REPORT TO CONGRESS ON THE DEFENSE INDUSTRIAL BASE:

CRITICAL INDUSTRIES PLANNING

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DEPARTMENT OF DEFENSE

Assistant Secretary of Defense
(Production and Logistics)
Office of Industrial Base Assessment

Mention of specific company names throughout this report is not an endorsement of a particular company, but rather serves to enhance the reader's understanding of the financial health and manufacturing issues associated with various U.S. industrial segments and specific critical technologies. Where appropriate, graphical and tabular data developed from financial databases, open publications and company sources are credited. The information in this study has been derived from a variety of organizations and individuals, with extensive coordination of factual data. However, DoD welcomes additional corrections, comments, and suggestions to the report, which can be provided to:

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EXECUTIVE SUMMARY

1. Introduction

This report on Department of Defense (DoD) actions to improve the industrial base of the United States was prepared by the Office of the Under Secretary of Defense for Acquisition in response to the requirements of subsection 842(c) of the National Defense Authorization Act for fiscal year 1990. The report documents DoD's progress in carrying out the key functions of the Defense Industrial Base Office and in identifying and analyzing industries that are important to U.S. national security.

The defense industrial base includes government and privately owned plants and equipment as well as government and private technology development efforts. The defense industrial base is both large and complex. It encompasses a network of prime weapon system manufacturers, many of whom are highly dependent on the DoD for business, and thousands of large and small subtier firms with varying proportions of commercial and military sales. The government-owned facilities are operated either by government or private sector firms. In addition to this vast array of United States industrial capability, our allies possess strong industries that support U.S. defense requirements. These industries often supply the U.S. with essential components and specific capabilities that enhance U.S. R&D and production efforts. In particular, the North American Defense Industrial Base (NADIB) represents U.S.-Canadian cooperation on industrial base issues.

No report could address all the industries relied upon for critical defense goods and services. Neither can robust industrial capabilities in all of these areas be maintained through DoD action alone. The primary purpose of this report is to identify and describe industries which, by virtue of their role as developers of critical technologies, are important to the DoD's ability to acquire weapon systems of the future. This will permit a better focus on developing policies and implementing programs that recognize the importance of these key domestic industries for meeting DoD's peacetime or wartime needs.

This report was developed by the Office of the Secretary of Defense in concert with the Army, Navy, Air Force, Defense Logistics Agency, Joint Staff, Defense Advanced Research Projects Agency, Strategic Defense Initiative Organization (SDIO), and selected industry groups. It was closely coordinated with technology agents of the DoD *Critical Technologies Plan*. Efforts are in place to continue coordination with these organizations and industry groups such as the Aerospace Industries Association (AIA) and Electronics Industries Association (EIA).

2. DoD Actions to Improve the Defense Industrial Base

The DoD is developing a defense industrial base strategy to bolster R&D and manufacturing capabilities in the U.S. while pursuing international cooperation to benefit the allied defense posture and defend our national security. The strategy has five broad thrusts:

- Organizational focus
- Reorienting resource expenditures to advance critical manufacturing process technology
- Promoting state-of-the-art manufacturing practices
- Reforming acquisition practices to promote access to the most advanced product and process technologies
- Improving analytic capabilities.

Organizationally, DoD has launched a number of important initiatives:

- The consolidation of OSD's industrial base and manufacturing policy, planning, and oversight functions in a single organization, the Deputy Assistant Secretary of Defense for Production Resources
- The Defense Science Board (DSB) agenda has been expanded to include manufacturing and industrial base issues as an important area of focus; and
- The Defense Advanced Research Projects Agency (DARPA) has increased

emphasis on advanced manufacturing process development initiatives.

As a result of these new organizational efforts, DoD is better able to direct its industrial base resources into activities that support the continued development and implementation of critical technologies. Several initiatives are underway:

- The DoD ManTech program is being refined to provide more top-down leadership by OSD in the formulation of priorities for investment in major thrust areas. OSD is sponsoring a joint effort with the Services, DARPA, and DLA to adjust the program in FY92 to provide a more streamlined and effective approach to program execution.

- The Industrial Modernizatic Incentives Program (IMIP) policy is being simplified to provide for more uniform application among the Services and top down guidance. OSD is in the process of developing a new policy that will be more efficient and facilitate more private investment in industrial base improvements

- The Defense Production Act (DPA) Title III program is being reemphasized to identify emerging material needs linked to critical technologies and likely future defense applications.

DoD has also participated in a number of joint private sector-government partnerships to provide additional resources and attention to improving the competitiveness of specific industries. The most familiar of these initiatives is SEMATECH, founded to develop advanced manufacturing technologies and transfer these technologies to member companies. SEMATECH is supported by funding from DoD (through DARPA) and member companies. In addition, SDIO has initiated several Manufacturing Operations Development and Integration Labs (MODILs), which are networks of national expertise and facilities involving government labs (both DOE and NIST as well as DoD), industry and academia. Other industry-government activities directed toward restoring the competitiveness of essential domestic industries include DOD's support for machine tools, optics, bearings, and precision gears.

In addition to its involvement in joint government-industry partnerships, DARPA is increasing its manufacturing process research in support of critical technology implementation. DARPA is engaged in development and demonstration of advanced manufacturing technologies such as X-ray lithography and infrared focal plane array producibility.

DoD and the military services have also organized several initiatives aimed at promoting state-of-the-art production practices among defense producers. These include the DoD/Industry Task Force On Concurrent Engineering to revise producibility policies and increase the focus on integrated product and process development as well as the Best Manufacturing Practices (BMP) program, which provides information and technology transfer between government, industry, and academia on proven manufacturing practices and processes.

Finally, DoD is also taking actions to improve the defense acquisition process. Actions include:

- DoD's Computer-Aided Acquisition and Logistic Support (CALS) to create a more uniform and electronic means of providing technical data to DoD and contractors

- Identification of acquisition policies that stifle innovation and threaten the economic health of defense industries

- Continuous review of standards and specifications with a view to eliminating outmoded and duplicative requirements to ensure DoD access to the latest state-of-the-art industrial product and process capabilities.

To make effective policy, management, and budgeting decisions, DoD requires timely and accurate information and analysis on issues ranging from worldwide industrial and manufacturing trends to the capabilities and capacity of individual firms. To meet this need, DoD has established, and continues to refine, an industrial base analysis program consisting, in part, of the Defense Industrial Network (DINET), an automated information system and management tool, and DoD's Production Base Analysis (PBA) process, the principal ongoing source of information for industrial preparedness planning.

3. Planning Industrial Capabilities for Critical Technologies

DoD's industrial base program is being reoriented to emphasize developing future production capabilities for critical technologies. Because the critical technologies, by definition, represent developmental capabilities, the race for world industrial leadership in each of these areas is still underway; in some areas, the race has barely begun. Advanced technologies represent a major opportunity for DoD to leverage its limited industrial base program investment funds and help establish competitive domestic production sources in technology areas that will have a major impact on defense production capabilities and weapon performance in the future.

DoD has identified the important industrial base issues associated with each of the critical technologies including:

- Current and likely future applications in defense and non-defense products
- The current and developing international competitive environment
- Current U.S. R&D activities
- Current and likely future capabilities of key U.S. industries.

Besides identifying the industrial capabilities that will be most important in these areas, DoD needs to improve its understanding of current U.S. and worldwide capabilities, trends, needs, and opportunities. From this improved knowledge base, it will then be easier to identify emerging vulnerabilities and validate areas where the private sector, DoD, or other Federal agencies must take action.

The analysis in this report builds a bridge between the 20 technology areas and their corresponding industry infrastructure. It is exceedingly difficult to select from the vast number of industries that support defense needs — nearly all are required to develop our most critical technologies and ensure their effective transition to production and into the field. Since the entire industrial infrastructure cannot be analyzed in a report of this nature, the approach has been to identify a limited number of industry segments which would illustrate the nature of criticality and the problems that are faced in establishing and maintaining a viable domestic capability. Because of the magnitude of the issue and the connections among critical technologies, this report separates the critical technologies into two groups. Table 1 lists the technologies in each of the two groups, along with the industry segments that receive particular attention in this report.

Table 1. Areas of Focus

Technology Areas (Eight)	Technology Areas of Lesser Focus (Twelve)	
Air-Breathing Propulsion	Biotechnology	Signal Processing
Composites	Computational Fluid Dynamics	Signature Control
Machine Intelligence/Robotics	Data Fusion	Simulation & Modeling
Passive Sensors	High Energy Density Materials	Software Producibility
Photonics	Hypervelocity Projectiles	Weapon System Environment
Semiconductors	Parallel Computer Architectures	
Sensitive Radars	Pulsed Power	
Superconductivity		

Highlighted Industry Segments			
Artificial Intelligence	High Temperature Superconductivity	Low Temperature Superconductivity	Phased Arrays
Fiber Optics	Investment Castings	NC Machine Tools	Polymer Matrix Composites
Focal Plane Arrays	Laser Radars	Machine Controls	Precision Bearings
Gallium Arsenide	Lithography	Metal Matrix Composites	Precision Forgings
Gas Turbine Engines		Optical Processing	Robotics
			Supercomputers

Our initial evaluation of the defense industrial base segments that support the DoD critical technologies provides an overview of the industrial base capabilities required to support each critical technology as well as a more detailed analysis of selected industry segments.

This report provides an in-depth review of twenty industry segments directly supporting eight of the DoD critical technologies. To a lesser extent, these segments indirectly support the other DoD critical technologies. As highlighted in the FY90 Defense Critical Technologies Plan, seven of the eight technologies are considered enabling or pervasive, and generally have a more defined infrastructure that allowed DoD to conduct the type of financial analysis requested by Congress. The eighth technology — superconductivity — is an emerging technology whose applications are difficult to define at this time. However, a detailed review was conducted to define the industrial base that is likely to emerge.

The other 12 technologies are addressed in considerably less detail. The analysis of these 12 technology areas describes applications, manufacturing capabilities, and the supporting industrial structure, but does not provide detailed information on the financial condition of specific industry segments. Table 2 summarizes the findings of this report.

Table 2. Summary of Findings

AIR-BREATHING PROPULSION

The 1980s was a very good decade financially for Gas Turbine Engine (GTE) producers, with these producers extremely well-positioned financially to support air-breathing propulsion technology requirements in the 1990s. However, the U.S. Government has been the major source of financing for capital expenditures and R&D investments for this industry. The anticipated decline in the Defense budget and in the procurement of GTEs in the 1990s could therefore cause a significant decline in capital expenditures and R&D investments in air-breathing propulsion technology.

DoD's ability to support developmental efforts may be felt by the specialty materials industries which have little market other than the GTE producers. The producers of high temperature coatings, superalloys, high temperature titanium alloys, and high temperature lubricants are expected to be strongly affected. Sales of these companies are in general insufficient to support the level of investment in R&D currently available as a result of DoD support to the GTE area. In order to maintain its current international competitive strength, the GTE industry will need to find new methods of supporting the necessary R&D, as well as facility and equipment investments, to replace the level of support which has historically been available from DoD sources.

COMPOSITE MATERIALS

Although DoD is planning a substantial investment in the next few years, increasing this funding will be necessary to maintain a lead over foreign competition in state-of-the-art technologies. Although the U.S. is generally considered the world leader in military applications, other nations are aggressively pursuing R&D and production of advanced materials and could quickly threaten the U.S. position if the pace of U.S. composites product and process R&D slackens. The DoC ***Emerging Technologies*** report and the DoD ***Critical Technologies Plan*** conclude the U.S. is lagging other nations in applying composites and advanced materials to manufacturing processes in the commercial sector.

MACHINE INTELLIGENCE AND ROBOTICS

Machine Intelligence and Robotics encompasses a broad range of technologies that are essential to nearly all critical technology areas addressed in this report. The strength of U.S. industry in machine intelligence and robotics varies, depending on the particular segment being considered. In some areas (such as artificial intelligence), the U.S. still holds the world leadership position, while in others (e.g., advanced machine tools) the U.S. has lost its former leadership position and is steadily losing ground to the Japanese.

In contrast to the precipitous decline in vital hardware areas, domestic capabilities in artificial intelligence are currently unparalleled. There is, however, some concern that the industry may have expanded prematurely and will be required to cut back to accommodate slower than expected growth in demand.

PASSIVE SENSORS

Profits and sales for the aerospace and electronic companies performing passive sensor work during the 1980s was favorable, though passive sensor sales generated only a small portion of these revenues. The industrial base is small, with industry investment oriented toward developing unique capabilities in specific material areas; little of the investment (to date) has been directed to developing a supplier base or developing flexible manufacturing lines that can support different applications of passive sensor products. Japanese and French firms have entered the market and are showing strong signs of matching U.S. capability.

PHOTONICS

The U.S. and Japan are considered the leaders in the development of this technology, but Japan has set the pace in transitioning successful R&D to commercial applications. Little attention is being given to the processes needed to develop low cost manufacturing techniques. There is some limited manufacturing technology funding to increase the ruggedness for military applications for fiber optic cable, but industrial efforts are generally believed to be fragmented. The potential for market applications is anticipated for both defense and commercial products — including telecommunications, information processing, storage and avionics. Given the current levels of investment in manufacturing, it will very difficult for U.S. companies to capture significant market share.

SEMICONDUCTOR MATERIALS AND MICROELECTRONIC CIRCUITS

As a "foundation" industry, semiconductor material and microelectronics serve as a primary enabling industrial sector that supports most of the other critical technologies. Although defense accounts for less than a tenth of the overall microelectronics market, the commercial and defense segments are closely linked and commercial success is necessary to maintain a healthy technology base. Similarly, the health of a nation's technology base is closely linked to the strength of its production base. The FY 90 ***Critical Technologies Plan*** estimates that although the U.S. leads its NATO Allies and the USSR in most aspects of new technology development, Japan has emerged as the world leader in many manufacturing support and industrial applications that are critical for our future defense. Concerns related to national security arising from the offshore movement of both the production and technology base have been underscored by the Congressional Budget Office.

SENSITIVE RADARS

The Federal government — and primarily DoD — provides the majority of the market for sensitive radar products. Though the U.S. is considered the world leader in all aspects of sensitive radar technology, it encompasses new technologies that have not yet reached production. Existing radar system manufacturers (generally components of major corporations) are expected to become key producers of sensitive radars as well. Declining defense budgets and a requirement to invest in new facilities and equipment to meet changing defense needs have led to a shakeout within some industry segments. Given the lack of a strong commercial market for these products, many of these firms will be entirely dependent on DoD, and the ability of the base to expand in response to DoD's requirements will be contingent upon Government investment and funding decisions.

SUPERCONDUCTIVITY

Successful development of superconducting technology has the potential to revolutionize large segments of industries. Industries potentially affected by High Temperature Superconductivity (HTS) technology include automotive and rail transportation, communications, power generation and transmission, manufacturing equipment, and electronics. Such a revolutionary technology will have a far-ranging impact on the industries that produce and use those products, but the achievement of superconductivity's full potential is a long-term prospect that faces considerable uncertainty.

DoD is likely to be dependent on the commercial industrial base for the development and manufacture of military products using superconductor technology. Consequently, DoD must be concerned with the ultimate establishment of an internationally competitive industrial base in the area. The primary concern among supporting industries is the ability of the Government to sustain high levels of funding over an extended period of time.

BIOTECHNOLOGY MATERIALS AND PROCESSES

Biotechnology is an emerging technology, with few defined defense industrial base applications. A manufacturing industry has not fully emerged and matured for defense products. The U.S. is currently recognized as the world leader in biotechnology R&D; however Japan is rapidly gaining in the manufacturing process and development area. It is expected that private industry will establish the manufacturing infrastructure for this technology, but some government sponsored manufacturing technology will be needed to develop DoD applications.

COMPUTATIONAL FLUID DYNAMICS

The most significant challenge facing CFD's industrial infrastructure is the development and manufacture of high-speed processing hardware to meet CFD's computational needs. In the past, use of CFD has been entirely dependent on the supercomputer, and the leadership enjoyed by the U.S. in CFD is a direct result of the nation's strength in supercomputer technology. Although applications of CFD have been constrained by the capabilities of current-generation supercomputers, these limitations may be overcome in the future by parallel processing approaches that will allow greater speed in highly complex computing on less expensive computer systems. The industrial base that supports CFD in these areas is described in more detail in Parallel Computer Architectures.

DATA FUSION

Data fusion is important to both defense and non-defense interests. The technology of information systems integration is an area of growing interest throughout the U.S. and internationally. Advances in this area will be supported by strong computer, software, and systems integration industries. The future of the industry relies on a healthy and innovative industrial base to meet many of its data system requirements.

HIGH ENERGY DENSITY MATERIALS

Government facilities have long been the bulwark of the ammunition and explosives base, and U.S. industry stands ready to produce HEDM products whenever such production can be profitable. There are already a number of private sector firms engaged in HEDM production and there are no major technological obstacles to sustaining that base if production quantities allow for adequate return on investment.

HYPERVELOCITY PROJECTILES

Support for hypervelocity projectile development and applications comes almost exclusively from DoD. There is little commercial application for hypervelocity projectile technology, with the possible exception of some aspects of power generation and advanced light weight materials. Future manufacturing and industrial base investments by the DoD in support of selected, high payoff technology challenges will be vital in maintaining the current domestic competitive advantage.

PARALLEL COMPUTER ARCHITECTURES

There is little concern about the ability of the nation's research base to achieve desired improvements in parallel processing. The implementation of the technology depends on the ability of the computer industry to effectively compete in the world market as new parallel processing products come on line. While the U.S. computer industry is currently strong, it is under increasing competitive pressure from Japanese as well as European firms.

PULSED POWER

The technology required to build pulsed high power systems that meet DoD's size and weight requirements is not yet available, and there has therefore been little incentive for industry to create a high-volume production base. At present, the vast majority of pulsed power research and development is supported by the Government. The risk, cost, and time to develop marketable commercial products limits the amount of product R&D that the commercial sector is willing to undertake. However, major improvements in this area will make possible revolutionary changes in battlefield operations through the development of high-power weapons and sensors.

SIGNAL PROCESSING

There is considerable commercial interest in near-term applications and use of products for signal processing technology. In particular, there is potentially a large commercial market for handwritten character recognition, speaker-independent speech recognition, several medical applications, and computing using neural networks. Generally, DoD is dependent on the existence of a strong commercial industry for such applications as integrated circuit processor and memory chips. The military industrial base that supports manufacturing process requirements has not been well-defined, with some applications not able to be produced because of high costs and low volume.

SIGNATURE CONTROL

This technology pervades numerous defense items and the industrial base associated with final application includes defense prime contractors and major subcontractors — producers of ships, submarines, aircraft, helicopters, missiles, gas turbine engines, small rocket engines, as well as laboratories, and suppliers of equipment and machinery. These contractors depend heavily upon DoD funding to develop the manufacturing process applications. With budget cuts looming and a decline in defense production expected, some shake-out in the industry may be imminent.

SIMULATION AND MODELING

Generally, the U.S. has been a leader in development of technology applications, but has been slow to implement the results. A more rapid pace of implementation of these technologies can have a dramatic effect on the cost and effectiveness of national defense — not only through their direct impact on weapon systems acquisition and support, but also through their potential to enhance the competitiveness of the U.S. manufacturing base.

SOFTWARE PRODUCIBILITY

U.S. leadership in software is inextricably tied to our preeminent position in the computer industry and weakening of our world leadership position in computers would also weaken the software base. Software producibility underlies almost all industries critical to both the defense and commercial industrial bases. Although the U.S. is strong in this area, a healthy interest by the Japanese may cause the U.S. position to weaken if U.S. funding is not increased.

WEAPON SYSTEM ENVIRONMENT

Weapon system environment technology requires the continued production and advancement of high-speed processing hardware platforms required for large-scale simulations, as well as the continued reduction in the cost of computing power. The continued health of the nation's computer industry will be of particular importance. Future military capabilities based on this technology are expected to require a significant number of advanced, high-capability computing systems, many of which will be hardened to withstand operational conditions. Acquiring such systems affordably will require a strong commercial industrial base.

A. INTRODUCTION

1. Report Requirements

This report was prepared by the Office of Industrial Base Assessment, part of the Under Secretary of Defense for Acquisition (USD(A)), in response to requirements in the FY90 Defense Authorization Act. Over the past two years, Congress has amended 10 U.S.C. 2503 to assign six specific industrial base planning and management responsibilities to the USD/A. These are to:

- "Develop and propose plans and programs for the maintenance and fostering of defense industrial readiness in the United States
- "Develop and propose plans and programs to encourage the use by the defense industries of the United States of advanced manufacturing processes and investment in improved productivity
- "Propose (consistent with existing law) the repeal or amendment of ... regulations and policies as may be necessary to eliminate any adverse effect that the regulations and policies may have on investment in improved productivity
- "Evaluate and propose for testing innovative ideas for improving defense industrial readiness in the United States, including ideas for improving manufacturing processes and the acquisition processes of the Department of Defense (DoD)
- "Establish and implement a consolidated analysis program a) to assess and monitor worldwide capabilities in technologies critical to the national security of the United States, and b) to monitor defense-related manufacturing capabilities of the United States
- "Identify the industries most important for national security applications of the technologies identified in the most recent annual defense critical technologies plan ..."

The FY90 Authorization Act also required the USD(A) to prepare a report that: a) describes actions taken to carry out these responsibilities to improve the defense industrial base; and b) evaluates the capability of the U.S. industrial base to conduct research and development (R&D) on the DoD critical technologies and to apply those technologies to the production of goods and delivery of services. This report was prepared in response to this requirement.

2. Current Trends Affecting the Defense Industrial Base

In this era of rapid political and technological change, the defense industrial base is affected by, and must respond to, a wide variety of external events and challenges. Probably the most significant impact on the industrial base is the reduction in U.S.-Soviet tensions. With the reduced threat of superpower conflict, outlays are projected to decline significantly in the coming years. Yet, the U.S. will continue to face worldwide instabilities and national security challenges at all levels of the conflict spectrum.

Reduced budgets will put increased pressure on all defense programs. While the industrial base specializing in defense production will contract, DoD must ensure that it can draw on the capabilities of a diverse industrial base that maintains technological leadership and remains efficient and productive. Increased industrial base planning and more flexible production capabilities will be required.

Another trend affecting the defense industrial base is the growing importance of technology to national power and the increasing technological leadership and economic power of Western Europe and Japan. Although no comprehensive assessment of technological leadership has been prepared, trade statistics in high technology products and services as well as special studies of particular industrial sectors and weapon systems document an increasing risk that the U.S. may lose its leadership position in some key technology areas essential for national security or economic prosperity. For example, the recent Department of Commerce (DoC) analysis of ***Emerging***

Technologies documented a rapidly eroding U.S. position (relative to Japan and Western Europe) in many of the same key areas identified in the DoD ***Critical Technologies Plan***.

A third broad trend that affects our industrial base program is the growing extent to which DoD relies on the output of commercially viable industries to maintain technological leadership. This is a relatively recent development. For many years after World War II, DoD frequently set the pace for new product and process technology developments. The number of important commercial products (e.g., jet aircraft and engines, microelectronics, numerically-controlled machine tools, computers) that were initially stimulated by DoD R&D funds is well-documented. Because of its traditionally high R&D spending and advanced performance requirements, DoD traditionally pushed the state-of-the-art in both advanced technology and often times in manufacturing processes. As a result, technology benefits tended to flow outward from DoD to commercially-oriented industries, with important benefits for the national economy.

Finally, the state-of-the-art in manufacturing technology is increasingly shifting to flexible integrated manufacturing processes, which allow more efficient, multiproduct, small volume production and facilitate simultaneous development of product and process technology. Advances in manufacturing process technologies provide both an opportunity and a challenge to U.S. manufacturers and DoD. If U.S. manufacturers keep pace with these advances, DoD will reap important benefits in the application of critical technologies to improve weapon system performance, quality, and affordability. To the extent U.S. manufacturers cannot capitalize on these manufacturing process improvements, the benefits of critical technologies R&D may be lost and the emerging lead of foreign competitors could widen.

3. The Industrial Base Challenge

U.S. national security policy promotes a strategy of offsetting numerical inferiority with technological superiority and higher quality weapons. Technology development forms the foundation for maintaining the needed superiority in future weapon systems. For the past two years, DoD has focused increased emphasis on a selected set of "technologies most critical to ensuring the long-term qualitative superiority of United States weapon systems."

However, developing technological capabilities is not enough. The industrial base is a crucial element in maintaining DoD's ability to apply these technologies by developing and producing affordable, superior weapon systems. In order to carry out this policy, DoD must have access to the latest technologies that will provide the superior performance, quality, and reliability of our weapon systems. The production base must be able to translate the latest technology advances into usable military capabilities. And, our acquisition process must facilitate investment in development and implementation of advanced production capabilities that ensure technology capabilities can be transformed into fielded weapon systems rapidly and affordably.

The most recent DoD ***Critical Technologies Plan*** and DoC analysis of ***Emerging Technologies*** highlight the challenge DoD faces in ensuring continued U.S. leadership in technologies. The DoD plan identifies 20 critical technologies and assesses the current position of the United States relative to our principal military and economic competitors. The DoC report evaluates both current position and trends of 12 emerging technology areas that closely parallel the DoD list. Both reports conclude that foreign capabilities have strengthened in a number of key technology areas.

This increasing trend of procuring products made in foreign countries and in foreign-owned U.S. facilities is generating concern within the Federal government, the private sector, and academe. Many agree that some U.S. industries, including defense industries, are bound to become increasingly international in character and that it would be futile to oppose this globalization process. There is also a case to be made that international cooperation in production capabilities improves the allied defense posture by fielding common items. Despite both of these arguments, there is a concern that market control over some products critical to our defense needs is becoming concentrated in the hands of a few foreign countries.

Because foreign companies (and their U.S.-located operations) are subject to regulation by their home countries, they might be encouraged or required by those countries to take actions inconsistent with U.S. national security interests or specific political actions. The essential issue is that all nations will exercise sovereignty over their economies and the national interests of our friends and allies will not always be consistent with those of the U.S.

4. DoD's Response to the Industrial Base Challenge

Since the mid-1970s, U.S. industry has lost its former leadership position in many key technology areas such as numerical control machine tools and microelectronics. U.S. industry's position in a number of other key areas, including optics and bearings, is also currently threatened. The result has been an apparent increase in foreign technology leadership, U.S. purchasing from foreign sources, and increased pressure for DoD to restrict its purchases in selected areas to domestic sources.

DoD has traditionally opposed domestic sourcing requirements except as a last resort because they can actually worsen the problem that is of greatest concern to DoD: access to the most advanced technologies for current and future weapon systems. Most studies of the problem have suggested that weapon system program managers typically purchase from foreign sources because of lower cost or superior quality or performance; rather than cutting ourselves off from superior foreign sources, DoD must ensure the availability of equally superior domestic sources.

DoD has developed effective industrial base initiatives to respond to these challenges. They are based on the principle of raising the visibility of industrial base issues at all levels of DoD and targeting our limited resources on making specific improvements in the performance of key industrial sectors. The basic thrust is to identify the industrial base capabilities and capacity that DoD will need for current and future weapon systems and to develop these capabilities through targeted investments, incentives, and management improvements affecting key sectors and technologies. Examples include:

- The Defense Production Act (DPA) Title III program
- The Manufacturing Technology (Man Tech) program
- Sectoral strategies for key industries, such as semiconductors, machine tools, optics and precision gears
- Technology-based programs such as the focal plane array producibility initiative
- Weapon system program producibility initiatives, such as producibility assessments and concurrent engineering
- The Industrial Modernization Incentives Program (IMIP)
- International defense industrial cooperation, particularly joint ventures and consortia.

The common denominator of all of these initiatives is the identification of improvements needed in our domestic production and technology bases and then implementation of procedures to act upon these improvements. Reliance on foreign sources in critical technology areas can put in jeopardy our ability to maintain access to the latest product and process technologies. Where this is driven by superior cost, performance, or reliability, DoD must ensure that its program managers have access to equally superior domestic engineering and production capabilities. But the principal focus should be on developing world-class domestic production capabilities, rather than restrictive domestic sourcing requirements.

DoD has recently taken a number of organizational and management actions to improve its focus on industrial base and manufacturing issues. For the first time, virtually all of the Office of the Secretary of Defense's (OSD) industrial base and manufacturing policy, planning, and oversight functions have been combined in a single organization, the Deputy Assistant Secretary of Defense for Production Resources, located within the organization of the Assistant Secretary (Production and Logistics). Functions reporting to this single office include:

- Industrial base planning and assessments and the Industrial Preparedness Program (IPP)
- ManTech/IMIP and related manufacturing productivity initiatives
- Producibility and manufacturing policy, including concurrent engineering and computer-aided acquisition and logistic support (CALS)
- DPA Title III incentives to expand capacity and supply for advanced materials that are essential to the national defense
- National stockpile and resources planning
- Standards and specifications.

This organizational focus on manufacturing technologies and industrial base issues is apparent within policy and technology development organizations as well. The Defense Science Board (DSB) agenda has been expanded to include manufacturing and industrial base issues as an important area of focus. Forthcoming DSB reports, that summarize ongoing DSB deliberations, include:

- A "Critical Industries" report (identifying methodologies for identifying criticality and remedies)
- A "Simultaneous Engineering" report (stressing the importance of early consideration of manufacturing during the design process)
- A "Foreign Ownership" report (recommending changes in public policy in connection with foreign ownership for critical defense producers).

The 1990 DSB Summer Study continued the increased focus on critical industries by establishing a "Technology Strategy Task Force." The report of this task force is also forthcoming.

DoD's increased emphasis on manufacturing technology development is also seen in the reorientation of the Defense Advanced Research Projects Agency (DARPA), which has substantially changed its traditional product R&D emphasis within the past five years to place greatly increased emphasis on advanced manufacturing process development initiatives. A Defense Manufacturing Office (DMO) has been established within DARPA to provide a focal point for efforts to develop advanced process technologies. A number of DARPA initiatives that relate directly to the critical technologies are noted in the individual technology area profiles that appear later in this report.

In summary, DoD's organizational structure seeks to provide greater emphasis on manufacturing and industrial base issues. At the OSD level, these responsibilities are focused within a single organization to ensure the proper coordination, synergy, resources, and level of attention. And enhanced resources are being provided through organizations with a traditional "manufacturing" mission (such as ManTech), reorientation of the mission of organizations that traditionally focused on product technology (such as DARPA), and establishment and funding of relatively new organizations (including the Title III program office, established in 1986).

5. Organization of Report

No single report can describe all of the industries that DoD relies on for critical defense goods and services. DoD is a direct or indirect user of the output and capabilities of virtually every industry in the United States. Neither can DoD action alone maintain robust industrial capabilities in all areas that are important to DoD. To an increasing extent, DoD relies on the technological and production capabilities of a healthy civil economy, whose continuing development is determined by influences beyond DoD's control. However, DoD has a continuing interest — as a principal user of the advanced technology products of the industrial base — in the health, diversity, and innovation in the industrial base. To carry out its responsibility, DoD must continuously develop, implement, and improve programs that foster industrial readiness and encourage the use of advanced production technologies.

Sections B and C describe actions DoD is taking to carry out the industrial base management functions assigned by the FY89 and FY90 Authorization Acts. As noted, many of these functions touch on issues of longstanding concern to DoD, and the main impact of the legislative changes is to refocus or reemphasize the importance of ongoing DoD activities. These initiatives represent the consolidated effort by OSD, the Military Services, the Defense Logistics Agency (DLA), and DoD agencies including SDIO and DARPA.

The activities described in these two sections parallel the industrial base functions enumerated by Congress in the FY89 and FY90 Authorization Acts. Section B describes DoD's actions to improve industrial readiness, increase industry's use of advanced manufacturing technologies, identify and recommend changes in DoD's acquisition policies and process, and establish a consolidated analysis program for industrial base issues. Section C describes DoD's ongoing activities to:

- Identify the industries most critical for national security applications of the technologies identified in the most recent annual critical technologies plan

- Ensure that industrial base issues are considered during development of critical technologies and science and technology plans and R&D strategies

- Integrate the critical technologies focus within ongoing industrial base planning and investment programs.

DoD also recognizes that we must go beyond developing the reports and plans requested by Congress and establish an effective industrial base program that integrates and considers the need for critical technologies.

B. DEPARTMENT OF DEFENSE ACTIONS TO IMPROVE THE DEFENSE INDUSTRIAL BASE

This section describes actions DoD has taken to carry out the functions assigned by the Authorization Act to improve the defense industrial base.

1. Actions to Improve Defense Industrial Readiness

Recent developments in Eastern Europe and in the Persian Gulf underscore the importance of maintaining flexible and effective industrial readiness plans and programs. Although national policies and threat estimates have changed considerably in recent years, DoD's Industrial Preparedness Program (IPP) has, until recently, continued to experience the effects of the longstanding U.S. perception that a short-warning, superpower conflict in Europe was the principal conventional conflict against which plans should be prepared. This threat perception tended to place primary emphasis on forward deployed forces and on-site materiel stocks as the major source of deterrence and conventional warfighting potential. Industrial base action — the ability to change production output rapidly to build up materials and end items — was not seen as a major factor in improving the readiness or sustainability of U.S. forces.

Three events are having an important impact on our industrial readiness program. First, the dramatic reduction in superpower tensions and the blossoming of democracy in Warsaw Pact nations has significantly reduced the likelihood of a short-warning, major superpower conflict. If this trend is reversed, warning and mobilization plans for this longer term possibility must focus on the ability of the defense industrial base to regenerate sufficient military power to convince any potential aggressor that it cannot gain a decisive advantage in either conventional or strategic forces in a mobilization race.

Second, the significant reductions in the defense budget are likely to affect all defense programs, including longterm force modernization, force structure, and readiness/sustainability. It is possible that the U.S. military force in the future will be smaller and more focused to respond to short-warning regional, vice global conflict than was planned a few years ago. The segment of the industrial base dedicated to defense production is also likely to be smaller. Maintaining an ability to reconstitute production rates to support regional conflicts, including possible Foreign Military Sales, on short notice is a challenging new issue for DoD.

Finally, the present crisis in the Middle East underscores the fact that the apparent reduction in superpower tensions does not necessarily reduce — and in fact may increase — the potential for regional conflicts that involve vital U.S. interests and which may require an industrial response. These events provide the backdrop to actions DoD has underway to address industrial readiness through a graduated mobilization response (GMR) process. DoD is revising its IPP program to provide a more flexible planning and response capability to ensure that our industrial readiness plans and programs are up-to-date and effective. A year-long review process is culminating in revisions to DoD's industrial base guidance and the IPP Manual, the latter a DoD document that outlines procedures for cooperative readiness planning with industry. Cooperative planning with Canada has been revitalized and updated through the operations of the North American Defense Industrial Base Organization. Canadian officials now participate in selected joint industrial base analyses and exercises. The comprehensive updates being made should ensure that DoD's IPP program can meet the challenges of the 1990s and beyond.

2. Actions to Promote Advanced Manufacturing Technologies

The development and application of advanced manufacturing technologies and processes are necessary to improve the producibility, quality, and affordability of advanced weapon systems. While continuing investments in developing critical technologies are necessary to enable the necessary performance improvements for future weapon systems, the development and demonstration of these technologies alone is not enough to ensure continuing qualitative superiority in U.S. weapon systems. The capability to incorporate these new technologies rapidly and affordably in U.S. weapon systems is a continuing challenge for DoD and U.S. manufacturers.

DoD has long been a leading force in the development of advanced manufacturing technologies, many of which have had wide application and important benefits throughout the U.S. economy. For many years, DoD's advanced performance requirements continuously pushed the state of the art in product technologies, and direct and indirect DoD investments stimulated important manufacturing capabilities as well. For example, as long ago as the late 1950s, the Manufacturing Technology (ManTech) program spearheaded the development and initial applications of numerically-controlled (NC) machine tools. More recently, DoD ManTech programs have been leaders in the development of computer numerically-controlled (CNC) and computer-aided design and manufacturing (CAD/CAM) processes. This traditional focus on manufacturing processes and capabilities is being reemphasized through a number of initiatives.

Manufacturing Technology — The ManTech program is DoD's best-known program to improve manufacturing capabilities. All military Services and DLA have mature ManTech programs. Typically, about 200 ManTech projects are funded each year, most of which are performed by industry. In general, ManTech funds the development and demonstration of a new manufacturing technology, while industry is expected to invest in the capital equipment necessary to implement the new technology. To qualify for ManTech funding, a project must represent a generic manufacturing project and be process oriented, be beyond normal risk for industry, and help meet industrial preparedness challenges and/or show potential for cost avoidance.

The cost savings potential from "traditional" ManTech projects that improve specific manufacturing processes is considerable. For example, a new laser welding process for tank engine components, developed at a cost of $1M, is estimated to have saved $3.5 million in improved productivity and higher quality welds. Another project, which successfully established a more efficient method of producing gallium arsenide integrated circuit substrate material, is estimated to have repaid the ManTech investment by the end of its first month in production.

Increasingly, the ManTech programs are also participating in major initiatives that have important implications for U.S. industrial competitiveness and the development of critical technologies. For example, the Air Force ManTech program is the DoD executive agent for the "Next Generation Controller" program, a joint industry-government effort that has major implications for the competitiveness of the domestic machine tool industry. All of the Service ManTech programs are actively pursuing advanced composites production methods.

Advanced Manufacturing for High-Risk Technologies — The Defense Manufacturing Office (DMO) of the Defense Advanced Research Projects Agency (DARPA) is also heavily engaged in development and demonstration of advanced manufacturing technologies. Developing advanced process technologies represents a relatively new mission for DARPA, which has traditionally focused on developing advanced product technologies. DMO places particular emphasis upon technologies needed to support DoD objectives while simultaneously ensuring a strong, commercially-competitive industrial base.

Many of DMO's activities are directly applicable to DoD's critical technologies. For example, the Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) program is developing advanced analog components essential to electronic countermeasures, smart guidance, and advanced communications systems. The project has a major focus on developing design tools and cost-effective manufacturing processes for integrated circuits using gallium arsenide semiconductor materials (a key focus in the microelectronics and semiconductor materials critical technology area). Ongoing DMO efforts on x-ray lithography, flat panel displays, and support for SEMATECH (discussed later in this section) also are directly relevant to this critical technology area. Similarly, DMO's Infrared Focal Plane Array (IRFPA) producibility initiative is attempting to establish an efficient manufacturing base for advanced infrared sensor arrays, a principal component of the passive sensors technology area.

Industrial Modernization Incentives Program — The Industrial Modernization Incentives Program (IMIP) was established as a DoD-wide program in the early 1980s after successful initial implementation within the Air Force. In contrast to ManTech, which develops advanced manufacturing technologies, IMIP provides financial incentives (through indemnification, cost sharing, and other actions) for contractor investments in productivity improvements.

Although IMIP has traditionally been associated with weapon system prime contractors, the program has placed greatly increased emphasis within the past few years on flowdown to the lower tiers. As part of this thrust, the Air Force has initiated a "sector IMIP" program that has initiated IMIP projects with vendors in the bearings, forgings, and materials industries. Although the Air Force has traditionally been the most aggressive Service in implementing IMIP, the other Services and DLA have recently increased their emphasis on and funding for this program.

Defense Production Act Title III Program — In contrast to ManTech, DMO efforts, and IMIP, which promote the development, transfer, and use of advanced manufacturing technologies, the Defense Production Act (DPA) Title III program has as its purpose the establishment of new industrial capacity for materials of all forms. Through Title III, the government provides financial incentives, in the form of guaranteed purchases, to provide domestic production capacity for essential materials that would not exist without the guarantee. It is the only DoD-wide program in which DoD expressly uses its purchasing power to establish new production capabilities and sources.

The Title III program is authorized by the Defense Production Act of 1950. Although there was an active Title III program throughout the 1950s and 1960s (which was responsible for establishing the domestic titanium industry and expanding the machine tools and various basic materials industries), the present-day program dates only from a 1984 Congressional modification and re-authorization of basic DPA authorities. The program's objective is to establish domestic manufacturing capacity for materials which are critical for national security reasons.

To obtain approval for a proposed Title III project, the project sponsor must demonstrate that the material is essential to the national defense, that the production capability will not be provided on a timely basis by the private sector without the Title III guarantee, that Title III is the most effective way to provide the capacity, and that the defense demand is greater than domestic capacity. In addition, because the primary purpose of Title III is to create viable domestic production sources, the sponsor must also show that the production capability created by Title III is likely to remain commercially competitive after the Title III guarantees have lapsed. The Title III program includes 11 projects whose total funding is about $150 million. Approved projects are providing domestic sources for materials such as silicon-on-insulator/silicon-on-sapphire, travelling wave tubes, quartz fiber, graphite fiber, discontinuous reinforced aluminum, accelerated cooled/direct quenched steel plate, and oxide dispersion strengthened (ODS) thin sheet. The Air Force Systems Command is Executive Agent for this DoD-wide program.

Producibility/Concurrent Engineering — Traditionally, defense producers have designed new weapon systems sequentially, focusing initially on the basic design and performance requirements. Producibility and support requirements have usually not been considered until after fundamental design decisions may have been made. It is believed that the failure to address production and support requirements early on in weapons design can result in missing cost and production schedule targets. In reviewing the engineering practices of world class manufacturing firms, a concept called "concurrent (or simultaneous) engineering" was found to result in the ability to deliver high quality products on time and on schedule. Concurrent Engineering (CE) integrates product and manufacturing and logistics process design and considers all elements of the product life cycle from concept definition through disposal. In addition, CE has been found to result in increased product-mix flexibility, and a greatly reduced interval between product conception and appearance in the marketplace.

A December 1988 Institute for Defense Analysis study concluded that implementation of the CE process can be a major factor in improving the possibility of achieving weapon system production costs and lead times and improving quality. DoD is now engaged in identifying processes, practices, and procedures that can inhibit CE: reviewing producibility policies to place greater emphasis on the role of a coordinated design policy; documenting the potential benefits of applying CE; and determining how to train acquisition executives in CE concepts. A Defense Science Board task force is also addressing this issue.

Best Manufacturing Practices — The Best Manufacturing Practices (BMP) program, sponsored by the U.S. Navy, addresses industry's problems of keeping abreast of simultaneous advances in weapons and production technologies. The intention of the program is to improve the quality of U.S.-made products by providing information on manufacturing practices and processes that have proven successful in other applications. This program increases the rate of diffusion of manufacturing advances and improvements throughout the industrial base. Although it is primarily intended for the benefit of defense contractors, the results are also applicable and available to non-defense manufacturers.

The manufacturing practices of BMP program participants are surveyed by government teams (drawn from all military Services and DLA) and "best practices" are documented in survey reports. BMP's computerized database gives U.S. industry access to abstracts and data on successful manufacturing practices and solutions to specific problems documented in the surveys. It is structured to respond to queries on a wide range of subjects, including equipment associated with best practices, companies surveyed, and abstract key word searches.

Computer-Aided Acquisition and Logistics Support — Computer-aided Acquisition and Logistics Support (CALS) is a combined DoD and industry strategy for transitioning from "paperwork" to a highly automated and integrated operations standard. Using data-exchange standards and related technology to facilitate the integration of data bases, CALS is designed to create large pools of product definition and support data. Ultimately, an automated system is envisioned to receive, store, distribute, and use weapon system technical data in digital form. CALS will not only simplify DoD's and contractors' administration of the acquisition and support process, but will directly facilitate in-factory integration of design, production, test, and other functions.

OSD has taken a major step toward routine contractual implementation of CALS by issuing the first in a series of national and international standards for digital data delivery and access. As a result, plans for new military equipment will include the use of CALS standards and specific opportunities for CALS implementation will be identified for systems now in full-scale development or production.

Industry-Government Programs to Bolster Industrial Competitiveness — Within the past decade, a growing number of U.S. industries — often at the lower tiers of the defense industry — have encountered increased international competition and corresponding losses in international and domestic market share. These reductions in domestic industrial competitiveness have caused concern on the part of the affected industries, the producers they supply with products, and government.

While actions clearly must be taken to improve the competitiveness of important domestic industries, DoD has not favored some of the "traditional" approaches to competitiveness problems. Trade barriers, by themselves, do not restore the competitiveness of U.S. industries and can have the overall effect of reducing U.S. access to state-of-the-art production capabilities. While direct government incentives can be more effective on a case-by-case basis, available funds for these purposes are very limited relative to the potential need.

Moreover, the private sector should be the principal catalyst of efforts to improve competitiveness; manufacturers are in a better position than the government to evaluate the effectiveness of proposed investments and actions. As a result, DoD has developed a number of joint private sector-government partnerships intended to provide additional resources or attention to improving the competitiveness of specific industries.

The most familiar of these initiatives is SEMATECH, which was founded in 1987 by 14 U.S. semiconductor companies along with DoD to develop advanced manufacturing technologies and transfer these technologies to member companies. SEMATECH is supported by funding from DoD (through DARPA) and member companies It has established a research agenda intended to restore world leadership to U.S. semiconductor manufacturers within a five-year period.

The Strategic Defense Initiative Organization has developed Manufacturing Operations Development and Integration Laboratories (MODILs) as part of their Producibility and Manufacturing Program. MODILs are partnerships between government, industry, and academia whose objectives are to address needed improvements in manufacturing methods and to pool existing national capabilities to address SDIO manufacturing issues. MODILs address SDIO issues such as Survivable Optics, Advanced Signal Processing, and Advanced Sensor material alternatives for which industry has few incentives to address given the uncertainty of production of SDIO systems.

Moreover, the MODIL is not a specific facility or Center of Excellence; instead, it is a network of interested parties who can be teamed to work on specific projects. Most MODIL funding goes through the MODIL manager to industry and universities since the objective is development, transfer, and use of new and leap frog manufacturing methods by U.S. industry. SDIO has the Survivable Optics MODIL fully operational through Oak Ridge National laboratory and has initial projects underway for the Sensor and Signal Processing MODILs through Sandia National Lab.

Other industry-government activities directed toward restoring the competitiveness of essential domestic industries include DoD's support for the machine tool action plan, the optics action plan, and the bearings action plan. Each case represents DoD's response to an initial request for import protection. They are closely linked to increasing the U.S. manufacturing competitiveness for several critical technologies (including air-breathing propulsion, machine intelligence/robotics, photonics, and sensitive radars). Each action plan recognizes that the capabilities of an industry that is essential for the national security are threatened by foreign competition. Tailored solutions that are specific to the industry's needs are developed under each of the action plans. For example, a key element of the Optics Action Plan is DoD's support (along with optics manufacturers and users, academia, and state governments) for a new Center for Optics Manufacturing, located at the University of Rochester. The Center will develop new manufacturing capabilities for certain types of glass optical elements that will be substantially less expensive to produce than current technologies. By way of contrast, the Bearings Action Plan involves temporary import restrictions to provide temporary relief from foreign competition as well as actions to encourage investments in productive capacity to restore the domestic industry's competitiveness.

3. Actions to Improve the Defense Acquisition Process

DoD wants the benefits of world-class engineering and production capabilities applied to meeting the needs for weapon systems. To do so, it must be a world-class customer and pursue buying practices that energize the technological and productive capability of U.S. industry. Consistent with the requirements of the Authorization Act of 1989, DoD has undertaken a number of actions to identify and delete or modify acquisition regulations and procedures that do not foster improved quality, affordability, or value in Defense weapon systems.

The Defense Management Report (DMR) initiatives reflect a multi-level approach to improving acquisition management — establishing a concise set of regulations and guidance; making changes to address professionalism and ethics in the workforce; increasing the efficiency of business operations; and implementing specific cost-reduction measures. Several ongoing efforts under the DMR include:

- A ***regulatory relief*** effort to address the administrative legal burden placed on the defense acquisition system. The objectives of the regulatory relief effort undertaken to date have been to reduce the sheer volume of regulatory guidance, streamline the system, and improve the process for developing new regulatory guidance. The review of regulations has been divided into three areas: Directives and Instructions; Procurement and Contracting Guidance (contained in the Defense Federal Acquisition Regulation Supplement (DFARS)); and Military Specifications and Standards.

- Steps toward improving the ***education, training and career development of the acquisition workforce***. To develop a more capable, better educated acquisition workforce, a central policy office has been established within the office of USD(A) to set DoD education and training standards for the acquisition workforce. This office intends to work closely with appropriate congressional committees to ensure our workforce initiatives meet the mutual goals of DoD and the Congress.

- A ***consolidation of contract administration services*** (CAS) has been completed under the Defense Contract Management Command (DCMC). Consolidating CAS under one agency will promote uniform interpretation of acquisition policy; provide a single face to industry; establish an organization dedicated to providing technical and other support to program managers; improve internal controls in contract administration; and eliminate unnecessary overhead.

The Under Secretary of Defense for Acquisition has chartered a major, year-long review of the acquisition process under the Defense Science Board (DSB). This DSB panel was asked to identify ways to cut the acquisition process in half without negatively affecting cost or quality. The panel is performing detailed case studies of nearly 100 DoD weapon programs and is developing DoD's largest single data base on the acquisition process in order to identify the principal sources of delay in the acquisition process and means to correct these problems.

DoD has also taken action to identify acquisition policies that stifle innovation and threaten the economic health of defense industries. In response to requirements in the FY89 Authorization Act, DoD has developed a preliminary "Integrated Financing Plan," to ensure that financing, return on contractor investment, and allocation of contract risk policies are structured to meet the longterm needs of DoD for industrial resources and technology innovation. The initial Plan, submitted in November 1989, addresses longterm financial goals and existing DoD policies and practices related to progress payments and other contract financing issues, return on contractor investment, and allocation of contract risk. The Plan noted that numerous policy changes initiated by DoD between 1984 and 1987 have been criticized for contributing to increased financial risk, reduced profitability, and reduced cash flow for contractors. The Plan identified several specific corrective measures that have already been taken to address these problems.

DoD continues to review standards and specifications with a view to eliminating outmoded and duplicative requirements and ensuring access to the latest state-of-the-art industrial product and process capabilities. The review has the objective of telling people what to do but not how to do it. An example of improvement is the concept of the Qualified Manufacturing Line (QML) that will be used to produce military computer chips. QML emphasizes qualification of the manufacturing process as opposed to the testing of individual products from that process. This concept reduces government oversight of production lines for certified manufacturers and reduces cost by allowing companies to produce military and commercial chips on the same line. Achieving desired costs, schedules, and performance in space and hostile environments for a whole generation of signal processing devices has made SDIO's Signal Processing Program a key player and supporter of the DoD QML effort.

4. Actions to Improve DoD's Industrial Base Analysis Capabilities

DoD recognizes that a broad range of management decisions and actions — many of which do not expressly concern "industrial base" issues — can have significant impacts on, or be affected by, the U.S. defense industrial base. To make effective policy, program management, and budgeting decisions, DoD requires timely and accurate information on issues ranging from broad worldwide industrial and manufacturing trends to the capabilities and capacity of individual production sources. To meet this need, DoD has several ongoing measures to establish an industrial analysis program.

The centerpiece of this analysis program is the Defense Industrial Network (DINET), an automated information system and management tool that is intended to help DoD identify and solve defense industrial base concerns dealing with products, suppliers, technologies, and weapon systems and to support crisis management actions regarding surge and mobilization. DINET links together various industrial data sources within the DoD and other Federal agencies to provide a comprehensive analytical and assessment capability. DINET is structured to provide information on issues such as: single or sole source manufacturers supporting critical weapon systems; offshore sources; foreign direct investment in U.S. defense-related industries; capacity, vulnerability, competitiveness, and technology profiles of lower tier industries and suppliers; surge and mobilization capabilities; and alternate sources of supply.

DoD's Production Base Analysis (PBA) process is a principal ongoing source of information for DINET. The PBA process also provides industrial base information to address specific management issues. Since 1985, all three Services and DLA have prepared annual assessments of the production base supporting critical items and programs. Recognizing the need for more standardized and timely production base assessments, DoD has convened a joint-Service working group to review the PBA process and develop a consensus within the planning community regarding assumptions, goals, and procedures for PBAs. The review involved defining the purpose of PBAs, developing analysis methodologies and data collection processes and formats, determining uniform data requirements, and defining the use and format of joint PBA reports.

This joint effort developed a conceptual framework that integrates the Industrial Preparedness Planning (IPP) and PBA processes more effectively into the programming and budget development cycle. It also provides a means to integrate industrial base issues into the weapon acquisition process, providing better support to operations planning. As an example, DoD is conducting a test case industrial base analysis for three major weapon systems. The results of this review are being incorporated into revised industrial base guidance procedures, discussed earlier.

DoD also performs a wide variety of special studies and analyses of specific industrial base issues and trends. These include analyses of the structure and responsiveness of key industry sectors such as infrared detectors, gas turbine engines, forgings, or precision guided munitions (performed as part of the PBA process by the Services); materials supply and demand analyses prepared by the national defense stockpile and DPA Title III programs; analyses of the industrial base impacts of mergers, acquisitions, and memoranda of understanding; and worldwide state-of-the-art surveys of selected industries and production technologies. Ongoing appraisals are made to ensure that these analyses are focused on the highest priority issues and deliver value to the ultimate users of the information — the policymakers and managers who make day-to-day decisions that affect the industrial base.

C. PLANNING INDUSTRIAL CAPABILITIES FOR CRITICAL TECHNOLOGIES

1. Overview

While DoD has long had an active Science and Technology (S&T) program, the specific focus on critical technologies is a relatively recent development. Nevertheless, the critical technologies planning process has already had an important impact on DoD's industrial base program.

The U.S. has traditionally led the world in advanced technology R&D, and continues to do so in most of the technology areas described in the ***Critical Technologies Plan***. However, both U.S. defense and commercial producers have often lost out to foreign competitors in capitalizing on U.S. technology developments with commercially viable products and fielded weapon capabilities.

DoC's ***Emerging Technologies*** report documents the risks faced by U.S. industry. This report identifies 12 emerging technologies that will have a major economic impact in the next decade, a list which substantially overlaps DoD's "critical technologies." The DoC report suggests that "if current trends continue..., before the year 2000, the United States could lag behind Japan in most emerging technologies and trail the European Community (EC) in several of them." (See Table C-1.)

In all segments of the economy, this loss of leadership could impact U.S. economic prosperity and continued economic leadership. With regard to defense production, loss of technology leadership — the ability to transform technology advances into weapon capabilities rapidly and at an affordable cost — can also cause an impact upon DoD's continued ability to field a force with superior performance capabilities.

These problems are multi-dimensional and are affected by some basic characteristics of U.S. industrial performance. However, DoD can contribute to solving this problem by creating an atmosphere conducive to development of advanced technology capabilities through its R&D strategies and priorities, its manufacturing policies, and its acquisition process. While the previous chapter addressed specific initiatives DoD is taking to improve its understanding of industrial base issues, the manufacturing capabilities of defense industries, and the Department's own acquisition processes, this section focuses on the critical technologies planning process itself.

Table C-1. Relative Standing in Emerging Technologies (U.S. versus Japan)

TECHNOLOGY	R&D	PRODUCT INTRODUCTION
Advanced Materials	Even/Losing	Behind/Losing
Advanced Semiconductor Devices	Even/Holding	Behind/Losing
Artificial Intelligence	Ahead/Holding	Ahead/Holding
Biotechnology	Ahead/Losing	Ahead/Losing
Digital Imaging Technology	Even/Losing	Behind/Losing
Flexible Computer-Integrated Manufacturing	Ahead/Holding	Even/Holding
High-Density Data Storage	Even/Holding	Behind/Losing
High-Performance Computing	Ahead/Holding	Ahead/Losing
Medical Devices and Diagnostics	Ahead/Holding	Ahead/Losing
Optoelectronics	Even/Holding	Behind/Losing
Sensor Technology	Ahead/Losing	Even/Holding
Superconductors	Even/Losing	Even/Losing

Source: DoC, ***Emerging Technologies***, Spring 1990

2. Institutionalizing the DoD Critical Technologies Process

Although DoD established the *Critical Technologies Plan* planning process less than two years ago, major steps have already been taken to institutionalize this process within DoD technology development and industrial base/manufacturing programs. The rapid institutionalization of this process was possible in large part for two reasons. First, the process fit well as an element of the ongoing S&T planning process, avoiding the need to establish a new planning process from the ground up. Second, the Congressional emphasis on an enhanced industrial base perspective within the critical technologies planning process conformed well with other ongoing initiatives within DoD to provide a coherent, systems approach to technology development, engineering, and production planning. Other initiatives include:

- Organizational streamlining and realignment initiatives to merge engineering and manufacturing organizations at DoD's principal systems acquisition organizations such as the Air Force Systems Command
- Increased focus on integrated product and process development through top-level policy and technology development organizations, including the merger of the Defense Science Board and the Defense Manufacturing Board and increased attention on manufacturing technology at DARPA
- Increased management emphasis on the concurrent engineering concept of integrated, rather than sequential, product and process development.

Mirroring these ongoing trends, DoD's industrial base/manufacturing program continues to interface and play a vital role in the critical technologies planning process. DoD's industrial base planning community participated actively in the development of the second *Critical Technologies Plan*, produced in 1990. This involvement was reflected in the contents of the Plan, which placed emphasis on U.S. and international industrial base and manufacturing issues. Ongoing planning for the FY91 *Critical Technologies Plan* has provided additional opportunities for enhanced coordination between the R&D and industrial base communities; DoD personnel are more fully integrated in this planning process and industrial base perspectives are reflected in consideration of critical technologies.

3. The Industrial Base Program and Critical Technologies

The industrial base program itself is being reoriented to emphasize the priority on developing future production capabilities for critical technologies. The area of critical technologies represents a major opportunity for DoD's industrial base program. DoD's efforts to enhance domestic industrial capabilities frequently suffer because fundamental weapons program design and acquisition decisions have already been made by the time industrial base issues are raised. By the time a specific weapons program enters full-scale production, it is generally too late to raise industrial base issues: producibility problems, foreign dependencies, and other industrial base problems may have been "designed-in," with the result that it would be expensive and difficult to correct them. Once a capable supplier network has been established, it is seldom cost-effective to qualify additional sources for a component or subsystem that may not be in production for much longer.

For all these reasons, it has proven to be extremely difficult for DoD to take effective action to enhance domestic production capabilities to support mature weapons programs. Because the critical technologies represent developmental future capabilities, the race for world industrial leadership in each of these areas is still underway; in some areas, in fact, the race has barely begun. Advanced technologies represent a major opportunity for DoD to leverage its limited industrial base program investment funds and help establish competitive domestic production sources in technology areas that will have a major impact on production capabilities and weapon performance in the future.

