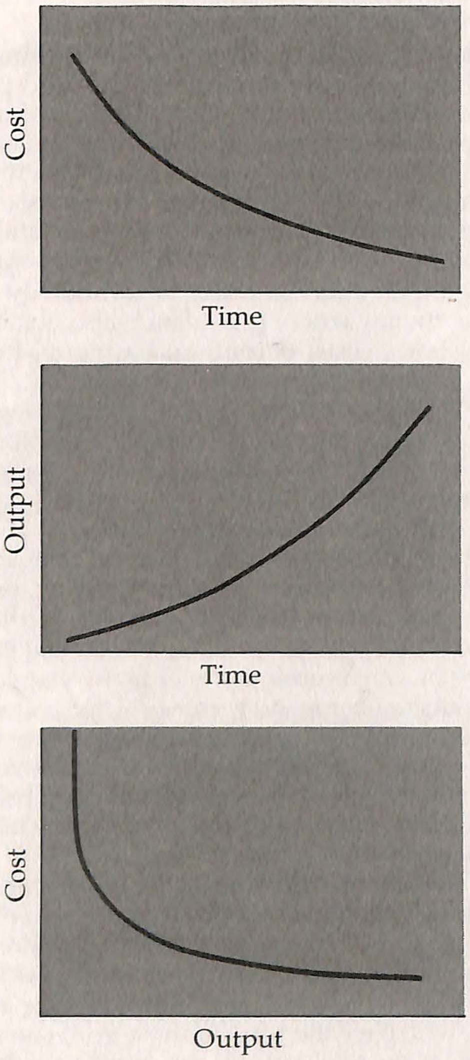
Industry analysts frequently use the learning curve as a tool for examining production costs and productivity in an industry or firm. The concept is simple: as output increases and employees gain experience in the production of a particular product or service, firms become increasingly efficient and able to produce the item at a lower average cost. When the outputs of all firms producing the same item are added together, a learning curve for an entire industry or technology can be plotted (assuming cost or price data is also obtainable). Figure 1 shows costs, output, and a typical industry learning curve for a hypothetical product.

Initially, costs are high due to inexperience with the technology, product, or service. As initial inexperience is overcome and the idiosyncracies of the process become more familiar through research and development and production experience, costs tend to fall substantially as output increases. When costs fall, the product becomes attractive to a wider market, prompting further expansion of output and still further cost reduction. This cycle of cost reduction, output growth, and diffusion often continues over many years. Later, as the product matures and becomes better understood, further cost reductions become more and more difficult to achieve and changes in output have relatively less effect on costs. Eventually, new technologies, products, or services may appear to displace the mature item and begin a new learning curve cycle.

When the cost is high during the initial stage, only a few users will find it economically worthwhile to utilize the new process or product. The innovation must provide substantial benefits to justify its costliness (and often riskiness). Those who enter at this stage are true pioneers, who pave the way for those who come later. By adding to the total output, the pioneers help push the costs downward along the learning curve and benefit those who will be able to use the innovation only after its costs have reached lower levels.

Throughout this study, AIA seeks to identify and quantify learning curves associated with the three technologies reviewed, and tries to identify and quantify the contribution of the aerospace industry to the expansion in output wherever possible. While aerospace firms are often among the early users of new technologies, they are not always the originators of those technologies. Other individuals and industries often create new ideas which cannot economically be used in fields where the premium for improved performance is not supported by the marketplace. Still other industries, including aerospace, provide the critical pioneer markets for such

FIGURE 1
Cost, Output Learning Curves for a Typical Product



innovations. If the pioneer market is relatively strong, the pace of cost reduction and diffusion to other industries is likely to be rapid. If, on the other hand, the pioneer market is small and uncertain, cost reduction and diffusion is likely to be slow.

Diffusion may also depend on changes in the performance requirements of potential secondary users. For example, widespread use of turbochargers in automobiles, trucks, and earth-moving equipment did not occur until the rising price of fuel made weight-saving and fuel efficiency a serious concern of equipment buyers, by which time turbocharged aircraft engines had already been displaced by jet engines.

Data Sources

Earlier case studies of technology movement have been heavily dependent on the willingness of firms to provide proprietary information. In this study, this difficulty has been reduced in significance by the broader and longer perspective utilized, and by the use of the learning curve concept. Although it is virtualy impossible to obtain complete and detailed firm-level data on costs and output, information on past industry markets and prices in selected years can sometimes be extracted from trade publications, government sources, and commercial information sources. While this is less than ideal for statistical purposes, it is far superior to most obtainable proprietary data, which may be suspected as self-serving.

The Smithsonian National Air and Space Museum (NASM) is internationally recognized for its expertise on the history of aviation and aerospace technology, yet this valuable resource has not been tapped by earlier studies. During this study, the NASM staff provided invaluable help in tracing the development and significance of many innovations which were initially considered as possible case study technologies. After the study had been narrowed to the three technologies described in the chapters which follow, much useful information, referrals, and counsel were obtained in several discussions with NASM staff and consultants.

The use of these previously untapped data sources helped considerably in the preparation of this study. It may also contribute to the quality and credibility of the results.

Many other individuals and firms, including many not associated with the aerospace industry, also provided information and assistance that contributed to the development of a broader perspective than could have been obtained otherwise.

Despite the help received from many sources, many quantitative questions remain unanswered. For example, in many instances data on prices and quantities of specific products prior to the 1960's seems to have been discarded, and what remains is sometimes incomplete, having survived largely by accident. While these difficulties leave occasional blemishes on the portraits reconstructed in the case studies, the main lines are clearly visible.

Turbocharger Technology

The aerospace industry has been a significant pioneer in the field of turbomachinery. The turbocharger, a part of the turbomachinery family, provides just one example of an aerospace contribution that has generated widespread technological advances and economic benefits to the remainder of the economy.

Turbomachinery includes all classes of machinery that utilize a turbine or wheel to generate energy. The actions of flowing water, steam, air or heated gases are used to power rotating shafts. Windmills, hydraulic turbines such as water wheels, steam turbines used to convert steam into mechanical energy, gas turbines, and most jet engines are all examples of turbomachinery.[1] The turbocharger is a relatively recent addition to the turbine field.

A turbocharger is a device which is attached to an internal combustion engine to increase its efficiency. Exhaust gases from the engine turn a turbine in the turbocharger. The turbine drives a compressor which, in turn, pumps inlet air into engine cylinders at higher pressures. Since an internal combustion engine depends for its power on its air supply, turbochargers act as auxiliary airpumps that increase engine power and performance by increasing the air supply.

The turbocharger was not an aerospace brainchild, but its initial application on a gasoline engine was on an aircraft. Its increasing use today on automobiles, business aircraft, and a wide range of industrial vehicles has been greatly aided by the aerospace industry's early involvement in turbocharger development. The experience and know-how gained in this development have been utilized and refined by the major U.S. producers of turbochargers, who have followed the market from aviation into other parts of the economy.

Early History of the Turbocharger—1900–1950

Many names are associated with the invention and early development of the turbocharger. Among them are Alfred J. Buchi, 1905 patent holder of a multi-stage turbine, axial-flow compressor and intercooler; Dr. Sanford Moss, creator of an early gas turbine while a graduate student at Cornell in 1901 and pioneer developer of the turbocharger at General Electric during World War I; Auguste Rateau, 1916 patent holder of a turbine-driven supercharger; General Electric; Packard; Pratt and Whitney; Garrett; Boeing; and Wright Aeronautical, among others. Appendix C provides a chronology of turbocharger development from 1901 to the present.

Early applications of the turbocharger were attempted on stationary powerplants, locomotives, cargo ships, and passenger vessels in Europe and the United States. Most of these applications coupled a turbocharger to a diesel engine, which is fired by the temperature created by high compression rather than by the timed firing of a spark plug. The turbocharger provides inlet air to the engine at higher pressures than a reciprocating engine could achieve without some type of pre-compressor.

During this early period, in the final stages of World War I, England and France began experimenting with turbocharging aircraft. The exhaust-driven turbocharger proved difficult to develop, so attention turned toward gear-driven turbines; these met with only limited success because of the added weight and complex chain-drive machinery they required. In the United States, attention promptly returned to turbocharging or "turbo-compression" techniques.

In 1917, the U.S. National Advisory Committee for Aeronautics (NACA) commissioned Sanford Moss, then an employee of General Electric, to develop a "turbo-compression" mechanism to maintain an aircraft engine's power and performance at altitudes higher than sea level. Moss and GE developed the first application of the turbocharged gasoline engine—in an aircraft. They used an Army Air Corps LePere biplane powered by a Packard-built Liberty V-12 engine. It was tested at Pikes Peak, whose elevation reaches some 14,000 feet and, after several false starts and necessary refinements, the turbocharged plane set a new altitude record of over 39,000 feet in 1920. This achievement was a major milestone in the development of the turbocharger and of high altitude flight.

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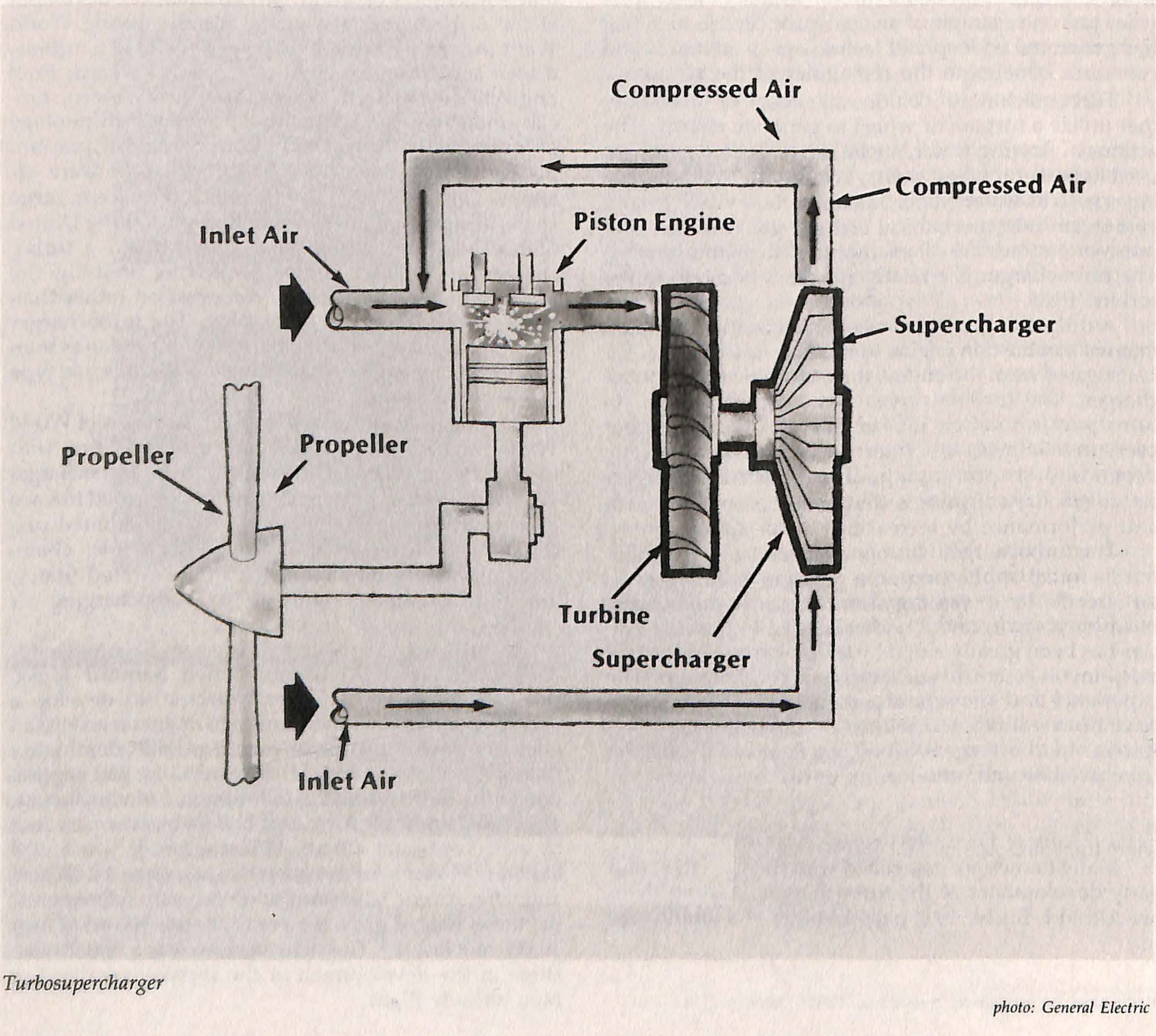
[1] "Turbine," *Encyclopedia Americana*, XXVII, 1969, p. 233.

With the end of the war and a changed political and economic climate, progress on the turbocharger slowed for several years. During the inter-war period, development was directed away from the military and toward commercial products. In addition, metallurgical developments failed to keep pace with the high-temperature demands imposed by a turbocharger attached to an aircraft engine. Moreover, another development—Lindbergh's solo trans-Atlantic flight in 1927—led the aviation industry to the false conclusion that air-cooled, rather than liquid-cooled engines, would be used in the future. Leading U.S. aircraft engine manufacturers, such as Pratt & Whitney and Wright Aeronautical, chose not to add the weight, complexity and high-temperature environment created by turbochargers. Gear-driven superchargers, though less efficient, were used with some air-cooled engines.

The development of turbochargers continued at a slow pace, with some activity in the automotive sector involving racing applications at the Indianapolis 500 and other championship events where high performance was vital. Though a fledgling technology was available, no significant market existed, either in aviation or autos. Nevertheless, although development of turbochargers slowed following World War I, the linking of the turbocharger with an aircraft engine near the end of World



Turbosupercharger

photo: General Electric

War I set the stage for the next 60 years for turbo-assisted propulsion in the aerospace industry.

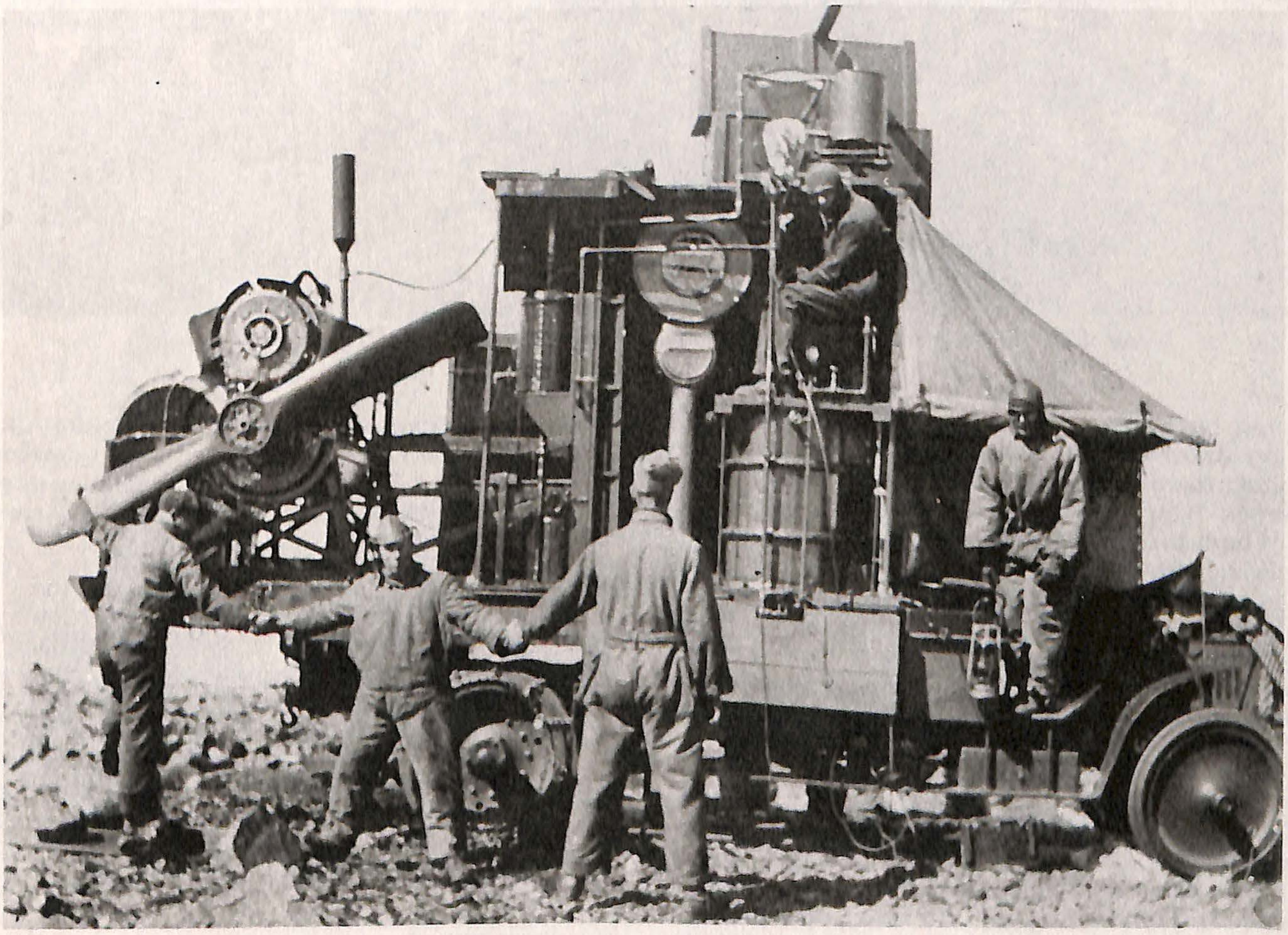
As World War II approached, military interest in turbocharging aircraft engines was renewed. With the advent of commercial aviation in 1936 and later years, the demand for turbocharged aircraft engines accelerated. The aircraft industry undertook to refine the turbocharger to take advantage of its exhaust-driven performance advantages. The disadvantage of high temperature was overcome by the application of an intercooler to cool hot compressed gases. The Garrett Corporation, a maker of small turbine engines, provided the intercooler used with GE turbochargers and Wright piston engines on B-17's used during World War II. Later turbocharged aircraft included Lockheed's P-38 Lightning, Consolidated's B-24 Liberator, Republic's P-47 Thunderbolt, and Boeing's B-29 Superfortress. The turbocharger also powered a number of the last generation of large piston-powered transport aircraft.

By the end of the war, substantial progress had been made in the development of turbo-machinery technology, culminating with the invention of the jet aircraft engine. Frank Whittle from England received the first patent on the jet engine in 1932. Dr. Hans von Ohain of Germany received a patent in 1935. Ohain's Heinkle engine made the first flight in 1939 followed by Whittle's engine in 1941. Dr. von Ohain, now a consultant to the Smithsonian National Air & Space Museum, notes the similarities between the radial turbocharger in use today by Garrett and others and earlier aerospace efforts.

During the late 1940's the jet engine came into prominence and U.S. aircraft engine manufacturers, including General Electric who had been the leading maker of aircraft turbochargers, channeled their efforts to meet this new means of aircraft propulsion. The turbocharged piston-driven aircraft engine, though successful, was replaced by a newer and even better aviation powerplant, the jet engine.

Recent History of the Turbocharger—1950–1985

By the 1950's, non-aerospace uses for the turbo-



In 1918, the turbosupercharged Liberty engine proved the virtues of Sanford Moss's design for General Electric by producing 356 h.p. atop Pike's Peak.

photo: General Electric

In 1921, the LePere biplane with General Electric's supercharged engine set an altitude record of nearly eight miles.

charger included commercial truck applications, largely on diesel engines. Most of these engines were manufactured by the Elliott Company (under Buchi license), Schwitzer, and later Cummins Engine.

Efforts to turbocharge trucks were impeded by high costs and frequent failures of both engines and turbochargers. Most of these failures were due to insufficient technical know-how and unsatisfactory materials. However, although turbocharging for heavy trucks was not an immediate success, work continued with earth-moving equipment, which often had to operate at high altitudes in mining and road-building operations.

Garrett applied the expertise it had acquired in building intercoolers for GE's aircraft turbocharger to adapting turbocharging to heavy earth-moving equipment. In 1954, Garrett was awarded the largest turbocharger contract of its time, an order for 5000 units from Caterpillar Tractor Company. The firm launched a turbocharger development program for ground vehicle engines which resulted in its becoming today one of the world's largest suppliers of turbochargers.

In 1955, Garrett announced the birth of its AiResearch Industrial Division, dedicated to the development and production of turbochargers. Crediting its experience in the development of aircraft superchargers, a Garrett announcement said:

> "Turbomachinery manufactured by the AiResearch Manufacturing divisions has been characterized by radial compressors and radial turbines of remarkable characteristics for about a decade. Millions of hours of field experience have been accumulated, frequently under the difficult conditions found in aircraft. This background knowledge enabled AiResearch to design and build turbocharger applications to meet the toughest requirements for heavy duty operations with superior performance."[2]

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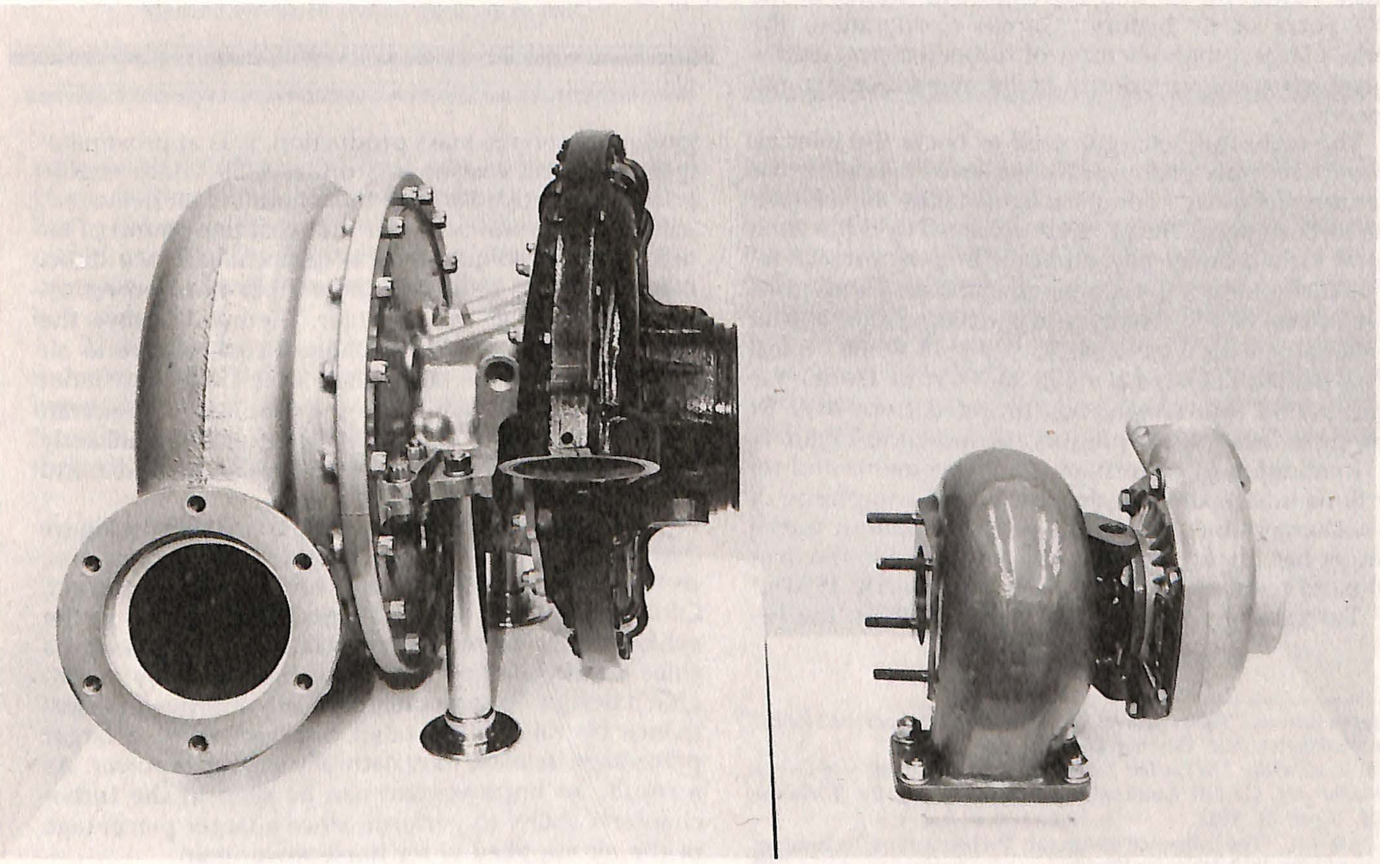
[2] "Turbochargers for Tractors Being Delivered—New Industrial Division Equips Caterpillar Diesels," *AiReporter* (The Garrett Corporation), May 1955, p. 1.

