NATIONAL CRITICAL TECHNOLOGIES REPORT

MARCH 1995

NATIONAL CRITICAL TECHNOLOGIES REPORT

MARCH 1995

March 17, 1995

Dear Mr. President:

The Office of Science and Technology Policy and the National Critical Technologies Review Group are pleased to submit the 1995 Biennial National Critical Technologies Report.

The technology areas and specific technologies identified in this report are those important to develop and further the long-term national security or economic prosperity of the United States. These technologies therefore deserve priority consideration for current and future federal research and development efforts.

Sincerely,

John H. Gibbons

John H. Gibbons
Director

NATIONAL CRITICAL TECHNOLOGIES REVIEW GROUP

John A. Young
Review Group Chairman
Chairman, President's Committee of
Advisors on Science and Technology
Former President and CEO
Hewlett-Packard Co.

Norman R. Augustine
President's Committee of Advisors on
Science and Technology
Chairman and CEO
Martin Marietta Corporation

Charles A. Sanders
President's Committee of Advisors on
Science and Technology
Chairman and CEO
Glaxo Inc.

Charles M. Vest
President's Committee of Advisors on
Science and Technology
President
Massachusetts Institute of Technology

Lilian Shiao-Yen Wu
President's Committee of Advisors on
Science and Technology
Member, Research Staff
Thomas J. Watson Research Center
IBM

Charles B. Curtis
Under Secretary
Department of Energy

John R. Dailey
Acting Deputy Administrator
National Aeronautics and Space
Administration

Leon S. Fuerth
National Security Advisor for the
Vice President

Mary L. Good
Under Secretary
Technology Administration
Department of Commerce

Lionel S. Johns
Associate Director for Technology
Office of Science and Technology Policy

Paul Kaminski
Under Secretary for Acquisition and
Technology
Department of Defense

William A. Owens
Vice Chairman
Joint Chiefs of Staff
Department of Defense

Jane Wales
Associate Director for National Security
and International Affairs
Office of Science and Technology Policy

NATIONAL CRITICAL TECHNOLOGIES REPORT

MARCH 1995

TABLE OF CONTENTS

TABLES

FIGURES

EXECUTIVE SUMMARY

This report presents the results of the third biennial National Critical Technologies Review. This report presents 27 National Critical Technology Areas in seven categories, as shown in Table S.1. It includes information about the state of development in each technology area, and about the US competitive position relative to the worldwide leading edge technology developments.

THE NEED FOR A NATIONAL CRITICAL TECHNOLOGIES REPORT

The development and use of technologies remains a driving force in U.S. economic prosperity and national security. Maintaining the strength and competitiveness of the U.S. technological enterprise, therefore, continues to be vital. In the current climate of intensifying global competition, rapid technological change, and geopolitical uncertainties, the need for identifying critical technologies for concentration of effort becomes even greater.

This report designates the technology areas and specific technologies which constitute priorities for the federal R&D effort. Specifically, it is intended to

- Identify necessary areas of focus for R&D;
- Help leverage limited resources most effectively in times when science and technology budgets are not growing as fast as they once did;
- Help coordinate government R&D activities by supplying agencies with a common set of priorities and providing Congress with information to support policy decisions;
- Serve industry as a guide for possible areas of cooperative R&D.

Technology selection criteria and detailed rationale are found in Appendix B.

Technology categories and technology areas within them are presented in alphabetical order. Although all of the technology areas included in this report are essential to economic prosperity or national security, it is difficult to find a rank order which would reflect the contribution to these two overarching goals of technologies as different as, for example, biocompatible materials and fuel cells. As a result, no priority is implied by the order in which categories are presented.

This report does not address issues of technology diffusion. It is important to note that leading in technology development does not necessarily imply having

Table S.1
National Critical Technology Areas

Technology category	Technology area
Energy	Energy efficiency Energy storage, conditioning, distribution and transmission Improved generation
Environmental Quality	Monitoring and assessment Pollution control Remediation and restoration
Information and Communication	Components Communications Computer systems Information management Intelligent complex adaptive systems Sensors Software and toolkits
Living Systems	Biotechnology Medical technology Agriculture and food technology Human factors
Manufacturing	Discrete product manufacturing Continuous materials processing Micro/nanofabrication and machining
Materials	Materials Structures
Transportation	Aerodynamics Avionics and controls Propulsion and power Systems integration Human interface

Figure S.1
National Critical Technologies
Technology Position and 1990-1994 Trend

US Technology Position Relative to:
- Japan ▷, ○, or ◁
- Europe ▶, ●, or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Energy					
Energy Efficiency			▶	○	
Storage, Conditioning, Distribution, and Transmission			●	○	
Improved Generation			●	○	
Environmental Quality					
Monitoring and Assessment				◁ ◀	
Pollution Control			○ ●		
Remediation and Restoration			◀	◁	
Information and Communication					
Components			▷	●	
Communications				●	◁
Computing Systems				●	◁
Information Management					▷
Intelligent Complex Adaptive Systems*			○	◀	
Sensors			▷ ▶		
Software and Toolkits				●	▷
Living Systems					
Biotechnology				○ ▶	
Medical Technologies				▷ ●	
Agriculture and Food Technologies				◁ ▶	
Human Systems				▶	▷
Manufacturing					
Discrete Product Manufacturing				○ ●	
Continuous Materials Processing*			○ ●		
Micro/Nanofabrication and Machining			▷	●	
Materials					
Materials				◁ ●	
Structures				●	◁
Transportation					
Aerodynamics				●	◁
Avionics & Controls				◀	◁
Propulsion & Power				◁ ●	
Systems Integration				●	○
Human Interface*					▷ ▶

*based on limited information

the leading share of the market. In order to reap the economic benefits of technological development it is important to move technology out of the laboratory into products and services, something that requires additional skills and investments. While it is exciting to note that the United States has a leading *technological* position in critical technology areas, this should not lead to the conclusion that the nation cannot do better in world-wide markets for products and services based on critical technologies.

OVERVIEW OF CRITICAL TECHNOLOGY AREAS

The report divided critical technologies into seven categories: Energy, Environmental Quality, Information and Communication, Living Systems, Materials, Manufacturing, and Transportation. Based on a comparison of technical positions, the U.S. is either at parity or in the lead in almost every technology area identified. This is shown in Figure S.1.[1] It should be noted, however, that the size of the U.S. lead has either declined or remained constant between 1990 and 1994, which argues for continued U.S. investment in technology development if the U.S. position is to be preserved.

Energy

Critical technologies in the energy category fall into three general areas—efficiency; energy storage, conditioning, distribution, and transmission; and improved generation. Technologies in the Energy Efficiency area—which include building technologies and non-internal combustion propulsion systems—increase U.S. economic productivity by increasing economic output per unit of energy input and by offering a growing export business opportunity; they also contribute to U.S. national security by reducing dependency on foreign energy sources and, when exported, by moderating energy demand in developing countries. Building technologies improve the competitiveness of U.S. construction and building industries in world markets by making the sale of turn-key installations more likely and make a small contribution to national security by allowing more efficient management of facilities that frees funds for other uses. Although U.S. technology now competes favorably in this area with the most efficient Japanese and European products, it still trails Japanese and European firms in some products. Non-internal-cumbustion propulsion systems—particularly in "clean cars"—could provide a significant advantage to a sector comprising one-seventh of the U.S. economy. Japan and Europe are about even with the United States in electric vehicle (EV) technology, and Japanese AC

---

[1]The figure shows both the U.S. position relative to the leading edge of technology development in Europe and Japan, and the trends between 1990 and 1994. The current position is indicated by the position of the symbol on the five-point scale from "Substantial Lag" to "Substantial Lead." The trends are indicated by the shape of the symbol and the direction in which it is pointing: the circle for lack of change, and a triangle for either increasing or decreasing lead/lag. The rate of change is not indicated in the figure.

motor technology lags that of the United States but is probably ahead of that of the Europeans.

Technology sub-areas in the Energy Storage, Conditioning, Distribution, and Transmission area—including advanced batteries, power electronics, and capacitors—are enabling for both economic prosperity with industrial, commercial, and residential applications, and national security with military applications. In advanced battery technologies, the Japanese are slightly lagging U.S. capabilities, although aggressive research is improving the Japanese position, and European firms are slightly behind U.S. firms. In power electronics, the United States is behind in high-power, solid-state switch technology except for a few niche areas. In capacitor technologies, the United States is the world leader, especially those suited for military applications, Japan is behind the United States and is losing ground, and Europe is also behind the United States and probably losing ground.

Technology sub-areas in Improved Generation—including gas turbines, fuel cells, next-generation nuclear reactors, advanced power supplies, and renewable energy—are critical to economic prosperity because of the confluence of rapidly growing demand for electricity worldwide, increasing environmental pressures from electric generation, and utility deregulation. In gas turbine technologies, Europe and Japan are slightly behind the United States in developing rotating machinery suitable for high-efficiency power generation. In fuel cells, the United States is the overall world leader across a wide range of fuel cell technologies but Japan is a very strong competitor in some segments, while European fuel-cell projects are highly dependent on foreign technology. In next-generation nuclear reactors, U.S. firms have remained competitive in design services and are active members of international alliances, because most current reactors are based on U.S. technology; however, the United States is likely to fall behind in next-generation reactors because of large funding cuts for reactor R&D. In advanced pulsed power supplies, Russia is slightly ahead of the United States, while Europe and Japan are behind the world leaders overall but are at parity in some niche areas, such as switching capacitors and transformers. In renewable energy, Europe and the United States are about even in solar thermal energy technology, slightly ahead of Japan; in photovoltaics, Japan is continuing to lag slightly behind the United States and Europe; Europe is slightly ahead of the United States in wind turbine technology, while Japan lags behind the world leader in innovative turbine designs; and Europe is slightly ahead of the United States in biofuels, with Europe leading in biodiesel fuels and the United States leading in ethanol production from biomass.

Overall, the United States is generally on par with the best in the world in critical technologies that fall into the energy category.

Environmental Quality

Critical technologies in the environmental quality category fall into three general areas—monitoring and assessment; remediation and restoration; and pollution avoidance and control. Technologies in the Monitoring and Assessment area include integrated environmental monitoring and remote assessment of biosystems. The former contribute to such national goals as the health of the U.S. population, job creation and economic growth, the efficiency of the physical infrastructure, and the ability for ecosystem management and ex-post monitoring and evaluation to understand how humans interact with the environment. These technologies also contribute to national security and warfighting capabilities by, for example, helping to assure non-proliferation of weapons of mass destruction and by providing accurate information about battlefield environments, thus increasing troop effectiveness and reducing casualties. Within this area, Russia is behind the United States in remote sensing technologies; the United States leads in satellite-based, multi-spectral data processing technology capability, followed by Russia (based on military capability), France, and Japan; and in the specific area of qualitative risk assessment tools, Europe lags the United States, with Japan further behind.

Development of timely and cost-effective remediation and restoration technologies is critical, both to reduce costs to the U.S. economy in addressing indigenous contamination problems and to promote U.S. competitiveness in global remediation markets. These technologies can contribute to job creation and economic growth, both by creating new jobs and by helping reduce clean-up cost liabilities faced by many manufacturers and can contribute to the health of the U.S. population by reducing risks associated with contaminants in the environment. There is general parity between the United States and Europe in bioremediation technology—the United States has conducted more basic research in this area, but Europe has successfully used U.S. technology for relatively large-scale, on-site remediation efforts. While Japanese firms are capable of being major players in bioremediation technology, they appear to lag slightly in actual demonstration of this capability. In nuclear wastes storage and disposal, Europe is slightly ahead of the United States in technologies for decontamination and decommissioning of nuclear reactors, with Japanese firms at about the same technology level as U.S. firms.

Pollution avoidance and control technologies contribute to the security of food, water, and air, to lowering costs of research and development activities, and to the health of the population. Foreign firms are slightly behind U.S. firms in separation technologies, although Europe is ahead in nuclear applications because of the policy decision to manage waste as it is produced rather than to accumulate it for future treatment. In non-nuclear separation technologies, European firms are behind U.S. firms, who have superior technology. Japanese firms are behind U.S. firms in both nuclear and non-nuclear separation technologies.

Overall, although the United States is currently a leader in many technologies in this category, trends indicate that other countries are making progress in attaining the same level of technology.

Information and Communication

Perhaps more than any other technical area, information and communication technologies are what make our society "modern." The ability to rapidly access and share vast amounts of information has been the driving force in economic growth and improved quality of life in the latter part of the twentieth century. Accordingly, information and communication technologies are essential to meeting national goals in economic growth and national security, and in helping other technical areas to realize their full potential. The technologies identified as critical include those contributing to the leading edge of components, communications, computer systems, information management, intelligent complex adaptive systems, sensors and software and toolkits. Of these areas, components, computer systems, communications, information management, and software and toolkits have the highest potential to contribute to economic growth. Computer systems (particularly high performance systems), intelligent complex adaptive systems and sensors have significant potential to contribute to national security.

With the exception of high-definition displays and high-resolution scanning, the U.S. is ahead, or at least at parity, in almost all the fields comprising the Information and Communication technology category. The U.S. invented and widely deployed such technologies as UNIX, the Ethernet, the Internet, LANs, and most of the field of artificial intelligence; U.S.-developed operating systems for personal computers are the world standard; our digital HDTV plans lead the world. The National Display Initiative will help to fill in the gap in high-definition displays, and in most areas where we have some weakness, U.S. firms are forming alliances with other firms in Japan and Europe, leading to multinational initiatives.

Living Systems

New industries such as biotechnology are emerging as knowledge is gained into the highly energy- and material-efficient processes employed by living systems for self-propagation and the formation of functional structures such as organs, shells, or musculo-skeletal systems. This knowledge is being applied not only to the agricultural and aquacultural production of food plants and animals, but human health protection and medical care. The Living Systems technology category includes four technology areas: biotechnology, medical technology, agriculture and food technology, and human systems.

Biotechnology is enabling both established and newly emerging industries to design, create, and produce highly specific substances derived from molecular structures and processes in naturally occurring biological systems. Currently, the two most important areas of biotechnology application are human health care and agriculture.

While the United States is the overall world leader in biotechnology, Europe and Japan pose strong competition in specific areas. The United States does more basic research in genetic engineering and molecular biology than any other country. Computer based methods for analyzing and modeling molecular sequences and interaction, as well as facilitating collaboration among widely dispersed groups have contributed to the rapid evolution and application of knowledge in these areas.

The integration of knowledge and practice of many technologies is essential to an effective and efficient system for protecting the public health and delivering health care services. Innovative biomedical research and information-based integrated decision support systems leading to prevention, more effective therapies and minimizing the need for long term care hold the key to advances that can restrain costs while enhancing the quality of public health and health care. Key technologies in this area are integrated information systems, functional diagnostic imaging, biocompatible materials, and the rapid identification of bacteria and viral infectious agents.

Global agriculture is facing the challenges of increasing human population, accelerating need for food, fiber, feed and raw materials for other industries, and a declining amount of cultivated land per capita. Sustainable agricultural systems must address the development of environmentally sound, productive, economically viable and socially desirable agriculture. Aquaculture is currently the most rapidly growing agricultural segment and will play a significant role in providing a stable source of fish protein in the face of declining yield of oceanic fisheries.

The human-machine interface is a critical component in a number of complex integrated systems such as power and communications grids, air traffic control systems, and highly automated process control and manufacturing systems. Such systems typically produce much more data than a human is able to digest in a time-critical situation, so the main job of the interface is to present the data in a form easily understandable by the human and to provide an easy means of interacting with the system to ensure continued safe and reliable operations. The United States has a pre-eminent technical position in understanding human capabilities, behavior and performance while interacting with engineered systems and environments, and in implementing advanced human-machine interfaces.

Manufacturing

The technologies in the Manufacturing technology category support much of the industry in the United States. In some cases, the technologies improve our ability to make a familiar substance such as polyethylene. In other cases, as with some new alloys, they open the use of a new material by producing it economically, changing a material from a laboratory curiosity to a commercial force. In still other cases, the technologies improve our abilities to design and to create a product, and to manage that overall process. This document divides manufacturing technologies into three technology areas: Discrete Product Manufacturing, Continuous Materials Processing, and Micro/Nanofabrication and Machining.

Discrete Product Manufacturing encompasses the most important technological developments in improving our ability to create manufactured products, from the ordinary—an automobile or a television, to the more exotic— a cooled turbine blade. As such, the technologies are important across the breadth of the manufacturing sector, both for the economic health of that sector and for its ability to create leading edge weaponry for the military.

Continuous Materials Processing concentrates on the developments of most importance to the chemical, petrochemical, and some solid materials industries. These are characterized by a continuous production of materials, which are usually then used in other processes or products. These industries, and thus these technologies, are important both economically and for the military. These technologies also often have the potential to reduce the harmful environmental effects either of alternative industrial processes or of other processes, as energy generation. This is both an end in itself and a growing industry in its own right.

Microfabrication refers to the creation of physical structures with a characteristic scale size of one micron, a millionth of a meter. Historically, this has been, and remains, important to the electronics industry, although other applications have also arisen. Nanofabrication refers to the creation of smaller structures, down to the control and arrangement of individual atoms. Such techniques are still developing, but offer fascinating potential. Both areas are also developing rapidly.

The United States is either on par or in the lead in all technology areas in this technology category. While this is not true in some individual technologies, such as the low and medium technology plastic packaging for semiconductor chips in which the Japanese lead, the United States either leads outright or is well-positioned for the future in all other specific technologies included in the report.

Materials

Materials allow the achievement of a wide range of national goals. Improved materials can help our economic prosperity, our health, our security, and the quality of our lives. A few materials contribute only to a single national goal. For example, our national security is enhanced by new combat aircraft that use stealth materials to help control their signature, but such materials are not at all desirable in use for commercial aircraft which need to be visible and easily identifiable. Such limitation is the exception, not the rule.

The ubiquitous nature of materials, entering into almost every industry and activity, makes materials a key set of enabling technologies for a multitude of goals. Advanced alloys, ceramics, composites, and polymers are enabling technologies for, among other ends, high-performance aerospace and surface transportation. This supports both civil and military systems. Functional materials, such as diamond thin films, can provide enhanced physical and electronic characteristics for a wide range of applications in the manufacturing and electronics industries. In turn, this couples not just to economic goals, but to other goals, from environmental to space exploration. New materials are also key to many manufacturing developments, whether through improving existing products or through creating entirely new possibilities.

The diversity of materials is also represented in the broad range of specific technologies listed under the sub-areas. No single assessment of the performance of the United States could be appropriate across such a range, and indeed, the international position of the United States in Materials is mixed. Although generally leading, there are some areas where the lead is shrinking or a lag has appeared. Some of these assessments are familiar, as the foreign lead in materials for semiconductor manufacturing, or the U. S. lead in polymer matrix composites. Others may be less familiar, as the good U. S. position in ceramic composites, where we do not yet lead the Europeans, but appear better positioned than the competition for the emerging market. Our long concentration on materials science has paid dividends.

Transportation

The following technology areas are addressed in the transportation category. Aerodynamics, Avionics and Controls, Propulsion and Power, Systems Integration, and Human Interface. At a more specific technology level, the report discusses aircraft and surface vehicle aerodynamics, aircraft and spacecraft avionics, surface transportation controls, aircraft turbines and spacecraft power systems. At the level of systems integration and human-machine interface, the report discusses intelligent transportation systems, spacecraft and aircraft integration, human factors engineering (as it relates to transportation systems) and spacecraft life support systems. The U.S. has preeminence in most transportation areas, except for Western European developments in commercial aircraft technology, the leadership of France, Germany and Japan in fielding high speed rail systems, and German and Japanese advances in mag-lev technology.

The area of intelligent transportation systems is one where the U.S., Western Europe, and Japan are all engaged in various private and public efforts to develop more effective and efficient surface transportation systems. This area will ultimately involve radical changes in both vehicular technology and infrastructure that have the capacity to alter the American transportation system by better incorporating modern information technology into virtually every phase of passenger and freight transportation including its intermodal elements.

ACTIVITIES RELATED TO CRITICAL TECHNOLOGIES

A significant proportion of the approximately $70 billion devoted annually by the federal government to the support of R&D directly involves the development of a broad range of critical technologies. With the exception of the Department of Defense which has a significant presence in most areas, agencies concentrate in only a few technology areas which are relevant to the performance of their missions.

The portion of federal R&D budget which is directly applicable to critical technologies is "applied research" and "development"as these terms are generally defined for all federal agencies. In the case of the Department of Defense, this includes those activities which fall within DOD's Budget Activities 6.2 (Exploratory Development) and 6.3 (Advanced Development). Similarly, for other agencies, it includes those activities that do not generally constitute "basic research," although there are some exceptions.

For those technologies that are relevant to the missions of multiple agencies, cross-agency coordination is becoming increasingly important. The cabinet-level National Science and Technology Council (NSTC) provides a formal mechanism by which the vast Federal R&D enterprise can be coordinated, priorities can be explicitly set, and unnecessary duplication of effort can be eliminated. The NSTC's participation in the preparation of this report is a reflection of its charter.

1. INTRODUCTION

This report presents the results of the third biennial National Critical Technologies Review. This report presents 27 National Critical Technology Areas in seven categories, as shown in Table 1.1.[1] It includes information about the state of development in each technology area, and about the US competitive position relative to the worldwide leading edge developments. It also discusses factors in the policy environment which influence the development of technology, including national critical technologies.[2]

PURPOSE OF THE REPORT

The development and use of technologies remain a driving force in U.S. economic prosperity and national security. Maintaining the strength and competitiveness of the U.S. technological enterprise, therefore, continues to be vital. In the current climate of intensifying global competition, rapid technological change, and geopolitical uncertainties, the need for identifying critical technologies for concentration of effort becomes even greater. This report designates the technology areas and specific technologies which constitute priorities for the federal R&D effort. Specifically, it is intended to

- Identify necessary areas of focus for R&D;
- Help leverage limited resources most effectively in times when science and technology budgets are not growing as fast as they once did;
- Help coordinate government R&D activities by supplying agencies with a common set of priorities and providing Congress with information to support policy decisions;
- Serve industry as a guide for possible areas of cooperative R&D.

Technology selection criteria and detailed description of the selection process and rationale are found in Appendix B.

This report does not address issues of technology diffusion. It is important to note that leading in technology development does not necessarily imply having the leading share of the market. In order to reap the economic benefits of technological development it is important to move technology out of the laboratory into products and services, something that requires aditional skills and investments. While it is exciting to note that the United States has a leading *technological* position in critical technology areas, this should not lead to the conclusion that the nation cannot do better in world-wide markets for products and services based on critical technologies.

---

[1]The complete National Critical Technologies List, including specific technologies and sample applications, is presented in Appendix A.
[2]For the purposes of this report, the quality of being critical or "essential" is tied to the importance of the system of which a technology is a part. For a full discussion and a more comprehensive definition, see Appendix A.

ORGANIZATION OF THE REPORT

The remainder of the report is organized as follows. Sections 2 through 8 provide descriptions of the critical technologies and the rationale for their selection at the technology sub-area level, i.e., one level further in depth than shown in Table 1. Each subsection also includes a benchmarking analysis of U.S. standing vis a vis the world-wide state of the art. Section 9 discusses federal government R&D activities in areas related to critical technologies and provides examples of specific programs in government and the private sector. Finally, Section 10 draws together the analyses in the previous sections and presents findings and recommendations as they relate to the development of critical technologies.

The names and activities of specific companies appear in many places in this report. These are included in order to provide specific examples in the discussion. No endorsement of any company or its activities is implied. The mention is also not intended to imply that those companies are the only ones engaged in the activities under discussion.

Table 1.1
National Critical Technology Areas

Technology category	Technology area
Energy	Energy efficiency Energy storage, conditioning, distribution and transmission Improved generation
Environmental Quality	Monitoring and assessment Pollution control Remediation and restoration
Information and Communication	Components Communications Computer systems Information management Intelligent complex adaptive systems Sensors Software and toolkits
Living Systems	Biotechnology Medical technology Agriculture and food technology Human factors
Manufacturing	Discrete product manufacturing Continuous materials processing Micro/nanofabrication and machining
Materials	Materials Structures
Transportation	Aerodynamics Avionics and controls Propulsion and power Systems integration Human interface

2. ENERGY

Critical technologies in the energy category fall into three general areas:

Energy Efficiency
Energy Storage, Conditioning, Distribution and Transmission
Improved Generation

Technologies in the Energy Efficiency area—which include building technologies and non-internal combustion propulsion systems—increase U.S. economic productivity by increasing economic output per unit of energy input and by offering a growing export business opportunity; they also contribute to U.S. national security by reducing dependency on foreign energy sources and, when exported, by moderating energy demand in developing countries. Building technologies improve the competitiveness of U.S. construction and building industries in world markets by making the sale of turn-key installations more likely and make a small contribution to national security by allowing more efficient management of facilities that frees funds for other uses. Although U.S. technology now competes favorably in this area with the most efficient Japanese and European products, it still trails Japanese and European firms in some products. Non-internal-cumbustion propulsion systems—particularly in "clean cars"—could provide a significant advantage to a sector comprising one-seventh of the U.S. economy. Japan and Europe are about even with the United States in electric vehicle (EV) technology, and Japanese AC motor technology lags that of the United States but is probably ahead of that of the Europeans.

Technology sub-areas in the Energy Storage, Conditioning, Distribution, and Transmission area—including advanced batteries, power electronics, and capacitors—are enabling for both economic prosperity with industrial, commercial, and residential applications, and national security with military applications. In advanced battery technologies, the Japanese are slightly lagging U.S. capabilities, although aggressive research is improving the Japanese position, and European firms are slightly behind U.S. firms. In power electronics, the United States is behind in high-power, solid-state switch technology except for a few niche areas. In capacitor technologies, the United States is the world leader, especially those suited for military applications, Japan is behind the United States and is losing ground, and Europe is also behind the United States and probably losing ground.