One principal area where the industrial base program's new emphasis on this issue has been seen is through the workings of a Defense

Science Board task force that has been examining the issue of "critical industries." Major areas examined by the Task Force include criteria for determining industry criticality and identification of potential policy tools and action plans that might be applied to affect the health and competitive development of selected critical industrial subsectors. The report of this task force is forthcoming.

The Defense Production Act (DPA) Title III program provides another important example of how the new focus on critical technologies is already having an effect on DoD's industrial base program. The Title III Program has developed a long-range plan to ensure that the Program's limited resources are focused on identifying and resolving the highest priority production base problems. The plan provides a way for the Title III Program to monitor development of the critical technologies in terms of emerging industrial base issues, vulnerabilities, and opportunities and also in terms of changing weapon program requirements. The underlying purpose is to identify and initiate Title III projects in a timely fashion to support needs in critical technologies areas.

The list of immediate project opportunities is currently somewhat limited because the critical technologies are, in large part, future-oriented and, therefore, not well-suited to immediate production capacity expansion initiatives. Nevertheless, general possibilities for Title III actions have been identified for nine technologies and analyses are ongoing to develop projects in these areas. The nine technologies are:

- Gallium arsenide
- Machine intelligence/robotics
- Microelectronic circuits
- Composite materials
- Superconductivity
- Integrated optics
- Fiber optics
- Air-breathing propulsion
- Biotechnology materials and processing.

Pursuing a critical technologies focus in Title III and other industrial base programs will help promote the development of products and production capabilities based on the critical technologies and ensure that U.S. industry and DoD can achieve benefits from U.S. technology developments.

D. INDUSTRIES THAT SUPPORT CRITICAL TECHNOLOGIES

1. Overview

Congress has requested that the Department of Defense identify and analyze the condition of the U.S. defense industrial base, giving special attention to the industries that are most critical for national security applications of the technologies identified in the FY90 *Critical Technologies Plan*. Of particular concern to Congress is industry's ability to perform research and development (R&D) activities relating to critical defense technologies and to apply those technologies to the production of goods and the furnishing of services. The legislative requirement asked DoD to consider financial factors such as trends in profitability, debt burden, levels of capital investment, and R&D spending of companies involved in R&D or application of critical technologies, as well as the consequences of mergers or acquisitions of these companies. DoD was also asked to consider the results of current DoD R&D spending on critical technologies and to forecast likely future R&D spending levels.

2. Background

The FY90 *Critical Technologies Plan* identified the 20 technologies that are most critical to national security on the basis of the following criteria:

- Performance criteria, which assess a technology's potential to enhance performance of conventional weapon systems and its ability to provide new military capabilities
- Quality design criteria, which consider a technology's availability, dependability, and reliability as it applies to weapon system affordability
- Multiple use criteria, which address a technology's pervasiveness across different categories of weapon systems and its contributions to the strength of the industrial base.

The analyses in the following sections build a bridge between these 20 technology areas and their corresponding industry infrastructure. Identifying the industries that support these technologies, analyzing current capabilities and trends to produce defense and non-defense products, and identifying necessary actions to strengthen their capabilities can guide limited DoD (and Federal civilian agency) resources toward the highest payoff areas. Such an emphasis can contribute to a competitive U.S. defense industrial base that can support not only the development and production of state-of-the-art materials and components for military systems, but also the dual-use products and processes that will yield benefits to both DoD and the nation at large.

In determining the likely future development of critical technologies, it is important to understand how this development can be affected by non-technological factors such as the cost of capital, industry investment horizons, foreign competition, and the stability of the business climate. While it is sometimes assumed that products and production capabilities will emerge more or less automatically once a technological capability has been demonstrated, in fact many factors can reduce industry's willingness or ability to invest in products derived from or production capabilities based on new technologies.

U.S. research institutions (including industry) have typically led the world in developing advanced technologies. However, U.S. industry has frequently seen the benefits of these technological innovations reaped by foreign competitors: transistors and semiconductors, color TVs, and video cassette recorders are well-known examples of U.S.-developed commercial technologies (with important military applications) that are now dominated by offshore producers. As shown in Table C-1, this trend is continuing; U.S. research efforts are much more competitive than product introduction in key technology areas. Therefore, it is at least as important to evaluate the ability of industry to develop products and production capabilities in critical technology areas as it is to evaluate trends in the development and demonstration of these new technologies.

3. Industry and Critical Technologies

There is not a one-to-one relationship between a critical technology and an industry. In fact, each technology is supported by a large and complex industrial infrastructure that is essential to perfect the technology, develop usable products, and bring these products to the market. Supporting industries for the critical technologies include specialized, "high-tech" industries in, for example, lithography and photonic computing as well as basic industries such as chemicals, machine tools, and metals.

Describing the effect of critical technologies on industry, and the likelihood that industry will be able to develop production capabilities to capitalize on them, is complicated by the differing impact these technologies will have on existing industry structures. Some critical technologies, such as air-breathing propulsion, will represent only incremental changes in existing industry structures. Although significant capital investments may be required to develop new engineering and production capabilities, the basic dynamics of the industry (dominant "players," buyer-supplier relationships, etc) are not likely to be changed radically.

The creation of production capability for other critical technologies may transform existing industries or require the creation of entire new industries. The advent of photonics, superconductivity, biotechnology, and other technologies will require major changes in the structure, capability, and interrelationship of the industries that produce or use products based on these technologies.

No evaluation of the ability of industry to support critical technologies can be complete without also considering the significant interrelationships among the technologies identified in the FY90 ***Critical Technologies Plan*** and how these interrelationships will affect the industries that will apply the technologies. For example, "Semiconductor Materials and Microelectronic Circuits" is a critical technology area in its own right and is also a major enabling technology for many of the others, such as passive sensors, machine intelligence/robotics, signal processing, parallel computer architectures, and pulsed power. Similarly, continuing improvements in software producibility are necessary for advances in machine intelligence/robotics (and many other critical technologies); machine intelligence/robotics, in turn, plays a pivotal role in developing the capability to produce products derived from most of the other critical technologies.

4. Organization of the Critical Technology Evaluations

This initial evaluation of the defense industrial base segments that support the DoD critical technologies provides an overview of the industrial base capabilities required to support each critical technology as well as a more detailed analysis of selected industry segments. Within each of these areas, it discusses current capabilities, ongoing activities, and likely trends as the technologies continue to mature. It notes primary areas of risk and opportunities for DoD action to ensure that these technologies can become areas of industrial strength.

The report provides an in-depth evaluation of eight of the twenty critical technology areas and a more modest review of the remaining twelve. The eight — air-breathing propulsion, composite materials, machine intelligence/robotics, passive sensors, photonics, semiconductor materials and microelectronic circuits, sensitive radars, and superconductivity — have the most coherent and reliable industry organization of the twenty technologies identified. Due to these eight technologies' defined industry structures, financial information from officials in government and industry and from written sources was more readily available than for the second grouping.

Also, these eight technology areas listed represent areas where national security interests appear to coincide with national economic interests. They represent the vast majority of the overlaps between the DoD ***Critical Technologies Plan*** and the DoC ***Emerging Technologies Report***. The ability of the industries profiled in this section of the report to develop production capabilities based on the critical technologies should be of substantial importance not just to DoD but to other Federal and state government organizations concerned with economic competitiveness.

These eight sections address areas such as industry structure, condition of the industrial base, U.S. investment, foreign mergers, acquisitions, and joint ventures and also highlight specific infrastructure segments. Although each industry segment cited has a significant degree of financial and business information provided to help describe the condition of the sector, there is variation with regard to the depth of the data that were readily available. The inclusion of this information was directly related to the visibility of the industry in available market and financial reports.

The 20 specific industry segments discussed in these detailed evaluations represent some, but by no means all, of the key industries supporting development of these technologies. Over 100 industrial sectors have been identified as playing an important role in supporting development of critical technologies (see Appendix A). The selection of industries for this report is intended to provide an overview of the industrial base issues affecting a cross section of the industry and to provide information as requested by Congress to illustrate the financial trends affecting critical technology development and commercialization.

The other 12 technologies are addressed in considerably less detail. The analysis of these 12 technology areas describes applications, manufacturing capabilities, and the supporting industrial structure, but does not provide detailed information on the financial condition of specific industry segments. In many cases, these technology areas represent highly advanced technologies or processes that are still somewhat immature from an industrial base point of view. The industries that support them are often newer segments of well established industries (such as in microelectronics, materials, or computers). In some cases, work on the technology is still centered in universities or laboratories. In other cases, these represent highly-specific technologies affecting only a relatively narrow industrial base (e.g., high energy density materials) or a highly diffuse industrial base (e.g., simulation and modeling or software producibility). A more complete assessment of these technology areas may be performed at a later date.

AIR-BREATHING PROPULSION

1. Introduction

Air-breathing propulsion (ABP) is a critical element in most major conventional weapon systems and for a large portion of our strategic forces. Systems using such propulsion, including aircraft, cruise missiles, and armored vehicles make up a major part of the annual Defense procurement budget. The size, mission capabilities, performance, and life-cycle cost of each of these systems is largely a function of its ABP component. ABP is essential to continued U.S. capabilities to project military power abroad and to field superior weapon systems.

Advances in this technology create benefits in such areas as weapon system payload, range, speed, maneuverability, maintainability, supportability, and reliability. Air-breathing propulsion technology also has the potential to extend military mission capabilities to new flight regimes with hypersonic speeds. Advances in this technology are critical to the feasibility of the National Aerospace Plane (NASP), which is intended to provide more economical and timely access to space. Hypersonic speeds could also greatly enhance military aircraft capabilities. Figure 1 summarizes air breathing propulsion technology challenges, major applications, and supporting industries.

2. Industry Structure

Key components of the industry structure supporting ABP technology are illustrated in Figure 2. Because of its historic domination of the ABP area, this assessment centers on gas turbine engines (GTE). Unlike the structure supporting a number of the other critical technologies, the GTE industry structure is well-established. It centers on the seven U.S. producers of GTEs. However, GTE customers have also played major

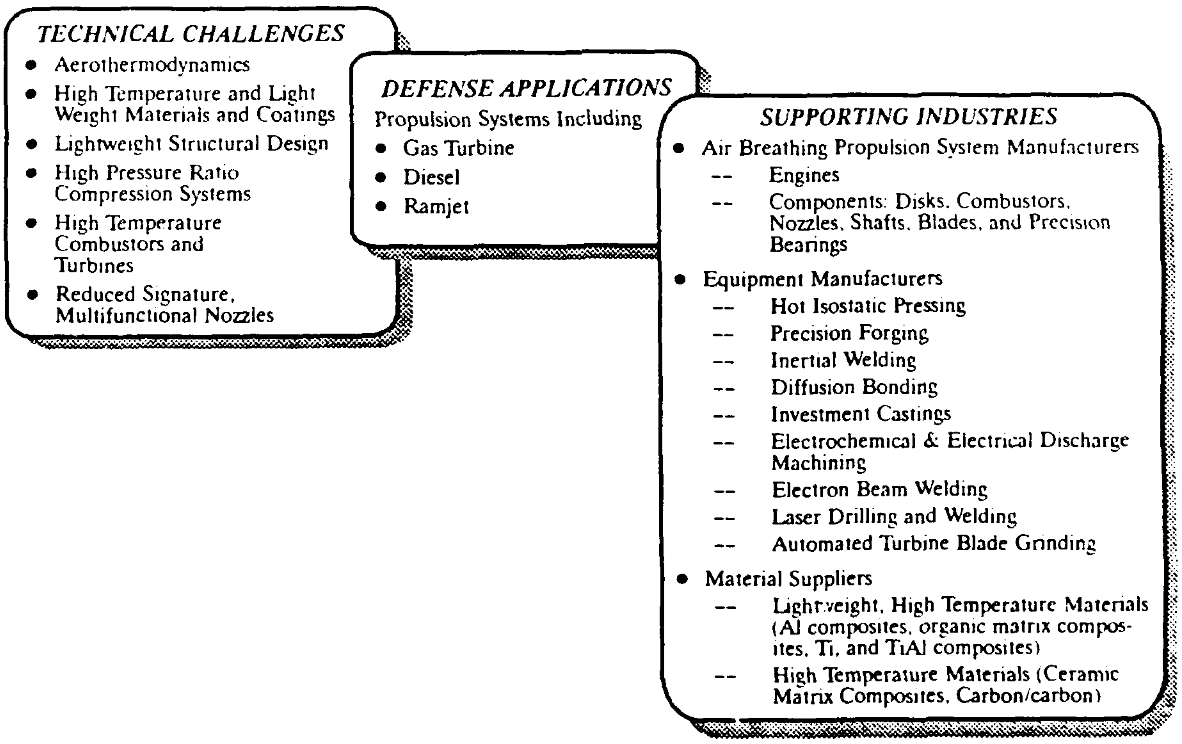


Figure 1. Technical Challenges and Supporting Industries

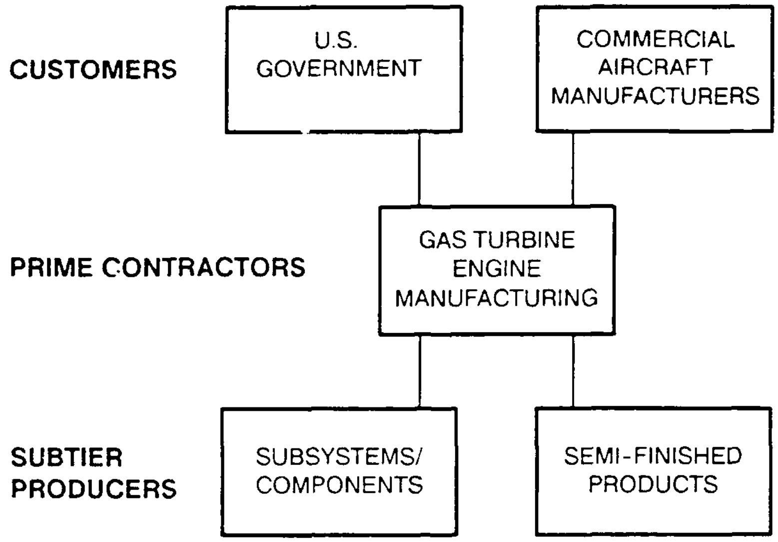


Figure 2. Key Players with Respect to ABP Technology

roles in promoting and financing advances in gas turbine engine technology in the past. Their continued participation in GTE research and development will be a determinant of how quickly ABP technology evolves. GTE subtier producers have played less-prominent roles in GTE R&D but are critical from the standpoint of production, by virtue of their 60-percent average share of GTE value added.

In the future, the industry's role will be affected by changes in machining, casting and forging. Composites manufacturing will grow in importance and be a replacement for many current subtier industries. New processes for producing these new materials will change the scope and nature of the current industrial base for advanced engines.

For the purposes of analyzing financial ability to support ABP technology, this industry structure should be divided into two segments: (1) large GTEs for aircraft and (2) all other gas turbine engines. Only two of the seven U.S. GTE companies produce the former, and these two companies — General Electric (GE) and Pratt & Whitney (P&W), a subsidiary of United Technologies — dominate the U.S. GTE market in all financial categories. Nevertheless, other GTE production (for smaller fixed-wing aircraft, rotorcraft, cruise missiles, armored vehicles, and ships) is critical to billions of dollars of Defense procurement each year and is also important to the analysis of industry's ability to support ABP technology. The other five U.S. GTE producers (as well as GE and P&W) are important contributors in this latter segment. These companies are:

- Allison Gas Turbine Division (of General Motors)
- Garrett Engine Division (a subsidiary of Allied-Signal)
- Teledyne CAE
- Textron Lycoming
- Williams International.

The customer portion of the industry structure is dominated by the U.S. Government and the two U.S. producers of large commercial aircraft — Boeing and McDonnell Douglas. While other aircraft companies and airlines also influence trends in ABP technology, their direct financial contribution for GTE R&D is small by comparison.

Advances in the performance and reliability of GTEs are directly related to lighter-weight, higher temperature resistant, longer lasting structural components. Although advanced design techniques and analysis procedures are necessary, such structures fundamentally depend on materials and components which can resist higher temperatures and loads for longer times with less weight. The companies producing materials, parts and components for GTEs are as varied as the items they supply, and are members of a number of industry sectors. This chapter will focus on three critical supplier industries — investment castings, precision forgings, and precision bearings.

However, several other subtier industries are not only important to current GTE products, but are also extremely important to the future health of the domestic GTE industry -- those industries which produce high-temperature, high-strength materials and components, as well as the equipments necessary for their production. In the materials categories are the specialty metals producers of superalloys, titanium and titanium aluminides in ingot, wrought forms and powder, as well as the producers of organic and metal matrix composites, fibers, carbon/carbon, ceramics and ceramic matrix composites. This category also includes producers of graphite, high temperature coatings, high temperature liquid and solid lubricants, and other specialty materials.

Several of these materials industries are discussed in other chapters of this report — metal matrix composites, ceramics, ceramic matrix composites and carbon/carbon. Continuous advances in high temperature materials and their associated manufacturing processes and facilities have been central to the steady growth of the GTE sector over the past 45 years, and will continue to be as vital in the future. Although commercial GTE sales now dominate the market, advances in GTE product capabilities have always been a direct result of extensive investment in high temperature materials and processes by the DoD. DoD has funded, both directly and indirectly, these developments as well as the first production implementation in military engines. The military experience is then applied to commercial GTE products with much lower cost and risk.

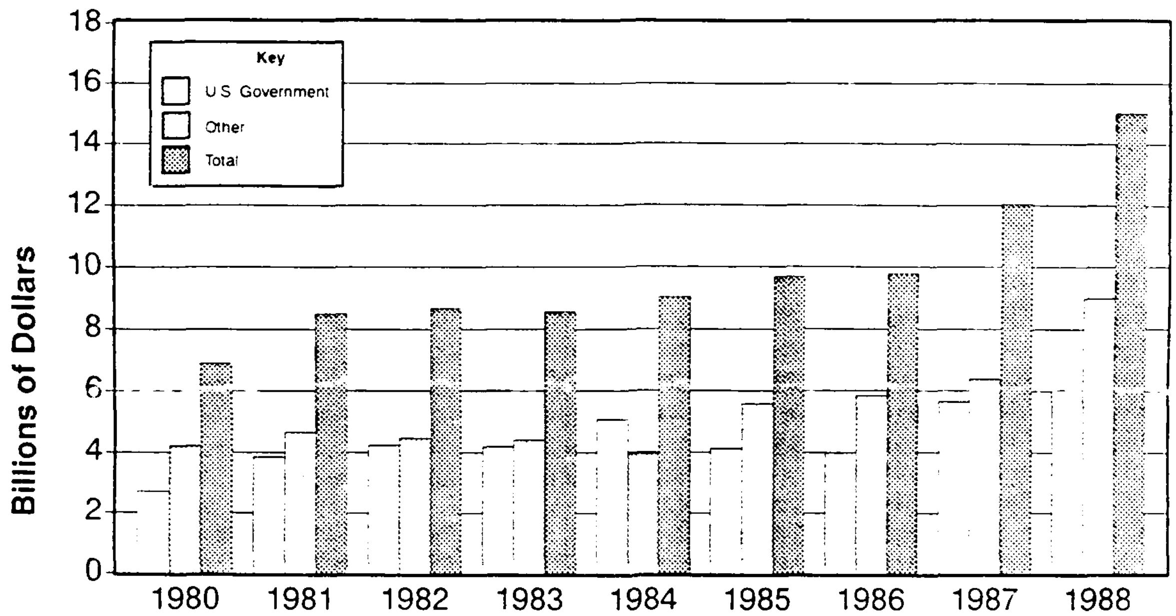
In addition to the three industries which are discussed in depth later in this chapter, the GTE companies as well as many of the subtier suppliers are supported by a host of other companies including suppliers of industrial gases, machine shops, specialty metal removal houses, specialty fabricators, heat treating companies, tool and die companies, etc. Many of these are small companies located near their primary customers. Potential reductions in DoD sales may cause the GTE industry, as well as the larger suppliers of forgings and castings, to increase the percentage of manufacturing work done in-house, which may impact many of these smaller companies.

The production of materials, components, and engines requires a wide range of technologically advanced equipment. Examples are: furnaces, isothermal forging equipment, HIP units, machine tools, CNC controllers, EDM and wire EDM, ECM, creepfeed grinders, powder making equipment, computer controlled hot rolling mills, lasers, and welding equipment. Many of these are supplied by non-domestic companies, and reductions in the level of DoD-sponsored development of world-class equipment in some of these areas is expected to result in a further reduction in the viability of domestic equipment producers.

3. Condition of the Industrial Base

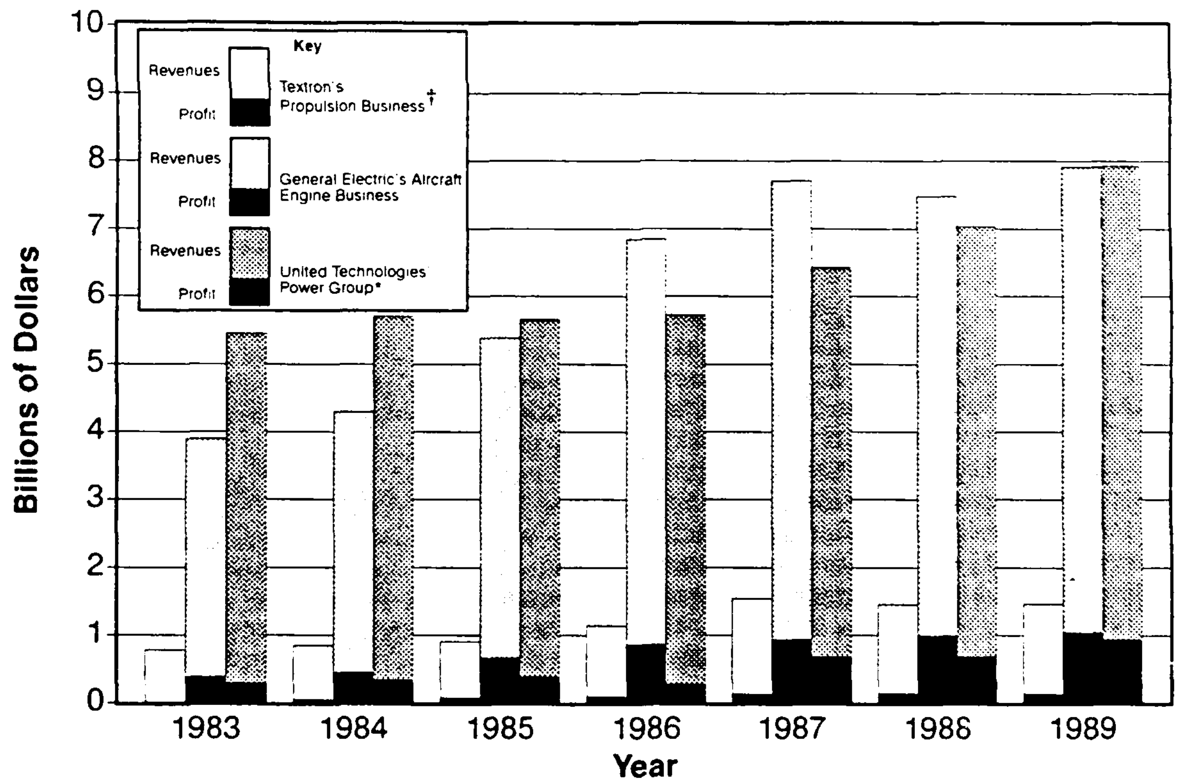
a. Sales

The GTE market was relatively flat during the early 1980s, when a decline in commercial and foreign military sales offset strong growth in sales to the U.S. Government. In the mid 1980s, the commercial market began to recover but lagging sales to the U.S. Government held down the overall increase in GTE sales. The current boom in the commercial transport market, combined with a surge in sales to the U.S. Government, has resulted in a corresponding increase in GTE sales since 1987. The trends in GTE sales are illustrated in Figures 3 and 4.



Source: "Backlog of Orders for Aerospace Companies," Annual Report, Bureau of Census

Figure 3. Sales of Aircraft Engines and Parts (by Customer)

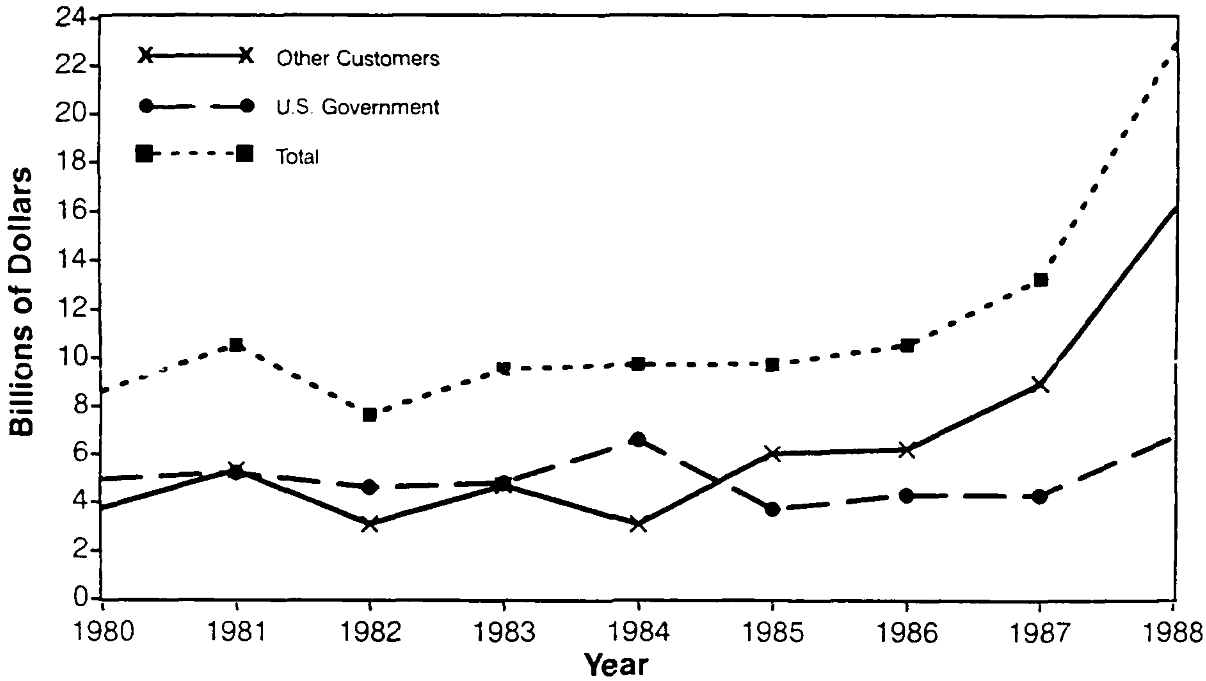


†1983 and 1984 numbers are for Avco's propulsion business. Avco was acquired by Textron in 1985.

*88 percent of the Power Group's revenues in 1989 were from sales of gas turbine engines and parts.

Source: Company annual reports.

Figure 4. Propulsion Divisions' Revenues and Operating Profits



Source: ***Aerospace Facts and Figures***, Aerospace Industries Association, 1989–90

Figure 5. Backlog of Orders for Aircraft Engines and Parts

Figure 4 also reveals how the increase in GTE sales has resulted in substantially higher profits for GTE producers. Between 1983 and 1989, profits from their propulsion divisions tripled from just over $700 million to over $2.1 billion for the three largest GTE producers.[1] Trends in the backlog of orders for aircraft engines and parts indicate that the surge in sales during recent years is likely to continue into the 1990s.

The trends from 1980 through 1988 are depicted in Figure 5. These trends do not, however, reflect the recent downturn in DOD outlays for aircraft procurement. This downturn (which is expected to continue into the 1990s), combined with growth in the commercial transport market, is expected to result in a decline in the military engine share of the GTE market.

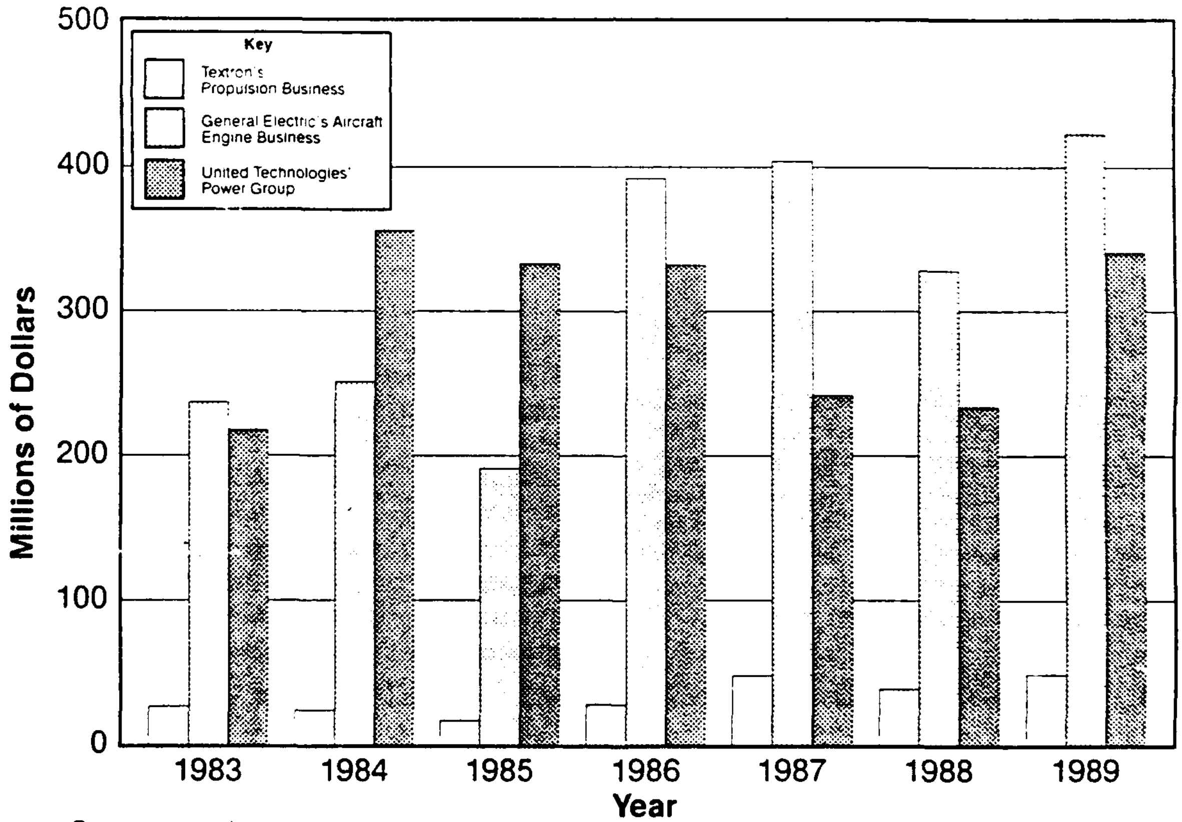
Prospects for the commercial transport market and for sale of engines to power these transports are evident in the near tripling of the Boeing Company's backlog of firm orders for these aircraft during the last two years, from $27 billion at the end of 1987 to $74 billion at the end of 1989. Increased sales of large gas turbine engines for these commercial transports should offset any decline in sales of large military engines and should fuel continued GTE sales growth for General Electric and United Technologies. However, an anticipated decline in smaller engine sales for military helicopters and armored vehicles may not be offset by a comparable surge in smaller commercial engines. This part of the GTE market may experience flat or declining sales, as a result.

[1] Allied-Signal, General Motors, and Teledyne do not report separate financial data for their propulsion segments. Williams International is privately held and does not publish any financial data. It is estimated that GTE sales by these four companies constitute less than ten percent of GTE sales by U.S. producers ***Ward's Business Directory of 1989*** reports the following sales and employment numbers: Garrett Engine Division (of Allied-Signal) — $500 million in sales and 4,000 employees; Teledyne CAE — $68 million in sales and 700 employees; and Williams International — $124 million in sales and 2,000 employees. (No numbers were reported for GM's Allison Gas Turbine Division.)

b. Investments

GTE producers have increased capital expenditures and R&D investments during the 1980s. Between 1983 and 1989, the three largest producers increased capital expenditures in their propulsion divisions by almost 70 percent (compared to revenue and operating profits growth of slightly more than 60 percent and slightly less than 200 percent, respectively). As Figure 6 indicates, these expenditures fluctuated from year to year for the individual companies, even though the trend was generally upward for the three companies combined. All three companies made substantial R&D investments during this same period, amounting to over $5.4 billion in 1989 alone, of which more than one third was in the propulsion area. It is important to note, however, that almost two thirds of the corporate-wide R&D totals and probably even more of the propulsion segments' shares were financed directly by the the U.S. Government or commercial customers. Additionally, much of the remaining one third financed with the GTE companies' own funds was included as overhead in Government contracts as an independent R&D expense. In other words, a major portion of R&D investments by GTE companies is dependent either directly or indirectly on Government contracts.

Even without customer financing of R&D expenses, GTE producers are expected to sustain financial resources to support air-breathing technology. Table 1 lists sales/revenues, net profits, and long-term debt trends for the six publicly held U.S. corporations with GTE operations. It is interesting to note that United Technologies' Power Group and General Electric's aircraft engine business would rank 68 and 69, respectively, on the Fortune 500 listing (if they were ranked separately).



Source: Company annual reports

Figure 6. Propulsion Divisions' Capital Expenditures

Table 1. Financial Data for Six Publicly Held U.S. Corporations that Produce Gas Turbine Engines (Millions of Dollars)†*

	Fortune 500 1989 Ranking	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
ALLIED-SIGNAL	31										
Sales		5,519	6,407	6,167	10,022	10,734	9,115	11,794	11,116	11,909	11,942
Net Profit		289	348	249	416	487	443	559	384	463	505
Long-Term Debt		885	857	700	1,343	1,544	2,086	2,127	2,017	2,044	1,903
GENERAL ELECTRIC	5										
Revenues		24,959	27,240	26,500	26,947	27,947	28,285	35,211	39,315	38,824	41,019
Net Profit		1,514	1,652	1,817	2,024	2,280	2,336	2,492	2,915	3,386	3,939
Long-Term Debt		1,000	1,059	1,015	915	753	753	4,351	4,491	4,330	3,947
GENERAL MOTORS	1										
Revenues		57,729	62,699	60,026	74,582	83,890	96,372	102,814	101,782	120,388	123,212
Net Profit		(-763)	333	963	3,730	4,517	3,999	2,945	3,551	4,632	4,224
Long-Term Debt		2,058	4,044	4,745	3,522	2,773	2,867	9,825	18,294	31,614	36,708
TELEDYNE	109										
Sales		2,926	3,238	2,864	2,979	3,494	3,256	3,241	3,217	4,598	4,636
Net Profit		344	412	261	305	574	546	238	371	392	259
Long-Term Debt		620	596	571	570	1,071	669	573	548	560	571
TEXTRON	61										
Sales		3,377	3,328	2,936	2,980	3,221	4,039	5,023	5,388	5,343	5,273
Net Profit		156	152	74	89	114	180	242	227	272	269
Long-Term Debt		302	287	246	232	200	1,503	2,182	1,486	1,757	1,779
UNITED TECHNOLOGIES	17										
Revenues		12,324	13,668	13,577	14,669	16,332	14,992	15,669	17,170	18,000	19,532
Net Profit		393	458	427	509	599	636	363	592	659	702
Long-Term Debt		867	832	927	869	1,178	1,289	1,723	1,856	1,643	1,960

Source: Value Line

†Williams not included because it is privately held.

*All figures include engine divisions of companies.

c. Joint Ventures, Mergers, and Acquisitions

Six of the seven GTE producers are segments of larger U.S. corporations. All of these corporations engaged in acquisitions or mergers of various businesses during the 1980s. On balance, these activities probably strengthened the abilities of these corporations to support advances in ABP technology. Despite the financial and marketing strengths of their parent corporations, GTE producers have also entered into an increasing number of joint ventures in recent years. While these joint ventures offer clear short-term technological and financial advantages for the development and production of ABP technology, the net long-term effects on U.S. leadership in this technology are uncertain.

Acquisitions and Mergers

The most recent acquisition involving GTE manufacturing capabilities was Textron's purchase of Avco in 1985. As summarized in Figure 4, sales and profits of the acquired GTE business have grown considerably since. Textron's long-term debt increased by more than 600 percent to an amount equal to 92 percent of its net worth in 1985, as a result of borrowings to finance the Avco acquisition. Since this acquisition, however, Textron's sales, profits, and net worth have grown by over 60 percent, nearly 140 percent, and over 100 percent, respectively. Textron's long-term debt equaled less than 70 percent of net worth in 1989, even though additional borrowings have been undertaken since 1985 to finance the acquisition of Ex-Cell-O (a major producer of airfoils) in 1986 and Avdel (a fastening systems manufacturer) in 1989. The higher debt does not appear to have affected capital expenditures and R&D investments adversely. Annual capital expenditures in the propulsion area during the last three years have averaged nearly twice Avco's expenditures in this area during the year prior to the acquisition. Textron's company-funded R&D investments reached a record high of $202 million in 1989.

Another major event involving GTE manufacturing capabilities in 1985 was the merger of Allied Corporation and Signal Companies to form Allied-Signal. Any direct financial impact on the Garrett Engine Division is hard to gage, because this division's financial results are reported in combination with six other aerospace and electronics divisions. Allied-Signal's combined aerospace/electronics segment's sales grew by 33 percent between 1985 and 1988, but income declined by 4 percent. Similarly, this segment's R&D investments grew by 46 percent over this period, but capital expenditures declined by 23 percent. Long-term debt of the parent corporation grew from $1.5 billion in 1984 to $2.1 billion in 1985 but had declined to $1.9 billion by 1988.

Other acquisition (and divestiture) activities of the parent corporations during the 1980s had no apparent impact on their GTE segments. General Electric invested $16 billion in acquisitions (including the RCA Corporation) during this period. While GE's long-term debt has increased by nearly 300 percent since 1980, current debt equals less than 10 percent of annual revenues and less than 20 percent of net worth. GE's R&D investments totalled nearly $19 billion between 1984 and 1989 (including customer-funded R&D), and capital expenditures in its aircraft engine business averaged more than $300 million per year over the same six years.

UTC divested major segments in 1985 and 1988 but still experienced positive financial growth during the decade. UTC's R&D investments averaged more than $900 million between 1984 and 1989 (including customer-funded R&D), and capital expenditures in its Power Group averaged more than $330 million per year during this same period ($385 million per year since 1987). General Motors' and Teledyne's GTE segments each generate very small fractions of the parent company's revenues, probably less than one percent for the former and less than three percent for the latter. There is no evidence that these segments were affected financially by either parent company's acquisitions or divestitures during the 1980s.

Joint Ventures

A combination of factors has contributed to the rise in joint ventures to develop, produce, and market GTEs. These factors include:

- The high cost of developing new engines (estimated at $1-2 billion for a large aircraft engine)
- A reduction in the number of different engines purchased for weapon systems
- The need to ensure access to offshore markets.

The first and second factors have led to a number of partnerships among U.S. companies to compete for development and production of GTEs for military helicopters and tanks. The first and third factors have resulted in a growing list of international consortia (with U.S. members) to develop, produce, and market GTEs, primarily for the commercial market. Some examples of recent joint ventures are:

- A Pratt & Whitney-Textron Lycoming team to develop an engine for the LH (helicopter)
- A GE-Textron joint initiative to develop and produce engines for future heavy armored vehicles
- CFM International — a partnership of General Electric and Snecma (a French GTE company) — to develop, produce, and market a variety of commercial GTEs
- International Aero Engines — a consortium of companies (including Pratt & Whitney) from five countries — to develop, produce, and market commercial GTEs
- A memorandum of understanding between Pratt & Whitney and

- Daimler-Benz AG (of West Germany) concerning technical cooperation in the propulsion sector
- An international partnership headed by GE to develop a new family of large commercial engines.

The trend towards international consortia and partnerships in developing, marketing, and producing aircraft engines mirrors a similar trend in commercial transport aircraft. While there are many contributing factors which result in this trend, the two most important are the policies of most other countries to develop and protect their aircraft industries and the high cost of developing new products. Japan and most European countries are increasingly imposing the requirement, as a mandatory condition of sales, that companies in their countries participate in the development and manufacturing of aircraft and engines sold to their military or commercial airlines. Under these business conditions, U.S. companies have little choice but to take on international partners. Such countries also often provide direct financial support to their aerospace companies for both research and development of new products. That, coupled with interest rates being considerably lower in most foreign countries, can substantially reduce the development cost of a new product to the U.S. firm.

d. Analysis of Infrastructure Segments

Sixty percent of the value of GTEs is produced by subtier industries. Purchased materials, parts, and components cover a wide spectrum, including electrical, mechanical, and structural items, as well as various lubricant and coating materials. This section will focus on three important segments in the GTE industry infrastructure — investment castings, precision forgings, and precision bearings.

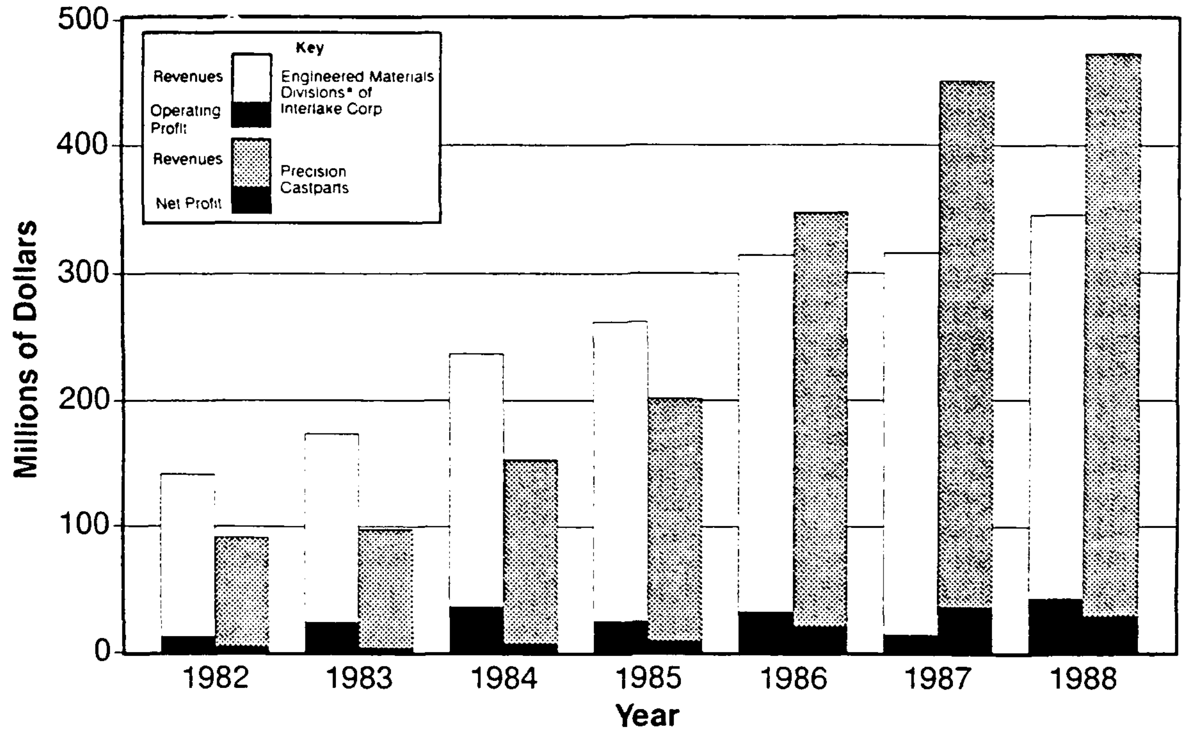
Investment Castings

Approximately 70 percent of investment casting sales are for use in GTEs. The bulk of these sales are engine blades and vanes, but the industry also provides large complex castings which constitute major portions of some engines, as well as smaller engine parts. While the investment casting industry is composed of over 150 companies, sales are dominated by a handful of companies. A 1987 report on the investment casting industry[2] lists three companies — Howmet, Precision Castparts, and Arwood — as the leading suppliers to the GTE market. These three companies present strikingly different financial pictures. Howmet Turbine Components Corporation is the largest producer of airfoils and investment castings, with slightly more than 50 percent of the U.S. market for airfoil castings. Howmet is a subsidiary of Pechiney Corporation (with estimated annual sales of $6.3 billion). Pechiney Corporation is majority owned by Pechiney S.A., a nationalized French company, with annual sales in excess of $15 billion. Howmet's 1988 sales were approximately $827 million. Clearly, Howmet has financial resources to advance investment casting technology to support ABP requirements.

Precision Castparts Corporation (PCP), the second largest producer of investment castings for the GTE market, experienced enormous growth in sales and profits during the 1980s, due in part to the acquisition of TRW's investment casting division in 1986. The sales and net profits of this company for the years 1982 through 1988 are summarized in Figure 7. PCP capital expenditures have grown from $21 million in 1986 to $32 million in 1989. R&D investments have grown, as well, from $1.2 million in 1986 to $4.4 million in 1989 and now equal approximately one percent of PCP sales. Long-term debt more than doubled in 1986 after the acquisition from TRW but has since declined to less than 20 percent of net worth and less than 10 percent of sales.

By contrast, the Arwood Corporation, a subsidiary of the Interlake Corporation, has experienced a negative shift in its financial situation. The primary cause of this shift is a $500 million recapitalization by Interlake Corporation to avoid a possible takeover. This increased the parent corporation's long-term debt from $77 million in 1988 to $524 million in 1989. In addition, Interlake has been negotiating the sale of Arwood. Recent sales and operating profits for Interlake's Engineered Materials divisions are listed in Figure 7. Capital expenditures for these divisions totalled $22.5 million in 1988. Aerospace components,

[2]*Investment Castings: A National Security Assessment,* U.S. Department of Commerce, December 1987.



*Includes revenues and profits of the Arwood Corporation.
Source: Value Line and company annual reports.

Figure 7. Sales and Profits of Two Major Investment Castings Producers

including Arwood's products, constitute more than half of these divisions' sales.

In conclusion, sales and bookings of new orders in the investment casting industry, as a whole, have increased in recent years, due largely to increased demand for commercial aircraft engines. This industry's revenues should continue to grow strongly into the 1990s, as a result of the continued strength of the commercial transport market.

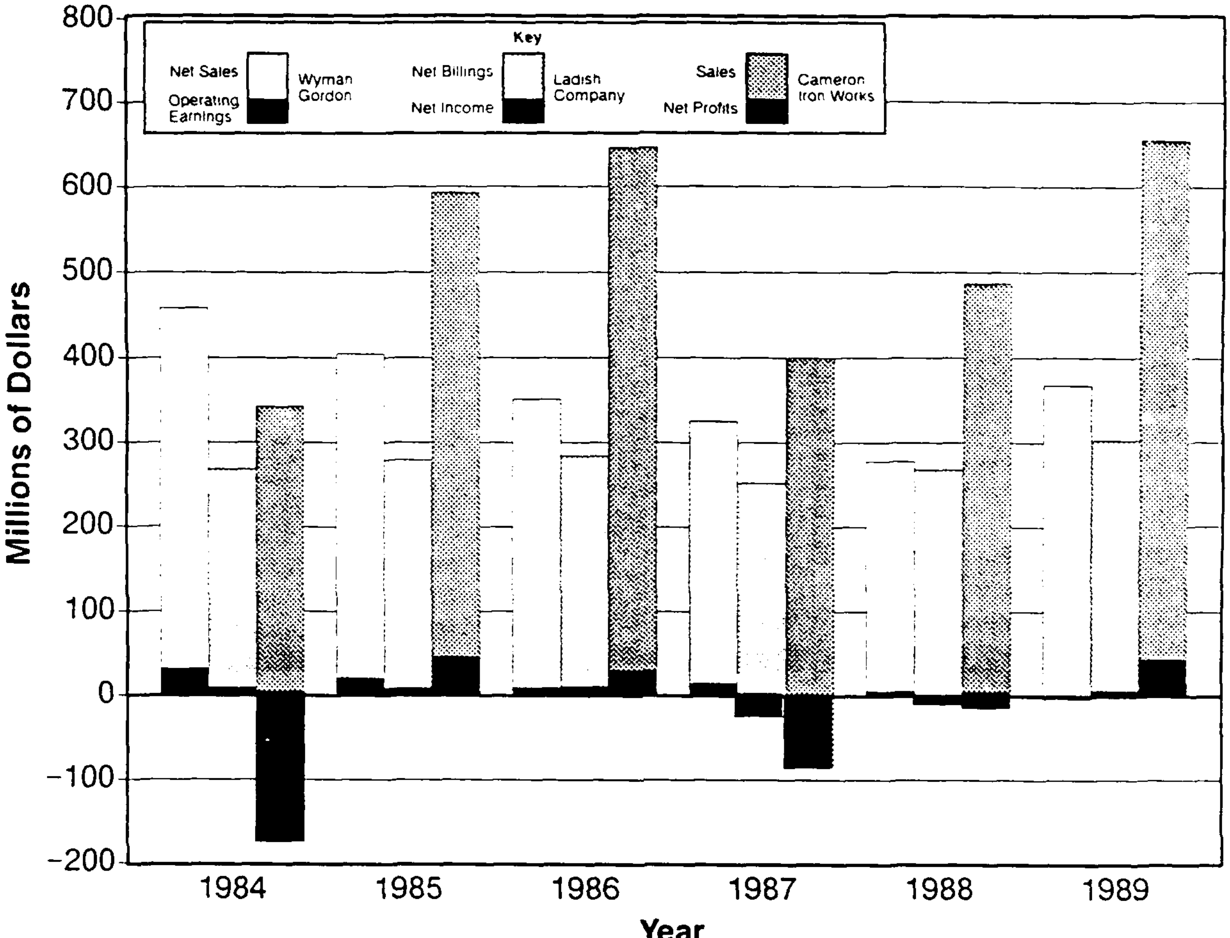
Precision Forgings

DoD's 1987 study of the GTE industry[3] identified more than two dozen companies as critical suppliers of forgings to engine producers. Three of the largest suppliers — Cameron Iron Works, Ladish, and Wyman-Gordon — are examined in this section. The sales and profits of these companies from 1984 through 1989 are presented in Figure 8.

Cameron Iron Works' overall financial strength is linked primarily to the oil drilling business. Despite losses in three of the last six years due to the slump in this business, Cameron has survived, albeit in a weakened financial condition. Approximately one sixth of Cameron's 1989 sales were forgings for use in aircraft engines. These sales constitute half of the sales of Cameron's Forged Products Division. Capital expenditures by this division fell from $11.7 million in 1988 to only $4.7 million in 1989.

Ladish, too, has experienced losses in two of the past six years, but like Cameron, turned a profit in 1989 after two straight years of losses. Since 1985, Ladish has changed ownership twice. Armco sold Ladish to Owens-Corning in 1985, and Owens-Corning sold Ladish to the Ladish Holding Company in 1987. Borrowings for the latter purchase have saddled Ladish with a long-term debt of $200 million, resulting in an annual interest expense of $24 million

[3] ***GTE Production Base Analysis Study: Final Report***, Aerospace Industrial Modernization Office, Air Force Systems Command, February 1987.



Source: Value Line, company annual reports, and 10-K reports.

Figure 8. Sales and Profits of Three Major Suppliers of Precision Forgings for GTEs

(approximately 8 to 9 percent of annual sales). Ladish's new independent status and heavy debt burden clearly leave this company in a weakened financial position to deal with downturns in its markets. Despite its debt burden, Ladish has been able in recent years to make substantial R&D investments with customer assistance. Customers funded $1.9 million of Ladish's $4.1 million R&D bill in 1988. One third of Ladish's forging sales in 1989 were for use in GTEs. Similarly, one third of total sales were for eventual use in Government programs.

Wyman-Gordon's financial position has also weakened in recent years. Sales and profits in 1981 of $610 million and $57 million, respectively, had declined by 1989 to $372 million and a loss of $3 million, respectively. Wyman-Gordon's debt burden doubled in 1989 as a result of the Company's acquisition of an investment casting firm and the formation of a joint venture with Scaled Composites. Nevertheless, long-term debt still equals less than 15 percent of net worth and less than 10 percent of annual sales. This debt could increase substantially, though, if Wyman-Gordon succeeds in its current efforts to acquire Arwood from Interlake Corporation. (See the discussion of Arwood in the investment castings section.)

The financial future of each of these forging companies is dependent, in large part, on the aircraft market and the GTE market, in particular. All three companies should experience a strengthening in their financial positions, as a result of surging sales of commercial transports in the 1990s.

Precision Bearings

Table 2 lists seven precision bearing producers that were identified as critical subcontractors in DoD's 1987 study of the GTE industry. These seven producers have widely different financial capabilities to support development and production of precision bearings for evolving ABP requirements. It is noteworthy that three of the seven have changed ownership since completion of the 1987 study. In each case they were acquired by other bearing producers in an industry-wide trend towards consolidation.

Three of these producers are now subsidiaries of large foreign-owned conglomerates that are among the world leaders in bearing technologies and sales. FAG and SKF have worldwide annual sales estimated at $1.6 billion and $4.1 billion[5] respectively. Bearings comprise a major share of each of these companies' businesses. It is expected that both companies will invest heavily in the future to maintain and strengthen their positions in the world bearing market. Recent evidence in this regard is provided by SKF's purchase of MRC Bearings Inc. from TRW. The 1986 ***Joint Logistics Commanders Bearing Study*** stated that this acquisition would give SKF 32 percent of the superprecision bearing market in the U.S.

Ingersoll-Rand and The Timken Company, two U.S. firms, are comparable to FAG and SKF in terms of annual sales ($3.4 billion and $1.5 billion, respectively, in 1989) and their commitment to bearing manufacturing. Ingersoll-Rand's acquisition of Fafnir Bearing Company from Textron in 1985 made this company the largest producer of bearings in the U.S. market and the fifth largest worldwide.[6]

Table 2. Bearing Producers Identified as Critical Subcontractors in the 1987 GTE Study

Company	Status	1988 Sales* (millions)
Barden Corp.[4]	Publicly Owned	$86
Fafnir Bearing Division	Division of Ingersoll-Rand (Publicly Owned)	$300 (est.)
FAG Bearings Corp.	Subsidiary of FAG Kugelfischer Georg Schaefer KGAA (German Company)	$100 (est.)
New Departure-Hyatt Div.	Non-automotive bearing business sold by General Motors to Ingersoll-Rand	Now part of Fafnir
SKF Bearing Industries	Subsidiary of SKF U.S.A. Inc. (a Subsidiary of the Swedish Company Aktiebologet SKF)	$375 (est.)
Split Ballbearing	Division of MPB Corp. (a subsidiary of the Timken Company)	$60 (est.)
TRW/MRC	Acquired by SKF and now SKF/MRC Bearings Inc.	Now part of SKF

*Estimates of sales are from ***Ward's Business of Directory 1989*** or ***Directory of Corporate Affiliations 1990***.

[4]FAG has made a tender offer for Barden Corporation, and the sale is currently pending.
[5]Source: ***International Directory of Corporate Affiliations***, 1990–91.
[6]Ingersoll-Rand 1985 Annual Report.

Table 3. Financial Data for Ingersoll-Rand, The Timken Company, and Barden Corporation (Millions of Dollars)

	1981	1982	1983	1984	1985	1986	1987	1988	1989
Ingersoll-Rand (I-R)									
Net Sales	3,378	2,775	2,274	2,478	2,637	2,799	2,648	3,021	3,447
Capital Expenditures	150	104	42	56	61	105	85	109	110
R&D (and engineering costs)	149	104	42	55	60	105	95	104	113
Long-Term Debt	565	590	599	441	420	316	313	280	280
I-R Bearings and Components Group									
Sales	1,078	879	830	925	1,020	1,265	1,300	1,471	1,634
Operating Income	135	58	76	124	160	187	161	154	200
Operating Income Percentage of I-R Total	31%	31%	116%	62%	71%	72%	55%	49%	52%
Capital Expenditures	56	43	21	29	35	63	66	69	57
The Timken Company									
Sales	1,427	1014	937	1150	1091	1058	1230	1554	1533
Net Profit	101	(-3)	1	46	(-7)	(-40)	10	66	55
Capital Expenditures	n.a.	n.a.	154	242	195	55	52	79	92
Long Term Debt	26	25	50	90	160	160	159	159	48
The Timken Company's Bearings and Bearings Parts									
Sales	975	732	676	809	775	763	826	1002	1042
Operating Income	n.a.	n.a.	(-24)	44	23	(-37)	47	94	102
Barden Corporation									
Net Sales	74	74	61	65	73	74	78	86	98
Net Earnings	8.1	6.8	3.9	4.6	5.5	3.2	3.7	4.1	5.6
Capital Additions		3	2.2	3.6	6.1	8.1	5.2	7.5	7.7
Long-Term Debt	6.1	5.4	3.3	2.7	1.7	1.1	0.56	—	—

Source: Company annual reports.

More recently, Ingersoll-Rand also acquired the non-automotive bearing business of General Motors' New Departure-Hyatt Division. As Table 3 indicates, Ingersoll-Rand's Bearings and Components Group accounted for 49 percent of the corporation's sales and operating income in 1988. Capital expenditures in the Bearings and Components Group during 1986 through 1988 were more than double the expenditures during the three preceding years; however, corporate-wide R&D investment has declined somewhat in recent years, even though it has remained in the $100 million per year range.

The Timken Company has also bolstered its position in the bearings market through acquisitions in recent years. As Table 3 reveals, sales of bearings and bearings parts constitute the bulk of Timken's business — 68 percent in 1989. Timken's annual R&D budget averaged $35 million over the past three years.

The financial resources of the four multi-billion dollar corporations — FAG, SKF, and Ingersoll-Rand, and The Timken Company — dwarf those of Barden Corporation. Ingersoll Rand's research and development investments alone far exceed Barden's annual revenues. Barden's recent financial history is summarized in Table 3. Barden's sales and profits took a downturn in the early 1980s, but have recovered gradually since. Capital expenditures during the 1986–1989 period averaged more than $7 million per year versus less than $4 million per year during the four prior years. Long-term debt also declined steadily from $6.1 million in 1981 to no reported debt in 1988 and 1989.