At the same time, Caterpillar announced that its new turbocharged D9 earth mover operated satisfactorily for more than 1,800 hours during 10 months of demanding duty—a milestone for a turbocharged earthmover. Substantial power increases, greater efficiency and reduced noise were credited to the new turbocharger. Since then, off-highway vehicles operating at high altitudes have been able to achieve performance levels unobtainable without turbochargers. For instance, a rock crusher powered by a 190 hp diesel engine lost 25 percent of its power and stalled under heavy loads when operating at 7,400 feet in the Rockies. After a turbocharger was applied, the original 190 hp was boosted by 13 percent and fuel consumption declined by 10 percent.[3]

By the late 1950's and early 1960's, diesel trucks using superchargers were increasingly common. Mack Truck, Detroit Diesel, and International Harvester began to apply turbochargers to their production line trucks. As early as 1952, Cummins had attached an Elliot turbocharger weighing 30 pounds to a diesel truck engine, raising its power from 150 to 400 hp. A racer powered by the Cummins-built engine captured the pole position at the Indianapolis 500, attracting considerable publicity for the firm.

The automotive industry also contributed to the development of turbocharging by testing the limits of turbocharger performance under difficult vehicular conditions, particularly for short bursts of power in racing. The introduction of several turbocharged automobiles in the 1960's was not a success. However, following some later successes in auto-racing circles, U.S. and foreign automobile manufacturers began testing the commercial waters again in the early 1970's. Several turbocharged foreign cars achieved mild commercial success. In 1972, Garrett joined with U.S. auto makers to design turbochargers for smaller engine production cars.

The "energy crisis" of the 1970's prompted the U.S. automobile industry to try smaller engines with fewer cylinders to cut fuel consumption. However, the driving public continued to demand the performance it had come to expect from larger, more powerful engines. The turbocharger offered the dual benefit of raising the



Two Garrett Corporation turbochargers illustrate technological progress over several decades. The 1982 version on the right achieves more than twice the speed at less than one-fifth the weight. It requires 53 parts compared with the 1953 version's 182 parts.

photo: Garrett Corporation

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[3] Ben Scarpero, Office memo to Wilton Parker, et al, The Garrett Corporation, May 20, 1977.

horsepower of smaller engines while also preserving lower fuel requirements. Chrysler, Ford, General Motors, and several foreign auto makers have introduced production models equipped with turbochargers in the last decade. Chrysler now installs turbochargers as standard equipment on about 10 percent of its fleet, the largest fleet percentage of any U.S. auto maker to date.[4]

Work on small, compact turbochargers for auto use has also led back toward improved aviation applications. The market for general aviation aircraft was improved in the mid-1960's when a Garrett-turbocharged Cessna set a new world's light aircraft altitude record of 39,000 feet.[5]

Economic Impact of Turbochargers

Since the 1920's, the turbocharger market has grown substantially, as shown in Figure 1.

The North American turbocharger market is an aggregate of units for off-highway use (tractors and special purpose equipment), automobiles, and general aviation aircraft. Smaller but important market segments include marine and industrial engine turbochargers, stationary powerplants, and railroad locomotive applications.

The current market for turbochargers has been significantly influenced by the aircraft industry's performance requirements and development efforts in the early years of its history. Garrett Corporation, the world's largest manufacturer of turbochargers, credits its technological superiority to its aviation roots and experience.[6]

The early turbocharger used to boost the inlet air pressure on early piston-powered aircraft is clearly the forerunner of today's compact, lightweight, and simpler auto turbocharger. The progress achieved over the years shows how dramatically different in performance today's turbocharger is even when compared with units built in the 1950's. Today's turbocharger operates at rotational speeds exceeding 85,000 rpm while typical 1950's models operated at about 40,000 rpm. During the same period unit weight has dropped from over 94 pounds to less than 17 pounds, as shown in Figure 2.

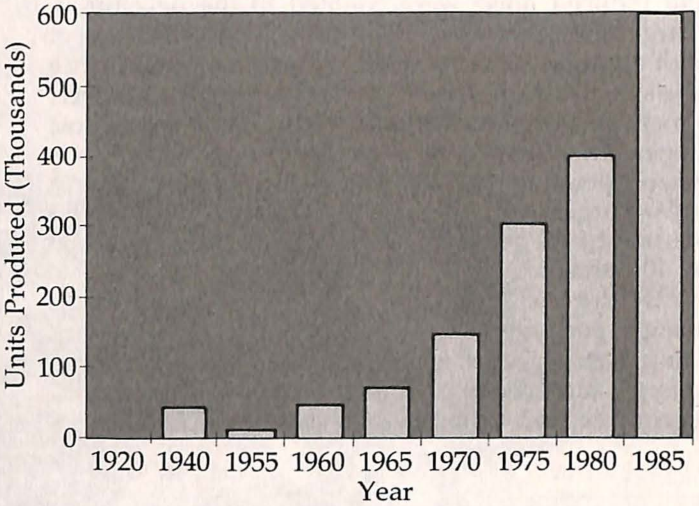
In addition to performance improvements and reductions in size and weight, the overall complexity of turbochargers has been reduced. The modern turbocharger has fewer than 50 parts, compared to the over 200 parts required by the models of the early 1950's.[7]

Turbocharger unit cost in the mid-1950's, the beginning of serious mass production, was approximately $1,000. Unit cost now is under $150. Since engine power is directly related to the amount of air delivered, a reduction in turbocharger unit cost per pound of air delivered per minute by the turbocharger is a direct measure of the reduction in cost per horsepower attributable to the turbocharger. Figure 3 shows the marked reduction of turbocharger cost relative to air delivered which has taken place since 1950. Were it not for the experience gained in the production of aircraft turbochargers, the curve would be at a significantly higher cost level, even though the downward trend would still probably exist.

Garrett and others expect the trend seen in Figure 3 to continue, with the rate of reduction becoming less, as the learning curve concept would lead us to expect. Of course, not all of the dollar savings shown in the exhibit can be claimed by turbocharger improvements since a turbocharger is aided or hampered by an engine's design. Engine builders have improved performance by raising the rated horsepower to a larger percentage increase over naturally aspirated power. As a result, an improvement can be seen in the turbocharger's ability to perform, since a larger percentage of the air supplied is for horsepower gain.

In a similar way, fuel efficiency is a by-product both of advances in turbocharger development and better overall engine design. Most estimates for fuel savings

FIGURE 1
North American Turbocharger Market



SOURCE: The Garrett Corporation for years 1955–1980; Shriner-Midland estimates for 1920 (160+ units), 1940 (40,000 units) and 1985 (600,000 units).

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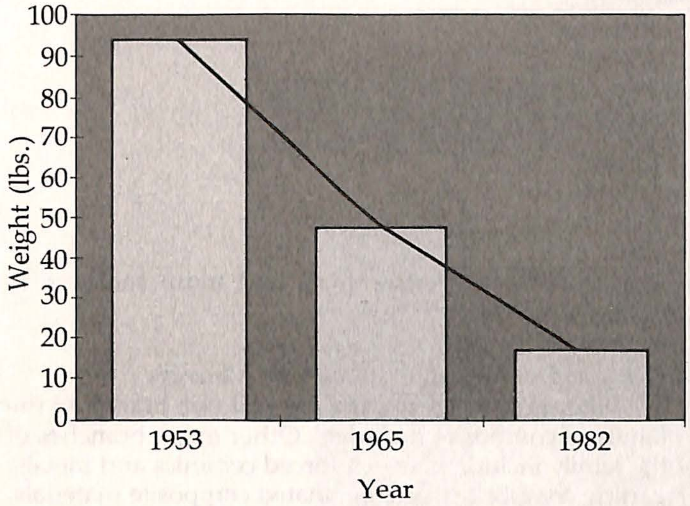
[4] Warren Brown, "Turbo Revival Puts Power Back Under the Hood," *The Washington Post*, October 21, 1984, pp. K1–K3.

[5] Kim Stocksdale, *The Garrett Turbocharger Book: A History of Garrett Turbochargers*, Garrett Automotive Products Company, Torrance, Calif., April 21, 1982.

[6] J.L. Mason, "The Influence of Aircraft Turbomachine Technology on Vehicular Turbocharger Design," paper presented at the 1983 Tokyo International Gas Turbine Congress, Tokyo, Japan, October 23–29, 1983 (paper # 88-TOKYO-IGTC-70).

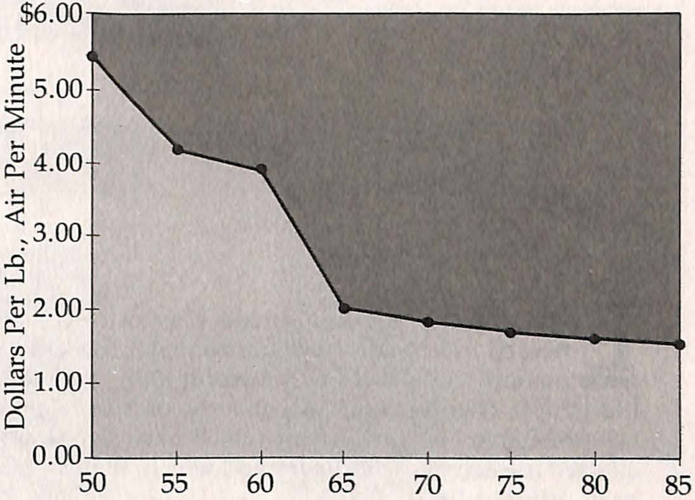
[7] Ibid.

FIGURE 2
Turbocharger Weight Reduction



SOURCE: The Garrett Corporation for 1953 and 1982. Shriner-Midland estimated weight for units in 1965.

FIGURE 3
Turbocharger Cost vs. Air Delivered



SOURCE: The Garrett Corporation for years 1955–1970. Shriner-Midland estimated cost vs. air delivered for the years 1950, 1975–1985.

average about 15 percent over non-turbocharged engines, ranging between 10 and 20 percent. On this basis, if we project 5 million cars with turbocharged engines, each driven 10,000 miles per year, the projected fuel savings amount to well over one-half billion gallons of gasoline annually.

The turbocharger, first pioneered by the aviation industry nearly 70 years ago, continues to find new and beneficial uses in other parts of the economy. These benefits were not quick in coming. Widespread use of turbochargers outside aviation did not occur until their use within aviation had already been eliminated by a newer and better technology, the jet engine. Yet, because of the pioneering developments which had been made earlier in aviation, and to a lesser degree in ships, turbocharger technology was available and cost-effective when the need for it arose in heavy equipment in the 1950's and in automobiles in the 1970's. It is difficult to measure the contribution uniquely attributable to the aerospace industry in such a situation; yet the evidence strongly suggests that the contribution is substantial.

Fiber-Reinforced Composite Materials

Light, strong fiber-reinforced plastics (FRP) pioneered in aviation have found major roles in recreation, construction, transportation, and other industries. This section looks at some of the major developments in FRP technology which have significantly affected the aerospace industry and which, in turn, have been affected by it.

Since the first aviation applications of FRP materials in the 1930's and 1940's, the aerospace industry has been an important pioneer in the development and use of FRP composites. Today FRP composite materials, especially carbon fiber and hybrid fiber composites, account for a rapidly increasing share of the total weight of contemporary aircraft. The latest generation of commercial jets are currently made with 10–15 percent FRP materials, and the percentage is expected to rise to 65 percent or more within 10 years. U.S. military aircraft are currently being produced with as much as 25–30 percent FRP materials, and this percentage may approach 60 percent by the early 1990's. Helicopter manufacturers, who have long used FRP's in rotor blades and for other purposes, are currently designing rotorcraft with 60–80 percent FRP materials. A new generation of general aviation aircraft currently being tested and certified for use in the late 1980's are built almost entirely of FRP's. Applications in other industries are also increasing, and many materials experts suggest that FRP's and other composite materials will be more widely used than metals in the next century.

While aviation and aerospace have not always been the originators of these developments, the industry has been among the first and largest users of new FRP technologies because of the performance improvements they provide. The high strength-to-weight ratio of FRP's, their corrosion resistance, and their ability to be readily fabricated into large complex structures make FRP's well-suited to many applications in aerospace and in other industries where these characteristics are important. The experience gained in aviation and aerospace has been a significant factor in reducing the cost of using FRP materials and in speeding up the rate of adoption by other industries whose requirements are less sensitive to performance and more sensitive to costs.

FRP's and the Family of Composite Materials

Fiber-reinforced plastics are just one branch of the family of composite materials. Other major branches of the family include fiber-reinforced ceramics and metals, particle composites, and laminated composite materials. Figure 1 shows the main branches of the FRP family and its principal relatives.

For centuries Man has recognized that bricks are stronger when reinforced with straw and that a wooden shaft is less likely to break when wrapped with cord. These are among the earliest examples of fiber-reinforced composite materials. But the application of this concept to other materials is relatively recent, and the complex chemical and mechanical interactions that can occur between different types of fibers and matrix materials has begun to be understood technically only within recent decades. Most of what we now know has been learned in just the last 20 years.[1]

Fiber-reinforcement can be used to strengthen and improve many kinds of materials. Fiber-reinforced plastics are probably the most common form, but rapid progress is being made in the development of fiber-reinforced ceramics and fiber-reinforced metals capable of operating at temperatures far beyond the capabilities of FRP's. While each fiber-matrix combination has distinct properties, the scientific principles are broadly applicable to all. Hence, progress in one area of fiber-reinforced composites tends to facilitate progress in other areas. Experience gained in the use of increasingly sophisticated FRP's accelerates progress in the development of fiber-reinforced metals and ceramics.

An important design advantage of FRP's (and other fiber-reinforced materials) is the variety and adaptability they provide. By choosing different types of fiber and plastic, different proportions between the materials,

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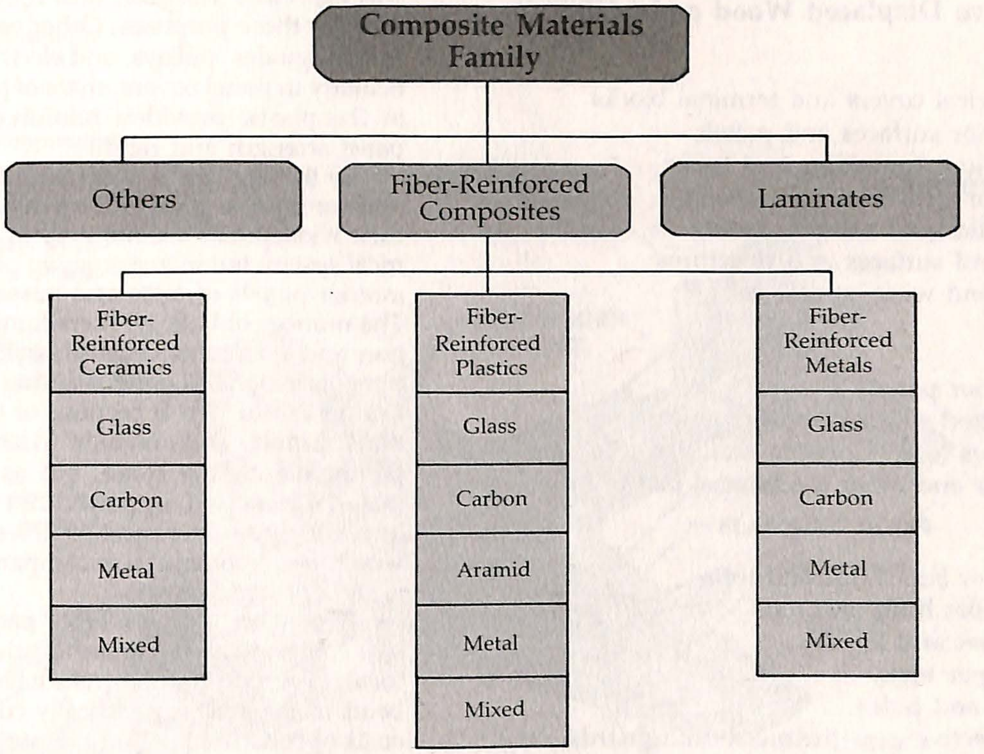
[1] H. R. Clauser, *Industrial and Engineering Materials*, McGraw-Hill 1975, p. 382.

FIGURE 1



and different alignments of the fibers, the designer can match the characteristics of the material more closely to his needs than is possible with monolithic materials such as wood and traditional metals. Glass, metal, carbon, and various synthetic fibers can be used to reinforce many different types of phenolics, epoxies, polyimides, acrylics, and other plastics, creating new materials whose weight, strength, elasticity, conductivity, corrosion-resistance, cost, and other characteristics can be custom-tailored to specific requirements. Figure 2 lists some of the many products in which FRP's have displaced wood and/or metal.

In addition to the design flexibility which FRP's provide, they also offer the prospect of major savings in production costs as fabrication techniques improve. First, FRP's require less energy to produce than a comparable amount of metal. Second, designs which require an intricate combination of large and small metal parts to achieve the desired shape, strength, and weight can often be replaced by a single large FRP component of complex design. The reduction in number of parts reduces production and assembly time. Third, FRP fabrication reduces material wastage, especially in complex metal components in which 50 percent or more of the original metal must be cut or ground away to create the part. This creates still further energy cost savings.

Until recently, most FRP fabrication was done by hand but many firms, particularly in the aerospace industry, are rapidly increasing the amount of automation in FRP fabrication. As these techniques are developed and used more widely, they will further reduce costs and improve the quality of FRP products.

Many examples of FRP fabrication techniques pioneered in aerospace have been identified in earlier studies. For example, Appendix D lists spinoffs of specific advances in composite technology from aerospace to other industries which have been studied by the University of Denver's Research Institute. Most of these spinoff cases represent directly traceable usages that occurred within a period of 1–5 years after the new technology was created. Even in that relatively short time interval, the impact of these spinoffs on costs and quality were significant.

The development of FRP's is generally representative of developments throughout the broader field of composite materials. This study will look at two specific

FIGURE 2
Products in Which Fiber-Reinforced Plastics Have Displaced Wood and Metal

Aerospace

- electrical covers and terminal blocks
- interior surfaces and panels
- pressure containers and tanks
- minor structural components
- nacelles and exterior panels
- control surfaces and structures
- tail and wing assemblies

Automotive

- interior panels
- selected exterior panels
- bodies (e.g., Corvette and Fiero, kit cars, etc.)
- gears and other mechanical parts

Recreation

- power boat hulls and tops
- sailboat hulls and tops
- canoes and kayaks
- camper tops
- skis and poles
- protective gear (helmets, shin guards, etc.)
- racquets and clubs
- fishing rods
- gun stocks

Appliances and Other Products

- radio/TV cases
- computer housings
- luggage

groups which are representative of other FRP groups as well—glass-fiber and carbon-fiber reinforced plastics. Glass-fiber composites developed at an earlier stage than carbon-fiber composites. Experience gained in the use of glass FRP's in the 1930–50's contributed greatly to the subsequent development and use of carbon FRP's from the 1960's to the present. A brief overview of developments in glass FRP's will pave the way for a somewhat more extensive look at the development of carbon fiber composites technology.