Technology sub-areas in Improved Generation—including gas turbines, fuel cells, next-generation nuclear reactors, advanced power supplies, and renewable energy—are critical to economic prosperity because of the confluence of rapidly growing demand for electricity worldwide, increasing environmental pressures from electric generation, and utility deregulation. In gas turbine technologies, Europe and Japan are slightly behind the United States in developing rotating machinery suitable for high-efficiency power generation. In fuel cells, the United States is the overall world leader across a wide range of fuel cell technologies but Japan is a very strong competitor in some segments, while European fuel-cell projects are highly dependent on foreign technology. In next-generation nuclear reactors, U.S. firms have remained competitive in design services and are active members of international alliances, because most current reactors are based on U.S. technology; however, the United States is likely to fall behind in next-generation reactors because of large funding cuts for reactor R&D. In advanced pulsed power supplies, Russia is slightly ahead of the United States, while Europe and Japan are behind the world leaders overall but are at parity in some niche areas, such as switching capacitors and transformers. In renewable energy, Europe and the United States are about even in solar thermal energy technology, slightly ahead of Japan; in photovoltaics, Japan is continuing to lag slightly behind the United States and Europe; Europe is slightly ahead of the United States in wind turbine technology, while Japan lags behind the world leader in innovative turbine designs; and Europe is slightly ahead of the United States in biofuels, with Europe leading in biodiesel fuels and the United States leading in ethanol production from biomass.

Overall, the United States is generally on par with the best in the world in critical technologies that fall into the energy category. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 2.1.[1]

ENERGY EFFICIENCY

Technologies for improved energy efficiency directly increase the productivity of the U.S. economy and thus are critical to the economic prosperity of the United States. Since the oil crisis of 1973, the U.S. economy has grown by 57 percent (in real dollars), while total energy consumption has increased by only 13 percent. Rising energy prices between 1973 and the early 1980s stimulated the development and adoption of many energy saving technologies in the industrial, commercial, residential, and transportation sectors. Efficiency improvements have continued during the past ten years even with constant or declining energy prices, thus permitting increased economic output per unit of energy input. The net savings to the U.S. economy have been estimated to exceed $130 billion per year from conservation measures put in place during the past two decades. More efficient use of electricity alone has saved more than $20 billion in new

---

[1]The figure shows both the U.S. position relative to the leading edge of technology development in Europe and Japan, and the trends between 1990 and 1994. The current position is indicated by the position of the symbol on the five-point scale from "Substantial Lag" to "Substantial Lead." The trends are indicated by the shape of the symbol and the direction in which it is pointing: the circle for lack of change, and a triangle for either increasing or decreasing lead/lag. The rate of change is not indicated in the figure.

Figure 2.1
Energy
Technology Position and 1990-94 Trend

US Technology Position Relative to:
- Japan ▷, ○, or ◁
- Europe ▶, ●, or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Energy					
Energy Efficiency			▶	○	
building technologies			▶	▷	
non-IC propulsion systems			◁ ●		
Energy Storage, Conditioning, Distribution and Transmission			●	○	
advanced batteries			●	◁	
power electronics		◁ ◀	▶*		
capacitors				▶	▷
Improved Generation			●	○	
gas turbines				○ ●	
fuel cells				◁ ●	
next generation nuclear reactors		◀	○		
power supplies		▶*		▶	▷
renewable energy			◀	○	

*Russia

power plants. Future advances in energy efficiency technologies can bring similar economic gains, as well as improve the quality of life by reducing environmental pollution from energy production and use. Efficiency improvements will be critical to meeting stricter future environmental standards, such as those for mitigating carbon dioxide emissions.

The U.S. imports 2.4 billion barrels of oil per year, of which 65 percent is used to fuel its transportation sector. Energy efficiency technologies reduce U.S. dependence on oil imports which are intrinsically linked to geopolitical tensions and regional instabilities. Reducing dependency on foreign energy sources is an important national security consideration. Furthermore, oil imports account for over half of the U.S. trade deficit, so reduced oil imports would lead directly to the improvement of the U.S. trade position. Moreover, energy efficiency technologies themselves represent a growing export business. Because energy is fundamental to economic growth, efficiency technologies contribute to global economic development with less environmental degradation, and are critical to many developing countries that lack domestic energy resources. Moderating energy demand through increased efficiency while encouraging sustainable economic growth in developing countries will contribute to stability throughout the world and, consequently, to U.S. national security.

Building technologies

Energy efficient building technologies comprise a wide range of components, systems and appliances, primarily for heating, cooling, ventilation and lighting. These technologies significantly affect five out of the six largest sectors of the economy, including manufacturing, services, and finance and real estate.

Residential and commercial buildings consume over one third of all U.S. primary energy and about two thirds of the electricity generated. By allowing more efficient energy utilization, advanced building technologies directly contribute to job creation and economic growth for manufacturers of the equipment involved, as well in the building and construction industries. These technologies improve the competitiveness of the U.S. construction and building industries in world markets by putting them in a more favorable position for selling turn-key installations overseas. In addition to making a direct contribution, advanced building technologies also contribute to productivity and job growth indirectly by improving efficiency of the physical infrastructure for all manufacturing and services. A reduction in the cost of providing goods and services which results from more efficient energy utilization allows U.S. companies to be more competitive on world markets. Building technologies also make a small contribution to national security by allowing more efficient management of facilities which frees funds for other uses.

Foreign firms took the lead from U.S. manufacturers of heating, cooling, air handling, and controls technologies in commercial buildings over a decade ago. Since then, U.S. firms have slowly regained part of their reputation and technological position and are now at parity with the European leaders. Europe remains ahead in ventilation and pulse combustion furnaces. The Germans, for example, have developed an innovative, gas-fired heater that rapidly heats small amounts of water—a concept applicable to small apartment furnaces, water heaters, and integrated appliances. Both Japanese and European firms have surpassed the United States in the efficiency of their gas-fired furnaces with some units achieving efficiencies as high as 97 percent.

Europe and Japan are generally ahead of the United States in materials technologies related to energy use in buildings,although the relative position depends very much on specific materials and applications including technologies for insulation, sound proofing, and thermal control. The U.S. does have some areas of excellence. U.S. technologies related to energy efficient windows, for example, are well ahead of Japanese efforts, especially with respect to low emissivity glazing and other advanced glazing technologies for warm climates.

The United States also has a small technological lead over Europe for window technologies appropriate for cold climates.

Foreign firms were, until recently, far ahead of U.S. firms in technologies for residential appliances. Because of energy efficiency standards and the internationalization of the industry, U.S. appliances have achieved major energy savings and are no longer considered inefficient or poorly designed. Although U.S. technology now competes favorably with the most efficient Japanese and European products, there are still areas in which the United States lags. For example, U.S. appliance manufacturers trail Japanese and European firms in the introduction and widespread application of advanced controls such as fuzzy logic and neural circuits for air conditioners and washing machines and are behind European firms in water and energy efficiency. The United States also lags both Europe and Japan with respect to ergonomic design and reduced environmental impact. The United States is well-positioned for next-generation lighting technology because of recent DOE-sponsored work.

Non-IC propulsion systems

As a mature, widely diffused technology, internal combustion (IC) engines for automobiles and other light vehicles have achieved relatively high levels of energy efficiency subject to the constraints of variable loads and emission control requirements. Non-IC vehicle propulsion systems are in earlier stages of development but hold promise of both increased energy efficiency and reduced levels of pollution. Energy storage and generation technologies for non-IC vehicles, such as electric batteries and fuel cells, are treated elsewhere in this report. However, the vehicle propulsion systems using these technologies require new design or redesign of many other components and subsystems including transmissions or drivetrains, starters, brakes, and such amenities as heating and air conditioning. Optimal energy efficiency for non-IC vehicles depends as much on integrated system design as on advances in individual components and subsystems. As a consequence, computer-aided design and manufacturing systems, on-board sensors and microprocessors, and advanced structural materials all play key roles in increasing energy efficiency for non-IC vehicle propulsion systems.

Automobiles are the largest single source of urban air pollution. If non-IC-powered cars had comparable performance to cars which run on internal combustion engines and were sold at comparable price, they could provide dramatically improved urban air quality, greatly mitigate the compliance costs for other sectors of the economy, and save billions of dollars in imported oil. In addition, U.S. automakers are beginning to pull even with Japanese automakers in adopting the "lean production" manufacturing techniques, so the product differentiation inherent in gaining a first mover advantage in a "clean car" could provide a significant comparative advantage to a sector currently comprising one-seventh of the U.S. economy. Advanced non-IC propulsion systems are essential to the success of the Partnership for the New Generation of Vehicles, an effort to build an advanced automobile for the next century.

Japan and Europe are about even with the United States in electric vehicle (EV) technology. Japan has an aggressive battery development program and has demonstrated high performance in some EV prototypes. Japanese automakers are cautiously watching foreign market developments before risking production of EVs. European automakers, on the other hand, are moving forward with EV production despite the fact that their battery, motor, and battery charger infrastructure programs are not as far along as the Japanese. Like the U.S. government, Japanese and European governments are funding technology development and providing market incentives to promote EV use.

Batteries are discussed elsewhere in this report. Foreign firms working on electric vehicles have had mixed results developing key associated technologies, particularly motors and chargers. Japanese AC motor technology lags that of the United States but is probably ahead of that of the Europeans, who are still equipping EVs with heavy DC motors that are difficult to maintain. The Japanese lead U.S. and European firms in the development of off-board chargers for EVs. Because the limited number of home garages in Japan requires a charging infrastructure, Tokyo is establishing a network of high-power rechargers in some major cities that can reduce charge times from eight hours to less than one. European researchers are developing more convenient on-board chargers, which use ordinary household outlets, but no firm has been able to significantly reduce the weight of these systems.

ENERGY STORAGE, CONDITIONING, DISTRIBUTION AND TRANSMISSION

Electric energy storage, conditioning, distribution, and transmission technologies are enabling technologies for both economic prosperity and national security. These technologies will enable intermittent, renewable energy sources on the electric gird. Electric energy storage technologies are essential for electric cars and/or hybrid electric cars and, thus, enable a new generation of non-polluting, non-oil burning motor vehicles. Advanced technologies for electricity conditioning, distribution, and transmission increase the quality, reliability and efficiency of electric power for industrial, commercial, and residential applications.

Energy storage, conditioning, transmission, and distribution technologies also have military applications. Power requirements for military equipment vary widely. A few watts may suffice for a wide variety of personnel communication units, but many kilowatts may be needed for surveillance radars and megawatts could be in demand for some potential weapon systems, such as directed energy. Efficient energy storage technologies will help bring power to run modern communications and information technologies to individual soldiers and unmanned vehicles. In addition to the amount of energy that can be stored per unit mass, important considerations in choosing a storage system are durability, low signature, alert status lifetime, operational lifetime (e.g., the number of discharge/recharge cycles that fuel cells or batteries can handle), and the rate at which power can be discharged.

Advanced batteries

Batteries are the most common electric energy storage system. Currently many different types of batteries are used in a wide variety of applications, from high-power density lead acid starter batteries in automobiles to light-weight nickel cadmium batteries for powering consumer electronics. To enable new uses in transportation or military applications, however, battery technology will need to improve in several dimensions. For use in electric cars, batteries must achieve currently unavailable levels of energy density (range), power density (acceleration), cycle life (lifetime), and low cost. They must also have minimal environmental impacts, and be safe, convenient, and reliable for consumer use.

Advanced batteries make a contribution to economic prosperity in several ways. They are a subject of an industry led R&D consortium, U.S. Advanced Battery Consortium, which includes the Big Three automakers, EPRI, and the Department of Energy. Batteries are also important to the Partnership for New Generation Vehicles which, if successful, would make a contribution toward improving the competitiveness of U.S. automobile manufacturers in domestic and world markets. Advanced batteries are an environmentally friendly technology because they may enable zero-emission vehicles, making a significant contribution to improving environmental quality.

Batteries are also needed for such critical military equipment as night vision devices, communications, and various manpack systems. Even devices that only draw a few watts of power could drain a battery pack within hours; thus, either considerable battery weight must be brought along or else advanced energy storage systems must be available. At present, military units that would benefit most from advanced energy storage systems include various special forces components. Special operations forces (SOF) must carry their own supplies with them, and the very significant fraction of portable weight that is taken up by batteries restricts the other equipment that SOF units can employ. Advanced battery technology, therefore, makes an important contribution to the ability of the U.S. military to employ a range of capabilities more suitable to actions at the lower end of the full range of military operations.

Japanese advanced batteries are slightly lagging U.S. capabilities, although aggressive research is improving the Japanese position. Japanese firms significantly lag in nickel-hydrogen ($Ni\text{-}H_2$) batteries, the battery of choice for high-power spaceborne applications. The Japanese have not yet space-qualified their Ni-H_2 batteries, while the United States has almost 50 satellites with Ni-H_2 batteries currently on orbit. Japanese nickel-metal-hydride (NiMH) battery R&D, a variant of the Ni-H_2 technology, is pressing the world state-of-the-art, although space applications will probably not occur until the late 1990s.

European firms are slightly behind U.S. firms in battery technology. European work is dominated by the Societe des Accumulateurs Fixes et de Traction (SAFT), the battery manufacturing subsidiary of France's electronics and telecommunications conglomerate Alcatel Alsthom. SAFT is the largest alkaline battery company in the world and produces Ni-Cd rechargeable batteries for applications ranging from aerospace to electric vehicles. SAFT's technology is slightly behind that of the United States in Ni-Cd batteries as well as in Ni-H_2 and Ni-MH batteries. SAFT's technology position will benefit from its purchase of two U.S. aerospace battery producers. For terrestrial systems, especially electric vehicles (EV), SAFT will improve its NiMH—the most viable mid-term alternative to lead-acid batteries for EVs—and on the aerospace side, SAFT will get nickel-hydrogen (NiH) battery technology. Industry experts prefer NiH batteries for aerospace applications such as satellites, launch vehicles, and missiles,because of their longer cycle and shelf lives, but prefer NiMH batteries for terrestrial application because of their superior energy densities and significantly lower cost.

No single country has a clear lead in electric vehicle battery technology. However, leaders are emerging in specific battery formulations. The Japanese lead in Ni-Cd batteries is unlikely to be relinquished as they are the only ones continuing development. Ni-Cd batteries store more energy than traditional lead-acid batteries and are able to recharge at a much faster rate than any battery that the United States has been able to develop. The Japanese may also have a lead in lithium technology on the basis of their efforts in the consumer electronics industry, a pool of developers that is virtually nonexistent in the United States. In contrast, European battery R&D is focusing on less expensive sodium formulations. These batteries offer a strong hope of providing to EVs the desired range of 300 kilometers at typical highway speeds by the end of the decade.

Power electronics

Just as low-power integrated circuits have revolutionized communications equipment, high-power semiconductor devices will profoundly change electricity transmission and distribution networks. Solid-state electronic switches, circuit breakers, and controllers offer significant improvements in efficiency, reliability and flexibility of the U.S. electric power grid. They increase the carrying capacity of existing power lines and permit power transmission over longer distances, thus permitting more efficient matches of electricity supply and demand.

Improved power electronics make an important contribution to job creation and economic growth by increasing efficiency of power distribution systems. The largest economic impact is on the utilities industry because improved power electronics allow the industry to efficiently manage utility grids, especially with numerous dispersed generating sources. This technology is likely to have a significant positive impact on the U.S. international trade balance because of large existing and projected world markets for power generation and distribution equipment. Power electronics are also a critical component of the "clean car," contributing to success of the PNGV and potential improvements in the worldwide position of the U.S. automobile industry.

Power electronics also have important national security applications. By contributing to better vehicles, power electronics contribute to rapid power projection capabilities and to lower casualties in conventional and unconventional conflicts.

The United States is behind in high-power, solid-state switch technology except for a few niche areas. The United States buys most of its high-power switches from foreign companies. Europe (Switzerland and the United Kingdom) and Japan lead in thyristors, Japan and Germany in insulated gate bipolar transistors, and Russia in dynistors.

Capacitors

Capacitors—one of the most common methods of short-term energy storage—store energy by accumulating electrostatic charges on two parallel metal plates. Thin film technology is important in the development of high energy density capacitors, because capacitors typically have low specific energy and hence require massive systems for delivery of large total energy. The ability to tailor material structures at the molecular level with thin film and other micro- and nanotechnologies will increase not only capacitor energy storage capabilities, but the ability to integrate microsize power systems with sensors and actuators to produce very small systems for such applications as surveillance, and detection and warning of hazardous agents; centimeter size devices with limited mobility could be dispersed by the thousands to cover an area with a detector net.

In commercial markets, capacitors are an important contender for power source of clean vehicles. They are an environmentally friendly technology which may enable zero-emission vehicles, which is important to improving environmental quality, as well as to improving competitiveness of U.S. automobile manufacturers in U.S. and world markets if environmental regulation becomes stricter and more prevalent. They also contribute to a reduction in dependence on imported oil supplies. In addition, capacitor energy storage systems are being developed for systems requiring high peak power from burst mode operation, such as pulsed weapons.

The United States is the world leader in high-power capacitors, especially those suited for military applications. Capacitive energy storage is frequently used in nuclear weapon simulators and for directed energy weapon and kinetic energy weapon systems. While few other countries offer any competition, Japan and Europe (France, Germany, and the United Kingdom) are doing some promising work in dielectric materials. Japan is behind the United States and is losing ground. Japanese manufacturers have produced standard quality capacitors, but have expended little effort to develop the high-energy-density capacitors required for advanced weapon systems. In several instances, Japanese laboratories have either used U.S. capacitors for their energy storage systems or purchased turnkey capacitor banks from U.S. manufacturers. U.S. developers remain dependent on Japanese suppliers for ceramic capacitors for microelectronic applications. Europe is also behind the United States and probably losing ground. The only European country doing quality capacitor research is France, and while French manufacturers are producing standard quality capacitors and are developing some high-energy-density systems, their overall efforts have not been sufficient to keep them from falling further behind the United States. This trend could be changed over time, but it would require a dedicated and significant investment of resources.

IMPROVED GENERATION

Improved generation technologies are critical to economic prosperity because of a confluence of several factors. Rapidly growing demand for electricity worldwide, increasing environmental pressures from electric generation, utility deregulation which promises to radically transform the market for electric generation within the United States, and several ripe technological opportunities together promise dramatically lower electricity costs, sustainable environment electric generation at affordable costs, and huge worldwide markets for the successful developers of improved generation technologies.

Gas turbines

Gas turbines are an important source of low-environmental impact electric power, providing a cheaper source of clean energy for manufacturing. Gas turbines are used in a variety of land-based applications, including electric generation for utilities and as part of cogeneration systems, and for driving pumps, compressors, and other mechanical systems in industrial applications. Gas turbines have a significant impact on the utilities industry by allowing more flexible siting, modular construction which reduces capital costs, and greater use of domestic fuels with reduced dependence on foreign oil.

Gas turbines make a contribution to the competitiveness of U.S. manufacturers in direct and indirect ways. Sales of efficient and environmentally friendly gas turbines in large and growing world markets for electric generation systems could make a positive contribution to the U.S. balance of trade. In addition, by providing U.S. manufacturers with cleaner sources of cheap energy, gas turbines increase the competitiveness of U.S. manufacturers in U.S. and world markets.

Europe and Japan are slightly behind the United States in developing rotating machinery suitable for high-efficiency power generation. European gas turbine and related technologies are primarily derived from aircraft propulsion engines. France has developed and manufactured at least three airbreathing turboshaft engine models with maximum power ratings exceeding 1 MW that are ideally suited to conversion for power generation purposes. Europe is about even with the United States for larger gas turbines (100 MW to 225 MW) for grid connected combined cycle power plants. Japanese capabilities in dynamic energy conversion suitable for high-efficiency (including aerospace) applications are generally behind world-class levels. Japanese production gas turbine technology is still based heavily on foreign developments; but Japan is rapidly advancing the state-of-the-art in ceramic gas turbines. The thermal efficiencies of metal gas turbines generally do not exceed 36 percent. The Japanese hope to operate ceramic components at turbine inlet temperatures of 1350°C or more, and reach thermal efficiencies over 40-percent in a 300-KW unit. Work has also been done on developing ceramic turbine blades for multi-megawatt turbine systems. This work lags behind advanced turbine developments in the United States.

Fuel cells

Fuel cells offer distributed modular generation, high efficiency, and low environmental impact. Like a battery, a fuel cell directly converts chemical energy of reactants into low voltage direct current electricity. Unlike a battery, however, a fuel cell uses externally-stored fuel for its reactants. To date fuel cells have been used primarily in space craft, but their potential for very high efficiencies (approximately 70 percent), low to virtually non-existent emissions (some versions operate with no emissions but carbon dioxide and water), ability to operate on a wide variety of fuels, modularity, and simple operational requirements make them an extremely attractive option for a variety of applications, including utility generation, industrial power, military applications, and a power source for long-range electric vehicle. Fuel cells are an important contender to serve as the power source for new clean vehicles being developed by the PNGV consortium.

In military applications, fuel cells offer a variety of advantages including low detectability with a low noise and infrared signature, low maintenance requirements, and high energy densities in remote applications. For instance, fuel cells could prove an alternative to advanced batteries in a variety of tactical power sources. As such, they contribute to the ability of Special Operations Forces to operate in a variety of environments.

The United States is the overall world leader across a wide range of fuel cell technologies but Japan is a very strong competitor in some segments. A great deal of U.S. fuel-cell technology was initially acquired from cooperative ventures and extended significantly by Japanese firms. There are over a hundred fuel-cell plants in Japan, in the 50-kW to multi-megawatt-capacity range, producing about 40,000 kW per year (U.S. capacity is estimated at 4,500 kW). Plans are underway for a 5-MW plant using strictly Japanese technology, although the fuel-cell stacks were built through a cooperative effort with a U.S. company. Similarly, smaller fuel cells are being developed, including man-portable 250-W fuel cells adequate for ground mobile use, but not yet ready for aerospace applications. Solid oxide fuel cells are being demonstrated by Kansai Electric Power and the Osaka Gas Company; these units are, however, built in the United States by a U.S. manufacturer. Japan also trails the United States and the world leader, Canada, in advanced solid polymer fuel cells. European fuel-cell projects are highly dependent on foreign technology. Further advances are more likely through technology transfer from the United States than through indigenous R&D. The current capacity of European fuel-cell plants is estimated at 3,500 kW, with the largest being a 1-MW plant in Italy built by a U.S. manufacturer. All demonstration plants in Europe are built by either the United States or Japan, although some plants using indigenous European technology are in the R&D stage. Italy has the largest European program, followed by Germany and the Netherlands, with lesser efforts in Belgium, Denmark, Norway, and Switzerland.

Next generation nuclear reactors

Nuclear power is the second largest producer of electricity in the United States, after coal. Nuclear power offers some significant advantages compared to coal and other major sources of electricity, including no dependence on imported fossil fuels, no emissions of the precursor gases to acid rain, and no emissions of greenhouse gases. However, no new nuclear plants have been built in the United States since 1978. A significant drop in the growth rate of electricity demand since the 1970s, escalating construction costs, concerns for safety, and waste disposal issues have all adversely affected the general acceptance of nuclear power.

Safer and cleaner scalable nuclear reactors, operating on non-proliferating fuel cycles, may be an important source of new electric generation capacity with reduced environmental impact for U.S. and world markets. A number of advanced nuclear reactors, now in design or development, offer significant gains in simplicity, operability, and safety over the most common light water reactors now in operation. Since nuclear reactors are in greater demand outside the U.S., next generation reactors could make a positive contribution to the U.S. trade balance.

International comparisons in reactor technology are greatly complicated by alliances and joint development efforts. Because the vast majority of current reactors are based on U.S. technology, U.S. firms have remained competitive in design services and are active members of international alliances. Westinghouse is working with Mitsubishi and GE is involved with Toshiba and Hitachi on evolutionary improvements of current systems. However, while the U.S. is preeminent in light water reactor technology, we are likely to fall behind in non-light water advanced reactors such as liquid metal reactors because of large funding cuts. Foreign efforts to develop these technologies are likely to continue although perhaps at a reduced rate as many foreign efforts involved U.S. participation.

Power supplies

Advanced power supplies include high-energy-density, low-mass supplies that deliver power over a sustained period, and pulsed supplies that provide high energy peaks with controlled waveforms for special applications. Both types have critical national security applications. High-energy-density, low-mass power supplies are critical for smart weapons systems, as well as for space systems, reconnaissance vehicles, remote sensing, and other military applications in which power must be available at remote sites.

Pulsed power supplies are critical for many military applications, including radar and other detection/targeting systems. In the absence of underground nuclear testing, pulsed electrical power supplies are critical to simulating nuclear weapons effects through the production of X-rays, particle beams, and electromagnetic pulses (EMP) under controlled conditions.

These power supplies are also of increasing importance for environmental monitoring, resource exploration, communications, and other commercial applications. Power supplies contribute to economic prosperity by contributing to distributed generation systems and providing potential new sources of energy for clean cars. While new power supply technologies will have some impact on the energy distribution equipment manufacturing industry, their biggest impact may be in the trade sector of the economy because there is a significant export market for advanced power supplies.

Russia is slightly ahead of the United States in advanced power supplies—i.e., high-energy or pulsed power supplies suitable for such applications as electronic warfare and directed energy weapon systems. Russia has long been the leader in magnetohydrodynamic research and has developed the most advanced explosive magnetohydrodynamic generators in the world. Europe and Japan are behind the world leaders overall but are at parity in some niche areas, such as switching capacitors and transformers. Europe has capabilities in all of the necessary core technologies, as well as some programs which could eventually require high energy/low mass power supplies, but catching up with the world leaders, will require substantial increases in resources. The Japanese also have some capability in most of the core technologies, but programmatic efforts are even more modest than those in Europe with R&D in switch development, energy storage, and overall power supply design generally emphasizing items needed for commercial use. The large amount of Russian technology becoming available on world markets could allow other countries to make rapid progress.