Ingersoll-Rand's, Timken's, and Barden's slumping sales and profits in the early 1980s, reflect the industry-wide trends for bearing producers. The 1986 Joint Logistics Commanders (JLC) study reveals that sales and net income before taxes declined from 1981 to 1983 by 20 percent and 85 percent, respectively, in the commodity/commercial bearing sector and by nine percent and 36 percent, respectively, in the superprecision bearing sector. Not surprisingly, capital expenditures by bearing producers also fell during these two years by over 50 percent in the former sector and by nearly 50 percent in the latter. These trends, too, are apparent in Ingersoll-Rand's, Timken's, and Barden's financial numbers. This decline in capital expenditures left the U.S. bearing industry with an aging, out-of-date capital equipment inventory, which has contributed to the decline in domestic companies' competitiveness in the U.S. and world markets. However, recent data points to the cyclical nature of the bearing market. Over the past few years, domestic production volumes and profits have generally increased. Sales across the domestic bearing industry in 1989 were approximately $4.5 billion, investments in equipment, modernization and expansion from 1987–1991 are projected to be $1.5 billion.

4. Summary

The castings, forgings, and bearings industries present a variety of strengths and weaknesses to support advances in ABP technology. Of these three industries, investment castings had the best financial results during the past decade and should benefit most from the strength of the commercial aircraft market in the 1990s. Precision forging companies supporting GTE production struggled financially during the 1980s and are financially weaker today than they were ten years ago. Nevertheless, their financial positions should benefit in the 1990s from the continued upsurge in commercial transport sales. The precision bearing market slumped in the early 1980s but not as badly as the commodity bearing market. The financial troubles in this industry have stimulated a trend towards consolidation and have created today an industry with fewer companies, but companies with a greater commitment to bearing production. A major portion of the U.S. bearing market is controlled by foreign-owned companies, which are world leaders in bearing technology and sales.

The 1980s was a very good decade financially for GTE producers, and these producers are extremely well-positioned financially to support ABP technology requirements in the 1990s. However, the U.S. Government has been the major source of financing for capital expenditures and R&D investments for this industry. The anticipated decline in the Defense budget and in the procurement of GTEs in the 1990s would, therefore, cause a decline in capital expenditures and R&D investments in ABP technology. If investments decrease and industry expenditures remain the same, a long term forecast for the industry in R&D and manufacturing could be a discouraging one.

The decline in DoD's ability to support developmental efforts will be felt especially by the specialty materials industries which have little market other than the GTE producers. The producers of high temperature coatings, superalloys, high temperature titanium alloys and high temperature lubricants are expected to be affected. Sales of these companies are generally insufficient to support the level of investment in R&D currently available as a result of DoD support to the GTE area. In order to maintain its current international competitive strength, the GTE industry will need to find new mechanisms to support the necessary R&D, as well as facility and equipment investments, to supplement the level of support which has historically been available from DoD sources.

COMPOSITE MATERIALS

1. Introduction

Composite materials have provided rapid advances in materials technology. These new materials surpass conventional materials in permitting greater strength, better performance, and lighter weight than has ever before been possible. In contrast to traditional materials, composites combine two or more dissimilar constituents so that the resulting material may be engineered to incorporate specific properties which impart superior performance over conventional material systems (e.g., metals, alloys or unreinforced plastics). They provide significant benefits for weapon systems, often permitting capabilities not attainable without composites. A vast number of composite materials are currently under development or in production, each exhibiting its own unique characteristics. The unique attributes provided by such material systems allow users to tailor these new materials to specific applications that demand performance characteristics that cannot be matched by conventional materials. Thus, advanced composites have ushered in a new materials revolution that will afford great economic rewards to those nations which quickly exploit their benefits.

Advanced composites generally consist of fibrous or particulate reinforcements impregnated in a matrix material. Composites are classified according to their matrix: polymer matrix composites (often called resin matrix), metal matrix composites, ceramic matrix composites, and carbon/carbon composites. This critical technology includes all four classes of composites. It also includes design methods and fabrication processes unique to composites, material production methods for fibers, particulates, etc., the creation and application of coatings that are required for exterior use and for control of mechanical and chemical interactions between fibers and matrices, and the adhesive or fastening systems used to join components made from such materials.

Figure 1 summarizes the composite materials technology challenges identified in the FY90 ***Critical Technologies Plan***, along with applications and the industrial base segments that are important for producing composites.

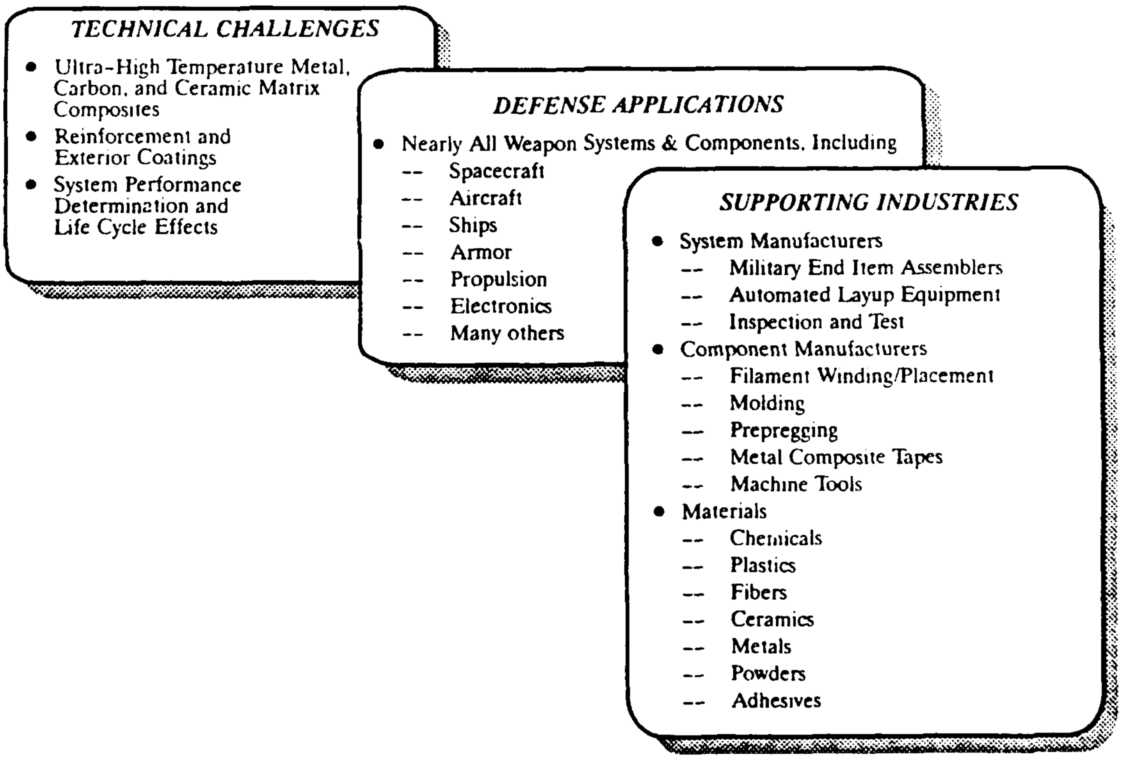


Figure 1. Technical Challenges and Supporting Industries

Advanced composite materials are used in most weapon systems and are viewed as critical enablers of weapon systems and subsystems. Although most often thought of in the context of structural applications, such as aircraft empennages, stabilizers, etc., they are increasingly important for a large number of other applications such as heat sinks and boards for electronics, heat exchangers for a range of power operations equipment and spacecraft, thermal expansion control, nonstructural signature reduction, environmental resistance, and especially resistance to high temperature environments. In FY 1988 alone, DoD committed to purchasing $80-billion worth of weapon systems that integrate advanced composite components.[1] This investment is spread among various existing and developmental weapon systems and subsystems, and represents a necessary investment in the further enhancement and improvement of the nation's defense capabilities and technology base. Transfers of this technology to the commercial sector promise to provide significant improvements in commercial aerospace, automotive and rail transport systems and infrastructure, communications, and biomedical technologies.

Due to their versatility, advanced materials have a significant supporting role in five of the other nineteen critical technologies including Machine Intelligence and Robotics, Signature Control, Air-Breathing Propulsion, Hypervelocity Projectiles, and Superconductivity. In addition, Simulation and Modeling developments are applicable to the design of both composite materials and composites manufacturing facilities. Advances in Machine Intelligence and Robotics technology are important to reduce composites cost and manufacturing time while improving material quality.

The two sectors where composites are used most widely and have the most profound impacts are the aerospace and automotive sectors. In aerospace, composites are being used in spacecraft and space vehicles, military and commercial aircraft, and launch and propulsion systems. Industrial applications, such as in the automotive industry, utilize similar high-performance materials (principally graphite fiber reinforced epoxy matrix composites).

Advanced composites find extensive use in industrial applications, such as machinery, electronics, and sporting goods. With the many commercial and defense applications for this material, the U.S. consumes an estimated 60 percent of the world's use of fiber reinforcements, used to fabricate advanced matrix composites. Asia is estimated to consume about 22 percent and Europe about 18 percent. The estimated allocation by market is about 80 percent for aircraft/aerospace, 15 percent for recreational equipment, and 5 percent for industrial/auto/other.

2. Industry Structure

The composites industry is generally considered to be divided into three distinct segments: materials suppliers (e.g., resin systems, fibers, and prepregs); fabricators (e.g., filament winders, molders, and casters); and assemblers (e.g., aerospace, automotive and sporting goods manufacturers). These divisions are further defined by the family of matrix materials used in the composites system (e.g., metal, ceramic, and polymer). Thus, a materials supplier may focus on ceramic precursors, while another will focus on polymer precursors. Few firms are horizontally integrated, providing products based on multiple precursors. Similarly, few firms are vertically integrated, engaging in the manufacturer of precursor materials, producing components, and assembling components into products. Vertical integration is expected to increase over the course of this decade, stimulated by defense cutbacks and the normal attrition that accompanies such contractions. The vertical integration trend is stimulated both by some overcapacity and by the need of systems producers to increase their work content in the final system.

The distinctions among various industry segments — systems manufacturers, fabricators, materials producers, and equipment producers — is far less clearcut than it is for some other technologies because

[1] ***Advanced Materials by Design***, Office of Technology Assessment, United States Congress, p.25.

composites are normally tailored for the specific application. Therfore, there is substantial interaction among companies specializing in the various areas in order to optimize the total manufacturing process while achieving the properties required by the design.

System manufacturers are the designers and producers of the military end items as well as key subcontractors. In the structures area, system manufacturers purchase materials in various forms from component suppliers or material suppliers and produce most of the final composite structures themselves. In terms of volume usage, military aircraft and helicopters consume the largest percentage of advanced composite materials, and a very high percentage of those materials are fabricated into final parts by the system producers. All producers of military and civilian aircraft and helicopters, including Lockheed, Northrop, Grumman, General Dynamics, Boeing, McDonnell Douglas, Bell, Sikorsky, Beech, Hughes and Rockwell, have substantial composites design and production capabilities, as do the major aerospace subcontractors such as Rohr and LTV.

Additionally, manufacturers of rocket motor cases such as Hercules, Morton Thiokol, Aerojet, Rocketdyne/Rockwell and others have extensive production capabilities. For the most part, these firms manufacture products made from polymer matrix composites using a highly versatile technique called filament winding. This is but one of several techniques used to produce polymer matrix composites.

The U.S. also has strengths in the manufacture of a variety of composites fabrication and inspection equipment. For example, the U.S. currently has extensive capabilities for the production of processing equipment used for the manufacture of polymer matrix composite structures. Firms such as Cincinnati Milacron, Alcoa/Goldsworthy, and Ingersoll Composites supply a variety of equipment such as tape layers, filament winders, plycutters, and pultrusion machines. Several additional firms such as McLean Anderson, EDO, and Dura-Wound also supply filament winding machines. Gerber Garment Technology is a major supplier of broadgoods cutting systems, and numerous other firms supply a variety of other types of cutters using lasers, waterjets, or mechanical cutting. Ultrasonic inspection system suppliers include McDonnell Douglas and Custom Machine Inc., although Japanese suppliers hold a large and growing market share. Autoclaves are supplied by McGill, MELCO Steel, Tenney Engineering, Thermal Equipment, and others. Other important domestically produced equipment includes plasma sprayers, manual and computerized x-ray machines, and neutron radiographic and computer axial tomographic (CATscan) equipment. A particular area of weakness is the industry's dependence on foreign sources for some types of equipment, including specialized heat treating furnaces, powder making equipment, computer controlled hot rolling mills, hot isostatic presses, robots, and three dimensional weaving machines. Suppliers of composites processing equipment will be especially hurt by a downturn in military spending, which has represented the major source of their sales.

Component producers include both producers of precursor materials used by the system producers and manufacturers of finished composite components. Starting material forms include dry fibers and tape and broadgoods prepreg, in the case of polymer matrix composites, and metal matrix composite tapes and semifinished shapes. The term prepreg refers to fibers or filaments pre-impregnated with the matrix resin, partially cured to a state suitable for layup into the final composite component. Tape products are supplied in the form of rolls of various widths, with the most common being 1, 3, 6 and 12 inch. Broadgoods are cloth-like thin sheets of material in rolls, with widths normally up to 60 inches, although wider products can be supplied.

Producers of metal and composite honeycomb also fall into the category of component suppliers. Honeycomb construction is extremely light for its stiffness, is widely used in secondary, lightly loaded airframe structures, and is highly important in signature reduction.

Carbon/carbon composites are supplied by both component suppliers and by system producers. Carbon/carbon is also an emerging material whose industrial base viability is difficult to identify due to limited volume. Carbon/carbon composites have been used in short duration, very high temperature applications such as rocket nozzle inserts and re-entry vehicle nose tips. The largest single market to date is aircraft brakes. Many companies have capabilities in carbon/carbon, both for development and for production. Demand is expected to increase substantially as R&D successes lead to the wider use of carbon/carbon composites components in turbine engines.

Other segments of the industrial base are important for composites production. The chemicals and plastics industries supply the starting chemicals and often the resins to support the component producers. This industry is also the source for most of the R&D on advanced polymer resin matrix materials. Different fibers are supplied by a range of different types of companies. The aramid fiber, Kevlar, is currently supplied only by DuPont. Graphite, boron, and silicon carbide (SiC) fibers are supplied by companies whose primary business is in other industrial sectors (e.g., Textron, ICI, BASF, etc.). Other products supplied to the component suppliers include individual fibers, filaments, whiskers, tows (bundles of filaments with no resin), and fabrics.

In addition to the chemical and materials industry, the software and computer industry are important contributors to the advanced materials industry. Because of the requirements to tailor composite designs, computer-aided design (CAD) and related software and computing capabilities are used to run the sophisticated calculations that are needed to design and analyze components for specific service environments. Furthermore, assembly tolerances are extremely important in composites, and the capabilities of CAD to quickly and accurately identify areas of excessive interference or gap are extremely valuable.

Tool makers constitute another important segment with relation to composites fabrication. Automated computer numerically controlled (CNC) tape layers, molding equipment, and ply cutters are produced by the machine tool industry. Other equipment requirements include, for example, powder making equipment, plasma sprayers, computer controlled hot rolling mills for foils, hot isostatic presses, robots, autoclaves, high-temperature controlled atmosphere retorts, three-dimensional weaving machines, pultrusion and filament winding machines. High-sensitivity nondestructive inspection equipment is also required. A variety of manual and computerized X-ray and ultrasonic inspection machines are in routine use.

3. Condition of the Industrial Base

DoD production and R&D programs represent the majority of the advanced composite materials market. Although currently strong and healthy, the materials suppliers and composites fabricators are expected to be seriously impacted by reductions in the size of the DoD market caused by the anticipated program cancellations and stretch-outs (V-22, B-2, C-17, A-12, ATF, ATA, etc.). Therefore, the composites industry is bracing itself for a significant contraction, and is seeking relief on several fronts in order to soften the anticipated effects of this market reduction. Among the strategies being employed are: 1) legislative efforts aimed at modifying the U.S. tax code to allow retroactive R&D credits; 2) increasing composite materials usage in commercial aircraft and domestic automobiles; and 3) increasing the market share for composite materials in sporting goods and biomedical applications. However, such efforts are not expected to offset reduced defense expenditures, at least in the near term.

In the future, the major subcontractor portion of the system producer base is expected to be one of the first to be impacted from cutbacks in defense system acquisition, and further postponements in system acquisition are projected to cause some shrinkage in the prime contractor base as well. Concerns about the high costs of composites may also slow the development of demand for the more technologically advanced materials. Since the prime contractor portion of the industry is well-equipped to produce composite structures, those which remain can be expected to retain as much production of composite structures in-house as possible. Competition for any remaining subcontracted composites production will intensify. While this consolidation of the industry takes place, little business is expected to be available for the current structures subcontractors. Commercial demand is unlikely to make up for declining DoD business, since commercial aircraft demand for composite structures is still relatively small and the commercial sector has traditionally shown more concern about minimizing the cost and technical risk of their product. However, commercial consumption of advanced composites in the industrial/automotive industry has been projected to grow substantially and may in a healthy economy grow to exceed aircraft/aerospace use in less than 25 years.

a. Sales

The current value of components produced from advanced composites in the U.S. is less than $2 billion per year. Sales projections through the year 2000 are highly variable, ranging from $5 billion to $20 billion per year. According to the Suppliers of Advanced Composite Materials Association (SACMA) and the United States Advanced Ceramics Association (USACA), sales in the U.S. could approach $10 billion by the year 2000 if the military/space markets stabilize quickly and commercial markets grow as expected.

To date, advanced materials have penetrated only 10–20 percent of the applications for which they are technically appropriate. The aerospace sector is the largest single source of demand for advanced composites. Fabricated composite aircraft parts (used worldwide) are expected to grow from roughly $1 billion in 1986 to $3 billion in 1995.[2]

In addition to the aerospace market, the U.S. ordnance market is a reliable consumer of advanced composites. Although this market today is small — roughly $20 million per year for fabricated parts — it is expected to grow rapidly, reaching $250 to $500 million by 1995 and $1 billion by 2000. The leisure industry, a large market whose applications include sporting goods, has experienced a production shift offshore because of lower fabrication costs. In commercial applications, as well as in defense, foreign involvement in the market is growing at a steady pace, sparking some concern over the volume of sales foreign companies enjoy relative to their U.S. competitors.

The U.S. has strong domestic capabilities in most areas of advanced composites, resulting primarily from a high level of spending in recent years. However, the U.S. is dependent on foreign sources in some areas such as high-performance ceramic fibers. The Japanese intention to enter the commercial aircraft and engine market will contribute to the expected shakeout in advanced materials. Japanese companies are rapidly relearning the aircraft business, building on programs such as FSX and commercial aircraft subcontracting. Not surprisingly, the Japanese are placing heavy emphasis on composites. A number of Japanese firms already produce PAN-based and pitch-based carbon fibers. PAN producers include Asahi Chemical, Mitsubishi Rayon, Toho Rayon, and Toray Industries. Producers of pitch-based fiber include Kureha Chemical, Nippon Oil, Nippon Steel, Osaka Gas, Petoca, Showa Shell Sekiyo, and Tonen. Japan produced about 8.4 million pounds of PAN-and pitch-based carbon fiber in 1989 and consumed less than one-half of its own output. As the Japanese seek to expand their market share, the structures subcontracting business is a logical entry point, which will put them in direct competition with U.S. structures subcontractors.

Other concerns with regard to foreign competition are in the areas of ceramics and powders. A strong ceramics industry is considered vital to the successful development of ceramic composites, low-cost, high-quality processing methods for them, and improved ceramic fibers and interfacial coatings. This industry has importance to other critical technology areas as well, including Air-Breathing Propulsion and Semiconductor Materials and Microelectronic Circuits. The high-technology portion of the domestic ceramics industry is rapidly falling behind the international competition, notably the French and the Japanese, where the U.S. has been estimated to be as much as four years behind. Other areas of potential concern include foreign investment in the titanium industry and the lack of a domestic capability for smelting aluminum.

b. Investment

The U.S. has invested heavily in composite materials over the past 25 years, and this investment has paid off in steadily increasing capabilities and rapid advances in the state-of-the-art. Federal Government and

[2] "Aerospace Market for Composites Poised to Take Off," Peter Hilton and Peter W. Kopf of Arthur D. Little, ***Research and Development***, February 1987, p.97.

industry investments alike have been concentrated in the development of the materials themselves. These investments have included development of matrix materials, fibers, and analysis methods. Universities and research centers are strongly concentrating on understanding the fundamental physics and chemistry of new classes of composites, including molecular composites, and are developing new materials based on that understanding. While investment in the development of new materials enjoys continued support, much of the investment capital for such endeavors now comes from abroad. Since 1985, the number of U.S.-based leaders in the resin and fiber industry segment has been cut in half. For the most part, these firms have been absorbed by foreign conglomerates (e.g., BASF, ICI, Rhone Poulenc, Hoechst, etc.).

Investment in the development of manufacturing processes for composite materials has been less impressive resulting in higher production costs than metal alloys. Despite the success of the R&D performed on materials, this high cost factor has slowed the incorporation of composites into production and delayed the introduction of new materials into military and commercial systems. Extreme performance requirements for military systems and spacecraft have led to the widespread adoption of composite materials despite these high costs. Thus, the defense industry leads the commercial sector in the production of composite components and in understanding the manufacturing processing requirements. Automated methods have been devised for cutting and layup of polymeric matrix composites, and computerized inspection equipment is available. Unfortunately, these systems are currently used only in the very latest military aircraft programs, and most composites production is still performed manually.

All military services are supporting Manufacturing Technology (ManTech) programs for composite materials. Air Force ManTech is pursuing a major nonmetals program in advanced composite processing, whereby artificial intelligence and real-time control software is used to cure composite structures. Also, a Composites Assembly Production Integration program, demonstrating the benefits of automating composite prepreg cutting and layup is being implemented. Similarly, the Navy's Center for Excellence for Composites Manufacturing Technology (CECMT) provides a national resource for the development and dissemination of composite technology with a focus on technology transfer to industry. The Army's contribution has been primarily focused on the production of composite rotor blades for Army helicopters and of composite light armor for troops and light transport vehicles. Recently, the Army has begun testing advanced ceramic and metal matrix armor systems for tracked vehicles including the M1-A2 and Bradley Fighting Vehicle. The Defense Production Act of 1950 (DPA) Title III program is sponsoring several purchase guarantees to provide a market to expand domestic production capability.

Private industry has supported the bulk of the efforts to develop low-cost production methods for fibers and prepreg. Most industry observers hold the opinion that much could be done to reduce the cost of these materials and forms through a substantial investment in manufacturing process and equipment development, but the current sales volume is apparently not sufficient to justify the levels of investment required by the industry.

Metal matrix and carbon/carbon composites are even more expensive per pound than polymer matrix composites. Again, there has been little investment in manufacturing processes, methods, equipment and facilities development relative to the amount invested in the materials themselves. In recognition of the need, the National Aerospace Plane (NASP) Materials Consortium is investing more than $200 million in materials — mostly metal matrix and carbon/carbon composites — and is giving priority emphasis to manufacturing process development. Nevertheless, industry must make major facility and equipment investments to reduce the cost of these materials enough to justify their wider use.

International competition from Europe and Japan is growing although the U.S. remains the world leader. Because the state of the art is advancing rapidly in this key area, the U.S. could lose its leadership position rapidly if the pace of R&D investments were to slacken.

c. Joint Ventures, Mergers and Acquisitions

The primary joint venture in the composites area is the NASP Materials Consortium mentioned above. Sponsored by the NASP program with significant industry investment, this venture not only includes the airframe and propulsion system competitors, but also a host of supplier and specialty fabricator companies. Development areas are divided among the participants, and all data is openly shared among participants. This consortium has made dramatic strides in processing methods for carbon/carbon and metal (primarily titanium and titanium aluminide) matrix composites. While major improvements in product form sizes, quality, reproducibility and cost are required in order to produce the experimental NASP vehicle (X-30), the developments achieved in this consortium could find their way into more conventional airframes, spacecraft and launch vehicles, and air breathing and rocket propulsion systems.

The most notable domestic acquisition in the composites area has been that of the AVCO specialty materials and aerostructures operations by Textron. The specialty materials operation has been a major supplier of graphite and boron fiber for 25 years and has continued to be as active since the acquisition. The aerostructures operation is a major subcontractor historically specializing in the production of wing structures for large military and civilian aircraft. A robust program to develop their capability to produce large polymer matrix composite structures has dimished markedly since the acquisition.

A number of foreign acquisitions were mentioned in section 3b of this chapter. Perhaps the most notable of these is the acquisition of Celanese by the huge German chemical conglomerate BASF. Since the acquisition, BASF has invested substantially in both development (with a particularly active program in thermoplastic matrix composites) and production facilities in the U.S., making the Celanese operations more competitive than before the acquisition.

4. Analysis of Infrastructure Segments

This section examines four segments of the composites market — polymeric matrix, metal matrix, carbon/carbon, and ceramic matrix, with primary focus in the first two areas. Figure 2 highlights current international market activity in these four areas.

a. Analysis of Polymeric Matrix Composites Segment.

The following discussion concentrates on structural applications of polymeric matrix composites (PMC), also called resin matrix composites, which constitute the majority of composites used today. PMCs are the most mature of the composites technologies, having been used in fighter aircraft structures and sporting goods applications since the early 1970s. Use of these materials has increased to the point where nearly 50 percent of the structures of some new U.S. fighter aircraft and helicopters will be made of PMCs. Military applications rely on several different epoxy formulations as the primary matrix material and several different glass and graphite fibers as reinforcements. Components made from PMC offer outstanding stiffness to weight ratios, as well as superior fatigue resistance, corrosion resistance, and vibration damping. Their primary drawbacks are their lack of ductility and temperature limitations.

Molded PMCs normally incorporate chopped or continuous fibers. The industrial base in this area could grow significantly if demand warrants. In particular, there is a substantial domestic industrial base of plastic molding expertise, and the processing changes necessary to incorporate chopped fibers are relatively small. Plastics molding companies can be expected to move into the composites market if that market becomes sufficiently large to justify the investment.

Whatever the manufacturing method used, post-cure inspection of composites represents a major bottleneck because it is time consuming and occurs after the component is fully completed. Each component must be thoroughly inspected for voids, porosity, fiber uniformity and integrity, resin-rich or resin-lean areas, and foreign substances (such as moisture and unremoved scrim), as well as for dimensional accuracy. Ultrasonic and X-ray inspection facilities to perform these tests are expensive and require highly skilled operators even for fully computerized equipment, which is increasingly being installed.

Depending on the particular manufacturing step and contractor involved, the operations performed during composites production can be manual or automated. Even where automated techniques are available, low production volumes dictate that the equipment must be capable of laying up many different parts. Development of processes that can efficiently satisfy these requirements has proven to be extremely difficult and has also been hampered by the level of available resources within the machine tool industry. As a result, airframe companies have undertaken some of the development effort themselves.

Another disincentive to modernization is that the equipment necessary to implement automated approaches to composites manufacturing, including tape laying and filament winding, can be extremely expensive. Large autoclaves are also very expensive, and efforts to minimize the per-part cost of autoclaves involve keeping them in nearly constant, three-shift operation. This requirement, coupled with the out-of-the-freezer shelf life requirements of epoxy composites and the time variability inherent in manual operations, makes efficient scheduling of composites factories extremely difficult.

The tooling on which composite parts are laid up and cured is an integral part of composites processing. Tooling must satisfy very demanding requirements and, therefore, is costly, difficult to modify, and time-consuming to produce. An inventory of hundreds or thousands of such tools of various sizes is required for a heavily composite structure. Traditional steel tooling is most often subcontracted to small and medium-sized companies by the system producers. Tooling is increasingly made from composites, particularly for large parts, and composite tooling is normally made by the system producer.

Decreasing the cost of composite components is critical to increasing the market for polymer matrix composites. The current high interest in thermoplastic resin matrix materials stems in large measure from their potential for significant manufacturing cost

INTERNATIONAL ACTIVITY IN TYPES OF COMPOSITES

Resin Matrx Composites (Polymeric Matrix Composites)	• The U.S. currently leads in this technology; • Increased European and Japanese involvement in materials and hardware; Japanese joint venture of Sumitomo and Enka challenges DuPont aramid fiber market; • U.S. involved in international forums on composites technology such as Versailles Advanced Materials and Standards project with France, Italy, W. Germany, U.K., and Japan, on research for resin matrix composites.
Metal Matrix Composites	• International activity is small compared to domestic; foreign industry trends towards commercial while domestic focus is on high-technology; • U.S. maintains lead in high modulus graphite fiber MMC; • U.K. and Japan explore MMC for auto engine applications; • Japan hopes to obtain ceramic fiber and whisker reinforcements markets
Carbon/Carbon Composites	• Large international market; • U.S. leads in structural c/c and in oxidation protection; • France leads in c/c structure and brakes; • U.S.S.R. interested in U.S. c/c work
Ceramic Matrix Composites	• Large international activity in CMC; • Japan and Europe exploring CMC for propulsion systems, heat exchangers and aerospace structures; • Technical grade ceramic powders and fibrous reinforcements are mainly supplied from Japan and Europe

Source: Aerospace Industries Association

Figure 2. International Activity in Advanced Composites

reductions. However, extensive, sustained national investment in processing R&D for reduced cost, even if properties are somewhat reduced, is regarded as necessary to accomplishing the significant cost reductions. Low cost, high speed processes such as molding and stamping, which are facilitated by thermoplastics, are high interest areas. Such processes have the potential to reduce costs and processing times to the extent required for substantial commitments to be made by the automotive industry.

The total number of processing steps required and the number of different elements in the industrial base make low component cost and production time extremely difficult to achieve. Traditional efforts to reduce total costs by focusing on improvements in individual processing steps have had positive effects but have not provided major cost reductions. Prepreg costs are in the range of $60 per pound, essentially an order of magnitude more than aluminum plate. Additional costs due to the individual processing steps, tooling, and inspection combine to make composite components very expensive. In order to make substantial improvements in overall total cost, each step in the process as well as the process as a whole must be considered — component design, resin formulation, fiber production, prepregging (in the case of tape or broadgoods), fabrication, inspection and assembly.

b. Analysis of Metal Matrix Composites Segment

Metal matrix composites (MMCs) are a family of metals reinforced by platelet, whisker, or fiber reinforcements that impart specific characteristics which enhance the performance of the new metal composite. These materials are slated to be incorporated in many future weapon systems for each branch of the armed services, leading to increased performance, reliability, and availability. Currently, metal matrix composites are to be incorporated into the A-12, the ATF, advanced armor systems, NASP, Boost Surveillance and Tracking System (BSTS), Space Surveillance and Tracking System (SSTS), Integrated High-Performance Turbine Technology (IHPTET) program, and microwave and millimeter wave circuitry (MMIC).[3]

The MMC industry is generally thought of in terms of three closely allied segments: metal suppliers; platelet, whisker, and fiber suppliers; and process/fabricators. Each is important to our capability to develop and produce products for defense, and the failure of one would in some instances severely affect the others. The material suppliers may be further subdivided into two distinct groups: (1) metal and ceramic materials suppliers and (2) inorganic chemical suppliers. The former supplies metal ingots and/or pure metal powders (e.g., boron, titanium, zirconium, aluminum, their oxides and alloys) and metal and ceramic platelets and whiskers (e.g., silicon carbide and nitride, etc.). Inorganic chemical suppliers generally supply fiber (and in some cases whisker) reinforcements (e.g., carbon fibers).

While possessing very attractive properties, MMC's are currently expensive, and with the exception of aircraft propulsion, little commercial demand can be expected unless order of magnitude cost reductions can be achieved. Sustained DoD funding for process R&D to reduce manufacturing costs, of the type and scope being pursued under NASP, is necessary to achieve such reductions. There is no other source of government funding, and the industry is dominated by small companies and small subsidiaries of domestic or foreign conglomerates.

Even if costs are driven down through process R&D, major investments in facilities and equipment will be required to develop competitive sources and production capacity.[4] To achieve these goals, the following hurdles must be overcome: 1) development of an adequate production base and 2) material specifications/industry standards.[5]

With the downturn in defense expenditures leading to program cancellations and stretch-outs, the industry is expected to shrink. Though industry experts predict a major restructuring of the industry within the next two

[3]*Assessment of Metal Matrix Composites Technology*, DoD Metal Matrix Composites Information Analysis Center (MMCIAC), Report No. 000719, April 1990, p. 11.
[4]MMCIAC Report No. 000719, pp. 8-9.
[5]MMCIAC Report No. 000719, p. 11.

years, it remains to be seen how many of the current independent U.S. firms will survive. Foreign interest and ownership in MMC firms is high, as is evidenced by the following examples:

Market projections for metal matrix composites vary widely. A 1989 market forecast prepared by the Kline & Company suggests that metal matrix composites will not play a significant role in the current advanced composite markets until 1995 or beyond. Technomics Consultants, on the other hand, forecast that non-military U.S. consumption of MMCs will reach $100 million by 1994, and worldwide commercial uses will reach $2 billion per year.[6] According to the U.S. Bureau of Mines, by 1995, the total U.S. market for MMCs could approach $775 million, while the total world market could be close to $1 billion.[7] Meanwhile, the DoD Metal Matrix Composites Information Analysis Center (MMCIAC) projects that the industry will achieve $100 million in aerospace sales by the year 2000 and $1.5 billion by 2010.

U.S. COMPANY	FOREIGN OWNER
ACMC	Tateho Chemical
Carborundum	British Petroleum
Dural	Alcan Aluminum
DWA Composites	British Petroleum
Thermal Ceramics	Morgan Crucible (UK)

As with sales data, consistent investment data are difficult to obtain. Since 1983, investment in metal matrix composites has risen dramatically. For example, Lanxide Corporation, which was formed in 1983, has received $280 million in investment capital as of June 30, 1990.[8] Overall, approximately $554 million was spent during this period to perfect materials and process technology. In contrast, little money has been spent on large-scale production facilities, with the exception automotive applications. For example, in May of 1990 Alcan Aluminum Corporation opened a 25-million lb/yr plant in Jonquiere, Canada to support automotive applications of MMCs at a cost of $65 million.

The MMCIAC conducted a study earlier in 1990 on the state of the industry and concluded that:

> ". . .these investments in MMC technology have brought MMCs to approximately the stage of development that graphite/epoxy was 15 years ago. An infrastructure exists and applications are emerging from most of the investments. . . . The introduction of MMCs into jet engines on commercial transports, particularly supersonic transports, account for most of the 15-fold increase between 2000 and 2010. Past investments give the U.S. a good opportunity to capture a large share of this market."

This report goes on to say:

> "Probably the most important result of this investment is the creation and maturing of a worldwide mentality that recognizes the viability of MMCs as a new structural, thermal, and/or functional class of materials that will substantially advance the capabilities of both military and commercial products."

With regard to improving U.S. military capabilities, the report noted that the MMC investment has not had a major impact on current military capabilities, but it could in the future.

However, these positive projections must be considered with some skepticism when considering projected defense R&D and procurement cutbacks. Top industry experts concede industry is in the middle of a shake out that is not nearly over: "The defense cuts won't hit materials companies until 1991 or 1992 . . . and it's going to get worse before it gets better."[9] To offset these cuts, many industry executives are looking to commercial aircraft, spacecraft, and industrial power generation.

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[6]*Advanced Materials by Design*, U.S. Congress, Office of Technology Assessment, OTA-E-3351, p. 115.

[7]*The New Materials Society: Challenges and Opportunities*, Volume 1, p. 216.

[8]"Strategies," *Performance Materials*, June 25, 1990, p. 9.

[9]"Strategies," *Performance Materials*, June 11, 1990, pp. 7-8.

5. Summary

The composites industry plays a vital role in securing the health and growth of many of the critical industries identified in this report. The unique properties of composite materials make them valuable replacements for traditional metals. Composites are essential to the performance of many current systems, and continued performance advances in future systems will, if anything, depend even more heavily on continuing advances in composite materials. Although the U.S. is currently the world leader, other nations are pursuing advanced materials aggressively and could quickly surpass U.S. industry, especially in lower cost areas, if the pace of U.S. composites product and process R&D slackens.

Defense production and DoD-sponsored R&D have been the dominant influence in composite materials technology since its inception. Significant reductions in the DoD market can be expected to have a corresponding effect on the domestic polymeric matrix composites industry, and to have a massive effect on the fledgling metal matrix industry. The commercial market for composites is not expected to expand significantly, at least in the near term, without major reductions in the cost and manufacturing process improvements of composite components. Achieving such reductions will be a difficult challenge for the industry and government.

MACHINE INTELLIGENCE AND ROBOTICS

1. Introduction

Aggressive development and application of machine intelligence and robotics technologies are needed for the U.S. to remain competitive on the battlefield as well as in manufacturing. The potential uses of Machine Intelligence/Robotics are extremely broad. In fact, the Navy terms it a "generic" technology because of its vast number of potential applications. It is very much a multi-use technology area, with equally strong benefits accruing from military, commercial, and space applications.

The term "machine intelligence/robotics" extends to a broad range of diverse technologies. For example, it includes controllers that impart "intelligence" to advanced machine tools, industrial robots that perform relatively simple and repetitive tasks, and sophisticated robotic devices that operate independently in space or undersea environments. Similarly, software systems extend from straightforward programs that run industrial machinery to expert systems, knowledge processing, and other evolving forms of artificial intelligence.

Machine intelligence is defined as the capability of computer-based systems to mimic or augment human intelligence. Machine intelligence can also be thought of as the execution of artificial intelligence (AI) software through a computer or computer guided machine. Machines that utilize AI possess the "human" characteristics of knowledge, understanding, perception, reasoning, learning, planning, reaction, and problem solving. Expert systems are also related to machine intelligence in that they provide "advice" and problem solving skill in specialized and well constrained knowledge areas as a human expert would. They are routinely used in a number of commercial applications involving troubleshooting, product evaluation and financial analysis and are beginning to find application in operations throughout the DoD.

An intelligent machine, one that can sense and interpret its environment and then perform successfully, combines the activities of perception, cognition, and action along with appropriate man-machine or machine-machine interfaces. To be useful, these activities must also be accomplished with acceptable speed and cost. Machine intelligence can be applied to many military and commercial requirements, two of which are robotic devices and machine tools that are controlled by computers, and which are discussed in later sections of this chapter. The key components of machine intelligence are depicted in Figure 1.

A summary of the technology challenges from the FY90 ***Critical Technologies Plan*** is shown in Figure 2, along with defense

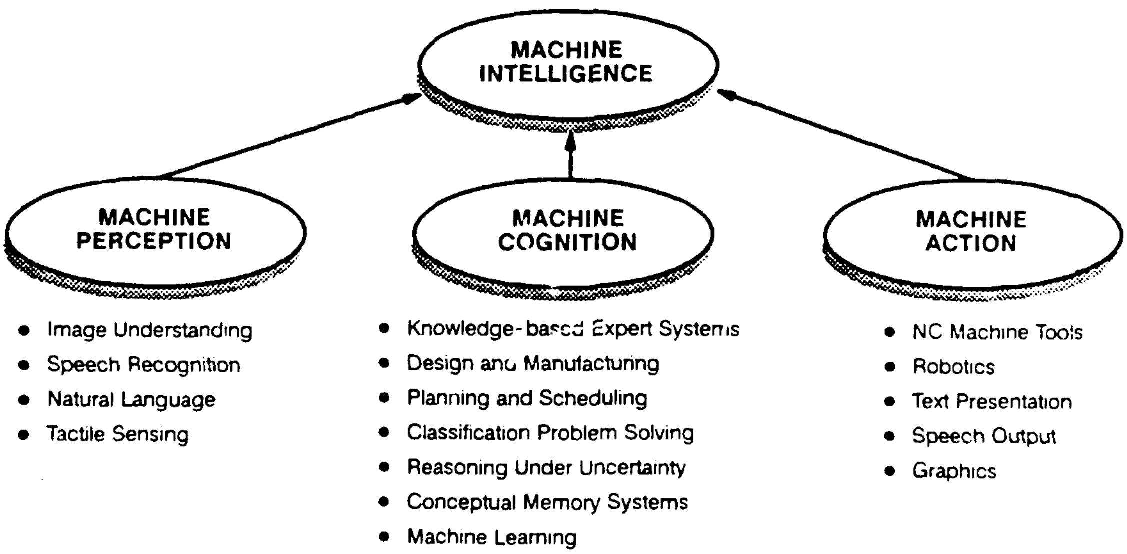


Figure 1. Key Components of Machine Intelligence

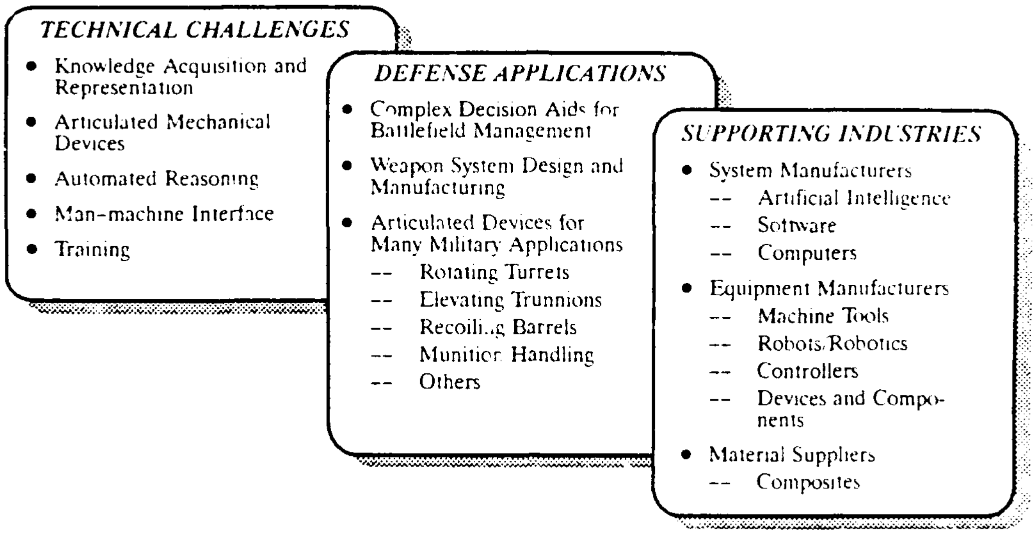


Figure 2. Technical Challenges and Supporting Industries

applications and supporting industries. In addition, other critical technologies support advancements in machine intelligence. These include Semiconductor Materials and Microelectronic Circuits, Software Producibility, Parallel Computer Architectures, Data Fusion, Photonics, Simulation and Modeling, Passive Sensors, Signal Processing, and Composite Materials.

2. Industry Structure

The industrial base that supports machine intelligence is extremely broad. Weapon systems applications for this technology will be developed, in most cases, by the defense prime contractors and major subcontractors. However, these applications will rely on existence of a strong commercial base of capability, experience, and products. The natural progression of capability is from simple, tightly-structured applications to complex, totally unstructured applications. The technology will progress incrementally, paced by solutions to the technology challenges that arise and by improvements in computing capability.

The industry structure that supports defense primes and major subcontractors in the design and manufacturing of military system applications of these technologies is as disparate as the technologies themselves. For example, the industry structure for AI R&D and product development is in itself very broad, ranging from the largest computer and software houses to individual entrepreneurs working alone. In total, this industry is robust, creative and fast-moving. Since many of the potential applications of AI are just now emerging from basic research in universities, there are many small start-up companies closely related to the significant university programs. Some applications of AI require specialized computers which are produced by relatively small companies, while others require large mainframes or even supercomputers.

Other aspects of AI, such as speech recognition and some expert systems, comprise growing commercial product lines. The relationship between commercial and military applications is indirect, and applications to military systems tend to be created by the defense primes and subcontractors.

The equipment industry sectors are distinctly different from the AI community, and the relationship between the two is somewhat tenuous. Competition in the machine tool industry is highly intense. Despite the large number of machine tool companies which have gone out of business during the decade of the 1980s, the industry still consists of primarily small and medium-sized companies that have little financial or personnel resources with which to conduct R&D in new manufacturing processes or new products.

The robotics portion of the equipment industry is dominated by foreign suppliers. The domestic production base includes a combination of a few machine tool companies, companies whose only equipment product is robots, and joint ventures between U.S. and foreign firms. Other important industry sectors supply both the machine tool and robotics producers with devices and components, incuding precision actuators, bearings, small motors, hydraulic systems and components, and many other necessary devices fall into this category.

This chapter will focus on AI, robotics, and CNC machine tools and machine controls. The organization of the chapter differs from others in this report because the diversity of the supporting industrial base prevents a generalized assessment of industry condition. Rather, the condition of the key industry segments will be discussed individually. The assessments focus primarily on manufacturing applications which provide very difficult challenges for these technologies. Even though most manufacturing environments are well-structured, the complexity of the application is often more than today's machine intelligence and robotics capability can successfully manage. However, these applications provide a large potential market that will provide the financial underpinnings for a strong industrial base, while simultaneously moving the technology closer to the military environments, which are very much more complex and unstructured.

3. Condition of the Industrial Base

a. Robotics

One of the most promising areas of machine intelligence is the field of robotics. In some cases, robotics and machine intelligence, when coupled with advances in compact, high performance computers, can obviate the need for human presence in dangerous environments. In other cases, enhancing the man-machine link will result in improved weapon system performance.

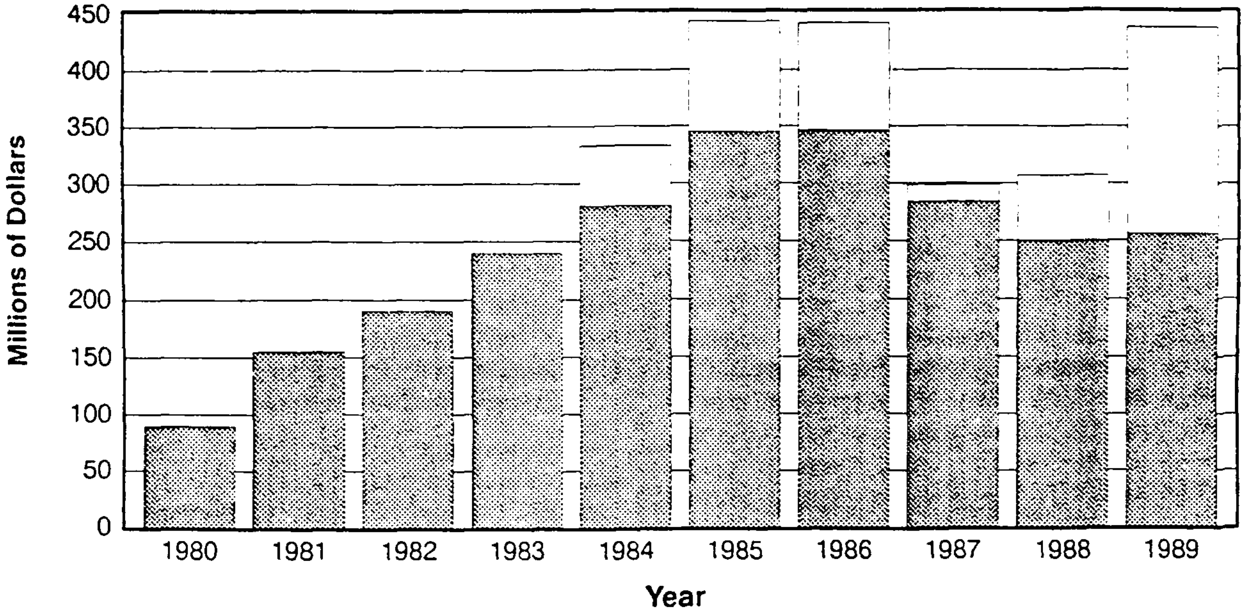
In general, the state-of-the-art of robotics is limited by the processing speed and level of intelligence resident in the systems that plan and control the machine actions. This is particularly true with vision systems that are tied to robot operations. The time required to scan an area, digitize the view, process the data, and then act upon the data is too long in many cases for practical application.

Most of today's military and commercial robotic systems operate in a deterministic mode, in which all actions are pre-programmed, including the actions that will be taken in response to specific sensory input. They require a very structured environment where the deterministic approach can be used efficiently and effectively. The future requirement is for robots with sufficient machine intelligence and speed to operate satisfactorily in nonstructured or undeterminable environments.

Since a high percentage of robot hardware is procured offshore and assembled in the U.S., domestic suppliers tend to concentrate their activity on software development and systems engineering. Both of these activities are critical to technology advances. They are also very difficult to summarize in terms of industrial capabilities, because the capabilities are diffused throughout the industrial base.

As noted above, the U.S. role as a supplier of leading-edge robotic systems has declined in recent years, despite the early success of domestic producers. During the early 1980s, shipments of U.S.-made robots increased rapidly as the market for these machines began to develop. Total sales of less than $100 million in 1980 were dominated by two firms — Cincinnati Milacron and Unimation — that equally shared 76 percent of the market. The next three companies in sales volume shared 18.2 percent of the market. One of these companies was a foreign manufacturer — ASEA. While the U.S. firms offered hydraulic systems, ASEA offered an electric drive system that was to set the trend.. The balance of 5.8 percent was shared by a hodgepodge of small venture start-ups, large expectant users of robots, and joint ventures between U.S. companies and foreign machine tool builders. By 1982, the situation had changed markedly. Cincinnati Milacron and Unimation had dropped to a 59 percent share of the market and the "others" share had increased to 26 percent. Total sales volume had almost doubled to $190 million from 1980 to 1982 and increased by approximately 25 percent a year through 1985.

By 1986, the market began to level out and significant drops occurred in both 1987 and 1988. (See Figure 3.) A turnaround in robot



NOTE: The higher figures are those reported by the Robotic Industries Association and include imports.

Source: Prudential-Bache Securities, "IM Newsletter" for years 1980 - 1983 and U.S. Bureau of the Census, "Current Industrial Reports: Robots (Shipments)," annually, for years 1984 - 1988. The Prudential-Bache estimates are substantially higher than the Census numbers from 1984 on.

Figure 3. Shipments of Complete Robots, Robot Accessories, and Components

consumption began in 1989 and the improvement was holding in the first quarter of 1990. However, domestic output remained relatively flat. The shaded areas in Figure 3 describe the domestic production as reported by the Bureau of the Census; sources in the industry note that this figure may be overstated since much of the content of so-called domestic robots comes from foreign sources. The higher figures, including the open areas, are figures reported by the Robotic Industries Association (RIA) and include imports. According to the RIA, the significant jump in the 1989 figure is due to a resurgence in demand for robots in the automotive and electronics industries. Imports, principally from Japan, fed this renewed growth. The most popular Japanese companies are Kuka and Motoman for welding robots and Panasonic for electronic assembly robots. There is no voluntary restraint agreement (VRA) with Japan involving robots, as there is for machine tools.

Moreover, despite impressive initial sales growth, most U.S. robotics producers were unprofitable during the mid 1980s. Lower than expected sales growth and the sales entry of some major robot users resulted in a market shakeout and consolidation. By the mid 1980s, the list of robot producers included such major corporations as General Motors (which had formed the joint venture GMF Robotics Corp. with the Japanese firm Fanuc), Westinghouse (which had acquired Unimation), IBM, and General Electric. Since the largest user of robots has been the automotive industry, and especially GM, the GM-Fanuc operation has controlled a large share of the total dollar market (estimated at over 40 percent in 1988). Between 1984 and 1988, the number of U.S. companies producing robots and robot parts declined from 75 to 56, according to U.S. Census data. General Electric dropped from the market completely and Westinghouse sold its line to a German company, although it retains distribution rights in this country.

Foreign firms are major participants in the U.S. robotics market, both independently and in joint ventures with U.S. companies. According to the U.S. Bureau of the Census, imports of robots, accessories, and components equalled 37 percent of the combined total of U.S. manufacturers' total shipments (including exports) and foreign imports from 1985 to 1988. This is somewhat higher than reported by the Robotic Industries Association. However, if

1989 is considered, the figure is approximately 25 percent. (See Figure 3.) It is very difficult to determine the exact percentage of imports since many domestic companies buy major robot components and prepare the assemblies in the U.S.

b. Artificial Intelligence (AI)

DoD is currently pursuing AI for a wide variety of potential applications. Most applications involve the use of expert systems for decision aids to enhance or accelerate human activities. In these applications, expert system programming techniques are often used to facilitate access to an extensive computer knowledge base on the particular subject area. Some applications are beginning to use the output of the AI application as input to the control of machines or equipment, but most of the output is to a human via a cathode ray tube (CRT). The partial list of DoD applications of AI-based systems contained in Table 1 illustrates the range of intended usage and the operational status.

Table 1. DoD AI Applications

NAME	FUNCTION	DOD U.S.ER
IMA	Inventory Data Validation	AFLC/DLA
ERIK	Message Processing	Coast Guard
--	ELINT Analysis/Situation Assessment	--
AEGIS Expert	Radar Maintenance Diagnostic Aid	USN AEGIS Cruisers
MACPLAN	Strategic Airlift Planning	HQ MAC
AALPS	Air Cargo Planning (Op)	ARMY/USAF
CAT	Watch Officer Aiding (Op)	USS CARL VINSON
B1 CEPS	B1 Maintenance Diagnostic Aid	SAC
IFL	Fault Location In Apache Helo	ARMY Aviation
FRESH	Force Analysis & Replanning	CINCPACFLT
IRU.S.	Natural Language Interface	CINCPACFLT
OB1KB	Order of Battle Intelligence Aid	9TH ID
J&A Advisor	Assist In J&A Preparation	AFLC
SSDS	Software Selection	AFLC
ASPA	Weapons Load Plng For Air Strikes	USS CARL VINSON
TEMPLAR	Air Strike Planning	USAF
FIS	Diagnostic Expert System Shell	NAEC/WRAFB
ASPC	Signal Understanding	--
QPA	Autoclave Curing of Composites	AFLC
--	Message Processing	NOIC
E.A	Tactical Munitions Maintenance Aid	TAC/AFLC
--	Buyer's Assistant	HQ DLA
--	Expert System Candidate	7CG & HQ USAF
COMPASS	Communication Planning Assistant	ARMY COMM STAFF
JAWS	Strategic Situation Assessment	NOIC
FSSB	Former Spouse Benefit Cases	NavFinCen
--	PHOTINT Assessment	USAICS
--	Interrogator ES (ELINT/COMINT)	USAICS
--	Targeting ES (Tactical Fires)	USAICS
--	Collection Management (CEWI)	USAICS
--	Intel Information Retrieval	USAICS
--	JINTACS Msg Parser	USAICS

Despite the extensive amount of AI R&D conducted over the past decade, AI is still quite immature and numerous technical challenges remain to be overcome. Only a few of the current DoD applications are fully operational; most remain in the prototype or developmental stages. Applications to robotics which would enable the emergence of truly "smart machines" dramatically lag in the use of AI for decision support. The few applications to machine planning and control seen to date have been largely for proof of concept and have generally addressed small or relatively simple portions of the total problem.

Although AI is emerging and much of the activity is still in the research stage, the supporting industry is relatively large and highly diverse. Computer companies, aerospace primes and large subsystem primes, and large manufacturing companies all have AI operations, chiefly centered in corporate labs. AI is generally applied directly to internal operations or to commercially marketed hardware/software packages. The aerospace firms are developing defense applications of AI in such areas as smart munitions, battle management, C^3I, maintenance diagnostics, and cockpit decision aids and automation. In addition, there have been some applications in manufacturing for cell-level and machine-level planning and control, process planning, and nondestructive inspection. AI has seen substantially greater application to non-defense problems and industries. Expert systems have proven successful in maintenance troubleshooting, medical diagnosis, financial analyses, product evaluation, and marketing. Several strong development efforts have attacked manufacturing planning and job shop production scheduling problems with limited success.

The level of effort expended on AI by these larger companies can be significant; in some cases — such as Digital Equipment — AI operations represent a considerable investment of corporate funds. AI is also pursued by a large number of smaller, entrepreneurial start-up companies. These companies tend to emphasize expert systems work, most of it for the commercial sector. Federally Funded Research and Development Centers and not-for-profit labs also play an important role. Finally, much of the basic and engineering research in AI is performed at universities, including the Universities of Illinois, Massachusetts, Southern California, Texas, Pennsylvania, Georgia Tech and Yale. Table 2 highlights the expertise of some of the start-up firms that are involved in the development of this technology.

Table 2. Industry Capabilities in Artificial Intelligence — Start-Up Firms

Advanced Decision Custom software for defense applications	**Exsis** Expert system tools for PC and vaxes	**Programs in Motion** Expert systems for PCs
Aion Corp Expert system tools for IBM mainframes	**Gold Hill Computers** LISP and expert system building tools (e.g., Goldworks) for PCs	**Quintus** Prolog
Applied Expert Systems Applications of expert systems to finance	**Inference Corp** ART, large-scale expert system building tool	**Radian** Expert system tools for PCs
Arity Corporation Prolog, expert system tools for PCs	**IntelliCorp** KEE, large-scale expert system building tool	**Semantic Microsystems** Natural language systems
Artificial Intelligence Technologies, Inc. Expert system tools and applications with DBMS	**Level Five Research** Expert system tool for PC	**Symbolics** (The largest of the small companies, around $100 million/year revenue) Large scale scientific workstations: Zetalisp environment
Athena Group Applications to financial services	**Lucid** Commonlisp	**Syntelligence** Large scale applications of expert systems for insurance and banking
Carnegie Group Large scale expert system building tools	**Palladian Software** Applications of expert systems to corporate financial management	**Cimflex Teknowledge** Large scale tools for expert systems applications
Cognitive Systems Natural language and case-based reasoning		

Source: DARPA

The U.S. is generally considered to be the world leader in development and application of AI, and the large amount of activity in the area gives testimony to the technology's promise for the future. The research organizations and companies active in the area are considered to be strong, creative, and well-supported. The industrial base has grown significantly throughout the 1980s, particularly due to the influx of start-up firms.

However, early forecasts for exploding demand for AI products, particularly expert systems, have not materialized. Many firms have left the business, and the growth of AI capabilities in aerospace firms has diminished — one company, GD Land Systems, has decided to disband its AI group altogether. Such a shake-out is not unexpected in an area which grew so rapidly in response to the promise of a new technology. In part, the shake-out is in response to the realization that expert systems are very application specific, and that very little of one successful application is germane to another. Hence, each application is expensive and time-consuming to complete, and there is little opportunity to apply economies of scale to the software. A number of the start-ups were built around products that could streamline the process of developing expert systems, but such generic tools were often found to result in applications which were more cumbersome than the market was interested in using.