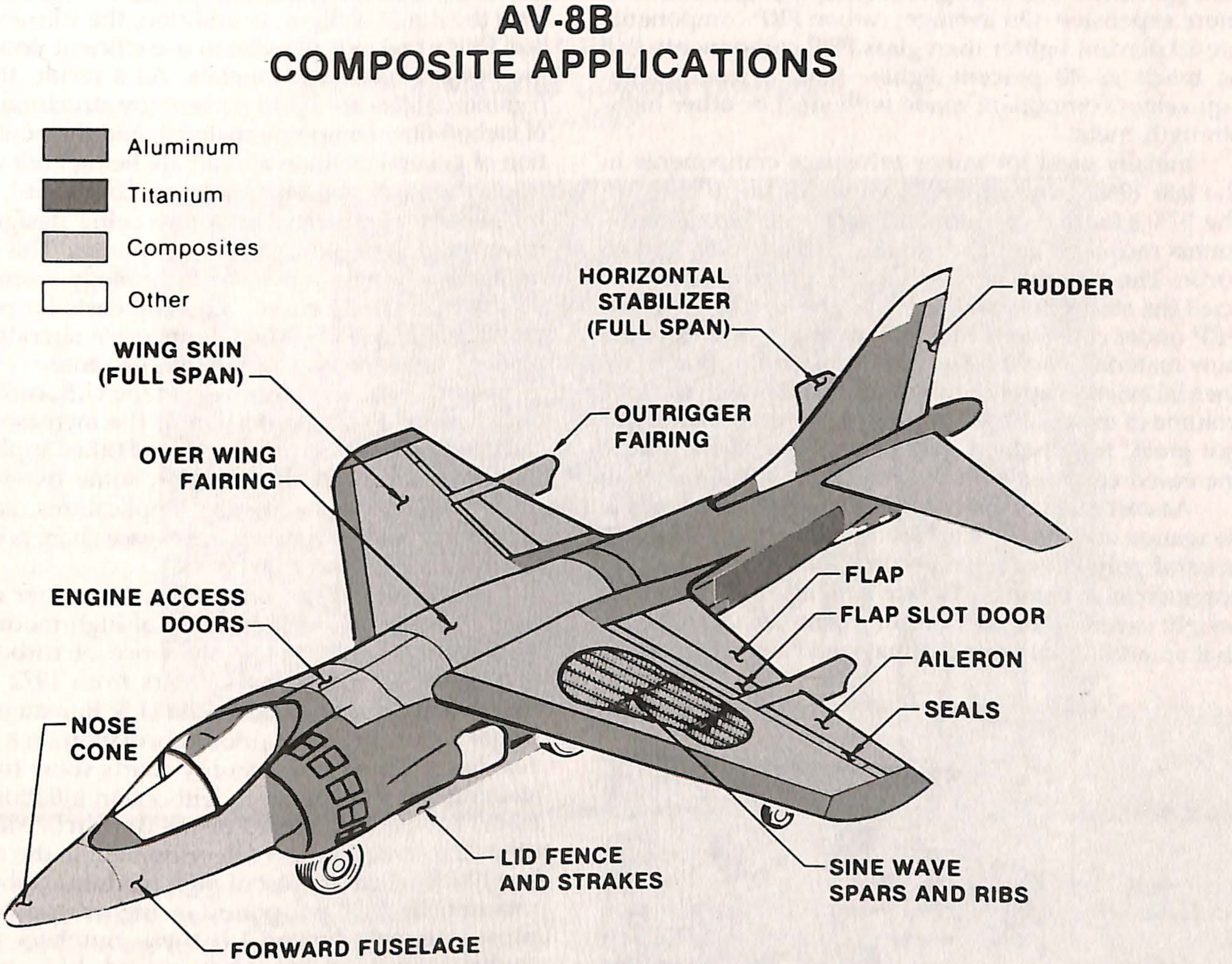
Glass Fiber Composites

Among the first uses of plastic were applications that took advantage of its non-conductivity and ease of fabrication. Thermoplastics, sometimes reinforced with chopped glass fibers, were economical, light-weight, and durable as electrical system components such as insulator blocks, receptacles, switch components, and so forth. These were the earliest applications of the material in aviation as well, where their light weight was especially valuable, and they are still extensively used for these purposes. Other early applications were as cable guides, pulleys, and electrical panel covers. Particularly in panel covers, mats of glass fibers imbedded in the plastic provided reinforcement that gave the panel strength and rigidity.

By the late 1940's, the value of strong, light-weight, non-conductive glass FRP's in aviation was reflected in their widespread use not only in and around the electrical system but increasingly in other areas such as the interior panels of crew and passenger compartments. The number of U.S. workers familiar with the production and maintenance of glass FRP panels and components expanded greatly during and immediately following World War II because of these aircraft applications. Similar uses outside aviation were largely experimental at that stage, but as familiarity with the material increased, opportunities for new uses became increasingly apparent and costs were approaching levels which were economical in comparison with wood, metal, and other materials.

Experience with glass FRP panels and electrical system components on aircraft in the 1940's led the way for a revolution in the construction of motor- and sailboats in the 1950's, drastically cutting weight and the costs of construction and maintenance. In 1946, wood or metal were the standard materials for boat-building, and the costs of maintaining a wood or metal boat were a major deterrent to ownership. By the mid-1950's, glass FRP had almost totally displaced wood and metal in the construction of outboard motorboats. Glass fiber boats were easier and cheaper to build, much less costly and time-consuming to maintain, and light enough to be easily towed by the family car. The result was a complete revolution in recreational boating in the United States.

The properties which made glass FRP's attractive to aerospace and recreational boating manufacturers also were important to other industries. In 1954, Chevrolet introduced the Corvette, the world's first production car with a glass FRP body. This pioneering step in the auto industry did not, however, lead to the same kind of revolution in auto making that had occurred in boat building. Light weight was less critical in most auto applications; mass production in the quantities needed by auto makers was not yet as economical as with metals and other materials; and car buyers were less interested in the characteristics provided by glass FRP bodies. While Corvette production of glass FRP bodies has continued for 30 years and provided extensive experience in the production of increasingly large numbers of FRP car bodies, other applications in the auto industry were limited until the 1980's when Pontiac introduced its Fiero, which uses a multi-fiber FRP, and



The AV-8B Harrier II, an advanced light attack STOVL (short takeoff and vertical landing) aircraft developed by the McDonnell Douglas Corporation, is 27 percent composite material by structural weight. The diagram shows the wide use of composite material versus metal. The AV-8B wing is one of the largest composite components produced in the world. At 28 feet wide, the lower half of the wing assembly weighs 265 pounds. If fabricated from metal, the wing would weigh 115 pounds more.

photo: McDonnell Douglas

other GM units began to use FRP panels in some parts of their bodies. These uses were prompted by efforts to reduce vehicle weight, to improve streamlining to meet higher fuel efficiency standards, and to reduce maintenance costs by providing improved corrosion-resistance.

Glass FRP's, often incorporating KEVLAR or graphite fibers as well, have become preferred materials in many industries since the 1950's. They are now used extensively in a wide range of transportation and recreation equipment where strength, weight, and economy are important. In the construction industry, low-cost maintenance-free FRP modules for kitchen and bath are widely used in home building. They are also used in the production of cases and components for many appliances. However, current data on the quantity and cost of FRP's used in these areas are difficult to obtain, and historical data has usually not been maintained by many of the firms contacted in the course of this study.

As the use of FRP's has increased, the cost has continued to decline (though at a slower pace than during the initial pioneering years) and usage in a wider range of products has become feasible. Without the early stimulus provided by the aviation industry, however, the pace of development and use would undoubtedly have been much slower.

Glass FRP's also helped pave the way for carbon FRP's, which first began to be used in the 1960's.

Carbon Fiber Composites

Carbon fibers (also called high-modulus graphite fibers) create FRP materials that are even lighter, stronger, and stiffer than glass FRP's, though somewhat more expensive. On average, carbon FRP components are 20 percent lighter than glass FRP components and as much as 40 percent lighter than a functionally-equivalent component made with steel or other high-strength metals.

Initially used for minor aerospace components in the late 1960's, carbon FRP's were quickly adapted in the 1970's for high-performance recreation equipment—tennis racquets, golf club shafts, fishing rods, and so forth. These early aerospace and sports applications used the strength, stability, and light weight of carbon FRP under conditions in which possible failures of the new material would be less life-threatening than commercial aviation applications might be. Though the total volume of material used in these early applications was not great, they helped give engineers and the public increased confidence in the reliability of the material.

As cost and reliability improved with experience in recreation and aerospace, carbon fiber-reinforced epoxies and polyimides have become increasingly used in commercial aviation and space systems. Each pound of weight saved in the airframe of a commercial jet means that an additional pound of payload can be carried, or that an additional pound of fuel can be carried to extend the range of flight. In addition, the stiffness of carbon FRP's makes it possible to use efficient designs that are not attainable with metals. As a result, the latest commercial jets are 10–15 percent (by structural weight) of carbon-fiber composite material, and the new generation of general aviation aircraft are being built with airframes almost entirely made of composite. By the mid-1990's, commercial jets now being designed will use 65 percent or more carbon composites. This expanded usage will help move the technology more rapidly down the learning curve, reducing costs for other applications. It will also directly increase aircraft fuel-to-payload efficiency by 25 percent or more.

Technicians work on the composite forward-swept wing of Grumman Corporation's highly maneuverable X-29 experimental aircraft. Composites have a direct impact on aircraft aerodynamics and have made the performance of the X-29 possible.

photo: Grumman Corporation

Figure 3 shows the growth in the U.S. carbon fiber output since 1972, a reflection of the increased use of carbon composites in aerospace and other applications. Of the total output shown here, some two-thirds or more has gone into aerospace applications, according to industry sources, and the aerospace share is expected to remain high into the 1990's.[2]

The increased utilization of carbon fiber in FRP's is reflected in the declining cost of high-modulus carbon fibers. Figure 4 plots the price of carbon fibers against U.S. output for the years from 1972 through 1983, using data compiled by the U.S. Bureau of Mines. Figure 5 plots the same price information on a year-by-year basis. These cost-quantity charts show the classic learning curve shape, even without an inflation adjustment. The period covered by the Bureau of Mines data omits the earliest years of development in the mid- and late 1960's when the cost of high modulus carbon fibers was initially $600 per pound or higher and quantities were extremely limited.[3] If these numbers were included, the learning curve would be even more dramatic than shown in Figures 4 and 5.

Using chemical industry estimates of the aerospace industry's share of carbon fiber usage, a conservative estimate can be made of the impact of aerospace usage on carbon fiber cost. The lowest price which would have been reached in the absence of aerospace usage is Price A on the curve in Figure 4; at that point, cumulative output is approximately one-third the final amount (Price B) shown by the curve. Note the difference between Price A and Price B—the price which has actually been reached and the lowest point on the curve. That difference is the *minimum* price effect attributable to aerospace usage.

The effect can be shown also in terms of time by revising Figure 5 to include a price curve calculated without aerospace usage. The revised chart is shown in Figure 6, where the higher curve is the path that carbon fiber price would probably have followed in the

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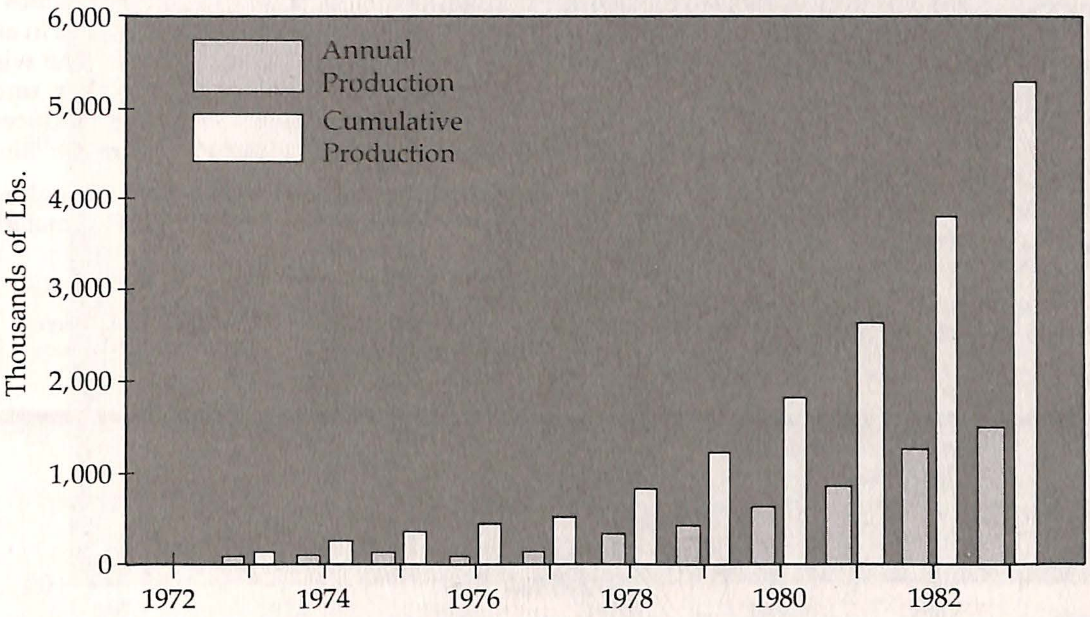
[2] "New Markets Strengthen Sales of Carbon Fiber," *Chemical Week*, April 28, 1982.

[3] L. Kuzela, "Nudging Northrop into the Future," *Industry Week*, July 26, 1982.

FIGURE 3

U.S. High-Modulus Graphite Production 1972–1983



absence of aerospace usage. The price would have been much higher in the early years especially, slowing development and use of carbon FRP technology in other industries and shifting the price curve still higher.

At the same time, it is instructive to note an important example of the impact of cost and uncertainty on diffusion and usage rates. Figure 7 presents a discussion of a possible link between increased uncertainty, cost, and slowed usage of carbon FRP's in the auto industry.

The cost of carbon FRP technology is not just a matter of carbon fiber cost, however, even though that is the component which seems to be most easily measurable. Other major costs include the cost of the plastic materials in which the carbon fiber is placed; the cost of fabricating the layers of fiber and plastic into a final product; the cost of designing each individual component with its complexities of shape, elasticity, strength, and so forth; and the cost of quality control to assure that the finished product conforms to the design.

It is significant that these are components which are common to all FRP technologies, not just carbon FRP's. While data on quantities and costs are scarce in these other areas, available evidence suggests that similar cost reductions are occurring and that the aerospace industry is at the forefront in promoting these improvements in efficiency and reductions in overall cost of the technology. The improvements which have been made, and which are currently being made in FRP design and fabrication technology, are illustrative.

FRP Design and Fabrication Technology

Improved fabrication methods such as filament winding, automatic tape-laying, and accelerated curing procedures are cutting production time and costs for aircraft and space systems and pioneering the way for applications in other industries.

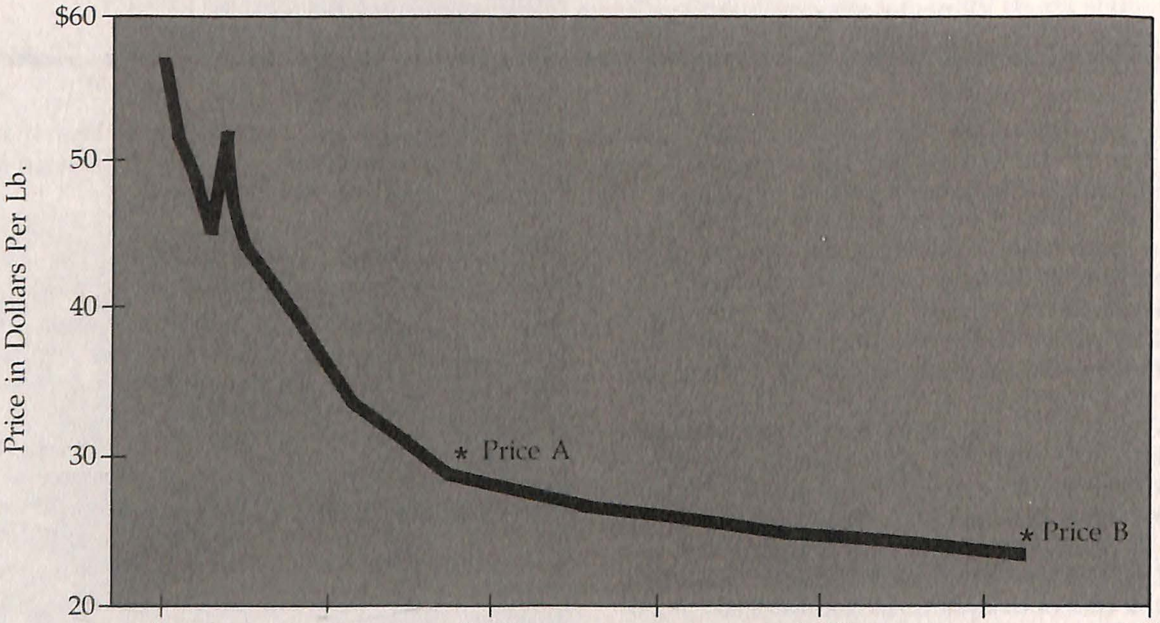
McDonnell Douglas, Northrop, Grumman, Boeing, Lockheed, Bell Helicopter, and other aerospace firms have devoted considerable investment toward improving the productivity and reducing the cost of their FRP design and fabrication facilities. Here are just a few examples:

- Northrop's efforts have been extensively covered in several business magazines, which characterize Northrop as "creating the factory of the future." Northrop engineers have linked together automated systems for formulating the design of a new FRP product, planning the most efficient use of materials, cutting many layers of fabric quickly and with minimum wastage, automatically positioning fabric layers in the exact orientation and location required by the design, and accelerating the FRP curing time with vacuum, microwave and other means.[4, 5]

- Hercules, the largest U.S. producer of carbon fibers, has gained extensive experience in the use of filament winding techniques of FRP fabrication for a wide range of aerospace applications. The same techniques are directly applicable to the fabrication of a wide range of non-aerospace products, ranging from automotive drive shafts to bicycle frames.
- Boeing has pushed its suppliers to develop improved plastic formulations and fabrication techniques to meet its stringent requirements for the new 757 and 767 commercial jets. One supplier indicated that his firm would not have made such a heavy R&D commitment in this area if it were not for the potential sales to Boeing and the credibility the firm hoped to achieve.
- McDonnell-Douglas has developed an "eight-pack" process for grouping plies of pre-impregnated ("pre-pregged") carbon fabrics together to speed fabrication of wing assemblies. Curing is accelerated by "cooking" the plies in an autoclave at 650 degrees F and 150 psi. The wing components are then mated together under strong vacuum pressure. The process reduces construction time by some 160 hours per aircraft.[6]

Similar examples can be found throughout the aerospace industry and its suppliers of FRP materials to illus-

FIGURE 4
Price vs. U.S. Output of High-Modulus Graphite
1972–1983



NOTE: The lowest price which would have been reached in the absence of aerospace usage is Price A on the curve in Figure 4; at that point, cumulative output is approximately one-third the final amount (Price B) shown by the curve.

SOURCE: U.S. Bureau of Mines.

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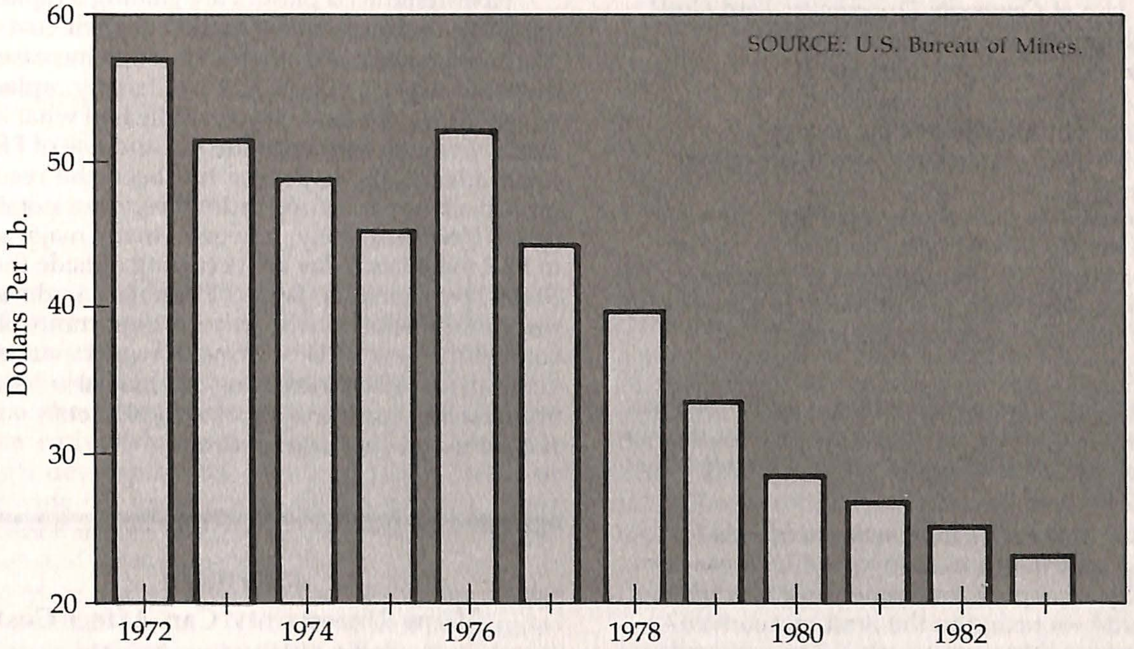
[4] Ibid.

[5] S. L. Jones, "Northrop's All Plastic Aircraft," *American Metal Market*, June 21, 1982.

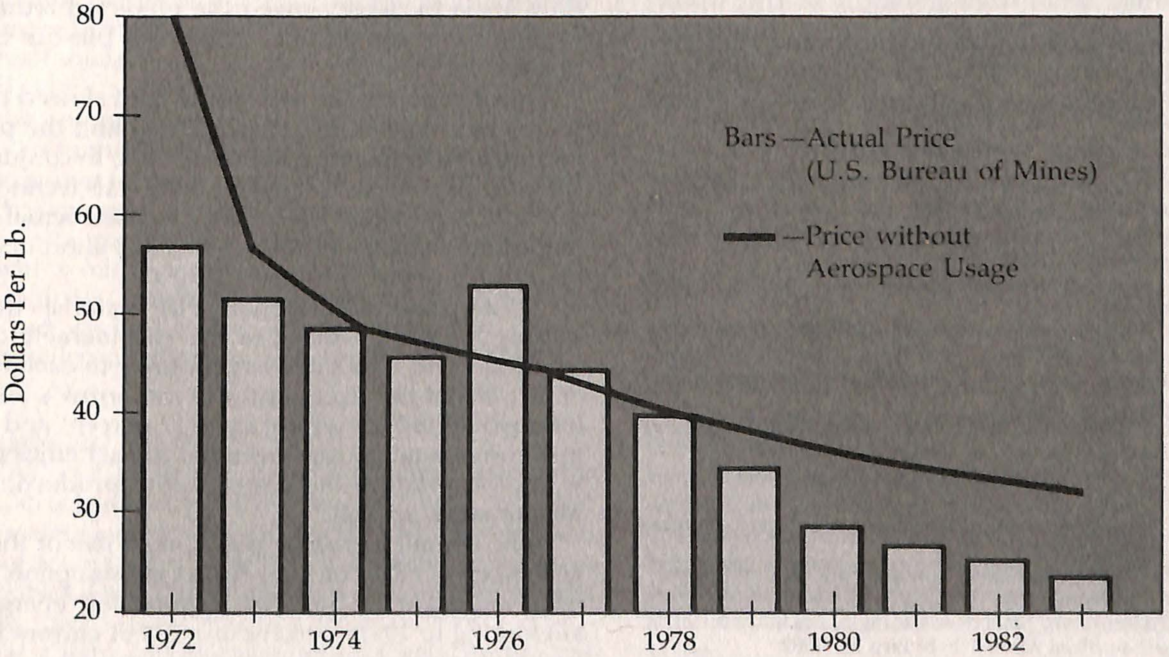
[6] A. K. March, "McDonnell Douglas Cuts Aircraft Construction Time," *Aviation Week & Space Technology*, January 9, 1984.