Russia and Ukraine are the world leaders in high-power microwave (HPM) generators and associated components such as pulsed-power supplies, mode converters, and antennas, as a result of several programs in radio-frequency weapons (RFW) development underway before the collapse of the Soviet Union. Before the disintegration of the USSR, the Soviets had a large and well-funded program in HPM technology conducted at institutes in the Russian and Ukrainian republics and were clearly the world leaders. They had built HPM generators producing record power and energy levels and had also devoted considerable resources to the development of ancillary HPM systems. Events of the past few years have resulted in a sharp curtailment of their HPM research and few new accomplishments have been reported. There is some European development of RFWs, which, if supplemented by purchase of technology from Russia or Ukraine, could be at world-class levels. Japan has only limited efforts.

Renewable energy

Renewable energy technologies are critical because the energy sources on which they are based can be regenerated, and they may have less of an environmental impact than conventional technologies. Critical renewable energy technologies include solar thermal power technologies, photovoltaics, wind turbines and biomass fuels.

To efficiently convert solar energy into power, mirrors are used as collectors to concentrate large amounts of sunlight which is then directed at a receiver, transferred into a fluid through a transport-storage system, and finally converted into power. Efficiency losses occur in each major element of the system. The collector subsystem is the most costly element of the system. There are three primary solar thermal technologies: trough systems, dish/engine systems, and power tower systems. Research in each of the three major collector designs may reduce capital costs and increase efficiency of solar thermal power generation.

Originally developed for the U.S. space program in the 1970's, photovoltaic (PV) energy systems are modular devices which absorb sunlight by photosensitive cells to produce direct current electricity (which is then generally converted to alternating current). PV offers low-maintenance, long life and zero-emission electricity production. PV systems can be of nearly any size and can be sited close to demand, cutting the need for expensive transmission and distribution equipment.

Wind turbine technologies may provide an important renewable source of new electric generation capacity with lower environmental impact for U.S. and overseas markets.

Biomass fuels or biofuels are fuels made from cellulosic biomass sources that include a substantial fraction of municipal solid waste, agricultural and forestry residues, and woody and herbaceous plants grown for production of fuels. Biomass fuels can offer lower emissions than fossil fuels and are renewable.

Research on biomass fuels focuses on developing cost-effective production processes and complementary combustion or direct-current electricity conversion technologies. Biofuels now under development through the support of the DOE Biofuels Program are biodiesel, ethanol, ethers, and methanol. Biodiesel fuels are produced by hydrolyzing oils from plants to form fatty acids and glycerol. The fatty acids can in turn be reacted with alcohols to make esters. These esters have similar fuel properties to diesel fuel and are often called biodiesel. However, because biodiesel is much lower in sulfur content than conventional diesel fuel, it substantially reduces sulfur emissions. As a result, use of biodiesel alone or blended with conventional diesel fuel improves air quality. The keys to low-cost production of biodiesel are low-cost sources of oils, highly efficient technology for converting the oils to esters, and use of coproduct glycerol. Fuel diversification can not only help reduce reliance on oil imports, but it can also reduce volatility of fuel prices. The potential resource base for production of biofuels is sufficient that enough such fuels could be produced in the United States to replace all gasoline.

Renewable energy technologies can serve to reduce reliance on fossil fuels, thereby increasing national energy independence and replacing polluting electricity sources. While cost is the major barrier to their commercialization, the modularity of most of these technologies promises significant cost reductions through mass production. Their impact on competitiveness of U.S. industry would be seen mostly in the ability to sell equipment based on this emerging generation technology in world markets. Cost effective energy storage (described separately) is important to most of the renewable but intermittent energy sources such as photovoltaics and wind.

Europe and the United States are about even in solar thermal energy technology, slightly ahead of Japan. Trough systems have been commercially deployed in over 380 MWe of power plants in California; dish/engine and power tower systems are expected to see commercial deployment near the end of the century. Researchers in the U.S. generally believe that power towers will achieve lower energy costs and larger market impacts than trough systems. Dish/engine systems are more modular systems and are not likely to compete against either trough or power tower systems in the near term.

Europe is slightly ahead of the U.S. in trough systems. The intellectual property rights to the trough designs that have been commercially deployed are owned by a Belgium/Israeli firm. European R&D firms and companies have been active in pursuing a next generation trough design for direct steam generation, which could decrease the energy cost in the plants by 20 percent. While this development is in the early phases, the United States has not been doing research in this area and is behind Europe. Japan has not been an active developer of trough systems for electricity. In the dish/engine technology, Europe and the U.S. are roughly equivalent in terms of technology development. Cost-shared programs with U.S. industry are spurring development of the technology, however, and it is possible that the U.S. will gain a significant leadership position in the coming years. Japan has been active in the development of engines (one of the critical components) for dish/engine systems but lags the U.S. and Europe slightly on the total system. Developments in power towers have taken a different technology focus in the U.S. and Europe. Europe is emphasizing systems using air as the working fluid, while U.S. systems are designed using molten salt as the working fluid. A new U.S. development applying the molten-salt technology with natural gas hybrid systems using combined cycles has the potential to reduce solar energy costs by over 50 percent. The United States has a clear technology lead on the concept and has both domestic and international patents pending.

In photovoltaics, Europe is now in a strong position, principally due to the purchase of two major U.S. photovoltaic companies by multinational companies headquartered in Germany. In 1992, Siemens Solar USA purchased ARCO Solar, the world's largest photovoltaic manufacturer. Siemens Solar produces crystalline silicon products and is developing a next-generation thin-film technology. In 1994, Mobil Solar was purchased by a German group and renamed ASE Americas Inc. Mobil Solar had a twenty-year history of developing a crystalline silicon technology with good performance and potentially low cost. The remaining U.S. photovoltaic companies are still strong in crystalline silicon technologies and especially strong in thin-film photovoltaic technologies, considered to be the most promising photovoltaic technology. The United States leads in concentrator technologies, but this market is small and confined to areas with extremely high solar resources. Japan continues to slightly lag the United States in photovoltaic technologies. Japan remains the leading producer of thin film photovoltaic cells used in consumer products such as solar cell calculators but their technical strengths in crystalline silicon technologies, which make up 96 percent of the world's photovoltaic products, continues to lag behind that of the United States. Japan also lags the United States in photovoltaic concentrator technologies, although the sales of this technology are still negligible.

Europe is slightly ahead of the United States in wind turbine technology, while Japanese researchers, with more modest R&D programs, lag behind the world leaders in innovative turbine designs. The effort to reduce the cost of wind turbines in the United States led most government-funded research and turbine developments toward light-weight, flexible rotors, such as two-bladed teetered rotors, developed commercially by four U.S. companies in the early 1980s (Boeing, Westinghouse, ESI, and Carter Wind Turbines). Europeans pursued a more mature, low-speed, heavy, structurally inefficient, three-bladed-rotor technology. Today, most European turbine manufacturers are developing light-weight, structurally efficient, three-bladed rotors in intermediate size ranges. For the larger sizes (500 kW and greater), there is a strong trend toward two-bladed-rotor technology. Because of the strong market for wind turbines in Europe and the need for larger turbines (due to the lack of real estate), Europe could quickly gain more experience than the United States in this area.

The trend in both Europe and the United States in wind turbine power generation equipment is toward variable-speed drives (using power electronics) and direct-drive generators. The variable-speed drive improves energy production and electrical power quality while reducing aerodynamic noise emissions. Direct-drive generators would eliminate the need for expensive, maintenance-prone gearboxes. While a U.S. firm has developed a sophisticated power electronics system, the Europeans are ahead in the quantity and variety of turbines using variable-speed drives. The Japanese have not yet deployed a commercial, variable-speed turbine. Europeans have deployed one commercial turbine using a direct-drive generator, and several others are near deployment. Two U.S. manufacturers are considering them and one component manufacturer has begun a government-funded development program.

The United States leads the world in developing airfoils for wind turbines. These developments have dramatically increased energy production and fundamentally changed the way turbine blades are designed. Many European wind turbine research organizations are now developing wind turbine airfoils and it is likely that the United States will lose its edge as the technology becomes familiar to other countries.

Europe is slightly ahead of the United States in biofuels. European firms are world leaders in the commercial application of biodiesel fuels, a promising low sulfur alternative to conventional diesel fuel. A number of European sites now produce over 32 million gallons of biodiesel annually and there are plans in place to produce more than 200 million gallons in a few years. However, the price of the biodiesel is much higher than for conventional diesel because high-cost conventional plant oils are being used in response to pressure from the agricultural sector, glycerol is not used effectively, and the conversion technology is new and applied at a small scale. Overall, the Europeans are positioned as the leaders in commercial application of biodiesel technology, albeit at a noncompetitive cost that requires government tax incentives.

The Japanese are well positioned for large-scale cultivation of algae to provide low-cost biomass sources. Nevertheless, the United States leads in biotechnology R&D for enhancing yields of biodiesel from low-cost microalgal sources. A number of promising microalgae strains have been isolated for producing low-cost oil and genetic engineering techniques are being applied to enhance the oil content from the 5- to 10-percent levels that typically occur to over 60 percent. Because microalgae require carbon dioxide to support growth and can efficiently take up this important greenhouse gas, the Japanese are funding substantial programs directed at developing approaches to capture carbon dioxide released from power plants.

The United States is the leader in ethanol production from biomass. Currently, fuel ethanol is made from cane sugar in Brazil and plant starch in the United States, but the price of these food materials is too high to allow ethanol to compete with gasoline without subsidies. The United States has made significant advances in the technologies, reducing the projected cost of production by about two thirds since 1980. An additional 50 percent reduction should make ethanol competitive with gasoline from oil at $25/barrel. Europe has some small programs and limited areas of expertise. Austria is working on pretreatment and enzyme production approaches to reduce processing costs, Finland has expertise in enzyme technology that could be important to commercializing ethanol from biomass processes, and Sweden has extensive experience in utilization of ethanol in vehicles and some small projects on ethanol production from biomass.

3. ENVIRONMENTAL QUALITY

The global market for all environmental technologies was estimated at $300 billion for 1992 and is projected to grow to $425 billion by 1997. While the U.S. is expected to continue to be the largest single market, $134 billion in 1992, growth in other geographic areas such as Latin America, Canada, Eastern Europe, and the former Soviet Union, is expected to outpace the U.S. market growth. In fact, these figures may underestimate the true size of the market because pollution prevention investments are not always recorded as such.

Critical technologies in the environmental quality category fall into three general areas:

Monitoring and Assessment
Remediation and Restoration
Pollution Avoidance and Control

Technologies in the Monitoring and Assessment area include integrated environmental monitoring and remote assessment of biosystems. The former contribute to such national goals as the health of the U.S. population, job creation and economic growth, the efficiency of the physical infrastructure, and the ability for ecosystem management and ex-post monitoring and evaluation to understand how humans interact with the environment. These technologies also contribute to national security and warfighting capabilities by, for example, helping to assure non-proliferation of weapons of mass destruction and by providing accurate information about battlefield environments, thus increasing troop effectiveness and reducing casualties. Within this area, Russia is behind the United States in remote sensing technologies; the United States leads in satellite-based, multi-spectral data processing technology capability, followed by Russia (based on military capability), France, and Japan; and in the specific area of qualitative risk assessment tools, Europe lags the United States, with Japan further behind.

Development of timely and cost-effective remediation and restoration technologies is critical, both to reduce costs to the U.S. economy in addressing indigenous contamination problems and to promote U.S. competitiveness in global remediation markets. These technologies can contribute to job creation and economic growth, both by creating new jobs and by helping reduce clean-up cost liabilities faced by many manufacturers and can contribute to the health of the U.S. population by reducing risks associated with contaminants in the environment. There is general parity between the United States and Europe in bioremediation technology--the United States has conducted more basic research in this area, but Europe has successfully used U.S. technology for relatively large-scale, on-site remediation efforts. While Japanese firms are capable of being major players in bioremediation technology, they appear to lag slightly in actual demonstration of this capability. In nuclear wastes storage and disposal, Europe is slightly ahead of the United States in technologies for decontamination and decommissioning of nuclear reactors, with Japanese firms at about the same technology level as U.S. firms.

Pollution avoidance and control technologies contribute to the security of food, water, and air, to lowering costs of research and development activities, and to the health of the population. Foreign firms are slightly behind U.S. firms in separation technologies, although Europe is ahead in nuclear applications because of the policy decision to manage waste as it is produced rather than to accumulate it for future treatment. In non-nuclear separation technologies, European firms are behind U.S. firms, who have superior technology. Japanese firms are behind U.S. firms in both nuclear and non-nuclear separation technologies.

Overall, although the United States is currently a leader in many technologies in this category, trends indicate that other countries are making progress in attaining the same level of technology. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 3.1.

Figure 3.1
Environmental Quality
Technology Position and 1990-94 Trend

US Technology Position Relative to:
Japan ▷ , ○ , or ◁
Europe ▶ , ● , or ◀

1990–94 Trend
Improved ▷
Declined ◁
Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Environmental Quality					
Monitoring and Assessment				◁ ◀	
integrated environmental monitoring				◁ ◀	
remote assessment of biosystems				◀	◁
Pollution Control			○ ●		
pollution control			○ ●		
Remediation and Restoration			◀	◁	
remediation and restoration (?)			●	◁	
nuclear wastes storage/disposal		◀	○		

(?) based on limited information

MONITORING AND ASSESSMENT

Environmental monitoring and assessment technologies are critical for understanding and predicting changes in the environment and for responding to the many pressing environmental problems which we currently face. Key technologies for environmental monitoring and assessment range from the macro level down to the micro and even molecular/nano level: satellite-based systems; airborne, land-based and ocean-based systems; networked monitoring systems; micro electromechanical systems and biomarkers. Such systems monitor at all levels: global; biosphere; ecosystems; regions; cities; towns; individual factories and homes; individual persons and organisms; to individual genes and chromosomes. Environmental issues that they monitor include: global warming, ozone depletion, regional air quality, biodiversity loss, point source emissions of air, water and hazardous waste, indoor air quality, noise pollution, and human health effects at the gene/chromosome level.

Integrated environmental monitoring

During the past few years, there has been increasing attention paid to the monitoring and control of pollution and other forms of environmental damage. The integration of the sensors, deployed to monitor various parameters in the environment, with the analysis of the information they collect, is an example of an integrated system. More specific examples include the environmental controls on power plants, both solid fuel and nuclear, the monitoring of acid rain damage in a forest, or an airborne military system to monitor chemical signatures over a suspected chemical weapons plant.

Integrated environmental monitoring technologies contribute to several national goals. By providing data which permit assessment of environmental effects on health, as well as by increasing food security through better monitoring and prediction of natural disasters, these technologies contribute to the health of the U.S. population. Environmental monitoring technologies also contribute to job creation and economic growth in a variety of ways. These technologies provide the basis on which the success of the "clean car" produced by Partnership for the New Generation Vehicle can be judged and on which environmentally friendly construction designs can be based. They contribute to the efficiency of physical infrastructure by providing a basis for a better understanding of how climate and weather affect transportation. They provide the basis on which energy production and utilization methods can be judged for their environmental effects. Finally, these technologies provide data which are a prerequisite for ecosystem management and *ex post* monitoring and evaluation for understanding interaction of humans with the environment.

Integrated monitoring and assessment technologies can make a significant contribution to our national security as well. By providing the ability to identify developing environmental disasters which may cause social and political turmoil and even conflict between nations, we may be able to intercede to prevent or mitigate such destabilizing events. This could, in turn, reduce the number and intensity of humanitarian relief efforts that are expensive in terms of manpower, materials, and national will. At a finer scale, that ability to monitor the physical environmental conditions on the battlefield can provide a warfighting advantage, and provide information with which simulations for future possible missions can be constructed as means of training. Environmental monitoring technologies are also essential to assuring non-proliferation of weapons of mass destruction.

Assessments of capability in integrated environmental monitoring using space-based systems are greatly complicated by the links between civil and military technology. Although many of the core technologies for commercial remote sensing are available from developments in the information industry and from such projects as the Hubble Space Telescope, the leading edge has always been defined by classified systems. As part of the defense conversion process, however, governments are increasingly willing to release portions of this classified knowhow to the civil sector. At present, Russia is only slightly behind the United States in remote sensing technologies. The Russians currently are marketing photographs down to 2-meter resolution and synthetic aperture radar (SAR) images down to 15-meter resolution. The French plan to launch SPOT 5 by 1998 with a 5-meter resolution, compared to current SPOT capability of 10 meters. The Europeans plan to launch a military system, Helios 1, in early 1995 with a 1-3 meter digital visible spectrum capability, but have stated that the system will not be commercialized. Currently, Japanese technology is at 8-meter resolution for visible light, 16-meters for multispectral (ADEOS scientific satellite to be launched in 1996), and about 18-meters for SAR as demonstrated in the JERS already in orbit. Japan plans to have a system by 2000 that would increase ground resolution to 2.5-meter visible light, 10-meter multispectral, and less than 8-meter for SAR.

The United States is currently the leader in satellite-based, multi-spectral data processing technology capability, followed by Russia (based on military capability), France, and Japan. Environmental monitoring is a fertile area for international cooperation, including cooperation in space-based monitoring with the Former Soviet Union— Russian platforms, such as the K-1870, ALMAZ and a possible follow-on, equipped with a variety of sensors, together with a body of published theoretical work, are indicative of Russian capability in multi-spectral processing. Russia, however, lags in applying this knowhow to environmental issues. The French SPOT and Japan's ERS-1 follow closely behind. Japanese industry has demonstrated significant progress in combining sensors and processing on the same chip; prototypes of multilayer imaging arrays with built-in primitive image processing functions have been developed. This work has expanded to include research in combined neural network/fuzzy logic devices. (See Information and Communications for basic discussion of sensors, large scale systems, and software capabilities.)

In the specific area of qualitative risk assessment tools, Europe currently lags the United States with Japan further behind. There is increasing financial, legal, and political pressure throughout Europe to change from the current statute concentration limits methodology to a qualitative risk assessment methodology as a more appropriate means of prioritizing environmental problems and making more efficient use of their limited financial resources. Within Europe (particularly Germany and the Netherlands), the principle approach to risk assessment has been based on various country lists that contain maximum concentrations for specific contaminations in soil, soil gas, and groundwater. If maximum concentrations are exceeded, investigative or remedial action is required and the appropriate action is taken to bring concentrations under the acceptable maximum limit. Recently, efforts in Switzerland and the United Kingdom are underway to alter their statute concentration limit approach in favor of a quantitative risk assessment for each contaminated site. In this approach, a risk factor is derived and used to generate a remedial action plan and lay out remediation goals. This risk assessment approach is similar to the quantitatively driven U.S. methodology. The quantitative values are derived from health and environmental degradation parameters at each site rather than legal standards which are applied to all sites. The Swiss developed risk assessment program called "ChemRisk," a useful tool for the objective assessment of health risks posed by contaminated sites.

Remote assessment of biosystems

Monitoring and management of large scale biosystems is increasingly important as a human activities have an increasing impact on global change. On an immediate basis we are faced with the problems of sustainable fisheries and forestry management. Longer term are the problems of air pollution's impact on regional forests, erosion, and watershed maintenance, and ultimately the functioning of forests and photoplankton in balancing atmospheric gases.

While higher resolution, multi-spectral satellite imagery will place an impressive demand on information and communications systems, and the related ability to store, access and display the raw data, interpretation will place unprecedented demands on technologies for acquiring and integrating ground truth data. Coupling ground truth data and pattern recognition will be necessary for meaningful monitoring, science and management. This would contribute improved environmental quality by supporting the development of a scientific basis for ecosystem management.

The remote assessment of biosystems is highly dependent on multi-spectral imaging (either satellite-based or high altitude photography) and the subsequent correlation with ground-truth data to adjust for species specific signatures and variability caused by trace minerals, plant hydration, plant seasonality and maturity, and atmospheric contaminants. The United States is the clear leader in the technologies needed for image acquisition and processing, and has also led in efforts to correlate image data with changes in the status of crops and forestry with significant efforts dating to the ERTS and LandSat satellite series, and more recent efforts to correlate the emergence of disease vectors and crop blights with multi-spectral changes in large area surveys. Recent analysis of multi-spectral space-based radar images has demonstrated the ability to differentiate plant types and moisture information via microwave reflectance characteristics. The space based radar capability can complement optical data to provide a richer environment for data analysis.

While the US is the clear leader in the underlying hardware-based technologies of image acquisition and the algorithms for computer analysis, there is a great deal of field work to be done concurrently to provide the physical bio-system status. The European efforts in this area are substantial, but limited by factors related to their actual investment in hardware, software, and field work in both the agricultural and environmental sciences. The commercial availability of high resolution imagery will certainly expand the access to data, but will still require substantial work on computer algorithms and field research in order to convert the images to useful imformation on crop estimates, and the effects of atmospheric changes on the status and productivity of forests.

POLLUTION CONTROL

Pollution control

Pollution control technologies render hazardous substances harmless before they enter the environment. These technologies include the treatment of pollutants or other natural or anthropogenic materials to eliminate or reduce environmental and human health hazards, or the reduction of pollutant/waste material volume or mobility to make subsequent management more effective. An example is the use of precipitators in fossil-fueled power plants to remove particulates from waste gas streams. Subsequent treatment of the pollutants is often required after their removal from the process streams. Another example is the use of catalytic converters on automobiles to convert combustion byproducts to less harmful substances prior to exhausting them. Other control technologies (also called "end-of-pipe" technologies) include incineration, separation, oxidation , reduction, bioprocessing, absorption, filtration, and neutralization.

Pollution control technologies also contribute to the security of food, water, and air. As worldwide environmental regulations become stricter, companies that develop and sell pollution control technologies will gain a competitive advantage. Increased sales of pollution control products and processes would contribute to job creation and economic growth in the U.S., particularly in Manufacturing, Transportation and Utilities, Agriculture, Forestry and Fishing, and Mining sectors. These technologies also substantially contribute to lowering costs to research and development activities because they facilitate management of mixed wastes generated as an unavoidable by-product. Such wastes currently constitute a significant financial burden and potential liability for the R&D communities involved.

Waste elimination is part of pollution control. Waste elimination technologies contribute to the health of the population by providing a reduction in environmental causes of disease. As a larger waste disposal industry is created, these technologies also contribute to job creation and economic growth through the fabrication and sales of equipment based on these technologies. Waste elimination technologies also contribute to national security by providing means of safe disposal for waste from reduction in nuclear stockpiles.

Foreign firms are slightly behind firms in the United States in separation technologies. European firms are closest to U.S. firms in capabilities and have some areas of leadership. In particular, Europe is ahead in nuclear applications because of the policy decision to manage waste as it is produced rather than to accumulate it for future treatment. An active reprocessing effort, led by the French with contributions from the United Kingdom has given Europe a strong lead over the rest of the world. German work has accelerated in the last few years because of concern about decontamination problems in the former East Germany. In non-nuclear separation environmental applications, European firms are behind firms in the United States. Europe may have a somewhat more favorable regulatory environment which permits technologies to be more readily implemented, but U.S. technology capability is superior. Europe's position could improve as a result of the introduction of skilled technical talent from eastern Europe together with increased resource commitments required to deal with the serious environmental problems there.

Japanese firms are behind U.S. firms in separation technologies. Japan's lag in nuclear applications may be a result of a research strategy of concentrating on reactor and fuel technology and relying on foreign work for waste treatment technology. There is some good Japanese R&D in transuranic separations, other radionuclide separations, and noble metal recovery, although much of it is an extension of U.S. and European work. Japan is also behind slightly in non-nuclear separation, but is doing good work in hydrometallurgy.

REMEDIATION AND RESTORATION

Remediation and restoration

Remediation technologies render hazardous substances less harmful after they have entered the environment, and restoration technologies renew and renovate ecosystems which have been damaged or changed, especially those which have declined due to anthropogenic effects. Together these technologies seek to redress existing environmental problems, and thus are especially important in the near term, that is, over the next ten to twenty years.

The current state of the art in remediation technology is unlikely to fully meet even basic requirements for remediating difficult contamination problems, much less to meet goals for achieving remediation in a cost effective and timely manner. Early "treatment" methods such as dig-and-store or incineration tend to be high-cost and to carry risks for further contamination. Some recently developed innovative technologies have found growing application. A report by EPA's Technology Innovation Office[1] estimates that soil vapor extraction techniques, first deployed in the early 1980's, now account for 40 percent of innovative applications. Bioremediation techniques account for 21 percent. Other innovative techniques currently being applied include thermal desorption, soil washing, and in-situ flushing. However, more development is still required, especially for nuclear materials, for other less common contaminants, for heterogeneous and often poorly characterized mixtures of contaminants, and for more difficult media.

A varied and comprehensive portfolio of remediation and restoration technologies will be needed to play a critical and rather unique dual role in the U.S. economy. This dual role derives from the dichotomy that, although remediation of sites within the United States will be a significant cost to the U.S. economy, the opportunities to remediate sites outside the United States will represent a large potential export market which may benefit the U.S. economy. Thus development of timely and cost-effective remediation and restoration technologies is critical, not only to reduce costs to the U.S. economy for addressing indigenous contamination problems, but to promote U.S. competitiveness in global remediation markets. These technologies can contribute to job creation and economic growth, both by creating new jobs, and by helping reduce clean-up cost liabilities faced by many manufacturers. They also contribute to the health of the U.S. population by reducing risks associated with contaminants in the environment.

There is general parity between the United States and Europe in bioremediation technology. The United States has conducted more basic research in this area, but Europe has successfully used U.S. technology for relatively large-scale, on-site remediation efforts. A European company was the first to use a fungi to bioremediate 10,000 tons of soil at a wood processing plant. While Japanese firms are capable of being major players in bioremediation technology, they appear to lag slightly in actual demonstration of this capability. Their strength is believed to lie in *ex situ* bioremediation, where large-scale bioreactor and bioprocessing facilities will be required.