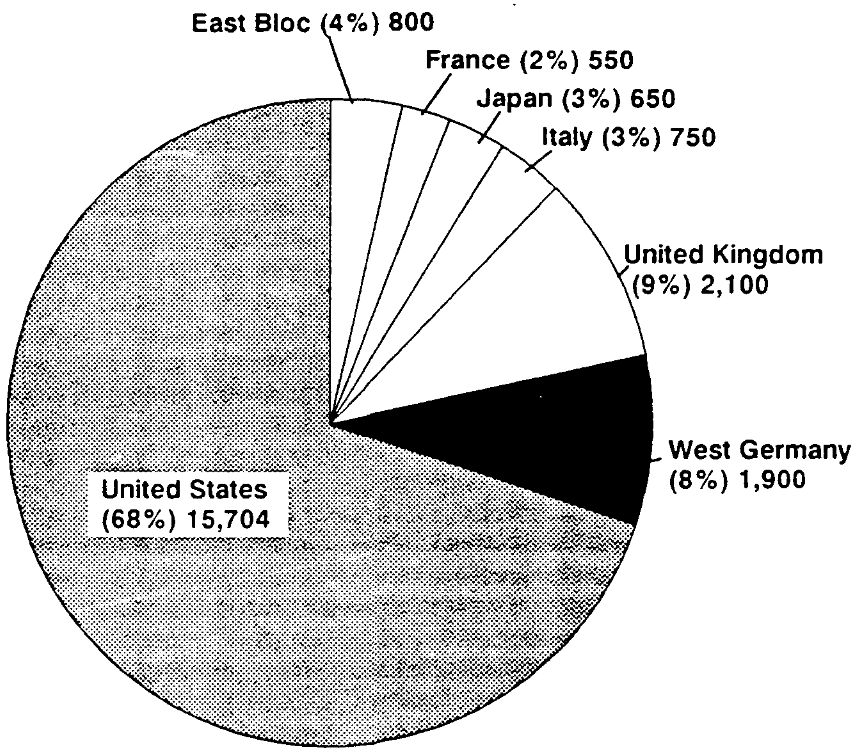
Another reason for the changing industrial base for AI relates to terminology. A significant amount of the early interest in expert systems stemmed from their promise to circumvent the memory and processing speed limitations of conventional computers and programming languages. In a very real sense, AI was often thought of as a software approach to solving problems which could not be solved acceptably through conventional algorithmic techniques. The continued steady decrease in the cost of increased computing power and memory has dramatically increased the number of problems that can be solved using conventional approaches. Therefore, the number of applications viewed as targets for solution through expert systems has diminished. The advent of parallel processing computer architectures is expected to further accelerate this trend because of their promise of massive increases in affordable processing speed.

Nevertheless, the importance of AI to military applications remains very high. Military applications often will require compact computers which are as light as possible, but which still are capable of rapidly processing vast quantities of data. AI programming approaches may continue to be the only viable methods of achieving that processing speed while meeting volume and weight constraints, so the continued strength of the AI industrial base remains very important to DoD.

The relatively fragmented nature of the industry is a concern for the future. While the U.S. has a strong research infrastructure, the body of scientists, universities and laboratories remains largely unconnected to industry. Although the bridge from science to applied technology may be understandably poorly defined in an emerging technology, the effectiveness of the international competition (particularly the Japanese) in quickly implementing new technology in products and manufacturing plants and equipment lends considerable urgency to more rapid, effective transition of laboratory research results in AI.

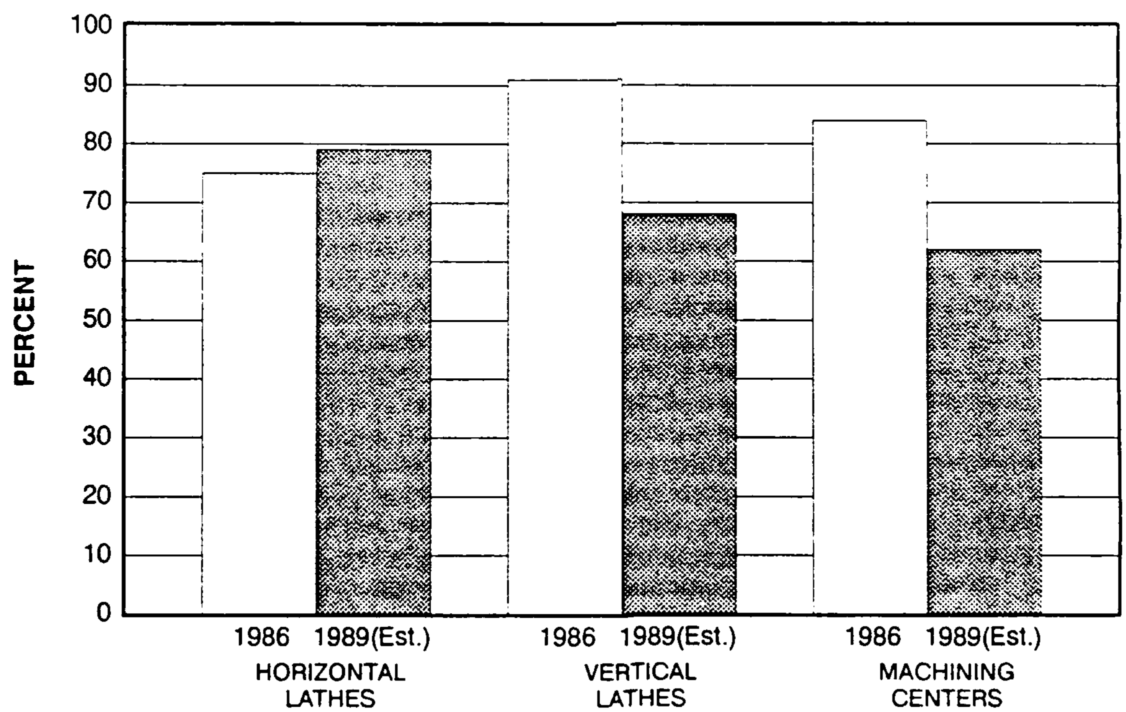
c. Numerical Control Machine Tools

Numerical control machine tools are not a new product; the first machine was developed and demonstrated in 1952 at Massachusetts Institute of Technology (MIT). For almost two decades, the U.S. held a commanding lead, having shipped more than twice the number of units as the rest of the world (see Figure 4). By 1986, the situation had changed dramatically, and Japan and West Germany became the major players. The number of machine tools built in Japan alone was almost ten times that built in the U.S. (39,000 vs. 4,000). Imports peaked in 1986, when the three leading types of NC machines were being imported at a better-than 75 percent rate. Figure 5 depicts this rise in imports during the 1980s. The reductions in two of the major types of NC machine tools by 1989 are due almost solely to the VRA entered into by the United States and Japan.



Source: Bureau of Census

Figure 4. Total NC Shipments Through 1968 (Units)



Source: National Machine Tool Builders Association

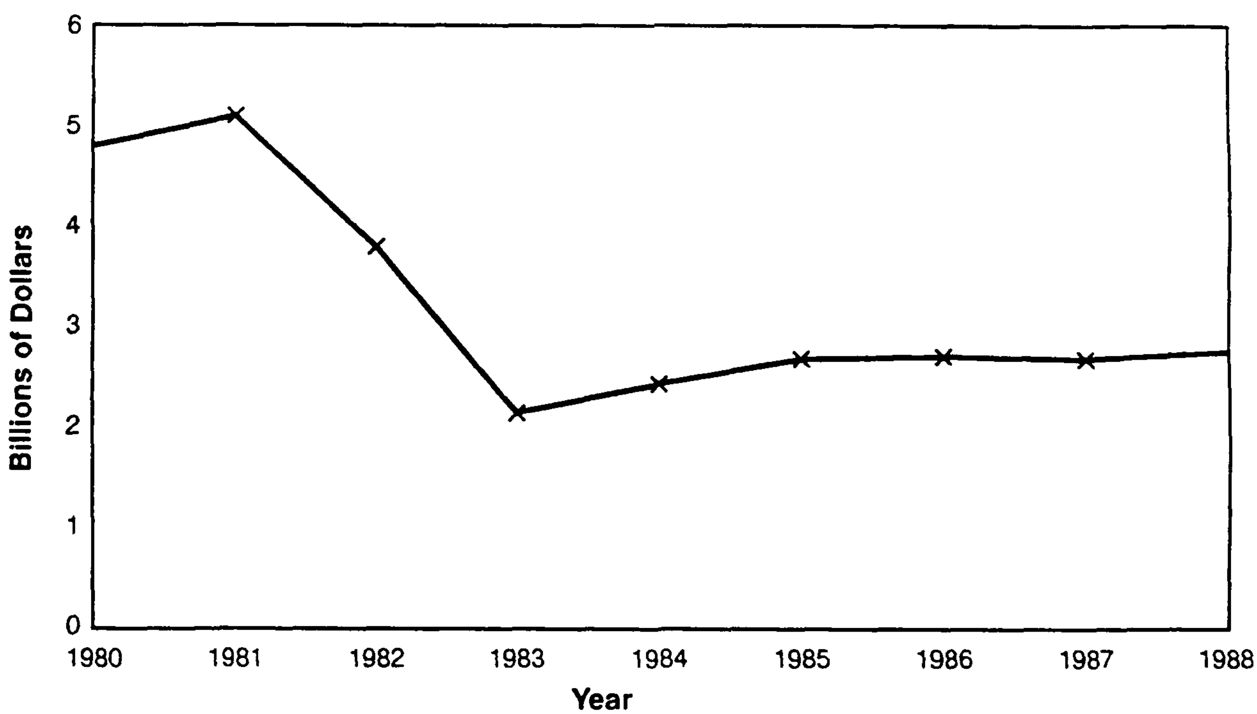
Figure 5. Percent Imports for NC Machine Tools

The impact of this rise in imports is reflected in Figures 6 and 7, which cover all metal working machinery. Figure 6 reveals that shipments by U.S. companies sharply dropped by 58 percent between 1981 and 1983 and had recovered to only 54 percent of the 1981 level by 1988. As seen in Figure 7, the impact of reduced sales on machine tool industry profits was even more dramatic. The industry profit level declined from a healthy 12.2 percent of sales in 1981 (12.9 percent in 1980) to a loss of 9.6 percent of sales in 1983. With the VRA, profits had recovered to only 2.2 percent of sales by 1988.

The negative effect on individual company sales and profits can be seen in Figure 8. The companies represented in this figure — Cincinnati Milacron and Cross & Trecker — are the two largest independent U.S. producers of machine tools. Cincinnati Milacron lost money during three of the past seven years, and its 1989 profits were less than one quarter of the level achieved in 1981. Cross & Trecker has fared even worse in recent years, losing nearly $30 million per year from 1987 to 1989, compared to average annual profits of over $37 million during the early 1980s.

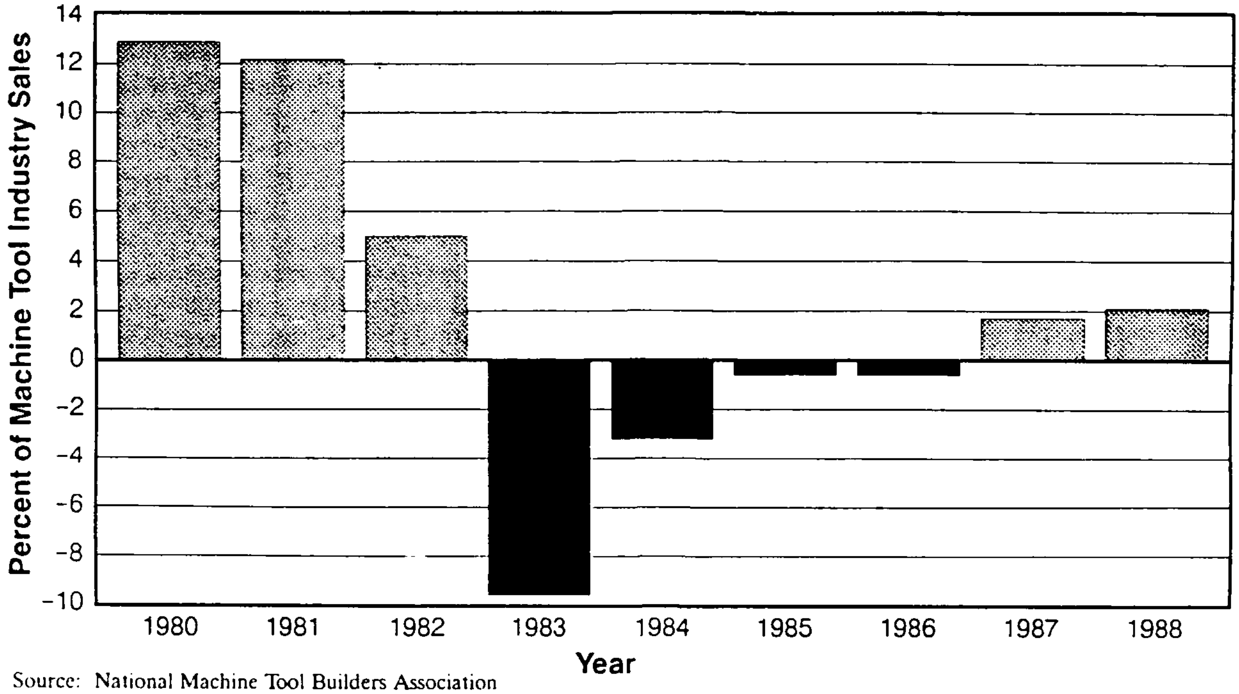
The financial position of the U.S. machine tool industry weakened during the 1980s as a result of the dramatic decline in sales and profits during this period. A corresponding decline is evident in the capital expenditures of Cincinnati Milacron and Cross & Trecker. Figure 9 shows that Cincinnati Milacron's and Cross & Trecker's annual capital expenditures fell by 47 percent and 77 percent, respectively, between 1981 and 1983. While both companies' capital expenditures increased from the 1983 lows in the following two years, they have declined again in more recent years. Combined capital expenditures for these two companies have averaged less than three percent of sales since 1986.

Despite slumping sales and profits, both companies continued to invest heavily in research and development during the 1980s. The impact of Cincinnati Milacron's generous R&D budget is measured by the fact that more than half of this company's sales in 1988 were products that did not exist five years earlier. As can be seen in Figure 10, R&D expenditures (as a percentage of sales) for both companies have fallen off during the past few years. Long-term debt has also soared for both Cincinnati Milacron and Cross & Trecker since 1981.



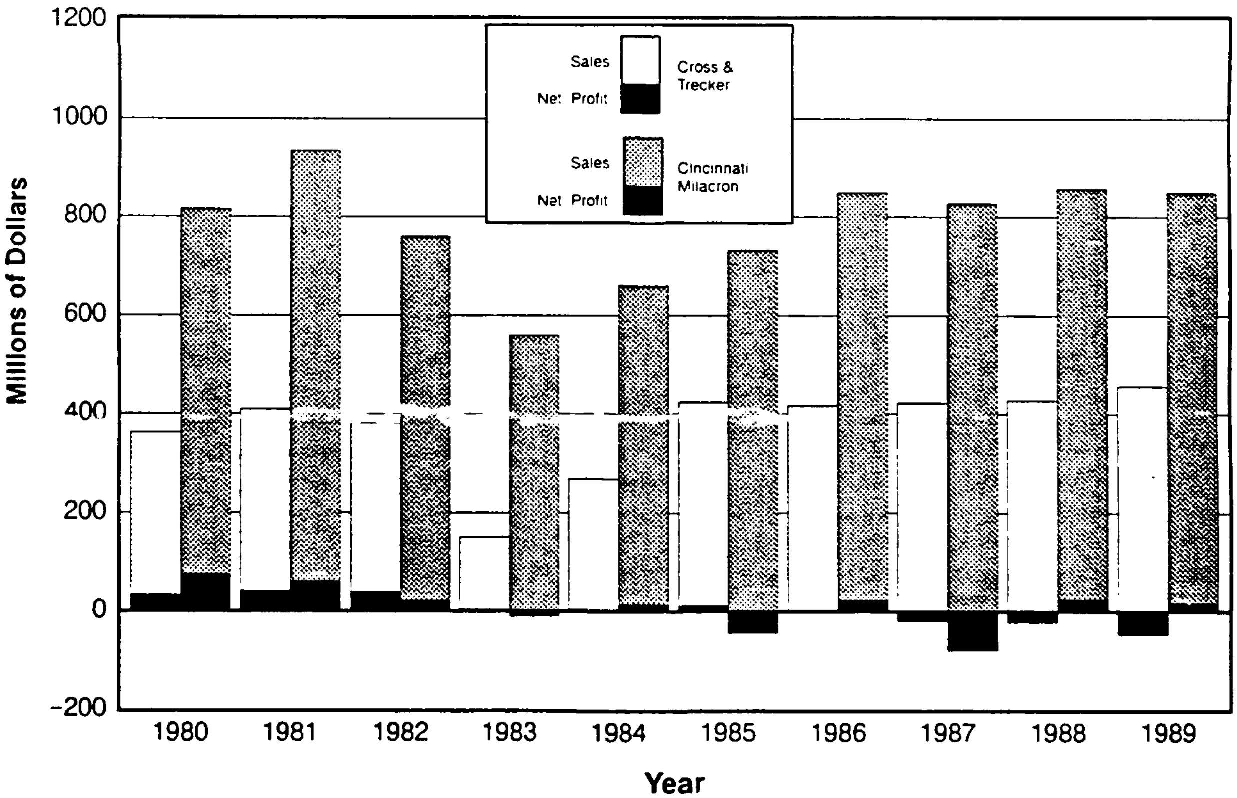
Source: "Current Industrial Reports: Metalworking Machinery," U.S. Bureau of the Census, quarterly and annual.

Figure 6. Shipments of Metalworking Machinery



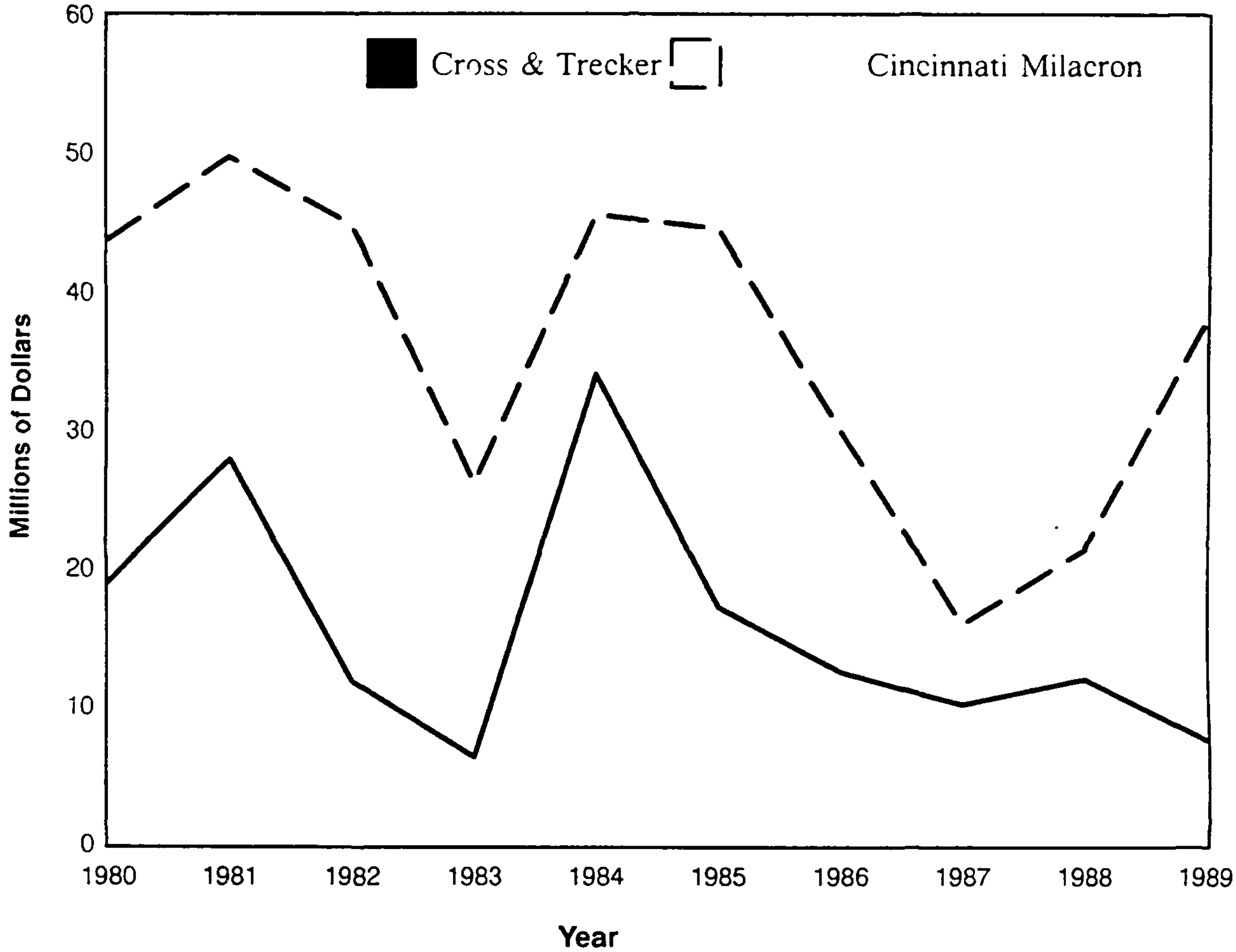
Source: National Machine Tool Builders Association

Figure 7. Net Income of the U.S. Machine Tool Industry



Source: Value Line

Figure 8. Sales and Net Profits of Two Major U.S. Producers of Machine Tools



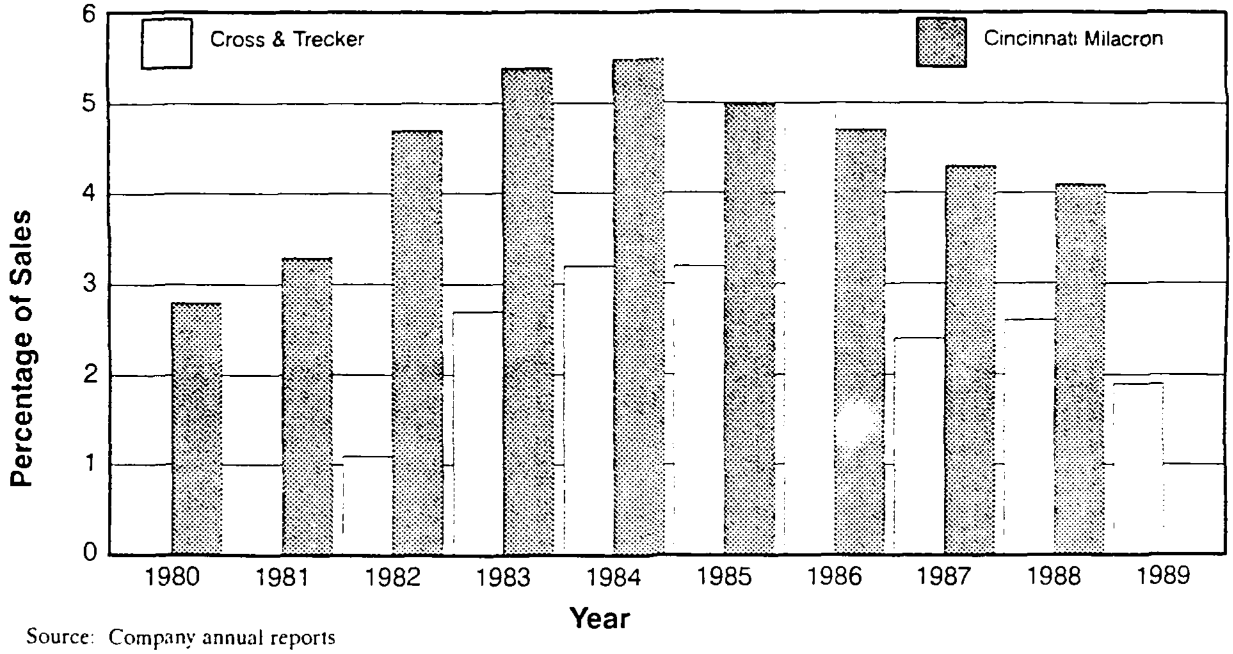
Source: Company annual reports

Figure 9. Capital Expenditures of Two Major U.S. Producers of Machine Tools

Cross & Trecker's debt now equals 65 percent of net worth, up from 10 percent in 1981. The comparable numbers for Cincinnati Milacron are 75 percent now versus 32 percent in 1981.

d. Machine Control Systems (Controller)

The technological evolution of electronic control systems for instructing numerical control machines started with digital vacuum tube circuits, advanced through solid state and then integrated circuits, and then finally in the late 1970s, into computer numerical control (CNC). The flexibility, memory, and speed of the computer opened a new world of capabilities for the NC machine tool. Many new functions were added and the cost was reduced significantly. Now, the controller and its associated software are the keys to machine tool performance. However, if machine intelligence is defined as the capability of computer-based systems to mimic and augment human intelligence, then the computer control systems operating NC machine tools are only beginning to function as truly intelligent systems. Referring back to Figure 1, NC control systems do have tactile sensing, which conforms to the machine perception requirement. For example, probes can automatically measure a part during the machining cycle. The results can then be compared to the measurement requirements in the cognition component and the proper machine action can then be taken to compensate for any errors (the action component). Far greater intelligence is planned. For example, the computer will be expected to determine the



Source: Company annual reports

Figure 10. R&D Expenditures of Two Major U.S. Producers of Machine Tool Control

complete methods procedure for preparing a part, given certain parameters such as the material and basic dimensions. NC machine tools will also be expected to operate intelligently and make real-time decisions in a family of other related NC machine tools, such as in a flexible manufacturing system.

The machine control field extends well beyond numerical control systems, although these are probably the most advanced computer oriented systems. Other controls such as programmable logic controllers and motor controllers constitute a large share of the industry.

Major producers of controls are generally divisions, subsidiaries, or joint ventures of electrical equipment or electronic component manufacturers. These include such companies as: Allen-Bradley (an operation of Rockwell International, but with Mitsubishi's ownership participation in the controller business); Anilam Electronics (a subsidiary of Core Industries); Dynapath-Hurco; GE-Fanuc Automation (a joint venture between General Electric and Japan's Fanuc); Square D; and Texas Instruments.

In general, financial data on the controller segments of these companies are not published. However, data from two of these companies suggest that U.S. machine tool control sales may not have been as hard hit by foreign competition as machine tools, especially in the area of programmable logic controllers, in which Allen-Bradley and GE still hold a strong domestic position. Table 3 summarizes sales data for Allen-Bradley and the industrial control segment of Square D. Profits data were not reported separately for Allen-Bradley, but the Rockwell International 1989 annual report states that Allen-Bradley earnings achieved a record level last year "due both to the expanding lines of industrial automation products and traditional lines of electromechanical industrial control devices." It is worth noting that Allen-Bradley has undergone an extensive modernization and automation of many of its product lines over the past few years. As can be seen in Table 3, Square D's controls business has also had operating earnings in recent years, though the ratio of earnings to sales has been lower for the industrial control segment than for Square D's electrical distribution segment. Moreover, Square D's Electronic Components segment, which contained much of the company's controller business (prior to Square D changing its segment groupings for reporting purposes), lost money in 1985 and 1986.

Table 3. Sales of Rockwell International and Square D by Their Business Segments Producing Industrial Controls* (Millions of Dollars)

	1986	1987	1988	1989
Allen-Bradley (sub. of Rockwell International)				
Sales	1,076	1,080	1,249	1,389
Square D's Industrial Control Segment				
Sales	N.A.	433	472	513
Operating Earnings	N.A.	38	41	35

*Allen-Bradley was acquired by Rockwell International in 1985. Square D recently began to report its segment data differently, so consistent data prior to 1987 is not available.

Good financial trend data are not readily available for the entire U.S. controls market. However, the entry of a number of the largest U.S. corporations into these markets during the past decade suggests that a considerable investment was made. For example, Rockwell International, spent $1.7 billion in acquiring Allen-Bradley in 1985 and has made additional acquisitions and capital expenditures in the controls business since. Evidence of a substantial R&D effort by Allen-Bradley is provided by the fact that it introduced more than 40 new automation control devices in 1989.

Major corporations entered the machine tool controls market, as well as the robotics market, largely because they viewed the technologies as critical to their competitiveness. Machine tool controls and robotics are recognized as critical technologies to improve productivity and quality, and to lower costs. Therefore, it is believed that major corporations will continue to provide considerable financial support for these technologies through purchases of controls and robots for their own manufacturing requirements and for investments in controls and robot development and production.

The U.S. Government has also played a major role in developing both machine tool control and robot technology through a variety of research and development programs, contract incentives to encourage capital investment by Government contractors, and programs to modernize Government-owned facilities and equipment. Government support for research and development in these areas is likely to become increasingly important as declining defense procurements reduce contractor incentives to invest in new equipment. The "Next Generation Controller" project is especially important: this Air Force-sponsored effort is intended to develop an advanced CNC controller with a flexible, open architecture to help U.S. manufacturers recover market share lost to imports.

4. Summary

Machine intelligence and robotics encompass a broad range of technologies that are essential to nearly all critical technology areas addressed in this report. The strength of U.S. industry in machine intelligence and robotics varies depending on the particular segment being considered. In some areas, such as AI — a software product — the U.S. still holds the world leadership position, while in others (e.g., advanced machine tools) the U.S. has lost its former leadership position to the Japanese, West Germans, and Italians.

Robotics is considered to be one of the most promising areas of machine intelligence for both manufacturing and military operations, especially when tactical and vision sensing devices are included. Although domestic suppliers were extremely successful in the initial market for robots, they quickly lost share to the Japanese.

Today the number of U.S. producers in the industry has been dramatically reduced and most of the existing firms assemble robots from components produced in other nations. The U.S. role has been delegated principally to robotics software and systems development. The sharp rise of robot procurements in 1989, from $250 million to $430 million, although impressive, can be largely attributed to automotive and electronics applications and does not foretell a general growth in the industry. Besides, almost all of this increase was supplied by Japan.

There are three major problems that appear to be impeding the robotics industry. One involves the development of hardware and to some extent, the software. Despite the fact that computer processing speeds are increasing geometrically, they are still not sufficiently fast to handle the intelligent type of operations required for manufacturing. Another impediment involves the users who, in many cases, do not have sufficiently trained personnel to establish, program, operate, and maintain robot hardware and software. The results have to be redesigned to be usable with a robot's and effort. The third impediment has been the inability to justify the cost — both initial and ongoing. Normally, large quantity lot sizes are required to justify a robotic installation.

The number of producers has been drastically reduced in the area of NC machine tools as well, where the Japanese share of the market has risen from less than 5 percent in 1976 to over 50 percent today. Overall, the number of machine tool manufacturing facilities has decreased from almost 1,400 in 1982 to 650 in 1987. Also, many of the these facilities are either foreign owned or both foreign owned and foreign operated.

A similar trend is apparent in the market for machine tool controls where Japan and West Germany have taken over the lead — worldwide as well as in the U.S. The U.S. Air Force is sponsoring the development of an advanced machine control system to counter this foreign dominance. Whether this will be sufficient to compete with foreign systems when it is finally developed is arguable. Also, foreign interests in domestic machine tool controller manufacturers appear to be another sign of weakness, since the foreign interests tend to dominate the engineering operations.

In contrast to the precipitous decline in hardware areas, domestic capabilities in AI are currently unparalleled. There is, however, some concern that the industry may have expanded prematurely and will be required to cut back to accommodate slower than expected growth in demand.

PASSIVE SENSORS

1. Introduction

Passive sensors are primarily performance enhancing devices related to navigation, surveillance, and fire control, and the capabilities that the technologies contribute to major weapon systems are critical to achieving required levels of performance. Passive sensors have two advantages in military applications: they help maintain secrecy of operations and they often provide more accurate target information. Figure 1 lists passive sensor technical challenges cited in the FY90 ***Critical Technologies Plan***, along with key applications and supporting industrial base segments. As indicated in the figure, the technologies associated with passive sensors are predominantly DoD-related. Many of these underlying technologies are also important to other critical technologies, including Photonics, Signal Processing, and Semiconductor Materials and Microelectronic Circuits.

There are many different types of passive sensors, including electromagnetic devices for surface weapons and acoustic devices for submarine applications. The passive sensor industry develops and produces such critical defense components as electronic support measures (ESM), infrared/electro-optical sensors, and multi-spectral sensors, and is developing advanced methods that will permit the detection of new weapons systems that are specifically designed to deceive radars, including advanced stealth technologies, high technology submarines and aircraft, satellites, and missiles. Intended future applications of this technology include smart munitions, glide bombs, and a variety of thermal sights and viewers.

TECHNICAL CHALLENGES

- Passive Threat Warning Sensors
- Microwave/Millimeter-wave Radiometry
- Passive Coherent Radar
- Advanced Thermal Imagers
- Infrared Search and Track
- Infrared Focal Plane Arrays
- Compact Antennae
- Superconducting Sensors
- Fiber Optic Sensors Systems
- Large, Volumetric Acoustic Arrays
- Sensor Integration/Correlation

DEFENSE APPLICATIONS

- Advanced Electro-optical Air Defense
- Multisensor Target Acquisition
- Smart Munitions
- Navigation
- Families of Advanced Small Arms
- Surveillance

SUPPORTING INDUSTRIES

- System Manufacturers
  - -- Electronic Support Measures
  - -- Infrared/Electro-Optical Sensors
  - -- Multispectral Sensors
  - -- Focal Plane Arrays
  - -- Advanced Acoustic Sensors
  - -- Fiber Optic Sensors
- Equipment Manufacturers
  - -- Diagnostic Tools
  - -- Dewar/Cooler Fabrication
  - -- Built-In Test
  - -- Compact Antennas
- Material Suppliers
  - -- Mercury Cadmium Telluride
  - -- Gallium Arsenide
  - -- Intrinsically Pure Silicon
  - -- Platinum Silicide

Figure 1. Technical Challenges and Supporting Industries

Table 1. Domestic and Foreign Sonar Transducer Manufacturers

Lead Zirconate Titanate	Piezoelectric Polymers	Composite Ceramic
Edo	Thomson[1] (France)	NTK[1] (Japan)
Honeywell	Pennwalt/Raytheon	Thomson[1] (France)
General Electric	Plessey	Edo
Sparton		Westinghouse
Allied Signal		
Westinghouse		
Massa Channel		

To illustrate the diversity of passive sensor applications, a variety of underwater acoustic sensors, sources, and actuators are extremely important to the Navy. An underwater acoustic sensor array might contain conventional piezoelectric ceramic sensors (a well-developed technology) or newer technologies such as fiber optics, piezoelectric polymers, or piezoelectric ceramic composites. Conformal arrays can also play a role in antisubmarine warfare by building sensors into the skin of the platform, thereby improving the capability of a hull-mounted array. The Navy has initiated a number of R&D programs to respond to these new requirements. Two particular thrust areas include composite acoustic materials and fiber optic sensor systems.

Acoustic sensors provide an example of the industrial base that supports passive sensors. The sonar transducer/sensor industry has been an active part of the defense industrial base for 50 years, and has been traditionally structured around defense and offshore oil applications, with a very minor sonar fishery application. Lead zirconate titanate is the best established material for source and sensor applications, but the industrial base that is involved in applications of this technology has been steadily decreasing due to a shrinking base of skilled manpower and procurement processes that effectively limit competition. Table 1 identifies major manufacturers based on their sensor/source material.

There is also shrinkage in the subcontractor base, and virtually none of these firms has a forward-looking IRAD program. As a result, it is being increasingly found that research results from U.S. universities and laboratories are being implemented by foreign firms before entering production domestically. The market for naval applications is expected to increase as more sensors and arrays are needed to address quieter threats, despite the overall decrease in U.S. Navy vessels. However, if U.S. industry is to meet the Navy's requirements, transitions from research to technology applications must occur in shorter timeframes.

Acoustic sensors represents only one of many applications and industrial infrastructures associated with passive sensors. Because of the diverse nature of the product and industry, the remainder of this assessment will concentrate on one particularly important element of passive sensors — infrared detectors. This type of sensor, which is used for strategic and tactical above ground applications, typically contains one or more detectors, readout electronics, and a cooling mechanism. Table 2 provides a list of weapon systems that will require focal plane arrays, which represent second generation infrared technology. Some of these applications (especially in the strategic arena) are well beyond the state-of-the-art.

[1]Foreign firm leads the U.S. in this technology.

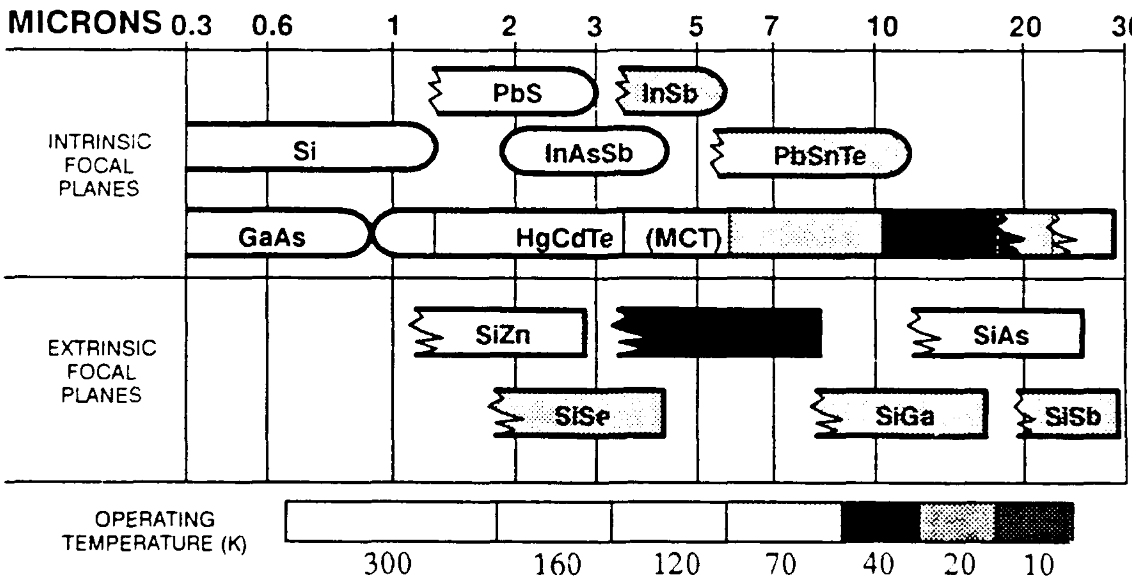
Table 2. Typical Weapons Systems Requiring Focal Plane Arrays

Tactical	Strategic
I.R. Maverick Missile	BSTS Satellite
AAWS-M Missile	SSTS Satellite
NLOS Missile	DSP Satellite
Stinger Missile	ERIS Missile
Sidewinder Missile	HEDI Missile
Aircraft FLIR Systems	Brilliant Pebbles Missile
Aircraft and Ground-Based IRST Systems	Airborne Optical Adjunct (AOA)
FLIR Systems for Armored Vehicles	
Thermal Weapon Sights	

2. Industry Structure

The infrared detector industry has been a small but active part of the defense industrial base for 25-30 years, over which time the product has evolved from simple first generation designs to the considerably more complex second generation systems of today. First generation designs generally contain single elements or small quantities of detectors whose signals are serially processed via individual electrical leads. Second generation systems — known as focal plane arrays (FPAs) — tend to have much larger numbers of detectors, are often integrated with readout chips, and their signals are multiplexor processed.[2]

Focal plane arrays detect at different wavelengths, using materials such as mercury-cadmium-telluride (MCT); platinum silicide (PtSi); indium antimonide (InSb); and extrinsic silicon (Si:X). These materials are at different stages of maturity and each possesses unique advantages and disadvantages for various applications. Figure 2 identifies the wavelengths associated with each of the major materials.



Source Rockwell International

Figure 2. Infrared Materials and Wavelengths

[2]First and second generation detectors are often distinguished by whether their electrical design principle is photoconductive (PC) or photovoltaic (PV). In first generation PC designs, the intensity of the infrared signal is measured as a change in resistance. In second generation PV designs, impinging energy is converted directly into voltage and measured as current.

Silicon-based PtSi is the best established material for FPAs, and the infrared FPA industry has directly evolved from the silicon electronics industry. Many of the processes used in the two areas — such as photolithographic techniques, handling equipment, clean areas and epitaxial growth techniques — are very similar if not identical, and the equipment used for many process, inspection, and test operations is provided by many of the same manufacturers that supply the microelectronics/silicon chip industry.

Despite these similarities with semiconductor manufacturing, many of the challenges faced by the industry are unique to the manufacture of FPAs. FPA production is a small, relatively undeveloped component of the semiconductor industry, and the production capabilities for most detector materials are immature relative to those for silicon-based circuits. All of the materials used in FPAs pose similar manufacturing concerns, which include throughput, handling, test equipment, and the need to integrate flexible computer-integrated manufacturing into the production process. In addition, common producibility issues include photolithography, detector readout interconnects, substrate size limitations, methods for active area growth, and radiation hardening. These manufacturing issues have become less pronounced as the maturity of the materials has increased.

Although complex FPAs are chiefly a developmental item, about 50 small and large firms are in operation today. Major participants in the industry include Hughes, Texas Instruments, Rockwell, and Loral, with at least $25 million in annual sales. Other, smaller companies have an equally substantial experience base and have annual sales in the $5-$15 million range. Figure 3 identifies many of the nation's FPA manufacturers, based on their specialization in particular detector materials.

Most firms in the industry are "captives." Captive firms include producers and integrators of major weapon systems and subsystems who produce IR products mainly for internal use. These producers include include Hughes, Texas Instruments, Loral, Rockwell, Aerojet, Westinghouse, Raytheon, and General Electric. Hughes clearly dominates the industry, and is responsible for an estimated 40 percent of the entire market. Although teaming between these firms and with merchant vendors sometimes occurs, there is active competition among companies whose capabilities have grown through their involvement in Government R&D and weapon system programs. Since most DoD programs have unique infrared sensing requirements, and capabilities are not easily transferable between systems, these firms have tended to position themselves as "niche" suppliers to meet the specific needs of a particular weapon system. Other large firms, such as Northrop, McDonnell-Douglas, and Martin Marietta, have at least some capabilities for manufacturing FPA modules and also act as system integrators.

In addition to these large captive firms, "merchant" vendors develop their capabilities for the purpose of teaming with or selling to other firms who are in turn responsible for system integration. Merchants include Amber Engineering, Cincinnati Electronics, David Sarnoff Research Center, Eastman Kodak, EG&G Reticon, and Irvine Sensors. Some of these firms supply only detectors, while others supply a wide range of detector components.

The success of FPA technology is also dependent on other important industries, such as a select group of cryogenic cooler and cryogenic equipment suppliers. These range from manufacturers of simple thermoelectric and Joule-Thompson gaseous coolers to producers of sophisticated closed cycle coolers. Marlowe is a prominent supplier of thermoelectric coolers and Cryodynamics provides Stirling Cycle cryocoolers. Other suppliers of coolers include Texas Instruments, Hughes Aircraft Co., Honeywell, New England Research, Aerojet, CTI, Magnavox, and Garrett Air Research. Specialty suppliers of cryogenic test equipment include Flexion, Amber, and several other firms.

3. Condition of the Industrial Base

a. Sales

It is difficult to estimate industry sales, since most major manufacturers are captives and incorporate most of their output into internally produced products. Furthermore, the cost of sensor elements is generally hidden in the cost of the sensor or weapon system. A recent survey of 20 firms that produce the vast majority

Identification of Manufacturers And Specific Materials in the Focal Plane Array Industry		
MCT	**Si**	**PtSi**
Texas Instruments	Hughes, Santa Barbara Research (Carlsbad)	Fairchild Semiconductor
Rockwell	Rockwell International	Kodak
Hughes, Santa Barbara Research	Aerojet	David Sarnoff Labs
LORAL (formerly Honeywell-Electro-Optics)		Hughes, Santa Barbara Research (Carlsbad)
New England Research	**InSb**	
General Electric	General Electric	
Westinghouse	Hughes, Santa Barbara Research	
Ford Aerospace	Raytheon	
Fermionics (material supplier)	Amber	
McDonnell Douglas Corporation	Ford Aerospace	
Raytheon	Westinghouse	
	Northrop	
	Cincinnati Electronics	

Source: TASC's Defense Industry Research Center

Figure 3. Domestic Focal Plane Array Manufacturers

of military related infrared (IR) detectors and an additional survey of 30 firms that produce IR photodetector chips for the commercial market found that the industry represented about $500 million in annual sales, about $450 million of which was for the military market.[3] About half the military sales are in MCT. The vast majority of the modules sold to the military become part of sensor systems that represent billions of dollars in annual sales. This is a small percentage of the more than $15 billion in annual U.S. semiconductor sales and an even smaller percentage of that market in terms of volume.

The FPA industry could grow significantly if future demand increases as projected. For U.S. military applications alone, approximately 140 weapon systems could require FPA detectors in some capacity over the next ten years. One of the major users of these systems in the future could be the Strategic Defense Initiative (SDI), which will utilize FPA technology in a variety of spaceborne sensor and missile seeker applications. SDIO's requirement was well beyond industry's current capability, and will be unaffordable unless current costs are dramatically reduced. SDI conducts and sponsors most of the R&D in the area of passive sensors.

Despite the relatively limited current demand for FPAs and, therefore, the limited production capacity to meet this demand, industry's financial potential to support sensor technology is enormous. Most of the FPA manufacturers identified in Figure 3 are divisions or subsidiaries of major U.S. corporations. The 12 largest of these firms had 1989 sales ranging from $1.2 billion to $123 billion. These companies can be grouped into three categories:

- Defense companies (with more than half of their 1989 sales to the U.S. Government — both directly or indirectly)
  - — Gencorp (parent of Aerojet)
  - — General Motors Hughes Electronics (a subsidiary of General Motors)
  - — Loral
  - — McDonnell Douglas

[3]Survey was performed under contract to Air Force Systems Command (AFSC/ENMS) for an assessment of the IR industry. Other published data suggest that the current level of military sales could be as high as $600 to $700 million, with an additional $100 million attributed to commercial sales.

- Northrop
- Raytheon

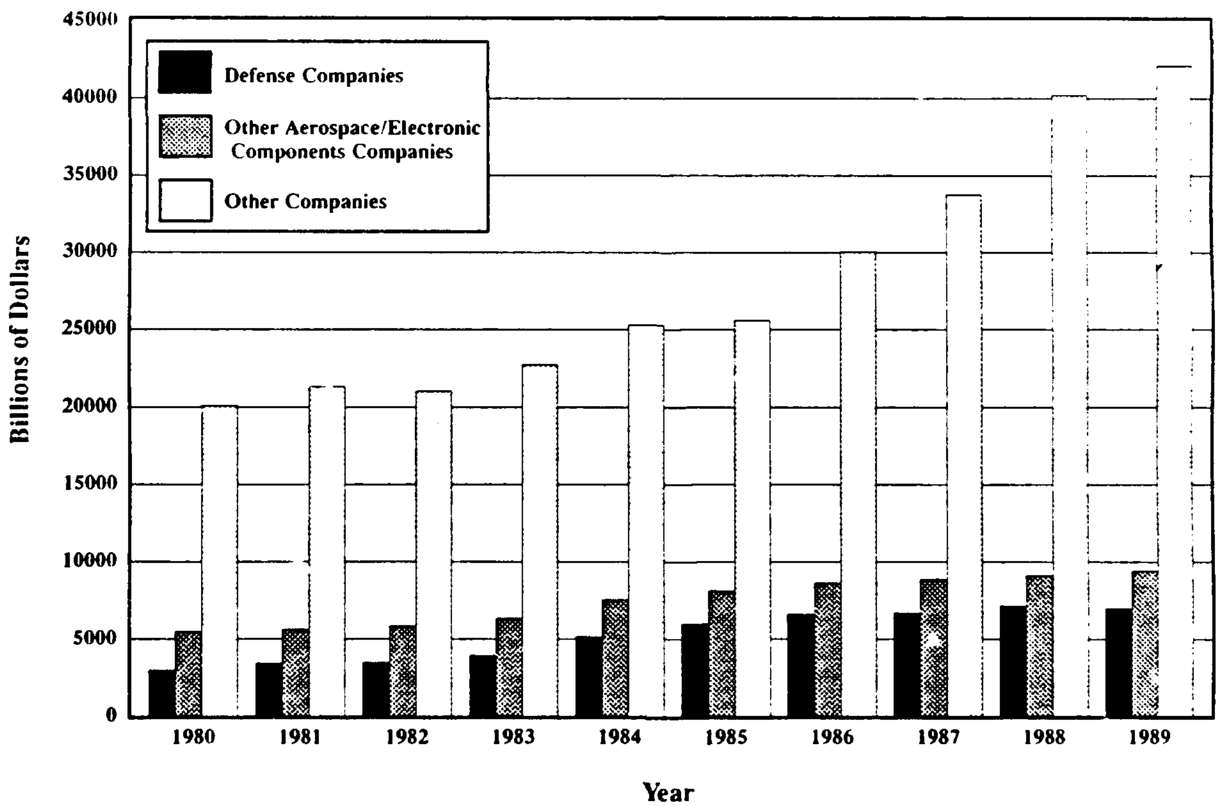
- Other aerospace/electronic components companies (with more than half of their 1989 sales in the aerospace and electronic components areas)
  - Rockwell International
  - Texas Instruments

- Other companies
  - Eastman Kodak
  - Ford Motor (parent of Ford Aerospace)
  - General Electric
  - Westinghouse.

While passive sensor sales generated a small, if not minuscule, portion of revenues and profits for these companies, sensors were critical components in a major portion of their products. This is particularly true for the defense companies. Therefore, the overall future financial performance of each of these companies is tied in no small part to their abilities to develop and produce passive sensors. Conversely, the overall financial strength of these companies is an important measure of their abilities to advance passive sensor technology.

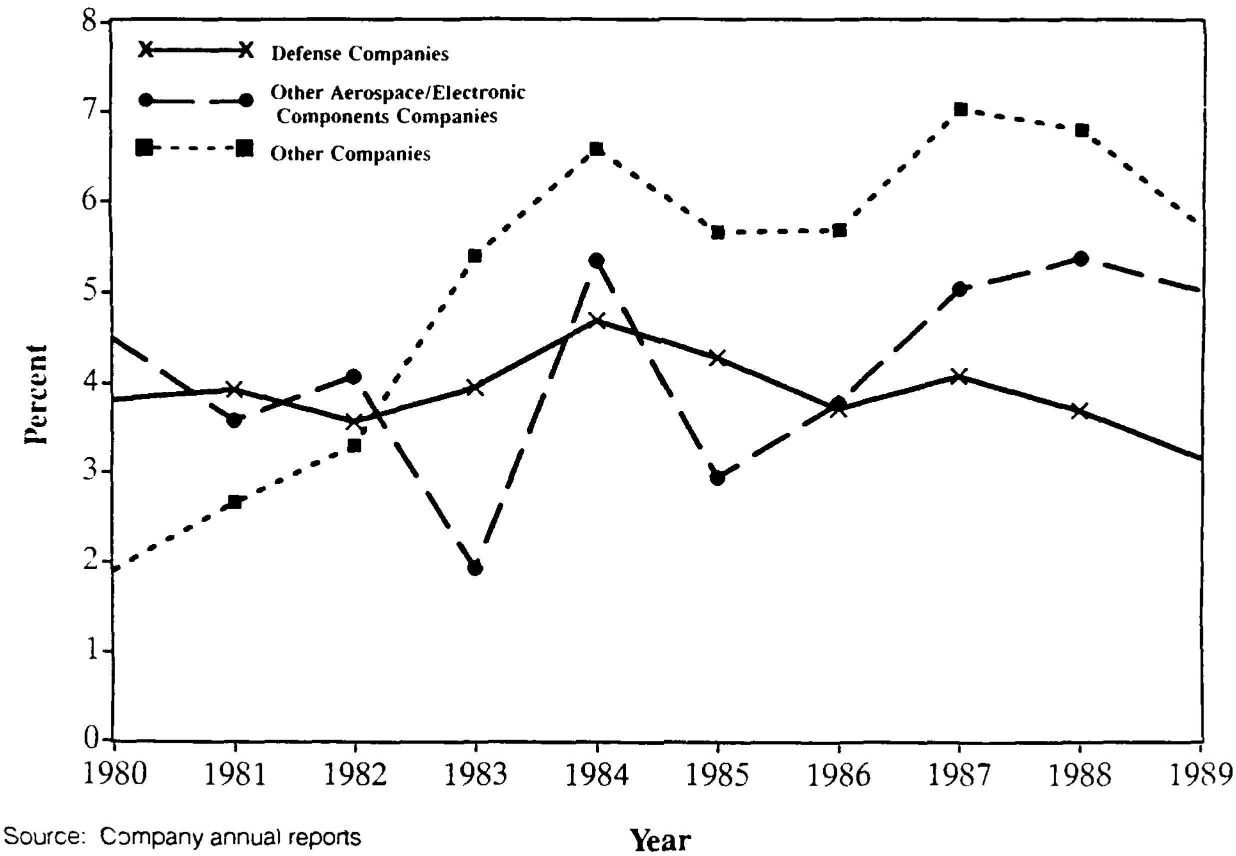
Figure 4 presents the average annual sales per company for each of the three groupings listed above. Sales of the six defense firms averaged more than $3 billion in 1989. The two other predominantly aerospace/electronic companies averaged sales of $9.4 billion each in 1989, up from $5.5 billion in 1980. The other four companies averaged much higher sales in 1989 — more than $42 billion — but it is important to add that a much greater portion of these sales dollars or items were products that did not encompass infrared detector technology.

Profits for these companies were also substantial during the 1980s. Average profits for



Source: Company annual reports

Figure 4. Average Sales Per Company for FPA Parent Companies



Source: Company annual reports

Figure 5. Average Net Profit Margin for FPA Parent Companies

the six defense companies, for example, peaked at $274 million each in 1987 before declining to $221 million each in 1989. Still, this 1989 average was nearly twice the profit level at the beginning of the decade. However, the net profit margin for the defense producers has declined somewhat since the beginning of the decade, as depicted in Figure 5.

Although there is a commercial market for infrared sensors, these applications are much less complex than their military counterparts and the market is relatively small. Of the materials that are currently in development, PtSi has the greatest potential for commercial use. The Japanese have introduced a camera using PtSi arrays that is comparable in size with standard video cameras, while domestic firms have introduced products using PtSi, InSb, and MCT. The commercial market for infrared detectors can be broken into four basic parts: laser diagnostics, spectroscopy, fiber optics, and thermal imaging. Figure 6 lists many of the key producers in these markets.

b. Investments

Relatively high R&D investments are typical of defense aerospace and electronics companies, due to the high-technology requirements of these businesses and the substantial U.S. Government funding of research and development in these areas. Among the defense companies currently producing FPAs, 1989 R&D expenditures (including U.S. Government R&D funding) ranged from 3 to 6 percent of sales. Among the other FPA producers, Eastman Kodak and Texas Instruments had even higher 1989 corporate-wide R&D-to-sales ratios of 6.8 and 8 percent, respectively.

LASER DIAGNOSTICS	*SPECTROSCOPY*
Photon Inc. Spricon Company Coherent Components Group	Acton Research Corp. American Holographic Inc. Bio-Rad Laboratories Bomen Inc. Ideal Lab Inc. Minarad Scientific Inc. Barrianger Research Lim. Contraves Goerz Corp. Geophysical Environmental Research Corp IRIS Fiber Optics ITT Corp. Magnavox Gov't & Ind Elec Co.
FIBER OPTICS	***THERMAL IMAGING (THERMAL INFRARED CAMERAS)***
Amorphous Materials Inc. Dolan-Janner Ind Inc. Electro-Optics Corp. Honeywell Optoelectronics Ensign-Bickford Optics Co. Galileo Electro-Optics Corp. Infrared Non-Linear Materials Co. IRIS Fiber Optics Inc. Vanzetti Systems Inc. Fiberoptic Engineering Corp. Fiberoptic Systems Inc. Saphikon Inc. SpecTran Corp.	Barnes Engineering EEV Inc. EEV Limited Electrophysics Corp. FIAR SpA Electro-Optics Hughes Aircraft Co. I.S.I. Group Inc. Image Technology Methods Corp. Inframetrics Inc. Insight Vision Systems Inc. IR Scientific Inc. LORAL Corp. (Fairchild) Mikron Instrument Co. Inc. Optromic Measurement and Control VERE Electronics Xedar Corp. AGEMA Infrared Systems Inc. Magnavox Gov't & Ind Elec Co. B.E. Meyers & Co. Inc. NCE of Florida Inc. Silicon Valley Group Thermo Electron Technologies Corp.

Figure 6. Producers of Commercial Infrared Products

Several large DoD contractors have invested $50 million or more to develop R&D and production capabilities for first and second generation technologies. This level of investment contrasts sharply with producers of commercial semiconductor devices, who may invest $500 million or more for a single facility dedicated to a particular type of device. Since much of the passive sensor market is DoD dependent and little commercial growth is envisioned, industry is typically reluctant to make the investments required to bring critical processes to maturity and to develop the throughput required to prove-out those processes.

Industry's investment has generally been oriented toward developing unique capabilities in specified materials areas: little of the investment is directed toward developing a viable merchant supplier base, establishing capabilities for high-rate production, or developing flexible production lines that can support the manufacture of a variety of products. Typically, investments are intended to enable firms to maintain a minimal capability that will allow them to bid on weapon systems that use FPAs in critical electro-optical components, thus enhancing any competitive advantage that the company might have at the system or subsystem level.

The pattern of investment now appears to be changing. Most infrared detector applications to date involve single element or linear/scanning arrays, but future applications are expected to emphasize staring (250,000 elements or more) arrays. To meet these needs, industry is establishing capabilities to produce second generation technologies and has been modernizing and increasing capacity in anticipation of increased requirements. However, given that the industry is highly dependent on DoD's commitment to field new, high-technology weapon systems, there is no guarantee that industry will continue to expand if expected military cutbacks occur.

In anticipation of greatly increased defense requirements, several producers, including Rockwell, Texas Instruments, and Hughes, have significantly increased their levels of investment. Although a number of firms are developing (or have developed) foundries, many are unwilling to sell material in the open market because FPA technology is considered to be a "leading edge technology" that provides an advantage in the competitive weapon system market. In addition, a number of small companies have emerged with specific expertise in a particular material or process, such as starting materials for detectors, detector readouts, and cryogenic devices. As a result of this industry expansion and the uncertainty of DoD demand, industry is now beginning to express concern about excess capacity.