FIGURE 5
U.S. High-Modulus Graphite Price
1972–1983



SOURCE: U.S. Bureau of Mines.

FIGURE 6
U.S. High-Modulus Graphite Price
in the Absence of Aerospace Usage
1972–1983



trate the progress in aerospace usage, which will soon affect industries outside aerospace.

Recent headlines in various trade magazines best illustrate the applications for carbon FRP's in other industries:

> *Volume Use of Composite Driveshafts: Ford Goal*[7]
> *Recreational Equipment: Fun on Wheels*[8]
> *Auto Tailgates: Steel or Composites?*[9]
> *Composites: Boom in Use Forecast*[10]
> *Composites Growth Spurred by Aerospace*[11]
> *Composites Help Automakers Meet Competitive Challenge*[12]
> *Close Encounters with Space Age Fibers (tennis)*[13]
> *Japan Aims for Non-Metallic Auto in the '90's*[14]
> *New Techniques Produce Intricate Composites*[15]
> *Aluminum, Steel Seen Losing Marts to Composites*[16]
> *Carbon Fiber Composites for Orthopaedic Implants*[17]

In his textbook, *Industrial and Engineering Materials*, Henry Clauser identifies two major reasons for the rapidly growing role of FRP's and other advanced composite materials:

> "One is that the increasing demands for higher performance in many product areas—especially aerospace, nuclear energy, and aircraft fields—is taxing to the limit our conventional monolithic materials. The second reason—the most important in the long run—is that the composites concept provides scientists and engineers with a promising approach to designing, rather than selecting, materials to meet the specific requirements of an application."[18]

Estimates by carbon fiber producers and others anticipate that their usage will continue to grow 30–50 percent annually for the next 15–20 years. Throughout most of the next 10 years, aerospace is expected to account for 75–80 percent of carbon FRP usage. Beyond that point, the share of usage by other industries is expected to expand, reflecting the pioneering role of aerospace in this new technology.

Fiber-reinforced plastics are gaining a rapidly growing share of the materials market as their cost declines and as experience with their fabrication increases. Many materials experts expect FRP's to largely replace many metals during the next 30 years. Much of what is known about the economical production and use of FRP's and other advanced composites has been the result of efforts in a few pioneering industries, most notably aerospace. Unquestionably, however, many major advances in FRP materials today are occurring outside the United States, principally in Japan. The ability to develop and use these materials will play an important role in the competitiveness of U.S. firms in world markets in the years ahead. Their increasing use may also reduce U.S. vulnerability to shortages of critical metals which are not mined in the United States.

FIGURE 7
How Uncertainty Can Affect Cost and Utilization Levels

In the late 1970's, uncertainty over the potential hazard which carbon fibers might pose to electronic systems temporarily slowed the pace of aerospace and other applications until the issue was resolved. This slow-down in usage slowed the predicted reductions in the cost of carbon fiber reinforced plastics by 2–4 years.

The temporary lag in usage in turn slowed the expected reduction in raw material cost and the pace of introduction in the auto industry. This, in conjunction with competitive improvements in metals technologies during this period of uncertainty, caused actual usage in the auto industry to fall considerably short of earlier projections made in the late 1970's.

Widespread use of various FRP materials in automaking are still projected to rise considerably during the 1980's and 1990's as costs continue to decline. Use of 50 percent FRP composites in tomorrow's automobiles would reduce weight by 8–12 percent and result in a corresponding improvement in fuel efficiency. It would also reduce the costs of auto production and maintenance as well.

The overall impact of widespread use of the new generation of FRP's on U.S. energy consumption would be a reduction in transportation-related energy use amounting to 10–15 percent or more of current industrial and transportation consumption.

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[7] A. Wrigley, "Volume Use of Composite Driveshaft: Ford Goal," *American Metal Market*, August 6, 1984.

[8] R. C. Beercheek, "Recreational Equipment: Fun on Wheels," *Machine Design*, May 10, 1984.

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[11] "Business Outlook: Composites Growth Spurred by Aerospace," *High Technology*, October 1983.

[12] W. P. Jenks, "Composites Help Automakers Meet Competitive Challenge," *Design News*, July 4, 1983.

[13] T. Leonard, "Close Encounters with Space Age Fibers," *Tennis*, June 1983.

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Computer-Aided Design and Manufacturing

The aerospace industry has been a pioneer in the advancement of many technologies. Because of the industry's high performance requirements, it uses new technologies at an earlier stage and pushes the pace of their development more rapidly. Aerospace and other early technological leaders thus absorb initially high developmental costs and risks. They also often provide the experience base upon which subsequent economies can be achieved, first within their own industries and later outside of them.

Aerospace was one of the first industries to use computer-aided design (CAD) and computer-aided manufacturing (CAM) to improve efficiency in design and production. High costs of meeting increasingly complex structural and computational requirements, and of minimizing the possibility of human error, have forced the aerospace industry to improve efficiency during the design and prototype stage of manufacturing. For example, developing a new commercial jet transport costs more than $2 billion. Developing such an aircraft requires thousands of complex components to be designed, built, and tested. For each component, there must be one or more design drawings to provide instructions to the manufacturing personnel. Using CAD, drawings that formerly took hours or days can be completed in minutes; using CAM, manufacturing operations can be controlled accurately to the design drawings with a minimum of wasted material, saving both time and cost. In fact, in some cases, CAD/CAM has permitted design, analysis, production and testing which could not otherwise be accomplished without it.

What are CAD and CAM?

CAD is a system to assist in creating designs for parts, structures, circuits, or other products. A typical CAD system includes a computer with a high-resolution display screen, plus a printer or a plotter to produce hard copies. Designs in the form of drawings are created on the screen using graphics commands or a device such as a light pen to make lines, boxes, curves, and other design elements. CAD software typically provides for interactive drawing, a database of design information for previously designed parts, and often rule-checking programs that test to make sure the new design or change conforms to specifications. Figure 1 lists common features found on most CAD software packages today. Many CAD systems also include additional design and engineering tools, such as computer models that enable the user to simulate how the finished product will respond to loads when it is put into use. Such tools, sometimes referred to as computer-aided engineering (CAE) systems, may also be used separately from the design system.

CAM is a system for computerized control of the actual production of the part or product. A typical CAM system uses a computer to instruct a metal-working machine just where and how deep to make a cut on the material placed in the machine. It may also include the capability to detect and measure its results and make adjustments when necessary. Some CAM systems also handle the task of loading the material into the machine quickly and accurately. The overall effect is to speed up the manufacturing process and make it more precise and consistent.

When CAD and CAM are fully linked together, the result is a computer-integrated manufacturing (CIM) system. CIM links the design, manufacturing, and testing processes through an exchange of computerized information. The CIM process begins with the preparation of the product design using a CAD/CAE subsystem. Design information is then passed to a CAM sub-system which uses computerized numerical-control machines (CNC) and, frequently, tests the result with automated testing equipment. In some cases, the system is also linked together with the firm's inventory control system.

"CAD/CAM" is often used as a catch-all term describing one or more of the general types of CAD and CAM systems mentioned here; however, some people apply the term only to systems in which CAD and CAM have been linked together into an integrated system. CAD/CAM is used here in the former, more generic sense.

CAD/CAM systems help increase the productivity of engineers, equipment operators, and machinery and to cut development time, paperwork, material scrappage, and quality assurance costs. Using a CAD/CAM system, engineering drawings are created on a CRT screen, not on paper, so that engineering changes are easier to prepare and examine. The design data base is then shared during the production process, achieving additional savings and improved product reliability.

As a result of adopting CAD/CAM, firms have commonly experienced productivity gains ranging from 2:1 to 15:1. Even higher productivity increases can be achieved in some fully integrated systems, which often radically alter and streamline manufacturing practices.[1]

Aerospace Industry's Leadership Role in CAD/CAM

The factors stimulating the use of CAD and CAM in the aerospace industry are somewhat different than the motivating factors in other industries which were also early users. In the auto and electronics industries, for example, a design may be repeatedly revised during the development stage but then, once production begins, the same design may be used to produce millions of copies of the same part. In the aerospace industry, however, the number of parts built from a particular design is relatively small—often fewer than 1,000 units—and engineering changes continue to occur throughout the production life of the aircraft, space system, or sub-system. The share of final cost attributable to design is, thus, considerably larger in the aerospace industry than in most mass-production industries, and the motivation to reduce the cost and improve the productivity of design effort is correspondingly higher.

Appendix E shows a chronology of CAD/CAM history since the 1950's and highlights the role of aerospace firms in it.

As early as the mid-1950's, aerospace firms were beginning to explore and develop early versions of CAD and CAM systems. Numerically controlled machine tools (NC), automatically programmed tools (APT), computerized numerical control machinery (CNC) systems, shell analysis and finite element analysis systems, and "sketch pad" techniques were all used at an early stage by aerospace firms. To assist in this effort, the U.S. Air Force helped underwrite the acquisition of state-of-the-art metal-working equipment able to handle very large components, such as wing and fuselage sections, and incorporating the latest type of numeric control devices to minimize errors in machining large components. The Air Force continues to encourage the development of automated production technology through its Technology Modernization (TECHMOD), Manufacturing Technology (MANTECH), and Integrated Computer-Assisted Manufacturing (ICAM) programs.

Figures 2 and 3 show the adoption rate of numerical control and computer numerical control systems and of CAM since 1950 among major U.S. firms. Much of the early use in the 1950's and early 1960's was due largely to the initiative of the aerospace industry.

In 1957, a group of aerospace firms, working through the Aerospace Industries Association, organized a joint R&D program on automatic programmed tools (APT)

FIGURE 1
Features of Current CAD Systems

CAD systems have improved greatly since their introduction in the 1960's. (See Appendix E for a chronology of CAD/CAM developments.) Early systems were essentially computer-controlled plotting pens. Sophisticated CAD systems employ software that permits geometric modeling, simulation, engineering analysis, testing for quality control, and integrated manufacturing. A modern CAD work station typically consists of a personal computer, a monitor, a digitizer pad drafting board and a hand-held cursor or pen plotter. CAD software currently available for use on personal computers typically has some or all of the following features:*

- Applications—two-dimensional or three-dimensional architectural drafting; two-dimensional electrical circuit, mechanical, and interior design; two-dimensional line art; two-dimensional flow diagrams and organizational charts. Some programs offer three-dimensional modeling and design.
- Boilerplate drawing—lines, circles, arcs, ellipses, curves, and solids.
- Placing, rotating, and scaling components.
- Cutting and pasting.
- Rubber banding—expanding components and stretching lines.
- Adding text to drawings.
- Multi-layered drawings—two-dimensional functions.
- Reporting distances between points and dimensions for rectangular areas or any closed polygons.
- Rotatable grids for plan and element variations.
- Orthogonal mode—two-dimensional function which forces lines to be vertical or horizontal.
- Data storage format for writing auxiliary programs.
- Zoom in and out; change scale.
- Foreign language capability.
- Several programming languages such as C, Pascal, and machine languages.

*Davis Straub, "Computer-Aided Design," *PC World*, October 1983, pp. 100–114.

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[1] J. Mearman, "Machine Tools: Computer Aided Manufacturing May Not Be for All," *U.S. Industrial Outlook 1983* (U.S. Department of Commerce), (Washington: U.S. Government Printing Office, 1983).

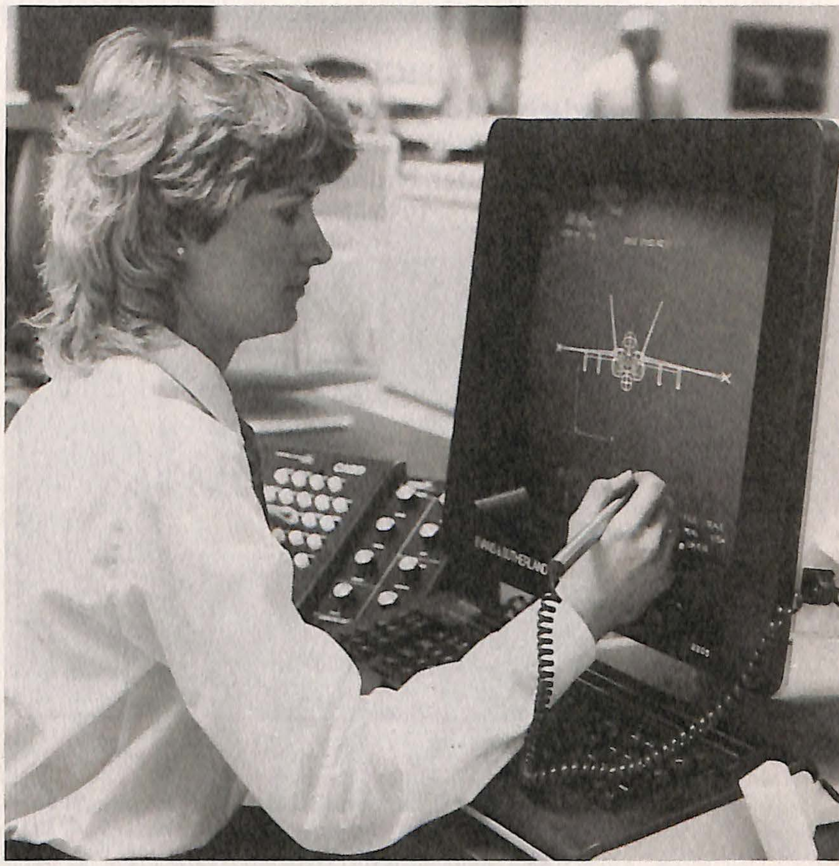
at the Armour Institute (now the Illinois Institute of Technology) in Chicago. A key initial goal of the project was to develop a common core of software and specifications that could be used by individual firms to build programmed tool systems that could be adapted easily to each firm's unique needs. In subsequent years the project was extended and participation by firms outside the aerospace industry was encouraged. Many non-aerospace firms joined the project to obtain a "window" on this new technology. By the late 1960's, several other industries began to show serious interest in the potential which CAD and CAM offered, based on the progress which was being made in the APT program and in aerospace. A tool programming language—APT—developed during the program is now widely used throughout industry.

NASTRAN (NASA Structural Analysis), a comprehensive computer package for performing dynamic structure analysis, was developed in the late 1960's and early 1970's for the National Aeronautics and Space Administration. It has provided many well-documented examples of CAD/CAE applications in aerospace and other industries. Appendix F shows examples compiled by Denver Research Institute.

In the early 1970's, CAD/CAM was used to save time and increase engineering productivity in the design and production of the AWACS early warning aircraft. NASTRAN was used to redesign the airframe used for AWACS, and other systems were used for designing and building the electronic components needed for the planes. For example, by joining CAD and CAM, large-scale integrated circuit boards were designed and produced 6 to 10 times faster than before. Moreover, the production of higher quality work with fewer human errors saved costs which would have been spent on reworking materials. Such increased productivity has helped U.S. aerospace firms meet increased competition from abroad.[2] It has also helped pave the way for similar gains in other U.S. industries that are beginning to use this new technology.

The leading role of aerospace firms in the development of CAD/CAM technology continues down to the present day. Figure 4 shows the 1982 adoption rates for CAD, NC, CNC, and CAM among major U.S. firms, according to a 1984 study published by the Joint Economic Committee of the U.S. Congress.[3] In every area, the adoption rate is highest among aerospace firms.

The study results suggest that computer-aided manufacturing, excluding CNC, is more widespread than computer-aided design and drafting activities in most industries other than aerospace. In addition, the differences in adoption rates between industries are narrower for CAM, with aerospace still the leader. Moreover, the study suggests that metal-working firms adopted CAM in part to meet the more demanding performance standards required by aerospace firms who used their products.



Share of final cost attributable to design is considerably larger in aerospace than in other mass production industries. Motivation to reduce design cost and improve design productivity is correspondingly higher.

photo: McDonnell Douglas

Aerospace firms have advanced the use of CAD/CAM within the industry and increased its utilization in non-aerospace applications as well. Major examples, in addition to those already mentioned, include the following:

- Lockheed was one of the first major U.S. aircraft manufacturers to implement its own CAD program in the 1970's. The program, CADAM (Computer-graphic Augmented Design and Manufacturing system), has widespread application within the industry as well as outside. Over 100 firms of various sizes, domestic and foreign, employ CADAM. This versatile system is used by most major aerospace firms including Bell Aerospace, General Dynamics, North American Rockwell, Northrop, and TRW. Significant users

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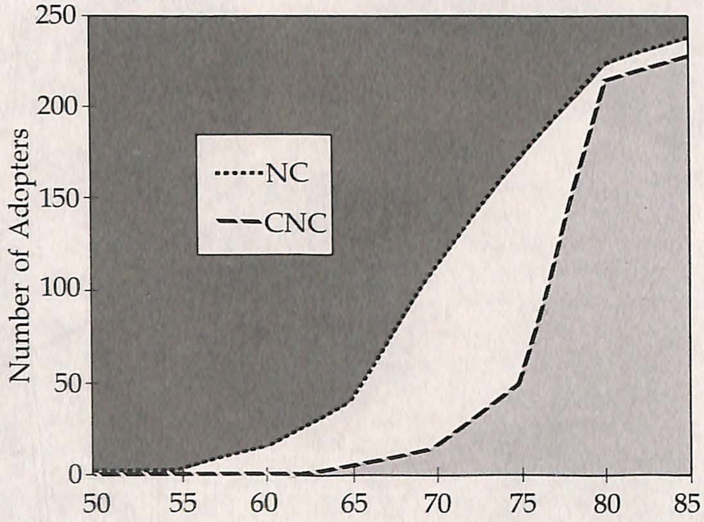
[2] Ripley Watson, "Computer-Aided Engineering Speeds Output," *The Journal of Commerce*, February 17, 1982, pp. 3A-5A.

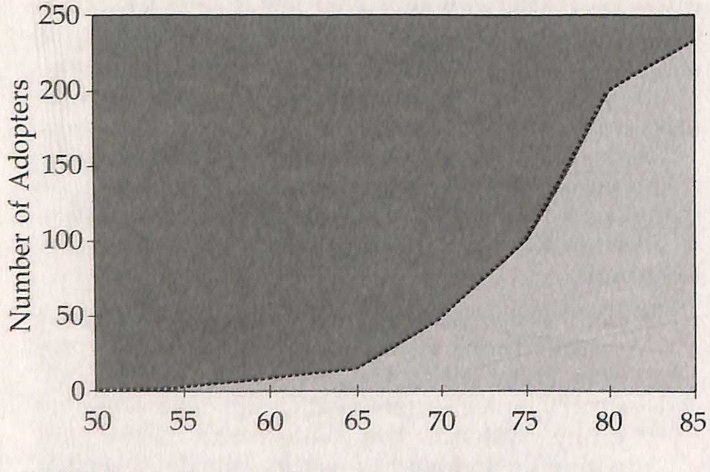
[3] John Rees, Roger Briggs and Donald Hicks, *New Technology in the American Machinery Industry: Trends and Implications* (A study prepared for the use of the Joint Economic Committee, Congress of the United States), (Washington: U.S. Government Printing Office, September 1983).

FIGURE 2
Cumulative Adoption Patterns Over Time for Numerical Control and Computer Numerical Control 1950–1985



SOURCE: Joint Economic Committee (1984), *New Technology In The American Machinery Industry: Trends and Implications*. Extrapolated for all years except for 1985 which was estimated by Shriner-Midland.

FIGURE 3
Cumulative Adoption Patterns Over Time for Computer-Aided Manufacturing 1950–1985



SOURCE: Joint Economic Committee (1984), *New Technology In The American Machinery Industry: Trends and Implications*. Extrapolated for all years except for 1985 which was estimated by Shriner-Midland.

of CADAM outside of the aerospace industry include International Harvester, Westinghouse, and General Motors.[4, 5] Tire-makers attribute much of their recent progress in tire design to CADAM, NASTRAN, and other CAD systems originally developed for aerospace use.[6] Foreign users of CADAM include British Aerospace, Dassault of France, Fuji and Mitsubishi of Japan, and Messerschmitt of Germany.[7, 8]

- McDonnell Douglas Corporation (MDC) originally developed its own NC tool language, McDonnell Control Language (MCL), to program machine tools. The firm later enhanced MCL to handle robot programming as well. The language is combined with a robot simulator and a CAD system. The fully integrated system enables a designer to vary the placement of robots relative to other tools and watch a computer simulation of the robot arm movements on a video screen. MDC is using the system to develop and program an experimental robot riveting cell for the manufacture of aircraft and parts.[9]
- MDC also uses its subsidiary, McDonnell Douglas Automation (MCAUTO), to promote the commercial application of its UNIGRAPHICS system. Piper, a general aviation manufacturer, uses UNIGRAPHICS to design parts for wing sections and nacelles for its 11-seater Cheyenne III turboprop as well as to produce numerous engineering and tooling drawings.[10] Another MDC subsidiary, Microdata, created SEQUEL, a high-speed, easy-to-use computer system for large businesses, and REALITY, a less sophisticated system for the small business user.[11]
- Boeing, the largest U.S. aircraft manufacturer, uses CAD extensively in its design of the 767 and 757 large transport aircraft. The aircraft are 90 percent CAD designed, including wing panels, front and rear spars, and inspar ribs.[12] Of the more than 18,000 designs developed in the 767 program, almost 7,000 employed CAD with sizeable labor savings and improved engineering ac-

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[4] Robert Waterbury, "CADAM: Earning Its Wings in Industry," *Assembly Engineering*, November 1980, pp. 42–44.

[5] Gene Kingsbury, "Aerospace: Computers Benefit Aircraft Designing," *U.S. Industrial Outlook 1981* (U.S. Department of Commerce), (Washington: U.S. Government Printing Office, 1981).

[6] Charles Dressing, "Tire Tech," *Science Digest*, November 1984, pp. 52–115.

[7] Robert Waterbury, "CADAM: Earning Its Wings in Industry."

[8] Gene Kingsbury, "Aerospace: Computers Benefit Aircraft Designing."

[9] Paul Kinnucan, "Computer-Aided Manufacturing Aims for Integration," *High Technology*, May/June 1984, pp. 49–55.

[10] John K. Krouse, "Automation Revolutionizes Mechanical Design," *High Technology*, March 1984, pp. 36–45.

[11] McDonnell Douglas Company, "Information Services," *McDonnell Douglas Annual Report—1981*, p. 6.