Nuclear wastes storage and disposal

There is an increasing emphasis within the United States on the need to mitigate the risks posed by all types of nuclear wastes, including spent nuclear fuel, high-

---

[1] *Innovative Treatment Technologies: Semi-Annual Status Report*, U.S. EPA, Technology Innovation Office, EPA/542/R-92/011, October, 1992

level wastes, transuranic wastes, low-level wastes, and mixed wastes. Radioactive contaminants pose a threat to public health and safety at many sites across the country, and adequate technologies to enable treatment of all types of nuclear waste are not currently available. As a result, the development of technologies to characterize, retrieve, pretreat, stabilize, and store nuclear wastes is critical. In general, the strategy for "treatment" of radioactive waste first requires identification of what contaminants are present. Pretreatment technologies are then used to minimize the volumes of more dangerous wastes (longer half-lives, more highly radioactive), usually by separating nuclear wastes into smaller volumes of more concentrated high-level wastes and larger volumes of low-level wastes. Each of these types of waste will then be stabilized as appropriate, possibly by vitrification for high-level wastes, and by immobilization in cement or grout for low-level wastes. The stabilized waste will be stored in appropriate repositories: geologic repositories for spent fuels, high-level and transuranic wastes; and approved "disposal" facilities (usually burial sites) for low-level wastes. Although some vitrification plants have been built and are currently at various stages of being brought on-line, more reliable and more cost-effective technologies are still needed for most stages of this process.

The efforts to stabilize and store radioactive wastes are expected to continue for many years. Most estimates indicate that substantial nuclear waste treatment activities can be expected to continue into the second or third decade of the next century. For example, DOE has a stated goal of having its continuing operations in compliance by the year 2019, and of having its surplus or inactive sites either posing, or proceeding safely and smoothly towards posing, no unacceptable risk to public health and safety, or to the environment. Thus impacts (primarily costs) to the U.S. economy will continue well into the foreseeable future. The worst problems result from past U.S. government nuclear weapons programs, and these costs must be met by the government. Approximately 381,000 cubic meters of high-level waste, which contain about 1.1 billion curies of radionuclides, are stored at just four DOE sites: Savannah River, Idaho National Engineering Laboratory, Hanford Site, and West Valley Demonstration Project. Improving technologies to be as cost-effective as possible will be a continuing necessity.

Nuclear materials storage/disposal technologies contribute directly to improved environmental quality. They also contribute to the health of the U.S. population by reducing the risks of exposure to radioactive substances. It is likely that a significant number of jobs will be created by the need to treat nuclear wastes; however, given the nuclear weapons complex drawdown, net job creation will be small. For example, Rocky Flats, which has an estimated 14.2 tons of plutonium to remediate, currently employs about 7,300 people. Although this is roughly the same number as were employed at Rocky Flats during peak production in 1989, many of these people are now employed monitoring, studying, and planning clean-up efforts.

Significant export markets may exist in the future for technologies which address nuclear wastes, especially among the countries of the former Soviet Union. However, estimates of the potential size of these markets are difficult to make, and most of the effort within the U.S. is focused on the indigenous market. This is in marked contrast to the areas of remediation and restoration technologies for hazardous (non-nuclear) wastes, where many U.S. companies are actively pursuing export opportunities. Experience exporting hazardous waste clean-up technologies may provide lessons learned for future attempts to export technologies to treat nuclear wastes.

Nuclear materials storage and disposal technologies contribute to increased security of weapons-grade materials, and to national security of the United States.

Europe is slightly ahead of the United States in technologies for decontamination and decommissioning of nuclear reactors. European firms have worked on decontamination methods such as using fogs or foams containing chemical reagents and in-situ hard chemical decontamination of the tube bundle from a pressurized water reactor steam generator. Methods have been developed for separating radioactive constituents of concrete including active pilot-level testing and recycling of contaminated aluminum, copper, and steel with alpha, beta, and gamma decontamination. Japanese firms are at about the same technology level as U.S. firms. No prototypical facility has yet been decommissioned but work has been done on remodeling, maintenance, and repair. Japanese firms also have experience in decontamination of the sodium removal facility and hot cell maintenance on fast breeder reactors.

4. INFORMATION AND COMMUNICATION

Perhaps more than any other technical area, information and communication technologies are what make our society "modern." The ability to rapidly access and share vast amounts of information has been the driving force in economic growth and improved quality of life in the latter part of the twentieth century. Accordingly, information and communication technologies are essential to meeting national goals in economic growth and national security, and in helping other technical areas to realize their full potential. The technologies identified as critical include those contributing to the leading edge of:

- Components
- Communications
- Computer Systems
- Information Management
- Intelligent Complex Adaptive Systems
- Sensors
- Software and Toolkits

Of these areas, components, computer systems, communications, information management, and software and toolkits have the highest potential to contribute to economic growth. Computer systems (particularly high performance systems), intelligent complex adaptive systems and sensors have significant potential to contribute to national security.

With the exception of high-definition displays and high-resolution scanning, the U.S. is ahead, or at least at parity, in almost all the fields comprising the Information and Communication technology category. The U.S. invented and widely deployed such technologies as UNIX, the Ethernet, the Internet, LANs, and most of the field of artificial intelligence; U.S.-developed operating systems for personal computers are the world standard; our digital HDTV plans lead the world. The National Display Initiative will help to fill in the gap in high-definition displays, and in most areas where we have some weakness, U.S. firms are forming alliances with other firms in Japan and Europe, leading to multinational initiatives. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 4.1.

Figure 4.1
Information and Communication
Technology Position and 1990-94 Trend

US Technology Position Relative to:
- Japan ▷, ○, or ◁
- Europe ▶, ●, or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Information and Communication					
Components			▷	●	
high-density data storage				▷ ●	
high-definition displays	○		●		
high-resolution scanning (?)		○		●	
Communications				●	◁
data compression				○ ●	
signal conditioning and validation (?)				●	○
telecom/data routing				●	◁
Computer Systems				●	◁
interoperability				●	◁
parallel processing				●	◁
Information Management				▶	▷
data fusion				○ ●	
large-scale information systems			○ ●		
health information systems and services					○ ●
Integrated navigation systems (?)				○ ▶	
Intelligent Complex Adaptive Systems (?)			○	◀	
autonomous robotic devices			○ ●		
artificial intelligence			○	◀	
Sensors			▷ ▶		
physical devices			▷ ●		
integrated signal processing				○ ●	
Software and Toolkits				●	◁

(?) based on limited information

COMPONENTS

Components comprise two general areas of technology. Data storage—the ability to retain information for future retrieval—is at the heart of most computing and networking applications. Peripherals—components of a computer concerned with input and output—that remain critical to future development include displays and scanners.

High-density data storage

High-density data storage comprises three main technologies: random access memory (RAM); high-density magnetic storage and optical storage. (Biomolecular electronics is part of the Living Systems section.) High-density random access memory is contained on semiconducting materials lined with electric transistor circuits making up an integrated circuit. Advances in random access memory are simply the extension of current trends towards more complex integrated circuits for the purpose of supplying more functionality at reduced costs. RAM's relatively simple circuit designs serve as excellent testbed for advanced semiconductor manufacturing technology, as well as for creating and sustaining the information infrastructure.

High-density magnetic storage is characterized by the ability to store information as a pattern of magnetic domains on a thin layer of ferromagnetic material on the surface of a disk or tape. To meet the demands of the computer, the recorded information must have very high density (that is, each bit must occupy a very small area), and reading and writing must be done at very high speed. The highest densities available commercially are 20 megabits per square centimeter for tape and 10 megabits per square centimeter for rigid disks. The theoretical limit to magnetic recording density is very high—about 16 gigabits per square centimeter for media based on iron. However, advances in other technologies such as recording heads are required before engineers can approach these densities. High density magnetic storage is critical to the success of the National Information Infrastructure and the National Electronics Manufacturing Initiative. It also has a significant array of applications in national defense.

Optical storage systems offer high information density per unit area. Compared to magnetic storage systems, optical systems have generally had slower access times, but offer significant advantages over magnetic storage, for example because it offers the prospect of three dimensional storage. Optical storage media also offer significant advantages for military applications particularly those where magnetic storage would be considered a vulnerability or where high temperatures would disable systems. Applications include radar and other detection/targeting systems. Storage in optical form enables writing data to, and reading data from, storage media without physical contact with the media, thus reducing wear and providing opportunities for the use of a number of different media. CD-ROM is becoming increasingly popular for the input of text, images, and data that need only be written once. Optical and magneto-optical storage remain active basic research areas, with research efforts in the U.S., Japan, and Europe in particular.

Parallel disk storage can theoretically occur on any of the storage media currently available or in development, including diamagnetic and paramagnetic materials, ferromagnetic materials, and antiferromagnetic. The challenges to parallel disk storage development come in increasing the density and speed of recording activities. Currently, there is a tremendous challenge in the design of recording heads. Competing technologies are magnetic and magneto-optic technologies, all still in development. In addition, advances in software will need to accompany hardware developments in order to see the full potential of this technology.

Parallel disk storage can have significant benefits to enabling warfighting capabilities. Military applications, including ballistic missile controls and multi-theater troop management, afford considerable challenges for rapid data storage and retrieval. Health applications, particularly biomedical research, often require similar high density, rapid access disk storage capabilities that could benefit from advances in this technology.

Enhanced storage capacity will contribute to job creation in the information sector, and will help improve the competitiveness of the manufacturing sector. It will be critical to improved health and education of the U.S. population. Among other things, improved delivery of health care depends on improved high-density storage as the volume of information about health care treatments continues to grow, and as the need to maintain patient information increases. Patient information will need to be stored in three dimensional images in the future, greatly increasing the need for enhanced data storage and high resolution displays.

Overall, the United States has a slight technology lead in data storage technology including a lead in rigid magnetic disk drives, the largest segment of the $65 billion worldwide computer peripheral equipment market. Producers such as IBM and Fujitsu, building disk units for their own equipment, account for nearly half of total production, with the remainder, the so-called merchant market, supplied primarily by five U.S. vendors—Seagate, Conner Peripherals, Quantum, Maxtor, and Western Digital. Leadership in rigid disk drive technology and fierce price competition have enabled these five U.S. manufacturers to dominate world markets. These firms are clear technology leaders in such advanced magnetic disk storage developments as high-performance magnetoresistive head assemblies and glass substrates. Japanese companies are forming alliances with U.S. firms, exchanging their production knowhow for U.S.-made designs.

Japanese, Korean, European, and U.S. firms are approximately equal in advanced DRAM technology—a significant change from the situation several years ago when Japan appeared in position to use its market share dominance to also attain a strong lead in technology. Leading firms from all regions are now producing 16M DRAMs, have developed 64M devices, and are well along in research on 256M designs. Japanese firms frequently dominate at technical conferences with the latest DRAM technology, but competitors generally have introduced DRAMs to the market at about the same time as the Japanese. The South Koreans, by concentrating government and industry efforts on the DRAM sector, are approaching—and, in the case of Samsung, exceeding—the Japanese in some aspects of DRAM device technology and manufacturing productivity. Some industry experts have rated Samsung's 16M DRAM as the world's most advanced and noted that Samsung also has the most advanced processes for producing them. In addition, Samsung beat the Japanese in moving to eight-inch wafer technology and equipment from the older six-inch technology for the production of its 16M DRAMs. As a result of its strength in device and production technology, Samsung became the first company to produce a million 16M DRAMs per month—a striking contrast to its two and a half year lag behind the Japanese leaders in reaching production of a million 256K DRAMs per month in the mid-1980s. The challenges of developing technology for future DRAMs and the billion dollar costs of fabrication facilities are forcing most firms into international research and production alliances. These alliances are resulting in a transfer and sharing of technology, which should keep DRAM technology roughly equal in all major geographic regions. Hitachi and Texas Instruments are cooperating on 64M DRAM R&D; IBM, Germany's Siemens, and Toshiba on 64M DRAMs and 256M DRAMs; Hitachi and South Korea's Goldstar on 16M DRAMs; and South Korea's Samsung and Japan's NEC on 256M DRAMs.

High-definition displays

"High-definition displays" is the term applied to a range of technologies that provide simultaneous presentation of high-resolution images, full color depth, and smooth motion to take full advantage of the capabilities of the human eye. Many promising alternatives are emerging for display technology. Color liquid-crystal displays with diagonal sizes greater than 25 centimeters are currently in production. Emerging flat panel displays that will be superior in resolution and weight to cathode ray tubes are being researched. Plasma displays which use photoluminescent phosphors that are excited by an ultraviolet gas discharge offer significant possibilities for application in the near term. Researchers are also exploring the possibilities of full color, active matrix liquid crystal display for portable computers. Another promising technology is liquid crystal based on ferroelectric materials. These materials allow displays to have a wider viewing angle.

Warfare in the future will become increasingly dependent on these technologies. In particular, flat-panel displays will be widely used to update outmoded technologies. For example, much of the sensor and imaging information used on military transports is presented in a fashion that is extremely complex. Flat-panel displays will provide the capability to integrate these complex interfaces into simple, large screens. Flat-panel displays are also far more reliable than the current CRTs, consume less power, and are much lighter and compact. All of these factors translate into a large cost savings to the maintenance of military systems requiring displays. Advanced display systems will be used in fighter planes, helicopters, and by individual soldiers carrying personal digital systems.

High-definition displays also promise to have many applications in the commercial world ranging from medical imaging, to computers, to avionics displays in commercial aircraft, to high definition television (HDTV). High-resolution displays are critical to meeting the President's goals for the interface between the Next Generation Vehicle with the Intelligent Vehicle Highway System. Success in manufacturing an efficient and cost-competitive display could create a large number of new jobs in both the display industry and in spill-over sectors including other high-volume electronic manufacturing.

Japan has used its dominant market position to acquire a substantial technology lead over U.S. firms in manufacturing of flat panel displays (FPDs). The primary computer application of FPDs is currently the notebook computer, but most industry experts believe FPDs will capture a portion of the desktop workstation market as production technology improves. Japanese firms dominate the FPD market with 90 percent of the $4.5 billion in 1993, and 95 percent of the $2.2 billion market for active matrix liquid crystal displays (AMLCDs)—the most advanced FPD currently available for computer applications. U.S. and European firms are minor players in both markets. The technology strengths of Japanese companies are primarily in production know-how gained through experience in high-volume manufacturing and these strengths are formidable. Japanese firms were the first to commit to full scale manufacturing of AMLCDs in the 8-10 inch sizes needed for notebook computer applications. Since 1991, these firms have improved yields from 5 percent to nearly 80 percent, as production rates increased from pilot levels to 100,000 per month at some facilities. The top producer and technology leader, Sharp, demonstrated a number of advanced prototypes in 1993, and is constructing an advanced large-scale production facility.

In recent years U.S. firms have made substantial advances in manufacturing equipment and process technology, in part, through R&D sponsored by the Advanced Research Projects Agency. For example, U.S. strengths in next generation photolithographic steppers for AMLCDs, excimer laser annealing equipment, advanced chemical vapor deposition machines, and in-line inspection, test, and repair technology are narrowing the AMLCD technology gap with Japan. If firms in the United States pursue large scale AMLCD production either independently or through the National Display Initiative, they will probably achieve technological parity with Japan by the turn of the century. European firms are currently at technological parity with U.S. firms, but have a limited degree of production experience. They also significantly lag U.S.

capabilities in next generation production equipment and are therefore likely to continue to lag.

High-resolution scanning technologies

Laser scanning is an emerging application in high-resolution scanning technology. Laser scanners are capable of digitizing virtually any black and white or color image into a format that is readily archived and processed by image processing/enhancement techniques. Work in this area eliminates film and the associated processing chemicals, substituting an appropriate detector and digitizing chain.

While it has significant potential for both commercial and military applications, laser scanner technology is at least five years from having a significant impact in the marketplace because of problems with software. High-resolution scanning technology would have a direct and highly significant impact on the ability of health care workers to process medical information.

Japanese government and industry researchers have long been interested in image processing technology, in large part because of requirements for working with the Japanese language. In addition, Japanese firms have leading-edge capability in optoelectronics and other technologies related to scanning. As a result, Japan has a slight lead over the United States in advanced laser scanning image processing techniques. NEC, one of the leading Japanese firms in this area, is pursuing medical and other applications.

COMMUNICATIONS

In communications, global access to increasing amounts of information, as exemplified by the World Wide Web on the Internet, will contribute to the increasingly rapid diffusion of knowledge to more and more people. Network-based finance and commerce are giving users a decided competitive advantage in an increasingly global marketplace. Advances in the ability to provide networked services will contribute particularly to the goal of harnessing information technology for economic growth, but the potential of networking as a tool for competitiveness, security, and education is nearly endless.

Data compression

Current compression technology falls into four categories: data (numerous techniques), audio (ADPCM), image (JPEG), and motion video (MPEG). Virtually any time that information is transmitted, or stored, there is an opportunity to pack it into a more efficient format than the one which was used for presentation or application. The cost of bandwidth, power, memory or storage media, and the competition for them, require that they be treated as a valuable resources.

For example, one key to high definition TV (HDTV) ability to sending twice as many lines of video per image frame and, correspondingly, twice as many pixels per line (four times as many pixels per image), is compression. The United States is finalizing its own unique HDTV standards in order to suppress foreign competition, domestically. However, recent mathematical breakthroughs in wavelet theory, which is more compactly supportable than the JPEG cosine transform, indicate that we can achieve far greater compression ratios, depending on the application. MPEG2 is likely to become the U.S. HDTV standard.

Data compression is essential to harnessing information technology since it enables the enormous data flows involved. It also supports other national goals, such as enabling advances in health care and education technologies and allowing U.S. companies to create communication and video equipment which is competitive in world markets.

Data compression has extensive applications for national security and warfighting. The enormous volume of imagery required for our advanced strategic and tactical planning requires that the imagery be appropriately compressed at each transmission. The initial transmissions from the sensor must be lossless, to facilitate photo-interpreter processing and annotating. Conversely, the imagery provided to those carrying out the mission, e.g., gunners, can withstand significant lossy compression without reducing its utility as long as they know what target they are looking at and where that target is located.

The United States has a slight lead over Japan and Europe in data compression components and algorithms. The U.S. lead is evident from such original work as a high-definition television digital compression standard that leap-frogged heavily funded foreign efforts to develop analog HDTV systems. The international research community in this area is very tightly connected (especially in academia) so that progress is very quickly shared, resulting in a short time between original result and its use by other organizations. China and Russia generally lag the U.S. by several years, although some outstanding theoretical work has been done in Russia.

Signal conditioning and validation

Virtually every signal, analog or digital, is acted upon by its environment—the signal is contaminated to some degree, and that contamination can have major impacts. Signal conditioning is the application of technology prior to, during, and after the exposure of a signal to its environment. In the analog domain, signal conditioning includes output line drivers that impress far more power on the pristine signal than can be countered by a noisy environment. Input line receivers are matched to the line which conducts the signal from its source. They perform the matching operation which minimizes distortion and optimizes coupling with successive circuits. In the digital domain, signal conditioning includes adding error detection codes to signals which are about to be sent through a contaminating medium. Decoding circuits, at the receiver, determine if specific portions of the signal have been changed. Damaged data are usually discarded and re-requested. Error correcting codes add more overhead at both the transmitter and receiver, but they enable the reconstruction of the damaged data. Additionally, an entire field of reconstruction, compensation, enhancement, etc., exists whereby contaminated data can be made more usable.

The primary contribution of signal conditioning and validation is to harnessing information technology. Electronic transactions of all kinds, including banking, stock and bond trading, medical diagnoses, distributed integrated simulation, require some appropriate form of conditioning, depending on the required fidelity of the data. Crashes on the information superhighway would result in bad decisions, wrong answers, incorrect numerical data, incorrect names, and destinations.

The errors in the national security domain could result in similar "crashes," but these would carry a much higher cost: casualties, materiel, infrastructure. This is why signal conditioning is very important for national security and warfighting. In general, military doctrine overlays a set of checks and balances because of the great potential losses involved. Digitization of the battlefield, increased use of imagery and data, routing via commercial space, etc., all put a greater emphasis on signal conditioning to suppress erroneous information from being applied to key decisions.

The United States is on a par with Europe and Japan in signal conditioning and validation technologies. The literature and codes are open to the market in general. Virtually every chip, manufactured anywhere, has embedded conditioning circuits which enable it to interface with the other chips on the circuit board. Therefore, other countries are able to follow the example of the leaders, and compete by virtue of their cost-effective production capabilities. With the proliferation of electronics, these essential capabilities have become rather commonplace geographically.

Telecommunications and data routing

The function of routing data using telecommunications involves a number of technologies and applications. The first three applications—long-haul terrestrial, subscriber loop, and undersea transmission—are generally associated with telephone services. Two others—local-area network and metropolitan area network—are generally associated with computer services. The differences between these applications is blurring, however, in the face of intense worldwide efforts to achieve interoperability (compatible operation) across diverse network architectures and diverse hardware implementations of networking equipment. Network transmission technologies include signal carriers such as conducted electronic signals and radio frequency waves, and transmission media such as twisted pair wires, coax, free-space, and optical fibers. In the past, most of this information used analog techniques. Digital techniques are being employed increasingly in almost all new network systems, placing significant challenges to the applications and technologies of communication routing.

There are active research programs in the U.S. and overseas providing the framework for the higher-speed networking services that will be needed as demand grows. There is a robust industry providing the necessary infrastructure, both for local and wide-area services. There are concerns about the structure of the protocols that will be needed for higher-speed networking, but the international standards community is actively studying this area. There is increasing use of digital (as opposed to analog) circuitry for networking, with fiber optics the dominant technology for exploiting this. Wireless networking is also a very active developmental area at the present time. Regulatory issues (such as the allocation of channels) are often as important in this area as the technical issues.

Networking is most important for harnessing information technology which will, in turn, enable the nation to realize various other goals. It will enable the sharing of vast amounts of information and advanced software available for improved health care and education; it will enable efficient use of computer-aided design and manufacturing techniques for greater competitiveness and productivity; and it will allow the strategic and tactical decision-makers to get military information in a timely manner, which will increase U.S. national security and improve warfighting capabilities.

Europe and Japan both lag slightly behind the United States in switching and transmission technology for public telecommunications networks. Two technologies for broadband networks are having a revolutionary impact on switching and transmission—asynchronous transfer mode (ATM) switching and new high-speed transmission systems called synchronous optical networks (SONET) in the United States and synchronous digital hierarchy (SDH) in Europe. These technologies are blurring lines between switching and transmission, hardware and software, private and public networks, and telecommunications and computer technology.

AT&T was the first to develop ATM technology and the United States remains the technology leader, with a number of trials underway and some commercial ATM services already available. The U.S. ATM lead is underscored by strong capabilities in ATM semiconductors and technology leadership in network operational support systems. European firms are slightly behind but ATM technology has been a major focus of research conducted under the European RACE program. An ATM trial involving 18 operators in 15 countries is giving European firms valuable test data with which to improve their capabilities. Although AT&T and Canada's Northern Telecom are participating, European vendors are the main suppliers and could catch up as they build on their experience and their huge installed base worldwide. European vendors rely on

U.S. software developers for some important network operating systems, however.

Japanese ATM capabilities also lag slightly, despite some notable achievements. Fujitsu was the first to introduce a commercial ATM switch, followed shortly thereafter by NEC; Fujitsu has a contract with a U.S. operator for volume sales of its ATM switch. NTT has committed considerable R&D effort to ATM technology for its proposed broadband network and has begun limited deployment of ATM switches. These early achievements in the emerging U.S. ATM public switch market are in sharp contrast to Japanese failure in the U.S. market for the current generation of digital switches. However, as stronger switching manufacturers introduce more capable ATM switches, limitations of the Japanese switches—particularly in software—are more apparent. Future Japanese technology improvements are expected to lag the already stronger U.S. and European ATM leaders. Japan's technology position could continue to improve, however, as both Fujitsu and NEC have moved production of ATM switches to U.S. facilities, and are improving software capabilities through active participation in U.S. standards organizations, and cooperation with U.S. software firms.

Foreign firms now are only slightly behind the United States in longhaul transmission technology, with some research equal to the best U.S. efforts. The United States, by 1985, had the first standardization effort for synchronous digital transmission system technology; but by the following year, Europe's CCITT began work on a competing standards which is now called SDH. Many of the key conflicts between the two standards were resolved in 1988, resulting in a surge of interest by both equipment manufacturers and public telephone operators. Japanese and European firms now produce equipment with features and speeds similar to U.S. manufactured equipment. AT&T's long distance division has even bought some Alcatel SDH digital cross-connects in preference to equipment made by AT&T's Network Systems. United States firms retain a slight lead because European manufacturers often rely on U.S. sources for some critical components such as microprocessor designs, optoelectronic devices and system software. Because differences in SDH/SONET technology are only slight, sales are often determined by availability, price, and added features.

U.S. firms have a slight lead in subscriber loop technologies such as digital loop carriers, fiber-to-the-curb, and asymmetric digital subscriber line technologies. Japanese companies continue to have a price advantage in component manufacturing, however; and European firms are improving their subscriber technologies as a result of several RACE sponsored programs and the financial incentives provided by Germany's massive infusion of fiber optics into its eastern states.

Foreign firms could face difficulties in the transmission arena as software becomes an increasingly important determinant of technological leadership. U.S.

firms have taken the lead in developing highly efficient operating and network management software for networks with gigabit per second data streams, control software for integrating equipment from different vendors, and complex routing algorithms to handle system failures in bi-directional rings. Foreign firms are gaining access to some U.S. software expertise to offset weakness; Fujitsu and Alcatel currently base their SONET network management systems on U.S. software.

Foreign firms trail in mobile data such as cellular digital packet data and other wireless systems. U.S. developed CDMA technology, proposed for both cellular and satellite-based systems, may have advantages over the European alternative for data. The United States was also the first to develop wireless LANs, including radio-frequency and infrared systems. Europe lags slightly in mobile data and is close to parity in wireless PBXs and wireless LANS.