Industry's investment has been supplemented by that of the government. The level of DoD investment has been relatively consistent, but not very high. The Air Force, SDIO, and DARPA are sponsoring contracts that address manufacturing issues associated with IR FPAs. In addition, several pending and one active weapon system program (AAWS-M) will expend significant resources to address manufacturing issues associated with these items.

Various government investment programs to advance IR detector product and process capabilities are currently underway. The Air Force has a Manufacturing Technology contract with Hughes-Santa Barbara Research Center and Rockwell involving 3-5 micron MCT. DARPA has contracts with Hughes and Rockwell involving MCT and with LORAL concerning PtSi. SDIO has made particularly large investments in these technologies — in excess of $120 million to date —and its sponsorship has covered all of the major types of detector materials as either a primary or back-up material. Furthermore, SDIO is establishing a Manufacturing Operations Development and Integration Laboratory (MODIL) through Sandia to look at alternative/next generation materials that may prove more affordable and producible than MCT devices currently being proposed for SDIO strategic applications. The MODIL will also address broad application improvements in manufacturing and in-process metrology that can be of benefit to all sensor materials. The SDIO work will address only strategic applications and any tactical fall-out will be purely incidental. The Army, primarily through the Center for Night Vision and Electro-optics Lab and the Missile Command, is addressing detector producibility, cryogenic dewars, cryogenic coolers, and packaging techniques. New programs addressing standard dewars and the producibility of a 128 x 128 MCT array are expected to be awarded soon. In addition to government investment in this area, several universities have put forth funds for research in materials and test equipment.

c. Joint Ventures, Mergers, and Acquisitions

There have been several mergers and acquisitions in the FPA industry, but most of these have involved domestic firms only. Two examples are the recent acquisition of the Honeywell Electro-optical Division and Fairchild by the Loral Corporation and the merger of Judson and Reticon into the EG&G Solid State Products Group.

Despite a lack of international acquisitions, U.S. firms have a number of active international competitors. While the U.S. has long dominated the infrared sensor market, French and Japanese firms appear to be attempting to capture certain market niches. One large French firm, Thomson CSF (sales $16B), is currently marketing Indium Gallium Arsenide (InGaAs) detectors and is also introducing a PtSi focal plane module (512 x 512) for application in military and commercial IR cameras, an important market for staring FPA devices. Thomson, partially owned by the French government, is also a dominant partner in a new public-private French consortium, Sofradir, which is developing and marketing sophisticated infrared detectors based on MCT technology. The U.S. Army Center for Night Vision and Electro–optics Lab has recently conducted a preliminary evaluation of these MCT detectors and plans to purchase and analyze additional Sofradir detector devices. Sofradir detectors are considered to be technically competitive with those produced by U.S. firms.

Large Japanese companies, such as Mitsubishi and NEC, are building on their strengths in the microelectronics market and are now pursuing infrared technology quite seriously, with an emphasis on PtSi. PtSi is considered the only material with any near term commercial potential and the domestic sources for the material are lagging the Japanese in introducing devices that incorporate PtSi. The other materials are, for all practical purposes, 100 percent defense dependent. Of the Japanese firms, Mitsubishi was the first to offer an IR camera utilizing a sophisticated 512 X 512 pixel PtSi detector array. (Eastman Kodak's 640 X 488 pixel PtSi FPA is believed to constitute today's PtSi technology state–of–the–art.) Hamatsu of Japan offers a broad line of less complex detector products utilizing a large variety of material technologies. With this strong base of experience, knowledgeable industry observers believe that a major Japanese push to enter the U.S. infrared detector market is imminent.

4. Summary

The U.S. has long exercised leadership in the FPA industry, in large measure because of the importance of military applications. The underlying technology is not new, and a small industrial base (centered primarily with defense primes and major subcontractors) has existed for many years. These firms have generally been weapon system oriented, producing a unique product for each new application. FPA production has long been plagued by producibility and affordability problems, although recent investment programs appear to have improved this situation. The relatively slow progress of the technology has now been speeded by the promise of a rapidly growing market, and industry is beginning to expand accordingly. With the possibility of 140 defense applications over the next 10 years, Japanese and French firms have also entered the market and are showing strong signs of reaching the level of U.S. capability. This will increase the competitive pressures on U.S. firms if demand grows as expected.

PHOTONICS

1. Introduction

Photonics encompasses technologies and devices that use both light (photons) and electronics (electrons) to perform functions that have traditionally been performed by electronics. Photonics and electronics are complementary rather than competitive technologies. The greatest near-term success of photonics is expected to be in areas where photonics can interface easily with electronics and take advantage of the large infrastructure and growth momentum that the electronics industry enjoys.

Photonics is still in its infancy and currently represents a very small percentage of defense hardware expenditures. At present, photonics is firmly established in range-finders, target illuminators, ground and ship communications, and guidance, low-level light, and forward-looking infrared (FLIR) sensors. In addition, there are many future applications that will improve capabilities in areas such as optical processing, where order-of-magnitude improvements in processing speed are promised. This is especially important to achieve the data processing rates required by emerging applications in electro-optical and infrared sensors, electronic warfare, and undersea surveillance. Other advantages of optical processing include size and weight reductions and improved reliability due to reductions in the number of connectors and enhanced resistance to electromagnetic interference.

Although fiber optics is not generally considered a true part of photonics, it is described in this section because it is a crucial supporting technology (and industry) for photonic systems. Fiber optics support much higher bandwidth communications, which make the technology important for supercomputers, high-throughput signal processors, and long-range communications. Development of ultra low-loss fluoride fibers could revolutionize undersea surveillance, long distance communications, and fiber guided missiles. In addition, fiber optic interconnections in photonic systems are instrumental in achieving low susceptibility to electromagnetic interference.

Figure 1 summarizes the photonics technology challenges identified in DoD's FY90 ***Critical Technologies Plan***, along with defense applications and the supporting industrial infrastructure. Photonics is both directly and indirectly related to other critical technologies. In particular, photonic systems are dependent upon technology and industrial capabilities associated with Semiconductor Materials and Microelectronic Circuits. Other critical technologies relating to photonics include Parallel Computer Architectures, Passive Sensors, Sensitive Radars, Signal Processing, and Data Fusion.

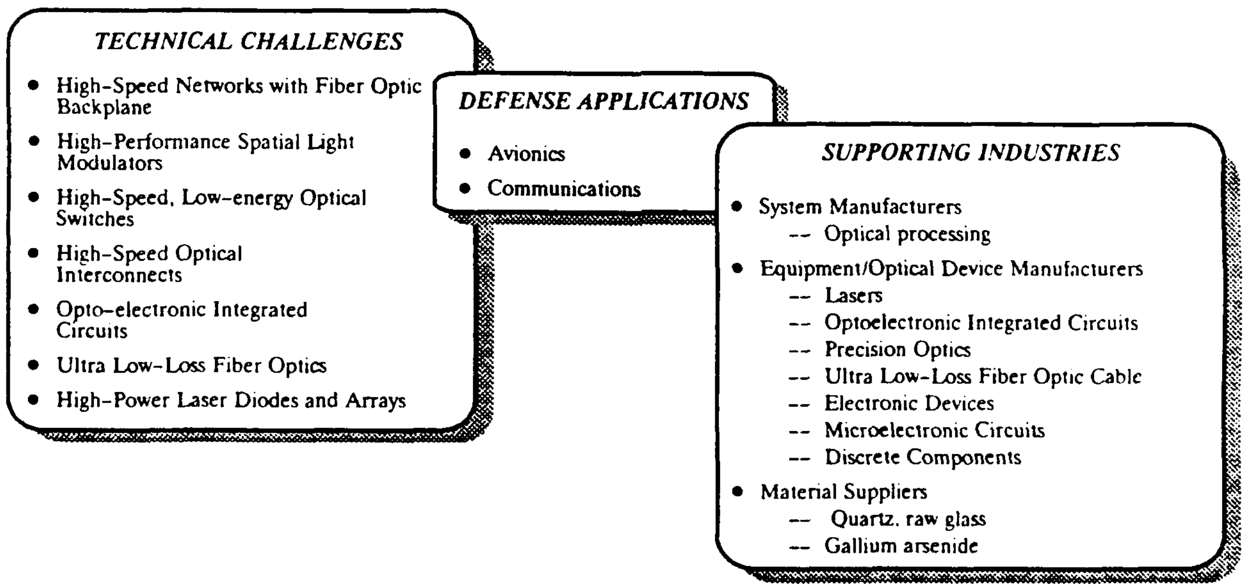


Figure 1. Technical Challenges and Supporting Industries

2. Industry Structure

With the exception of fiber optics and precision optical components, most photonics-related technologies are still in development. As a result, the supporting industrial base is only loosely structured and significant changes are anticipated to support the variety of likely applications. The spending on photonics is projected to be significant enough to require both the creation of new industries and the expansion and reorganization of existing ones. New industry sectors will be required to produce large quantities of photonic devices efficiently, while existing major corporations may be restructured to develop, manufacture, integrate, market, and support these new products. This infrastructure will in all likelihood comprise several existing industry sectors that have not traditionally been trading partners and do not have established linkages.

Optical processing provides an example of the changes in existing industries that may occur as photonics applications reach production. The differences between existing technologies and optical processing are sufficiently great that an essentially new industrial sector should be formed from pieces of two current industries: electronics and optics. This process is expected to be difficult and time-consuming from business and cultural standpoints. For example, design skills required for photonics will be different from (and perhaps in conflict with) the skills and organizational structures that have typified the electronics and optics industries. New manufacturing processes, controls, and facilities will be required. New business territories and niches will be created as the field expands. Optical processing will involve not only different kinds of products that fill existing and new market needs, but also new business relationships involving trading partners and suppliers.

Figure 1 identifies some of the industrial base elements that are major contributors to photonics technology. System manufacturers - many which are computer companies, weapon system and subsystem producers, and producers of optical memories — design and assemble photonic systems, using components and parts supplied by the other industries on the chart. With some exceptions, subsystems producers tend to be large, well-established companies with active photonics programs that are applicable to current lines of business.

Among the other industrial elements, optical device manufacturers produce solid state lasers and optoelectronic integrated circuits, as well as the equipment for producing these products. Fiber optics — optical quality fibers for communications and optical processes — involves a separate group of producers who represent a healthy and relatively mature industry. Several types of electronic devices are also critical to photonics systems, and suppliers of microelectronic circuits and discrete electronic components form another important industrial base segment. Across all of these industrial base elements are hundreds of companies engaged in some aspect of photonics R&D or product development. A representative group of firms that are current participants in the photonics area is shown in Table 1.

Table 1. Representative Firms in Photonics Industry 50 Stock Index

Technology Area	Representative Firms
Analytic Instruments	Hewlett-Packard, Perkin-Elmer
Optical Components	Bausch & Lomb, Eastman-Kodak
Lasers	Coherent, Quantronix
Electro-Optics	EG&G, EDO
Fiber Optics	Coming, Raychem, AT&T
Imaging	Aydin, Floating Point

The competitive challenges facing the nation's photonics industry are similar to those that face electronics suppliers. Since defense-related products are expected to represent a small percentage of the total market, the quality, cost, and technological content of military photonics systems will be largely determined by the strength of the commercial industry. The ability of the photonics industry to compete effectively in the commercial marketplace — both domestically and internationally — is therefore of paramount interest to defense.

Foreign sourcing is common in many of the supporting industrial sectors for photonics. The ability of the domestic precision optics industry, including optical materials, to support the needs of emerging photonic systems is questionable. This industry sector is increasingly unable to supply domestic needs for either electronics or photonics, including diode lasers, integrated circuits, and semiconductor lasers. Fabrication equipment for optics is already largely foreign-sourced.

There are a number of other supporting industries for photonics whose viability is threatened by foreign competition. The fiber optics industry is slowly losing its parity with the Japanese, who are beginning to emerge as the world leader. Electronic integrated circuits and discrete devices are also an important part of photonics, since virtually all future photonics systems will have critical electronic components. Suppliers of microelectronic circuits are facing strong foreign competition (see Semiconductor Materials and Microelectronic Circuits) and, while the discrete devices industry in the U.S. is generally strong, some weaknesses could appear in specialized devices necessary for photonics applications.

3. Condition of the Industrial Base

a. Sales

The industrial base for photonics is highly diverse and the maturity of different product lines and strength of various segments varies considerably. There are some current sales in the area, many of which involve commercial products and are derivative of existing technologies. As an example, several industry sectors now supply optical devices for photonics systems. Lasers are produced over a wide power range by many different companies for many applications. Total worldwide laser sales are about $1 billion per year — approximately 10 percent are military sales, primarily solid state lasers.

However, the true potential of photonics products lies in the future. There are several major markets envisioned to have a high potential for photonics applications, including telecommunications, information processing, information storage, avionics, and other defense products. Each of these markets has worldwide hardware sales of $100 billion or more per year. Applications of photonics and opportunities for sales growth within these industries are as follows:

- In telecommunications, fiber optics equipment is already the most rapidly growing item in the industry, and photonics is expected to increase in importance, particularly as a supportive technology for electronics. Inroads by photonics will be determined by the progress of integrated optics and integrated optoelectronic technologies.
- Information processing provides growth opportunities for photonics because of the dramatic advantages offered by fiber optics. In particular, the future growth for photonics is envisioned to occur in the interconnections between electronic box areas. This will include connecting printed circuit boards to one another and eventually connecting chip-to-chip as well as within a chip. An example of a rapidly growing photonics application in the information processing market is the laser printer.
- In the area of information storage, photonics-based optical disk technology is projected to grow at an overall rate of 15 percent per year over the next five years and is expected to capture a large fraction of the market away from magnetic storage. Today, photonics is firmly established in write-once, read-only archival storage optical disks, as well as in video and audio compact disks. Optical storage media can store 500 times more data than a floppy disk of comparable size. There will be intense international competition in this area as the use of

optical disk technology grows. Japanese firms are well ahead of U.S. companies in cost and quality of optical disks, and the level of investment being applied to the areas in the U.S. is not expected to reverse Japan's well-entrenched leadership position.

- In avionics, photonics currently has a very small percentage of the market, although it is firmly established in low-light level and IR sensors and navigational systems, such as the laser gyro and fiber optics gyro. Future growth is forecast in fly-by-light systems, fiber optics data bases, air-to-ground laser radars, obstacle avoidance systems for helicopters, fiber optic sensors embedded in composite structures to monitor the structural health of high value mechanical airborne structures, and air data and recording systems for aircraft flight controls.
- In addition to these future markets, photonics has other potential applications that are unique to defense. The one military application for photonics with no parallel application in electronics is directed energy/laser weapons.

The growth potential of other photonics products is noteworthy. Solid state lasers have been identified as a key technology for long-term growth of the laser market. For photonics applications, the main area of interest is semiconductor lasers, a subset of solid state lasers. Diode pumped solid state lasers serve as a source of energy to power photonics devices, and their market is reported to be doubling every year. Although some U.S. capability to produce laser diodes exists, they are chiefly purchased from Japan for both quality and cost reasons. Military sales average $5 million per year (200 units) compared to 1989 commercial sales that were about $7 million (500 units). Commercial sales in 1990 are projected to grow to about $15 million (1100 units).

Commercial applications are important drivers in the growth of the photonics industry and are responsible for many of the advancements that are being made today. Thus, there is a considerable overlap between defense and non-defense applications. Optical processing is a particularly important commercial market for the future and is considered a leading means of continuing the historically steady reduction in the cost of computing power. The fiber optics market is already well-established and the use of fiber optics in communications continues to grow rapidly. The current status and future condition of the fiber optics and photonic computing industries are discussed below.

b. Investments

With such a broad range of potential applications, photonics is the subject of intense R&D throughout the world. The DoD ***Critical Technologies Plan*** provided data on overall R&D investments for photonics. Reliable industry data on the degree of investment in photonics R&D and product development are not available. However, a growing non-defense market has stimulated a large number of companies to enter the field. As an example, the January 1990 issue of ***Photonics Spectra*** stated that, in addition to many small companies, over 400 New York firms are engaged in some aspect of photonics, including Corning, IBM, Eastman Kodak, General Electric, and Xerox.

The non-defense effort provides an important source of technology and technical expertise in areas that are projected to be critical to future defense systems. A large number of companies, for example, are pursuing R&D and product development in commercial applications of optical processor and diode lasers. A healthy commercial "photonics industry" will therefore be of considerable importance to DoD.

Despite the industry-wide interest in photonics, there are reasons for concern about the R&D base. First, payoffs are diminished by the fact that much of the R&D performed in the U.S. is fragmented. Among larger firms, privately funded R&D and product development activities are very closely held and rarely shared. The heavy involvement of smaller companies fosters this fragmentation because the resources of these firms are limited and they also tend to hold their results.

The limited amount of R&D for process technologies is the second concern. Despite the relatively large amount of R&D that is being performed, relatively little attention is given to the R&D that is needed to develop low-cost manufacturing techniques and processes that will eventually permit the rapid production of quality products. In contrast, there is every indication that the historical Japanese concentration on R&D to improve manufacturing quality, cost, and speed is also the case in photonics. This may well give them the future competitive edge.

A third concern about the state of R&D is that most of the cooperative efforts in the U.S. are centered around universities. Such arrangements are very effective in research, but have proven quite ineffective for rapidly transitioning research successes into marketable industrial products. The U.S. has traditionally been weak in making this transition in most high technology areas.

c. Joint Ventures, Mergers, and Acquisitions

There is little information available on joint ventures, mergers, and acquisitions in photonics. However, foreign nations (particularly Japan) are vigorously pursuing photonics technologies. The international competition is strong in both R&D and in the race to field successful products. The U.S. and Japan are generally recognized as the co-leaders in the development of this technology, with Europe very close behind.

In Europe, there are numerous company-sponsored development activities and several cooperative efforts, most centered around European universities. These R&D initiatives are multinational in nature, with the largest being the European Joint Optical Bistability Project. The level of effort in Europe is not known, but is thought to be roughly comparable to that in the U.S.

d. Analysis of Infrastructure Segments

Fiber Optics

Fiber optics technology is rapidly growing in importance in both military and commercial products. The next decade is expected to see the proliferation of fiber optics applications to a wide range of sensors, communications equipment, and electronics products because of the advantage fiber optics has over copper. Compared to copper cables, fiber optics have four orders of magnitude greater information carrying capacity, two orders of magnitude lower energy loss in signal transmission (with current fiber materials), and far greater resistance against electromagnetic interference. The rapidly growing field of semiconductor lasers will provide even greater improvements in information-carrying capacity.

The U.S. and Japan are considered to be the world leaders in fiber optics. Efforts in both R&D and production applications are underway in the U.S., Japan, and Europe, as well as in the U.S.S.R., Israel, and Korea. As is the case in many new technologies, U.S. and European R&D is more heavily focused on advanced product capabilities, while Japanese efforts concentrate much more strongly on manufacturing capabilities. The competitive concern is that Japanese concentration on manufacturing quality and cost may ultimately pay off in worldwide market domination in fiber optics. Military applications for fiber optics are expected to represent a small percentage of the total market, so the strength of the commercial side of the industry is of significant interest to DoD.

The telecommunications industry is performing extensive R&D and currently provides the strongest volume demand for fiber optic technologies and products. A number of experimental and demonstration projects provide combined information services and television to individual homes. Widespread implementation of this concept would result in increased demand for a variety of fiber optics products. Other commercial applications include process control, medical, and safety monitoring. The combination of semiconductor lasers and fiber optics is projected to see increasing application in computers and many other electronic devices.

In addition to military versions of these commercial applications, fiber optics are expected to provide order of magnitude improvements to many surveillance and guidance needs. Fiber optic communication links will add a new range of capabilities for missile guidance since they allow wideband, non-line-of-sight two way communications. They also will provide local and tactical voice and data communications networks with much greater capacity, reliability, security, and survivability. Fiber optical sensors will allow major improvements in underwater acoustical detection and surveillance, as well as providing the basis for autonomous underwater vehicle guidance. Solid-state fiber optical gyros offer the potential for improvements in both cost and accuracy, along with significantly improved ruggedness and reliability.

A number of U.S. companies are involved with military and commercial applications of fiber optics, as well as in the development and production of the related materials and components. Development programs are in progress which use fiber optics cable instead of metal wire for communications, phased array radars, and aircraft "fly-by-light" controls. Fiber optic gyros are also under development, and there is some commercial application for successful fiber optic gyro products.

U.S.-based manufacturing capability for fibers and interconnects rests in five companies, although there are other, specialty producers. Of the five companies, two produce fibers and interconnects largely for the telecommunications industry; one of these is French-owned. One company supplies fibers and interconnects to telecommunications, as well as speciality fibers. Its low-loss fiber product is based on a German license. Two other companies are fiber producers who also supply specialty fibers so important to many defense applications. However, foreign suppliers from Japan are reported to be the leaders of high quality specialty fiber. Their responsiveness may be largely because of their continuing interest in remaining aware of applications of the technology in the U.S. Employees of some of these firms participated in fiber optic gyro development efforts at U.S. universities.

U.S. interests in, and capabilities for, supplying the military's requirements for fiber optics are of increasing concern because of anticipated defense market size and because of international competition. Never anticipated to be large, the DoD share of the fiber optics market is likely to shrink further with the anticipated decline in defense systems acquisition. As is the case with many other critical technologies, a healthy commercial market will be necessary to sustain defense operations.

It is not clear that domestic companies are currently making, or are able to make, the investments considered necessary to match the international competition over the longer term. European and Japanese companies have a considerable advantage in being able to benefit from a range of cooperative efforts which do not exist in the U.S. Further, they benefit from substantial government funding for commercial product development and manufacturing process and equipment development that has no counterpart in the U.S. Aside from an Army-funded effort to develop a rugged, non-kinking fiber optic cable for the Fiber Optic Guided Missile (FOG-M), there is little manufacturing R&D supported by DoD. Industrial efforts are not well characterized, but are believed to be substantially less than those being pursued in Japan. Without substantial change, the long-term ability of U.S. producers to even retain domestic market share is being increasingly questioned.

Optical Processing

The advantages of military applications of photonic computing are similar to those of commercial applications, including much higher processing speeds and bandwidth. Computing systems that possess these advantages would have pervasive application to defense. The ability of such systems to process large amounts of data effectively, simultaneously delivered from multiple sensors, is extremely important to such functions as: automatic target detection, recognition, and tracking; Electronic Counter-Countermeasures (ECCM) for all types of sensors; and undersea surveillance. An important intermediate stage in the application of optical processing is dedicated photonic processors, which could act as sensor front ends to reprocess data from sensors and reduce data rates so that they are compatible with electronic processors.

Military application of optical processing techniques, however important to defense capabilities, is anticipated to make up a very small segment of the market. Defense requirements will be too small to sustain a separate industrial infrastructure, and military application must draw on robust engineering and manufacturing capabilities that are created and maintained by non-defense markets. Therefore, the analysis in this section primarily focuses on the commercial drivers and competitive factors with which industry sectors must contend.

Optical processing has been projected to have the potential to revolutionize the computer industry. Such projections are founded on the belief that all electronic computing could be ultimately converted to photonics, beginning with applications now addressed by supercomputers, mainframes, and minisupercomputers.

Optical data storage methods are projected to replace magnetic methods rapidly in larger-scale computer systems. Optical data storage capabilities and retrieval rates provide order of magnitude capability increases over magnetic storage devices. These applications are steadily growing and are expected to grow much more rapidly as costs are reduced and as familiarity with the technology continues to grow.

Although the power and capability of personal computers will continue to grow rapidly, larger-scale computers, from superminis up through supercomputers, are the backbone of the entire computer industry. Projections that optical processing will revolutionize this industry also make it very clear that companies which do not match the pace of international competition in introduction of photonics-based computing projects cannot be expected to remain viable into the future. Therefore, such projections conclude that the ability of the U.S. to retain a strong computer industry is a direct function of the ability of that industry to compete successfully in photonics applications.

A particular area of Japanese strength is optical processing, and Japan's R&D programs in this area enjoy the widespread support of government, industry, and universities. Levels of funding are thought to be considerably higher than in the U.S. A special organization, the Opto-electronic Industry and Technology Development Association, was founded in 1984 to coordinate industrial activity, foster cooperation, and encourage standardization. Also in 1984, the Japan Society of Applied Physics established a research body, the Optical Computer Group, composed of government, university, and industry participants. Establishment of cooperative organizations indicates the seriousness with which the Japanese are treating the area and the formidable international competitive environment faced by U.S. participants.

Introduction of successful commercial optical processing products and the growth of an internally competitive photonics computer industry are therefore expected to require not only the rapid, successful merging of elements of the current electronics and optics industries, but also the successful development and affordable availability of several critical elements. These were depicted in Figure 1 and include: high-performance spatial light modulators; high-speed, low-energy optical switches; high-speed optical interconnects; opto-electronic integrated circuits; and high-power laser diodes and arrays.

4. Summary

Analysis of the above requirements for achieving a viable optical processing industry reveals four different sets of priority problems to be solved: reversing the semiconductor industry decline; successful development of technology to create the critical elements; merging of the photonics and electronics industries; and rapid manufacturing implementation of the critical elements. The semiconductor industry situation is discussed in detail under Semiconductor Materials and Microelectronic Circuits. There is considerable R&D effort being spent to solve the technical problems presented by the critical elements. On balance, these efforts match the international competition, although more cooperation and focus among the commercial efforts would be beneficial.

Merging portions of the optics and electronics industries will be difficult. The precision optics industry is not strong and is largely consumed by an effort to retain its current markets. The situation is only slightly better for microelectronics. Management and technical energies available for the area at present are being spent on the technology development activities, with business relationship changes being treated as evolutionary. The concern is that an evolutionary approach may not proceed rapidly enough to match the international competition, particularly the Japanese.

Rapid manufacturing implementation of successful R&D in the critical elements is a concern. The historical inability of domestic industries to match the pace set by the Japanese has been discussed elsewhere in this report because it is so pervasive. It is particularly a problem in photonics due to a lack of emphasis on process R&D and focus on short-term return on investment. R&D emphasis (based on the critical technology elements) is strongly focused on device and potential product R&D. As a result, it will be time consuming for domestic companies to create the manufacturing facilities and equipment necessary to produce the critical elements. With their emphasis on manufacturing and market share, the Japanese companies can be expected to introduce products of higher quality and with a relatively low price. In that event, it will be very difficult for domestic companies to capture significant market share, even in the domestic market.

Establishment of a viable domestic commercial industrial base for optical processing is critical to future defense needs. However, it is forecasted to be very difficult, given the current industry structure and investment posture.

SEMICONDUCTOR MATERIALS AND MICROELECTRONIC CIRCUITS

1. Introduction

Microelectronics underlies nearly all segments of the commercial economy and represents a crucial part of virtually every DoD system, from weapons to communications. Advances in this technology will improve the performance, cost-effectiveness, reliability, and availability of existing defense systems and make the development of entirely new weapon system concepts possible. These goals require industry to break new ground in a variety of microelectronics technologies and processing techniques. Figure 1 summarizes the microelectronics technology challenges identified in the FY90 ***Critical Technologies Plan***, along with industrial base segments that will be called upon to meet these challenges.

2. Industry Structure

The industry is generally thought of in terms of two closely linked segments: semiconductor manufacturers and semiconductor materials and equipment (SME) producers. Both are important to our capability to develop and produce products for defense, and their strong relationship makes each segment crucially dependent on the other's success. The two types of firms in the semiconductor manufacturing segment are "captives,"[1] which produce integrated circuits (ICs) and related products for internal use, and "merchants," which manufacture these products for sale to others. Within the SME segment, materials suppliers provide pure silicon, gallium arsenide (GaAs), specialty chemicals and gases, and other materials needed in the production of complex semiconductors, while the equipment segment manufactures equipment to produce and test semiconductor products at every stage of the production cycle. As will be described below, both segments are facing rapidly declining market shares and a growing inability to meet DoD's development and production needs.

Additionally, flat panel display manufacture is closely related to semicondcutor manufacture. It utilizes many of the same tools, processes, and materials. Many of the top competitors in display

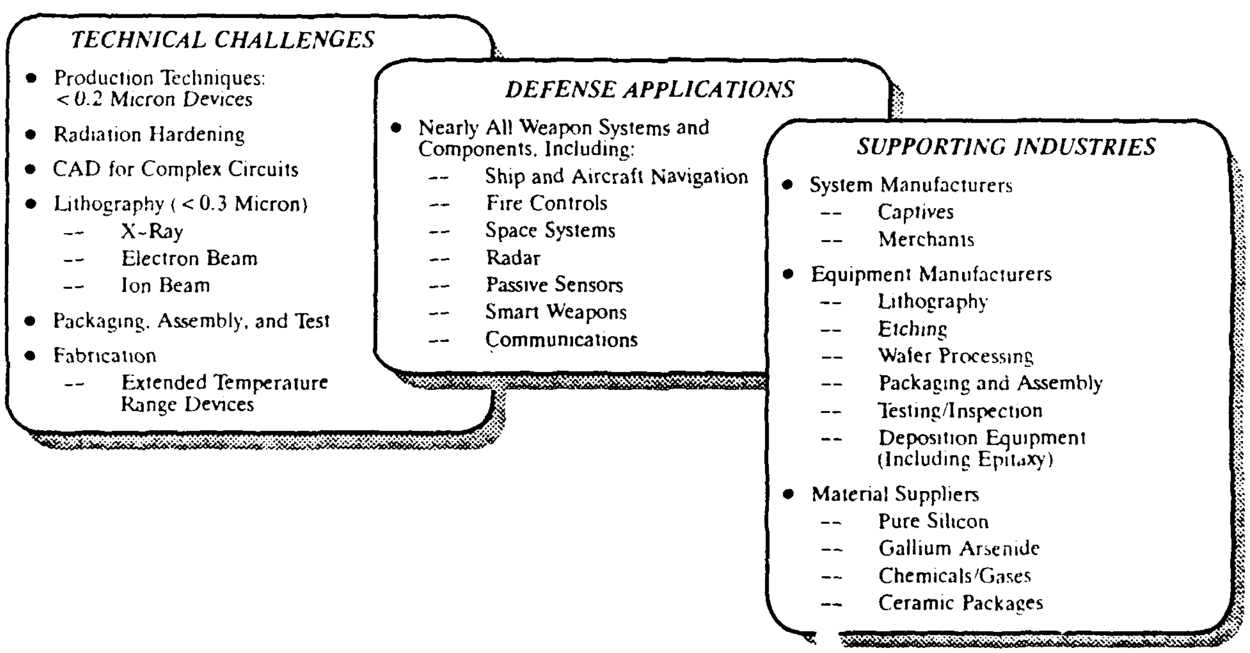


Figure 1. Technical Challenges and Supporting Industries

[1]Many of the largest electronics firms in the U.S. (such as IBM, which produces about 85 percent of its own ICs) are captives; however, most data exclude captive producers.

technology today have penetrated that market based on their experience in semiconductor fabrication. In particular, thin film transistor active matrix liquid crystal displays (AMLCD) are sometimes described as IC on glass. The display itself is fabricated by first depositing silicon on a glass substrate, then processing with plasma etchers, steppers, and other semiconductor manufacturing equipment. An AMLCD display contains a transistor for each pixel and may also contain on-glass-driver and demultiplexor circuitry. Other flat panel display technologies such as plasma and electroluminescent likewise make extensive use of semiconductor tools, processes, and materials.

Flat panel displays are critical for many military applications. They improve the functionality and effectiveness of aircraft cockpits, armored vehicles, man-packed portable communications and intelligence equipment, and shipboard and submarine combat information centers. The specifications of such military applications are often significantly different from commercial and consumer applications, such as the need for square pixels in cockpit displays. Reliable and affordable sources that can produce display devices to military specifications are necessary. Although much of the flat panel display technology was initially developed by U.S. companies, the domestic flat panel display industry has been under intense pressure from foreign competitors. As described in Table 1, many companies have either ceased to exist, or have ceased to develop and manufacture flat panel displays.

Table 1. Status of U.S. Producers of Flat Panel Displays

COMPANY	EL	LCD	PDP	OTHER	STATUS
Alphasil		•			ceased operation
AT&T			•		ceased operation
Cherry	•				production
Coloray				•	seeking funding
Control Data			•		ceased operation
Crystal Vision		•			ceased operation
Electro-Plasma			•		production
EPID				•	ceased operation
GE		•			sold technology
GTE	•				ceased operation
IBM			•		ceased operation
Magnascreen		•			developing
Ovonic		•			developing
Owens-Illinois			•		ceased operation
Panelvision		•			sold technology
Photonics			•		production
Planar	•				production
Plasma Graphics			•		ceased operation
Plasmaco			•		developing
Sigmatron Nova	•				ceased operation
Texas Instruments			•		ceased operation
Xerox		•			developing

Key: EL = Electroluminescent; LCD = Liquid Crystal Display; PDP = Plasma Display. "production" = Company is a going concern producing flat panel displays

SOURCE PLANAR SYSTEMS, INC

Other important contributions to this critical technology area are also made by industries that develop and produce computer-aided design (CAD) tools, software, computers, machine tools, and other products and equipment necessary to sustain the nation's microelectronics base.

3. Condition of the Industrial Base

a. Sales

The semiconductor manufacturing segment, which supports the $760 billion per year global electronics market, had worldwide sales of $55 billion in 1989. The market has historically grown at an annual rate of about 16 percent and could reach $70 billion by 1993. Sales and profitability for various product lines differ considerably. The ten leading semiconductor products,[2] which chiefly include Metal Oxide Semiconductor (MOS) digital memory and microdevices, grew by an average of 134 percent between 1987 and 1988, with growth of an additional 42 percent forecast for 1989. Worldwide sales in other product lines (such as the bipolar digital and analog markets) have been flat and were expected to decline by 20 percent or more in 1989.[3] The market shares of the five leading firms in each major semiconductor product line are indicated in Table 2. U.S. companies have lost significant market shares in the high-growth markets, which are now dominated by Japanese firms. As an example, the U.S. share of the $4 billion DRAM market declined from 100 percent to less than 5 percent over a ten-year period, leaving Japan as the only major supplier of DRAMs in the world today.

Table 2. Market Shares and Sales for Leading Semiconductor Products (Percentage of Market, Rank)

COMPANY	INTEGRATED CIRCUITS								
	BIPOLAR DIGITAL			MOS DIGITAL					
	Bipolar Digital	Bipolar Digital Memory	Bipolar Digital Logic	MOS Memory	MOS Micro-devices	MOS Logic	Analog	Opto-Electronic	Discrete
U.S.									
Advanced Micro Devices	10 8 (3)	23 5 (2)	9 1 (5)						
National Semiconductor	9 8 (5)	9 5 (4)	9 8 (3)				6 1 (2)		
Texas Instruments	14 4 (1)		16 4 (1)						
Motorola					9.9 (3)	5 8 (4)	4 9 (5)		10 2 (2)
Intel					23 5 (1)				
Hewlett Packard								9 1(5)	
LSI Logic						6 3 (3)			
Japanese									
Fujitsu	13 4 (2)	27 7 (1)	11.3 (2)	8 4 (4)		5 3 (5)			
Hitachi	10 5 (4)	18.8 (3)	9.3 (4)	9.8 (3)	6 8 (4)				9 1 (3)
Philips		7.8 (5)					5 1 (3)		5 8 (5)
NEC		7.8 (5)		11.3 (2)	12 5 (2)	9 7 (2)			7 3 (4)
Sony								10 6 (3)	
Toshiba				12 3 (1)		10 0 (1)	6 2 (1)	9 2 (4)	11 2 (1)
Mitsubishi				7 8 (5)	5 5 (5)				
Matsushita								13 0 (2)	
Sharp								14 0 (1)	
Sanyo							5 0 (4)		
TOTAL MARKET (1989)	**$4.6B**	**$0.6B**	**$4.1B**	**$15.6B**	**$8.1B**	**$8.6B**	**$9.1B**	**$2.3B**	**$7.6B**

Source: Dataquest

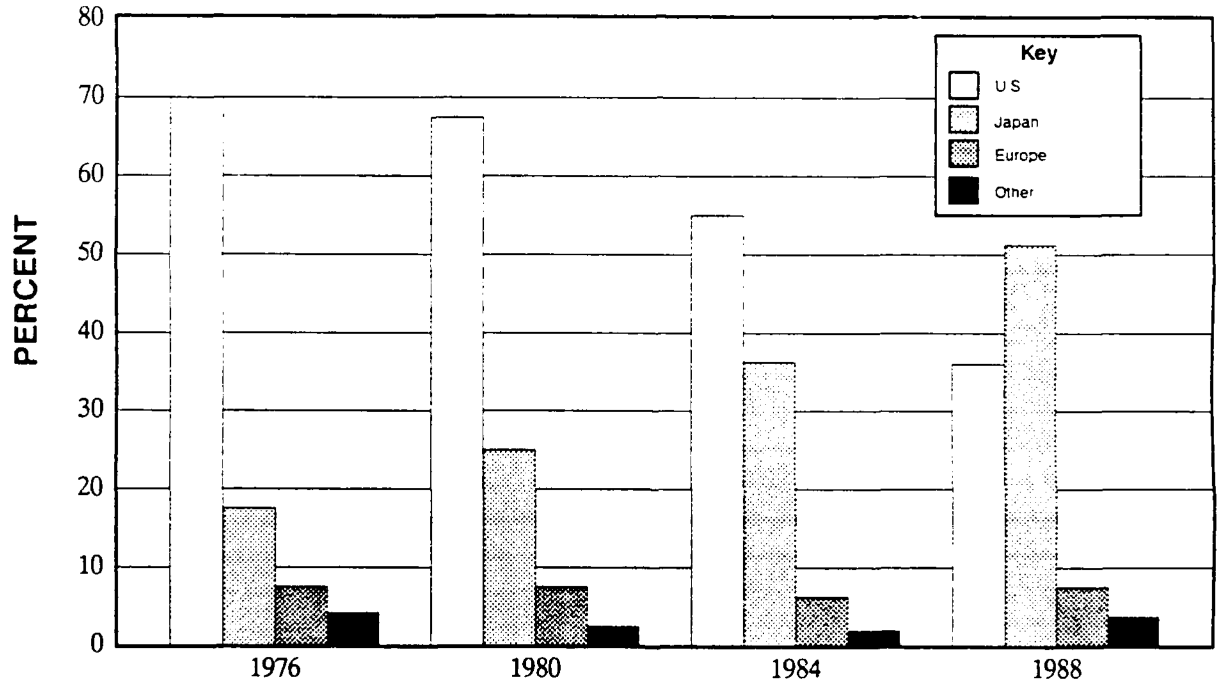
[2] High-growth products are CMOS DRAMs, CMOS MPRs, CMOS MPUs, CMOS PLDs, CMOS EEPROMs, CMOS EPROMs, CMOS SRAMs, NMOS DRAMs, CMOS ROMs, and CMOS MCUs.

[3] Slower growth markets include Bipolar PROMs, NMOS SRAMs, NMOS MCUs, SSI/MSI S/TTL, SSI/MSI ECL, NMOS MPRs, NMOS EPROMs, NMOS MPUs, other Bipolar Logic, and LSI S/TTL.

Although there are nearly 300 captive and merchant semiconductor manufacturers throughout the world, the industry is dominated by the ten largest firms, which account for well over half of the world's sales and are among its largest manufacturers.[4] The U.S. once dominated the top ten, but only three firms on the current list — Motorola, Texas Instruments, and Intel — are U.S.-owned. Although the U.S. industry has been generally profitable, the domestic market share for semiconductors has declined significantly over the past decade, calling into question the ability of firms to generate revenue to continue to develop, produce, and market leading-edge technologies. In 1980, the U.S. was world leader in both technology development and sales, with a 67-percent global share.

By 1986, Japan had emerged as the world leader. Figure 2 depicts the shift in market share that has occurred over the past 15 years.[5]

Although large firms play an important role in the semiconductor materials and equipment segment, most of the 850 firms in the domestic industry have annual sales of less than $25 million. Figure 3 represents worldwide market share for Semiconductor Manufacturing Equipment. Further, many small vendors have disproportionate importance to the national defense because they occupy narrow product niches (and may be sole-sources) of critical products. In contrast, Japan and Europe have far fewer firms — about 200 and 174 respectively — but these companies are significantly larger and better

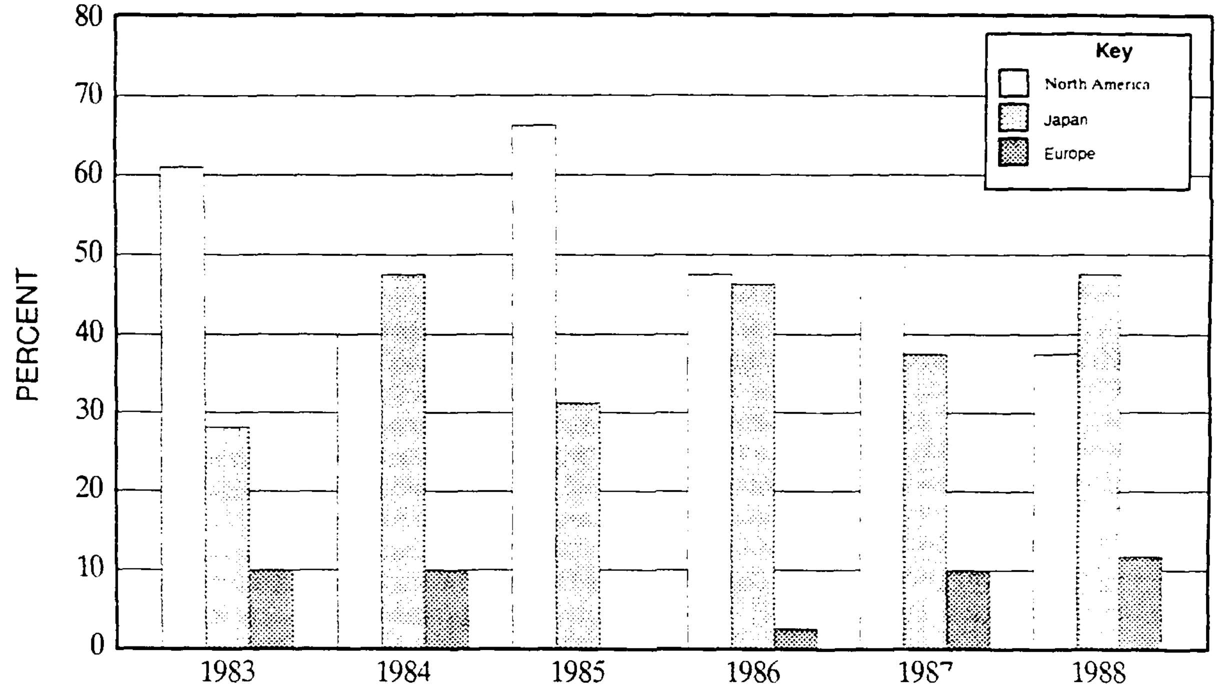


Source: Integrated Circuits Engineering

Figure 2. Worldwide Merchant Semiconductor Market Share

[4]For example, the two largest semiconductor suppliers — NEC and Toshiba — both had 1989 revenues of nearly $5 billion. Dataquest, Research Newsletter, 1990-1.

[5]***Mid-Term 1989 Status and Forecast of the IC Industry***, Integrated Circuit Engineering Corporation, p. 1-9. Japanese sales growth can be attributed to a number of factors: success in marketing such high-volume and/or high-growth products as DRAMs, SRAMs, EPROMs, and Applications Specific Integrated Circuits (ASICs); competitive pricing and quality advantages; effective strategic planning; low cost and improved access to capital; favorable exchange rates; lower profitability expectations; and greater vertical integration. In addition, many observers believe that Japan has benefited from targeting actions, which have closed its market to U.S. semiconductor manufacturers.



Source: VLSI Research, Inc.

Figure 3. Worldwide Market Share for Semiconductor Manufacturing Equipment

financed than their U.S. counterparts. This has given them a competitive edge in the volatile and rapidly changing SME market.

This market has also seen a shift to offshore sources since 1980. Although the U.S. has retained world-class capabilities in some technologies, Japan is now the acknowledged industry leader. As examples of our foreign dependence, recent surveys have shown significant U.S. foreign sourcing for such key items of equipment as stepping aligners, resist processing, scanning electron microscopes, wafer saws, die bonders, tape automated bonders, mold and sealing equipment, and molding presses. In many cases, the dependency for these items is nearly total. This decline in U.S. capabilities is projected to continue, and the National Advisory Committee on Semiconductors now forecasts that 75 percent of the next-generation processing equipment purchased by U.S. companies will be of Japanese origin.

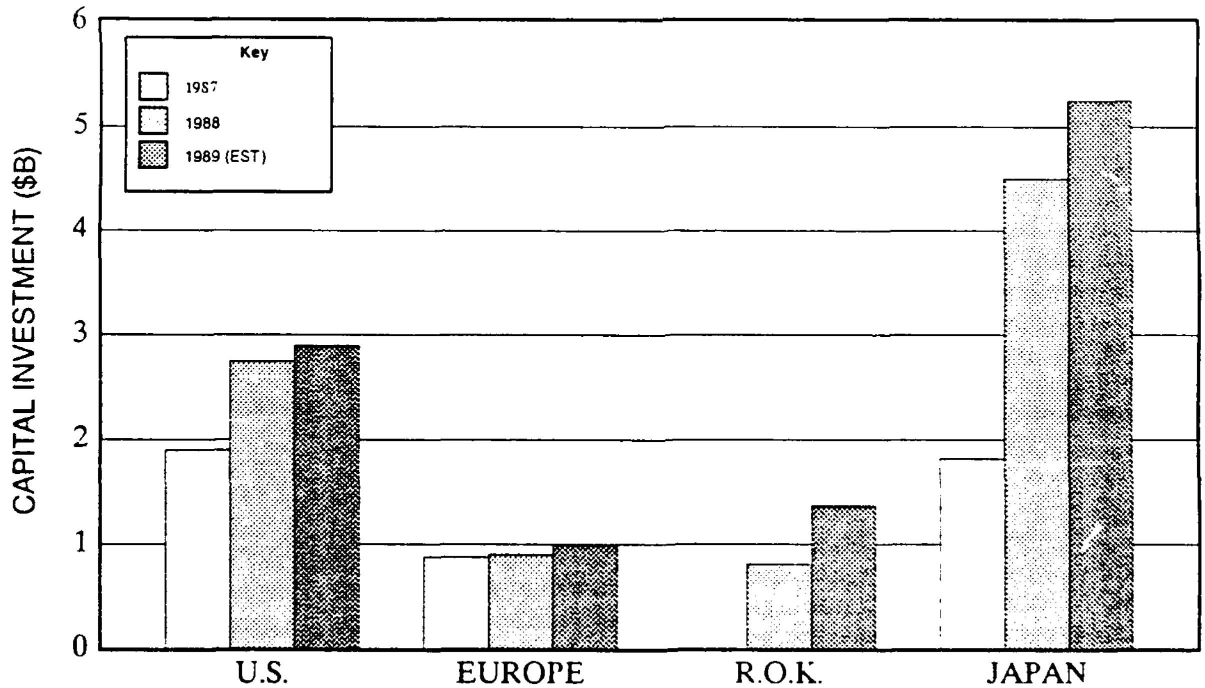
b. Investments

An important indicator of an industry's condition is its ability to maintain adequate investment in R&D and plant and equipment. Prior trends in this industry have shown a strong correlation between higher than average capital expenditures and market share gains. Consequently, the lower than average level of U.S. investment in recent years has presented serious implications for the future viability of the domestic industry.

The microelectronics industry is highly capital-intensive due to the rapidity of technological change. The dramatic loss of U.S. market share in consumer electronics has led to an even greater erosion in revenue for R&D and has impeded the ability of U.S. semiconductor manufacturers to sustain the high level of investment that is required to remain at the leading edge. In an industry where a new generation of products is introduced every 2 to 5 years, investment in new product development can reach as high as 25 percent of sales — many times higher than other industries. In addition, semiconductor production equipment required by manufacturers is complex and expensive and may need to be replaced every few years as new generations of products come on line. Like semiconductor manufacturers, the SME industry must make large investments to keep pace with rapidly changing processing requirements of new semiconductor technologies. The life cycle of a typical item of equipment is generally under ten years. One recent analysis concluded that "...the capability of a modern IC plant is a function of the capital equipment installed. Plants with sets of three-year-old equipment cannot economically produce state-of-the-art designs at reasonable yields, and may not be able to build them at all."[6]

Despite the U.S. Government and private industry spending record of $3 billion in industry-wide R&D and another $3.5 billion in capital investment in 1988, the Japanese have consistently outspent the U.S. since 1982 — by $2 billion in 1988 alone. In 1989, Japanese capital investment is projected to be twice that of the U.S. Recent trends in capital expenditures are shown in Figure 4. The disparity in overall investment between the U.S. and Japan is also reflected in expenditures by individual firms. During 1988, leading U.S. semiconductor manufacturers invested slightly over $200 million each in plant and equipment, while the investment of leading Japanese firms averaged well over $400 million.

Although it is clear that the bulk of R&D and capital funding must originate with the private sector, the Federal Government has assumed a more active role in helping industry to develop and bring to production a variety of new microelectronics products. Increasingly, these initiatives represent a partnership between the public and private sectors. In August of 1987, for example, several U.S. semiconductor and computer firms (both "merchant" and "captive" producers) banded together to form Sematech, Inc., a consortium designed to respond to the loss of U.S. semiconductor market share. Operating under the leadership of DARPA, Sematech was established to conduct research and development in the semiconductor industry in order to increase domestic capability and achieve eventual world leadership in semiconductor manufacturing. Congress appropriated $100 million in FY88 and another $100 million in FY89 as the Government share. In return, member companies are required



Source: Integrated Circuits Engineering

Figure 4. Microelectronics Capital Investment

[6] ***Free-World Microelectronic Manufacturing Equipment***, Foreign Applied Sciences Assessment Center, Technical Assessment Report (FASAC), December 1988, p. 1-3.

to provide at least 50 percent of Sematech's operating budget of about $200 million per year. Another consortium to increase domestic capabilities in the industry — U.S. Memories — has been unsuccessful. Established in 1989 to promote R&D in high-speed DRAMs, the partnership had a life span of only six months. The push to start a DRAM consortium modeled after Sematech was by the request of U.S. systems manufacturers, who feared an increase in dependence on foreign manufacturers. However, the $1 billion in starting capital needed to sustain the venture could not be generated in the time frame needed. As a result, U.S. companies failed to pledge the equity required for U.S. Memories, nor would they commit to purchases of the consortium's products.

c. Joint Ventures, Mergers, and Acquisitions

Joint ventures, mergers, and acquisitions can offer benefits to domestic industry and provide a needed source of capital and expertise. However, they can also impede the ability of industry to support national defense requirements. Of particular concern to DoD is that a lack of domestically-controlled sources may result in the denial or delay of access to the most advanced technologies, thus preventing the timely acquisition of state-of-the-art electronics required for defense. Unfortunately, once technologies and skills are lost overseas, they are difficult for a nation to regain.

The sale of U.S. firms (and the technologies that they embody) to foreign interests is both a cause and a consequence of the decline of the domestic semiconductor products and equipment industries. Foreign firms with an excess of capital have found recent success in quickly capturing U.S. microelectronics technology and market share through mergers with or acquisitions of U.S. businesses, which may be relatively unprofitable but represent a strong technology or production base. To illustrate the scope and nature of foreign direct investment, Table 3 lists a sample of Japanese IC fabrication facilities that have opened in the United States since 1988, while Table 4 lists recent foreign acquisitions of domestic firms. Firms within the SME segment are also being sold to foreign interests. For example, during 1989, the sale of Micro Mask to Hoya increased our foreign dependency for mask blanks, the sale of Materials Research Corp. to Sony increased our dependency for sputter targets, and the nearly total domestic loss of technology and manufacturing capability for stepping aligners through the sale of Perkin-Elmer's Semiconductor Equipment group to Nikon was only narrowly averted. More recently, Union Carbide negotiated the sale of the nation's only source of high purity polysilicon to Komatsu. The material is the highest grade of polysilicon manufactured anywhere in the world and is the only material that meets certain DoD requirements.

Table 3. Foreign Investment in Domestic IC Fabrication Facilities

DIRECT INVESTMENT		
Company/Location	**Products/Processes**	**Comments**
Fujitsu Gresham, Or.	ASIC/CMOS, BIMOS, ECL, CMOS DRAM.	Opened 10/88. Uses E-beam technology. Will produce 1M & 256K DRAMs.
Hitachi Irving, TX	256K CMOS SRAMS	Full production by 1989; using 150 mm. wafers.
Mitsubishi Durham, N.C.	CMOS ASIC and 1M CMOS DRAM production began in 1989.	4M DRAMS expected in future. ASIC line costs $3.6M; DRAM line $100M.
NEC Roseville, Ca.	256K NMOS DRAMS, CMOS ASICs	45K sq. ft. clean room. Will build another 465K sq. ft. for 4M DRAMs. $300-$500m.
Oki Tualatin, Or.	CMOS ASICs	Includes a 60K sq. ft. DRAM and ASIC assembly and test facility.
Toshiba Sunnyvale, Ca.	R&D and metallization of gate arrays	Completed construction of 5K sq. ft., $26M clean room, 1989.

Source: Integrated Circuits Engineering

Table 4. Acquistion of U.S. Semiconductor Manufacturers

MERGERS AND ACQUISITIONS		
Seller	**Buyer**	**Product**
Monsanto Corp.	**Huels** (W.G.)	Silicon wafers
Cincinnati Milacron	**Osaka Titanium** (J)	Semiconductor Material
Analytic Products Group	**High Voltage Eng. Europe (HVEE)** (Eur.)	Ion Beam Electronics
	Matra Aerospace (Fr.)	Space Defense Electronics; 8/27/89
Larn Research Corporation	**Sumitomo Metals** (J)	Cross-licensing agreement-Sumitomo will manufacture rainbow etch systems
Applied Process Technology	**CONVAC U.S.A (Subsidiary of GmBh** (WG))	Consolidation of Mask-making Product Lines; 5/89
AVX	**Kyocera** (J)	Remaining interest in the field of electronic capacitors
MRC	**Sony** (J)	1989. Equipment material for thin-film deposition

Source. Securities and Exchange Commission

Strategic alliances also have become commonplace within the industry. These arrangements can be beneficial to both sides and yield capital or access to new technologies or markets. A representative list of recent agreements involving major U.S. manufacturers is shown in Table 5. An example is the recent announcement by Texas Instruments and Kobe Steel (of Japan) of a joint venture to manufacture computer chips. The companies intend to build a $350-million fabrication plant in Japan and begin making advanced logic chips for the Japanese market in 1992. The deal provides Texas Instruments a means of expanding its access to the Japanese market, while providing Kobe with a capability for a new product line through access to TI production technologies for logic chips and other complex electronic devices. The Kobe-Texas Instruments venture is the fifth major U.S.-Japanese joint venture on semiconductors announced during the first quarter of 1990 alone. There have also been a number of joint ventures for the development and marketing of U.S. semiconductor manufacturing equipment. These include GCA's 50-percent partnership with Sumitomo Shogi to jointly produce GCA's DSW wafer stepper and wafer trace system and Varian Associates' joint venture agreement with Tokyo Electron Ltd. (TEL) for the joint production of the Varian CF-3000 ion implanter, a medium current implanter.

Table 5. Representative Microelectronics Joint Ventures

U.S. FIRM	FOREIGN FIRM	NATURE OF AGREEMENT
TI	Kobe (Japan)	• Fabrication facility and chip manufacture
TI	Hitachi (Japan)	• Develop 16M DRAM (By 1992)
TI	ACER, INC.	• $250M DRAM fabrication facility (Taiwan)
AMD	Sony (Japan)	• High-speed SRAMs
Motorola	Toshiba (Japan)	• Share Toshiba 4M DRAM design/Motorola MCU core cells
IBM	Samsung (Korea)	• Cross licensing of semiconductor patents
Siemens	Toshiba (Japan)	• Joint development for high-density CMOS gate arrays
AT&T	NEC (Japan)	• CAD tools for ASIC

Source: Integrated Circuits Engineering

d. Analysis of Infrastructure Segments

As the above discussion indicates, both semiconductor manufacturers and materials and equip ·ent suppliers are facing rapidly declining worldwide market share and may potentially find themselves unable to meet DoD's needs. Although an overview provides insight into the status of domestic capabilities, the picture becomes clearer when the condition of individual firms and narrow (but important) business segments are assessed. Two of these important segments are GaAs and lithography equipment. This analysis is not intended to single out individual parts of the industry as particularly critical; rather, conditions within these segments illustrate broader trends that affect other important parts of the industry. Today's domestic semiconductor industry is composed of nearly 1,200 firms in diverse market niches, and nearly all make strong contributions to both our competitive posture and our national defense. The following provides a more detailed discussion of the condition of domestic GaAs and lithography equipment suppliers.

Lithography

The semiconductor equipment segment is highly diverse, producing a range of specialized manufacturing and test equipment for semiconductor manufacturers. These products divide the segment into separate niche industries which support "front end" and "back end" processing. Front-end processing — which accounts for over half of the equipment sold — involves the application of a chemical coating known as a "resist" on the surface of a silicon or "nonsilicon" wafer. Lithography equipment is used to project the microscopic image of the pattern through a mask onto the resist, which is struck by light to induce a chemical reaction.

The image, etched into the wafer by means of chemical gases, is then processed according to the type of layer required. The underlying silicon may be doped with impurities to create semiconductive regions in which the metal may be deposited to create circuit interconnectors. After this front end series is repeated many times, the device is tested to ensure electrical integrity.[7]

Optical lithography is the technique that has been most commonly used by the industry. The technology has been available worldwide, with market share distributed among U.S., Japanese, and European firms. However, since optical lithography cannot meet the requirements of advanced DoD and commercial applications, the technology is being challenged by emerging techniques. The most prominent of these is X-ray lithography, which allows the user to create a slimmer line width at greater production speed. Initially, X-ray lithography was envisioned as a technique for production of bubble memories and Very High Speed Integrated Circuits (VHSIC). Now it is emerging as a technology with more standard and higher volume applications and shows promise for manufacturing commodity ICs at much lower cost than techniques used today. Development of X-ray lithography manufacturing processes therefore could result in a significant competitive advantage — in fact, some experts believe that an inability on the part of the U.S. to maintain parity in this technology could lead to the Nation's total loss of the IC commodity market. Other less-promising processes, such as electron beam and ion beam technologies, are also potential follow-ons to optical lithography.