[12] John K. Krouse, "Automation Revolutionizes Mechanical Design."

curacy. Production of the Boeing 747 jumbo jet uses a robot driller and does away with templates by transferring data to drill bolt hole patterns for the 340 floor panels, no two of which have exactly the same configuration. This one system saves Boeing nearly $500,000 annually.[13]

- Northrop has developed an "integrated flexible automation center" for automatically cutting and fabricating FRP composite materials. It includes a graphite material dispensing unit, a Gerber reciprocating knife-cutter, a material distribution unit or "flying carpet," and a robotic transfer and laminating unit. Controlled by a computer, graphite pre-impregnated material is fed from the roller, cut into preprogrammed shapes, and transferred to a robot, which stacks the cut material properly for forming and curing.[14]
- Hughes Aircraft Company produces a precision laser range-finder and optical system housing in an automated, totally integrated machine shop that includes automatic material handling, machining, drilling, and inspection for five different aluminum parts. The flexible fabrication system produces these five parts at about 20 percent of the cost of using conventional manned numerically controlled machines. Company estimates show that the work accomplished by these nine computer controlled machines and three operators would otherwise require 25 machines and operators.[15]

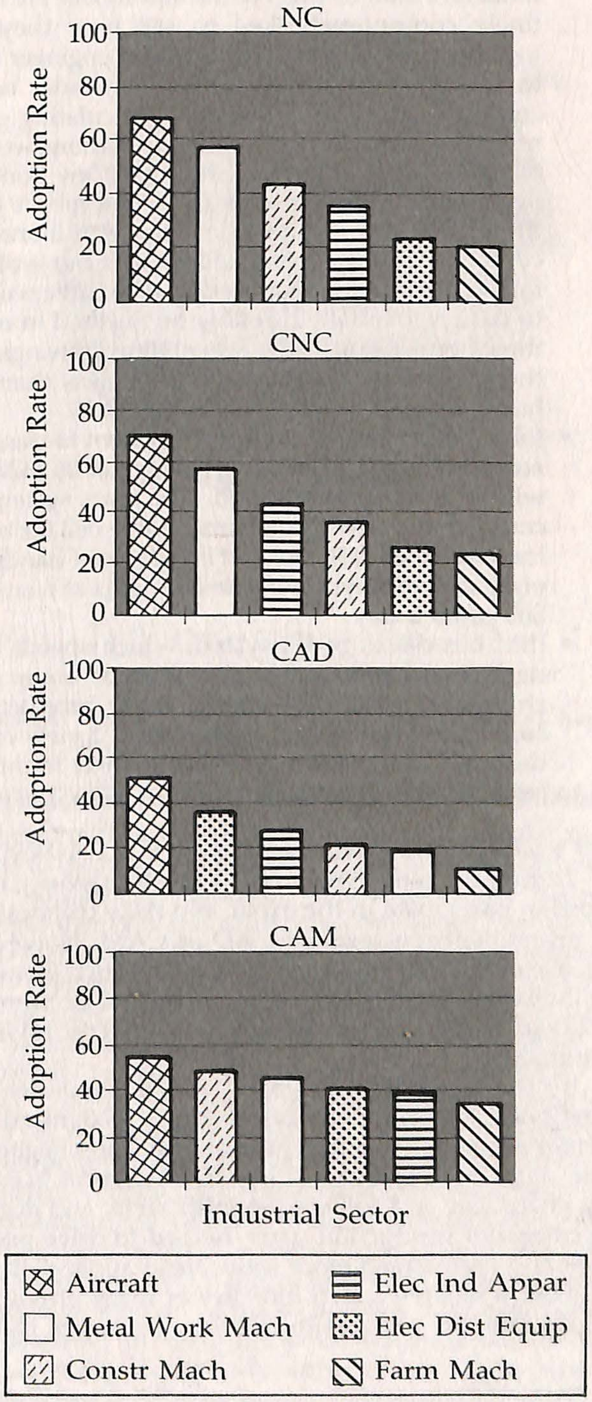
These examples are typical of the progress aerospace firms have made in developing CAD/CAM. But the future prospects are even greater, according to a recent report from the U.S. Department of Commerce:

> "Aircraft manufacturers have only scratched the surface in a field of tremendous potential. The success of CAD in current aircraft manufacturing programs will encourage engineers to expand future use of computer-aided design. This will reduce overall start-up costs and enhance aircraft efficiency and durability."[16]

The following examples illustrate some of the increased productivity and cost savings realized by nonaerospace firms using CAD/CAM:

- Chrysler, which claims to now have one of the world's most advanced CAD systems, does 60 percent of its design work on air, fuel, and emission components (fuel controls, speed controls,

FIGURE 4
Adoption Rates for CAD/CAM Systems, By Industry Sector
1982



SOURCE: Joint Economic Committee (1984), *New Technology In The American Machinery Industry: Trends and Implications.*

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[13] Paul Kinnucan, "Computer-Aided Manufacturing Aims for Integration."

[14] William B. Scott, "New Methods Create Composite Parts," *Aviation Week & Space Technology,* August 2, 1982, pp. 80-81.

[15] Hughes Fabricating Precision Parts with Automated System," *Aviation Week & Space Technology,* April 11, 1983, p. 66.

[16] Gene Kingsbury, "Aerospace: Computers Benefit Aircraft Designing."

air cleaners, and exhaust gas recirculators, for example) using CAD tools. By 1987 Chrysler plans to automate this design work completely.[17]

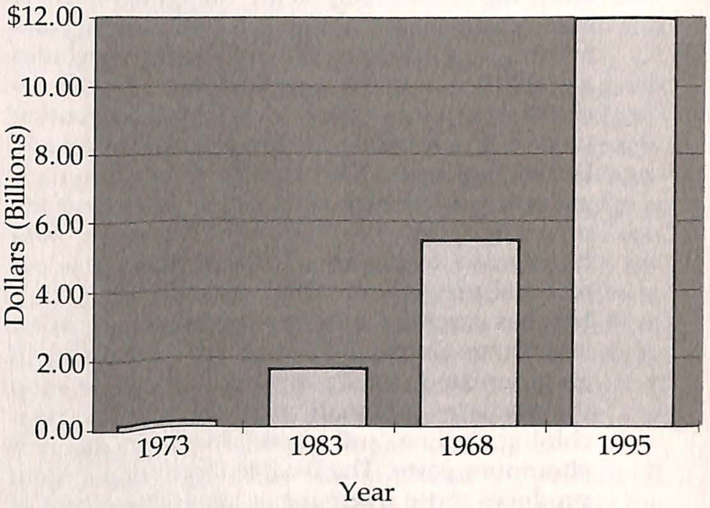
- General Motors uses CAD in its Pontiac Division to handle chassis design, induction/emission and transmission/axle work. Three-dimensional models of various parts of the automobile are routinely computer-checked to see how they fit together. Previously an experienced engineer had to spend six weeks designing a cylinder head combustion chamber, manually calculating geometric constructions to ensure dimensions would meet EPA emission requirements. Now Pontiac designers can accomplish the same job in just three days using CAD systems. Additionally, complex contoured surfaces such as those of an intake manifold which used to take three weeks to design manually can now be finished in only three hours using CAD. Assembling drawings for the chassis and engine now takes less than 24 hours instead of six to eight weeks.[18]
- John Deere uses a CAD/CAM system to classify and code parts, producing savings of $6 million within an 18-month period. The parts system is coupled to a new flexible machining cell for tractor transmission blocks and is capable of handling eight different types of transmissions at a rate of 300 units a day.[19]
- IBM has developed a system which speeds the design and production of prototype computer chips and automates nearly every production step. The system can turn around a new chip design in one week instead of the three months' time previously required.[20]

Cost Reduction and Broader Industry Use of CAD/CAM

During the early 1960's, only a few industries could afford to participate in the exotic and risky technological investment required for CAD or CAM. However, because of the continued involvement by such pioneering industries as aerospace, automotive, and electronics, progress toward greater productivity and cost savings continued.

By the late 1960's and early 1970's, the potential benefit of CAD and CAM systems was recognized by a wider range of users and greater utilization began to occur outside the aerospace industry. Advances in computer hardware and software sophistication, and declining computer production costs, helped to drive prices lower and encouraged more widespread application. In addition, a newly-created industry of firms providing serious support services to smaller businesses in the form of commercial systems has expanded overall utilization.

FIGURE 5
U.S. CAD/CAM Market (Shipments)
1973–1995



SOURCE: Predicasts, "U.S. CAD/CAM Markets," Industry Study No. E93.

The cost of a CAD/CAM system includes two major components: hardware and software. The cost of both has been declining rapidly since the late 1960's.

Prior to the introduction of minicomputers in the 1970's, most CAD or CAM system operations were custom-designed by the intended user. In many instances the user was a large aerospace firm, where the system was installed on a large "mainframe" computer. The cost of the system typically exceeded $1 million, often by several times, discouraging adoption by most firms.

Other industrial users began to benefit from this early experience as the advent of the minicomputers helped to drive system costs to lower levels. In the early 1970's, minicomputers were introduced that cost between $100,000 and $300,000. Later, when the 8-bit processor was developed, computer manufacturers were able to lower system costs to $80,000 to $100,000. Today CAD can be used with 16-bit minicomputers costing under $10,000. Small CAD systems can even be used with popular microcomputers costing $2000 or less. The introduction of 32-bit mini- and micro-computers will increase the sophistication of CAD systems available for smaller firms and greatly broaden their use.

Today the incremental cost of peripherals for entering data and producing hard copy is between $1,000 and $32,000, and there are estimated to be 50 to 100 different CAD software packages available for microcom-

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[17] John K. Krouse, "Automation Revolutionizes Mechanical Design."
[18] Ibid.
[19] J. Mearman, "Machine Tools: Computer-Aided Manufacturing May Not Be for All."
[20] Ibid.

puters such as the Apple, IBM-PC, and other popular models, at prices ranging from $850 to $20,000. Some less sophisticated CAD software can be purchased for under $100.[21, 22]

Paralleling the reduction in hardware and software costs has been the emergence of a new industry made up of firms specializing in the creation and sale of completely integrated CAD and CAM systems on a "turnkey" basis.

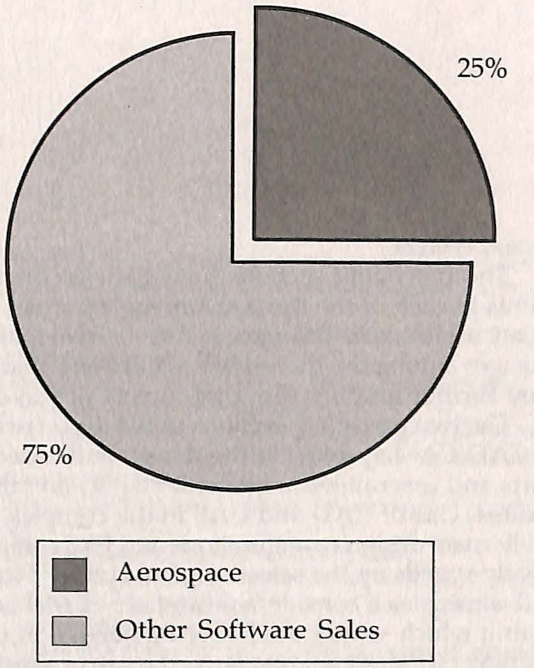
Computervision Corporation, founded in 1969 and one of the first of these turn-key start-ups, illustrates the role played by these firms. Now one of the largest firms in this new industry, Computervision gained much of its initial experience in the aerospace industry. It now designs, manufactures, markets, and services CAE, CAD, and CAM products and systems for a wide range of industries in the United States and overseas. Computervision systems are used by aerospace companies, automotive firms, mechanical equipment machinery manufacturers, and fabricated materials companies to assist in mechanical analysis, design, drafting, and automated manufacturing. These CAD/CAM systems and modular software enable users to increase productivity and product quality. They shorten the product development cycle time and reduce the time required for manufacturing start-up or construction of new plants or facilities.

As a result of the combination of reduced hardware and software cost, experience gained in aerospace and other pioneer industries, and the emergence of a completely new industry of CAD/CAM firms, the use of CAD/CAM has and will continue to grow at a rapid pace. It is likely to be a major factor in the ability of U.S. firms to compete effectively against the growing number of foreign industrial competitors which they face. Figure 5 shows the growth in the CAD/CAM market since the early 1970's and the projected growth into the middle 1990's.

The aerospace industry continues to foster broader utilization of CAD/CAM outside the industry by providing a substantial base of development and experience. The industry remains important to the overall CAD/CAM marketplace as a user of hardware and software. Data Resources, Inc. (DRI) estimates that CAD/CAM hardware sales to the aerospace industry will surpass $749 million by 1988 (in 1983 dollars), or be about 66 percent higher than 1983's $451 million sales level. Total software sales in 1988 are estimated by Input, a market research firm, to be between $35 billion and $40 billion. Aerospace purchases are expected to support an estimated 25 percent share of that market, as shown in Figure 6.

FIGURE 6

Aerospace Industry—An Important Slice of the 1988 CAD/CAM Software Market



SOURCE: Input (Cited in *Aviation Week & Space Technology*, August 13, 1984, p. 142).

While the aerospace industry will form an important part of future CAD/CAM markets, it will also continue to contribute substantially to CAD/CAM technology and further productivity gains in the future. Recently a number of major aerospace companies announced their intention to form a joint R&D "software productivity consortium" to devise software tools and techniques for computer-aided design and engineering.[23]

The aerospace industry has made a pioneering contribution to the development and diffusion of CAD/CAM technology in the United States. It served both as a developer and as a major market for developments created by others at a stage when other industries considered the costs and risks to be too great. By making a commitment to the technology and to the development of a highly skilled workforce able to function effectively with the new technology, the aerospace industry helped move the technology downward along the learning curve to the point where it has become economically attractive for other industries to become users.

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[21] Steve Rosenthal, "CAD/CAM," *A+*, December, 1984.

[22] Davis Straub, "Computer-Aided Design," *PC World*, October 1983, pp. 100–114.

[23] "Software Consortium Files with Justice" (Business Roundup Section), *The Washington Post*, January 18, 1985, p. B1.

Cross-Linkages and Conclusions

Cross-Linkages

The preceding sections have focused on developments in each of the three technological areas, with little regard for cross-linkages. However, two major cross-linkages among the three cases should be noted because they further amplify the total impact of the cases.

The two preceding sections noted the increasing use of CAD/CAM systems in the design and fabrication of parts and assemblies made with FRP's and other composites. Use of CAD and CAE in the complex analysis of alternate design configurations and FRP compositions greatly speeds up the selection of an optimal FRP design and eliminates a considerable amount of trial-and-error testing which would otherwise be needed in developing new FRP designs. Similarly, the use of special CAM systems and robotics for FRP fabrication greatly increases productivity in the plant, speeds the production process, and reduces error rates. The cumulative impact of the combination of these two important technologies can only be speculated upon at this stage, but it is likely to dramatically change the choice of materials and the organization of production for products in many industries in the next 30 years.

Similarly, FRP's and other composite materials are being used to make lighter, stronger turbocharger components and parts for other turbo-machinery. For example, FRP's account for a growing share of the exterior and non-rotating components in jet engines, where they expand and contract less with temperature changes than metallics in addition to their light weight, strength, and stiffness. In auto designs currently being produced, combined use of turbochargers and light-weight FRP body material reduces fuel consumption by 15 percent or more.

When combined with the 15–20 percent fuel savings that carbon FRP composites are estimated to achieve for jet transports and the reduced energy which FRP fabrication requires versus the production of metal components, the per capita energy needs of the U.S. in the late 1990's will be reduced by some 15 percent or more compared to 1980 if present projections of FRP utilization are in the ball-park.

Conclusions

When looked at from a long-term perspective, these and other technologies which aerospace has helped develop have radically changed the economic structure of the United States and the world, and are continuing to do so. Without the stimulus provided by the aerospace industry and its continual search for improved performance, the pace of development of these technologies would have been much less rapid. If the U.S. share of aerospace markets had been smaller, the advantages and stimulation to the U.S. economy would have been less. Like other nations, the United States might now be straining to make its domestic aerospace industry stronger to provide greater technological impetus to other industrial sectors of the U.S. economy.

For the future, the United States must be concerned with maintaining a leading share of the international aerospace market. Unfortunately, since 1970 the U.S. share of the free-world aerospace market has declined in every major market segment: airframes, engines, equipment, and space. If present trends continue, the U.S. share of free-world output will soon fall below 50 percent in every area except space, where the United States still retains a significant lead (Appendix G). However, even there, other countries are making a concerted effort to capture a significant share of the rapidly expanding market for space systems. To the extent that the United States continues to lose its share of this critical technologically pioneering industry, it will be losing parts of an important stimulus for development in many other U.S. industries.

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Appendix A—Catalog of NASA Spinoffs By Technology Type and Application Area*

*As published annually in "Spinoff" by the National Aeronautics and Space Administration.

Noting Technology Origin,[1] Application Status,[2] Economic Impact,[3] and Year Cited

AERODYNAMICS

Consumer/Home/Recreational Products

• Skiing Simulation Low speed wind tunnel and aerodynamic technology used in skiing simulator	NO	IP	L	1983

Transportation

• Streamlined Livestock Trailer Aerodynamically designed tractor trailer reduces air drag by 10 percent	NO	IA	L	1980
• Business Jet Design Improved business jet design results from NASA Aircraft Efficiency Program	NW	IA	L	1980
• Aerodynamically Improved Business Jet Use of advanced computational fluid dynamics improves commercial design	NO	IA	L	1980

BIOMEDICAL

Health and Medicine

• Implantable Heart Aid Uses miniaturized space circuitry to correct various heart conditions	NWO	A	L	1984
• Analytical Device Automated electrophoresis process based on blood analysis in weightlessness	ON	IA	L	1983
• Ingestible Toothpaste Ingestible and foamless toothpaste	ON	PA	L	1984
• Biotelemetry System Uses miniature transmitters to study human-implanted devices/locomotion	NWO	PA	L	1984
• Airline Wheelchair Project undertook design of wheelchair for airline applications using NASA data	NOW	IP	L	1982
• Space-derived Health Aids Computerized pumping unit dispenses medication; programmable pacemaker	NO	IA	L	1981
• Talking Wheelchair Electronic system & synthesized speech	NO	IP	L	1981

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[1] Technology Origin Codes:
W = Within aerospace industry
O = Outside aerospace industry
N = NASA facility
Combination codes indicate cases where joint efforts were undertaken (contract, license, etc.) and order of importance (i.e., primarily W, O, or N)

[2] Application Status Codes:
A = Actual product uses and/or market sales have been made
P = Potential use of product or future market
I = Improved product contributes to sales or market
Combination codes indicate cases cited in order of importance

[3] Economic Impact Codes: (Based on estimated annual sales)
L = Under $25 million
M = $25 million–$100 million
H = Over $100 million

technology based on aerospace communication				
• Cordless Instruments Self-contained powered surgical drill/driver-reamer and sagittal saw	NO	IA	L	1981
• Biomedical—Medication Device Fluid system components (peanut valve) used in medical field/PIMS system	NO	IA	L	1982
• Portable Medical System Compact battery-powered vital signs monitor and defibrillator (black bag technology)	NO	IA	L	1982
• Human Tissue Simulator HTS is an implantable system using a nickel cadmium battery and telemetry	NO	IP	L	1982
• Medical Gas Analyzer (RMS) Improved patient care based on astronaut respiratory gas analysis device	NO	IA	L	1983
• Heart Rate Monitor Uses thin dielectric film on stainless steel surface	NO	P	L	1984
• Slow Scan Telemedicine Freeze frame and TV transmission of medical and patient profiles	NO	PA	L	1984
• Bacteria Counter Photometer device rapidly and accurately counts bacteria in body fluid samples	N	IA	L	1981
• Compound Separation One-step liquid-liquid extraction unit reduces costs in medical area	N	IA	L	1981
• Communicable Disease Research COSMIC* program (FITLOS) aids in communicable disease research	N	IAP	L	1982
• Portable X-ray Device Medical & industrial uses for self-contained battery-powered fluoroscope	N	IP	L	1983
• Temperature Measurement Aid Device more accurately measures skin surface temperature (thermistor)	N	IA	L	1979
• Suspension Harness Device developed for weightlessness simulation has rehabilitation potential	NO	P	L	1976
• Servo-controlled Infrared Optometer Device provides for rapid accurate vision check	NO	PA	L	1976
• Programmable Pacemaker Device allows physician to reprogram pacemaker without surgery	NO	IA	L	1980
• Positive and Negative Pressure Devices Chamber seals have medical potential to increase respiration and circulation	NO	P	L	1976
• Medical Data Bank Medical information system uses image processing technology from NASA	N	IA	L	1979

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*Computer Software Management and Information Center, University of Georgia, at which NASA maintains one of the nation's largest software libraries for engineering analysis and other programs.