The United States is far ahead of Japan and Europe in local area network (LAN) technologies, which include PC LAN network interface cards or adapters, network operating systems, intelligent wiring hubs, and internetworking devices such as bridges and routers. European vendors have some strengths in systems integration to the end user—which is gaining in importance as LAN interconnect becomes a larger market. Japan has a clear lag in LAN technology. In addition to the more limited use of PCs and lack of connectivity, Japanese manufacturers underestimated the early user demand allowing foreign manufacturers the opportunity to position themselves strongly as the leading providers of these technologies to Japanese end users. Firms in the United States are introducing new technologies so rapidly that Japanese firms cannot keep up. European companies, Canada's Newbridge, and several U.S. firms are at overall technological parity in wide area network (WAN) technologies, which include high-speed transmission lines (up to 1.544 Mbits/s), multiplexers to combine independent data streams, packet switching, and modems. Japanese firms lag significantly in WAN technology, in large part because of limited consumer demand for public data communications services. Most observers believe that demand growth has been slowed by the Japanese telecommunications regulatory environment. In general, rapidly evolving markets are best served by firms that are in very close communication with customer requirements—thus, it is difficult to develop technology leads using an export-led strategy.

COMPUTER SYSTEMS

Computer systems are now pervasive. The most critical class of these is the high-performance computing systems, which by definition are the most powerful computing capabilities available at any given time. High-performance computing is the enabling technology for many important commercial and defense-related activities, particularly the management, simulation and design of complex systems and processes. Advanced aircraft and spacecraft design, for example, use computer simulation rather than physical models, for hardware development. The challenges being addressed by the High Performance Computing and Communications Initiative, such as weather prediction and the human genome project, require the most powerful computers possible. Defense use of high-performance computers for weapon design and intelligence analysis continues to give the U.S. a considerable advantage over potential adversaries.

Interoperability

A number of problems arise when computer systems must be made to interoperate with each other. The problem is particularly acute for large-scale integrated systems. Given the custom nature of such systems, open standards have rarely been used in the past for their data management tasks, even where such standards existed. As a result, it is a monumental task to interconnect such systems, as the defense modeling and simulation community has discovered.

The majority of data exchange standards as well as product data exchange mechanisms in widespread use today in the computer industry did not evolve through the coordinated efforts of international standard setting bodies. Instead, most of these standards started as vendor-specific specifications that eventually became widespread *de facto* standards due to the strong market success of particular products. In many cases, vendors, of these products seeking to capitalize on the economic advantages of owning an industry *de facto* standard, made their particular specifications widely available, primarily though licensing agreements. Usually, only after a *de facto* standard has been absorbed throughout the industry, do standard making bodies attempt to define and control such a standard.

Because of the importance of interoperability to military systems, the Defense Modeling and Simulation Office (DMSO), has invested significantly during the past few years to develop appropriate standards. The continuation of such standardization efforts is a critical requirement for the foreseeable future. It is also increasingly important in commercial systems as larger and larger computer systems are used for design, manufacturing, and education.

The bulk of *de facto* standards in widespread use throughout the commercial computer industry were defined by U.S. computer makers. For example, one of the most standardized operating systems, Unix, which includes a rich set of hardware-independent data transfer protocols, was initially developed and widely licensed by the U.S. vendor, AT&T. In another case, the standard operating system, DOS, and later Windows, provided a widespread common hardware independent software platform on which a number of applications software vendors base their products. This process enabled vendors of different systems to communicate easily using the operating system's communications facilities as a common language.

Both Europe and Japan have lagged the U.S. in developing their own standards in this area. Neither Japan nor Europe has the worldwide market presence needed to establish a *de facto* standard. Japanese and European computer makers are still primarily limited to serving their domestic markets and lack strong capabilities to successfully market products internationally. For its part, Japan has concentrated on protecting its company-specific proprietary hardware and software base and has for the most part avoided interoperability issues until only recently. In Europe, most vendors have struggled towards standardized products, but they have been frustrated by a lack of a unified customer base. More so than their U.S. counterparts, European firms face wide-ranging and often divergent user requirements that cut across customer segments, such as the financial industry, manufacturing, government, as well as those that cut across country boundaries. Both Japanese and European firms recognize their lag in this area. Closing the gap will be difficult as the ability to establish standards arises not from any specific technology capability, but more as an offshoot of being a major, or at least significant, international supplier in a particular market sector. That requirement has eluded suppliers from both these regions in the past and will continue to be a formidable barrier.

Parallel processing

Parallel processing is the capability to simultaneously conduct a large number of computing functions offering significant advantages in terms of speed and capacity. There are now several companies marketing so-called massively parallel processors (MPP), consisting of from tens to thousands of individual processors and memories interconnected by a variety of methods within the same machine. Successful exploitation of particular multiple processor architectures such as systolic arrays and hypercubes remains a real challenge to the U.S. research community. In addition to technical difficulties with memory capacity, another difficulty facing the MPP field is the lack of appropriate software. These systems are still very difficult to program efficiently, in spite of considerable research investment in the relevant software over the past decade or more. This lack may limit the use of such machines to a small (but important) niche market. Even so, massively parallel processing offers considerable promise, and research into this area continues to flourish both in universities and commercial companies.

Among the specific parallel processing computing technologies, the one that has drawn the most interest over the past few years has been the so-called MIMD (for multiple instruction, multiple data stream) machines. These consist of from tens to thousands of individual processors and memories interconnected by a variety of methods within the same machine. Many startup companies, often with federal government support, have been formed to exploit this technology. This technology has the advantage over the traditional vector supercomputer in that it is cheaper to build, and scales more easily to larger capacity. In particular, there is a consensus that this is the only technology with the potential to reach teraflop speeds (a million million floating point instructions per second) in the foreseeable future.

Massively parallel computing has direct applications in national defense warfighting and weapons control, war gaming, in the Partnership for the Next Generation Vehicle, and the Global Climate Change and Human Genome research programs. While commercial applications are further off than research applications, parallel processing can have a secondary impact on the capabilities of U.S. science and engineering to maintain world class status.

The U.S. has a technology lead in nearly all aspects of high-performance computers. Japanese computer firms continue to lag their U.S. counterparts in parallel computer technology and are facing mixed prospects. Japanese computer firms—primarily Fujitsu, NEC, and Hitachi—possess strong capabilities in some key supporting technologies. These firms have, for example, outstanding semiconductor component and circuit interconnection capabilities that could give them a distinct advantage over many of their U.S. counterparts in the hardware area. Japanese capabilities in components and board-level interconnection designs give them tremendous freedom to design innovative architectures. However, Japanese firms must overcome some tough technical hurdles before they can develop commercially successful parallel computer systems. Their most important task will be to close the large gap that exists with leading U.S. firms in parallel operating systems and applications software. Because the capabilities of a parallel system are largely determined by the capabilities of the systems software, any serious attempts by the Japanese to challenge U.S. dominance in parallel computers will require significant improvements in the software area.

The United States and Europe have pursued parallel computing through increasing integration of processors, whereas Japanese efforts have emphasized peak vector processor performance. As a consequence of this difference in strategy, Japan has not produced massively parallel machines on a par with those in the United States. While Japanese multi-processor computers have a much higher theoretical peak performance than do their U.S. or European counterparts, U.S. systems can generally sustain higher performance for important applications. Most Japanese development projects started out emphasizing hardware systems tailored to specialized uses—such as image processing and simulation—but are now moving to more general applications in order to respond to market requirements.

Europe also generally lags the United States in parallel processing computer technology. Individual European countries have the necessary R&D talent, but lack the capability to build a marketable product in a timely fashion. Despite the aid of numerous government programs to develop computational hardware technology, European firms remain far behind companies in the United States and Japan. Although there are many organizations within academia, government as well as in the private sector conducting high-quality research in this area, most of these efforts will never move beyond the research stage. Many European governments recognize parallel processing as a critical technology for the next generation of high performance computers, and have initiated a number of research programs to address Europe's shortcomings. Many of these programs are highly speculative in nature and likely will not result in any significant technology or competitive advantage.

INFORMATION MANAGEMENT

The ability to control and manage the increasing amounts of information available to us today remains a major technological challenge. The elements of this that are particularly critical are: data fusion, i.e., the ability to integrate data from a variety of different sources into a meaningful form; the design and manufacture of increasingly more complicated information systems to manipulate and analyze the available information; health information systems and services, and integrated navigation systems that increasingly control more and more of the nation's transportation system.

Data fusion

Data fusion involves forming useful relationships between data from different sources to provide salient information which is more readily assimilated. Examples of data fusion are:

- Sensor fusion: where an image is synthesized which combines the key information from disparate sensors, such as infrared and radar. In this case key information would be emphasizing objects which have both the desired thermal and range (or scatterer) characteristics.

- Visualization: where complicated relationships between otherwise abstract or multi-dimensional variables are displayed in some metaphor space. For instance, a three-dimensional space could be constructed which clarifies the "volume" of acceptable combinations of output, cost, time, and risk.

On one hand the information age imposes a certain degree of information overload, and on the other hand it can provide the filters, "digesters," and human interfaces, both to highlight key relationships and to suppress extraneous data. These have direct application to economic optimization by decision-makers and their staffs, and by organizations which provide input to decision-makers. Alternatively they provide the tools for modeling and synthesizing new products, such as pharmaceuticals, exotic materials, lower cost common materials. Therefore, data fusion is an important part of harnessing information technology, and to obtaining better information for other endeavors.

There is also important applicability of data fusion to national security and warfighting. Highlighting key relationships, and simultaneously suppressing extraneous data can have direct application to tactical and strategic decisions made by commanders. They would have presented to them a digitized battlefield, plus its companion decision support system. This real-time data concerning locations of friendly and enemy forces, casualties, resource expenditures (such as ammunition, fuel, food, water, etc.) can be presented in a manner which is customized for the particular style of each commander who receives it. Other key applications are in reducing casualties and in force multiplication. Automatic Target Recognizers, Pilot's Associate, and other automated aids help to both reduce the vulnerability, and increase the lethality of our numerically limited forces.

The United States is probably at the forefront of this immature field. Japan is next, with Europe close behind. Because of its history of leadership in super-computing, remote sensing, and movie making, the U.S. has the most experience in operating on complex data to put it into a useful form, be it displaying turbulent flow, multispectral satellite imagery, or complex, imaginary worlds on the silver screen. The new NASA EOSDIS (Earth Observation Satellite Distributed Implementation System) will be the biggest user of data fusion in the world. However, discriminating salient information from a morass of multi-dimensional data, and then operating on it to produce cognitively transparent relationships is a challenge. The understanding of how to do this will likely evolve in response to a parallel evolution in algorithm development, new interfaces such as virtual realities, as well as an improved understanding of the cognitive process, itself.

Large-scale information systems

Large-scale information systems contain millions of lines of code, usually distributed over many computers and geographic sites. Price tags for such systems in the tens to hundreds of millions of dollars are not uncommon. They are needed for a variety of complex tasks upon which the U.S. economy is based, such as airline ticket reservations systems; the Federal Aviation Agency's (FAA) flight control systems; national and international banking networks exchanging billions of dollars of transactions per day; control software for nuclear power plants, and thousands of other such applications. These systems tend to be produced in small quantities, ranging from only one to tens of copies. In each case, the system is customized. Their development is routinely plagued by cost and schedule overruns, and not infrequently the abandonment of entire multi-million-dollar development projects (e.g., the recent California Department of Motor Vehicles attempt at integrating driver's license records with vehicle registrations).

Such systems are vital to the U.S. economy, since they are the basis of critical systems upon which many of our transactions depend. These large-scale systems are also needed to operate and control U.S. defense logistics, command and control, intelligence gathering and dissemination, and a variety of other military operations. The ability to create these systems effectively, and to meet schedule and cost goals, is critical to their future development.

Large-scale systems tend to have a strong dual-use potential. For example, a system for Olympics-level sporting competition management would require the integration of high-speed, redundant, computers, local area networks, large-scale graphics displays, communications protocols, database management techniques, and so on. The same capabilities would be required in a system used for military logistics.

Both Japan and Europe lag the United States in the underlying software technology needed to design and build large-scale information systems. In database software, Japanese dependency on custom software has retarded development of Japanese database software because such development has proven to be too expensive for single-client products that comprise the bulk of Japanese software development. The larger Japanese computer firms have traditionally concentrated their development activities on mainframe platforms and have poor programming skills for PC and distributed computing platforms that comprise the basis for distributed information applications. In network software, for example, Japan's slower development of the PC market forced Japanese users to rely on foreign networked products in the Japanese market. As a result, Japanese firms are attempting to catch up primarily by forming alliances with leading U.S. network software firms. In network software, European users have developed capabilities for interconnection software for their systems. Most of the firms supplying products however, look to U.S. counterparts to define the technology, and implement the first products.

Health information systems and services

Integrated health information systems will be at the heart of the decision support systems needed to enable physicians, payers, and patients to choose among an array of evolving alternatives. Integrated health information systems will also be essential to the decision support systems needed to enable community, state, and national public health officials to detect emerging health threats and to allocate resources among competing public health problems that affect the populations as they age. To capitalize on the natural experiments occurring in health care settings and to identify and evaluate potential cost-effective alternatives for improving the personal and public health care systems is an on-going challenge. Clinical decision making must be improved, and this could be done by computer-aided diagnostic systems enabling efficient selection by physicians and patients among an increasingly complex range of alternatives in diagnosis and treatments. Improved outcome data on comparable and competitive approaches will provide the basis for informed patient management and the evaluation of alternative services structures. While many isolated systems have been developed and demonstrated in well-bounded settings, the availability of an integrated system of information on clinical practice, patient management and outcomes is still on the far horizon. Because most data bases are administrative in nature, few contain any meaningful clinical or outcome information; and because of the nature of our health insurance system, they do not contain population-based or longitudinal data. Emphasis must be placed on linking the ultimate outcome and health status changes for many patients over time with data regarding the specific preventive/clinical intervention/treatment as well as effects of financing structures, organization, demographics, procedures, guidelines, and care processes. Cost-effective public health surveillance requires the ability to link aggregate data obtained from the personal care system to regional, state, and local data on environmental pollution, occupational hazards, disease vectors, etc.

Such work is dependent upon development of data systems, agreement on standardized data elements to be collected for computer-based patient records, and administrative data files as well as consumer surveys. A major focus of activity also needs to be the linkage of existing personal care and public health data systems and incorporation of meaningful clinical and outcomes data (measures and reporting formats) that can be electronically exchanged. The results should improve the ability of physicians to stay abreast of state-of-the-art treatments and outcomes in specific circumstances, and enable patients to take a more actively informed role in their own health care. The broader acceptance of telemedicine and the emergence of virtual medical groups may enable more fully informed decisions to be made in remote clinics or community hospitals. These systems would also provide increased national security by allowing the military to minimize battlefield casualties by facilitating out-of-theater support for limited forward medical teams.

The U.S. has developed a broad technology base at the sub-systems level in both hardware and software, but has not yet been able to benefit from the synergy of decision support systems, networking and communications, and large scale data storage and retrieval capabilities. The development of standards for data exchange is in progress to provide commonality of definitions, messaging and data formats which will be necessary to link large, presently independent systems. As part of the High Performance Computer Consortium (HPCC) program, health care related systems include testbed networks and collaborative applications to link remote and urban patients and providers to the information they need. This includes database technologies to collect and share patient health records in secure, privacy assured environments, advanced biomedical devices and sensors, and the system architectures to build and maintain the complex health information network. Virtual reality technology is being used to simulate operations for medical training, and combined with teleoperator technology for remote surgical procedures. Graphic image reconstruction software and visualization techniques are being combined with high resolution serial sections and CT and MRI imagery to development a virtual atlas of human anatomy for training and education.

Yet, the history of further development into commercial products with multi-institutional adoption has not been encouraging, encountering a host of non-technical barriers which have not been related to the system's ability to improve patient management and outcomes, reduce length of stay and related health care costs. The barriers include physician resistance, cultural differences, and conflicts between societal values. Confidentiality, privacy, and security issues may be an on-going challenge to systems implementors because a patient's right to privacy has been defined by the U.S. Court of Appeals as a constitutional right which is more compelling than "just" a statutory right, and administrative convenience was not deemed to be a defense against compromising patient privacy. To truly benefit from the capabilities of integrated health care information systems, these systems will have to bridge a multiplicity of medical institutions, third party payer reporting requirements, and even widely varying public health reporting requirements on a state by state basis. Telemedicine and the inter-state transfer of medical decision support software have already met regulatory challenges that demonstrate that 60-year-old policies need to be revised.

The breadth of the U.S. AI/knowledge based support systems, often developed at universities with close working relationships to major medical research centers, has led to the U.S. having an unsurpassed base of experienced researchers and demonstration projects. Networking and communications infrastructure will play a significant role in wide-spread application, again an area benefiting from U.S. leadership. European interest in Medical Informatics has also been strong for over 20 years, with a history of involvement with AI/decision support research. While the Japanese have shown a strong interest in quantitative medicine and the application of their biosensor technologies, they have not had the extensive development of AI/decision support systems, and have been further limited by user interface, networking and institutional issues. Universal solutions are unlikely as an integrated system must encompass patient and physician education, medical diagnosis and patient management, third party payers and national public health data acquisition needs while complying with individual privacy rights. Implementation will be incremental, modules will be developed, certified and integrated locally and regionally; while there will be strong economic incentives for commonality, cultural differences will play an enormous role in actual utilization.

Integrated navigation systems

Navigation systems are good examples of large-scale integrated systems. Each commercial airliner and large seagoing vessel includes a system for this purpose. Many such systems are customized for the particular vessel. In other words, although the individual components may be similar, the whole system is one-of-a-kind. Land-based systems for the command and control of inland waterways are another example.

The greatest change in the past few years in this area has been the increasing use of the global positioning system (GPS) for navigation. By now, even the smallest seagoing vessels rely on a GPS receiver for this purpose, as do increasing numbers of airplanes. GPS use is projected to bring about major changes in the commercial air traffic control system in the next few years, which will require redesign of most of the airline and FAA navigational systems now in use.

Given the specialized nature and the large scale of the systems required for integrated navigation, there are a limited number of enterprises that produce them. Although there are more such enterprises in the U.S. than elsewhere, bidding in this area is very competitive, and organizations in both Japan and Europe have been equally successful in competitions against U.S. firms. For example, Mitsui in Japan has been successfully building maritime navigation systems for many years, and Siemens in Germany has built major control systems for a variety of applications.

INTELLIGENT COMPLEX ADAPTIVE SYSTEMS

One of the most critical challenges facing the information and communications community is the ability to include "intelligence" in the systems needed to manage many of the more onerous and difficult tasks, particularly those that involve hazardous materials or situations.

Autonomous robotic devices

Robotics, in its full meaning, refers to an autonomous system, capable of responding to much greater uncertainty in its environment than the flexible manufacturing systems currently in use. As robots become more autonomous, it becomes possible to substitute them for people in particularly hazardous situations such as fire fighting, mine removal, processing of hazardous materials and in space.

The competitiveness of U.S. industry depends critically on the increasing automation of many of its manufacturing processes in order to reduce labor costs. For such devices to be most effective, they must also be very flexible so that they can be easily reprogrammed for another task. The importance of such development has been recognized by NIST in their support of automated manufacturing systems. Machine tool companies, particularly those in Japan and Germany, are also making considerable investments in robotic devices for manufacturing. Automobile companies such as Mercedes Benz have announced research programs in autonomous on-road vehicles.

Autonomous robotic device technology contributes to job creation and economic growth in many ways. It is an important part of future automated factories which will include autonomous robots, as well as currently available robotic machine tools. It also allows greater automation of building and construction, especially in dangerous situations. Development of robotics also contributes to harnessing information technology by stimulating research into software algorithms for combining theoretical part dimensions with material characteristics, sensor outputs, and information about motion in space.

There are important applications of robotics in improving national security. It contributes to the improvement of the defense manufacturing base in the same ways as it contributes to the civilian manufacturing base. In addition, robots have the potential to significantly improve U.S. warfighting capabilities and reduce casualties. They can safely remove mines, handle and dispose of hazardous materials, and perform construction under fire. They can also provide real-time reconnaissance information and target spotting without exposing humans to danger.

Europe, Japan, and the United States are at rough parity in robotics technology in terms of repeatability, accuracy, mobility, and speed of motion; but have strengths in different technology areas. For example, Europeans have what some industry experts believe are the best vision systems recognition algorithms, Japan is generally strong in robotics hardware such as manipulator and servomotor technology, and the United States excels in systems integration, robot control, sensors, and vision software. Despite the overall technology parity enjoyed by the United States, the world market for robots is dominated by European and Japanese firms. The current world leader is Asea Brown Boveri followed closely by the Japanese firms Fanuc, Yaskawa, Matsushita, and Kawasaki. Japanese firms are far ahead of the rest of the world in the number of industrial robots installed but most of these are low- or medium-technology products. Japanese market success has been based on high-volume, less sophisticated robots while European firms have been more successful in advanced robots.

Artificial intelligence

The aim of the discipline of artificial intelligence (AI) is to permit computers to act in such a manner that, if a human acted similarly, his or her actions would be considered intelligent behavior. It embraces such fields as voice recognition; pattern and image recognition; "expert systems" containing numerous rules of behavior that act according to those rules; control of robots and similar devices; game playing; neural nets and genetic algorithms that learn patterns of behavior from examples, feedback and (in the case of genetic algorithms) mutation to produce new solution strategies or possibilities.

The definition of AI is constantly evolving. Computer behavior that used to appear intelligent, once understood and more commonplace, tends to become regarded as merely programming; examples include list processing and logic systems capable of deduction. Therefore, in practice, AI is often regarded (at least by its aficionados) as the cutting edge of computer science, where programming of computer behaviors is attempted that has not been done before, or whose logic and structure are as yet poorly understood.

Artificial intelligence is important to U.S. economic goals precisely because it embodies much of advanced computer science—pushing the limits of what computers are capable of. Within AI, novel programming and computer architecture techniques are discovered that, in turn, can lead to export and patent advantages. (As recognition of this, Japan has embarked on a variety of advanced computing initiatives, such as the "Fifth Generation" program that had very explicit artificial intelligence-related goals and aspirations.)

AI is vital to U.S. security interests because computer-based intelligence is needed to process the huge volumes of satellite photography and other signals intelligence, looking "intelligently" for patterns of interest within vast signals databases. Advanced pattern recognition and interpretation is also vital to the smart weapons that can provide pinpoint accuracy and thus save the lives, sorties, and munitions required to deliver "dumber" weapons.

A study of knowledge-based systems (KBS) in Japan, sponsored by ARPA and NSF and published in May, 1993, concluded that the U.S. was ahead or about even with Japan in about the same number of areas as the number of areas in which the U.S. was lagging. The areas of knowledge-based research and application in which Japan was ahead of the U.S., and with a trend that was level or gaining, were:

- quantity and quality of fuzzy logic systems initiatives
- quality of parallel symbolic computation initiatives
- quality of applied R&D in advanced KBS research in industry
- the support structure for applications of expert systems (ES)
- applications of ES in consumer products
- integration of ES with other software

The Japanese are strongest in applying fuzzy logic concepts to consumer products and control systems (e.g., for railroads, elevators). This assessment still represents the current relative state of development.

European AI research at several top institutions (University of Edinburgh, the Turing Institute in Glasgow) is comparable to that at top U.S. institutions, but does not appear to be ahead of the U.S. in any area, and in Europe as a whole it has less depth and breadth than within the U.S.

SENSORS

Sensor systems record and disseminate information about their immediate environment. Sensors are important components in information systems because they provide input data that, depending on the circumstances, can be used for either imaging or non-imaging applications. Beyond this support role, certain sensors also could have exciting roles in the very mechanisms by which computation and storage processes are performed. When the transducers are combined with processing circuits and actuators, microelectro-mechanical systems (MEMS) can be created that, in addition to providing detection and identification of a wide range of phenomena, can create control devices to respond to these observed phenomena. The field of microsensors is related to transducers and actuators, such as found in MEMS production.

Physical devices

Sensors can be divided into categories in different ways. One common distinction is between active and passive sensors, i.e., between sensors which send out a signal and react to the response (like radar) and sensors which simply process information about the ambient environment (like thermometers). Another way to sub-divide sensors is into imaging, i.e., those that produce a "picture" of the physical object they sense, and non-imaging, which do not. As an example of imaging sensors, charge-coupled devices (CCD) are used in cameras to give high-resolution images limited by the number of pixels used. Sensor arrays containing millions of pixels, each a few microns across, are possible. As pixel size has shrunk and data available to the system has grown, processing has gained importance. Because of their particular importance, imaging, non-imaging, and passive sensors are singled out in this discussion.

A variety of civilian and military applications are dependent on imaging sensors. Imaging sensors are also critical in remote sensing from space, scanning microscopy, and machine vision (an important area of robotics). Imaging sensors contribute to a number of national goals, including healthy and educated citizenry, job creation and economic growth, harnessing information technology, improved environmental quality, and enhanced national security.

Although imaging sensors are very important in providing "visual" information, a collection of non-imaging sensors can be used to measure a vast range of phenomenology. Examples include devices that measure temperature, pressure, humidity, radiation, voltage, current, or presence of a particular chemical or biological material. In addition to passive sensors, there are active sensors such as laser or radar altimeters. Specialized microsensors can be used to detect particular chemical or biological agents.

Non-imaging sensors are used in a variety of industries and applications. Environmental monitoring and hazardous site characterization are important applications for non-imaging sensors, including biosensors and chemical sensors.

Miniaturization of biosensors is important to medical diagnostics, food process control quality assurance. Small and inexpensive if produced in large volumes, biosensors can detect small changes permitting earlier treatment with smaller doses of medication. Chronically implanted devices employing a microbiosensor can be therapeutic as well as diagnostic. For example, a smart device employing a microbiosensor could respond to changes in metabolic rates and circulating biochemicals, and adapting to the patients present physiological status, automatically release the proper dosage of a therapeutic medication.