Despite the importance of X-ray techniques, U.S. semiconductor manufacturers have been hesitant to pursue the long-lead developments necessary for switching from optical to X-ray lithography. Experts believe that mainline semiconductor processing for this technology is five to seven years away. The shift to X-ray lithography is hampered by the difficulty in making masks and the concern of the cost-effectiveness of synchrotron sources. The synchrotron serves as the light source for about 16 steppers; this large initial investment (relative to optical lithography), coupled with the fact that its failure will close the production line, is an impediment to broad use. The lack of maturity of the X-ray equipments and processes implies higher costs of implementing production lines, further delaying its use, even though X-ray systems will be a cost-effective long-term investment. The cost for a complete facility in the 1995 time-frame will be in the $500M to $1 billion range — twice the current price of a commodity IC fabrication facility.

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[7] ***A Competitive Assessment of the U.S. Semiconductor Manufacturing Equipment Industry***, Executive Summary, U.S. Department of Commerce, International Trade Administration, Washington, D.C., 1985.

The U.S. was the early leader in lithography, and most elements of the photolithography process were developed by Perkin Elmer, a U.S. company that has maintained its reputation as leader in the field. However, due to the complexity and high cost of producing the equipment, known as steppers and aligners, production has moved offshore and the U.S. has lost its dominance over the last decade. U.S. market share for stepping aligner equipment decreased by 65 percent between 1979 and 1988, and the U.S. resist processing equipment industry lost 43 percent of its share over the same period.[8] At the same time, Japan has become the world's major supplier of lithography equipment. Not only have Japanese products been found to meet the needs of U.S. users, but Japanese firms are aided by government subsidies, and companies have little pressure to generate quick profits, making it easier to invest in long-term R&D. Nikon and Canon, which only entered the business ten years ago, are now the leading suppliers of lithography equipment, commanding 80 percent of the world market. U.S. firms — ASM (owned by Philips), GCA Ultra Tech Stepper (owned by General Signal), and Perkin Elmer (which is to be taken over by Silicon Valley Group) — currently command most of the remaining 20 percent. Figure 5 lists major suppliers of different types of lithography equipment worldwide.

MANUFACTURERS OF OPTICAL STEPPERS (1X, 5X, 10X)

United States	Japan	Europe
OCA	Nikon	ASM-L Philips
Silicon Valley Group (SVG)	Canon	Matra
	Hitachi	Censor (now Perkin Elmer)
ASET	Matsushita*	
Ultr.tech	Fujitsu*	
Eaton	Toshiba*	

*Captive only

MANUFACTURERS OF MICROLITHOGRAPHY LENSES

United States	Japan	Europe
Tropel (GCA)*	Nikon*	Carl Zeiss
Silicon Valley Group*	Canon*	Cerco
Ultratech*	Olympus	Leitz/Wild
	Minolta	

*Captive only

CAPTIVE AND MERCHANT SUPPLIERS OF PHOTORESISTS

United States	Japan	Europe
Shipley	Tokyo Okho	AZ Hoecst
KTI	Toyosoda	Merck
Olin Hunt	Ni&T*	Dynamit
Nobel	Hitachi*	UCB
Aspect/Monsanto	Matsushita*	
MacDermid	Japanese Synthetic Rubber (JSR)	
Dynacherm		
Dupont		
IBM*, AT&T*, TI*		
GE (contrast enhancement materials)		

*Captive only

SOURCE: Foreign Applied Sciences Assessment Center (FASAC)

Figure 5. Worldwide Suppliers of Lithography Equipment

[8] VLSI Research Inc., 1989.

Just as Japan increased its market share in optical lithography, it has obtained market leadership in X-ray lithography as well. Table 6 compares the capabilities of U.S. and Japanese firms. In addition to the private initiatives, Japan's efforts are aided by those of the Sortec consortium, which was established by the Ministry of International Trade and Industry (MITI) in 1986 to perform X-ray R&D. As a result of these Japanese efforts, there is concern that even today's limited domestic capability could be eroding. This danger became particularly acute when Nikon threatened to take over Perkin-Elmer's lithography operation, which has been a major source of innovation in the U.S. The takeover was ultimately averted by a bid by the Silicon Valley Group, a private consortium of leading U.S. firms with interest in maintaining Perkin-Elmer's unique capability onshore.[9] Nevertheless, there is a danger that this nation may lose its ability to develop and produce this critical new technology through continued market losses and an inadequate level of investment.

Various cooperative efforts in X-ray lithography development have been initiated in response to this concern. DARPA, IBM, and Sematech have all focused specific investments on gaining and maintaining U.S. industrial capabilities for X-ray lithography. In the DARPA program, Brookhaven National Lab is working with Grumman Corporation and General Dynamics to develop domestic industrial base capabilities for X-ray lithography equipment that can be used in production of ICs with features of .25 um and below. DARPA sponsorship will

Table 6. U.S. and Japanese Lithography Capabilities

U.S.	SOURCE			R&D		
ORGANIZATION	IMPACT	PLASMA	SYNCH	MASK	RESIST	ALIGNER
IBM WATSON	•		•	•	•	•
AT&T BELL LABORATORIES	•			•	•	•
DEC					•	
HP	•			•		
HUGHES	•					
INTEL	•		•			
MOTOROLA	•					
TI	•					
EATON	•			•		•
MICRONIX	•			•		•
SILICON VALLEY GROUP	•			•		•
VARIAN	•				•	
WESTINGHOUSE	•					
HAMPSHIRE						
MATHEMATICAL SCI NW		•				
MAXWELL & BROBECK		•	•			
SPECTRA TECHNOLOGIES		•				
SPIRE	•			•		
HUNT/OLIN				•		
KODAK/UNION CARBIDE				•		
ROHM & HAAS				•		
BROOKHAVEN/NSLS			•			
LINCOLN LABS/MIT	•			•		
STANFORD/SSRL			•	•		
UW-MADISON/SRC			•	•	•	•

JAPAN	SOURCE			R&D		
ORGANIZATION	IMPACT	PLASMA	SYNCH	MASK	RESIST	ALIGNER
CANON	•	•	•	•	•	•
CHIBA UNIVERSITY	•	•	•	•	•	•
ELECTROTECHNICAL LAB	•	•	•	•	•	•
FUJITSU	•	•	•	•	•	•
HITACHI	•	•	•	•	•	•
JAPAN SYNTHETIC RUBBER	•	•	•	•	•	•
MATSUSHITA	•	•	•	•	•	•
MITSUBISHI	•	•	•	•	•	•
NEC	•	•	•	•	•	•
NIKON	•	•	•	•	•	•
NIPPON SEIKO	•	•	•	•	•	•
NTT	•	•	•	•	•	•
OKI	•	•	•	•	•	•
OSAKA UNIVERSITY	•	•	•	•	•	•
SANYO	•	•	•	•	•	•
SHARP	•	•	•	•	•	•
SHIMADZU	•	•	•	•	•	•
SONY	•	•	•	•	•	•
SUMITOMO ELECTRIC	•	•	•	•	•	•
SUMITOMO HEAVY IND	•	•	•	•	•	•
TOKYO OHKA KOGYO	•	•	•	•	•	•
TOKYO UNIVERSITY	•	•	•	•	•	•
TOMIMASU	•	•	•	•	•	•
TOSHIBA	•	•	•	•	•	•
SORTEC CONSORTIUM	•	•	•	•	•	•

Source: DARPA

[9] In addition, Perkin-Elmer's E-beam lithography division was sold to Etec of Haywood, California, to a group of Perkin-Elmer employees, and various companies like IBM, Grumman and Dupont. Its maskmaking division was sold to Dupont Inc.

develop processing for mask and wafer fabrication and establish domestic suppliers for key equipment and materials. Also, the program seeks to promote synchrotron technology transfer from national labs to equipment manufacturers and provide the IC industry with wider access to synchrotrons. The DARPA X-ray lithography R&D program was funded at a level of $15 million in 1988, $20 million in 1989, and $30 million in 1990. Sematech does not have the financial resources to sustain an aggressive X-ray lithography program in addition to its ongoing optical lithography program, and it currently spends less than $1 million per year for X-ray research.

Although the large corporations engaged in X-ray lithography in Japan have matched their government's investment, there has been relatively little independent research and development on the part of U.S. industry. A major exception is IBM, a captive firm that has long been a world leader in semiconductor and equipment technology. IBM is doing significant work in synchrotron-based X-ray lithography to support its own chipmaking operations and has invested approximately $40–50 million in 1989 alone. It projects total expenditures on the order of $1 billion over the life of the program. The company spent $100 million to install a synchrotron and related equipment in its new East Fishkill, New York facility, with the expectation of becoming operational by 1991 and reaching fullscale production by 2005. Motorola will support the effort by assigning six to eight engineers to participate in IBM's initiative.[10]

Gallium Arsenide (GaAs)

GaAs is another emerging microelectronic technology that will have significant payoffs for defense. Although silicon has long been the primary semiconductor material, GaAs is expected to be pivotal to future electronics applications, and some experts believe that sales could grow to $1 billion per year by 1993. The advantages of GaAs over silicon — especially for military applications — lie in an electron speed seven times faster than silicon and inherently better resistance to radiation damage. Major military applications today are in microwave and millimeter wave devices and circuitry, as well as in electro optic devices. GaAs is also considered an enabling technology for future defense systems, including the Advanced Tactical Aircraft (ATA), Advanced Tactical Fighter (ATF), and space systems. These platforms, as well as most others that use microwave and millimeter wave frequency electronics, must rely on advances in GaAs technology for their required performance.

The U.S. is the world's largest user of GaAs, consuming about 80 percent of the world's output. About 70 percent of this material is used for military applications. In the commercial sector, demand for GaAs is also projected to grow, particularly for use in computer systems, but also for communication systems and automobile collision avoidance applications. Although many believe that GaAs is still too costly and immature to achieve commercial acceptance, the use of GaAs in the new Cray-3 supercomputer may break the barrier to widespread commercial use. Nevertheless, improvements in material quality continue to be required to achieve systems requirements for many applications. GaAs demand was expected by many to grow significantly during the 1980s, and some firms invested heavily in plant and equipment in anticipation, but industry's inability to transfer technology from R&D to production and reduce impurities — and thereby lower material costs, improve yields, and improve reliability — have inhibited the expected growth of GaAs technology and its supporting industry. The DARPA sponsored MIMIC Program is responsible for a significant improvement in this situation.

There are relatively few producers of GaAs material in the world today. Japan is believed to have a strong lead in both GaAs materials and applications, having invested significantly in GaAs technology since the late 1970s. For example, SONY alone has about $1B annual business in predominantly commercial applications of GaAs (CDs, video players) and is producing High Electronic Mobility Translator (HEMTs) and Metal Schottky Field Effect Transistor (MESFET) devices by the hundreds of thousands per month. They may not be producing GaAs devices that meet DoD desired performance level, but they have established a viable commercial base for GaAs technologies and have a wealth of GaAs

[10] "Motorola/IBM Collaboration on X-ray Lithography Program," *Solid State Technology*, April 1990, p.66.

manufacturing know-how and experience. Although generally considered to be behind both Japan and the U.S., European nations are also investing heavily, chiefly through the European Program for Research and Development in Information Technology (ESPRIT) and the Joint European Submicron Silicon (JESSI) consortia. Despite considerable U.S. Government support for GaAs research, U.S. firms have generally been reluctant to make the private investment in technology and capacity that is required for a leading role in GaAs development and use, or to achieve parity with Japanese and European spending levels. The result is that the U.S. presently has no internationally competitive source of raw material and was previously unable to meet DoD's current and projected requirements for components that utilize GaAs technology.

About 25 U.S. firms have GaAs programs, but there is a continual change from both new entrants and established firms leaving the business. Due to low profitability, many smaller startup firms quickly leave the business or sell out to larger firms, which in turn abandon the market because of inadequate demand. Ford Microelectronics recently left the merchant GaAs IC market, and two domestic wafer manufacturers (Morgan Semiconductor and Spectrum Technology) have also closed. Although ten GaAs firms merged with other firms or were acquired during recent years, none involved actions by foreign interests.[11]

Although a number of large semiconductor manufacturers and defense prime contractors have GaAs operations, most are captives, leaving the merchant market to much smaller (and frequently undercapitalized) firms. For GaAs chips and devices, captive producers such as Texas Instruments, Hughes, TRW, McDonnell Douglas, and AT&T constitute 70 percent of the current market, producing chips predominantly for specialized military applications. Table 7 provides information on the leading U.S. merchant producers of digital GaAs chips. The rule of thumb is that $12 million or more in sales are required for a GaAs operation to be profitable. Only one of the five firms, GigaBit Logic, realized a profit in 1988.[12] There is considerable interaction between firms within the industry, particularly with respect to foundry services, and both sales and profitability appear to be on the upswing. Among the industry highlights for 1989, for example, were Vitesse's $14.1 million order for gate arrays from GE, Gazelle's $16.9 million foundry pact with TriQuint, and GigaBit Logic's $29.3 million contract with Cray for GaAs ICs. In terms of capital investment, TRW's $25 million investment in a new MIMIC GaAs facility, capable of producing 100 3-inch wafers per week, was also notable.

The U.S. GaAs materials industry is even smaller than the industrial base for chips. In the materials area, major U.S. merchant suppliers include American Xtal Technology, Crystal Specialties, Airtron, Bertram Laboratories, and M/A-Com. Bell Laboratories is a major captive supplier. These firms use different techniques to grow bulk GaAs from substrates, each having unique advantages for GaAs purity and yield. Processing technologies continue to be an area of emphasis in GaAs research.

Due to the potential importance of GaAs technology to the national defense, the Government has taken a number of actions to ensure that the U.S. retains sufficient technological and industrial capabilities to meet future defense needs. An estimated $100 million in DoD S&T funds will be spent in FY90 for GaAs-related research. DARPA's MIMIC program is the largest of the Government's efforts, involving an investment of about $500 million over a seven-year period. The program is geared toward achieving higher integration, lower cost, and improved manufacturability of GaAs MIMIC devices and will also develop computer-aided design tools that will permit suppliers to design chips that can be produced by a number of GaAs foundries. There is also potential for commercial spinoffs that will increase the financial viability of domestic firms. Prime contractors in the MIMIC program include TRW, Hughes/General Electric, ITT/Martin Marietta, and Raytheon/TI. In another GaAs program that dates to the early 1980s, DARPA has achieved considerable success in establishing digital pilot production lines to manufacture GaAs memories and logic chips, as well as in developing materials, processes, design tools, packaging and special devices. Participating

[11] GigaBit is currently being acquired by Hanson Telecon, a South Korean Company, as of July 31, 1990.

[12] "The Race for Chip Supremacy," ***High Technology Business***, November 1988, p. 21.

Table 7. **Leading U.S. Merchant GaAs Chipmakers**

Company	Founded	Capitalization	1988 Sales	Capabilities/Approach
Gain Electronics	1985	$20M	$1.5M	First to license high-electronic mobility translator (HEMT) technology from AT&T, which results in highest-performing GaAs chips. Concentrating on developing high-density digital products for computer, telecommunications, and instrumentation markets. Has 15K wafers/year capacity and packaging and foundry fabrication services.
Gazelle Microcircuits	1986	$6.5M	<$1M	Targeting the highest volume microconductor markets, makers of high-performance computer systems. Has followed silicon strategy - rather than building chips, concentrates on designing chips and farming out production. DARPA intends to support GaAs operations through $4M investment program.
GigaBit Logic*	1981	$36M	$15M	Targets computers, communications, instrumentation, and military markets; 65 percent of business is foundry, while customers design their own chip. Cray is GigaBit's largest customer and investor, and GigaBit will provide chips for Cray-3. Offers largest range of catalog parts in industry.
Triquint Semiconductor	1985	N/A	$15 - 20M	Offers standard components, foundry products and services, gate arrays and standard cells, and ASICs. Foundry provides 65-70 percent of business.
Vitesse Semiconductor	1984	$18M	$4 - 5M	Trades computer speed for higher yields, greater chip complexity, and silicon compatibility. As of 1990, known to produce chips with complexity of 4,500 gates at yields in excess of 50 percent.

Source: *High Technology Business*, November 1988 and DARPA survey data 1988. *See Footnote 11.

firms include Rockwell, McDonnell Douglas, and AT&T. These programs have been instrumental in moving GaAs technology to its current state-of-the-art. The latter program, for example, was responsible for introducing the world's first fully functional GaAs 16K-bit static RAMs and 32-bit microprocessors. Still another DARPA GaAs program, initiated in 1988, is designed to accelerate the fielding of subsystems based on digital GaAs, in order to speed the development of the digital GaAs IC market, ensure continued U.S. leadership in the field, and take early advantage of GaAs benefits through technology insertion. The program includes demonstration, prototype test and qualification, procurement, and successful installation in existing military systems. Prime contractors obtain their digital GaAs ICs from domestic vendors, including Vitesse Semiconductor, TriQuint Semiconductor, and GigaBit Logic. Another DARPA-sponsored program, Intelligent Processing of Materials, with GE and Airtron, is resulting in improved GaAs substrates.

The Military Services are also promoting the development and use of GaAs technology. For example, an Air Force Transmit/Receive (T/R) Module program is developing and validating manufacturing technologies for GaAs discrete and monolithic IC devices. Other GaAs-related programs involve fabrication of a variety of GaAs devices, wafer scale technology, epitaxy and superlattice technology, and supporting disciplines. Work in the materials area includes the development of a high-pressure liquid encapsulated crystal puller for production of GaAs boules, and efforts to improve the control and uniformity of epitaxial GaAs layers through such technologies as metal organic molecular beam epitaxy, molecular beam epitaxy, and metal organic chemical vapor deposition.

4. Summary

Although defense accounts for less than a tenth of the overall microelectronics market, the commercial and defense segments are closely linked and commercial success is necessary to maintain a healthy technology base. Similarly, the health of a nation's technology base is closely linked to the strength of its production base. The FY 90 ***Critical Technologies Plan*** estimates that although the U.S. leads its NATO Allies and the U.S.S.R in most aspects of new technology development, Japan has emerged as the world leader in many technologies that are critical for our future defense. The concerns to national security arising from the offshore movement of both the production base and the technology base have been underscored by the Congressional Budget Office:

> ...the deterioration of U.S. semiconductor producers could soon lead either to dependence on foreign

sources for components for sophisticated weapons systems, or to a decline in the technological base needed to develop and use these components. Domestic production facilities dedicated to semiconductors with military applications could be procured to overcome any dependency on foreign suppliers. If, however, the ability to use the technology is lost, such facilities would be irrelevant to future generations of semiconductor technology.[13]

This statement makes clear their concern on the part of U.S. producers not to depend on current successes in certain areas of the semiconductor market. The health of this particular market, basic and prevalent to so many technologies, will depend on increased attention in both the defense and civil sectors.

[13] ***The Benefits and Risks of Federal Funding for Sematech***, Congress of the United States, Congressional Budget Office, September 1987, p.xvii.

SENSITIVE RADARS

1. Introduction

Sensitive radars differ from existing systems in their ability to detect targets with relatively small cross-sections at much greater resolutions and longer detection ranges. Since the term sensitive radars refers to classification, recognition, and identification of targets as well as detection, different technical approaches are being pursued, including laser, synthetic aperture, ultra-wide band, bistatic, backscatter, lower frequency, and other methods. Many of these techniques are in the early stages of R&D, and a significant amount of the detailed information in this area is classified. Figure 1 summarizes the sensitive radar technology challenges identified in the FY90 ***Critical Technologies Plan***, along with industrial base segments that will be required to support the area.

The Federal Government — and primarily DoD — provides the vast majority of the market for sensitive radar products, as well as the only source of support for new product R&D. Several other critical technologies are especially important to Sensitive Radars, as they provide crucial technical and industrial base underpinnings to sensitive radar applications. The most important supporting technology is Semiconductor Materials and Microelectronic Circuits, since continued advancements in microelectronics capabilities and costs are required to produce and field affordable sensitive radar systems. Other technologies with important contributions to Sensitive Radars are: Machine Intelligence and Robotics, Signal Processing, Photonics, Software Producibility and Data Fusion.

2. Industry Structure

The industries supporting sensitive radars can be broken down into radar system manufacturers, component manufacturers, and material suppliers. The system manufacturers are defense components of large corporations, which have longstanding expertise in traditional radar system market areas such as airborne fire control radars and search and ground based

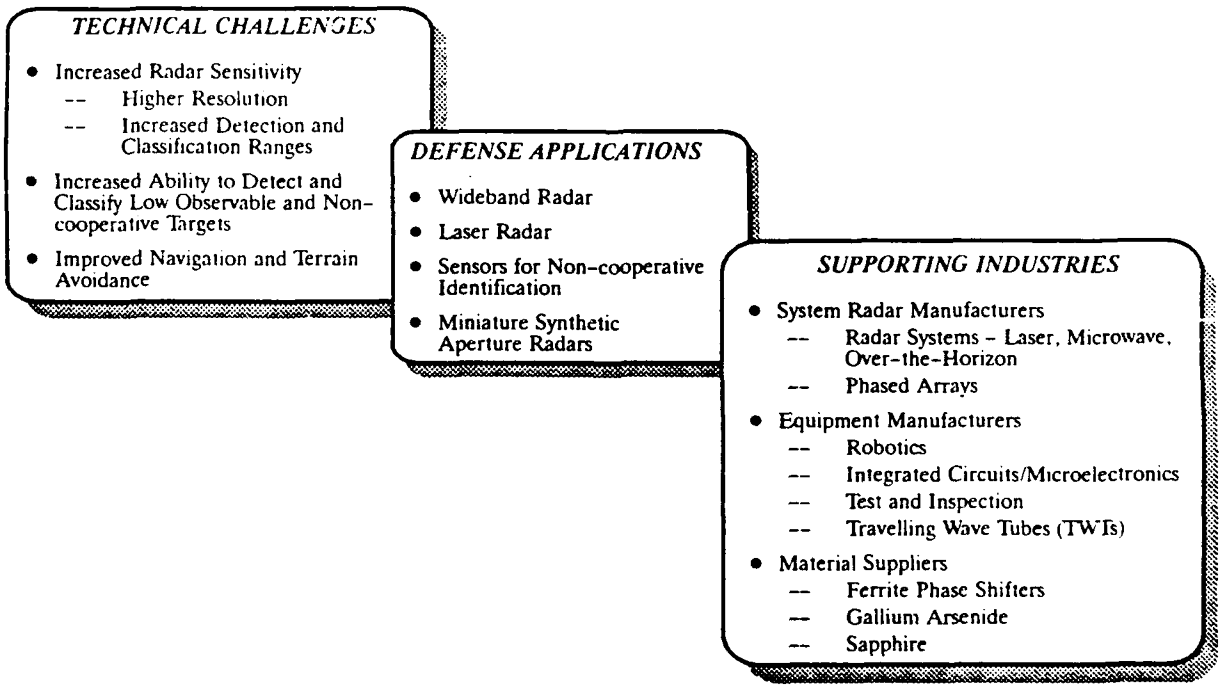


Figure 1. Technical Challenges and Supporting Industries

radars. The emergence of sensitive radars may enlarge the existing base by allowing other defense companies to enter the market by teaming with smaller firms that specialize in the newly emerging technologies.

Component manufacturers provide a variety of subsystems to the system manufacturers. These component manufacturers vary considerably in terms of product, composition, and strength. This segment of the industrial base includes parts of the microelectronics base, the signal processing base, and more specialized segments such as the phased array component base, described in the infrastructure section of this chapter.

The materials suppliers of most interest to sensitive radars are those that supply silicon and gallium arsenide (GaAs) to the semiconductor industry, and producers of conventional and solid-state laser materials. Issues facing the silicon and GaAs industries are described under Semiconductor Materials and Microelectronic Circuits, while suppliers of lasers are discussed in more detail below. Optical materials, primarily fiber optics, and precision optics are also very important. Japan and the U.S. are generally considered to be the world leaders in fiber optics, with Europe a very close third; however, Japan appears to be gradually taking the lead. A detailed description of the nation's competitive position in fiber optics can be found in Photonics.

A number of other industries are crucial to our ability to manufacture and field sensitive radars. Among these are printed circuit boards, fabrication and assembly equipment and associated controls, software, and computers. Although a mix of companies supply the printed circuit board market, ranging from small specialty houses through major primes and subcontractors, system manufacturers tend to produce the relatively low volume, highly complex boards that are required for sensitive radar applications. Suppliers of polyimide and ceramic board materials and of the various metals and metal forms required for board manufacturing are also an important part of the supporting base. The industry further relies on fabrication and assembly equipment as well as a considerable range of specialized equipment. Equipment for fabricating integrated circuits, printed circuit boards, electronic components, and fiber optics, and for assembling circuit boards, transmit/receive (T/R) modules, lasers, and other electrical components are specialized, relatively low volume items made by companies other than those normally associated with the machine tool market. Other important specialized equipment includes diamond turning machines, optical blank and component polishing equipment, and highly sophisticated equipment for electronic and optical alignment.

3. Condition of the Industrial Base

a. Sales

Radars represent an industrial base in transition. Conventional radars are a well-established commodity for military systems, while sensitive radar technologies are still in development and do not constitute a significant present-day market. The systems manufacturers who now produce conventional radars and are expected to be major producers of sensitive radar systems in the future are considered to be strong and viable. For the most part, these are divisions of very large U.S. corporations such as General Motors, General Electric, ITT, Texas Instruments, United Technologies, and Westinghouse. With annual sales in the billions of dollars, these companies are expected to be able to support DoD's R&D and product development requirements into the foreseeable future, provided that this line of business is considered sufficiently profitable.

Both the conventional and sensitive radar markets are driven by DoD, although the Federal Aviation Administration (FAA) represents a cyclical market for conventional radar products and there is a continuing market for foreign military sales. However, the projected decline in the defense budget is expected to affect the overall health of the industry. Although some observers forecast that the number of systems manufacturers will be reduced in response to cutbacks in the procurement of new systems, the impact on radar manufacturers could be cushioned by the continued need for spares, modifications, and retrofits, as well as active participation in foreign military sales. The international events which impact U.S. defense budgets will have a similar effect on European radar producers, who compete in the same international military sales markets. Therefore, the international market is expected to become steadily more competitive.

Microwave tubes — which are important in radar applications as well as communications and electronic countermeasures — can illustrate the difficulties inherent in the industry's transition from conventional radars to advanced products. The industrial base for microwave tubes is exceedingly small — only three companies produce tubes for aircraft use, and one supplier dominates space applications. Although these suppliers are often one arm of a much larger company that has considerable financial backing, their ability and willingness to continue in the microwave tube business is fundamentally dependent on the level of support provided by DoD. Existing microwave tubes are noted for their high cost, high variability and low reliability. To date, DoD and industry-funded efforts to increase the yield and reduce the variability through improved manufacturing processes and increased process automation have had only limited success. These continuing cost, variability, and reliability problems have caused high, sustained interest in developing solid state technology to replace microwave tubes, which has further discouraged industry's interest in solving the problems that plague present-day systems. At present, this segment of the industry is declining and the number of microwave tube suppliers has decreased. As declining defense budgets reduce the demand for microwave tubes, further shrinkage in the number of companies producing tubes is expected to occur, and the unit cost of tubes is expected to increase. There is some concern that reduced volume will further exacerbate the variability and reliability problems that exist today.

b. Investments

Market forces such as these can be expected to put considerable pressure on domestic radar producers in the future, potentially reducing the number of active manufacturers still further and constraining the amount of industrial funding available for R&D. Shrinking of the market will also reduce the funds that firms are willing or able to make available for the facilities and equipment necessary to implement new technologies. This can be expected to slow the introduction of new sensitive radar capabilities, and to increase the manufacturing cost of such products at their time of introduction. The high cost of new technologies, in turn, could affect DoD's ability to retrofit desirable capabilities onto existing weapons systems.

With little incentive for R&D investment beyond that necessary to service the DoD market, any reduction in industrial funds will make advances in the area almost totally dependent on DoD. DoD funding can be expected to focus on the development of new radar products, and relatively little Government or industry investment is allocated to the development of improved manufacturing processes to produce those products. The availability of DoD funds for product and manufacturing process R&D, facilitization, and production therefore could become the pacing factor in advances in sensitive radar systems.

c. Joint Ventures, Mergers and Acquisitions

No information was available at the time the report was issued.

d. Analyses of Infrastructure Segments

Laser Radar

Laser radars are a direct analog of microwave radars, but they offer advantages of bandwidth, physical size reduction, and higher resolution. Laser radar is expected to provide significant advantages in 3-D characterization of concealed targets; high-resolution, large-volume strategic surveillance; standoff chemical agent detection; and navigation and guidance of helicopters, cruise missiles, and robotic vehicles. The major differences between laser and microwave radars lie in T/R sections and cooling systems. Once the received laser radiation is converted into electrical signals, the signal processing and computing sections of the two radar types are comparable. In both laser and conventional radars, the signal processing, computing and mechanisms subsystems dominate acquisition costs.

There is little direct crossover in technology application between the laser radars developed by DoD and the industrial or medical laser markets, largely because of differences in power, frequency, and control. Although there are potential applications to police radar and to industrial robots and automated guided vehicles, these applications are not cost-effective because the commercial applications do not require the performance advantages of laser radars. Hence, there is little market stimulation for private or industrial funding of R&D or product development. Non-defense applications for tunable solid state lasers appear potentially significant in laser remote sensing, which is being funded by NASA, and in environmental monitoring including chemical effluents associated with illegal drug production, but developmental efforts in the area are almost totally funded by the Federal Government.

The industrial segments of most importance to laser radars are systems manufacturers, laser producers, precision optics materials and components industries, and fabrication and equipment manufacturers. The systems manufacturers generally are the same as for other radars, although the industry structure may become modified as these new applications take hold. As one of several promising and complementary approaches in sensitive radar technology, laser radar development must compete for funds with the other technologies in an era of declining budgets.

The development of new types of lasers specifically for radar applications is a major R&D emphasis, led by the development of tunable lasers that use sapphire crystals doped with small amounts of titanium. The fabrication process is very sensitive, requiring an extended period of high temperature annealing under a hydrogen atmosphere. At present there is only one source for such lasers. No other potential domestic sources have indicated an interest in entering the field. This situation is a potentially serious problem for the future, should laser radar systems using the sapphire crystal be needed in production quantities.

With the emphasis on developing new laser radar technologies for DoD, the approaches followed to date involve the adaptation of commercially available lasers for military uses. The laser industry — which is not a part of the traditional radar system infrastructure — comprises many companies supplying the medical and industrial laser markets. Industrial lasers are primarily used for metal removal, drilling, and cutting, with some application to surface heat treating, while medical lasers (such as YAG lasers) are primarily used in surgical applications. In the case of adaptation of commercially available lasers for military use, the basic approach has been to apply CO_2 lasers occupying the low power end of the industrial laser category, with modifications to meet military requirements (e.g., ruggedness). Several companies provide laser subsystems to radar system producers. The dependence of these firms on DoD varies, based on their involvement in commercial and DoD markets. For many, their existence is totally dependent on DoD support, and any significant reduction in the level of DoD spending in this area will reduce the number of viable firms.

Optical laser pumps are another important component of laser radars. High-efficiency laser diode pumping of solid-state lasers is desirable because of space, weight, and heat generation considerations. These materials have many potential applications beyond DoD and their development is aided by funding from industrial sources. There are several vendors of optical laser pumps, and there are many potential vendors of laser diodes for pumps, so there appear to be no serious industrial base issues in this area.

The domestic precision optics industry is also important to this industry, but it is widely reported to be in serious decline and unable to support defense needs.[1] The present condition of the commercial precision optics industry is sufficiently weak that its ability to remain viable is seriously questioned. In 1987, there was only one domestic supplier of optical glass and seventy percent of the glass used by domestic component producers was imported. The production of optical elements has almost totally moved offshore — in 1986, imports accounted for over 98 percent of total U.S. consumption and approximately 50 percent of DoD's consumption. Fabrication equipment for producing optical components is largely produced overseas, with German and Swiss companies dominating the U.S. market.

Phased Array

Most sensitive radar applications depend on phased arrays. The phased array approach generally does not have a moveable, mechanical antenna. Rather, it employs an array of fixed T/R electronic modules which steer the transmitted energy beam through signal phase

[1] ***Joint Logistics Commanders Precision Optics Study***, June 1987.

shifting. This approach provides substantial gains in reliability, resolution, and weapons system design flexibility, and is therefore fundamental to space and airborne sensitive radar applications. There are potential sensitivity and cost advantages to phased array technology in ground and sea applications as well.

In aircraft applications, the phased array approach reduces observability to enemy radar because it eliminates the large return from the airborne mechanical antenna. Difficult performance trade-offs in fighter system design are normally necessitated by the conflicting needs for the largest possible radar antenna and the smallest possible fuselage diameter, coupled with aerodynamic shaping of the nose of the aircraft. Improved coverage can be achieved by placing arrays in different locations around the aircraft. The sensitivity advantages of phased arrays stem from the ability to design different sizes and shapes of arrays of active elements or T/R modules, thereby tailoring the radar to the platform and intended end use. This design flexibility extends from small to very large arrays.

Phased array antennas can be built from a large number of relatively low-power active elements (T/R modules), or from a smaller number of high-power radiation sources that provide power to many transmit elements. Significant manufacturing difficulties currently exist with both approaches, and considerable effort has been expended to ameliorate them.

In the case where a small number of high-power sources are used, microwave travelling wave tubes (TWTs) and ferrite phase shifters present cost and reliability concerns. Both TWTs and ferrite phase shifters are very costly, and are produced by a small number of companies. The market is primarily driven by DoD requirements and production volumes, which have been insufficient to justify the implementation of automated production techniques that could reduce costs and improve quality. As a result, product quality varies, the first-pass manufacturing yield is low, production time span is difficult to predict, and late deliveries are commonplace.

In the case where a large number of T/R modules is used, cost is again a concern. Each T/R module is a separate, small circuit board containing a number of discrete electronic components and chips. Each board must be packaged in a separate housing, and the completed module is physically and electrically installed in a precise location in the array. While there are costs associated with the installation because of the precision location requirements, the primary cost issues rest with the modules themselves. A typical aircraft array based on this approach, such as the Advanced Tactical Fighter (ATF) radar, requires on the order of 2,000 modules. Designs for higher sensitivity arrays, such as conformal arrays on aircraft or ground and ship based arrays, require many times that number. Manual production methods are used for X-band T/R modules required for the ATF and ATA aircraft , and costs must be reduced in order to make weapon system commitment to such arrays economically feasible. Another driver in the cost of the modules is the need for GaAs integrated circuits. Issues associated with this technology are discussed in Semiconductor Materials and Microelectronic Circuits.

Solving the T/R module cost problems will require manufacturing advances in a concerted attack on all aspects of production and test. DoD has several integrated module development and manufacturing technology programs in place which are addressing the problem through the development of product and manufacturing process design. Achieving current goals for production rate and cost for the ATF and other applications involves the following:

- Working with manufacturing experts. T/R modules must be designed for lowest possible manufacturing cost, even at the expense of some performance capability
- Concurrently with the design process, innovative, automated manufacturing processes and controls need to be developed for minimum cost, maximum production throughput, and integrated, automated test
- Integrated factory planning, scheduling, and production control information systems need to be implemented which eliminate, or greatly simplify and then automate, all non-touch manufacturing functions
- Maximizing manufacturing quality and minimizing production time requires

implementation of statistical process control techniques along with process and factory layout simulation and modeling

- Automation equipment and control systems need to be designed simultaneously with module design and the manufacturing process and test development.

This integrated product and manufacturing process development procedure may well prove to be a model for how weapon systems and subsystems will be created in the future. The activities will take maximum advantage of commercial practices, and several of the assembly and test processes developed also may be applicable to the commercial electronics industry.

While these activities are pursued, several facets of the industrial base may hamper the speed and effectiveness of the total program. The situation in the microelectronics industrial base typifies some of the issues that are pertinent to reducing T/R module costs. Key among them is the rapidly declining health of the electronics fabrication and assembly equipment industry. Fabrication equipment for making high quality, low cost GaAs integrated circuit chips is mandatory. Automated equipment tailored for assembling specific T/R module designs will be required to achieve the necessary cost and manufacturing throughput. This must be innovative, world-class equipment, designed in concert with the modules themselves.

T/R modules are designed and built by radar system manufacturers, who are expected to accomplish most of the effort required to achieve cost and quality goals. The system manufacturers are considered capable of meeting this requirement, since they have the personnel skills and financial resources to supplement DoD funding. However, an effort of this type will be required for each major phased array radar introduced, and it is unlikely that a separate facility for each production program will be a feasible alternative. Therefore, it is to each company's advantage to ensure that new facilities are as flexible as possible. Flexible automated facilities for T/R module production also will benefit DoD by reducing program cost, achieving economies of scale, and decreasing development time. In order to commit the capital for such facilities, companies will need high confidence that the anticipated future production volume is sufficient to justify the facility and equipment investment. With the uncertainties inherent in the declining budget situation, attaining the necessary confidence level may be difficult.

4. Summary

Sensitive radars encompass new technologies that have not yet reached production, but they build upon an extensive industrial infrastructure that has grown to support conventional radar systems. With some modifications, existing radar system manufacturers (generally components of major corporations) are expected to become key producers of sensitive radars as well. Although the situation is somewhat analogous within the highly diverse supplier base, many of these companies are finding the transition from existing systems to new technologies difficult. Declining defense budgets, declining DoD R&D spending to improve costs and production efficiencies for existing systems, and a requirement to invest in new facilities and equipment to meet changing defense needs will result in a shakeout within some industry segments. Further, the new technologies for sensitive radars will require the addition of a new set of suppliers to the industrial base. Given the lack of a strong commercial market for these products, many of these firms will be entirely dependent on DoD, and the ability of the base to expand in response to DoD's requirements will be contingent on Government investment and procurement decisions.

SUPERCONDUCTIVITY

1. Introduction

Superconductivity represents an advance in the field of electricity, since it allows a continuous flow of electrical current, is capable of repelling a magnetic field, and transmits electricity without energy loss. These unique properties have benefited such products as magnets, motors, generators, and sensors, as well as such revolutionary commercial products as magnetic resonance imagery and levitated trains. In the future, the capability of superconductor materials to dramatically reduce electrical resistance and power loss holds promise for electric power generation, electronics, electromagnets, computers, and other applications.

Discovered in 1911, superconductor technology is not new; however, technical impediments have long impeded the technology's practical use. Chief among these is that components must be refrigerated to nearly absolute zero. Initially, the cooling of superconductors was accomplished with liquid helium, and the process of cooling superconductors to such a low temperature demanded a great deal of precision, time, and money. This effectively limited the use of superconductors to a laboratory setting. Recent advances in the field have led to techniques that permit higher temperatures in transferring, which has increased the practical uses of superconductivity in defense as well as commercial applications. This new method has permitted cooling with much less time and cost, opening the way to many new applications.

Military applications in superconductivity include computer capabilities, infrared and magnetic detection, magnetic propulsion, hyperkinetic weaponry, and energy storage. All military services are promoting applications using superconductive technologies. For naval applications, superconductive applications in motors, generators, and power transmission devices will reduce weight, leaving greater capacity for weapons on a smaller-sized vessel. Also, R&D into superconductor-based engine technology is on the horizon. The Air Force has been conducting superconductivity research for a quarter of a century, and its most recent application is a Very High Speed Integrated Circuit (VHSIC) chip for the F-111D signal transfer unit.[1] Government support of these high-risk technologies — which was considerable in the past — is desired to establish a strong U.S. competitive position for the future.

Figure 1 outlines the technology challenges and supporting industries involved in defense applications for superconductivity.

TECHNICAL CHALLENGES

- Creation of Higher Conductive Temperatures
- High Temperature Super-Conductor Materials and Processing
- Low Temperature Super-Conductive Applications
- Integration With Semiconductor Devices

DEFENSE APPLICATIONS

- Potential Applications Include:
  - -- Higher Efficiency Electric Drive Systems for Ships, Land Vehicles, and Aircraft
  - -- Electric Generators
  - -- Electric Energy Storage Systems for Directed Energy Weapons
  - -- Electromagnetic Guns and Aircraft Catapults
  - -- Magnetic and Electromagnetic Shields
  - -- Supermagnets and Cavity Resonators for Microwave And Millimeter Wave Generation
  - -- Infrared Optical Detector Elements

SUPPORTING INDUSTRIES

- System Manufactures
  - -- Low Temperature Superconductors (LTS)
  - -- High Temperature Superconductors (HTS)
- Equipment Manufactures
  - -- Wire and Cable
  - -- Analog Digital Electronic Components
  - -- Magnets
  - -- Machine Tools/Robotics
  - -- Microelectronics
- Material Suppliers
  - -- Advanced Metals
  - -- Advanced Composites
  - -- Chemicals

Figure 1. Technical Challenges and Supporting Industries

[1] "Superconductivity: The Tantalizing Possibilities," Colonel Robert Berens, *National Defense Magazine*, January 1989, p. 27.

2. Industry Structure

Superconductivity has enormous market potential and future applications of the technology are expected to lay the foundation for as yet undefined multimillion-dollar industries.

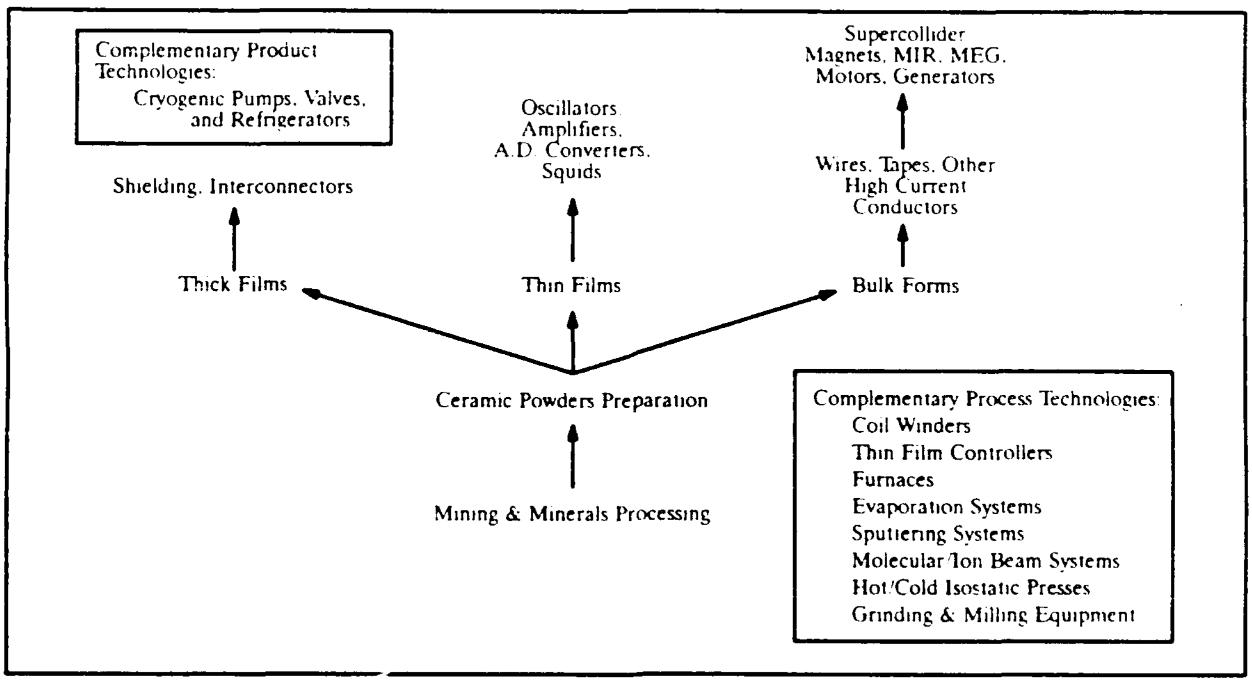
Today's "superconductivity industry" can be roughly divided into two industry segments: one comprising firms that produce products based on Low Temperature Superconductor (LTS) technology and the other comprising firms that are developing High Temperature Superconductor (HTS) applications. The LTS-based industry provides commercial products and services — wire and cable, magnet winding, analog electronics, and sensors — while the HTS-based industry, newer and not as far advanced, largely provides information, "know-how," and special devices for laboratory applications. At this time, the HTS industry is providing the materials for future applications of electronic components, medical and industrial instruments, and eventually, electric power and transportation equipment subsystems. It is not uncommon for firms to be involved in R&D, and sometimes production, for both low and high temperature components for defense and commercial applications.

The vertical structure of the superconductivity industrial base is shown in Figure 2.

As the figure shows, mining and minerals processing is the foundation of the industrial structure for superconductors. Despite the limited number of present-day products, an embryonic superconducting materials industry currently exists, and will expand considerably as R&D progresses into production applications. Perovskites, the mineral family to which many superconductor materials belong, already form the basis for the $20 billion electroceramics industry.

At the next step in the chain, powder suppliers purchase basic materials from mineral, mining, and processing firms and use these materials to form ceramic powders. The process used is to mix elemental minerals at high temperatures to form ceramic compounds, which are then cooled and ground into fine powder.

Bulk superconductor producers next compress powders into a desired form by hot



Source: ***Superconductor Industry 1990 Buyers Guide*** (Winter 1989)

Figure 2. Vertical Structure of Superconductor Technology/Industry Base

pressing, extruding, tape casting, and other methods. Thin and thick film producers then prepare superconductor components by laying down films of superconductor material on various high-quality substrates, such as strontium titanate. Processes include various forms of evaporation, sputtering, laser ablation, and plasma spraying. Bulk and film producers feed distinct industry tiers. Bulk materials are used by producers of wire, tape, and other high-current conductors. Thick film superconducting material is used by producers of shielding and wiring interconnects, while thin film processors feed a potentially very large market for industrial and military sensors and many other electronic devices.

Although the HTS and LTS industries are currently distinct, some observers believe that the two industries will begin to merge as HTS matures and begins to compete for applications served by LTS and non-superconducting material technologies. There are important reasons for better integrating the two segments, and experts believe that this merger will be necessary for the industry as a whole to become highly profitable. For example, revenues generated from the sale of near-term LTS-based products could be used to underwrite needed research for longer-term HTS applications. The two technologies already share a common infrastructure and observers believe that additional industries will soon develop to help HTS and LTS firms resolve product and manufacturing process difficulties that affect both technologies.

With the eventual production of HTS-based products, the competition for HTS will involve both LTS applications and other, steadily improving non-superconducting technologies. HTS technology is expected to find its first applications within 5-10 years in electronics and communications for defense and space systems; secondly in medical and industrial applications (10-15 years); and eventually in high-energy physics, electric power, and in transportation (>15 years). Table 1 categorizes specific HTS-based product applications according to their potential for competing with LTS-based applications.[2] Categories 1 and 2 contain the most probable short-term applications since they have a mature LTS technology base from which to proceed.

Table 1. HTS vs LTS Potential for Selected Product Market Applications

1. Significant potential for LTS and HTS technology – Magnetic separators for industrial processes – Pick up coils for magneto-encephalography (MEG) – Superconducting quantum interference devices (Squids)	**2. Significant potential for LTS technology and possible for HTS** – Passive electronic devices such as antennas, filters, and delay lines
3. Insignificant potential for LTS, significant potential for HTS – Transmission Lines – Auxillary Power Equipment – Industrial and Defense Sensors	**4. Insignificant potential for LTS, possible for HTS** – Electric Generators (rotors) – Superconducting Magnetic Energy Storage (SMES) – Electric Drives (ships) – Motors

Source: Office of Technology Assessment

[2] This categorization is extrapolated from a recent Office of Technology Assessment study, ***High Temperature Superconductivity In Perspective***, April 1990. See Tables 3-1 thru 3-6 of chapter 3, "Applications of Superconductivity," pp. 31-58

3. Condition of the Industrial Base

a. Sales

The U.S. has a strong position in the relatively few LTS superconductor-based products that have already come to market, including wire and cable production, magnet winding technology, superconducting analog electronics, and sensors.[3] U.S. firms are also dominant producers of Magnetic Resonance Imaging (MRI) magnets, the single largest market for LTS-based technology. Sales data for these initial product lines were not available for inclusion in this report. The primary importance of this technology is future, rather than current, markets. The condition of the technology/industrial base with respect to bringing new products to fruition is described below.

b. Investments

Despite today's limited market for products based on superconductivity, approximately 400 U.S. firms are engaged in production, service, and research in superconductivity-based technologies. However, the involvement of many of these firms in technology development and production is extremely limited, and the distribution of research spending is uneven. For example, the Office of Technology Assessment (OTA) found that only half of the firms are responsible for 90 percent of U.S. industry's research effort, and that the top five of these 400 firms account for 55 percent of all industrial research in superconductivity. In the area of industrially funded HTS research, just fourteen firms, each of whom invests more than $1 million annually, account for 75 percent of the $66 million (1988) total. For LTS, over half of the $14.7 million of industry research dollars (1988) were spent by only four firms. Each of these four firms commits $1 million or more annually to LTS R&D. Nevertheless, small firms play a significant role in the industry. While they account for less than ten percent of total industry funding for HTS, they receive 44 percent of all Federal research funds targeted at private industry. Table 2 identifies selected U.S. superconductivity firms by research specialization.

Now that superconductivity is beginning to offer some near- and mid-term benefits, Federal funding for HTS and LTS research has risen from $144.5 million in 1988 to an estimated $228 million in 1990. Of the $187 million in 1989 funding, 69 percent was allocated to HTS and 31 percent went to LTS technology.[4] Superconductivity's contribution to solving a large number of commercial and military problems is noteworthy, and Table 3 shows the distribution of Federal funds among Government agencies concerned with superconductivity research.

Of the HTS R&D funded by these agencies, approximately 45 percent is performed in Federal laboratories, 30 percent in universities, and 25 percent in industry. The Department of Defense supports nearly all of the $24.1 million of HTS research performed by industry. In addition to the agencies listed, the Department of Transportation and the Department of the Interior fund small efforts in HTS, but are not involved in LTS R&D.

State governments also sponsor an extremely limited amount of superconductivity research (generally under $1 million annually). Most is funnelled to major State universities. As a result, university systems in California, Florida, Illinois, Maryland, New Jersey, New York, and Texas have significant programs.

Since the 1988 release of the report of the Presidential Advisory Committee on Superconductivity, the number of industrial, university-based, and national lab-based consortia has grown considerably. A partial list of HTS consortia is shown in Table 4.

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[3] "Superconductivity: Fact vs. Fancy," ***IEEE Spectrum***, May 1988, p. 39.

[4] Estimates for 1990 indicate a levelling to 57 percent for HTS.

Table 2. U.S. Companies by R&D Specialization[5]

1. MATERIALS RESEARCH/MFG	2. WIRE, CABLE, MAGNETS, NUCLEAR M-R DEVICES
Applied Signal Aerospace	American Magnetics
AT&T Bell Labs	Applied Superconetics (Sub of GA Technologies)
DuPont	ERIEZ Magnetics/ERIEZ Mfg.
Energy Conversion Devices	General Dynamics
General Motors	General Electric
IBM	Intermagnetics General
Microelectronics & Computer Technology	Supercon
Teledyne	Teledyne
Westinghouse	American Superconductor
Am Superconductor	Conductor Technologies
Applied Technology of Indiana	
ARCH Development	
Ceromecs Process Systems	
Electro-Kinetic Systems	
Guernsey Coating Laboratories	
3. ELECTRONICS	**4. LARGE POWER APPLICATIONS**
AT&T Bell	Bechtel Material Inc.
Bell Communications Research	TRW
Biomagnetic Technologies	Westinghouse Electronic
Ford Motor	Monolithic Superconductors
General Motors	
Hypress	
Quantum Design	
Westinghouse Electric	
Conductor Technologies	
Conductors	
Guernsey Coating Laboratories	

Table 3. Distribution of Federal Funds Among Government Agencies in 1989

LTS		HTS	
DOE	$37.0M	DOD	$58.0M
DOD	1.5M	DOE	38.5M
NSF	3.8M	NSF	22.4M
NASA	3.0M	NASA	4.9M
NIST	0.5M	NIST	4.8M

Source: Office of Technology Assessment

[5] "Superconductivity: Fact vs Fancy," ***IEEE Spectrum***, May 1988, p. 39.

Table 4. List of Selected U.S. HTS Consortia

CONSORTIUM TYPE	MAJOR PARTNERS
Industrial:	
MCC Austin, TX	Bellcore, Boeing, DEC, DuPont, Motorola, 3M, Westinghouse
Superchip Washington, DC	Tektronix, others to be announced
Superconductor Applications, Inc. Princeton, NJ	To be announced
University-based:	
Consortium for Superconducting Electronics Cambridge, MA	AT&T, IBM, Lincoln Labs, MIT
TCSUH Houston, TX	DuPont, plus joint membership of MCC partne
NSF S&T Center Urbana, IL	University of Illinois, Northwestern University, University of Chicago, Argonne National Lab
Lehigh University Consortium for Superconducting Ceramics Bethlehem, PA	AT&T Bell Labs, BOC Group, U.S. Navy
NY State Institute on Superconductivity Buffalo, NY	SUNY Buffalo plus partners to be announced
National lab-based:	
Argonne Argonne, IL	Beldon Wire, DuPont, GE, MagneTek, United Technologies
Los Alamos Los Alamos, NM	American Superconductor, AMP, Hewlett Packard, DuPont, Rockwell
Oak Ridge Oak Ridge, TN	Corning Glass, DuPont, FMC, IBM, GE, Westinghouse
Jet Propulsion Lab Pasadena, CA	To be announced.

Source: Source: Office of Technology Assessment

c. Joint Ventures, Mergers and Acquisitions

Although no information pertaining to mergers or acquisitions of U.S. firms involved in superconductivity research or production by foreign firms could be obtained, it is clear that other countries — especially Japan and European nations — have also recognized the promise of superconductivity and are pursuing aggressive research programs of their own. Table 5 identifies Japanese and other foreign firms by their area of research specialization.

The research spending patterns in the U.S. and foreign nations are considerably different, and capabilities cannot be easily compared. For example, recent reports suggest that Japanese firms are ahead of the U.S. in the size and breadth of their private sector superconductivity research efforts, while the U.S. still maintains the largest overall effort

Table 5. Foreign Companies by R&D Specialization[6]

1. MATERIALS RESEARCH/MFG	2. WIRE, CABLE, MAGNETS, NUCLEAR M-R DEVICES
JAPAN: Fujitsu, Mitsubishi Electric	JAPAN: Furukawa Electric, Hitachi, Kawasaki Steel, Mitsubishi Electric, Nippon Steel, Toshiba
EUROPE: ASEA-Brown Boveri	EUROPE: ASEA-Brown, Cryogenic Consultants, General Electric, Oxford Instruments Grays, Siemens
3. ELECTRONICS	**4. LARGE POWER APPLICATIONS**
JAPAN: Fujitsu, Hitachi, Matsushita Electric Industrial NEC, Nippon T&T, Sumimoto Electric Industries	JAPAN: None
EUROPE: Cryogenic Consultants, General Electric, Plessey	EUROPE: None

nationwide. Because of Japan's many strengths — including a high concentration on HTS R&D, a focus on manufacturing quality and efficiency, world class ceramics and electronics capabilities, continued development of LTS, the ability to sustain a long-term commitment, and the high degree of cooperation among industry, finance and government — many believe that the Japanese will be the leading international competition for the U.S. in the future. To illustrate the level of this commitment, a major cooperative R&D program was established in 1988 under the leadership of MITI, which involved an initial 21 companies in a centralized research facility. At the same time, the Japanese government purchased mineral rights in China to ensure availability of the required raw materials. These Japanese strengths are partially offset by continued U.S. investments in R&D, but U.S. R&D results are readily available to the Japanese companies through the open literature or acquisitions, whereas Japan's advantages and markets are inaccessible to U.S. firms. Table 6 compares the spending and structure of the two nations' superconductivity research programs.

4. Summary

Successful development of superconducting technology has the potential to revolutionize large segments of industries. This is particularly true for HTS. Major segments of industry potentially affected by HTS technology include automotive, other transportation, communications, power generation and transmission, manufacturing equipment, and electronics. In many cases, the products created with HTS technology will be entirely new. Such a revolutionary technology will have a far-ranging impact on the industries that produce and use those products, but the achievement of superconductivity's full potential is a long-term prospect that faces considerable uncertainty.

[6]"Superconductivity: Fact vs Fancy," ***IEEE Spectrum***, May 1988, pg. 39.

Table 6. Comparison of U.S. and Japanese R&D Programs

	U.S.	Japan
Private investment in superconductivity R&D (1988)	$81 million	$129 million
Spending on LTS technology (%of total)	18%	27%
Government spending on superconductivity R&D (1989)	$185 million	$146 million
Degree of HTS/LTS Integration	Low	High
Firms spending over $1M on HTS	14 firms	20 firms
Government spending on HTS (% 1989 total)	69%	48%
Firms spending over $1M on LTS	4 firms	12 firms
Government spending on LTS (% of total)	31%	52%

Source: OTA, 1990

Although state-of-the-art materials and processes are not yet ready to support this potential, the rapid pace of discoveries over the past three years has led to the expectation that critical breakthroughs could occur at any time.

As HTS technology begins to mature, DoD is likely to be dependent on the commercial industrial base for the development and manufacture of military products using superconductivity. Consequently, DoD must be concerned with the ultimate establishment of an internationally competitive industrial base in the area. Since the development of HTS products and industries will require considerable time, resources, and commitment over a sustained period, U.S. leadership in future superconductivity markets is far from assured. The achievement of this goal will require the U.S. to improve its ability to translate new technologies into manufacturing capabilities and marketable products as quickly as the international competition, surmount domestic cultural and legal barriers to industrial cooperation, and diminish industry's strong current emphasis on short-term returns. The nation must find ways to surmount these barriers if it is to develop and maintain internationally competitive HTS industries.

BIOTECHNOLOGY MATERIALS AND PROCESSES

1. Introduction

Biotechnology is the use of microbial, plant, and animal cells as factories for the synthesis or conversion of materials. It involves a diverse set of technologies, applied to a diverse set of problems. Unlike many other critical technology areas, in which defense paves the way for commercial applications, the field of biotechnology is dominated by health, agriculture, and other non-defense industries. With relatively few exceptions — predominately metallized biotubals, lithography, and medical/health technologies — most defense-related applications are not well advanced.