• Meal System for Elderly Astronaut food-preparation system is applied to food systems for elderly	NW	IP	L	1977
• Implantable Heart Aid Miniaturized circuitry used in patient heart-assist device	NO	IA	L	1980
• Heart Sonar Images Echo-cardioscope provides internal images for medical use	N	P	L	1976
• Device Aids Surgical Treatment Optical profilometer electronically measures patient profile casts	N	IA	L	1980
• Dental Arch Wire Nitinol/nickel and titanium alloy with elastic qualities used in dentistry	NO	IA	L	1979
• Cardiology Mannequin Electronic mannequin used to train medical students aided by NASA	N	IA	L	1979
• Breast Cancer Detection Solar cell sensors used to reduce amount of X-ray radiation required	N	P	L	1976
• Blood Pressure Testing Device Electronic sound processor automatically analyzes blood pressure	NO	IA	L	1979
• Blood Cell Storage Electronics and cryogenics knowledge can be used to store blood cells	NO	P	L	1976
• Biological Isolation Garment Germ-free environment potential as adjunct to patient isolation rooms	N	P	L	1976
• AutoMicrobe System —Medicine Multi-module tool detects and identifies disease-producing microorganisms	NW	IA	L	1979
• Arteriosclerosis Detection Transducer-evolved technology leads to arterial pulse-wave transducer	N	P	L	1976

CAPITAL EQUIPMENT

Consumer/Home/Recreational Products

• Hair Styling Appliances Thermal video system measures heat visually, has commercial application	WN	IA	L	1984

Energy

• Hydrogen Generator (Cooling System) Fuel cell technology used in solid polymer electrolyte hydrogen generator	NW	IA	L	1983

Industrial Productivity

• Heat Recovery System Heat exchanger system with commercial applications	NO	AP	L	1984
• Robotic System Newly-designed robotic arm	ON	IP	L	1984
• Manufacturing Aids Computer-aided fully-automatic system for spraying hot plasma on engine parts	NW	IA	L	1983
• Computerized Motor Controller Improved version of electric motor	NO	P	L	1984

controller—more power/less waste				
• Multiple Industrial Aids Various examples	NW	IA	L	1977
• Lap-Polishing and Grinding Tool Diamond-powdered charged-aluminum lap plate yields improved results	ON	IA	L	1977

Safety and the Environment

• Water-powered Tools Spacecraft turbopump technology used to develop tools that limit explosions	NW	P	L	1976

Transportation

• Electronic Vehicle Scales Electronic technology used to weigh commercial vehicles (trucks)	NO	A	L	1984
• Motor Controllers DC energy efficient brushless motors used in research submarines, industry	NO	A	L	1984
• Portable Welder Hand-held induction gun joins thermo- and non-thermoplastic materials	NO	A	L	1984
• Log Truck-Weighing System Space-derived computerized weight-and-balance system used for logging trucks	NO	A	L	1977

MANUFACTURING PROCESS/DEVICE

Construction

• Anodizing Process Multipurpose anodizing electrolyte process used in architectural applications	NO	IA	L	1983
• Flat Wire Spacecraft flat electrical wire has potential in office and housing	N	PA	L	1976

Industrial Productivity

• Joint R&D (Deere & NASA) Low-gravity materials/propulsion/composite materials/ceramics, et. al.	ON	IP	M	1984
• Improved Copying Machine NASA technology aids low-cost injection molding process to improve valve	N	IA	L	1981
• Laser Wire Stripper Carbon dioxide laser wire stripping machine is fast, clean and precise	NW	IA	L	1983
• Heat Pipe Technology Injection molding processes benefit from heat pipe technology	NO	IA	L	1981
• Automatic Welding System Closed-circuit TV signals aid automatic guidance of industrial welding torch	NO	IA	L	1982
• Pump Design Improved impeller design using titanium	N	IA	L	1981
• Laser Balancing Laser machining process improves balancing precision—fast & accurate	N	IP	L	1981
• Contamination Control Sterilized drug procedure is im-	N	IA	L	1983

proved using static electricity technology				
• Monel Machining NASA research aids monel metal machining process	N	IA	L	1983
• Electronic Packaging Techniques Use stichbonding and parallel welding technology to compress components	NO	IA	L	1979
• Deep Sea Drillships Deep sea drilling operations benefit from space technique—dynamic positioning	NW	IA	L	1979
• Automatic Design System Computerized system aids in production of large-scale integrated circuits	NO	IA	L	1980

Safety and the Environment

• Sewage Treatment Activated carbon produced out of solids by high-temperature heating and reused	N	P	LM	1976

MATERIALS

Construction

• Aerospace-originated Roofing Fabric Fiberglass fabric coated with Teflon used commercially as roofing material	NO	IA	L	1982
• Protective Coating Anti-corrosive/high-temperature resistant coating for bridges/exterior surfaces	NO	PA	L	1984
• Flat Wire Cable Thin flat wire cable used in offices & other commercial applications	N	IA	L	1983
• Space Paint Improved inorganic paint with corrosive-resistant properties for bridges, etc.	N	P	H	1976
• Noise Protection Liquid plastic compound mixture used to dampen sound in industrial settings	NO	IA	L	1980
• Musical Instruments Composite materials and aerospace vibration technology used in guitars	NW	IA	L	1978
• Foam-insulation Material Used in fishing industry to insulate tuna boats, better preserve catches	NW	A	L	1977
• Coated Fiber Glass Roofing Fabric Apollo spacesuit fabric fosters improved material for commercial applications	NO	IAP	L	1978
• Cellulose Insulation Fire-retardant cellulose insulation used in commercial application	N	IA	L	1980
• Anti-Corrosion Coating Zinc-rich coating with superior adhesion characteristics has commercial use	N	IP	L	1977

Consumer/Home/Recreational Products

• Temper Foam Impact protective foam used for sporting goods/cushions/protective clothing	N	IA	LM	1981
• Cool Sportswear New line of athletic wear incorporates space suit-derived technology	NO	IA	L	1982

• Sunglass Lens Scratch-resistant lens uses abrasion-resistant coating	NO	IA	L	1984
• Solar Equipment NASA data aids improved solar equipment using ultraviolet-resistive material	N	IA	L	1983
• Woodburning Heaters PYROMARK coating used in commercial applications	NO	IA	L	1979
• Thermal Gloves and Boots Improved insulation techniques used in ski-wear and other outdoor wear	NO	P	L	1976
• Sportswear Material for satellite reflection has sport uses; warm and reflective	NO	PA	L	1976
• Sports Helmet Uses super shock-absorbent foam material to protect against injuries	NW	IA	L	1977
• Solar Screen Improved window screen deflects 70 to 80 percent of heat from sun	N	IA	L	1979
• Smoke Detector Household smoke detector uses sophisticated circuitry and sensors	NW	IA	L	1979
• Quartz-crystal Clocks Highly accurate clocks and watches are now consumer products	NO	AP	LM	1976
• Protective Outdoor Clothing Material used in sports clothing, boots and bicycle seats—Apollo heating technology	N	IA	L	1977

• Padding Material New padding material developed for air passenger seats has many commercial uses	NO	IPA	L	1976
• Metallization Vacuum-vaporized metal has foil-like effect and many commercial uses	NO	IA	LM	1980
• Fogless Ski Goggles NASA coating prevents fogging	N	P	L	1976
• Composite Golf Clubs Boron-reinforced material increases golf club shaft rigidity and flexibility	NO	PA	L	1976

Energy

• Watt Count System Energy efficient engineering system used in residential-commercial buildings	NO	IA	L	1981
• Coating Process Black chrome coating used on solar collectors in space has energy uses	NO	IA	L	1983
• Solar Cells Square-shaped solar cells developed by NASA contractor for commercial uses	NO	IA	L	1983
• Window Insulation Highly reflective satellite insulating material offers energy savings	NO	IA	L	1979
• Infrared Heaters Energy efficient panel-bloc infrared heaters use space coating material	NO	IA	L	1979
• Heat-recovery Devices Modified use of heat pipe for housing/commercial and industrial applications	NW	PA	LM	1976

Heat Pipe Used in Alaskan Oil Pipeline project to eliminate freeze-thaw concerns	NW	AP	L	1976
Alaska Pipeline Insulation Metal-bonded polyurethane foam protects oil pipeline	NW	IA	L	1979

Health and Medicine

Springback Foam—Chair Seat Foam developed for protective airplane seat padding has commercial use	N	IA	L	1979
Protective Coatings Synergistic coatings/dry lubricants bonded to metal surfaces useful in medical equipment	NO	IA	LM	1980
Portable Dental System Composite materials used in compressed air tank as part of dental system	N	IA	L	1980

Industrial Productivity

Magnetic Fluids Ferrofluid technology employed in various commercial-industrial areas	NO	IA	MH	1981
Insulation Material Heat-absorbing ablative reinforcement	ON	AP	L	1980
Welding Curtains Heavy-duty vinyl plastic protects bystanders during welding process	ON	PA	L	1984
Ceramic Powders Ultrafine boron carbide used as an abrasive (grinding) and in ultrasonic machining	ON	PA	L	1984
Materials for Master Modeling Space Block epoxy resin with uses in automotive and other industries	NW(O)	P	L	1984
Perforated Materials Screening material for manufacturing processes, walkways and other uses	NO	A	L	1981
Commercial Netting Safety net technology increased as NASA requirement drives non-aerospace firm	NO	IA	L	1983
Space Camera Improved camera uses non-migratory lubricant technology	NO	IA	L	1983
Noise Abatement Liquid plastic acoustic material (SMART) has many commercial/office uses	NO	IA	L	1983
High-temperature Lubricants Withstands high-temperatures and is self-lubricating (Surf-Kote C-800)	NO	PA	L	1984
Thermal Insulation Flame-resistant/vibration-damping thermal insulator (Solimide)	NO	A	L	1984
Irrigation System Lubricant used in gears of irrigation systems	NO	A	L	1984
Composite Materials Composite material characteristics are improved using impregnation technology	N	IA	L	1983
Space Coatings Various uses	NO	IA	LM	1980
Plastic Lens' Coating Salt-coating of infrared lens has	ON	P	L	1976

potential use in photography				
Plasma Spray System Metallic-ceramic coatings improve aircraft turbine engine efficiency	NW	IPA	L	1980
Improved Safe Handling Practices Conductive material aids in reducing production losses and improves safety	NO	IA	L	1980
Gasoline Vapor Recovery Anti-pollution device aiding in gasoline vapor recovery uses NASA-developed lubricants	NO	IA	L	1979
Circuit Connectors Beryllium-copper wire used in compact packaging of electronic devices	NO	IA	L	1979
Bonded Lubricants Dry anti-corrosive lubricant coating bonds to metal surface for industrial use	NO	IA	L	1977

Safety and the Environment

Fire-Resistant Material (Solimide) Ignition resistant polyimide foam and smokeless wire cable used in subways	NO	IA	L	1981
Protective Fire-Resistant Clothing Beta Glass material is spinoff of earlier contractor work for Apollo program	NO	IA	L	1981
Triaxial Fabrics Improved treble-weave yields super strength for emergency goods & clothing	NO	IA	L	1981
Poultry Plant Noise Control Sound-absorbing panel with easy-to-clean covers to meet sanitation needs	NO	IP	L	1982
Fire Resistant Materials Improved material (Durette fabric) is fire resistant, no noxious fumes	NO	IA	L	1982
Fire Protection Materials Commercial application of fire resistant material to industry use	NO	IA	L	1980
Flame Resistant Foam Vibration/fire-resistant lightweight foam (SOLDAMP)	NO	A	LM	1984
Weight-Saving Technology Helicopter performance aided by use of composite materials	NW	IA	L	1979
Studless Winter Tires Stronger/better wearing/temperature-resistant tire for automotive use	NO	IP	L	1976
Invar Insulation for Ships Carrying Liquefied Natural Gas Polyurethane foam reinforced in three dimensions with fiberglass threads	NW	IA	L	1979
Composite Brake Linings Offer potential in commercial buses; more durable and less noise	NW	IP	L	1976

RESEARCH TOOLS

Computer Processes or Technology

COSMIC—Software Programs Information processing, design	N	IA	LM	1982

and analysis software used commercially				
• Nacelle Design—Commercial Aircraft Engine nacelle assembly (cowling, exhaust nozzle & outer skin) uses COSMIC software	NW	IA	LM	1982
• Gear Drive Testing COSMIC program aids in insuring gear design accuracy during testing	N	IA	LM	1982
• Ship Design NASTRAN (NASA structural analysis program) used in design of naval ships, oil drilling rigs and barges	N	IA	LM	1982
• Customer Service Programming COSMIC package (STRCMACS) aids in computer programming area	N	IA	LM	1982
• Turbine Blade Research Pressurized fluid bed (PFB) combustion process improves turbine/uses COSMIC	N	IA	LM	1982
• Oil Recovery System COSMIC program used in design of thermodynamic simulation	N	IA	LM	1983
• Nuclear Plant Inspection Crack growth analysis detection system based on COSMIC software package	N	IA	LM	1983
• Equipment Analysis NASTRAN software aids in design and equipment analysis in electronic area	N	IA	M	1982
• Computer Generated Graphics Hidden Line Computer Code—COSMIC	N	A	L	1984
• Auxiliary Power Units Aerospace firm uses COSMIC's VISCEL to design seals for APU's in aircraft	N	A	L	1984
• Noise Prediction COSMIC package predicts noise levels in various commercial-industrial settings	NSF(N)	A	L	1984
• Air Combat Simulator Computerized simulator trains fighter pilots	NO	IA	L	1981
• Computer Component Tester Improved testing device	NO	I	L	1984
• Pump Flow Analysis COSMIC program (MERIDL) aids in design of power plants and analysis of pumps	N	IA	L	1981
• Sub-Ocean Drilling COSMIC program aids in ship conversion design and feasibility studies	N	IA	L	1981
• Medical Products Research Computerized searches conducted by NASA aid in medical products research	N	IP	L	1982
• Crew Escape System Aerospace firm uses COSMIC Program	N	A	L	1984
• Underwater Simulator Aerospace-derived training simulator aids installation of tall oil platform	NO	IA	L	1980

Construction

• Construction Equipment Critical load-strength testing improved using COSMIC software packages	N	IA	LM	1983
• Wind Engineering NASA research aids in architectural design of modern buildings	ON	IA	L	1983
• Ultrasonic Monitor Ultrasonic stress measuring device for bolts has industrial application	N	IA	L	1983
• Solar Systems Solar panel design aided by technical support package	N	IA	L	1979
• Solar Schematic Solar house plans aided by NASA technical package	N	IA	L	1979
• Ship Design COSMIC (SHCP) software program aids in conversion and design of ships	N	IA	L	1980
• Pipelaying Barges COSMIC software package (SHCP) solves basic naval architecture problems	N	IA	L	1979
• NASTRAN NASA structural analysis software (NASTRAN) applied to construction applications	N	AP	LM	1978
• Oil Industry Aid Computer software package (NASTRAN) aids in design of offshore oil platforms/vessels	N	IA	LM	1979
• Energy Software Program NASA Energy Cost Analysis Program (NECAP) aids in building design/construction	N	IA	L	1979
• Citrus Grove Mapping Aerial mapping of citrus groves using color infrared film (CIR)	NO	IP	L	1980

Energy

• Solar Energy Systems Thermal modeling technique used to design solar collectors	NO	IA	L	1981
• Solar Simulator Sunlight simulators used in labs to test and calibrate solar cells, and dyes and paint	N	IA	L	1981
• Solar Collector Development Device Radiant energy emission on solar panels tested using Emissometer	NO	A	L	1979
• Infrared Images Imaging devices assist in detection of heat loss/heat output, etc.	N	IA	L	1980

Health and Medicine

• Crawling Aid Special device assists brain-injured infants in crawling stage	N	IP	L	1982

Industrial Productivity

• COSMIC—Computer Software COSMIC programs aid industry in broad application food processing, et. al.	N	IA	L	1979
• Bank Record Processing COSMIC program (STATCOM) aids	N	IA	LM	1982

in design of financial system				
• Heat Transfer Research COSMIC aids in design and calculation of heat transfer; industrial use	N	IA	LM	1983
• Drying Thermoplastics Retrospective data searching at NASA aided selection of thermoplastic drying agents	N	A	L	1976
• Helicopter Design Analysis COSMIC software (VASP) used in design of commercial helicopter	NW	IA	L	1982
• Monitoring Device for Supercold Fluids Measurement and monitoring system used for cryogenics and fuel management	NO	IA	L	1982
• Pressure Measurement Wind tunnel offshoot device uses solid-state pressure-sensing transducers	NO	IA	L	1982
• Flow Calibration Hydraulic flow device used to calibrate flowmeter equipment; industrial use	NO	IA	L	1983
• Testing Composites Ultrasonic ''stress waves'' are injected into composite materials to test flaws	N	AI	L	1981
• Loose Particle Detection Device detects loose particles on integrated circuits using transducer	N	IP	L	1981
• Gem Analysis Thermoluminescence and cathodoluminescence methods advanced by NASA research	N	IP	L	1981
• Quality Assurance Set of techniques aids in evaluating electronic component reliability	N	IAP	L	1981
• Capacitance Meter Meter tests capacitors for precise voltage; used by hobbyists & industry	N	IA	L	1983
• Ultrasonic Inspection Nondestructive method of inspecting welds (Delta Manipulator)	NO	AP	L	1976
• NASTRAN NASA structural analysis software—Bell, GM, Disney World are among many users	N	PA	LM	1977
• Steam Turbine Manufacture NASTRAN aids in turbine manufacturing	N	IA	LM	1979
• Sensing System Used in Cable Cars Sensors used to detect cable wear and improve life	N	IA	L	1979
• Piping Analysis Flow analysis/stresses/temperature and weight aspects using COSMIC program	N	IA	L	1980
• Laser Research COSMIC software package aids imaging technology and photographic science	N	IA	L	1979
• Industrial Turbine Fans COSMIC program used to identify	N	IA	LM	1980

damaging particulate matter				
• Equipment Failure Analysis NASTRAN aids in design of production equipment (chemical industry) and smoke stack design	N	IA	LM	1980
• Engine Design NASTRAN package aids in turbofan/turbojet and turbomachinery design	N	IA	L	1979

Safety and the Environment

• Lightning Current Detector Design aid device uses magnetic tape to record lightning strikes	NO	IP	L	1981
• Visibility Studies COSMIC program (RADTMO) used in environmental research	N	IP	L	1982
• Atmosphere Analyzer Device using crystal sensor detects particles for air-pollution studies	N	IP	L	1982
• System for Assessing Passenger Comfort Ride development engineers devise systems for commercial applications	N	P	L	1984
• Firefighting Trainer Computer video simulator tests firefighter response and knowledge	N	PA	L	1984
• Weather Forecasting Aid Barometric pressure readings monitored more accurately for improved forecasting	NO	IA	L	1979
• Smokestack Monitor Mobile laser system monitors velocity of materials being discharged	NW	IA	L	1980
• Skid-Resistance Research Testing of skid-resisting surfaces using "pulsed braking" technique	NO	P	L	1977
• Simulator Aids in Safety Research Highly realistic computerized simulators use advanced aerospace technology	NO	IA	L	1980
• Safer Liquid Natural Gas NASA techniques used to reduce risk of liquid natural gas	N	P	L	1976
• Pollution Measuring System Portable microprocessor-controlled air pollution monitor measures sulfur dioxide	N	IA	L	1980
• Pollution Detection Devices Remote sensor capable of measuring sulfur dioxide and nitrogen dioxide	NO	IA	L	1980
• Earthquake Testing Wyle-3S testing device measures stress on equipment in simulated environment	NO	IA	L	1979
• Auto Emissions Testing Dryden equations used for humidity-adjusted emissions data in auto industry	N	IA	L	1979
• Airport Safety Aid Laser Doppler Velocimeter (LDV) remote wind sens-	NW	IA	L	1979

ing system assesses wake turbulence				

Transportation

• Turbocharged Diesels COSMIC software package aids in design of turbocharged truck engines	N	A	L	1984
• Cruise Missile Engines COSMIC software aids in design of cruise missile engines	NW	IA	L	1982
• Structural Steel Testing Method NASA fracture toughness tests are applied to highway bridge programs	NO	IA	L	1977
• Highway Profiles Device could improve ride-quality on highways and railways	N	P	L	1976
• Breadboard Facility Array of electrical and electronic equipment used in automotive industry	NO	A	LM	1977
• Bearing-failure Detector Gyro-monitoring technology used in development of bearing testor	NO	P	L	1976
• Automotive Engineering Software NASTRAN used in automotive design, stress analysis and buckling	N	IA	LM	1980
• Aircraft-icing Research NASA wind tunnel/icing technology results aid in helicopter design	N	A	L	1977
• Aircraft Design Analysis NASTRAN aided design of executive aircraft	N	IA	LM	1979
• Wind Turbine (Boat Building) Boat builder employs improved wood-laminating system using plastic substances to build wind turbine	ON	IA	L	1982

OTHER

Communications

• Suitcase Communicator Portable satellite relay communications device used in remote-emergency cases	WN	PA	L	1984
• Firefighters' Radio New lower cost, short-range two-way radio is also more rugged	N	P	L	1976

Computer Processes or Technology

• Power Plant Valves NASTRAN aids design of flow control valves for power plants	N	IA	LM	1981
• Computer Graphics Image processing used in business graphics/CAD-CAM/animation and mapping	N	IA	LM	1983
• Drone Control System Military fighter aircraft control system aided by COSMIC software	N	IA	LM	1983
• Star Mapper COSMIC aids in design of optical system for star mapping equipment	N	IA	LM	1983
• Microcomputer Software Improved Software (MicroRIM) devel-	N	IA	LM	1983

oped using NASA mainframe data base MIS				
• Aircraft Controls COSMIC aids design of helicopter and fixed-wing aircraft controls	N	IA	LM	1983
• Computerized Translation System Computer program (SYSTRAN) "reads" one language and produces another	NO	IA	L	1981
• Agricultural Aerial Application Computerized service to improve business efficiency in agricultural area	NO	IA	L	1981
• Farm Equipment COSMIC program used to analyze engine components for tractors	N	IA	LM	1980

Construction

• Tech House Space-age technology—equipment and design features —in model house	NOW	IP	L	1978
• SPECSINTACT Catalog computer program maintains master building specifications	N	AP	L	1978
• Solar Meter Solar meter used by architects, engineers and others in construction	N	IA	L	1978
• Liquefied Natural Gas (LNG) Transfer Cryogenic fluid technology used in system to transfer LNG ship-to-shore	NO	IA	L	1980
• Flat Conductor Cable Flat wire used in building construction	NO	IA	L	1980
• Collapsible Towers ASTROMAT Portable collapsible tower used for lighting and communications	NO	IA	L	1976
• Cable Tension Equalizer Tool Potential use in moveable ceilings, elevator and crane cables	NW	IAP	L	1976
• Bolt Stress Monitor Accurate, inexpensive, portable ultrasonic bolt stress monitor	N	IP	L	1978

Consumer/Home/Recreational Products

• Cordless Consumer Products Hand-held cordless drill and vacuum are spinoff from Apollo	NO	IA	LM	1981
• Hang Gliders Hang gliders use advanced airfoil frame and aerospace technology	NO	IA	L	1981
• High-intensity Lighting Advanced lamp design using tungsten electrodes plus quartz bulb and xenon gas	NO	IA	L	1982
• Water Filter Compact lightweight electrolytic water sterilizer is bactericide-deodorizer	NO	IA	L	1982
• Icemaking System Advanced tubing system (ICEMAT) distributes a working fluid for commercial use	NO	IA	L	1983
• Advanced Welding Tool Self-contained portable heat-induction welding	N	IA	L	1982

gun used to join composites				
• High Intensity Lights Sunlight simulator used in space aids development of commercial lighting	N	IA	L	1983
• Tool Carrier Improved version of tool caddy incorporates rows of vinyl "fingers"	NW	IA	L	1980
• Solar Heaters Solar-powered swimming pool heaters	NO	IA	L	1977
• Solar Devices Multiple examples	N	P	L	1977
• Showride Moving capsule-room with total-sensory techniques produced for entertainment	NO	P	L	1976
• Portable Home Welder Small welding-torch for do-it-yourself applications	N	P	L	1976
• Packaged Food Non-refrigerated foods (compressed and dried)	NO	IP	L	1976
• Loudspeaker Performance Aid Ferrofluid is used to cool voice coil and improves speaker performance	NO	IA	L	1980
• Light Controller Electronically controlled/uses sensors to maintain light intensity	N	IA	L	1979
• Instructional Aids for Golfers	NO	IA	L	1980
• Hang Gliders for Sport Use	N	P	L	1976
• Hand-held Searchlight Bright hand-held search or flashlight	N	P	L	1976
• Graphic Video-Computer System Electronic palette	N	IA	L	1979
• Camera Design Plastic-cushioned lever advances film and switches on built-in light meter	NO	IA	L	1980
• Aluminum Oxygen Cylinders Aluminum- and fiberglass-reinforced system for mountain climbers	N	IA	L	1977
Energy				
• System Monitors Oil and Gas Flows Telemetry-based system automatically measures flow of oil and gas wells	ON	IA	L	1983
• Remote Sensing Multi-use devices aid energy firms in oil or natural gas exploration	NW	IA	L	1982
• Switching Transistor Improved switching devices to control high power electrical circuits	NO	IA	L	1981
• Solar Heating Equipment Improved solar heating system for residential use	NO	IA	L	1981
• Heat Loss Imagery Aerial thermography to detect heat loss on wide scale	NO	IA	L	1981
• Power Controller Power Factor Controller conserves electricity and senses current changes	NO	IA	L	1983