The transportation industries are finding uses for microsensors and MEMS. Microsensors have use in the automotive industry for system controls and diagnostics. Non-imaging sensors have a role in remote sensing. Laser profilers (LIDARs) and radar altimeters can be used to measure range, and hence altitude giving surface. These can be used as navigation aids, and are related to imaging systems to the extent that surface profiles are being probed. Soil-sounding radars are an important recent development. Robotics is an important area for non-imaging sensors. Tactile sensors are often considered second in importance only to machine vision. Sensors are also important for balance and kinematics. Military applications of biosensors, chemical sensors, and microsensor variants include detection and warning of the use of chemical or biological agents in warfare.

Given the wide range of applications to which non-imaging sensor technologies contribute, they can be said to contribute to meeting almost all of the President's goals.

Passive sensors have a special importance in military applications because they do not reveal their location or characteristics to an adversary. There are several important applications that can be emphasized for passive sensors. For example, they can provide warning of an adversary's active sensors, enhance night vision, or be used for thermal imaging to identify and target military assets and then perform damage assessment. Radar guided missiles, laser designation systems, and laser range finders are a few examples of offensive systems that detectors could search for, and upon detection alert friendly forces to imminent threats. Damage assessment is a vital task to follow-up strikes, and with the advent of new weapon types remains particularly critical.

Europe and Japan have lost their leads in chemical and biosensor technologies over the last several years, although the Japanese are involved in a very broad range of biosensor development for both biomedical and bioprocess control applications. U.S. firms have stepped up R&D efforts as a result of environmental monitoring needs, a rekindled interest in developing better chemical and biological defense detection capability, and the marketing success of some biosensor-based medical diagnostic kits, e.g., "consumer-friendly" home pregnancy and blood sugar tests. But, there are specific areas in which Europe and Japan continue to excel. Sweden has made impressive strides in the development and successful commercialization of surface plasmon resonance-based biosensing systems. In Japan there has been excellent work in food quality testing (e.g., flavor sensors) and human fatigue sensing (e.g. a prototype wristwatch-like device that measures fatigue). Likewise, in chemical sensor technology there are areas of excellence around the world. Germany, for example, has made notable gains in mass spectroscopy-based sensors and is one of the world leaders in this area.

The United States and Europe are the current leaders in machine vision research. As charge coupled device cameras for capturing images have become readily available, technology advantages in machine vision are accruing to those firms most adept at processing the images produced. Europe is on a par with the United States in machine vision technology with the Dutch company, Delft, for example, having vision systems ranking among the best in the world. Another example of European excellence is Germany's Siemens AG which has developed a unique three-dimensional recognition system using lasers instead of cameras. The Japanese have made advances in machine vision over the last decade, but still lag, primarily because of weaknesses in the design and implementation of software to perform the functions required in sophisticated vision systems. Much of the work on vision processing in Japan has been to reduce computational requirements through new algorithms, the application of fuzzy logic and neural networks, and the use of special purpose processors—all areas in which Japan lags. Japanese companies have some notable achievements. Yaskawa Electric Mfg. Co., Ltd., developed "Moto-Eye," a vision system with improved image processing designed for use on assembly lines. Fujitsu developed a video sensor eye that can distinguish objects almost as clearly as the human eye; the robot eye operates at 30 frames per second compared with human eyes, which can capture 60 images per second.

The Japanese have advanced to rough parity with the United States and lead the Europeans in the development of tactile sensor technology. Tactile sensors provide information about the contact between the workpiece and industrial robots. They are critical to many assembly activities, because vision systems cannot supply all the information needed for delicate assembly operations, such as determining whether an object is being grasped properly or whether there is any friction between the fit of two parts. Japanese R&D has already yielded some commercial applications. The Daihen Corporation has a touch sensor for arc welding application used to find mispositioned workpieces and to adjust welds for deviations in the workpiece size. The Tokyo Sensor Company manufactures tactile sensors for use in precision robots with an incremental sensitivity of 10 grams. These sensors were among the first commercialized that were small enough and had the sensitivity to be used at the fingertips of robot hands. Despite some leading edge research, Europe lags both Japan and the United States.

Integrated signal processing

Signal processing technologies enable the extraction of relevant information from signals received from sensors. Signal processing is present whenever a signal, or combination of signals, electrical, optical, fluidic, etc., is intentionally acted upon to increase the over-all usefulness, or value. Signal processing can be applied to monitoring and measuring, such as, for example, when an image is formed of a slice through a person's brain (magnetic resonance imaging) by combining numerous non-invasive images taken around the head. Signal processing can also be used to influence, or control, dynamic processes. For example, some fighter aircraft are only conditionally stable. It is the task of a control system, incorporating signal processing, to keep the multi-dimensional state of that aircraft within its performance envelope. Many systems additionally "push back" on the pilot's controls to give him a "feel" for the maneuver, because he is flying a computer while the computer is flying the plane.

Signal processing is a vast enabling technology, whose boundaries sometimes overlap those of other fields, such as software, integrated circuits, communication, imaging, display, etc. Signal processing technologies include microelectronics, specific hardware designs, software correlation techniques, neural networks and algorithm development. Advances in signal processing support reconnaissance and surveillance systems, machine vision, robotics, and autonomous systems. They also have application in law enforcement. It is a key element of the manufacturing, test, diagnosis, and repair process. As signal processing technologies advance, decision-making processes can be automated. It is increasingly becoming integrated into the very products which are being manufactured, tested, diagnosed, and repaired.

Signal processing holds a key to both economic advantage (by providing superior, or previously nonexistent, performance) and also to military advantage (for the very same reasons).

Integrated signal processing is the field wherein the processing is physically integrated (often within the same microcircuit substrate) with the sensor. MEMS (micro electro-mechanical systems) technology best illustrates this field at the current time. The same technology which is used to etch and deposit layers of materials to form microcircuits is also used to micro-machine structures.

An important commercial application of sensor-integrated processing is pursued by Caltech's Carver A. Mead, who is developing a silicon retina which possesses both the photo-sensor and the rudimentary neural capabilities of an eye. The silicon retina reads cursive writing on checks automatically, and then inputs the information into a data base. Mead and his colleagues have developed several additional generations of neuromorphic vision systems which are now being developed through a venture-capital-financed start-up. Future applications have to do with automated manufacturing, operator aids to reduce workload, and improved precision and uniformity in virtually any manual operation. They also lead to manufactured products which perform their functions in a more optimal, and more unsupervised, manner. Thus, integrated signal processing could make a significant contribution to job creation and economic growth by improving productivity in U.S. industry and enabling new manufacturing capabilities.

National defense/security applications include missile guidance, unmanned air vehicle autopilots, engine monitoring and control systems.

The United States is the world leader in digital signal processing (DSP) technologies, driven by a variety of applications including the home entertainment market. In particular, the strong U.S. position in multimedia computing is a major asset. In addition, the military, though no longer the primary technology driver, is still funding important DSP R&D. The Japanese produce many DSP components including DSP "cores" around which other functional components can be added to construct an application-specific DSP device. Japanese firms are world leaders in the technologies to actually fabricate DSP devices but not in their architectures and implementation. Europe, like Japan, trails the United States on most theoretical aspects of DSP. European commercial firms also lag in producing state-of-the-art components.

While the U.S. leads in the underlying technology, Japan leads in exploiting it in the commercial marketplace. Europe is closer than Japan to challenging much of our military technology, while it is simultaneously an active competitor to Japan in many commercial venues. The U.S. may lead in military applications such as synthetic aperture radar technology, but the Japanese camcorder processes such as image motion compensation, digital zoom, automatic light controls, etc., have virtually no current competition in the U.S. Furthermore, because of the profit-driven need to demonstrate leadership, the U.S. often creates its own competition by revealing costly lessons for the free publicity. The trends are not in favor of the U.S. in this technology.

SOFTWARE AND TOOLKITS

Software

Computer software is one of a few key technologies that daily affect almost every aspect of our lives. The instructions embodied in software run the telephone switching system; make our automobile transmissions shift smoothly by reacting to dozens of sampled factors many times a second; encode and route electronic funds transfers among the nation's—and the world's—banks; provide the displays and communications vital to our air traffic control system and the control systems of individual planes; guide machine tools in forming complex parts; and hundreds of thousands of other such applications, including such routine but vital business functions as word processing, spreadsheet calculations, and electronic mail.

Software is critical to U.S. economic prosperity for the following reasons:

- It is so ubiquitous in consumer products, manufacturing processes, and the provision of services that, if other countries were to leapfrog the U.S. in the ability to design and deliver effective tested software, the result would be a relative increase in manufacturing costs and services delivery costs that would seriously affect the U.S. export position and trade balance;

- National infrastructure (utilities, monetary flows and control, traffic control, telecommunications) increasingly depends on software processes. If the U.S. cannot better assure the security and safety of these systems, both from intentional attack—ranging from hacking to terrorist or government-sponsored intrusions—and from inadvertent embedded errors not caught during testing, then the nation faces risks that are fundamental to our safety and well-being;

- Software production is a key industry in the U.S. It accounted for $2.26 billion in exports in 1993 data.

- Software is an enabling technology in the development of other technologies. Most other scientific and engineering progress is directly dependent on software. In many cases, software is the limiting factor on how fast the other technologies can evolve.

Software is critical to U.S. national security for at least the following reasons:

- Ultra-smart weapons, capable of pinpoint accuracy, are critically dependent on advanced software technologies. Such weapons will be dominant factors in future conflicts, with the potential–illustrated in Desert Storm operations–of greatly reducing number of sorties required, tonnage of ammunition required, and lives lost.

- Intelligence analysis and dissemination requires ever more advanced software technologies. With gigabytes of photographic and other signals intelligence becoming available each minute from satellite systems, the volume of raw data to be culled for interesting developments is overwhelming traditional manual photo interpretation and signal interpretation methods. Highly advanced–perhaps even self-adaptive–pattern recognition and interpretation software is increasingly required to perform first-level automatic scanning of incoming data for interesting patterns and changes marked for subsequent human review and analysis.

- Command and control systems distribute information, as it becomes available, to those who need it. Information from diverse sources undergoes "fusion" to create an integrated, consistent picture of events. On today's distributed and joint-operations battlefields, linked to stateside (CONUS) intelligence and command systems, highly advanced software is critical in routing, fusing, and disseminating voluminous information from its sources to those commanders and support units who need it, when they need it, and in a form in which it can be assimilated despite battlefield distractions.

- As defense budgets continue to shrink, it is possible to envisage significant reductions in training costs, but with a concomitant increase in effectiveness, through training based heavily on simulations and virtual reality-type environments. Recent demonstrations using a Distributed Interactive Simulation testbed, and plans for a Defense Simulation Network show early promising results in this direction.

- Software, in the form of database management systems, communication network routing instructions, transaction-based systems, etc., makes logistics management possible in an environment where military roles and missions have never been so numerous and diverse. Next steps in adopting common data object formats among services, and redesigning many "stovepiped" systems for true interoperability, are critical software issues upon which logistics management depends in the coming decade.

International differences tend to be common across the various classes of software, so all technology sub-areas in this technology area will be addressed as a group.

The United States is the world leader in software development across a wide range of products including network and systems software, applications packages, and software production tools. Japanese software developers are trying to respond to recent demands for packaged software in their home market, but face an uphill battle with developers from the United States. Because unique Japanese language requirements have limited Japanese interface software development, most Japanese computer makers are increasingly trying to adapt U.S.-designed programs. Added to this, the strategic error by Japanese firms of pushing proprietary operating systems has left them far behind their U.S. competitors in the market for standard operating systems such as DOS, OS2, and Unix. The slow acceptance of PCs in Japan also stunted the growth of network software. Japanese firms are attempting to catch up, primarily by forming alliances with leading U.S. network software firms. Developing competitive packaged applications software, such as database management, has been much too expensive for the customized, single-client products that have traditionally been produced by the large Japanese firms. Smaller, more entrepreneurial firms have never been as significant in the Japanese software sector as they have in the United States.

While Japan remains substantially behind the United States, its relative position has improved somewhat over the last several years. The Japanese have come to fully realize their weakness in software and have undertaken measures to improve their position. Japan is emphasizing management of the software development process and initiatives commonly known as "Software Factories" that emphasize quality, make great efforts to reuse code, and rely more on programmer experience than on computer science education. The Japanese use a variety of conventional software tools that, although different from those used by U.S. programmers, appear to be comparable in sophistication. To cope with a shortage of software professionals, the Japanese Ministry of International Trade and Industry recently implemented several programs specifically designed to improve Japanese capabilities to produce software and expand production capacity, but these efforts have not been as successful as hoped. Japan is less capable in expert system technology, but the Japanese have developed strong programs and devoted considerable resources to develop and improve fuzzy logic software and continue neural network R&D.

European software development skills, although superior to those of their Japanese counterparts, still generally lag behind those of the United States. There are a large number of skilled applications software developers in Europe, but most of them are employed by U.S. firms. The European applications software market tends to be fragmented into specific industries and regions, making it difficult for any single firm to have a major impact. European software vendors have focused on customizing software for particular industries or regions, while following the standards and programming paradigms defined by leading U.S. software houses. As a result they are vulnerable to the major technological shifts that frequently occur in this sector. For example, despite their best efforts to take a technology leadership role, most European software houses had to wait for U.S. firms to define and implement the early open system products—like Unix operating systems and related network software—before they could begin development of their own products. European users have been in the forefront in demanding interconnection software for their systems, but most vendors look to U.S. counterparts to define the technology and implement the first products. There are some areas in which European research work is quite good. A German software firm, SAP, has done excellent work in network software and the French have artificial intelligence technologies (primarily expert and knowledge-based systems) that are only slightly behind comparable U.S. efforts. The leading European firms are also among the world leaders in many areas of software for automated manufacturing systems.

Europe is at parity with the United States in software packages for computational structural mechanics. European firms have produced fewer general purpose finite element codes but have some notable successes. Dassault (France) is regarded as the technology leader with the integrated CATIA/ELFINI analysis and optimization code. Dassault has successfully implemented a module in CATIA to more accurately distribute aero loads, which dramatically improves performance of the analysis and optimization code ELFINI. Some experts regard this as a convincing advantage over any U.S. origin aerostructural code. Germany, Sweden, and the United Kingdom also have active programs in analysis and optimization, and have reached maturity with use on the most recent commercial and military aircraft design efforts. European capabilities in hydrocodes for impact dynamics are state-of-the-art. A French firm, ESI, originated the PAM-CRASH code for automotive crash analysis. In weapons-related R&D, the French Ministry of Defense has investigated ballistic analysis for armor materials, projectile/target interaction, and the constitutive laws for materials at very high strain rates. (See discussions of CIM Support Software in Manufacturing and Modeling/Simulation Tools.)

Education/training software

Software for education and training permits a wide variety of learning modes, from repetitive drill with an infinitely patient computer to advanced simulations and "virtual realities" that allow users to immerse themselves in, and interact with, rich environments representing aspects of the world with which they wish to become more familiar or more skilled.

Examples of education and training software might be simple games to teach arithmetic or typing; information retrieval software for accessing large databases of relevant information; commercially available simulations such as SimCity; or just software that lets teachers, students, tutors, and resource experts exchange electronic mail or "chat" regarding homework assignments, schedules, useful peer-provided information, etc.

The use of simulators has become more prevalent for job training which involves the interaction between humans and complex systems, reflecting the need for realistic re-creation of the systems' possible failure modes so that responses can be developed, studied and practiced. For example, simulation training enables flight crews to be trained and familiar with threatening situations well before the events occur, and to maintain their proficiency in responding to otherwise rare events. Coupling human factors engineering (see "Transportation" and "Living Systems") with high-fidelity simulation has proven its worth in commercial and military aircraft as well as tanks and advanced highway vehicle systems.

The lifelong education and training of U.S. citizens is vital to our economic and social health. If relevant information can be accessed by people where and when they need it, in order to improve job skills or political/social awareness, the entire U.S. economy benefits. With decreasing trade barriers, the U.S. niche in the world economy will increasingly involve high-technology, information-intensive jobs, continuing access to education and training software is vital to keep the U.S. at the forefront of new services, technologies, and manufacturing techniques.

U.S. defense forces conduct perhaps the most intensive education and training programs anywhere under one authority. They have tremendous need for continual training programs in advanced weapon systems, obtaining and retaining pilot skills, and thousands of other skilled jobs and tasks. Much of this training now involves live bullets, tanks, ships, and planes—at great taxpayer expense. If a significant portion of this training can be replaced with software creating sufficiently realistic conditions for effective learning, there is the potential for greatly reduced expense and improved training (for example, because alternatives can be explored that would be excessively dangerous or costly in real life). Recent initiatives in distributed interactive simulations via networks and the Defense Simulation Network show promise in this area.

Network and system software

Network software controls routing and allocation of network nodes, lines and information packets that increasingly carry the transactions of our society. As more of our economy moves into "cyberspace," the network software that allows the smooth operation of these networks becomes critical to our nation. Network software exists in a variety of data networks tying computers together: local area networks (LANs), metropolitan area networks (MANs), wide area networks (WANs)—as well as many other specialized applications, such as nationwide and international telephone switching systems.

It is vital that the U.S. retain control of its voice, cable, satellite, and other networks, since the transactions upon which our economy and national defense depend are increasingly carried on these nets. We must not become dependent on network software created by others, that may contain flaws (unintentional or deliberate) that we might have avoided. The security of these systems from attacks by hackers, terrorists, foreign commercial enterprises, or even other nations, will be of increasing concern as our economy depends increasingly on transactions carried out in this "cyberspace."

System software controls the operation of computers. It ranges from rather simple operating systems such as DOS (Disk Operating System) on personal computers, to software that allocates tasks among various computing units accessible via network, and perhaps allocates computer resources in real time to keep up with data flows emanating from processes occurring in the external world. Among the many important services provided by system software are ones dedicated to securing the system from unauthorized access, or modification or destruction of information.

System software is the essential underpinning to our nation's information systems. The availability and security of these systems are only as good as the system software on which they are based. The U.S. has traditionally led the world in operating system software (DOS, Macintosh Operating System, Multics, Unix, IBM mainframe operating systems, etc.). By controlling this fundamental software component, we have been well positioned to create application software, such as word processors, spreadsheets, database transaction systems, etc., capitalizing on the operating system's features and facilities. Continued U.S. strength in this area is vital to maintaining that critical advantage, and thereby supporting the U.S. export advantage in software systems.

National security is equally dependent on effective and trustworthy system software. DOD will increasingly use commercially available off-the-shelf (COTS) system software for its needs, rather than developing and maintaining specialized systems. Our defense systems are therefore dependent on an economically healthy and advanced system software development industry within the U.S.

Modeling and simulation software

Modeling and simulation software allows the creation of software models, and subsequent exploration of them through simulation, of a variety of physical, social, communication, and other systems. Simulations may be time-stepped or event-based (or some combination of both). They may be localized, or distributed over a variety of cooperating "nodes" on a network. Simulations may represent the formation of galaxies, molecular interactions, the complexities of social interactions, portions of our economy or specific markets, the operation of a specific aircraft for pilot training, the operation of an anthill, and a boundless set of other alternatives.

The nation that can simulate better can analyze more deeply, predict more accurately, train more thoroughly, and provide a more substantive education in the development and operation of complex systems. As such, it is a critical technology for analysis, training, education, and much of the advance of science and technology.

U.S. national security depends critically on modeling and simulation software; this is emphasized by the recent creation of DOD's Defense Modeling and Simulation Office (DMSO) to coordinate the thousands of models and simulations, and the databases on which they depend, within our Defense establishment. Among the many goals of DMSO is better verification (assuring that the software is a faithful representation of the algorithms that it encodes), validation (assuring the simulation accurately represents the portion of reality it seeks to represent), and accreditation (assuring that the model and its data are appropriate to the task for which they are to be used).

Software engineering tools

Software engineering (SE) involves the creation of software systems. Tools for SE are software programs that enable and facilitate that process, and help assure the timeliness and accuracy of the resulting software. Such tools often use the rubric CASE (computer-aided software engineering).

Perhaps the greatest weakness in computing and communication systems worldwide is in software engineering: software engineers are often unable to create complex software systems on time and on budget, and with assurance that they will perform as required or desired. Advances in software engineering are vital if we are to continue developing software of the complexity required to manage and control our networks, transaction systems, simulations, and computers themselves. Integrated circuit (IC) design is also increasingly dependent on the effectiveness of the design software. If any nation creates a breakthrough in their effectiveness in creating complex software, it will give that nation a tremendous advantage in the world economy—especially since software development is one of those symbolic jobs that can easily migrate (via data networks and telecommunications) to any country or locale on earth.

The U.S. Department of Defense is highly dependent on the development and maintenance of large scale software systems. Better tools for software development are of vital interest to them, as software development is *the* critical element (pacing schedule and cost) in many new weapon and control systems. It is also important that our critical defense systems continue to be developed by teams of people who are U.S. based, and whose integrity and trust can be assured. It is therefore important that the U.S. leads in software development tools, so that we can maintain control of critical systems development, and not be dependent on more advanced tools and techniques available elsewhere.

Pattern recognition

Pattern recognition is of critical importance in many commercial and military applications. Computationally intensive processes such as speech recognition, image, understanding and handwriting recognition depend on pattern matching techniques for their success. Although much progress has been made during the past few years, there is still much more research necessary before these techniques are widely available. The approaches being considered involve both hardware and software solutions. Several parallel processing architectures are very effective at pattern recognition but are currently expensive to produce. New software techniques such as neural networks promise effective solutions on more conventional hardware.

Much of the recent work on pattern recognition has been conducted as a subfield of artificial intelligence. Further examples can be found in that section.

Software production

Despite the trends in packaged software, there is a continuing strong demand for special, custom-developed software to integrate systems of hardware and software, often connected by wide area networks. Examples of such systems include air traffic control systems, environmental monitoring systems, marine navigation systems, factory automation systems and military-related command and control systems. Also included are smaller embedded systems such as medical scanners and life-support systems. These systems often involve processes that take place and are controlled by computer systems more or less in real time, with actions occurring at rates too fast for human intervention. In addition to performing conventional computing tasks, such systems must often be capable of effectively integrating and responding to sensor information. The growth in systems integration reflects the increasing sophistication and complexity of many larger computing systems.

Software production tools allow rapid prototyping and testing of complex code, helping overcome the greatest barriers to efficient creation of software. By speeding production and reducing development costs, software production tools contribute to improved productivity, job creation and economic growth in the software industry and other industries which require customized software. They also contribute to the goal of harnessing information technology, to enhanced national security.

5. LIVING SYSTEMS

New industries such as biotechnology are emerging as knowledge is gained into the highly energy- and material-efficient processes employed by living systems for self-propagation and the formation of functional structures such as organs, shells, or musculo-skeletal systems. This knowledge is being applied not only to the agricultural and aquacultural production of food plants and animals, but human health protection and medical care.

The Living Systems technology category includes four technology areas:

- Biotechnology
- Medical technology
- Agriculture and food technology
- Human systems

Biotechnology is enabling both established and newly emerging industries to design, create, and produce highly specific substances derived from molecular structures and processes in naturally occurring biological systems. Currently, the two most important areas of biotechnology application are human health care and agriculture.

While the United States is the overall world leader in biotechnology, Europe and Japan pose strong competition in specific areas. The United States does more basic research in genetic engineering and molecular biology than any other country. Computer based methods for analyzing and modeling molecular sequences and interaction, as well as facilitating collaboration among widely dispersed groups have contributed to the rapid evolution and application of knowledge in these areas.

The integration of knowledge and practice of many technologies is essential to an effective and efficient system for protecting the public health and delivering health care services. Innovative biomedical research and information-based integrated decision support systems leading to prevention, more effective therapies and minimizing the need for long term care hold the key to advances that can restrain costs while enhancing the quality of public health and health care. Key technologies in this area are integrated information systems, functional diagnostic imaging, biocompatible materials, and the rapid identification of bacteria and viral infectious agents.

Global agriculture is facing the challenges of increasing human population, accelerating need for food, fiber, feed and raw materials for other industries, and a declining amount of cultivated land per capita. Sustainable agricultural systems must address the development of environmentally sound, productive, economically viable and socially desirable agriculture. Aquaculture is currently the most rapidly growing agricultural segment and will play a significant role in providing a stable source of fish protein in the face of declining yield of oceanic fisheries.

The human-machine interface is a critical component in a number of complex integrated systems such as power and communications grids, air traffic control systems, and highly automated process control and manufacturing systems. Such systems typically produce much more data than a human is able to digest in a time-critical situation, so the main job of the interface is to present the data in a form easily understandable by the human and to provide an easy means of interacting with the system to ensure continued safe and reliable operations. The United States has a pre-eminent technical position in understanding human capabilities, behavior and performance while interacting with engineered systems and environments, and in implementing advanced human-machine interfaces.

For the most part, the U.S. is in a strong position in the technologies included in the Living Systems category. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 5.1.

BIOTECHNOLOGY

Biotechnology is enabling both established and newly emerging industries to design, create, and produce highly specific substances derived from molecular structures and processes in naturally occurring biological systems. Currently, the two most important areas of biotechnology application are human health care and agriculture. Other application areas, including biomining, specialty chemicals, energy, environment, electronics and advanced materials, make up significantly smaller segments of the biotechnology industry.

While the United States is the overall world leader in biotechnology (primarily because of its extensive medical applications), Europe and Japan pose strong competition in specific areas. The United States does more basic research in genetic engineering and molecular biology than any other country. Europe, primarily Germany, France, and the United Kingdom, also conducts world-class basic research. Japan, which has always emphasized applied research, continues to be a world leader in microbial strain selection and manipulation, and has a very strong background in bioprocess engineering, particularly in the food, brewing, and antibiotics industries. Japanese firms have not established basic research programs in areas such as genetic and protein engineering that are comparable to those in Europe or the United States.