The distribution of spending on biotechnology underscores the technology's non-defense orientation. According to National Science Foundation estimates, U.S. industrial spending on biotechnology R&D totalled about $1.4 billion during 1987. Of the total, nearly 69 percent was for medical and health care; 13 percent involved plant agriculture; animal agriculture received 8 percent; chemicals and food were 5 percent; and all other areas (including defense) made up the remaining 5 percent. This industrial funding was supplemented by about $2.7 billion in U.S. Government spending on biotechnology research and expenditures of an additional $150 million by 33 states.[1] The major Government sponsor of biotechnology research is the National Institutes of Health, whose annual investment far exceeds that of DoD. DoD funding for biotechnology, as summarized in the FY 90 ***Critical Technologies Plan***, is projected to increase slightly between FY91 and FY96. Only about 40 percent of the programmed funds will be used for new defense applications such as bioelectronics, biosensors, biomaterials and bioprocessing; the other 60 percent will support DoD's research in medicine and health.

Despite its lack of maturity, biotechnology has been designated a critical defense technology because of its potential to improve the manufacturing of a wide range of defense products, eliminate hazardous substances, and obtain desirable product characteristics through innovative processing techniques. Specific benefits that can be obtained through biotechnology include lower energy use during processing, less environmental damage, greater speed, greater specificity and selectivity, and an improved ability to operate a process under varied conditions and environments. Biosensors, which combine biological and electrical components, illustrate the great promise of biotechnology for DoD. Biosensors are in a very early stage of development but have potential for providing highly specific detection of targeted substances, feedback and control for medical diagnostic testing, drug delivery, and monitoring water and soil quality. As another example, cost-effective applications have already been identified for metallized tubals, a key biotechnology area that is now receiving attention. Among the potential applications relating to other critical technologies are passive sensors (light detection), sensitive radars (microwave components), signature control (anti-fouling paints), and high-energy density materials (detonators).

Figure 1 summarizes key component technologies for defense biotechnology, major areas of application, and the supporting R&D and industrial base.

2. Industry Structure and Capabilities

Biotechnology is of great interest from an industrial base viewpoint. The technology's primary value lies in processing and, as a new and emerging technology, its successful transition from basic science and laboratory-grade technology into practical, industrial-scale processes is of considerable interest to DoD. Established companies are watching biotechnology developments carefully to take advantage of alternate production processes as they emerge, and small startup companies are expected to provide an additional means of producing improved materials and substances as biotechnologies mature. Organizations with active programs include the Naval Research Laboratory; Boeing (bacterial

[1] ***Industrial Outlook*** — 1990, U.S. Department of Commerce, p. 20-2.

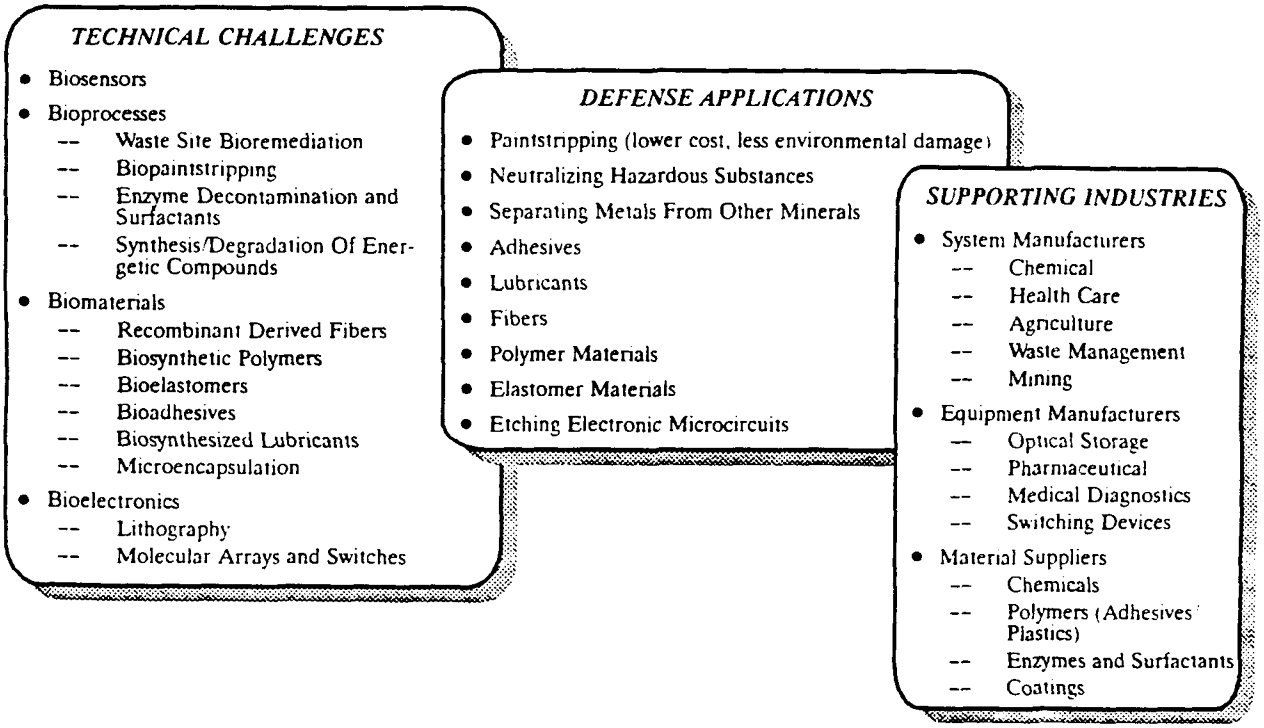

Figure 1. Technical Challenges and Supporting Industries

rhodopsin); the Stanford Institute for Manufacturing and Automation; and Genetech.

Although potential defense technologies may differ from non-defense uses, defense applications can to some degree be supported by the broader industrial infrastructure that is already established in the biotechnology field. If a need to rapidly develop and produce biosensors, biomaterials, and bioprocessing devices were to arise, the existing industrial base that supports the medically-oriented biotechnology field might be able to transition into related defense applications. This industry typically has been unwilling to pursue defense applications because of the high cost and complexity of defense R&D.

Overall, the biotechnology industry consists of the R&D community, start-up companies and academia, and the medical and health sector, which contains a few large companies and many smaller ones. Most of the 500 or so newer biotechnology companies were founded after 1975 and more than 75 percent are privately owned. Many of these companies are unprofitable and rely on funds from outside sources to support R&D. Some 200 other manufacturing firms have branched out into the field through research or through mergers and acquisitions. An additional 300 firms supply materials, instruments, and equipment to support research and development activities.

Early in the establishment of the biotechnology industry, research was found to be financially rewarding and partners could easily be found to provide financial backing for biotechnology startups. Other financing was obtained from venture capital companies, institutional investors, and in many cases public share offerings. Companies such as Cetus, Genex and Genetech arose, establishing themselves as the key players in the biotechnology field. Biogen, which was founded in Switzerland, has set up a major laboratory facility in the U.S. and has also become a key player. Until 1980, most of these biotechnology firms mainly performed contract research for large pharmaceutical, chemical, and oil companies. As a result of expectations of rapid growth and profitability, heavy investment into this new and exciting industry occurred, leaving many large and overzealous companies with new biotechnology divisions that eventually failed. Now, contract research is done on a more conservative basis. The trend is to invest in health related products with the understanding that biotechnology cannot deliver quick results. In the U.S., many stock offerings have been very successful and some of the major public companies still possess revenues from interest on share capital. As a result, the industry is a target for manipulation or takeovers. In the past few years, for example, two promising biotechnology companies have been the targets of acquisitions: Genetic Systems by Bristol-Meyers and Hybritech by Eli Lilly.

Although the basis of biotechnology engineering is found in the medical field, some of this work is directly or indirectly applicable to DoD. Research in biomedical technology supports the military by providing vaccines against disease in specific deployment areas and by making available innovative medical techniques to quickly aid troops. Additionally, an important defense application for biotechnology — shared by non-defense sectors — is in pollution control and the safe disposal of toxic chemical waste, which is a growing problem among defense firms. The varied metabolic capabilities of microorganisms mean that they can digest sewage and can also break down various unusual compounds such as pesticides, and oil. Other direct applications to defense are still in R&D and cannot be assigned to an existing industry sector. Examples include piezoelectric crystals and protein semiconductors, which are being studied by EMV Associates and other companies, and biochips for computer use, which are still in the conceptual stage but which someday may offer advantages to DoD.

Bioprocessing is another component technology that is important to DoD. However, pharmaceutical and biotechnology companies perform very little research in this area, and the equipment and expendables vendors provide little research capital for advanced technologies. Bioprocessing has been and is yet a very small market. Although the food industry is dependent on bioprocessing, these applications have not warranted the development of a strong technology and industrial base.

In Japan, much of the biotechnology research has been done by large companies, where many of the fermentation processes have already been well-established. Historically, Japan has been strong in applied research and product and manufacturing process development and has concentrated on commercial applications. Although many of biotechnology's early products in health care are credited to U.S. firms, Japan has since dominated product development in areas such as food processing, cosmetics, and bulk chemicals. In contrast, Europe's biotechnology industry has a history that is similar to that of the U.S., with limited funding and a wide range of large and small firms that share the new biotechnology market.

3. Summary

Biotechnology is an emerging technology, with few defined defense industrial base applications. A manufacturing industry has not fully emerged and matured for defense products. At present, government laboratories and universities are the primary agents for activity, which chiefly involves research. It is expected that private industry will establish the manufacturing infrastructure for this technology, but some government sponsored manufacturing technology will be needed to develop DoD applications. Japan also is pursuing this area aggressively. Whereas, U.S. efforts are somewhat fragmented and research-oriented, Japanese efforts appear to be more coordinated and focused on applied research and product development.

COMPUTATIONAL FLUID DYNAMICS

1. Introduction

Computational Fluid Dynamics (CFD) is a design tool for developing products whose environment involves fluid flow. Industrial process design may also benefit from CFD, particularly in applications such as chemical vapor deposition and plasma spraying, which require fluid flow or mass transfer analyses. The industrial base for CFD is closely linked to that of Parallel Computer Architectures, since the nation's capability to develop and produce products in both technology areas is strongly dependent on the computer industry — an area of current U.S. strength. More specifically, the progress in both of these areas has occurred because of steady developments in the area of supercomputers. The ability of the supercomputer to solve highly complex numerical problems (such as those posed by CFD) is dependent upon the quality of the software and its ability to be vectored and paralleled so that the numbers of processors can be increased. Both CFD and parallel processing are crucial for providing fast results to complex computing problems inherent in solving defense-related problems. From a technology standpoint, the most critical issue is the validation of CFD codes, deemed essential for testing of future flight vehicles in wind tunnel applications. Figure 1 depicts the technical challenges, defense applications, and supporting industries in this area.

2. Industry Structure and Capabilities

From an industrial base viewpoint, CFD includes both application software and the high-speed processing (both hardware and operating systems) that runs the software. Although the use of CFD is expected to grow considerably as the technology matures, its expanded use depends on further developments in applied mathematics that can resolve such issues as software validation, calculational efficiency, improved algorithms, and reduced reliance on approximations. Academia and research institutes form a large portion of the research base for developing CFD technology to the point where it can be widely implemented in the defense community. Industry is not generally involved with CFD development or the

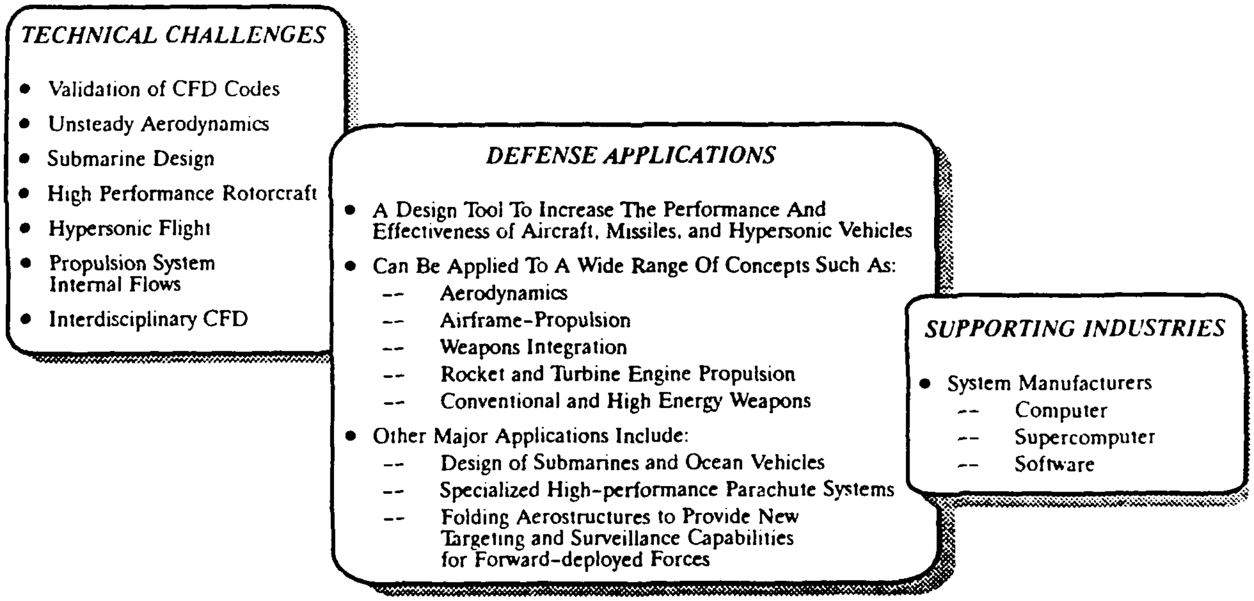

Figure 1. Technical Challenges and Supporting Industries

generation and application of implementation software.

As one example of the use of CFD today, Pratt and Whitney has designed a new combustor for aircraft engines that is expected to achieve significant improvement in time between repairs over existing components. CFD was specifically used to determine the complex flows associated with combustors. The company expects to implement 3-D CFD technology by the end of the decade, when the technology has matured. In addition, Lockheed utilized CFD to obtain a solution for a fighter aircraft wing operating at a 15-degree angle of attack. The solution was obtained from a high resolution color monitor linked to a parallel computer's processors. Pressure contours appear on the surface of the wing and a color scheme denotes the pressure level. These analyses are extremely important and permit a reduction in the amount of wind tunnel testing otherwise required. There are also many commercial applications of CFD within the automobile industry, which uses CFD techniques for analysis of design alternatives. The Applied Technology Department of Onan Corporation's Engine Division uses the Ansys finite-element analysis program of Swanson Analysis Systems for verification and analysis of components for internal combustion engines. Additionally, automotive engineers use Cham Ltd.'s Phoenix Computational Fluid Dynamics program to optimize the airflow within an automobile.

3. Summary

The most significant industrial base challenge rests with the development and manufacture of high-speed processing hardware to meet CFD's computational needs. In the past, use of CFD has been entirely dependent on the supercomputer, and the leadership enjoyed by the U.S. in CFD is a direct result of the nation's strength in supercomputer technology. Although applications of CFD have been constrained by the capabilities of current-generation supercomputers, these limitations may be overcome in the future by parallel processing approaches that will allow greater speed in highly complex computing on less expensive computer systems. The industrial base that supports CFD in these areas is described in more detail in Parallel Computer Architectures.

DATA FUSION

1. Introduction

Data fusion includes a range of technologies necessary to rapidly generate information from many different data sources. The technology includes the acquisition, integration, filtering, correlation, and synthesis of data into useful and readily interpretable form. It concentrates on the acquisition of data from a variety of existing sources, the extraction of information that is pertinent to the problem being addressed, and the combination and presentation of that information in a form that is most useful to the end user, whether a machine or a human.

Data fusion must integrate various types of data that have been collected in a wide range of formats for many different purposes. Most often, the ultimate end use of the data cannot be well-specified very far in advance. Therefore, the primary strategy followed in the data fusion process is to provide generalized solutions that can subsequently be identified in the design of a specific weapon system or capability. The primary exceptions to this generalized approach are found in the development of algorithms tailored to a specific problem and in the modeling of discrete military scenarios that incorporate these algorithms. Even in these cases, there is some opportunity to generalize from the particular application — for example, by benefiting from the strategies and approaches used.

From an industrial base viewpoint, the critical technology needs are integrating distributed real-time systems, man-machine interface, expert system development, and security. Because these needs are important to any organization whose activities are information intensive, many potential applications of data fusion technologies and products are found elsewhere in the federal government, state governments, and manufacturing and service industries. Specific manufacturing applications of data fusion technology range from shop floor control of automated manufacturing cells to integration of information systems between end item manufacturers and suppliers. Figure 1 lists the major technology challenges, defense applications, and supporting industries.

Data fusion technologies are extremely software intensive — not only application software, but also operating system and database software. This software intensiveness requires improvements in software producibility and reusability (as discussed under Software Producibility). In addition, computer hardware is expected to be used to carry out some of the integration functions which might otherwise be performed by software, as a means of satisfying rigorous performance requirements. As a result, a

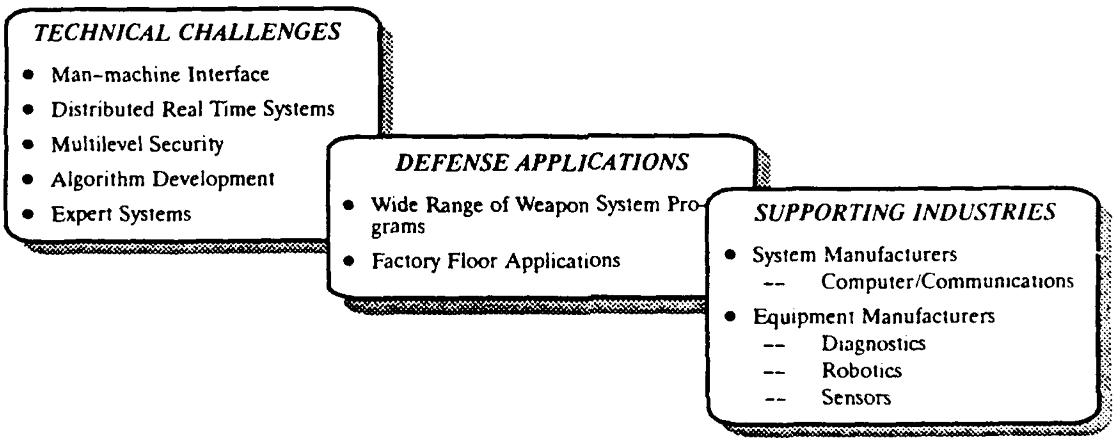

Figure 1. Technical Challenges and Supporting Industries

strong, vibrant computer industry — a subject covered in Computational Fluid Dynamics and Parallel Computer Architectures — is also essential to the nation's ability to develop and produce new data fusion technologies. The industries associated with several other critical technologies also play an important role in data fusion, including — Passive Sensors, Semiconductor Materials and Microelectronic Circuits, Photonics, Machine Intelligence and Robotics, Signal Processing, and Simulation and Modeling.

2. Industry Structure and Capabilities

DoD can draw from a robust R&D base in technologies supporting data fusion. Because of data fusion's pervasiveness, there is considerable R&D and product development that is not directly sponsored by DoD but is closely related to DoD's interests. This creates a capable base for technology development that extends beyond the formal sources available to DoD. Academia, research institutes, computer hardware and software companies, many State and Federal agencies, systems integrators, and medium and large manufacturing and service companies are all involved in R&D for data fusion technologies, and most are available to directly or indirectly contribute to meeting DoD's needs. Thus, the base of knowledge and creativity available to DoD is viable and projected to remain strong.

The industrial base challenges in data fusion stem from the requirement to integrate heterogeneous, distributed information systems, and to incorporate emerging technologies such as object oriented methods, parallel processing, and expert systems. These challenges must be met in an environment that is software intensive and which is characterized by many potential applications.

The first challenge is in systems integration. Since broad-scale integration of information systems of many kinds is a major goal of information intensive organizations, integration strategies and supporting products are expected to find a large domestic and international market. This potential market could include state and Federal Governments, all manufacturing sectors, and service companies such as insurance, banking and finance, educational and training, distribution, retail, and communications.

There is a strong commonality of interest between industry and DoD in fostering the development of technologies for information integration. Manufacturing management and product development strategies such as computer-integrated manufacturing (CIM) and concurrent engineering (CE) are all dependent on industry's ability to implement information systems integration.

In response to the need for improved systems integration, several initiatives are underway in the U.S., Europe, and Japan to create an information integration framework. The standards will provide a mechanism whereby users can specify integration software products that meet accepted standards and vendors can develop affordable products that comply with those standards. This interlocking of industry and Government interest mandates that DoD information integration strategies maintain a high degree of commonality with the directions being followed by the U.S. private sector and other nations. DoD producers are a small percentage of the potential integration products market, and can be expected to have little influence on the directions taken by the rest of the domestic and international community.

The second challenge for data fusion lies in the integration of emerging technologies such as object oriented methods, parallel processing, and expert systems. These technologies are important to achieving the goals of data fusion and are also applicable to many scientific, manufacturing, and service industries. Their development is being pursued by individuals and organizations under commercial, defense, and nondefense sponsorship. For example, continued development of object-oriented programming will offer advantages in software reusability, which can be of considerable value to information integration. It also allows easier identification and extraction of manufacturing features automatically from computer-aided engineering systems. This latter advantage could streamline manufacturing engineering functions such as process and assembly planning, generation of tooling design, and processing instructions.

Implementing these emerging technologies requires the creation of techniques and computerized tools to provide an acceptable software and system development environment. The nation's ability to successfully pursue these emerging technologies is dependent on the health of our software base — an area in which the U.S. has long been a world leader. However, the U.S. capability in software is due to our preeminent position in computers, and weakening our world leadership position in computers will also weaken software capabilities. Current risks to the computer industry are assessed under Computational Fluid Dynamics and Parallel Computer Architectures.

Although the required software tools are frequently the product of software entrepreneurs working individually or as part of small start-up companies, the source of innovation and development in software can range from a single individual to a large computer company. The activities of a software developer are often invisible until the product is ready, so planning for a technology or system that would incorporate the results of the activities is extremely difficult. Considerable effort is being expended on these technologies by industry and DoD systems and industrial base initiatives will benefit considerably from such commercial developments.

3. Summary

Data fusion is important to both defense and non-defense interests. The technology of information systems integration is an area of growing interest throughout the U.S. and internationally. As a result, DoD can draw on a healthy and innovative industrial base to meet many of its data fusion requirements. Manufacturing advances will be dependent largely on the advances of computer and communication technologies. Advances will come primarily from computer, software, and systems integration industries, with the U.S. competitive position generally considered strong in data fusion industries.

HIGH ENERGY DENSITY MATERIALS

1. Introduction

High Energy Density Materials (HEDM) are compositions of high–energy ingredients used in the fabrication of explosives and propellants. The importance of these materials is evidenced by the fact that they are used in almost all DoD tactical and strategic weapon systems.

The U.S. chemical industry forms a vital part of the industrial infrastructure for HEDM. Most forms of HEDM contain binders and energetic materials which readily affect their working characteristics. Binders, which bond fuels and oxidizers together, alter the characteristics of HEDM in areas such as processing, curing, energy release rate, energy, and sensitivity. The properties of the binder generally determine the processing conditions that can be used to manufacture an energetic material.

In addition to binders, energetic materials affect the characteristics of high energy density materials. Explosive properties, which bear excellent resistance to thermal threats, have proven more difficult in resistance to certain kinds of hypervelocity impacts, such as those in the form of detonation of a neighboring warhead, fragment impact, and direct shaped charge jet impact. Thus, it is a goal of explosive manufacturers to produce materials that are both insensitive to shock attack and fracture resistant — in other words, that exhibit both thermal protection and toughness.

Another important facet of HEDM technology development is safety. Because of the inherent risk of explosion, the Services have begun to produce explosives and propellants that are less sensitive to hazards such as shock, fire, and impact with fragments.

Figure 1 summarizes the technical challenges associated with HEDM, along with defense applications and industries supporting development and production.

Some of the R&D for defense applications in this area is being done through the Department of Energy. DoE defines HEDM as a non–standard energetic explosive, including the latest research in areas where standard applications are years away. The area of HEDM addressed in this section references standard HEDM, where applications are more readily applicable. In this standard explosives area, DoE is performing R&D in areas such as insensitive nitroguanadine; LOVEX, a new low vulnerability explosive; and extrusion cast explosives, which can be applied to precision warhead applications such as shaped warheads.

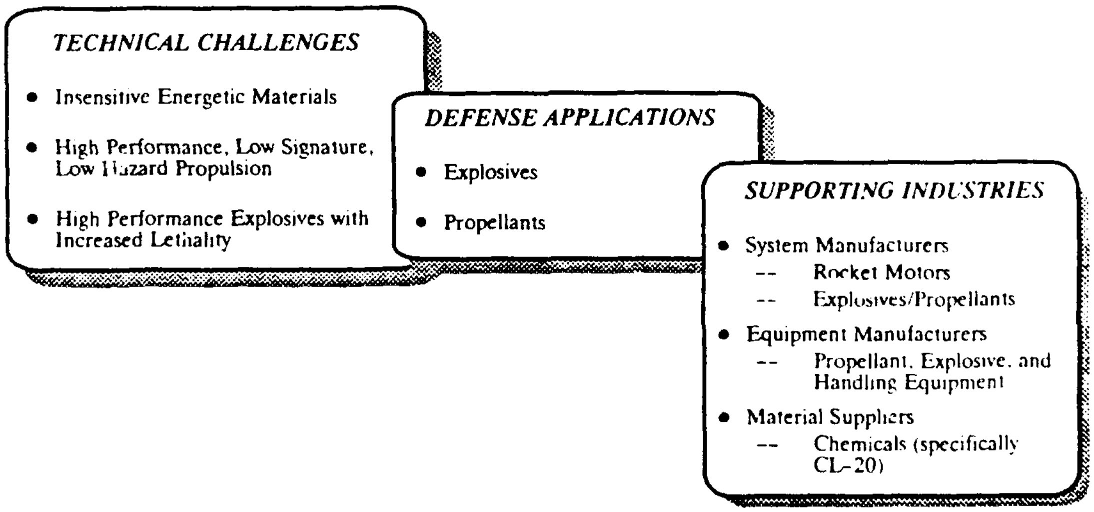

Figure 1. Technical Challenges and Supporting Industries

Additional areas of R&D include liquid propellants and underwater explosives, while other research initiatives in non-standard HEDM include carbon-hydrogen systems, metastable compounds, and nuclear isomers. In addition to defense applications, there are an increasing number of commercial uses for HEDM technology including explosives which have been used extensively in the mining and construction industries. Other practical uses for HEDM began with weapons and munitions systems that were designed in the 1950s. Since then, other design applications such as fire protection systems and other safety areas have become increasingly important. For example, a popular device is the frangible link assembly which controls smoke dampers, closes fire doors, activates smoke release valves, opens windows, and controls safety devices.

2. Industry Structure and Capabilities

Today's industrial infrastructure for HEDM is the product of decades of Government and industry efforts to advance the readiness of the nation's ammunition base. U.S. policy has long held that a strong production base for ammunition must be maintained and advanced in order to assure preparedness in time of war. During World War I, the War Industries Board constructed sixteen plants for manufacture of powder and explosives and a similar number of loading plants, but this base was dismantled at the end of the war. Similarly, the nation found itself with essentially no private industry for munitions at the beginning of World War II, and the Government was forced to build 84 plants to meet its wartime needs for explosives and propellants. Thirty eight of these plants remained operable at the start of the Korean War in 1950 and eleven plants were still active when the Vietnam buildup began in 1965. After Vietnam, the Army was assigned DoD responsibility as the Single Manager for Conventional Ammunition (SMCA) and has since modernized some of the remaining production base. Advanced manufacturing processes and state-of-the-art equipment have been installed to upgrade existing facilities and establish several new Army Ammunition Plants.

Government-owned plants continue to play a pivotal role in the nation's infrastructure for explosives. These plants produce propellants and explosives and perform load, assemble, and pack (LAP) operations. As an example, only one facility in the U.S. — the Holston Army Ammunition Plant — manufactures large quantities of RDX and HMX-based explosives for DoD. RDX and HMX represent the explosives vital to all military Services' propulsion or warhead production programs. Because of concern over the single sourcing of this critical commodity, the Army, in conjunction with Lawrence Livermore Labs and Monsanto Corporation, is reviewing a proposal to establish a backup facility for HMX in Longhorn, Texas. However, due to DoD budgetary constraints, the pilot program is currently on hold and the material continues to be produced by a single, domestic source.

Various government facilities participate in HEDM research, development and production. The Army Armaments Research Development Engineering Center (ARDEC) and the Naval Weapons Center (NWC) perform approximately 80 percent of the R&D for HEDM in the U.S., while many government-owned ammunition plants, including Badger, Crane, Lone Star, Radford and others, are responsible for full-scale production. The Naval Ordnance Station/Indian Head (NOS/IH) and Yorktown Detachment are unique DoD facilities that conduct R&D for the later stages of development, engineering for transition of HEDM from development to production, and pilot and low rate production. Los Alamos and Lawrence Livermore Labs perform HEDM R&D for DoE. Also, the DoE has a facility near Amarillo, Texas that processes HEDM.

In addition to the R&D work accomplished at these Government facilities, some of the design work towards new explosive concepts and ingredients is performed by universities under contract with the various Services. This work includes synthesis studies at facilities such as University of Massachusetts, University of Akron, University of New Orleans and the University of California at Los Angeles; characterization and modeling at the University of California at Berkeley, University of Delaware, Loyola University, Penn State, Iowa State, University of Illinois, Georgia Tech, BYU, Princeton University, Stanford University, Texas A&M, and Washington State; and development of new diagnostic techniques at various universities.

DoD has its greatest industrial base investment in the Government-Owned Contractor-Operated (GOCO) ammunition production base of active and inactive facilities, which are conservatively estimated to be worth $20 to 30 billion. This production base is dominated by energetics manufacturing facilities, either in the propellants and explosives and pyrotechnics area or in energetic LAP operations.

The primary commercial investments for DoD work in HEDM products and production are represented by the Contractor-Owned Contractor-Operated (COCO) facilities. DoD annually procures energetic based ammunition and missile components having an approximate value in the $2 to 4 billion range. For example, Aerojet General Corporation, Hercules Inc., and Morton Thiokol research, develop, and produce strategic rocket propulsion systems and materials; Atlantic Research Corporation performs rocket motor development and production for the Army's Multiple Launch Rocket System (MLRS); and Hercules Inc., which operates the Radford Army Ammunition Plant, produces propellant ingredients. Morton Thiokol Inc. and United Technologies' Chemical Systems Division manufacture propulsion systems for space systems. Aerojet, Olin, and Honeywell are among those that maintain capabilities for explosives R&D. Figure 2 represents the degree of private investment in the HEDM area.

ACTIVE PROGRAMS IN EXPLOSIVE INGREDIENTS OF FORMULATIONS

Corporation	Development Capability		Production Capability
	IR&D $	SERVICE $	
Aerojet	X	X	Large
Thiokol	X		Large
Hercules	X	X	Large
Atlantic Research Corp.	X	X	Large
UTC	X		Large
Olin Corp.		X	Moderate
Ensign-Bickford		X	Moderate
Teledyne	X		Moderate
Fluorochem			Moderate
Rocketdyne			Moderate
Chemtronics			Moderate

Large = Over $1 million

Moderate = Under $1 million

Figure 2. Private Investment in HEDM-Related Programs

There are also significant foreign capabilities to develop and produce HEDM and related products. The strongest of the producing nations are France, the U.K., and the U.S.S.R.

Production technology for most commonly available energetic materials, such as nitroglycerine, nitrocellulose, TNT, etc., is widely available from a number of countries throughout the world. Certain countries, such as Italy and Switzerland, have an acknowledged lead in production capabilities for nitroglycerines. The raw materials for the manufacture of these materials are widely available in every country with an established chemical process industry. At the present time, the French and British appear to have a program to develop new generations of HEDM about 20 percent more energetic than RDX. These materials are similar to those chemicals currently under development and certification in the U.S. There have been no noticeable development efforts which would indicate a comparable program in any other allied or friendly country at this time.

3. Summary

Government facilities have long been the bulwark of the ammunition and explosives base, but U.S. industry stands ready to produce HEDM whenever such production can be profitable. There are already a number of private sector firms engaged in HEDM production and there are no major technological obstacles to sustaining that base if production quantities allow for adequate return on investment. However, private industry is typically reluctant to invest in the special types and capacities of facilities required, particularly when the products are made primarily or exclusively for the military. Industry does invest small amounts of IR&D funding in energetic material preparation processes, and has been willing to accept government funding to help in early stages of HEDM development, but the major contribution from industry is expected to come during the production phase for those explosive materials that meet munition requirements.

HYPERVELOCITY PROJECTILES

1. Introduction

The technologies associated with hypervelocity projectiles not only involve methods to achieve high velocities, but also involve analytical and experimental methods for understanding the behavior of projectiles and targets at such velocities. Weapons systems based on hypervelocity projectiles have tactical, theater, and strategic applications; as a result, there is considerable breadth in the underlying technologies. R&D thrusts include computational techniques for external and internal ballistics; penetrator–target interaction physics and analytical prediction methods; propulsion systems; power generation; guidance; and materials development.

Many of the industries that support this technology are also fundamental to other critical technologies. Except for structural and penetrator materials, the technologies and industrial base associated with propulsion systems are discussed under Pulsed Power and High Energy Density Materials, while issues associated with power generation are subsets of Pulsed Power. Industrial base considerations applicable to the potential use of metal and organic matrix composites are discussed under Composite Materials.

Technology challenges, applications, and industrial sectors important to hypervelocity projectiles are summarized in Figure 1.

2. Industry Structure And Capabilities

The industrial base issues in hypervelocity projectiles arise from specialized materials requirements and small, light guidance inertial measurement units (IMUs). Because of lack of funding, lack of maturity, and limited number of hypervelocity facilities in the nation, the industrial base for this technology is considered sparse. Table 1 outlines government, industry and university involvement in the area of hypervelocity projectiles.

Electromagnetic and electrothermal guns generate material requirements that are substantially new, and largely unrelated to non-defense markets. DoD could therefore be expected to support any required facilitization

TECHNICAL CHALLENGES

- Projectile Design
  - -- Advanced Batteries
  - -- Improved Barrel Life-times
  - -- Reduced Size/Weight of IMUs
- Projectile Propulsion
  - -- 5–10x Increase In Speed
  - -- Velocities >2km/sec.
- Projectile–Target Interaction
  - -- Automatic Launch Control/Tracking
  - -- Decreased Time of Flight/Increased Range
  - -- High Rate of Fire

DEFENSE APPLICATIONS

- Electromagnetic Guns
- Electrothermal Guns
- Travelling-Charge Guns
- Hypervelocity Rockets
- Explosively Driven Shock Tubes
- Development of:
  - -- Launchers and Propulsion Systems
  - -- High-G Miniature Guided Projectiles
  - -- Characterization of Projectile Flight/Stability
  - -- Pulsed High-power/Compact Power Supplies
  - -- High-energy Density Capacitor Technology
  - -- Homopolar Generators
  - -- High-power Density Alternator Technology
  - -- Composite Materials
  - -- Superconductivity

SUPPORTING INDUSTRIES

- Projectile Manufacturers
  - -- Propulsion Systems
  - -- Penetrators and Launchers
  - -- Kinetic Energy Projectiles
- Equipment Manufacturers
  - -- Machine Tools/Metal Cutting
  - -- Explosives/Propellant Processing
  - -- Load, Assemble and Pack
  - -- Composites Processing/Forming
- Material Suppliers
  - -- Explosives and Propellants
  - -- Composite Materials
  - -- Depleted Uranium
  - -- Tungsten and Tungsten Alloys

Figure 1. Technical Challenges and Supporting Industries

Table 1. Source of Involvement in Hypervelocity Projectiles

GOVERNMENT	INDUSTRY	ACADEMIA
• Army	• GE	• University of Texas at Austin
• Air Force	• Maxwell Laboratories	• Auburn University
• DNA	• Westinghouse	• University of Tennessee
• DoE	• Boeing	• University of Miami
• SDIO	• McDonnell Douglas	• University of Washington
	• General Atomic	
	• SPARTA	

by industry and there is considerable concern over the potential cost of such components. A similar concern arises in the area of guidance, where cost and quality problems are a concern. Furthermore, there are no known industrial base issues associated with either computational techniques or penetrator-target interaction. Sources of development in these areas include prime contractors, software houses, and research institutes, most of which are well-equipped to perform necessary developmental work.

a. Materials

Hypervelocity projectiles generate many different materials requirements that are unique to defense applications. Electromagnetic and electrothermal guns require new materials for rails, armatures, and electrodes that possess various combinations of light weight, resistance to electric arc erosion, and resistance to electromagnetic forces. New materials are required for high length-to-diameter ratio projectiles, which must be stiff yet tough, and for very light sabots. Material requirements for gun applications exceed those seen in non-defense applications. However, the potential production volumes are small compared to customary gun markets, and traditional materials producers have shown little interest in supporting development efforts. If new facilities and equipment are required to process the materials developed for these applications, DoD will be expected to bear the cost of the investment.

Nevertheless, the industrial base for basic metals, specialty materials, coatings, and coating processes is sufficiently strong and capable of fulfilling anticipated production needs, given sufficient DoD funding for process development and facilitization. Highly specialized materials based on technologies not resident in these industries can be produced by the developers or by specialized materials houses, given sufficient volume requirements and the successful transfer of manufacturing process technologies. Regardless of the producer, these materials can be expected to be extremely costly because of the low volumes and the lack of a potential commercial market.

Penetrator materials are required for both the projectile body and the nose tip. Producers of conventional velocity penetrating munitions represent an adequate industrial base in the area of hypervelocity projectile bodies. The projectiles themselves must be as dense as possible, leading to the selection of materials such as tungsten, tantalum, and depleted uranium. The use of tungsten and depleted uranium is well-established in conventional projectile production, and industry is expected to be fully capable of meeting production requirements if sufficient DoD support is provided.

The aerodynamic heating of projectile nose tips has led to the selection of three-dimensional carbon-carbon composites as the material of choice. These materials are relatively well-established for reentry vehicle nose tips and rocket nozzle inserts. Potential applications to turbine engine components are also expected to become production commitments in advance of hypervelocity applications. Other carbon–carbon applications include the high endoatmospheric defense interceptor (HEDI) of the SDI program, which is developing a sapphire window to protect the infrared sensor system, a shroud to protect the interceptor's nose in early stages of flight, and a gaseous nitrogen transpiration cooling system. Hence, the carbon–carbon industry is expected to be fully capable of meeting the anticipated needs in this area.

b. Guidance and Control

Guidance and Control (G&C) systems also place new requirements on the industrial base. Stringent accuracy, responsiveness, size and weight requirements must be satisfied by IMUs of guidance systems and IMU components. The guidance industry is composed of vertically-integrated companies. Advancements in guidance technology have historically resulted from DoD investments in both R&D and manufacturing process development. Although other applications with less stringent requirements can also benefit from the results of R&D in this area, little private support for either R&D or facilitization is likely to come from the G&C industry because of the low production volumes.

The G&C industry is currently able to produce the small number of IMUs required for hypervelocity projectile requirements. However, this industry is highly sensitive to fluctuations in weapon system demand and the anticipated decline in Defense budgets may have two negative effects on the industrial base. First, the number of viable companies in the industry is likely to be reduced by any protracted reduction in production volume (including spares and replacement units). Second, remaining companies can be expected to concentrate very heavily on increasing market share of existing product lines. In that event, adequate brainpower may not be available to develop the dramatically new concepts in G & C that are required by hypervelocity projectiles, especially in process development and manufacturing R&D. Without substantial progress in manufacturing cost reduction and quality improvement, hypervelocity projectile guidance and control costs will be extremely costly. This will place heavy requirements on the DoD to do more manufacturing science and production technology.

3. Summary

Support for hypervelocity projectile development and applications comes almost exclusively from DoD. There is little commercial application for hypervelocity projectile technology, with the possible exception of some aspects of power generation and advanced light weight materials. Future manufacturing and industrial base investments by the DoD in support of selected, high payoff technology challenges will be vital in maintaining the domestic competitive advantage.

PARALLEL COMPUTER ARCHITECTURES

1. Introduction

Parallel computer architectures are widely regarded as the most promising approach to increasing computing performance and decreasing the cost of computing power. However, there are still issues to be resolved before parallel computer architectures find widespread use. Most of these issues encompass product design technologies and integration of high parallel processors into operating systems. In manufacturing technology, issues include memory and wafer-scale integration and manufacturing of optical devices. Figure 1 summarizes technical challenges and supporting industries. These industries are similar to those that support other critical technologies, including Computational Fluid Dynamics, Simulation and Modeling, Signal Processing, and Weapon System Environment.

Parallel processing ranges from "high-end" applications represented by supercomputers to "low-end" applications that can be performed with personal computers. The technology will provide greater computing performance than exists today, but at similar or lower cost. This gradation in capability can be viewed as extending from parallel mainframe computers to individual chips in parallel. It is this range of parallel processing, coupled with performance and cost advantages, which lead many to predict that the future of the entire computer industry lies in parallel processing.

2. Industry Structure and Capabilities

Since many of the architecture, software, and integration technologies associated with parallel computing are still in basic and applied research, academia and research institutes play an important role in the development base. Important work is also being performed in the research laboratories of major computer manufacturers — notably, AT&T Bell Labs and IBM Watson Labs — but most of this effort is directed toward improving existing product areas, rather than long-term innovation.

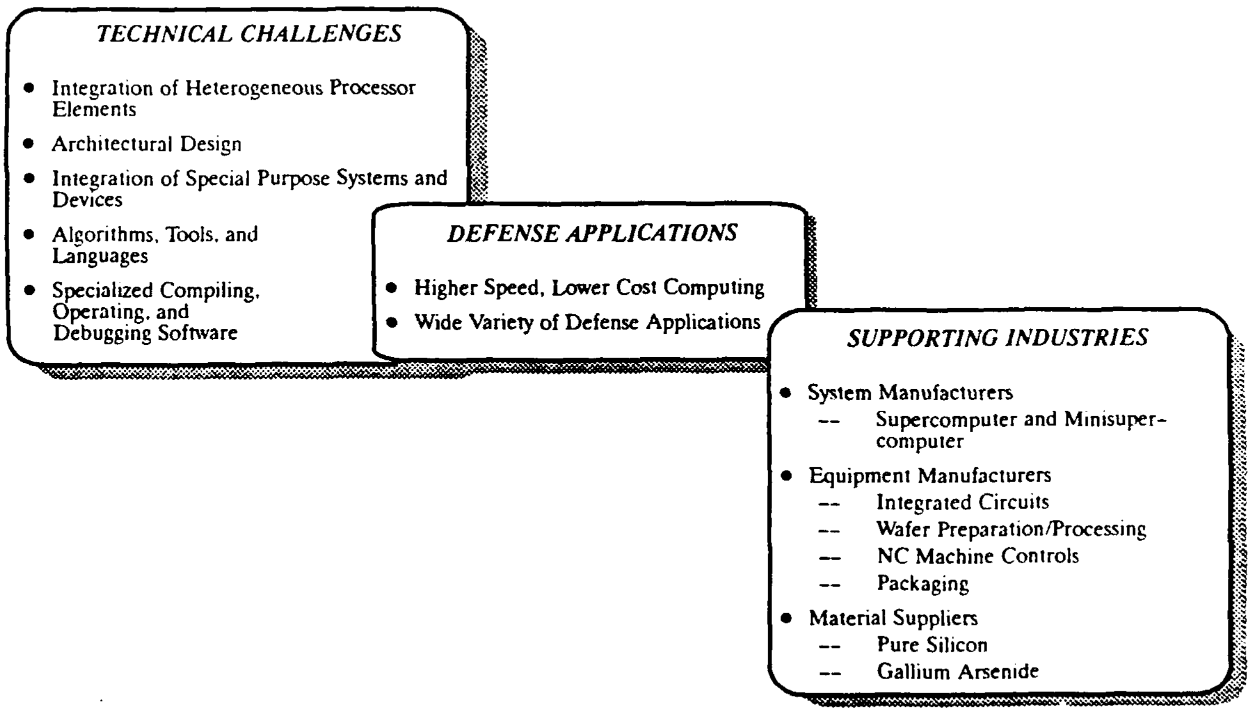

Figure 1. Technical Challenges and Supporting Industries

The challenges that face the computer industry now face supercomputer manufacturers as well. Since 1976, the supercomputer market has been one of the most stable high technology growth markets. Although the market is small, it is considered a critical enabler of several defense technologies and, therefore, is the focus of our discussion for parallel computing.

The relationship between parallel processing and supercomputing is important to note. Parallel processing allows for many parts of a problem to be manipulated all at the same time, then quickly coordinated and presented in answer form. Supercomputers, without the use of parallel computer architectures, perform operations in a sequential rather than concurrent fashion and are therefore geared towards manipulating certain types of problems that can be analyzed sequentially.

The term "supercomputer" is defined by characteristics that differ from other types of computers, specifically, the speed of operation. The ability of the supercomputer to solve numerically intense problems is unique. Supercomputers, measured by using Livermore Loops or Linpack benchmark execution rates measured in floating point operations per second, are deemed the fastest of all computers and can manipulate an abundance of information in seconds. Supercomputers can also be characterized by price: the largest and most complex supercomputers range in the $1 million to $20 million bracket, mini-supercomputers from $100,000 to $1 million; and graphics supercomputers at about $100,000. Recently, personal supercomputers costing between $15,000 and $50,000 have been introduced on the market.

The international market for high-performance supercomputing is about $2 billion. Increasingly, more and more industries rely on high performance computers to design high quality products faster. Defense applications are about equal to the large numbers of commercial applications, ranging from pharmaceuticals to oil.

However, many believe supercomputers will be made more affordable and accessible to a growing number of users. Companies are now offering affordable multiprocessor machines to perform the high-speed computing work. These multiprocessor machines may employ parallel architecture and could become the main-line time-shared computers and smaller workstations of the future. The multiprocessor has been used as a research tool of the parallel processing community for use in computational models. Currently, Government funding for R&D for high performance computing totals $500 million annually.

Because of the prevalence of the supercomputer across so many defense and non-defense technologies, a proposed 5-year, $2 billion supercomputer plan that would support the development of advanced systems was given the backing of the Office of Science of Technology Policy (OSTP) and DARPA. The plan, entitled ***The Federal High Performance Computing Program***, is proposed to support the continued viability of domestic sources of high performance computers and their critical components. The proposal addresses both government and private sector producers in defense and commercial applications. Because of the new capabilities and more diverse product lines, Dataquest predicts that the international supercomputer market will enjoy a steady growth from $1.06 billion in 1988 to a predicted $2.46 billion by 1992. However, some experts believe that the market is too small for the growing number of competitors. There were layoffs in one of the two mini supercomputer makers in an attempt to survive plummeting prices. Also, last year, Control Data Corporation closed its supercomputer division, leaving only Cray, Cray Research, and IBM as the leading U.S. producers.

The most prominent U.S. supercomputer producer is Cray, which is responsible for half of the supercomputers sold in the world today. Cray Research, a recent spinoff of Cray Inc., will present the Cray 3 this year (16 processors at twice the speed of the Cray 2) to be followed in 1992 by the Cray 4. The Cray 4 will use 64 processors. This domestically produced computer is expected to supersede Japan's NEC SX-3, which has been touted as the world's fastest computer.

In addition to IBM, Cray, and Cray Research, supercomputers and parallel processing machines are being built by a number of other firms, using a variety of architectures to optimize computing performance. Evans and Sutherland produce the ES-1 general purpose supercomputer that accommodates up to eight processors and operates at 1,600 million instructions per second (MIPS). This scalar architecture provides an advantage over vectorized computers such as Cray when attempting to solve non-well structured computational problems. Another type of architecture involves crossbar switching where separate busses are established for each global memory module. The busses are connected to all the processors in a grid-like pattern. A third type of architecture designed to improve data flow between linked processors is the multistage or "Butterfly" switch designed by BBN Advanced Computers, Inc.

The Japanese supercomputer sector, consisting of NEC Corporation, Fujitsu Ltd., and Hitachi, is expected to be highly competitive with U.S. companies. The U.S. market has been fairly impenetrable, and buyers have been reluctant to purchase and install Japanese supercomputer models. Moreover, current DoD policy restricts the purchase of Japanese supercomputers for military-related or government use. Conversely, although Cray Research has had great success in installing systems in Japan and Europe, Japan continues to buy most of its own domestically produced machines, which they feel are better tailored to Japanese needs.

It is debatable whether the Japanese are ahead or behind the U.S. in supercomputer capability. Cray seems to have the lead in the number of installed machines in the U.S. and in Japan. However, U.S. companies are becoming increasingly dependent on Japanese computer suppliers. Cray, for instance, depends on Fujitsu memory chips in its current generation X-MP and Y-MP supercomputers. The U.S. is said to be dominant in software for the supercomputer, but many believe it is only a matter of time before the U.S. loses its competitive edge.

The development of "niche" markets in parallel processing architectures will have an enormous impact on the competitiveness of domestic firms. In order for the U.S. to maintain leadership in market areas now served by supercomputers, it is important for U.S. companies to pursue advances in parallel processing, which will allow them to "leapfrog" current and near-term supercomputer products and provide similar or greater processing power and speed at a significantly lower cost. This new market is equally important to Japanese firms, which can be expected to incorporate parallel processing architectures into products that involve less than a half dozen chips, such as industrial process controllers, to their most powerful computers. At present, NEC's SX-S's characteristics, which allow the machine to operate in parallel, has distinct advantages over Cray machines which do not allow for parallel speed processing. Because of Japan's international preeminence in silicon and gallium arsenide technology and their unlimited access to the most advanced memory and processor chips, the advent of parallel processing could tip the scales in favor of Japanese computer companies and further erode the U.S. position in computers and supercomputers.

In addition to the proposed ***Federal High Performance Computing Program***, the Government has initiated a variety of programs to help industry maintain its competitive position in parallel processing technology:

- DARPA recently awarded a contract to Thinking Machines Corp. to develop a new supercomputer parallel processor with peak speeds above one trillion instructions per second. A computer of this complexity will be used for semiconductor circuit design and testing and world climate prediction

- General Microelectronic's CAPPS (Configurable Architecture Parallel Processing System) was successfully tested against Cray, Intel, and IBM supercomputers. The CAPPS supercomputer, developed with funding from DARPA and Northrop, boasts competitive high speed computing and unique computing techniques. CAPPS will be used for many military computer needs, including flight control, CFD, structural analysis, electromechanics, and artificial intelligence

- Hypercube, which extends communications beyond two dimensions, was created to facilitate data communications between an almost infinite number of processors. Thousands of processors are employed to achieve supercomputing performance with a scalar architecture

- NCube Corp. is the producer of the 8192 processor NCube 2, which incorporates a 64-bit computer system into a single computer chip. The NCube 2 reportedly offers more processing power than any other computer now available.

3. Summary

Although there is little concern about the ability of the nation's research base to achieve desired improvements in parallel processing, the implementation of the technology depends on the ability of the computer industry to effectively compete in the world market as new parallel processing products come on line. While the U.S. computer industry is currently strong, it is under increasing competitive pressure from Japanese as well as European firms. The computer industry, along with its supporting microelectronic and software industries, is a critical foundation domestic industry. It is enormous in and of itself and is an enabler of most other manufacturing and service sectors.

PULSED POWER

1. Introduction

Pulsed power encompasses techniques for the conversion, storage, pulse-forming, and transmission of electrical energy used to power a variety of advanced high-power applications. Research in this technology is geared toward improved efficiency and fault tolerance, increased energy at a reduced volume, increased capability to handle high voltages and currents, and lighter weight, higher reliability/maintainability, lower cost power control systems.

Pulsed power technology comprises final delivery systems as well as power sources. Delivery systems include such applications as electromagnetic launchers, earth-to-orbit launchers, ultra-wideband radars, particle beams, and high-power microwaves. Many of these potential delivery systems are in the developmental stages. While the feasibility of some has been demonstrated in small-scale laboratory or field experiments, others are still in the exploratory stage. Critical component technologies for energy storage, pulse formation or conditioning, and matching the pulse to the load underlie the delivery systems, and R&D successes in these technologies will be required to bring delivery system concepts to fruition. The most critical needs in component technologies are compact power sources, power conditioning, and power switching.

Major improvements in pulsed power technology will make possible revolutionary changes in battlefield operations through the development of high-power weapons and sensors. These include directed energy weapons (DEW), kinetic energy weapons (KEW), improved target identification and surveillance systems, and rapid fire earth-to-orbit (ETO) launchers. Pulsed power technology should also prove vital to assessing and simulating the vulnerability and lethality of present and future systems to nuclear, DEW, and KEW systems. Figure 1 summarizes the technical challenges, applications, and supporting industries associated with pulsed power technology.

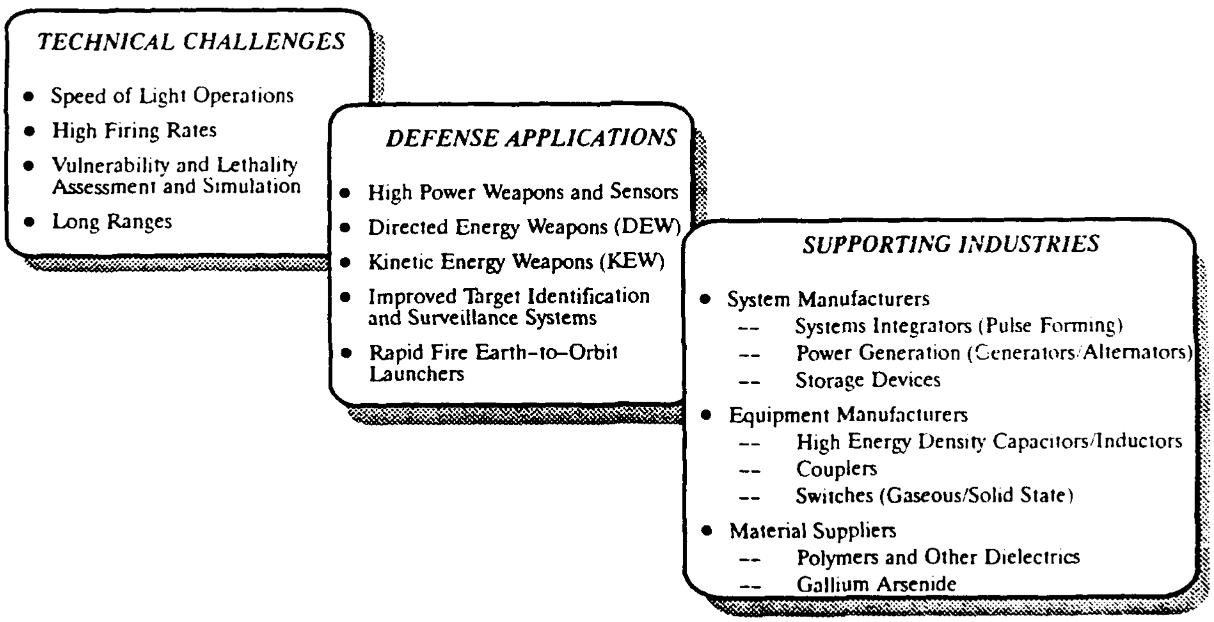

Figure 1. Technical Challenges and Supporting Industries

2. Industry Structure and Capabilities

The pulsed power industrial base is best described as an industry with two prominent parts: applications and components. Although both are important, achieving required pulsed power capabilities depends more on advancements in component technologies than on the ultimate applications themselves. This section will discuss some industrial aspects of end applications, followed by a discussion of industry sectors that supply critical components.

The industrial base associated with end applications is essentially the high technology arm of the defense industry. There are potential pulsed power applications in space, land, sea, and air, and the industrial base consists of prime contractors and major subcontractors who provide weapons systems or subsystems in all four regimes. However, pulsed power applications are sufficiently different from traditional weaponry that new divisions have been formed within defense companies to address developmental needs and new relationships among firms have been established. Acquisition of the requisite technical skills in these new technologies has also been a problem for the industry, but this is now largely overcome.

One important application of pulsed power — high peak power ultra-wideband radars — is being pursued by the traditional radar manufacturers — Boeing, General Dynamics and others. R&D activities within these companies are developing the new technologies required for precision controlled switching and extremely fast modulation. Substantial new organizations or relationships with other companies have been required. Although the problems associated with this technology have yet to be resolved, the companies in this segment are trying to develop basic technology.

High-power microwave applications present a dramatic change in the state of technology for companies that currently supply microwave-based products. Potential applications involve both narrow and ultra-wide bandwidths, and major advances in power sources, conditioning, and control are required, as well as in antennas. The primary emphasis at present is on the component technologies, where R&D breakthroughs are required before serious application design work can proceed.

Electrothermal guns, electromagnetic launchers, neutral particle beams, free electron lasers, and charged particle beams represent dramatically new applications concepts. As such, there is no established industrial base from which to draw. Most work is now being performed by large defense producers, who have established new organizations to pursue systems concepts for these applications. Even in these companies, major system development efforts are sufficiently far in the future that DoD funding is required to sustain current activities. The health and stability of the defense industry, and its continued willingness to pursue these future applications, is a direct function of the funding and application priorities established by the Government.

For the components industry, there is currently little incentive for manufacturing firms to venture into the low-volume market. With few near-term commercial uses, pulsed high power for military applications has been and continues to be needed only for applied and basic research. This has resulted in a military requirement for only limited quantities of pulsed-power components and hardware, which is being met by small, research-oriented firms. A partial list of companies on contract in FY89-90 to develop key components for pulsed power applications such as capacitors, switches, and pulse rotating machines include Maxwell Laboratories, Physics International, Pinnacle, IAP Research, and Parker Kinetic Designs. Typical contracts were only in the one to three million dollar range.

Larger companies have supplied components to the military as a sideline to their main commercial business, and in some cases these firms have ceased to manufacture them. This has led to foreign sourcing of many components, such as solid state switches and pulsed power semiconductor devices, which were formerly made in the U.S. U.S. firms occupy a leading international position in high energy-density capacitors, where major technology advances already have been made. In their current form, capacitors are made using precision polymer-film winding machines. For future applications, however, larger devices will be required and larger, more precise equipment must be developed. This equipment is not produced in the U.S., and there is no assurance that U.S. capacitor manufacturers will have timely access once it is developed. The weakness of the nation's computer controlled equipment industry, coupled with small demand, makes it very unlikely that such equipment will be developed and produced domestically without DoD support. There are current domestic sources for the advanced materials used to fabricate such capacitors and the foundation materials industry is considered strong and able to provide necessary materials.