• Solar Energy System Solar counter/ recording device	NO	PA	L	1984
• Measurement Instruments Used in reflectivity studies; aids in design of lighting and window controls	NO	P	L	1984
• Steam Turbines Energy efficient radial inflow steam turbines based on NASA research	N	IA	L	1981
• Home-made Solar Systems Tech Briefs aid do-it-yourself solar systems for residential application	N	IP	L	1981
• Solar System Controller Computerized program on solar energy aids design of solar controllers	N	IA	L	1981
• Temperature Sensor Thermocouples/ temperature sensors have commercial-industrial uses	ON	IA	L	1980
• Solar Collectors Improved solar collectors for domestic and commercial heating systems	NO	IA	L	1980
• Heat Pipes Heat pipe resolved freeze-thaw cycle concern in Alaskan pipeline project	NW	AP	L	1977
• Flatplate Solar Energy Collector Basis of new enterprise formed	N	P	L	1976
• Emergency or Night Lighting Highly efficient lighting system with commercial applications	NO	IA	L	1980
• Electric Power Monitor Sophisticated dispatch computer system monitors/ controls energy distribution	NO	IA	L	1980

Health and Medicine

• Anti-contamination Garments Improved garment for medical-industrial use	ON	IA	L	1983
• Multipurpose Compound (Livestock) Alicide compound aids treatment and prevention of bovine mastitis	NO	IPA	L	1983
• Meals for the Elderly Refrigeration-less, compactly-packaged food system uses astronaut-type meals	NO	IA	L	1980
• Lead-poison Detector Portable device can mass-screen for lead poisoning in blood stream	NO	P	L	1976
• Hospital Food Service Integral heating system aids in food color and taste retention	NO	IA	L	1977
• Gait Analysis Laboratory Motion-analysis lab uses NASA-type techniques	N	AP	L	1976
• Environmental Simulator—Vacuum Drying Environmental chamber used for crop drying and other applications	NW	IA	L	1980

Industrial Productivity

• Liquid Hydrogen—Cryogenics NASA contractor applies knowledge gained for commercial use	NO	IA	LM	1982

• Inventory Management COSMIC software used to design inventory control system in industry	N	IA	LM	1983
• Pressure Controller Device using pressure transducer improves furnace combustion efficiency	NO	IA	L	1981
• Management Information System (MIS) Automated MIS uses microcomputer to display data in rapid time	NW	AP	L	1984
• Cool Vest Lightweight cooling industrial clothing based on space suit technology	NO	IA	L	1982
• Power Supply Unit Converter switches dc voltage into forms suitable for electronic equipment	NO	IA	L	1982
• Power Controller Power factor controller conserves electricity and senses current changes	NO	IA	L	1982
• Engine Recovery System Advanced industrial cogeneration system based on Organic Rankine Cycle engine	NO	IA	L	1983
• Airborne Imagery Geologic mapping technique used in mining and agricultural industries	NO	IAP	L	1983
• Workplace Design Study conducted by Johnson Space Center	NO	PA	L	1984
• Bolt Stress Monitor Inexpensive and accurate device measures stress using ultrasonic sound	N	IA	L	1981
• Rotation Measurement Encoder instrument electronically measures angle of rotating shaft	N	IA	L	1979
• Management Technique Total integrated systems approach used in agricultural programs	N	IA	L	1980
• Gas Flow Controller Device accurately controls reactive gases; used in semiconductor industry	NO	IA	L	1980
• Automated Check-out Equipment Apollo's check-out system has commercial applications	N	PA	L	1976
• Industrial Meat Tenderness Tester Telemetry technology applied to food industry to test hanging carcasses	IA	A	L	1977

Safety and the Environment

• Air Pollution Surveillance System Air monitor based on space sensors and telemetry	NW	IA	L	1983
• Mineral-Water Analyzer Highly miniaturized power-efficient portable unit aids in exploration	NW	IA	L	1983
• Drunk Driver Testing Testing device for drunk drivers based on 20-year-old behavioral system	NW	P	L	1984

• Firefighting Module Portable module uses rocket-engine pump/lightweight materials-packaging technique	NO	P	L	1981
• Space-Derived Sewer Monitor Device helps locate underground sewer leaks using fluid flow technology	NO	IA	L	1982
• Electronic Nose Device detects (senses) accelerants—hydrocarbon gases etc. Fire safety use	NO	IA	L	1982
• Self-righting Life Raft Improved life raft design with industrial/commercial potential	NO	IP	L	1982
• Image Processing Advanced scanner-plotter-film recorder aids remote sensing	NO	IA	L	1982
• Ground Use Sensor (radiometer) Hand-held sensing device used for ground analysis/mineral content, etc.	NO	IA	L	1982
• X-ray Systems (Medical & Commercial) X-ray telescopic technology used in cargo inspection and tomography	NO	IA	L	1983
• Remote-Controlled Industrial Machinery Coal mining and roof bolting equipment improved through NASA research studies	NO	IP	L	1983
• Gas Analyzer Portable device detects toxic gas leaks in industry	NO	IP	L	1983
• Crashworthiness Program Jungle Aviation and Radio Service program saves lives; aids in development of safer products	NO	IA	L	1984
• Firefighting Module Operates on land and water surfaces	NO	PA	L	1984
• Yacht Race Monitoring Space-based monitoring system locates ship positions; assists emergency services	N	IP	L	1981
• Multispectral Photography Advanced aerial camera used in forestry, agriculture, water pollution areas	NO	IA	L	1982
• Weather Data Receiver Satellite-dish antenna design based on NASA research	N	IP	L	1982
• Sewage Treatment Aquatic plants thrive on sewage; offer potential by-product uses	N	AP	L	1984
• Water Quality Monitor On-spot water analysis monitor uses microelectronics technology	NO	IP	L	1979
• Waste Treatment Shipboard waste treatment technology has sea and land applications	NW	AP	L	1977
• Vacuum Drying Technique Large environmental chamber used to dry water soaked items (e.g., books, etc.)	NW	IA	L	1979
• Trace-gas monitoring Portable device	NO	P	L	1976

monitors contaminants				
• Toll-booth Air Purification System Air-purified toll-booths use aerospace laminar flow techniques	NO	IA	L	1977
• Small-particle Pollutant Device Proton-induced X-ray emission technique monitors atmospheric pollutants	NO	P	L	1976
• Sewer Mouse Sewer waterflow monitoring device helps locate pollution-causing sewer leaks	NO	IA	L	1979
• Satellite Beacon Portable monitoring system transmits signal for tracking balloon	NO	IA	L	1979
• Restoration Process—Law Enforcement Law enforcement officials use ultrasonic cavitation process to restore ground-off serial numbers on guns, etc.	N	IP	L	1979
• Radioactive Leak Detector Small, portable radioactive leak detector	N	IP	L	1980
• Personal Security Device Pen uses ultrasonic sound transmitted to monitored master console	N	IA	L	1980
• Personal Alarm System Ultrasonic pen-sized transmitter uses space telemetry technology	NO	IA	L	1977
• Linear Explosive Devices Devices based on rocket-stage explosives used in building demolition, etc.	NO	AP	L	1976
• Lightning Protection Design features to protect aircraft from lightning	NW	IA	L	1980
• Law Enforcement Videofile Videotape storage and retrieval system adapted as law enforcement tool	NO	AP	L	1977
• Laser Surveying Tool Laser Range Pole uses laser transmitter-receiver for surveying	NO	IPA	L	1977
• Fireman's Air Tanks Lightweight air tanks	N	P	L	1976
• Firefighting Aid Automated information system uses sensors/energy devices and satellite	NO	AP	L	1977
• Emergency Lighting System Extendable mast used in connection with emergency vehicles	NW	IA	L	1980
• Emergency Lighting Industrial plant emergency and supplemental lighting uses space technology	NO	IA	L	1977
• Educational Packages Remote sensing imagery potential broadened using educational packages	NO	P	L	1977
• Coast Guard Firefighting Module Portable device uses rocket-engine pump/lightweight	NO	P	L	1977

materials-packaging technology; later used more extensively by fire fighters				
• Carbon-monoxide Detector Nondispersive infrared spectroscopy technique used to monitor carbon monoxide	NO	IP	L	1976
• Buoy Raft Uniquely-stabilized/inflatable liferaft used by fishing boat operators	NO	IP	L	1978
• Ambulance Handbook Astronaut checklist has potential use for emergency personnel	N	P	L	1976
• Air Sampling Filter Filter paper cartridge or cassette offers improved air sampling	N	IA	L	1980
• Air Safety Spinoffs Examples include weight-savings in aircraft design and underwater locator	NWO	AP	L	1977

Transportation

• Control Systems Pilot control software packages—flight management systems (ORACLS-COSMIC)	N	A	LM	1984
• Methane-powered Airplane Liquid methane-powered civil aircraft	WN	P	L	1984
• Aircraft Inlet Ducts Permits increased efficiency of general aviation aircraft engines (heat exchanger)	ON	A	L	1984
• Methane-powered Vehicles System designed for conversion of cars and trucks to liquid methane operation	NW	IA	L	1982
• Jetliner Alert Systems Synthetic voice/visual and other alert criteria aids design of cockpits	N	IA	L	1983
• Space-Derived Waterjets Waterjet in commercial use similar to turbopump technology used in Saturn V	NW	IA	L	1979
• Preserving Perishables Controlled environmental container (Dormavac) extends lifetime of perishables	NW	IPA	L	1979
• Electric Car Passenger vehicle borrowing space-battery technology has potential use	N	IP	L	1977

Appendix B—AIA Civil Aviation Advisory Group Survey Results Summary

The cases selected for this Aerospace Industries Association (AIA) study were among those recommended during two surveys of members of the AIA Technical Council's Civil Aviation Advisory Group (CAAG) in mid-1984. In the first survey, CAAG members were asked to suggest possible candidate cases and to indicate their assessment of the availability of documentation to support a study of the proposed case. The results of this first survey were tabulated and, along with a list of cases previously studied by NASA (shown in Appendix A), sent to CAAG members with a request that they designate their "Top Five" choices from among the candidates list. The complete list of case study candidates is shown on the survey form at the end of this appendix. The results of the second survey are indicated below, along with the recommendation of the study contractor developed while the survey was in progress.

CAAG "Top Five" Choices

Crashworthy Structures
Structural Bonding
*+CAD/CAM
Titanium and Aluminum Alloys
Filament Winding
*+Composite Materials
Swaged Couplings
+Automobile Aerodynamic Stabilization
Automobile Antiskid Systems
Automobile Microprocessors
*+Turbochargers

+Multiple respondent selection
*Case recommended by contractor

The recommendation of the contractor was based on the diversity of the three proposed cases, which was considered to be an important factor to strengthen the generality of the study conclusions. The contractor's letter of recommendation noted:

Turbochargers are a type of *device* pioneered by the aviation industry over 65 years ago and increasingly used in autos, trucks, and earth moving equipment to increase power without a corresponding engine weight increase.

Composite materials (with attention restricted to FRP composites) are a type of industrial *material* pioneered by aviation over 40 years ago and continually advanced in the years since. Because of its special strength, weight, and durability characteristics, composite material is increasingly used in vehicles, sporting equipment, and for many other industrial and consumer products.

CAD/CAM is a *process* which has been evolving during the last 20–25 years, with important contributions by the aviation industry, which is significantly changing the organization of engineering and manufacturing activities, and future changes will have even greater impact.

The complete list of candidate cases suggested by CAAG is shown in the survey form below.

SUMMARY OF CAAG QUESTIONNAIRE RESPONSES PROPOSED TECHNOLOGY DIFFUSION CASES

Please review this list of CAAG-suggested cases and *mark the Top Five cases you consider the best overall candidates for detailed study.* On the back of this and the second list sheet, please *indicate briefly WHY you believe each of your preferred cases should be a strong candidate.* Some of the factors you may want to consider in this selection are the magnitude of the impacts a technology has had, the number of other industries which have been affected by the technology, the "documentability" of origins and impacts, etc. If you have suggestions for additional cases you believe should be in your Top Five rankings, please add them and indicate why they are strong candidates.

MANUFACTURING PROCESSES/DEVICES

____ * Welding (invented elsewhere) 1976, 1982
____ * Seals (RSG) 1978 #
____ * Printed Circuits (RSG) 1977, 1979, 1980
____ ° Structural Bonding (RDE)
____ ° Super Plastic Forming (Ti & Al) (RDE, RDT)

____ ° Precision Casting (RSG)
____ ° Chemical Etching (RDE)
____ ° Super-cooled Metals (RDE, RDT)
____ ° Tape Laying (RSG)
____ ° FRP Paneling (RSG)
____ ° Filament Winding (RDE, RDT, ISB)
____ ° Adaptive Control of Curing Process (Polymers) (RDE, RDT)
____ ° Low-Cost Fabrication of Ti (B alloys) (RDE, RDT, ISB)
____ ° Swaged Coupling Fittings (RDE, RSG, RDT, ISB) #
____ ° Flush Crown Rivet System (RDE, RSG, RDT, ISB) #
____ ° Stress Coining (RSG) #
____ ° Thermal Fuse (RSG) #
____ ° Computerizing of electron beam

CAPITAL EQUIPMENT

____ * Computer Aided Design (RDE, RDT, ISB) 1982, 1983, 1984
____ * Color Graphics (RSG) 1982, 1983
____ * Robotics (RSG) 1984
____ ° Micro Electronics (RDE, RSG)
____ ° Hydropress (RSG)
____ ° Instrument axion
____ ° Computers—vibration testing
____ ° Computers—microwave
____ ° Automation of Composite Fabrication (RDE, RDT)

MATERIALS

____ * Composites (RDE, RSG, RDT, ISB) 1976, 1979, 1983
____ * Powdered Metals used by tools industry have been advanced by aircraft engine makers, later used by earth-moving industry 1984
____ * Ivadizer (RDE, RSG, RDT, ISB) 1979 #
____ * Aluminum Alloys (RSG) 1977
____ ° Aluminum-Lithium Alloys (RDE, RDT, ISB)
____ ° Unidirectional Fiberous Materials (RSG)
____ ° Kevlar (RSG)
____ ° Steel Alloys (RSG)
____ ° Rapid Solidification Technology—Powdered (TI & Al) (RDE, RDT, ISB)
____ ° Titanium and Aluminum Alloys (RDE, RDT, ISB)
____ ° SPF/DB Titanium (RDE, RDT)
____ ° Skydrol (RSG) #
____ ° SiC-Al Alloys—Collimated & Whiskers (RDE, RDT, ISB)
____ ° Hi-Temperature Aluminum Alloys (RDE, RDT, ISB)

AERODYNAMICS

____ * Rotor Aero for Windmills and Industrial Fans (RDE, RSG) 1979
____ * Reduced Drag for Improved Efficiency (RDE, RDT) 1977, 1980
____ ° Improved Aerodynamic Stability & Control of Autos (RDE, RDT)
____ ° Liebeck Foil (RDE, RSG)
____ ° Computational Fluid Dynamics for Auto Design (RDE, RDT)

RESEARCH TOOLS

____ * Simulation (RDE) 1980
____ * Computer Aided Design & Mfg. (RDE, RDT) 1978, 1982, 1983
____ * Computer Generated Images (RDE) 1978, 1982
____ * SOMLA (seat occupant) (RDE, RDT) 1984
____ * Wind Tunnels (RDE, RDT) 1979, 1982
____ * NASTRAN Computer Software for Structural Analysis used in nuclear, auto, and civil engineering (RDE, RSG) 1976, 1977, 1978, 1979, 1980
____ ° Modeling (Crashworthiness Analysis and Design) (RDE, RDT)
____ ° KRASH (structures) (RDE, RDT)
____ ° Composite & Metal Crashworthy Structures (RDE, RDT)
____ ° Analytical Tools for Crash Dynamic Analysis (RDE, RDT)
____ ° Sale of CAD Design Tools (RDE, RSG, RDT, ISB)
____ ° Smoke (Heated) Generator (RDE, RDT)
____ ° DYCAST (structures) (RDE, RDT)

OTHER

____ * Management methods for complex projects (RDT) 1980, 1984
____ * Anti-skid system for airplanes now used in automotive industry 1977
____ ° Automotive turbochargers derived from aerospace technology (RDE, RSG) #
____ ° NASA work in E-3 had mfg. process spinoff
____ ° PLASI—Pulse Light Landing Aid (RDE, RSG) #
____ ° Joint Services Advanced Vertical Lift Aircraft Program (RDE, RDT) #
____ ° Advanced Rotorcraft Technology Integration (ARTI) (RDE, RDT, ISB) #
____ ° Licensing Agreement for Micro HUD (RSG, ISB) #

LEGEND: RDE = Saved R&D Expenditures
RSG = Revenue Stream Generated
RDT = Time Saved in R&D and Demonstration
ISB = Improvement in Supplier Base
# = Commercial Agreement
* = Earlier Case Study in NASA Spinoff Report for year(s) shown
° = Potential New Case

Appendix C—Turbocharger Technology

1901 Sanford Moss, graduate student at Cornell University, tried to build gas turbine.

1905 Alfred J. Buchi, Swiss engineer, patented drawings of a multi-stage turbine, a multi-stage axial-flow compressor, and an intercooler.

1909 Through 1912, Buchi built and tested the first exhaust driven supercharger at Sulzer Co. in Switzerland. Results were not encouraging.

1915 England became aware of advantages of supercharged aircraft engines. By 1916, developmental work started between England and France. Work continued in England on turbine-driven superchargers until around 1925, favoring a gear-driven type of supercharger.

1916 Auguste Rateau became French patent holder of a turbine-driven supercharger intended to make high-altitude flight possible. Also designed and patented widely used steam turbines.

1917 General Electric, with Rateau license, began development of aircraft engine turbocharging, under guidance of Sanford Moss.

1920 GE turbocharger installed on a Liberty V-12 aircraft engine set a new altitude record of 39,000 feet. Turbocharged aircraft engines remained in experimental stage until 1930's, primarily due to slow metallurgical developments.

1922 Buchi designed turbocharger on ten-cylinder MAN diesel engine for two new twin-screw vessels built for German navy and completed by 1925. Output boosted from 1,750 h.p. to 2,500 h.p.

1926 Brown, Boveri & Co., together with Swiss Locomotive & Machine Works, formed Buchi Syndicate and developed turbochargers for Swiss railroads (4-cylinder 2,065 cubic inch 750 h.p. diesel). After 1930, interest intensified.

1928 *Rady Castle*, first English turbocharged ocean-going vessel.

1928 Several diesel-powered cargo and passenger ships in Ireland were turbocharged.

1929 The first turbopowered submarine, a Russian Navy vessel, was Swiss made.

1929 Japan installed the first turbocharged diesel in a power station, in the Chinese city of Nanking.

1933 Buchi Syndicate introduced high-speed diesel engines using exhaust turbocharging on German rail cars.

1933 Maybach began turbocharging its V-12 locomotive diesel. Deutz followed in 1934 and Saurer in 1935.

1936 U.S. Navy indicated interest in turbocharged engines.

1936 Through 1937, Cooper-Bessemer, Baldwin, and American Locomotive began production of turbocharged locomotives.

1936 GE turbocharger, Garrett intercooler and Pratt & Whitney engine developed and installed on B-17.

1937 Wright Aeronautical began production of turbocharged Cyclone engine, an 18-cylinder engine for B-17 and B-24.

1938 Saurer started test of world's first turbocharged diesel truck.

1940 Sanford Moss received the Collier trophy for development of the turbosupercharger.

1940 Elliott Company of Jeanette, Pa., purchased a Buchi license and began production for American engine builders.

1940 Between 1940 and 1945, more turbochargers and turbocharged engines were produced in the U.S. than had been manufactured in the entire world since turbocharging was introduced. During World War II, superchargers were used on tens of thousands of aircraft: B-17, B-24, B-29, P-38, and P-47, among others.

1945 By this time, basic turbocharging technology was at Detroit's doorstep.

1949 Saurer began production of turbocharged diesel trucks. MAN followed in 1951.

1950 Elliott began using turbochargers on some diesels.

1951 GM Research Lab began evaluating turbocharger potential for small engines.

1952 Cummins, using an Elliott turbocharger weighing 30 lbs., boosted its diesel truck engine from 150 h.p. to 400 h.p. at "Indy 400" and won pole position, stunning auto industry. Failed to win the race, however.

1952 Some 20,000 engines, of which 8,000 were for locomotives and 7,000 were for ships, had been equipped with Buchi-designed turbochargers for a combined power output of 21 million horsepower.

1952 Brown, Boveri and its licensees had been the only suppliers of commercial turbochargers since 1926.

1953 Through 1955, first use of turbocharged engines in off-highway applications, in Caterpillar tractors. Garrett T-02 model employed three features not successfully used before in turbocharged vehicles: (1) did not use any water cooling; (2) solidly mounted to engine's exhaust manifold, without flexible members; and (3) used engine's oil supply instead of an independent oil supply. Production model was T-15, and Garrett sold 5,000 units at a price of $1,185 each—the largest turbocharger production order in the world. By 1954, Garrett's turbocharger division had been separated from its Gas Turbine Department.

1957 Cummins, not content with Elliott or Schwitzer turbochargers, began manufacturing its own line of turbocharged trucks.

1958 Garrett's AiResearch Division developed its own turbocharger design, began production, and became a licensor primarily to Howmet in England. Schwitzer of Indianapolis followed and Eberspacher and Kuhnle, Kopp & Kausch in Germany also became leading makers.

1959 Garrett pioneered development of small, lightweight, low-cost turbochargers matched to aircraft-type engines. Initial application was on a helicopter power plant and later on fixed-wing aircraft for business use.

1960 During this period, Mack Truck, Detroit Diesel, Caterpillar, and later International Harvester, began to apply turbochargers to their production-line trucks.