European countries have made significant advances in recent years both in human-health-related and agricultural biotechnologies and are slowly beginning to narrow the gap with the United States. Technical advances are likely to continue with the support of increased government funding and greater industry

Figure 5.1
Living Systems
Technology Position and 1990-94 Trend

US Technology Position Relative to:
Japan ▷, ○, or ◁
Europe ▶, ●, or ◀

1990–94 Trend
Improved ▷
Declined ◁
Maintained ○

	Lag			Lead	
	Substantial	Slight	Parity	Slight	Substantial
Living Systems					
Biotechnology				○ ▶	
bioprocessing				○ ▶	
monoclonal antibody production				○ ●	
protein engineering				◁ ●	
recombinant DNA technologies				○ ●	
vaccines				▶	▷
Medical Technologies				▷ ●	
biocompatible materials				●	○
functional diagnostic imaging			●	○	
bacterial/viral detection and screening		◁	●		
medical devices and equipment				○ ◀	
Agriculture and Food Technologies				◁ ▶	
sustainable agriculture production				◁ ●	
food safety assurance		○	●		
aquaculture and fisheries		○			▶
Human Systems				▶	▷
advanced human-machine interface				▶	▷

involvement. In addition, the EU is beginning a slow process of amending biotechnology regulations to better support the industry. Japanese firms have had some success as manufacturers and marketers but are now addressing the perception that they lacked quality pharmaceutical and biotechnological R&D. For the most part, Japanese biotechnologies have been obtained through alliances with smaller U.S. biotechnology firms, rather than through in-house R&D. As a result, Japanese researchers are behind their peers in the United States and Europe in most areas of biotechnology. In addition, Japanese industry R&D expenditures, a very important component of R&D support, are low in comparison to those in both the United States and Europe, leaving Japanese researchers at a significant disadvantage.

Bioprocessing

Bioprocessing is the use of microbal, plant, or animal cells for the production of chemical compounds. Bioprocessing exploits a range of biological phenomena extending from the fermentation processes to produce beer, wine, and commercial ethanol products to state-of-the-art processes for the production of specialty chemicals such as enzymes, amino acids, biocatalysts, and pharmaceuticals. Such production methods can be more energy efficient, product specific and environmentally friendly than traditional methods of organic synthesis.

One specific bioprocessing technology is mineral extraction or biomining. Biomining utilizes microbes that leach out minerals without the harsh conditions of physical mining methods, while improving recovery rates and reducing capital expenses and operating costs. Now widely used, about 25 percent of worldwide copper production is based on bioprocessing, and applications to gold and phosphate extraction are promising.

Bioprocessing supports a number of national goals. It creates jobs in the food, pharmaceutical, chemical, mining, and biotechnology industries, and contributes to the competitiveness of those industries in global markets. By creating possibilities for new and highly specific chemical production, bioprocessing allows the creation of new drugs which supports the health of U.S. citizens. It also supports national security by providing better medicines and organic compounds for the use of the military.

European and Japanese technical capabilities in human therapeutics lag those of the United States; however, Europe lags only slightly and is improving. Efforts in human therapeutics in Europe have been led by the United Kingdom—which has Europe's largest biotechnology industry—but significant technical capabilities also exist in both France and Germany. New biopharmaceuticals are being developed in Europe for such wide ranging applications as treatments for shock, asthma, and cancer. Much of European biotechnology research is still being done by the large pharmaceutical and chemical firms such as Glaxo (UK), Rhone-Poulenc (France), and Schering-Plough (Germany), however, innovations may increasingly come from new, smaller companies. For example, British Biotechnology has a number of biopharmaceuticals at various stages of development, including an anti-cancer compound and a drug that reduces the detrimental effects of chemotherapy agents.

Japan has only limited capabilities in nearly all segments of human therapeutics. While assessment teams and reviewers of Japanese programs have found little cutting edge basic science and discovery of new compounds, they have seen impressive implementations, and the application of automation and robotic techniques to technology largely developed outside Japan. By mastering the production processes of current bioprocesses, the Japanese are extremely well prepared to support new products coming from their discovery programs.

The Japanese are also making significant investment in the application of bioprocessing techniques to energy and environmental issues such as the de-sulphurization and de-nitrification of coal. They see this as a way to approach the acid rain problem they encounter with Chinese coal combustion.

The Japanese approach to bioprocessing curiously does not focus on basic engineering principles, but is more biologically oriented, emphasizing screening, selection, and medium development. Biotechnology is well accepted in Japan as an extension of their historical involvement in fermentation products, and bio-derived detergents and cosmetics are actively marketed by emphasizing the bio-processing technology in their production. This stands in marked contrast to the European attitudes which seem to be very distrustful of biotechnology processes and products, and have created a political environment that had substantially inhibited European corporate activities in these areas—but encouraged them to invest in R&D and production facilities in the U.S.

Monoclonal antibody production

While antibodies alone can be used to kill cancer cells, they are most often used as carriers of other substances for either therapeutic or diagnostic purposes. Chemotherapeutic agents can be attached to monoclonal antibodies to deliver high concentrations of these toxic substances directly to tumor cells. Theoretically, this approach is more effective than conventional chemotherapy and less toxic because the delivery of harmful agents to normal tissues is decreased. For diagnostic purposes, they can be radioactively labeled and used to locate metastases previously undetectable by other methods.

Monoclonal antibody therapies involve the development of specific antibodies directed against antigens located on the surface of tumor cell. These techniques are highly patient specific and require that samples of the patients tumor cells be taken and processed to produce specific antibodies to the tumor associated antigen. In order for this to work a sufficient quantity of antigens unique to the tumor cells must be present. The tumor antigens must be sufficiently different from the antigens elaborated by normal cells to provoke the desired antibody response.

Monoclonal antibody treatments still have significant limitations. Monoclonal antibodies are made using mouse antibodies, and as foreign proteins they often trigger an immune response. They can be neutralized before any therapeutic effect can occur. They may also lack sufficient specificity for tumor antigens and may not be different enough to ensure only cancer cell destruction. These problems may in the future be resolved. Studies into the use of monoclonal are in progress in the treatment of T cell lymphoma, chronic and acute lymphocytic leukemia, melanoma, colorectal cancer, and neuroblastoma.

The primary contribution of monoclonal antibody technology is to the health of the U.S. population. This technology also contributes to job creation and global competitiveness of the drug and medical diagnostics industries, and greater efficiency of the health care industry. By providing better tools for military doctors, it also contributes to U.S. warfighting capabilities.

While there are noteworthy British and French programs in these areas, the bulk of the research and subsequent exploitation by biotechnology firms is occurring in the U.S. supported by venture capital and alliances with the large pharmaceutical companies.

Protein engineering

Protein engineering, that is creating proteins sequences whose specific functions are determined by their three dimensional shape, holds the key to tailoring protein catalysts and rational drug design. While it is now well established that more than 500 proteins each routinely fold into single conformations out of hundreds of millions of possibilities, the general folding rules have yet to be defined. While gene sequences are converted to protein sequences by ribosomes, the process of correctly converting sequences to folding patterns is not well understood. The sequence of amino acids in a protein regulates the folding of the protein chain, with the folding pattern dependent on interactions among the amino acid's side chains. The final shape of the protein affects its functional ability to selectively bind and interact with specific sites. Once the protein folding riddle is solved, it should facilitate the development of synthetic and entirely new proteins and materials. Promising results are just beginning to become available from protein crystals grown in space.

Protein engineering technology contributes to several national goals. By permitting precise design of more specific and more potent drugs, protein engineering improves the health of the U.S. population, as well as the warfighting capabilities of the U.S. military. New and more potent drugs involve the possibilities of increased sales and more jobs in the pharmaceutical industry. Because it is on the leading edge of understanding molecular structure, it contributes to maintaining U.S. leadership in science and engineering.

The bulk of the physics of protein folding is being done in U.S. universities and national labs. Activities ranging from the computational simulation to using tools developed for the study of disordered systems in condensed matter physics have been applied to these problems. The two predominant areas have been protein folding and the behavior of folded proteins. The primary basic physics work has been done in the U.S. with some mathematical elaboration in the former Soviet Union, Japan and Switzerland.

Recombinant DNA technologies

Recombinant DNA techniques involve the transfer of genetic material between differing organisms, a process popularly referred to as genetic engineering. This transplanted genetic material contains encoded instructions for characteristics of the original cell, namely the production of specific proteins. This is done to enable recipient organisms to synthesize increased yields of compounds, to form entirely new compounds, or to adapt to different environments.

Research in gene therapy has grown dramatically since 1990, with more than 40 therapeutic gene transfer protocols approved since that time. Pending positive results in animal models, many researchers believe that gene transfer could be potentially used to remedy serious human diseases caused by genetic mutations including sickle-cell anemia, emphysema, hemophilia, and even extremely high levels of cholesterol. Work is in progress on developing therapies for hepatitis and other liver diseases, AIDS, and diseases of the cardiovascular and central nervous systems, as well as inserting genes that stimulate the production of immune cells that fight cancer. Other approaches involve introducing genes through viral vectors such as adenovirus or through protein binding "receptors." Another approach called "Antisense" tries to do the opposite of what other techniques do—it tries to turn off genes that code for the production of harmful proteins.

Targeted gene replacement provides access to more than 5,000 human disorders attributed to genetic defects. As the genes and disorders are identified, the same mutations can be produced in mice, and the mouse models should make it possible to trace the events leading up to the manifestation of the disease. Understanding the molecular pathology of the disease should facilitate the development of more effective therapies. The various mutations of the cystic fibrosis gene are being studied this way. The study of mammalian neurobiology also looks attractive for this technique.

Transgenic animals are being developed for a variety of purposes, from mice for specific disease research to purposes such as leaner meat or increased milk production. Transgenic plants such as rot-resistant tomato, and insect and herbicide resistant corn and cotton have been aggressively pursued. The present pursuit of herbicide resistant crops is considered controversial due to concerns that they may encourage the increased use of herbicides. Progress in animals and plants has been somewhat slower than in cell culture preparations as they are frequently constrained by the gestation period in animals or the growing seasons for plants.

One of the most intriguing application of rDNA technology is the past year is biomolecular electronics. It is conceivable that for certain kinds of algorithms molecular computation might compete with electronic computation. Energy efficiency and storage density would be quite impressive. Storing information in DNA molecules and achieving an information density of approximately 1 bit per cubic nanometer would lead to a substantial improvement in capabilities over conventional video tape which stores data at a density of approximately 1 bit per 1012 nm^3.

Progress in recombinant DNA technology will contribute first and foremost to the health of the U.S. population. In addition, by facilitating care of chronic diseases and more productive agriculture, it contributes to a more productive economy. Agriculture-related biotechnology applications are potentially extremely important. As in human-health-care related biotechnology, there are currently only a handful of products on the market. However, researchers are developing a variety of transgenic animals and crops that will probably have significant market impacts after the turn of the century.

The U.S. is a world leader in rDNA technology, although the extent of the U.S. lead varies from area to area. Europe is only slightly behind the United States in the development of transgenic animals, with research taking place primarily in the United Kingdom and the Netherlands. European firms have developed significant capabilities in transgenic plant technology, and, although they lag the United States slightly, they are likely to improve over the next five years. Technical capabilities lie primarily within the United Kingdom, France, Belgium and the Netherlands. The United Kingdom—which has conducted the largest number of field trials in the European Union (EU)—and France have developed and are field testing transgenic varieties of many different plants with many different traits. These countries are also working on some collaborative projects including R&D on the Euromelon, a joint British, French, Spanish and Greek research project, which is now being field tested. Belgium has a number of important achievements, perhaps the most significant of which is the development of a new type of oilseed rape, genetically engineered to be herbicide resistant. The crop was recommended for general sale and use for the first time in the EU by a panel of government experts and now awaits approval by the Environment Secretary, the Agriculture Minister and the EU. If approval is given, as industry experts believe likely, the scale of genetic crop development will change from small scale to mass production. In the Netherlands, biotechnology has been applied in plant breeding and seed propagation for the last 15 years. While the Netherlands have been a leader in these technological developments, strong public opposition has hindered field trials and thus, slowed research. The Dutch company, Van der Have Groep, for example, had to abandon trials of corn engineered to be herbicide-resistant after environmental activists objected to the release of these plants' pollen into the environment.

While some feel that Japan has virtually no technical capabilities in the development of transgenic animals and has not begun significant research in this area, its potential in transgenic plant development should not be underestimated. Small highly focused efforts such as the Rice Genome Project were designed to make them pre-eminent in rice research. The Japanese map of the Rice Genome (smallest of the major cereal grasses, one sixth that of wheat) linkages and markers has been highly productive with 53 scientists and a budget of $5.5 million. In a collaboration with British molecular biologists, begun in 1991, they have determined that many markers are in the same relative position on wheat and rice. The colinearity has been observed in barley and rye as well, offering the possibility for a generalized map of the genome of the ancestral grass that provided the basis for all these contemporary cereal grains. There have been recent announcements that the agricultural ministry, buoyed by its success in the

Rice Genome Project, will soon start on an animal genome project using the pig as a model.

Vaccines

Vaccines for prevention are a cost-effective way to control or even eradicate selected infectious diseases. Recently, vaccine therapies for cancer are also being aggressively explored. Active research efforts presently focus on HIV, malaria, tuberculosis, pneumococcus, cholera, rotavirus, measles, varicella zoster, cytomegalovirus, and respiratory syncytial virus. The classical approaches to vaccine development were based on stimulating the body's immune system with attenuated living pathogens (measles, polio, tuberculosis) or with killed infectious agents—a protein from the pathogen and an adjuvant (diphtheria, tetanus, and whooping cough). With genetic engineering techniques, the "blueprint" for specific infectious pathogens antigens can be isolated and subsequently inserted into harmless bacteria or viruses which can then produce the antigen. This can then be used to stimulate the immune system's ability to attack the pathogen without direct exposure to it. Such recombinant sub-unit vaccines have been successfully developed (such as the MS&D vaccine for Hepatitis B) and similar techniques are being pursued to prevent Lyme disease, measles, and malaria.

An alternative approach is the live recombinant vehicle vaccine based on incorporating a gene for a specific antigen into a harmless bacterium or virus which is subsequently introduced into the body. The live organism will then manufacture and deliver the antigen to the body's immune system. These can be more effective as they tend to persist longer in the body and by carrying multiple foreign genes may be able to allow simultaneous vaccination against multiple pathogens. Some are better at stimulating antibodies and others better at stimulating T lymphocyte production. Virus vehicles are being explores for polio virus and adenovirus. The BCG bacterium is being engineered to produce antigens for the pathogens that cause Lyme disease, tetanus, and malaria.

Work on improving preventative vaccines is stirring less interest than the potential for vaccine therapies. A number of small biotechnology firms are pursuing vaccines to stimulate the immune system to fight tumors. Based on advanced cell culture techniques to identify specific tumor antigens, then monoclonal antibody techniques and polymerase chain reaction (PCR), these firms are making rapid progress in identifying cytokines, the chemicals that control the immune system, with the intent of mobilizing the T cells to attack specific tumor types.

Vaccine development makes an immediate and critical contribution to the health of the U.S. population. Given the scientific basis on which vaccines are developed, it also contributes to the goal of retaining U.S. world leadership in science, mathematics, and engineering. Vaccines also have significant implications for national security by protecting U.S. soldiers, sailors, airmen, and marines during peacekeeping and other missions, and by assuring the health of their families while they are on deployment.

There is little commercial interest in the development or production of vaccines for diseases that do not afflict developed countries because of the inability of companies of companies to recoup their investment. Work in this area is performed predominately by smaller biotechnology firms which form marketing and distribution alliances with larger firms to support clinical trials. The NIH is the world's largest funder of vaccine research, spending more than $300 million annually. The Walter Reed Army Institute for Research also a major research funder. There is a joint working agreement in effect to coordinate the efforts of the DOD's U.S. Army Medical Research Command (Walter Reed Army Institute of Research), the U.S. Agency for International Development, and the National Institute of Allergy and Infectious Diseases (NIAID). There are productively active research groups in France, Belgium, Venezuela and England.

MEDICAL TECHNOLOGY

The integration of knowledge and practice of many technologies is essential to an effective and efficient system for protecting the public health and delivering health care services. Innovative biomedical research and information-based decision support systems hold the key to advances that can restrain costs while enhancing the quality of public health and health care.

Health information systems and services

Health information systems and services are discussed in the "Information and Communication" section under Information Management.

Biocompatible materials

Biocompatible materials are materials which are designed to exist and perform specific functions within living organisms. These include a broad range of substances such as structural metallic orthopedic prosthetic implants, artificial blood and skin, and surface coatings for implantable sensors for chronic (long-term) patient monitoring or electrodes for functional electrical stimulation. While implant durability is one concern, the major problem is the body's ability to reject these materials as foreign objects either through an adverse immune system response or by attempting to "wall them off" by surrounding them with a protein layer. Newer porous materials for total joint replacement, by contrast, allow the existing bone to grow into the replacement joint. Structural orthopedic implants are primarily joint replacements for the hip or knee. While implants in less active elder patients were often structurally sufficient, the activity levels of younger patients caused premature device failure, often requiring multiple surgical replacement. Artificial blood and skin have great appeal by expanding a relatively limited resource and avoiding the problems of type matching and screening for bacterial or viral contamination. Chronic monitoring and functional electrical stimulation open the door to more effective low-dose therapies and functional restoration.

Artificial blood and skin have great appeal by expanding a relatively limited resource and avoiding the problems of type matching, screening for bacterial or viral contamination and a very limited shelf life. Most approaches to artificial blood are based on hemoglobin, the protein inside red blood cells that binds and transports oxygen. While hemoglobin can be pasteurized to minimize disease and given to anyone regardless of blood-type, breakdown in the circulatory system with resulting kidney damage remains as a problem. Several methods for using ultrasound to form an aqueous solution of hemoglobin microbubbles are now yielding excellent results, although they have yet to be tested in humans. Though widely pursued, particularly by the Japanese who have had substantial programs in this area, artificial blood remains an elusive objective.

An entirely different approach to biocompatible materials is emerging from the ability to manipulate the body's own immune system. Exemplified by projects to manipulate animal derived extra-cellular matrix to create biologically derived materials for reconstructive applications such as vascular grafts, ligaments or tendons, these are intended to stimulate the body's own cells and induce them to rebuild the lost material. Other efforts are underway to develop implantable "microreactors" containing living cells isolated from the body's immune system to treat diseases requiring replacement of hormones, enzymes, factors, and other cell-produced bioagents. Progress in this area is closely linked to research and development in protein engineering and subsequent tissue engineering.

Biocompatible materials make a direct contribution to the improved health of the U.S. population by enabling a variety of biomedical applications. These materials and their adaptation are part of the growing biotechnology industry, contributing to job creation in that industry. Progress in these areas will be valuable for improved outcomes and reduced length of stay for trauma and surgical procedures. The importance of minimal anesthesia and proper tissue perfusion and oxygenation cannot be over emphasized, particularly in infants or geriatric patients. These materials are also important for the restorative care of battlefield casualties, and so contribute to reducing the damage from military operations.

The U.S. has a substantial leadership position in this area across metallic, ceramic, and organic materials with the possible exception of artificial blood where the Japanese have had a significant concentration of effort.

Functional diagnostic imaging

High-resolution medical imaging techniques, including CAT scans, MRI and Ultrasound, are revolutionizing medical diagnosis and treatment. As a result, they have emerged as critical components of the nation's health system.

Computer driven image processing (enhancement, comparison of episodic changes, quantitative analysis of absorption ratios) has held great promise and is becoming more clinically acceptable with better displays, faster processors, storage systems and networks. As the imaging parameters become more complex in modes such as MRI, decision support systems will become more valuable in making a differential diagnosis based on tissue response to the various excitation modalities available in MRI.

Functional MRI complements earlier methods of functional neurological imaging which used positron emitters carried in the blood stream. One method using labeled water allows the visualization of alterations of blood flow, labeled glucose allows visualization of altered regional metabolism. As astronomers learned that they could benefit from images registered from different parts of the electromagnetic spectrum, brain researchers and neuro-radiologists are beginning to utilize the multi-spectral perspective.

Optical coherence tomography uses infrared radiation to provide cross-sectional images of biological tissues with 10 to 20 micron resolution. While its immediate applications will be in the eye for non-invasive detection of glaucoma and macular degeneration, the ability to analyze the top few millimeters of any biological structure should include arteries and mucosal tissue. As many pathologies such as skin cancers and atheroscelerosis begin on tissue surfaces, the use of various wavelengths may enable rapid, minimally-invasive differential diagnosis. Incorporated in endoscopic procedures, it could provide real-time data on tissue hydration, oxygenation, and guidance for highly selective laser angioplasty.

Functional diagnostic imaging has the capability to improve early diagnosis and through earlier proper treatment, provide improved patient outcomes at lower costs. They also contribute to job creation and economic growth through global export of medical imaging systems. As the imaging chain becomes fully digitized, chemical wastes from film processing will be reduced, reducing the impact of medical technology on the environment. Techniques developed for clinical imaging are also being adapted to industrial quality control as they permit non-destructive testing and visualization of internal structures and flaws in complex metal and composite assemblies.

Functional diagnostic imaging also makes a contribution to the nation's warfighting capabilities. Digital images can facilitate the medical decision making process in isolated or remote military environments, both ship-board and land based, not so much in the management of gross combat casualties, but in the daily experience of sick-bays and medical operating groups. In the event of large scale deployments, digital medical imaging could augment the interpretative capabilities on-site by using state-side radiology and pathology consultants linked to the forward areas.

The U.S. holds undisputed leadership in ultrasonic imaging of the heart and soft abdominal tissues. This is supported by an extensive technology base in ultrasonic transducer design, digital signal processing, and data display.

Computerized tomography is also dominated by U.S. companies after a major marketing-based sorting out that occurred in the mid-1980s. While the initial invention was done at EMI in England, the mathematical reconstruction algorithms were derived from astronomy work and were ultimately dependent on both computer processing capabilities and low noise, high sensitivity detector technologies. Two recent innovations using high speed CT are also enabled by the existing strong U.S. technology base. One system developed by a group affiliated with the University of California at San Francisco Medical Center is derived from linear accelerator technology—the chief physicist in the group having previously worked at the Stanford Linear Accelerator (SLAC). Another system of note is capable of functioning as a "virtual colonoscope"—that is reconstructing an animated visualization of the bowel based on a series of high speed CT images of the air filled bowel—without actually inserting an intrusive instrument. The technology is also dependent on high speed graphic workstations and animation /image reconstruction software.

Magnetic Resonance imaging (MRI) and formerly known as Nuclear Magnetic Resonance imaging (NMR) is derived from a technology used in physical chemistry since the late 1940s. The new systems are dependent on superconductor magnet technologies, digital signal processing and the supporting electronics—areas where the U.S. has a dominant technology base. The most recent developments in the field, functional or spectrographic imaging also draw on that technology base. Bruckner Instruments of Germany is the preferred supplier of ultra high field strength instruments used for research applications.

Although they have not been developing the technology themselves, the Japanese have been eager investors in American technology. For example, Diasonics/Toshiba licensed a highly innovative high field NMR instrument from Imatron, a spin-off from University of California at San Francisco Diagnostic Imaging Group.

Bacterial/viral detection and screening

Rapid identification of bacterial and viral contamination is becoming more important because of newly emerging viruses and the re-emergence of old diseases such as bubonic plague, tuberculosis, and cholera. In contrast to the 1918 influenza epidemic which took 30 days to spread globally in the days of steam ships, present estimates for worldwide spread are on the order of less than seven days. Public water supply contamination has been reported on the increase with presently installed water processing facilities unable to assure the water quality released downstream, and subsequent re-uptake for public water supply unable to adequately filter and remove the viral burden. Improved methods are also needed for assuring a safe, uncontaminated food supply. Hospital infections, their etiology, prevention and control could also benefit from more rapid techniques for differential identification of both bacterial and viral presence. Similarly, antibiotics could be more selectively prescribed with an effective, economic antibiotic susceptibility testing system. Rapid detection and identification of bacterial and viral contaminants is also an issue in an era of the rapid deployment of troops into remote regions for either peacekeeping or regional conflict resolution. In this case both air and waterborne contaminants are of concern as is the provision of s safe water supply. The value of improved systems to dealing with the treat of biologic warfare agents does not require further comment. A range of techniques ranging from the less selective such as bioluminescence based on the presence of ATP and electroconductance methods of bacterial detection to highly specific antibody techniques have been demonstrated under laboratory conditions. Yet a broad spectrum, high sensitivity system with real-time or near real time response is not available for bacteria much less for viruses.

The need for an effective global surveillance and reporting systems cannot be overstated. Bacterial/viral detection and screening technologies would contribute to the health of the U.S. population by assuring a safe water and food supply, reducing hospital acquired infections, and improving the effectiveness of antibiotic therapy in the face of increasingly resistant antibiotic strains. They would contribute to economic growth by contributing to global trade in agricultural products. They would contribute to the improvement in environmental quality by improving the ability to monitor and thus control the discharge of contaminated water into rivers and streams.

Bacterial/viral detection and screening would also improve the ability of the U.S. military to carry out its missions. These technologies would provide support for troops in remote regions without water supplies of known quality, and would also provide an early warning system against biological warfare agents.

There are no clear cut leaders in this area although the Japanese biosensor work and U.S. work of applying monoclonal antibodies hold considerable promise. While the breadth of the Japanese program is quite extensive with over 50 systems having been announced, and they are being developed for both food process monitoring and human health applications, the actual progress and performance is difficult to assess until they are released for independent testing.

Medical devices and equipment

A broad array of electronic monitoring devices are essential for life support and patient monitoring. Providing real-time information on patient status, they are a hallmark of modern medical care in circumstances ranging from hospital operating room to roadside heart attack patient, trauma victims, or battlefield casualties. Passive monitoring instrument for electrophysiology (EKG) and blood pressure are used by the medical staff of the operating room or critical care unit to assess patient status and stability, and the progress of various interventions. Blood gas instrumentation (oximeters and CO_2 monitors) may be used to control respirators or cardio-pulmonary bypass pumps. While these technologies are relatively mature, reduced size, reduced response time and increased stability, accuracy, and precision remain challenges for competitive advantage. Critical parameters such as the adequacy of tissue perfusion and actual real-time cardiac output are being approached by a variety of ultrasound and optically coupled techniques. Signal processing of the raw data and the computer assisted display of the array of multiple parameters so as not to overwhelm the medical staff remain as challenges.