In addition to high energy density capacitors, pulse-forming networks require inductors with an order of magnitude greater capacity than is available today. Methods for achieving such performance are not yet clear, and today's manufacturing methods may not be adequate to meet future needs. With sufficient incentives, the industry should be able to invest in the equipment and training necessary to adapt to the new procedures.

Switches are gaseous or solid state. Gaseous switches require significant reliability improvements, higher voltages, and increased capacities over current variants. The most promising approaches to meet these requirements are spark gaps, ignitrons, and thyratrons. Although hydrogen thyratrons are currently in production in the U.S. for medical applications, the necessary advances in gaseous switches have little commercial value. DoD funding will be needed to develop the technology and support the industrial base.

Solid state photo-conductive/semiconductor switches offer advantages in power level, short pulses, light weight, and direct, precisely-timed pulses. In particular, ultra-wideband radars may require photo-conductive switches to be successful. Japan is the acknowledged world leader in the production of both photo-conductive materials and large boule, low-impurity gallium arsenide, which are required for solid state switching applications. The inherent speed of gallium arsenide at low impurity levels, coupled with wafer scale integration, is regarded as a very high value technology. The U.S. trails Japan in understanding and producing gallium arsenide, with U.S. firms having less than five percent of the international market. This small share cannot support the level of R&D required to enter a niche market such as this. Without significant DoD investment, it is projected that the U.S. applications industry will be largely dependent on foreign sources of solid state switches.

3. Summary

The technology required to build pulsed high power systems that meet DoD's size and weight requirements is not yet available, and there has therefore been no incentive for industry to create a high-volume production base. At present, the vast majority of pulsed power R&D is supported by the Government. Pulsed power or related programs are sponsored by the Army, NASA, DARPA, SDIO, and DOE. For example, a Federally Funded Research and Development Center was established to support the Army's tactical electric gun program and associated machine pulsed power supplies. Although commercial applications of pulsed power technology have been identified in the medical, electric utility, and electric drive and control industries, there has been only limited interest in possible near-term products that might result from pulsed power developments. The technology has received little support from the commercial power industry because the rise times and pulse rates required for their systems are generally slower and lower than those specified for military systems. Further, the risk, cost, and time to develop marketable commercial products limits the amount of product R&D that the commercial sector is willing to undertake, and most product R&D narrowly focuses the Government's R&D results onto solutions for selected commercial problems.

SIGNAL PROCESSING

1. Introduction

Signal processing allows a human or a machine to make decisions by extracting relevant information from signals received by sensors. The underlying technologies in signal processing include specialized sensors, processors, and algorithms that permit real-time acquisition, analysis, discrimination, and recognition of specific targets. There are land, sea, air, and space applications of signal processing technology. The ultimate goal of most of these applications is automatic target recognition (ATR). Only limited capabilities for ATR are in place or ready for engineering development today, and significant progress toward true ATR must await the results of research and/or exploratory development. From an industrial base viewpoint, the most critical ATR-related needs are in high-speed microelectronic processors, advanced software techniques including model-based approaches and neural networks, and large aperture or conformaly-phased arrays (radar or acoustic). Figure 1 depicts the technology challenges, defense applications, and supporting industries for signal processing.

Several of the industries that support other critical technologies also play an important role in signal processing. Among these technologies are Passive Sensors, Parallel Computer Architectures, Semiconductor Materials and Microelectronic Circuits, Data Fusion, Photonics, Sensitive Radars, and Simulation and Modeling.

2. Industry Structure and Capabilities

Sources of R&D include academia and research institutes, defense prime and major subcontractors, and companies having substantial non-defense interests (e.g., character analysis and speech recognition). There is considerable R&D ongoing in non-defense industries, and these sources are considered generally capable of performing the type of research, design, and systems production required for defense. Although a substantial amount of the commercial

TECHNICAL CHALLENGES

- Matched Filter Techniques
- Model-based Approaches
- Artificial Neural Networks
- Hybrid Optical-digital Techniques
- Signal Processing for Phased Arrays
- Algorithm Development
- Training Set Development

DEFENSE APPLICATIONS

- Target Tracking, Recognition, and Identification
- Multisensor Correlation/Fusion
- Intelligence Situation Assessment
- Mapping and Charting Geodesy
- Speech Recognition
- Text Understanding
- Indications and Warning Analysis
- Optical Implementation of Algorithms
- Adaptive Antenna Nulling/Beamforming
- Smart Skin Technology
- Auditory Localization
- Brain-actuated Control
- Noise Reduction
- Diagnostics
- Missile Evasion
- Adaptive Navigation

SUPPORTING INDUSTRIES

- Signal Processing Manufacturers
  - -- Smart Munitions and Weapons
  - -- Target Acquisition Systems
  - -- Focal Plane Arrays
  - -- Phased Array Radars (Acoustic)
  - -- Space Platforms
  - -- Neural Networks
- Equipment Manufacturers
  - -- Biomedical
  - -- Microelectronics
  - -- Electronic Devices
- Material Suppliers
  - -- Silicon
  - -- Sapphire

Figure 1. Technical Challenges and Supporting Industries

work is considered highly sensitive and proprietary, companies pursuing product R&D in related commercial areas represent a significant resource upon which DoD signal processing development can draw.

Some military applications for advanced signal processing are underway, such as autonomous vehicles. In addition, AT&T has designed an advanced modular signal processor for the Navy that incorporates new technologies. The initial application is for anti-submarine warfare to analyze multiple signals from acoustic sources to sort out background noise. AT&T also has an Air Force contract for the next generation integrated avionics processor that will include electronic warfare, radar, sonar, navigation, communications, and video.

A new class of semiconductors is emerging that is potentially superior to silicon. Semiconductors using III-V compounds provide a wide range of flexibility in energy band-gap and lattice constant engineering. The SDIO Signal Processing MODIL with Sandia and a technology program with Los Alamos are looking at applications of III-V compounds for SDIO sensors.

Key device technologies at Rockwell include work in field effect transistors using III-V compounds. They are also using molecular beam epitaxy (MBE) and metal-organic- chemical vapor deposition (MOCVD) to fabricate heterostructure layers.

Hughes reports that the pervasive technology is high density electronics packaging and interconnections using techniques such as silicon-on-silicon for signal paths to provide more dense three-dimensional configurations. They also report there will increased development of multispectral sensors. Millimeter wave will be combined with an advanced infrared sensor and fiber optics would be used to provide pinpoint accuracy.

Lockheed has funded development of a transistor operating at frequencies up to 200 gigahertz using indium phosphide material. Material for aluminum gallium arsenide and the indium phosphide will be deposited with a new MBE machine.

Many of the industrial base issues affecting signal processing capabilities have been discussed in detail elsewhere in this report. These issues — which are heavily dependent on the health of the commercial sector — include maintaining strong and innovative computer hardware and software industries, and ensuring immediate access to the latest in integrated circuit technology, both processors and memory. The most important signal processing applications depend on advanced high-speed, high throughput processors. These are primarily based on Very High Speed Integrated Circuit (VHSIC) technology and possibly including wafer-scale integration, as well as on further advances in high-speed, high-capacity memory chips. VHSIC is being applied to components such as core processors for all levels of electronic warfare systems. Major companies involved in VHSIC development efforts include Westinghouse, TRW, Northrop, Magnavox, Harris, Hughes, Raytheon, and others.

While the industrial base issues associated with microelectronic circuits are discussed under Semiconductor Materials and Microelectronic Circuits, some of the effects of the continued decline in the domestic semiconductor industry will have a particularly dramatic impact on signal processing technology. If the domestic industry's capability to maintain advances in circuit design and to supply advanced chips diminishes, the necessary leading edge capabilities may be available only from foreign sources, particularly Japan. Japanese producers also dominate the international market in gallium arsenide (GaAs) boules and wafers and chips, which may be necessary to handle the high-speed and radiation-hardening requirements of signal processing applications. The Defense Advanced Research Projects Agency (DARPA) is attempting to accelerate the insertion of GaAs by upgrading fielded military systems. The Army's Hellfire missile seeker and Navy radar and countermeasure systems are targeted for GaAs insertion.

Several other signal processing technologies are also important from an industrial base perspective. Some high-performance signal processing concepts require large-scale arrays of small sensor/signal processor packages, which may be required in the thousands or scores of thousands. These concepts can include large aperture or conformal phased arrays (radar or acoustic), as well as smart skins. The nation does not currently have the capability to produce such packages at an affordable cost. Research, development, and manufacturing efforts are currently focused at the chip level, but packaging the chips into large numbers of small modules may be as costly as the chips themselves and can be expected to continue to represent the major source of reliability problems. Unlike other areas of signal processing, the array technology will be unable to benefit directly from commercial R&D and manufacturing methods. The large-volume manufacturing concepts employed in non-defense industries may not be applicable because of special military requirements, such as in-process test requirements and environmental protection. In addition, the anticipated production volumes, even though high for military production, may be insufficient for the commercial techniques to prove economical.

In other areas of research relating to the manufacture of signal processing devices, Hughes and a Texas Instruments/Westinghouse joint venture have received Air Force Manufacturing Technology (ManTech) funds to research producibility, manufacturing, and cost issues associated with Transmit/Receive (T/R) modules. The programs will involve the design of a module for manufacturability, utilization of new cost effective material, and assembly and testing techniques. Hughes also has in-house programs designed for Low Temperature Cofired Ceramics for integrated substrates and housings and for flip chip mounting of high power microwave components. These processors should result in high volume production and will greatly reduce the cost of phased array modules. Additionally, microwave wafer-scale integration (WSI) technology is being developed by TRW, Martin Marietta, and Westinghouse. WSI, which offers much denser packaging and greater processing speeds, takes into consideration important environmental issues which need to be addressed in the implementation of both defense and non-defense systems.

3. Summary

There is considerable commercial interest in near-term applications and use of products for signal processing technology. In particular, there is potentially a large commercial market for handwritten character recognition, speaker-independent speech recognition, several medical applications, and computing using neural networks. Generally, DoD is dependent on the existence of a strong commercial industry for such applications as integrated circuit processor and memory chips. Other applications such as large aperture or conformal phased arrays will require significant quantities of small modules, which cannot be produced today at costs acceptable for the anticipated volumes.

SIGNATURE CONTROL

1. Introduction

Signature control involves modifying any emissions that can allow an enemy to detect, recognize, track, or engage a weapon system. Aircraft and helicopter structures and propulsion systems; rocket propellants; submarine and ship structures, machinery and propulsion; missile structures; and various kinds of decoys are all dependent on some type of signature control. The underlying technologies are diverse, since they encompass reducing, changing, or enhancing emissions in a wide range of frequencies and wavelengths, including visual, acoustic, infrared, and microwave (radar). Most applications involve passive approaches such as coatings and vehicle shaping, but active methods such as enhancing and tailoring the return from decoys are also being pursued. The objectives of signature control can be achieved using relatively simple technologies such as camouflage paint and netting, as well as through the use of highly advanced materials, processes, electronics, and computational procedures and methods As a result of the many types of signature control applications, the technology is supported by a wide range of industries, from predominantly commercial businesses to those that produce specialty defense products. Unfortunately, classification precludes a discussion of the more advanced technologies and applications. Products and industrial sectors important to this technology are summarized in Figure 1.

Signature control is a defense-unique product; among the very few non-defense applications are TV-absorbing materials and radar absorbing automobile covers. Nevertheless, signature control draws directly from design methods and materials used in the commercial sector, and many supporting firms (for example, the paint industry) are primarily focused on commercial business. Further, the technology relies on many of the same industries that support other critical technology areas described in this

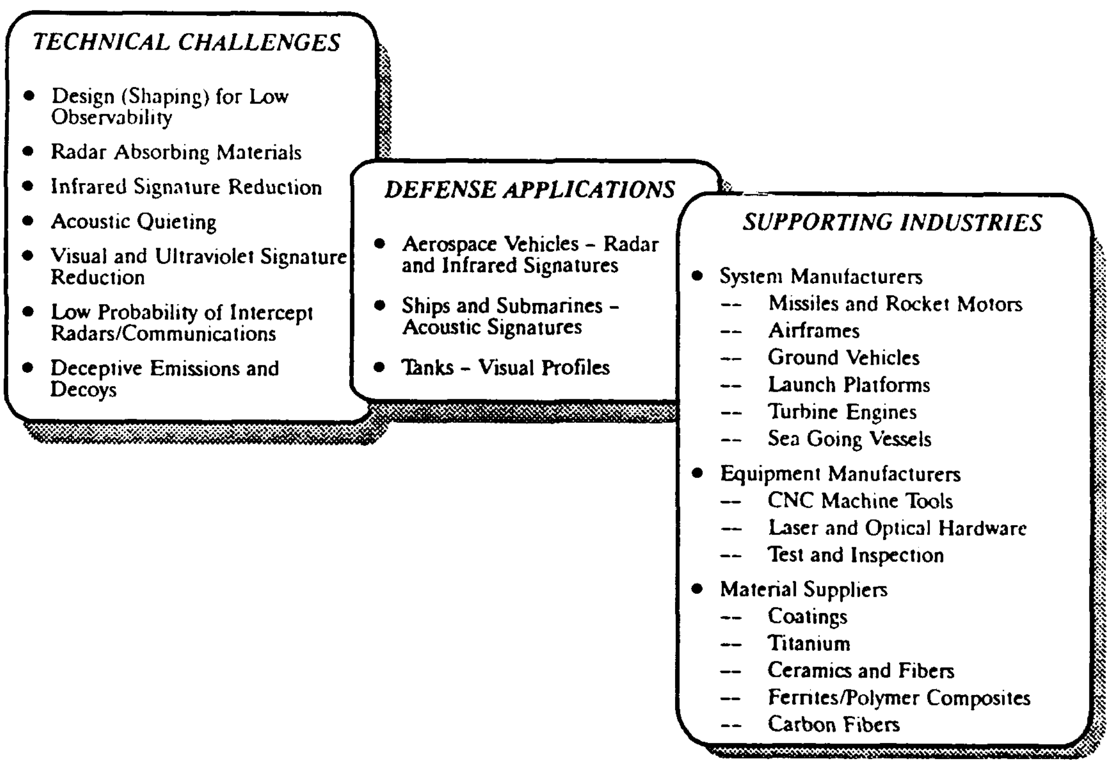

Figure 1. Technical Challenges and Supporting Industries

report. The following presents two illustrations of signature control's dependence on the area of Machine Intelligence/Robotics.

The first example is acoustic control of ship and submarine propulsion. Acoustic signature control requires a capability to manufacture a continuous surface that is repeatable for each blade of the propellor. Since traditional manufacturing methods cause variability that can influence the propellor's acoustic signature, improved technologies are being developed that employ work cells comprising computer numerically controlled (CNC) machines, laser welding, computer-aided design (CAD) systems, and laser/robotic inspection systems. The second example is the industrial base that produces quiet components and materials for machinery silencing for the Navy. Key contractors include manufacturers of quiet machinery components and manufacturers of noise transmission attenuation components and treatments.

Signature control's requirement for advanced computational techniques, hardware, and software for designing and analyzing complex shapes and structures is pertinent to other areas such as Computational Fluid Dynamics, Parallel Computer Architectures, and Soft- ware Producibility.

Active signature control is fundamentally dependent on electronics technology, and the industrial issues are the same as those covered under Semiconductor Materials and Micro-electronic Circuits and Signal Processing.

Finally, some elements of structural shaping as well as radar absorbing structures rely on epoxy or polymeric matrix composite materials, which are represented by Composite Materials.

2. Industry Structure and Capabilities

Signature control is supported by two distinct groups of industries: those involved in end applications, and those that provide materials, products, and capabilities that support the end application. Signature control pervades nearly all defense end items and the industrial base associated with its final application includes defense prime contractors and major subcontractors — producers of ships, submarines, aircraft, helicopters, missiles, gas turbine engines, and small rocket engines, as well as shipyards, laboratories, and suppliers of equipment and machinery. Most signature control technologies and production facilities have few non-defense applications and are therefore largely dependent on DoD funding and demand. The availability, quality, and cost of products produced by supporting firms — including honeycomb, high-performance fibers, and rocket motors — is highly sensitive to DoD weapon system decisions and budgetary priorities. In contrast, the ability of other industries to efficiently and effectively perform to DoD requirements derives from their strength in commercial markets. This is especially true for producers of elastomers, paints, and metallic particles. Therefore, this section gives an overview of both defense and nondefense industries that support signature control.

Because contractors in the first group are heavily dependent on defense, the continued strength of signature control technology depends on the priority and funding brought to bear on the area by DoD. The non-DoD market for helicopters and fighter aircraft is small; the U.S. non-defense shipbuilding industry is weak; and there is no commercial market for submarines, decoys, and small rocket engines. While many producers of aircraft and gas turbine engines are also active in non-defense markets, they have little use for signature control techniques in their non-defense work. Because of the dearth of commercial applications, there is no alternative source of revenue for R&D and anticipated reductions in defense funding will put considerable pressure on the size and health of the industry that develops and deploys signature control. Shrinkage in the number of fighter aircraft producers is widely projected, and the same can be expected for producers of helicopters, missiles, and possibly small gas turbine engines. Defense cutbacks and industry shrinkage will reduce the availability of both direct and IRAD funding, thereby forcing a greater selectivity in the approaches to signature control that are pursued and capabilities that can be demonstrated.

The second group of industries supplies the materials, products, capabilities that are required for end-applications of signature control. Some of these industries are defense oriented, while others are primarily commercial. This industry includes businesses that supply elastomers, paints, honeycomb, fibers, ceramics, metallic particles, and rocket propellants to the defense contractors concerned with signature control applications.

Firms who supply the different types of elastomeric materials used in coatings as carriers for signature control materials are primarily driven by non-defense interests. DoD is simply "another customer." The same is true of paint suppliers, who supply specialty formulations of their products according to the specifications of defense primes or subcontractors. Defense consumes a very small percentage of the output of these companies, and their health and availability to DoD depend on their success in the very competitive commercial markets they serve. While some firms may engage in R&D that is indirectly related to DoD needs, R&D targeted at signature control applications is directly funded by DoD or by defense producers. Companies are unwilling to invest in these technologies because the market for any resulting products is small and profit margins are insufficient to recover R&D costs.

Producers of honeycomb, such as Hexcel, are an important and specialized industrial segment in signature control, but there are relatively few firms in the industry. Honeycomb producers apply signature control materials to both metallic and nonmetallic honeycomb, and good process control during the application process is critical to the subsequent performance of the structure. The health of honeycomb producers is largely dependent on the DoD market and continuing investment in R&D is required. In particular, radar absorbing structures that rely on fibers embedded in the honeycomb material will require substantial process development by the honeycomb producers, because the properties of the honeycomb material may be changed by the new fibers. Declining defense budgets could have a deleterious effect on the ability of these few companies to support the process R&D necessary to incorporate new signature control materials into their production lines.

Fiber producers are similar to honeycomb producers in that defense products represent a major element of their business. Commercial aircraft are expected to generate a growing volume of business as graphite/epoxy composites applications increase, but commercial and private aircraft represent the only significant market for high-performance fibers other than defense. Advanced fibers possessing improved signature control properties require the expertise of these companies not only for R&D, but also for the development of affordable and reliable production processes. Fiber producers will experience the same problems as honeycomb producers if defense spending is significantly cut back.

R&D for ultrastructured and macromolecular ceramic materials for signature reduction is in an early stage of development and is primarily carried out in academia and Government laboratories. In the absence of a commercial market, the domestic ceramics industry can be expected to be completely dependent upon DoD funding for development and production of ceramics for signature control purposes. The domestic industry is steadily losing ground in the development of structural ceramics, particularly to the Japanese. The requirement to develop and implement processing procedures capable of achieving the tight, reproducible properties required for signature control has a close analogy with structural ceramics, and is often regarded as the area of greatest weakness in the domestic ceramics base. As the domestic ceramics industry continues to lag in the highest technology areas, its ability to efficiently perform the development efforts required in signature control will degrade. Similarly, a decline in market share will result in less financial and manpower support for small-market areas such as signature control and a substantial DoD-funded effort could be required to field these materials.

Radar absorption performance is critically dependent on metallic particles having very carefully controlled shapes and size distributions. The sizes required are smaller than those needed for commercial applications, and are available either as by-products of commercial production or from special purpose production facilities. In the former case, particle availability is dependent on the commercial market — unless DoD is willing to purchase an entire lot of material to take delivery of only a small percentage. In the latter case, the willingness of a company to maintain a specialized facility is dependent on order volume and profit margin. With the anticipated decline in weapon system production, the specialty facilities may no longer be available unless special efforts are instituted to keep them open, at considerable cost.

Considerable R&D is being undertaken to develop smokeless propellants for missile rocket motors. These efforts are closely allied to efforts to develop pollution-free solid and liquid propellants for large motors. The industries involved are the rocket producers — Hercules, Thiokol, Aerojet General, Rockwell, Martin-Marietta, and United Technologies — along with a substantial involvement of chemical producers. This area is largely dependent on DoD funding, but there is some support from NASA in the large motor area.

3. Summary

Systems manufacturers in the area of signature control are dependent upon DoD funding for their current survival. While some groups of industries that supply materials, products, and capabilities to the end item have commercial customers, the major contractors who are engaged in production and assembly are reliant upon DoD funding and continued defense requirements. Moreover, there are few commercial applications for signature control technologies, so that the R&D investments of even commercially-oriented companies are largely influenced by current or anticipated DoD funding. With budget cuts looming and a decline in defense production expected, some shake-out in the industry may be imminent.

SIMULATION AND MODELING

1. Introduction

The industrial base assessment for simulation and modeling focuses on many of the same issues that face other critical technologies whose advancement depends upon the viability of the nation's computer hardware and software base. In particular, technologies and industrial capabilities discussed under Computational Fluid Dynamics, Parallel Computer Architectures, Weapon System Environment, Semiconductor Materials and Microelectronic Circuits, Software Producibility, Signal Processing, and Data Fusion also contribute to advancements in Simulation and Modeling.

Simulation and Modeling encompasses hardware and other computer-related technologies. The hardware portion involves computer-controlled simulations whose complexity ranges from the manufacturing flow associated with a single machine tool to large-scale battlefield exercises. The simulations are generally carried out for training or analysis purposes and the degree to which reality can be reflected is a direct function of the capability of software and computer hardware. Emerging artificial intelligence and object oriented programming approaches promise considerable increases in computer capability. Other emerging technologies such as speech recognition and enhanced computer graphics will also make significant contributions.

Although most defense-related applications involve weapon system or operational simulations, another area of potential is in manufacturing and industrial support functions. Application of a wide range of smaller-scale simulations throughout the U.S. defense and non-defense industrial base is important to improving the competitiveness of many manufacturing and service industries. These applications will not only increase the speed with which new products are developed and introduced into the market, but also improve quality and reduce manufacturing time and costs. More extensive use of simulation and modeling techniques can have a major influence on the quality, producibility, reliability, performance, and cost of military systems and commercial products alike. Among the industrial applications of simulation and modeling are:

- Dramatically compressing product development times and manufacturing span times, including enhancing the ability for integrated product and manufacturing process development (i.e., concurrent engineering)
- Designing new materials and products of many kinds, such as advanced polymers, new medical treatments, and high performance ceramics and intermetallic compounds
- Providing the ability to do research without the necessity for costly and time-consuming trial and error experimentation
- Designing industrial unit processes such as forming, casting, forging, powder consolidation, and welding for much greater efficiency and quality
- Designing and optimizing the performance of manufacturing cells, centers, and process flows prior to expensive hardware commitment and
- Designing and managing communications networks and integrated information systems.

Figure 1 summarizes the technical challenges, defense applications, and industrial infrastructure for Simulation and Modeling.

2. Industry Structure And Capabilities

Simulation and modeling R&D is most frequently performed by academia, research institutes, and defense prime contractors. In large-scale military applications such as wargaming, battlefield simulations, and specific weapon system simulators, industry often provides Independent Research and Development (IRAD) funds. Industry has been much less willing to invest in R&D for major industrial applications. Although the challenges of simulating the behavior and performance of a manufacturing facility are similar in nature to these large scale military applications, and many benefits to industry could be achieved through increased IRAD, industry does not aggressively pursue R&D in this area because of the scope, risk, and duration of the required investment. As indicated above, Simulation and Modeling is also extremely important to a wide range of smaller scale industrial applications. In this

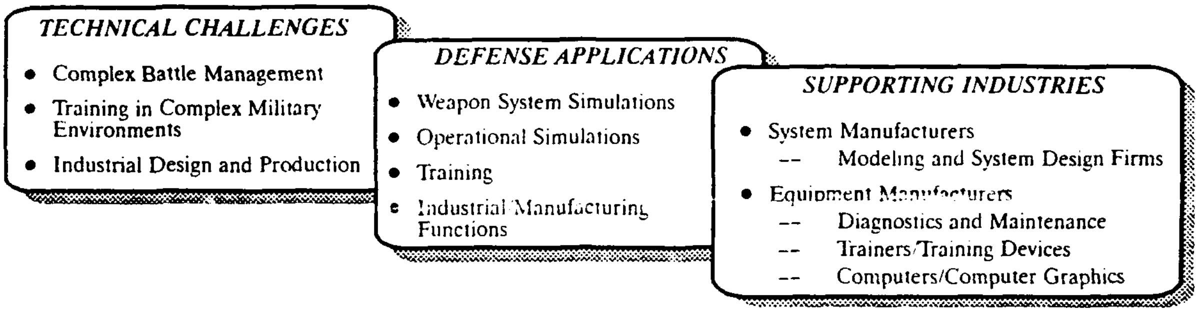

Figure 1. Technical Challenges and Supporting Industries

area, simulation and modeling technology is being pursued by a large number of companies, which creates a large and capable industrial base from which DoD can draw.

The major industrial issues associated with Simulation and Modeling rest with developing and producing the high-speed processing hardware platforms required to perform large-scale simulations and the need for continued reductions in the cost of computing power. The challenge of these two industrial base issues is fundamentally the same — assuring continued access to leading edge computing technology in an environment of increasing foreign competition. A third industrial base issue involves developing and applying more efficient and accurate computer processing approaches and application models in such areas as manufacturing, training, and communications.

Advances in computer processing speed and power are now allowing complex situations to be simulated and modeled. Current and projected increases in computing speed are linked to the development and use of parallel processing and the emergence of new software approaches that permit higher computational efficiency — most notably, through artificial intelligence. These approaches are increasing the range of problems that can be successfully addressed, contribute to increases in speed, and can significantly alter industrial management approaches to product development, manufacturing, and support.

For example, SDIO is one of the prime users and drivers of simulation and modeling technology because it will require unprecedented complex battle management, gaming and simulation of weapon systems (Elements') performance in various scenarios, reliability and maintenance strategies, operational simulations, etc. SDIO has established a National Test Facility (NTF) in Colorado Springs and has a contract with Martin Marietta to develop and operate the NTF. This subject area is critical to SDIO's viability and upcoming decisions about the feasibility and capability of SDIO technologies and systems. Besides these systems level operation simulations, most of the nascent SDIO industrial base will have to make use of simulation technologies if they are to move from production research lab demonstrations to relatively high volume production of reliable components using their advanced technologies.

As with many new technologies, the U.S. has been a leader in development of such techniques as simulation and modeling, but very slow to implement the results of those developments. The importance of simulation and modeling, coupled with the nation's historically poor record of implementation (in comparison with international competitors), is a cause of concern for the future of the industrial base. In manufacturing, for example, many software packages are available that can accurately model and simulate production flow in discrete parts manufacturing. They run on most sizes and brands of computers from personal computers through mainframes, and some have sophisticated animated color graphics. These techniques permit a variety of manufacturing and industrial engineering analyses for efficiency improvement including analyzing the effects of changed processes, use of differing scheduling approaches, and analyzing the effects of different batch sizes.

However, their acceptance and use in industry, though slowly improving, has been limited.

Faster implementation of modeling techniques in the defense industry is important in order to realize the many benefits of simulation and modeling in the development and production of weapons systems. Such broader application in turn will greatly expand the knowledge and experience in simulation available to DoD for the larger-scale applications of predominantly military importance.

3. Summary

Simulation and modeling presents the same industrial base issues regarding the future health of the domestic computer industry that were discussed under Computational Fluid Dynamics and Parallel Computer Architectures. More specifically, however, Simulation and Modeling presents industrial base issues that directly involve the ability of domestic defense and non-defense industries to improve the time, quality, and efficiency of product development, manufacturing, and support. A more rapid pace of implementation of these technologies can have a dramatic effect on the cost and effectiveness of national defense — not only through their direct impact on weapon systems acquisition and support, but also through their potential to enhance the competitiveness of the U.S. manufacturing base.

SOFTWARE PRODUCIBILITY

1. Introduction

Software has become a vital tool for managing modern society. It is an important high technology industry in and of itself and is also an enabler of most other industries and critical technologies examined in this report. As such, a strong software industry is important to DoD and to the entire nation.

The defense industrial base is challenged by an escalating need for larger quantities of more complex and reliable software for defense systems. The military's reliance on this technology gives impetus to the need to quickly and competitively develop, manufacture, and standardize software, with the goals of both improving software performance and reducing development time and cost. Figure 1 illustrates the technical challenges, applications, and supporting industrial base for software producibility.

2. Industry Structure and Capabilities

The technology area of software producibility is broad. First, it includes software that is designed for a wide range of purposes — from weapon systems software to software used to plan, schedule, and control factories which produce those weapon systems. Second, the area includes a range of disciplines, including software development tools and environments, software generation, integration applications, software reusability, and security. A third factor involves software "platforms," which range from personal computers to supercomputers. The diffuse nature of software producibility makes it nearly impossible to define a "software producibility industry" with precision. Industries that make up the infrastructure for software producibility contribute to the design, creation, implementation, use, and maintenance of large and small software systems alike. This base extends from individuals working at home, to "cottage industries," large computer companies, "systems houses," and defense primes.

The domestic software industry is extremely large and the U.S. has long held a leadership position in the technology. Nevertheless, there are a number of issues facing the software base today, and many believe that the current industry is insufficient to meet DoD's needs. As worldwide software capabilities move offshore to Japan and low labor cost nations such as Brazil, it has become increasingly clear that improvements to software producibility are required.

As is the case with hardware production, software producibility is hampered by differing terminology and varying levels of maturity in design and production processes. Quantitative management methods and procedures that are commonly used in hardware production cannot

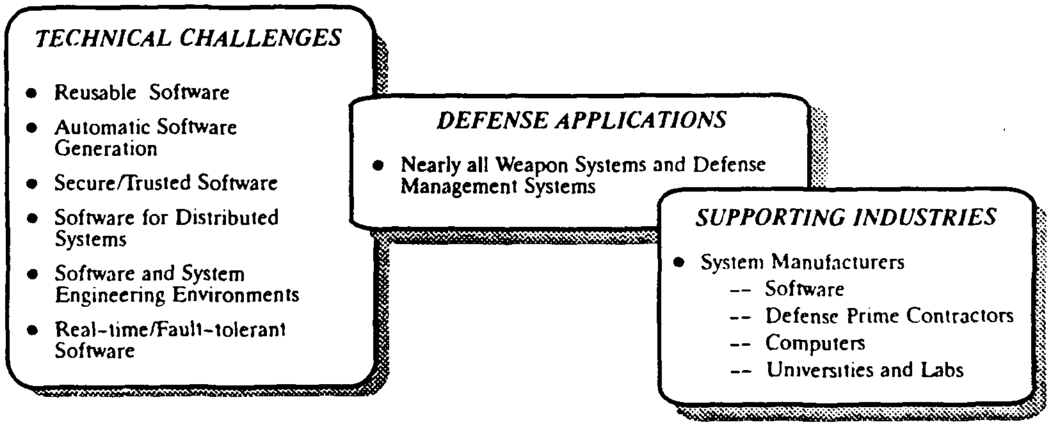

Figure 1. Technical Challenges and Supporting Industries

be readily applied to the software industry, and the software development process is simply not understood by many in the field. Industry's inability to identify software characteristics and time required for production and measurement has led to a lack of standardization, which impedes the ability of industry and DoD to make needed software improvements. There is also a lack of accurate, complete, and relevant data on which to base cost and schedule estimates, monitor progress, and implement appropriate management control procedures. The need to create a common ground from which to assess software development benefits and risks is one of the greatest challenges facing computer experts today.

DoD has a strong interest in strengthening the nation's software base and helping industry resolve these software producibility issues. DoD is a large buyer of software, and many believe that the industry is not large or efficient enough to meet DoD's expanding needs. Experts state that as much as 10 percent of the entire defense budget is allocated for software development and maintenance, with 80 percent of that figure going towards labor intensive rework and updating. At this level of funding, it is estimated that the defense community has only a third the number of software engineers and programmers to meet even the present demand for software development. The requirement placed on the industry's labor pool is even more striking when one considers that commercial demand far exceeds that of DoD. Although software is often considered a dual-use industry and many DoD requirements mirror those of the private sector, DoD also has unique software requirements that push the state-of-the-art beyond commercial applications. These include weapons system software, a variety of Ada applications, and massive software applications that are required for Strategic Defense Initiative (SDI) and other major defense programs. In the case of SDI, for example, it would be necessary to develop millions of lines of executable code that must perform with high confidence of no mission-critical errors. Production of that code demands advances in software technology for time-critical applications, large numbers of external interfaces, distributed processing over a dynamic computer network, testability, and security — all well beyond that required for any commercial application. These requirements cannot easily be met with today's software development techniques.

DoD's Software Master Plan is an important step in ensuring that software producibility is improved and the software base remains responsive to DoD. The Plan outlines the objectives to be reached through DoD's software investments, setting the agenda for software development throughout DoD. Figure 2 identifies the tooling and design concepts that can aid in producing software that is responsive to defense.

Within the context of the Plan, two aspects of software producibility are particularly important to DoD. These are architectures and development techniques for the creation of new software, and techniques that will permit the more effective utilization and reuse of existing software. R&D in high level languages, Computer-Aided Software Engineering (CASE) tools, and modular software will contribute significantly to both the efficiency with which software is produced and the reusability of substantial amounts of code. Research efforts include DoD's investment in the Software Engineering Institute, the Ada Joint Program Office, the STARS (Software Technology for Adaptable, Reliable Software) program, and manufacturing-related programs such as Computer-Aided Acquisition and Logistics Support (CALS) and Sematech. Because of the dual-use nature of the product, commercial efforts such as the General Motors C4 program and PDES, Inc. are also expected to stimulate solutions and products that will benefit DoD.

3. Summary

Software represents a large, and growing, share of defense program costs. Software products are developed and produced by a wide and diverse "industry," which ranges from individual enterpreneurs to major computer system producers. U.S. leadership in software is inextricably tied to our preeminent position in the computer industry, and weakening of our world leadership position in computers would also weaken the software base. An assessment of current capabilities and risks to the computer industry is covered in this report under Parallel Computer Architectures and Semiconductor Materials and Microelectronic Circuits. Moreover, the software industry underlies many other industries critical to the defense and commercial industrial bases, including Weapon

DoD SOFTWARE MASTER PLAN

KEY TOOLING AND DESIGN CONCEPT

1. SOFTWARE ENGINEERING ENVIRONMENT - STIMULATE COMMERCIAL SOFTWARE TOOLS
2. SOFTWARE ENGINEERING TOOLS
3. PROTOTYPING TOOLS AND CAPABILITIES
4. CLASSIFICATION, RETRIEVAL AND EVALUATION OF REUSABLE SOFTWARE ASSETS
5. DOMAIN-SPECIFIC SOFTWARE ARCHITECTURES
6. SOFTWARE RE-ENGINEERING
7. MANAGEMENT TOOLS (METRICS/COST ESTIMATION)
8. DISTRIBUTED AND PARALLEL SOFTWARE
9. ULTRA-RELIABLE/SECURE SOFTWARE
10. SCALABLE AI CAPABILITIES
11. SYSTEMS SOFTWARE

Figure 2. DoD Software Priorities

System Environment, Simulation and Modeling, Signal Processing, and Machine Intelligence and Robotics.

Despite the importance of this industry and the longstanding U.S. leadership position, there are widespread concerns about affordability, producibility, and reliability of software. Future generation weapon systems will require major software improvements, to enable both affordable production and mission performance.

WEAPON SYSTEM ENVIRONMENT

1. Introduction

Weapon System Environment (WSE) is a highly diverse technology area, composed of several inter-related scientific disciplines. The technology is focused on the development of techniques and methods for the accurate definition and prediction of the environments in which DoD weapon systems operate.

Technologies related to WSE should enhance the performance of many different systems by allowing accurate consideration of oceanic, terrestrial, and atmospheric environments, and by using that knowledge to mitigate the increasing influence of environmental factors on weapon system performance. These enhancements are particularly necessary for the detection and tracking of high-performance threat submarines and low-observable air and ground targets, and for improving the performance of smart weapons by substantially decreasing false alarm rates.

The technology challenges, defense applications, and supporting industries associated with this technology are shown in Figure 1.

2. Industry Structure and Capabilities

As Figure 1 indicates, the most important thrusts in this area include oceanographic and underwater modeling; high accuracy environmental prediction — atmospheric and terrestrial; and scene modeling for design and analysis. Progress in these applications is paced by the need to develop extremely large and accurate data bases and supporting computer hardware and software. Operational environmental forecasting industry members are prime examples of niche market development. In the civil sector, the value of the forecast service is measured in the billions of dollars saved from avoiding or preparing for storm damage. Yet only a handful of small groups exist to provide this extremely valuable information to very small numbers of clients. These are typically ocean transportation companies interested in optimum track ship routing; airlines interested in optimum path aircraft routing; off-shore oil platforms interested in drilling termination due to sea state; and local area or city forecasting firms which provide city managers with predictions of local weather patterns. This closely parallels the military environmental forecaster and user community. Included in this group are the specialty teams which produce new forecasting models. Development groups focus on one or more of the following modeling frontiers: weather forecasting; atmospheric radio frequency refraction; operational visibility; ocean wave; ocean temperature; ocean currents; and satellite data analysis for fisheries.

The broad field of instrument design manufacture is commercially addressed for all

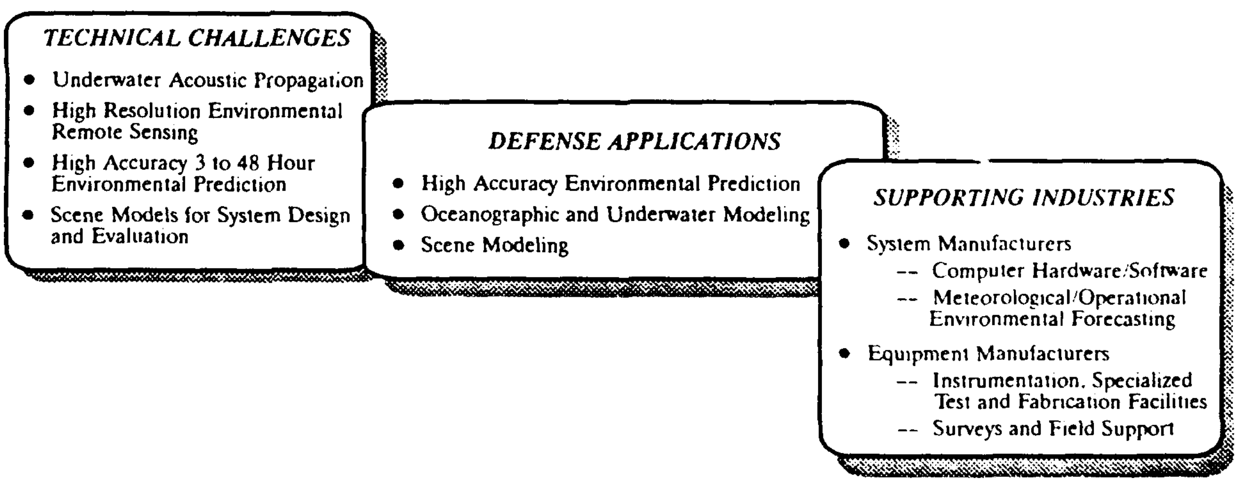

Figure 1. Technical Challenges and Supporting Industries

parts of the environment. Several sources provide electronic atmospheric profilers and vertical atmospheric sampling equipment, to provide a capability to monitor environmental conditions from the boundary layer to the upper levels of the stratosphere. These commercial enterprises also provide equipment for data telemetry, storage, and processing. Instrumentation and data management equipment is also commercially available to sample from the surface to the depths of the ocean. Instrumentation is available to measure ocean temperature, color, turbidity, chemistry, biology, acoustics, currents, tides, and waves.

Packaging of almost any combination of ocean and atmospheric instrumentation is also available, including drifting and moored buoy technologies, and stand alone automated weather observing facilities for remote areas. Expendable instrument packages which can be launched from virtually any land based, floating, or airborne platform, as well as autonomous and remotely controlled vehicles are available to carry instrumentation suites aloft or beneath the ocean.

Scattered among the environmental support industry is a small group of firms which offer specialized testing or fabrication facilities. Available are in-tank sea ice dynamics testing facilities, controlled pressure test vessels which simulate ocean depths, and altitude simulation test chambers which control ambient atmospheric pressure.

Survey and field support has many facets. To the acoustic technology community it can be in the form of providing small ships and acoustic transmitters, receivers, and data processing equipment. The cost of this type of operation and extremely small numbers of clients has limited the number of support offerors to less than ten. This market is limited and in times of budget shortfalls sponsors are forced to lay-up established contract resources rather than not fund the contractor at all and lose unique resources. Field support to other interests can be in the form of contract ocean bottom and sub-bottom charting and profiling. The petroleum industry is the prime investor in this technology niche.

3. Summary

The WSE industrial base is made up of subsidiaries and small divisions of larger diversified corporations, small companies, partnerships, and individual consultants. Estimates place this total industry at about 1000 small groups (excluding universities) of scientists and technologists working on today's defense and commercial environment problems.

In particular, WSE relies on the hardware and software industrial segments that address computationally complex problems. The continued health of the nation's computer industry will be of particular importance. Future military capabilities based on this technology are expected to require a significant number of advanced, high-capability computing systems, many of which will be hardened to withstand operational conditions. Acquiring such systems affordably will require a strong commercial industrial base.

APPENDIX A
INDUSTRIES SUPPORTING CRITICAL TECHNOLOGIES

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INDUSTRIES SUPPORTING CRITICAL TECHNOLOGIES

DEFENSE CRITICAL TECHNOLOGY	INDUSTRIAL SEGMENTS		
	SYSTEM MANUFACTURERS	EQUIPMENT SUPPLIERS AND RELATED MANUFACTURING PROCESSES	MATERIAL SUPPLIERS
Air-Breathing Propulsion	Engines (Gas Turbine, Ramjet, Diesel) Components: Disks, Combustors, Nozzles, Shafts, Blades, and Precision Bearings	Hot Isostatic Pressing Precision Forging Inertial Welding Diffusion Bonding Investment Casting Electrochemical and Electrical Discharge Machining Electron Beam Welding Laser Drilling and Welding Automated Turbine Blade Grinding	Lightweight, High Temperature Materials (Al composites, organic matrix composites, Ti & TiAl composites) High Temperature Materials (ceramic matrix composites, carbon/carbon)
Composite Materials	Military End Item Assemblers Automated Layup Equipment Inspection and Test	Filament Winding/Placement Molding Prepregging Metal Composite Tapes Machine Tools	Chemicals Plastics Fibers Ceramics Metals Powders Adhesives
Machine Intelligence and Robotics	Artificial Intelligence Software Computers	Machine Tools Robots/Robotics Controllers Devices and Components	Composites
Passive Sensors	Electronic Support Measures Infrared/Electro-Optical Sensors Multispectral Sensors Focal Plane Arrays Advanced Acoustic Sensors Fiber Optic Sensors	Diagnostic Tools Dewar/Cooler Fabrication Built-In Test Compact Antennas	Mercury Cadmium Telluride Gallium Arsenide Intrinsically Pure Silicon Platinum Silicide
Photonics	Optical Processing	Lasers Optoelectronic Integrated Circuits Precision Optics Ultra Low-Loss Fiber Optic Cable Electronic Devices Microelectronic Circuits Discrete Components	Quartz and Raw Glass Gallium Arsenide

APPENDIX A

INDUSTRIES SUPPORTING CRITICAL TECHNOLOGIES (Continued)

DEFENSE CRITICAL TECHNOLOGY	INDUSTRIAL SEGMENTS		
	SYSTEM MANUFACTURERS	EQUIPMENT SUPPLIERS AND RELATED MANUFACTURING PROCESSES	MATERIAL SUPPLIERS
Semiconductor Materials And Microelectronic Circuits	Captives Merchants	Lithography Etching Wafer Processing Packaging and Assembly Testing/Inspection Deposition Equipment (Including Epitaxy)	Pure Silicon Gallium Arsenide Chemicals/Gases Ceramic Packages
Sensitive Radars	Radar Systems (Laser, Microwave, Over-the-Horizon) Phased Arrays	Robotics Integrated Circuits/Microelectronics Test and Inspection Travelling Wave Tubes (TWTs)	Ferrite Phase Shifters Gallium Arsenide Sapphire
Super-conductivity	Low Temperature Superconductors (LTS) High Temperature Superconductors (HTS)	Wire and Cable Analog/Digital Electronic Components Magnets Machine Tools/Robotics Microelectronics	Advanced Metals Advanced Composites Chemicals
Biotechnology Materials And Processes	Chemical Health Care Agriculture/Waste Management Mining	Optical Storage Pharmaceutical Medical Diagnostics Switching Devices	Chemicals Polymers (Adhesives/Plastics) Enzymes and Surfactants Coatings
Computational Fluid Dynamics	Computer Supercomputer Software		
Data Fusion	Computer/Communications	Diagnostics Robotics Sensors	
High Energy Density Materials	Rocket Motors Explosives/Propellants	Propellant, Explosive, and Handling Equipment	Chemicals (specifically CL-20)

APPENDIX A

INDUSTRIES SUPPORTING CRITICAL TECHNOLOGIES (Continued)

DEFENSE CRITICAL TECHNOLOGY	INDUSTRIAL SEGMENTS		
	SYSTEM MANUFACTURERS	EQUIPMENT SUPPLIERS AND RELATED MANUFACTURING PROCESSES	MATERIAL SUPPLIERS
Hypervelocity Projectiles	Propulsion Systems Penetrators and Launchers Kinetic Energy Projectiles	Machine Tools/Metal Cutting Explosives/Propallent Processing Load, Assembly, and Pack Composites Processing/Forming	Explosives and Propellants Composite Materials Depleted Uranium Tungsten and Tungsten Alloys
Parallel Computer Architectures	Supercomputer and Minisupercomputer	Integrated Circuits Wafer Preparation/Processing NC Machine Controls Packaging	Pure Silicon Gallium Arsenide
Pulsed Power	Systems Integrators (Pulse Forming) Power Generation (Generators/Alternators) Storage Devices	High Energy Density Capacitors/Inductors Couplers Switches (Gaseous/Solid State)	Polymers and Other Dielectrics Gallium Arsenide
Signal Processing	Smart Munitions and Weapons Target Acquisition Systems Focal Plane Arrays Phased Array Radars (Acoustic) Space Platforms Neural Networks	Biomedical Microelectronics Electronic Devices	Silicon Sapphire
Signature Control	Missiles and Rocket Motors Airframes Sea-Going Vessels Ground Vehicles Launch Platforms Turbine Engines	CNC Machine Tools Laser and Optical Hardware Test and Inspection	Coatings Titanium Ceramics and Fibers Ferrites/Polymer Composites Carbon Fibers
Simulation And Modeling	Modeling and System Design Firms	Diagnostics and Maintenance Trainers/Training Devices Computers/Computer Graphics	

APPENDIX A

INDUSTRIES SUPPORTING CRITICAL TECHNOLOGIES (Continued)

DEFENSE CRITICAL TECHNOLOGY	INDUSTRIAL SEGMENTS		
	SYSTEM MANUFACTURERS	EQUIPMENT SUPPLIERS AND RELATED MANUFACTURING PROCESSES	MATERIAL SUPPLIERS
Software Producibility	Software Defense Prime Contractors Computers Universities and Labs		
Weapon System Environment	Computer Hardware/Software Meteorological/Operational Environment Forecasting	Instrumentation, Specialized Test, and Fabrication Facilities Surveys and Field Support	

APPENDIX B
CONGRESSIONAL REQUIREMENT

SEC. 842. DEFENSE INDUSTRIAL INFORMATION AND CRITICAL INDUSTRIES PLANNING

(a) EXPANDED FUNCTIONS OF THE DEFENSE INDUSTRIAL BASE OFFICE.—Section 2503 of title 10, United States Code, is amended—

(1) by striking out "at a minimum—" in the matter preceding paragraph (1) and inserting in lieu thereof "at a minimum, do the following:";

(2) by amending the first word of each of paragraphs (1) through (4) so that the initial letter of such word is uppercase;

(3) by striking out the semicolon at the end of each of paragraphs (1) and (2) and inserting in lieu thereof a period;

(4) by striking out "; and" at the end of paragraph (3) and inserting in lieu thereof a period; and

(5) by adding at the end the following new paragraph:

"(5) Establish and implement a consolidated analysis program (A) to assess and monitor worldwide capabilities in technologies critical to the national security of the United States, and (B) to monitor defense-related manufacturing capabilities of the United States.".

(b) CRITICAL INDUSTRIES PLANNING.—Section 2503 of title 10, United States Code, as amended by subsection (a), is further amended by adding at the end the following new paragraph:

"(6) Identify the industries most critical for national security applications of the technologies identified in the most recent annual defense critical technologies plan submitted under section 2508 of this title.".

(c) REPORT ON DEFENSE INDUSTRIAL BASE.—(1) The Secretary of Defense, acting through the Under Secretary of Defense for Acquisition, shall submit to the Committees on Armed Services of the Senate and House of Representatives a report on the actions taken under section 2503 of title 10, United States Code, for the improvement of the defense industrial base of the United States.

(2) The report shall include Under Secretary's analysis of the condition of the defense industrial base of the United States, particularly with respect to the financial ability of United States businesses—

(A) to conduct research and development activities relating to critical defense technologies, including the critical technologies identified in the first annual defense critical technologies plan submitted pursuant to section 2508 of title 10, United States Code, as added by section 841(b) of this Act;

(B) to apply those technologies to the production of goods and the furnishing of services; and

(C) to engage in any other activities determined by the Secretary of Defense to be critical to the national security.

(3) In preparing the analysis required in paragraph (2), the Secretary, acting through the Under Secretary of Defense for Acquisition, shall consider—

(A) trends in the profitability, levels of capital investment, spending on research and development, and debt burden of businesses involved in research on, development of, and application of critical defense technologies;

(B) the consequences of mergers, acquisitions, and takeovers of such businesses;

(C) the results of current Department of Defense spending for critical defense technologies; and

(D) the likely future level of Department of Defense spending for such technologies during the four fiscal years following fiscal year 1990 and the likely results of that level of spending.

(4) The report under this subsection shall be submitted not later than March 15, 1990.

APPENDIX C
GLOSSARY OF ACRONYMS

APPENDIX C
GLOSSARY OF ACRONYMS

AAWS-M —Advanced Anti-tank Weapon System-Medium
ABP — Air Breathing Propulsion
AI — Artificial Intelligence
AOA — Airborne Optical Adjunct
ARDEC — Armament, Research, and Development Engineering Center
ASICs — Application Specific Integrated Circuits
ATA — Advanced Tactical Aircraft
ATF — Advanced Tactical Fighter
ATR — Automatic Target Recognition
BMP — Best Manufacturing Practices
BSTS — Boost Surveillance and Tracking System
CAD/CAM — Computer-Aided Design/Computer-Aided Manufacturing
CALS — Computer-aided Acquisition and Logistics Support
CAT — Computerized Axial Tomography
CAPPS — Configurable Architecture Parallel Processing System
CASE — Computer Aided Software Engineering (tools)
CE — Concurrent Engineering
CECMT — Center for Excellence for Composites Manufacturing Technology
CFD — Computational Fluid Dynamics
CIM — Computer Integrated Manufacturing
C^3I — Command Control Communication and Intelligence
CMC — Ceramic Matrix Composites
CMOS — Complementary Metal Oxide Semiconductor
CNC — Computer Numerically-Controlled (machine tools)
CO2 — Carbon Dioxide
COCO — Contractor-Owned, Contractor-Operated (see GOCO)
CRT — Cathode Ray Tube
DARPA — Defense Advanced Research Projects Agency
DEW — Directed Energy Weapon
DINET — Defense Industrial Network
DLA — Defense Logistics Agency
DMO — Defense Manufacturing Office
DMR — Defense Management Review
DoC — Department of Commerce
DoD — Department of Defense
DoE — Department of Energy
DPA — Defense Production Act of 1950
DRAM — Dynamic Random Access Memory
DSB — Defense Science Board
DSP — Defense Satellite Program
ECL — Emitter Coupled Logic
ECM — Electrochemical Machining
ECCM — Electronic Counter-Countermeasures
EDM — Electro-Discharge Machining
EEPROM — Electrically Erasable Programmable Read-Only Memory
ERIS — Exoatmospheric Re-entry Vehicle Interceptor System
EPROM — Erasable Programmable Read-Only Memory
ESM — Electronic Support Measures

ESPRIT — European Program for Research and Development in Information Technology
ETO — Earth-to-Orbit
FAA — Federal Aviation Administration
FASAC — Foreign Applied Services Assessment Center
FFRDC —Federally Funded Research and Development Center
FLIR - Forward Looking Infrared Radar
FOG-M — Fiber Optic Guided Missile
FPA — Focal Plane Array
FRG — Federal Republic of Germany
FSX — Fighter Support Experimental
G&C — Guidance and Control
GaAs — Gallium Arsenide
GB/SEC — Gigabit per Second
GOCO — Government-Owned, Contractor-Operated
GTE — Gas Turbine Engine
HEDI — High Endoatmospheric Defense Interceptor
HEDM — High Energy Density Materials
HEMT — High Electronic Mobility Translator
HgCdTe — Mercury Cadmium Telluride
HIP — Hot Isostatic Pressing
HTS — High Temperature Superconductors
IBP — Industrial Base Planning
IC — Integrated Circuit
IEEE — Institute of Electrical and Electronic Engineers
IHPTET — Integrated High-Performance Turbine Engine Technology
IMIP — Industrial Modernization Incentives Program
IMUs — Inertial Measurement Units
InGaAs — Indium Gallium Arsenide
InSb — Indium Antimonide
IPP — Industrial Preparedness Planning/Program
IR — Infrared
I-R — Ingersoll-Rand
IRAD — Independent Research and Development
IR&D — Independent Research and Development
IRFPA — Infrared Focal Plane Array
JESSI — Joint European Submicron Silicon
JLC — Joint Logistics Commanders
KEW — Kinetic Energy Weapon
LAP — Load, Assemble and Pack
LCP — Liquid Crystal Polymer
LH — LH Helicopter
LOVEX — Low Vulnerability Explosive
LSI — Large-Scale Integration
LTS — Low Temperature Superconductor
ManTech — Manufacturing Technology
MBE — Molecular Beam Epitaxy
MCT — Mercury Cadmium Telluride
MCUs — Microcomputer
MEG — Magneto-Encephalography
MESFET — Metal Schottky Field Effect Transistor
MIMIC — Microwave and Millimeter Wave Monolithic Integrated Circuit
MIPS — Millions of Instructions Per Second
MIT — Massachusetts Institute of Technology

MITI — Ministry of International Trade and Industry
MLRS — Multiple Launch Rocket System
MMC — Metal Matrix Composites
MMCIAC — Metal Matrix Composites Information Analysis Center
MMIC — Monolithic Microwave Integrated Circuit
MOCVD — Metal-Organic-Chemical Vapor Deposition
MODILs — Manufacturing Operations Development and Integration Laboratories
MOS — Metal Oxide Semiconductor
MPU — MicroProcessor Unit
MRI — Magnetic Resonance Imaging
MSI — Medium-Scale Integration
NASA — National Aeronautics and Space Administration
NASP — National Aerospace Plane
NATO — North Atlantic Treaty Organization
NC — Numerically-controlled (machine tools)
NLOS — Non-Line of Sight
NMOS — N-Channel Metal Oxide Semiconductor
NOS/IH — Naval Ordnance Station/Indian Head
NWC — Naval Weapons Center
ODS — Oxide Dispersion Strengthened (thin sheet)
OSD — Office of the Secretary of Defense
OSTP — Office of Science and Technology Policy
OTA — Office of Technology Assessment
PAN — Polyacrylonitrile
PBA — Production Base Analysis
PC — Photoconductive
PLD — Programmable Logic Device
PMC — Polymer Matrix Composite
PROM — Programmable Read-Only Memory
PtSi — Platinum Silicide
PV — Photovoltaic
P&W — Pratt and Whitney
R&D — Research and Development
RDT&E — Research, Development Test and Evaluation
RIA — Robotics Industries Association
ROM — Read Only Memory
S&T — Science & Technology
S/TTL — Schottky Transistor-Transistor Logic
SBRC — Santa Barbara Research Center
SDI — Strategic Defense Initiative
SDIO — Strategic Defense Initiative Organization
SEMATECH — Semiconductor Manufacturing Technology program
Si:X — Extrinsic Silicon
SiAs — Silicon Arsenic/Arsenide
SiC — Silicon Carbide
SiGa — Silicon Gallium
SiSb — Silicon Antimonide
SiSe — Silicon Selenide
SiZn — Silicon Zinc
SMCA — Single Manager for Conventional Ammunition
SME — Semiconductor Materials and Equipment
SMES — Superconducting Magnetic Energy Storage
SQUIDs — Superconducting Quantum Interference Devices

SRAM — Static Random Access Memory
SSI — Small-Scale Integration
SSTS — Space-based Surveillance and Tracking System
STARS — Software Technology for Adaptable, Reliable Software
T.I. — Texas Instruments
TNT — Trinitrotoluene
T/R — Transmit/Receive
TWTs — Travelling Wave Tubes
U.K. — United Kingdom
U.S. — United States
USD/A — Under Secretary of Defense for Acquisition
U.S.S.R. — Union of Soviet Socialist Republics
VHSIC — Very-High Speed Integrated Circuits
YAG — Yittrium Aluminum Garnet
WSI — Wafer-Scale Integration