1960 This period also saw increased use of turbocharged engines in agricultural use. John Deere, Allis-Chalmers, J. I. Case, International Harvester, and Ford all began using turbochargers on their production lines, adding turbochargers to their industrial and construction lines as well.

1960 GM's Pontiac division turbocharged a 389-cubic inch V-8 for drag races and set speed records with great success.

1963 Ford began experimenting with turbocharging and installed turbocharged 390-cubic inch V-8's in some Thunderbirds. These automobiles ran well but were not released for commercial production or sale.

1963 The Oldsmobile Jetfire used an aluminum V-8 engine, turbocharged by Garrett. Also, GM's Chevrolet division used TRW turbocharger. Both models were discontinued at the end of the model year.

1966 Cessna, with a Garrett turbocharger system, set a new world's light aircraft altitude record of 39,344 feet.

1967 Drake-Offenhauser engine with Garrett turbocharger won "Indy 500" in a direct challenge to Ford.

1968 Ford's V-8, turbocharged by Schwitzer, entered Indy 500.

1968 BMW turbocharged its four-cylinder 2002 for racing using a Kuhnle, Kopp & Kausch unit built under Schwitzer license.

1969 Michael May, Swiss engineer, began modifying Eberspacher diesel-turbo for use in small gasoline engines and began making conversions for sale, beginning with Ford Capri and later the Opel.

1970 By this time, Ford was delivering 800 h.p. and Offy 735 h.p. despite a new displacement limitation of only 161.7 cubic inches.

1972 Porsche began turbocharging it competition cars.

1972 Garrett began marketing its turbocharger designed for use with smaller engines to Detroit for production cars.

1973 During this period, the "energy crisis" and the need for more fuel-efficient engines reinforced Detroit's dependence on turbocharging.

1974 Porsche introduced turbocharged production models with Kuhnle, Kopp & Kausch units.

1976 Saab introduced slant four-cylinder engine with Garrett turbocharger system.

1978 Mercedes-Benz 300D, a five-cylinder diesel, lacked power until it incorporated Garrett turbocharger.

1978 Buick's V-6 turbocharged engine was introduced.

1979 Ford met with Garrett to discuss introduction of Ford turbocharged engines for production use.

1984 Chrysler, GM, and Ford all have some production models equipped with turbochargers, as do many imported automobiles. Chrysler leads the way domestically with approximately 10 percent of its fleet having turbochargers installed as standard equipment.

Appendix D—NASA Spinoffs of Composite Materials Technology

In addition to the developments which have been made in composites technology by individual firms, the National Aeronautics and Space Administration (NASA) has stimulated developments among its contractors, which have often led to further developments in other commercial applications. The following list shows such "spinoff" applications identified by Denver Research Institute, by type of application and DRI case number:

A. *Manufacturing Consumer Products*

A-3 Composite materials data compiled by NASA ... used by *Babcock & Wilcox Co.* in designing composite products ... used in golf club shafts and tennis racquets produced for *Wilson Sporting Goods* ... also produce composite parts for business machines and computer manufacturers, such as *Xerox.*

B. *Manufacturing Capital Goods*

B-87 Composite materials data ... used by *Babcock & Wilcox* to produce a composite ball valve designed for use in high temperature and severely corrosive environments ... can replace valves made with exotic alloys, such as nickel or titanium ... valves used in chemical processing, pulp and paper, and basic metals industries.

I. *Construction*

I-4 Beta fiber yarn invented by *Owens-Corning Fiberglass Corp.* ... company developed first applications for fiberglass fabric with NASA contract for nonflammable clothing and structures; included developments of Teflon coating for fabric ... application experience used to develop commerical market ... current uses include protective clothing and roofs ... coated fabric used commercially in air structures developed by *Birdair Structures, Geiger-Berger & Assoc.* and others ... installations include a vinyl-coated fabric covering for the U.S. Pavilion at Expo 70 in Japan; Teflon-coated fabric coverings for stadiums, arenas and other recreational facilities, such as "Silverdome" in Pontiac, Mich., University of Northern Iowa stadium, University of South Dakota stadium, sports arena at Laverne College, Calif., the multipurpose student center at Milligan College, Tenn., and the picnic areas at Sea World in San Diego, Calif. ... recent applications include roofs for office buildings, department stores, and airport facilities ... in 1980, over $200 million worth of construction involved this material.

I-8 Coating composition patented by *Emerson Electric Co.* ... first market was space program use as heat shield coating for reentry vehicle ... coating sublimates when heated and protects substrate from high temperature ... spinoff firm created and patented new product THERMOLAG ... significant advance in commercially available fire retardant coatings ... reliable, effective, inexpensive coatings used by construction industry to protect building components, such as structural steel and electrical cables, during fires ... structural steel coating 0.2 inches thick will give two-hour fire protection comparable to 4.0 inches of concrete coating ... other applications include railroad tank cars and propane tanks.

M. *Air Transportation*

M-10 Friction characteristics of graphite and graphite-metal, developed for NASA ... used by *B. F. Goodrich Co.* to develop new brake linings for commercial and military aircraft.

M-15 Composite tank for fireman's breathing apparatus developed for NASA by *Structural Composites, Inc.* ... used to develop new product line of lightweight filament-wound pressure vessels for commercial aircraft escape slide systems ... reduces aircraft weight by 200 lbs. ... now sold to *Boeing* and various airlines.

M-38 In-situ polymerization of monomer reactants (PMR) produces polyimide resins with excellent thermal stability, lower handling costs and long shelf life . . . used by *Ferro Corp., Composites Div.*, to synthesize PRM plastics for fiberglass-based composite . . . material used to fabricate high temperature aircraft turbine and wind tunnel compressor blades, as well as structural components; used primarily by aerospace companies, including *General Electric, Hamilton Standard, United Technologies*, and *Boeing*, for construction of engine and wind tunnel components requiring long-term heat aging up to 600 degrees F . . . also used by *HITCO, U.S. Polymeric Div.*, to develop high strength graphite-polymer composite molding fabric suitable for applications up to 600 degrees F, such as aircraft engine components . . . also used by *Fiberite Corp.* in production of similar product.

M-52 Graphite/epoxy composites moisture test used by NASA to select doors for Space Shuttle . . . measured effects of moisture on various commercially available graphite/epoxy compounds—specifically absorption tendencies of compounds and effects on shear strength and stiffness at various temperatures . . . used by *Boeing Co., Inc., Boeing Vertol Div.*, to determine probable effects of humidity on helicopter components constructed from graphite/epoxy composites . . . for conversion of CH-47 helicopter for use in servicing oil rigs in the North Sea . . . substantial savings realized by avoiding expensive materials testing program.

M-53 Composite airframe structures developed for NASA by *United Technologies Corp., Sikorsky Aircraft Div.* . . . feasibility of co-cured, integrally molded skin/stringer/frame concept for low cost airframe structures tested on CH-53D helicopter . . . allows 30 percent weight reduction in airframe components . . . experience gained with co-curing systems used in design of S-76 SPIRIT commercial helicopter . . . first commercial helicopter with primary composite structures certified by the Federal Aviation Administration.

M-54 Boron/epoxy reinforced airframe designed and tested for NASA by *United Technologies Corp., Sikorsky Aircraft Div.* . . . CH-54B Skycrane helicopter redesigned to use boron/epoxy reinforced aluminum strips instead of a thick aluminum skin . . . performance analysis of prototype proved such stringers are effective in reducing the weight required for airframe stiffening and have above-adequate strength for structural integrity . . . experience enabled division to use boron/epoxy reinforcement stringers in design of UH-60A Black Hawk helicopter . . . over 1,100 units to be produced.

P. *Health Services/Rehabilitation*

P-2 Composite materials developed by NASA for spacecraft, aircraft, and rocket motor applications . . . used to design lightweight leg braces . . . heavy, metal brace components replaced by molded composite braces weighing 50 percent less . . . new braces improve mobility and are more attractive . . . new composite processing methods recently developed result in 10–20 percent reduction in manufacturing costs and greater flexibility in design . . . other applications currently being developed include lightweight footplates for use by arthritics, aneurism clamps and skull plates that would elminate problems of X-ray interference and biochemical effects caused by metal clamps and plates, and lightweight wheelchairs to be produced at reasonably low cost.

SOURCE: Denver Research Institute, *Space Benefits: The Secondary Application of Aerospace Technology in Other Sectors of the Economy, 81-1* (NASA contract NASW-3113), 1981.

Appendix E—CAD/CAM Chronology

1950	Early to middle 1950's, complex full-sized computers were introduced to a limited market.
1950	Also early 1950's, Massachusetts Institute of Technology (MIT) under USAF contract developed the first numerically controlled machine tool (NC).
1953	Thirteen companies had IBM computers at nine installations.
1954	Fifty companies using Univac I.
1955	All computers installed in use could make ¼ million calculations per second. Today, one PC can make 2.5 billion calculations per second.
1955	Mid-1950's, shell analysis undertaken by aerospace firms; stress and definition techniques studied with aid of computers; beginning of computer-aided engineering (CAE). Aerospce firms continued study of trade-offs between weight, strength, and materials performance.
1957	Aerospace firms began serious applications of numerically controlled machine tools and required general purpose programs. Together with MIT, 21 firms (mostly aerospace) collaborated in R&D activity which culminated in an expanded and refined practical production system of languages and computer programs known as APT, for Automatically Programmed Tools.
1960s	Early 1960's, IBM combined with North American, Lockheed, Rolls Royce, and McDonnell Douglas to determine early uses and demands for "digit graphics." Project "Demand" started.
1960s	From 1960's on, individual aerospace firms take off on their own to develop computer-aided design, both concepts and software.
1960s	From late 1950's through 1960's, computer languages such as COBOL, APL, and FORTRAN were developed.
1960s	NASTRAN and related advanced structural design software developed for aerospace industry by NASA.
1960s	Zone-growing of crystals refined, providing for the development of the transistorized chip.
1960s	Early 1960's light pen introduced for "drawing and designing" with computers.
1960s	Finite element analysis techniques first used by aerospace and nuclear industries.
1962	Ivan E. Sutherland, MIT, introduced the "sketch pad" computer graphics concept.
1964	Aerospace firms built on feasibility of sketch pad techniques for aircraft design and analysis.
1964	Batch-mode approach used in computer processing of design and analysis—put questions into computer and get the results back later to study; not yet interactive engineering analysis.
1965	Limited interactive systems created via computer time-sharing.
1965	By mid-60's, Lockheed had developed an interactive computer graphics system—CADAM (Computer-graphics Augmented Design And Manufacturing System). MIT, GM, and Bell Labs also had on-going interactive computer graphics research programs.
1965	Lockheed established special team for computer applications and numerical control parts system programming.
1966	Lockheed's full numerical control parts production system becomes operational.
1969	Computervision, a start-up firm aimed specifically at development and sale of CAD systems, is founded.
1970's	True interactive systems introduced. Previously all systems were "refresh" type. Techtronics introduced storage tube CRT device, enabling computers to be fully utilized for computational efforts, rather than a major portion of computer memory and capability being dedicated to repeatedly redrawing the CRT screen.
1970's	Minicomputers introduced, reducing cost of computer time substantially.

1974 ''Turn-key'' companies make serious in-roads in CAD/CAM, providing integrated systems. Prior to this time all systems were basically ''custom-designed,'' including development of in-house software.

1980's Extensive use of CAD and CAM techniques in aircraft design and production, substantially reducing ''paper production.'' Lockheed L-1011, McDonnell-Douglas DC-10, Boeing 767 and 757, Grumman X-29, and other aircraft are developed with extensive CAD/CAM usage. All major aerospace firms have direct experience in developing or using CAD and CAD/CAM systems. Several are serving as CAD/CAM suppliers to other industries.

Appendix F—NASTRAN—A Major Contribution in CAE

In the 1960's, the proliferation of many different kinds of software for dynamic structural analysis among different design and engineering groups prompted NASA to provide funds for the development of a standardized package which could be used to obtain reliable and consistent results in a wide range of aerospace applications. The result was called NASTRAN (NASA Structural Analysis). Major components of NASTRAN and related computer packages were later adapted by industrial users to meet design requirements for rail, auto, and other non-aerospace equipment.

To aid in the dissemination of NASTRAN and other software which it has created, NASA maintains one of the nation's largest software libraries for engineering analysis and other programs at its Computer Software Management and Information Center (COSMIC) at the University of Georgia. Copies of software are made available at prices based on the cost of running the center and the cost incurred in creating and maintaining the software. NASTRAN currently sells for about $3,500 for the public domain version; the better documented and more refined commercial version rents for $900 a month.

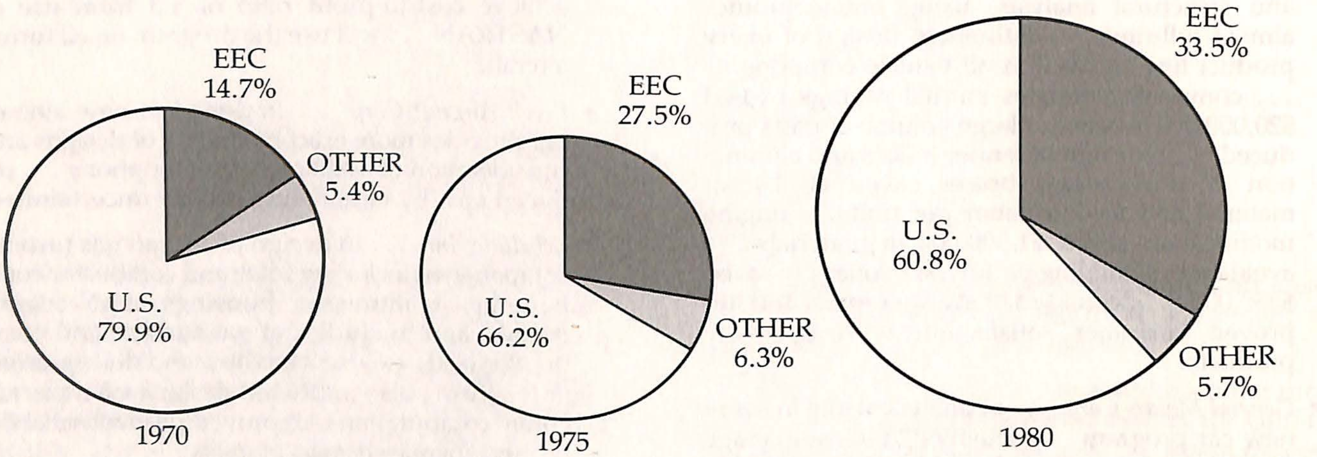
NASTRAN is the most widely used computer program developed by NASA. As of 1981, the agency estimated that direct cost savings to NASTRAN users had exceeded $700 million since the program was released in 1971. Cases of significant NASTRAN use documented by Denver Research Institute included the following:

- *General Atomic Co.* used NASTRAN for dynamic modeling of high temperature gas-cooled reactors and design analysis in DOE-funded Doublet-III Fusion Experiment . . . save four person-months in program development.
- *Turbodyne Co.* . . . for dynamic modeling and analysis of steam turbine wheels, including blades and blocks . . . saved $50,000 in development costs, with continued annual savings of $10,000–$15,000 . . . also provided added engineering capabilities and improved products through increased product safety and reliability . . . company produces combustion and steam turbine systems and electrical equipment for domestic and overseas markets.
- *Babcock & Wilcox Co.* . . . to avoid buckling problems in design of industrial boilers for *Gulf Oil Corp.*, where boilers are used for steam processing in petroleum refineries.
- *Budd Co.* . . . to redesign railroad passenger cars used in the high speed Metroliner train system between Boston and Washington, D.C. . . . achieve Department of Transportation ride quality standards.
- *Pullman Standard, Inc.* . . . to simulate dynamic behavior of railroad cars used for bulk commodity transport and develop improved design.
- *Walt Disney Productions* . . . to design the support structure for "Space Mountain" and "Big Thunder Railway" roller coasters at Disney Land and Disney World . . . determined the size and strength of structural components needed . . . provided "substantial cost saving" from not over-strengthening track supports.
- *Eastman Kodak Co.* . . . to design buildings and production equipment for chemicals, plastics, and fibers . . . for analysis of stress in piping systems, wind load on exhaust stacks, and vibration of processing equipment . . . saved many engineering hours, thousands of dollars in equipment costs.
- *E-Systems, Inc., Aeronautical Sciences Div.* . . . for installation of airborne command post communications equipment on *Boeing* aircraft . . . provided analysis of structural effects of removing 12 feet of aircraft fuselage for installation of electronics equipment . . . enabled company to modify aircraft with greater confidence in the structural tolerances and to select optimum positioning for the equipment . . . program used on a continuing basis by approximately 20 structural engineers.

- *Ford Motor Co.* . . . for design analysis of car, truck, and farm tractor components since 1971 . . . more than 500 employees trained to use commercially available NASTRAN package; currently used on full-time basis by 150 design engineers and structural analysts, using one computer almost full-time . . . influences design of every product line, as well as all vehicle components . . . company estimates annual savings exceed $20,000,000 because of large volume of parts produced . . . redesign of fender braces and elimination of unnecessary braces saves 11 lbs. of material and $6–7 in labor per unit . . . engine modification saved $1,500,000 in materials . . . avoidance of building prototype in one case saved $250,000 . . . decreased warranty repairs and improved customer satisfaction with company products.
- *General Motors Corp.* . . . as analytical tool in every new car program . . . achieved 700 lbs. average weight reduction on each of 1.5 million cars produced in 1977 (400 lb. weight reduction is equivalent to a saving of one mile/gallon) . . . average weight reduction of 650 lbs. on 1978 intermediate cars . . . more efficient body structure designed for 1979 front-wheel drive cars . . . over 300 employees trained to use NASTRAN, with 150 currently using program full-time.
- *United Technologies Corp., Sikorsky Aircraft Div.* . . . to model fuselages of helicopters to determine natural frequencies so that mechanical vibrational frequencies do not coincide and cause resonance . . . to determine amount of bend and twist in the fuselage when helicopters undergo various maneuvers . . . improved helicopter design helped achieve cost-to-profit ratio of 1:3 from use of NASTRAN . . . will use the program on all future aircraft.
- *Beech Aircraft Corp.* . . . in design of new aircraft . . . provides more exact modelling of designs and consideration of additional desgin options . . . reduced cost by eliminating design uncertainties.
- *Teledyne, Inc.* . . . in design of aircraft gas turbine components (including rotor and combustor components, compressor housings and engine frames) and in studies of gas turbine and compressor blades . . . several thousand dollars saved annually . . . also improved designs via more accurate computations, improved product reliability, and increased marketability.
- *Lockheed Aircraft Corp.* . . . to design wing panels and analyze composite floor posts on L-1011 and S-3A aircraft . . . annual savings estimated at 2,000 person-hours and $300,000, plus improved product safety and reliability, improved productivity and increased marketability.

SOURCE: Denver Research Institute, *Space Benefits: The Secondary Application of Aerospace Technology in Other Sectors of the Economy, 81-1* (NASA Contract NASW-3113), 1981.

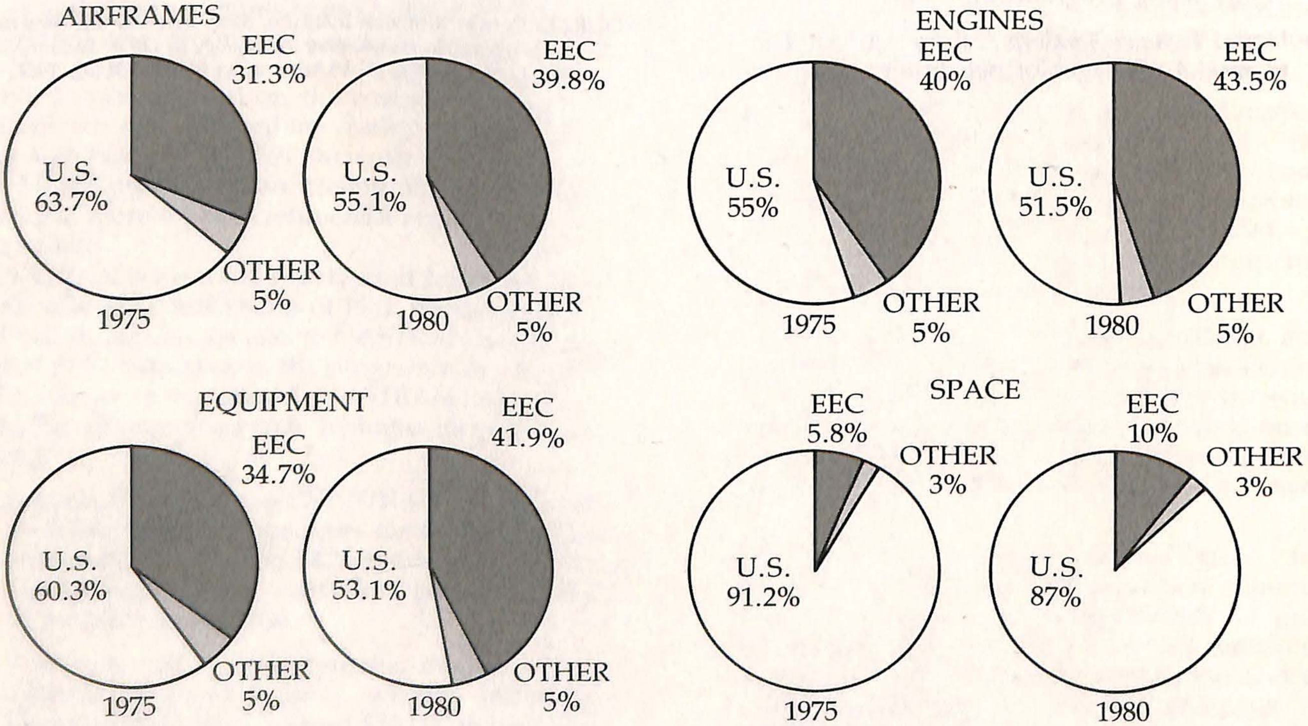
Appendix G—Free-World Aerospace Sales By Producing Country 1970-1975-1980



SOURCE: Shriner-Midland Company, compiled for Aerospace Industries Association (AIA) from official European Economic Community (EEC) and U.S. data.

NOTE: Based on constant 1972 dollars. (1) U.S.—excludes "non-aerospace" sales. (2) EEC—data *include* intra-community transactions. (3) Other—estimated.

Aerospace Sales By Type



SOURCE: Shriner-Midland Company, compiled for Aerospace Industries Association (AIA) from EEC and AIA data.

NOTE: (1) Sales figures for U.S. exclude "non-aerospace" sales and include military and civil sales. (2) EEC data understated since data for United Kingdom are incomplete (excludes airframes). (3) EEC—data *include intra-community transactions. (4) Other—estimated.*

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