Another example of a group of medical devices are the devices for functional electrical stimulation (FES) which offer great promise for moving the disabled and elderly toward greater independence. Cardiac pacemakers are one example of functional electrical stimulation which have enhanced the lives of millions while providing the basis for a substantial industry with domestic and export markets. Cochlear implants to help with hearing impairments and selective stimulation of nerve and muscle groups to restore paralyzed limbs have made limited progress over the past two decades. FES has also been explored for respiratory support in spinal cord patients with diaphragm activation problems, as well as for bladder and rectum control.

Medical devices and equipment make a major contribution to the health of the U.S. population and to the improvement of quality of life for individuals. These technologies provide greater independence and functionality for the elderly and the injured, allowing them to remain productive members of society longer, and contribute to the effectiveness of the U.S. health care system. They also reduce the human costs of U.S. military actions by providing injured soldiers with care on and off the battlefield and with more normal lives following battle injuries.

The U.S. biomedical industry is estimated to supply 49 percent of the global market. While there are competent competitors in most device markets, the technology base, supporting R&D, and ready availability of quality components all contribute to U.S. technical leadership. There has been a strong academic interest in Biomedical Engineering departments since the late 1960s. Technology transfers and development funded by the aerospace sector contributed to early development. Component sub-systems for imaging such as x-ray tubes and ultrasonic transducers drew on a technology base developed to support microwave transmitter tube and ultrasonic sonar transducers. Laser based instruments have drawn on a technology base developed by national labs for physics research and military applications. While significant innovations such as the lithotriptor and color coded ultrasonic cardiac flow visualization systems have been developed overseas and introduced to the U.S. market, they are an exception.

AGRICULTURE AND FOOD TECHNOLOGIES

Global agriculture is facing the challenges of increasing human population, accelerating need for food, fiber, feed and raw materials for other industries, and a declining amount of cultivated land per capita. There is a growing realization that agriculture, as a form of ecological system, is concerned with the regulation of the abundance, distribution, and behavior of species. Naturally occurring, historic inter-species competition has its counterpart in agriculture which tries to control the inputs of energy, nutrients, and water into productive crops.

Sustainable agriculture production

Sustainable agricultural systems address the development of environmentally sound, productive, economically viable and socially desirable agriculture. The stability and sustained fertility of the soil depend on prevailing soil-climate conditions and on the effects of human activity, There are strict limits to the extant of human influence over soil substrates, ground, soil and surface water, and the resident flora, fauna and micro-organisms which are essential to productive agriculture. The preservation of arable land must continually meet the challenges of desertification, deforestation, salinization, soil degradation and soil erosion. Regional and global climate change also has the potential to alter the productivity and suitability of many crop systems.

Selective breeding to enhance desirable attributes has been a long-standing hallmark of agricultural R&D. Biotechnology and genetic engineering are facilitating the manipulation of seed stock to create food and fiber crops with selectively enhanced attributes such as drought tolerance or pest resistance. Cereal grains such as wheat and rice are being intensively studied, with traits such as growth cycle, disease resistance and stalk height already well known. Efforts are well underway to improve their resistance to fungal, bacterial, and viral diseases, as well as insects, drought and increased salinity.

The preservation of wild seed grain is of continuing importance. Many crops have become highly specialized, whether to enhance crop yield, flavor, or shelf life, but in the process may have become more vulnerable to drought or specific pests or disease. It has frequently proven invaluable to return to historic wild seed to study the basic attributes which may have been "bred-out" in the pursuit of more economically attractive strains. The resulting monocultures reduced tolerance in not problematic under narrowly defined conditions, but when environmental conditions shift significantly (as in the 1970,s mid-West drought and subsequent corn blight) they can be highly vulnerable. Thus the importance of ancestral seed collections as a "reference resource."

Through efforts of the USDA and various land-grant university Departments of Agriculture, the U.S. investment in this area is substantially greater than that of other nations. The published work from Germany and the Netherlands is oriented to production in semi-arid regions such as West Africa. The globally dominant position of the United States in world-wide food production is reflected in the research in this area.

Food safety assurance

Ensuring food safety to the best extent possible is an on-going challenge because the route from field or catch to table is a long one with many handlers involved in processing, storage and transportation. No technology for processing food is universally protective. Pasteurization is quite effective but cannot be applied to solid foods. The increase in food poisoning from bacteria, viruses, and parasites is escalating in almost every country that collects statistics on the subject. Explanations for this increase have ranged from improved reporting and detection, to increased demands for meat and animal products. Attempts to halt these trends in food poisoning occurences have focused on the re-establishment of surveillance systems and attempting to require new testing and standards on the food industry. A system of checks known as the Hazard Analysis Critical Control Point (HACCP) system, initially devised by NASA in the late 1960,s will be required by European Union directive by December 1995.

The application of advanced technologies to monitor food quality and detect bacteria, viruses, parasites, or chemical contaminants is still quite limited in the processing/production environment. While techniques including flow cytometry, immuno-assays, and DNA-hybridization including polymerase chain reaction (PCR) have demonstrated capabilities in the laboratory, it is not currently economic to deploy them in the large volume production environment in today's food processing plants. These tecnologies all offer promise for improved microbial quality assurance and drug or residue detection, but different areas of the food industry such as highly processed foods, fermented foods, and foods of animal origin will require different approaches.

Aquaculture and fisheries

The worldwide demand for fish is steadily increasing, and the wild supply is steadily being depleted. As a result, the interest in aquaculture, i.e., fish farming, has grown globally to an estimated $26 billion a year industry. Aquaculture is increasingly dependent on specially bred stocks and high quality supplies of water which must be properly treated prior to discharge. Acceptance of cultivated seafood among food processors and restaurant operators has been good, driven by the perception that the farmed fish are cleaner and more consistent in quality than the wild catch. The use of feed has grown increasingly efficient with state-of-the-art producers using 1.4 pounds of feed to produce a pound of fish. This compares to chicken farming where the ratio is 2 to 1; a significant improvement from the 15 pounds of feed to produce a pound of chicken that was the norm in 1925.

Aquaculture and fishery technologies make a significant contribution to the safe and abundant food supply in the U.S. They also make a positive contribution job creation and economic growth, and to the U.S. balance of payments by reducing dependence on imported seafood and increasing U.S. exports of fish and shellfish.

Accounting for over 12 percent of the global fish harvest, aquaculture is making a significant contribution to the global food supply. It is estimated that 90 percent of global aquaculture activity is in China where the indoor systems are primarily hatcheries. While Israel, Japan and India have very active programs in this area represented in the open literature, high tech aquaculture is flourishing as a private enterprise in California, Massachusetts, Mississippi, Florida, and Hawaii. Many operators consider their processes to be proprietary, publishing little.

HUMAN SYSTEMS

Advanced human-machine interfaces

A number of integrated systems have been proposed or designed for situations where a human needs to be considered as a necessary part of the system. In such cases, the human-machine interface is a critical component of the system. Such systems typically produce much more data than a human is able to digest in a time-critical situation, so the main job of the interface is to present the data in a form easily understandable by the human and to provide an easy means of interacting with the system. Advanced work on the human-machine interface was initially done by the Department of Defense because of the need to support pilots in combat situations, but as automation and information intensity increase in other fields, human-machine interfaces become increasingly important to the safety and efficiency in a variety of work places.

The field of human factors focuses on human capabilities, behavior and performance while interacting with engineered systems and environments. While the classic perception of human factors deals with aircraft cockpit displays and ergonomics, today it is a design oriented discipline that covers the range of human interaction with complex systems and environments such as the control rooms of power plants, air traffic control, manufacturing, and telecommunications networks. In future "highly automated systems," when staff size is small and the operating environment stressful, the cognitive demands of large, complex and dynamic nonlinear or digital systems quickly outstrip the control capacity of the unaided human. Neglecting human factors can result in labor-intensive operations and increased operating costs, high workload and fatigue, and higher rates accidents resulting from human error. These problems are far from trivial and they can be life threatening.

The design of systems to assist operators in managing cognitive workload, situational awareness, and decision making in automated, multi-task environments is still evolving. Mental workload assessment and guidelines are based on either behavioral or performance-based techniques, subjective assessment techniques or psychophysiological techniques such as heart rate, eye blinks, and brain waves. These techniques can be combined to derive a composite workload estimate that takes advantage of the sensitivities of the various measures. These techniques have been the basis for the development of crew resource management training which is now a standard training protocol for commercial aviation crews. The application of these techniques to the less constrained environment of industrial process control is still in its infancy.

Both the assessment techniques and the decision support aids can be applied to a wide range of task design and training situations, and should be of value in both the transportation and industrial process control environments. Advances in human-machine interface technologies will lead to greater productivity and greater safety in U.S. industry. This technology is also critical for warfighting in the "information-intensive" battlefield.

The DOD Crew System Ergonomics Information Analysis Center, NASA's Space and Flight Human Factors groups, and their affiliated universities and support contractors have been the leaders in the development of advanced human-machine interface. While the information has been widely available, industry has only recently shown a broader interest in incorporating it in system design. While the European community has been more amenable to standards activities such as video display terminal standards and workstation ergonomics, the U.S. has developed a substantial body of knowledge that could be more effectively exploited in the design of large systems and consumer products. Japanese industry has shown some interest in the field and has increased its research funding but the U.S. efforts are so much greater that the U.S. lead in this area is increasing.

6. MANUFACTURING

The technologies in the Manufacturing technology category support much of the industry in the United States. In some cases, the technologies improve our ability to make a familiar substance such as polyethylene. In other cases, as with some new alloys, they open the use of a new material by producing it economically, changing a material from a laboratory curiosity to a commercial force. In still other cases, the technologies improve our abilities to design and to create a product, and to manage that overall process.

The following technology areas are addressed in the Manufacturing category:

Discrete Product Manufacturing
Continuous Materials Processing
Micro/Nanofabrication and Machining

Discrete Product Manufacturing encompasses the most important technological developments in improving our ability to create manufactured products, from the ordinary—an automobile or a television, to the more exotic— a cooled turbine blade. As such, the technologies are important across the breadth of the manufacturing sector, both for the economic health of that sector and for its ability to create leading edge weaponry for the military.

Continuous Materials Processing concentrates on the developments of most importance to the chemical, petrochemical, and some solid materials industries. These are characterized by a continuous production of materials, which are usually then used in other processes or products. These industries, and thus these technologies, are important both economically and for the military. These technologies also often have the potential to reduce the harmful environmental effects either of alternative industrial processes or of other processes, as energy generation. This is both an end in itself and a growing industry in its own right.

Microfabrication refers to the creation of physical structures with a characteristic scale size of one micron, a millionth of a meter. Historically, this has been, and remains, important to the electronics industry, although other applications have also arisen. Nanofabrication refers to the creation of smaller structures, down to the control and arrangement of individual atoms. Such techniques are still developing, but offer fascinating potential. Both areas are also developing rapidly.

The United States is either on par or in the lead in all technology areas in this technology category. While this is not true in some individual technologies, such as the low and medium technology plastic packaging for semiconductor chips in which the Japanese lead, the United States either leads outright or is well-positioned for the future in all other specific technologies included in the report. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 6.1.

DISCRETE PRODUCT MANUFACTURING

This technology area supports most of the manufacturing sector. The technology sub-areas encompass the most important technological developments in improving our ability to create manufactured products, from the ordinary products—an automobile or a television—to the more exotic products such as a cooled turbine blade. As such, the technologies are important across the breadth of the manufacturing sector, both for the economic health of that sector and for its ability to produce affordable leading edge weaponry for the military.

Figure 6.1
Manufacturing
Technology Position and 1990-94 Trend

US Technology Position Relative to:
- Japan ▷, ○, or ◁
- Europe ▶, ●, or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Manufacturing					
Discrete Product Manufacturing				○ ●	
CIM support software			◀	○	
equipment interoperability			●	◁	
intelligent processing equipment			○	●	
robotics			○ ●		
automated systems for facilities operations				▷ ●	
net shape processing			●	◁	
rapid solidification processing				○ ●	
Continuous Materials Processing (?)			○ ●		
catalysts				◁ ◀	
surface treatments			○	●	
ultrapure refining methdos	○ ●				
pollution avoidance			○ ●		
predictive process control			○ ●		
Micro/Nanofabrication			▷	●	
microdevice manufacturing techniques				◁	◀
semiconductor manufacturing			▷	◀	
semiconductor integration techniques			○	●	
artificial structuring methods					○ ●

(?) based on limited information

CIM support software

Computer integrated manufacturing (CIM) combines manufacturing hardware and software technologies to integrate product, process, and manufacturing management information into a single interactive network, greatly reducing the number of "transactions" necessary to produce a product. Although only in the initial stages of industrial implementation, CIM systems are significantly increasing productivity and lowering manufacturing costs by linking previously independent portions of the production cycle such as computer-aided design terminals and numerically controlled machine tools (usually integrated manufacturing cells) that actually produce the finished part. CIM incorporates a number of other technologies that are industries unto themselves, such as CAD/CAM, machines tools, controllers, material handling equipment, data management software, and robotics. CIM support software allows the movement of information between parts of the manufacturing process, and is thus the key to making CIM work.

This technology contributes to several national economic prosperity goals. Its major contribution is to job creation and economic growth because it is an essential part of the new manufacturing infrastructure centered on computer-controlled manufacturing. For example, by contributing to producibility and lower costs of "clean cars," CIM support software plays an important role in making clean cars more economically viable and giving U.S. industry advantage in the new generation of vehicles for world markets. It provides one of the tools which can be used to excel at the products and processes identified by the NEMI as essential for future competitiveness of U.S. electronics industry in world markets. It provides the capabilities to work with new materials tailored specifically to the needs of automotive, electronics, construction and aircraft industries, and is essential to the design and economic production of sophisticated new automobiles and aircraft. Finally, CIM support software contributes to the harnessing of information technology because many of the physical components of the information infrastructure, e.g., integrated circuits, can be manufactured more productively with reliance on CIM.

By increasing the efficiency of the industrial base, CIM support software also helps U.S. national security by increasing the efficiency of the industrial base used for defense applications—particularly important in times of falling procurement budgets.

European developers have made rapid gains during the past few years and are at rough technological parity with the United States in CIM technology. Japan will probably continue to lag in CIM because of an inability to link the various portions of the manufacturing cycle through sophisticated software. Two key factors affecting the future of CIM technologies will be the battle for dominance of operating systems and the adoption of international data standards.

Standardization of manufacturing data would greatly facilitate the exchange of information and, in turn, ease the implementation of CIM.

The United States and Europe are generally ahead of Japan in development of software for manufacturing applications. The U.S. CADAM software package is exceptionally useful for transferring CAD data into numerical control programs, and the recent integration of CADAM with the French CATIA design software provides a powerful system with significant capability for both design and transferring CAD data to production equipment on the shop floor. A large number of competing vendors provide software tailored for various industries and company sizes, running on a variety of platforms. This enables even smaller companies to afford some CAD/CAM capability. Major Japanese companies, on the other hand, tend to use proprietary software, and their smaller companies must purchase foreign software for CAD and CIM applications. Although the Japanese packages used in proprietary applications may be of similar quality to U.S. and European products, the relative lack of off-the-shelf packages in Japan is a market disadvantage.

Equipment interoperability

Equipment interoperability addresses the ability of entire factories to be connected, to share designs and information, and to optimize the manufacturing process. It can also allow sharing between different companies involved in the manufacturing process. As such, it shares the contributions to the future as outlined above for CIM, upon which it depends. In terms of specific technologies, this sub-area includes the CAPP and factory scheduling tools that allow organizational optimization. It also includes the information systems needed to tie together disparate manufacturing operations.

The full contributions of CIM and equipment interoperability can only be captured when the organizations adopt a management method appropriate to their flexibility. This method can be called "lean" or, as in the Defense Technology Plan, Advanced Manufacturing Processes. In a sense, this managerial method is the most important application of these technologies. Together, equipment interoperability, CIM support software, intelligent processing equipment, and the advanced manufacturing processes are important to the health of much of the U.S. manufacturing industry, and thus important to economic growth and national security.

A worldwide movement is underway to standardize factory automation computer data with a focus on CAD/CAM/CAE information. The emerging international standard is called the Standard for the Exchange of Product Model Data (STEP), and nearly all manufacturers recognize it as the future protocol for data transfer/translation in industry. Because of its probably impact on worldwide manufacturing, both Japan and Europe are actively contributing to the formation and structure of STEP.

Intelligent processing equipment

Intelligent processing equipment is manufacturing equipment that uses controllers and sensors to improve the efficiency of the manufacturing process. These sense the state of the tools and the parts and provide feedback to modify the fabrication instructions to meet the design.

Intelligent processing equipment is an important contributor to job creation and economic growth because it is an important part of the new manufacturing infrastructure based on computer-controlled design and production equipment. Specifically, it allows improvements in aircraft production by allowing for variation in materials, tighter tolerances, and greater automation. It also makes partnerships more effective by allowing companies to use shared design and production data. PNGV is one such partnership—decreasing cost and increasing quality of clean cars would make them more economically competitive. NEMI is another such partnership.

Intelligent processing equipment also contributes to harnessing information technology. It provides a specific and sophisticated application for research on software algorithms which combine material characteristics and sensor outputs with spatial and temporal definitions of finished parts. It also allows individual companies to take advantage of databases and networked systems for manufacturing, giving them greater access to information relevant to their products and production processes.

By increasing the efficiency of the industrial base, intelligent processing equipment also helps U.S. national security by increasing the efficiency of the industrial base used for defense applications. Such equipment can efficiently produce equipment from new materials and in new shapes and to tolerances that might be different from those for commercial equipment without having to be specifically designed and constructed for the purpose.

Europe, Japan, and the United States are at overall parity with respect to shop floor level hardware. Japan is ahead in using computer numerical controls (CNCs) and flexible-manufacturing systems—particularly in smaller companies, indicating a significant depth of capability. Only 20 percent of small- to medium-size U.S. manufacturers use CNC technology, while 50 percent of comparable Japanese companies take advantage of CNC. Most of this technology is considered to be below the CIM level but, nevertheless, forms an important market strength and supports the development of upper-level CIM and CAD/CAM systems. At the highest technology levels for CNC, however, Japan is being challenged. ARPA and NIST are developing the next-generation controller that may be used in future CIM applications. European ESPRIT programs also have similar efforts underway to create their next generation controller.

Robotics

Robotics, in its full meaning, refers to an autonomous system, capable of responding to much greater uncertainty in its environment than the flexible manufacturing systems currently in use. Robotics are discussed in greater detail in Intelligent Complex Adaptive Systems/Autonomous Robotic Devices under Information and Communication.

Automated systems for facilities operations

Automated systems for facilities operations are systems that track and adjust resource usage as needed. There are two specific types of technologies under discussion here. One is the automatic ability to monitor and adjust the operating environment in the building. The other is the ability to use automation to control inventories and materials flow during the production process.

Computer controlled management systems for heating, cooling, ventilation and lighting can provide a better environment for human activities at much lower energy consumption and dollar cost than conventional manual controls. "Smart buildings" that offer real-time information about energy usage and costs also allow building owners and tenants to become more energy efficient. Building automation systems are an important part of the physical infrastructure of the future, leading to many changes in the way buildings are designed and built. Automated systems will allow more precise control of environments which will reduce wasteful use of resources, providing important competitive benefits to U.S. firms. It will have a similar effect on other kinds of facilities. Defense manufacturing facilities are likely to benefit in the same way as civilian manufacturing facilities.

Automated monitoring and control of the production cycle, especially of parts flow and inventory, is improving the efficiency and productivity of U.S. industry. Computers that track inventory levels and automatically originate purchase requests when inventories reach pre-specified levels allow a more efficient use of inventories and more efficient production of parts and sub-assemblies. Automated scheduling allows for a better loading of production equipment and more efficient production schedules. However, many of these systems are not yet linked in a meaningful way with CAD, CAE, and financial systems of companies.

Japan and Europe lag the United States in computer controlled management systems for production flow. For example, advanced systems such as Materials Requirements Planning (MRP) and Manufacturing Resource Planning (MRP II) are computerized manufacturing control and support systems that plan and execute production by matching inventory and materials needs. By tracking availability vs. factory need and automatically originating purchase requests, production is kept moving on a predetermined schedule. Because these technologies are software-intensive, Japanese firms have not yet made large inroads in these areas. Rather, Japanese manufacturing depends more on Just-in-Time and other manufacturing practices that are less software-intensive, but highly effective in dealing with material and production flows. For the most part, Europe is not limited by software capabilities and is pursuing production flow technologies similar to those in the United States.

Net shape processing

Net shape processing refers to any manufacturing process which creates an object in its finished form *without* the need for finish machining or other actions. The obvious benefit is in the saved labor needed for finishing, and the consequent cost savings. Less obvious is the potential for quicker production, which fits better the overall lean production paradigm. Net shape processes are as familiar as the forming of glass bottles or the injection molding of simple plastics. What is new is the applicability of these methods to new materials. An example that appears to be important to the Partnership for a New Generation Vehicle is production of polymer composite parts where small fibers are included in an injection system. Other techniques, such as superplastic forming, are applicable to other materials, in this case, superalloys.

The major contribution of net shape processing is to job creation and economic growth because it enables cost reduction in the manufacturing process and makes some applications economically feasible. For example, net shape processing is important for economic fabrication of potential next generation vehicle power plants such as small gas turbines. Additionally, injected composite parts are likely to play a large role in the weight reduction sought in the program. Net shape processing contributes to other sectors of the economy by improving economic feasibility of working with non-traditional materials, e.g., superalloys and ceramics for turbine blades.

Net shape processing contributes to national security by contributing to the strength of the industrial base.

Europe and the United States are essentially equal in application of superplastic forming (SPF) of titanium and aluminum products. European firms have used SPF to produce secondary aircraft structural components. France's ACB Alsthom is equal to U.S. firms in development of commercial SPF press equipment and systems. The UK Superform Company leads the world in aluminum SPF, and its French and U.S. subsidiaries provide those countries with substantial capability. Japan trails slightly, but has a very strong research program that may contribute to an eventual lead in some aspects of the technology. However, their small aerospace industry has generated few practical applications. No country has mastered solid state bonding of aluminum SPF components in the same processing step.

Rapid solidification processing

Rapid solidification processes allows the creation of new alloys. Some metals, when together in a melt, segregate. By spraying or otherwise adding the metals in controlled amounts directly into the solid phase, new compositions can be fabricated. In some cases, these alloys have unusual temperature properties, or high strength. Rapid solidification processing strengthens the industrial base for both commercial and military applications by improving the ability to work with difficult to shape materials. As a result, parts with better characteristics can be created in the longer term.

Both Europe and Japan are slightly behind the United States in rapid solidification processing, or powder metallurgy technology, and are expected to remain in that position over at least the next several years. Development of powder metal technology within Europe has been led by turbine engine manufacturers in the United Kingdom, France, and Germany. Capabilities have grown through a combination of indigenous development and acquisition of technology through joint ventures with U.S. companies. Japanese firms also have a strong powder metallurgy R&D program established for both the automotive and aerospace industries, with laboratory work rivaling that of the U.S. leaders. However, they tend to lag the United States in applications. The Japanese appear to be content to remain near the leading edge of technology, without undertaking the increased risk of pushing the technologies to new levels.

CONTINUOUS MATERIALS PROCESSING

This technology area concentrates on the developments of most importance to industries such as chemicals, petrochemicals, and some solid materials which are characterized by continuous production, the end products of which are usually then used in other processes or products. These industries, and thus these technologies, are important both economically and to support the military. These technologies also often have the potential to reduce the harmful environmental consequences of certain processes.

Catalysts

Catalysts are materials which speed up a chemical reaction without being consumed by it. In many cases, this speed-up makes a reaction commercially important, and the catalyst vital. An example of such criticality is the catalyst in a polymer electrolyte fuel cell. At the low temperature of that fuel cell, about 100°C, the reaction of hydrogen and oxygen that produces the power would proceed at such a slow rate as to be only a curiosity. Noble metal catalysts make the rate useful for a host of applications, perhaps including transportation. As our ability to design materials on the atomic level has grown, new possibilities seem promising, as for artificial zeolites. Very different catalysts are those created in biological systems, where they are the base for metabolism and many other functions. Here, there is a potential to create new drugs.

Catalysts are important to the near-term aims of the Partnership for the New Generation Vehicle. In particular, a NOx catalyst is important in enabling options like a lean-burn diesel. Catalysis can be an important step in removing key contaminants, both from power plant effluent and from process plants, contributing to efficient energy production and utilization. Catalysis is also important to the chemical and petroleum industries, where advances have created many new products and processes, from Kevlar at DuPont to the Monsanto process for acetic acid. The importance of catalysis should increase as our ability to analyze and to design catalysts improves.

The United States has historically led in the technologies of catalysis, which supports our strong chemical and petrochemical industries. In fact, much of the research in catalysis is funded by those industries and remains proprietary. Overall, the United States remains the world leader in petroleum catalysis; is among the world leaders in catalysis for commodity and specialty chemicals; and is improving in environmentally related catalysis.

Several European nations and Japan support research in catalysis generally, recognizing the importance of the area. This has produced important new discoveries in those nations. The most striking such recent development is the revolution in olefin polymerization, which promises widespread benefits or cost savings for most polymers. The new developments in metallocene catalysts were discovered in two German universities, and are now being aggressively developed in Europe, the United States, and Japan. In the United States, these compounds are being aggressively developed both by Dow Chemical Corporation and Exxon. While the United States is still the overall world leader in catalysis, and so was able to exploit this breakthrough quickly, the competition is getting stronger.

Surface treatments

Surface treatments include various hardening techniques, from chemical to laser, and range all the way to thin films, an example also of artificial structuring. In general, the treatments offer a way to tailor the surface properties of a material without changing the bulk properties. This allows very hard cutting tools to have great strength and toughness, for example, or allowing materials to survive very corrosive conditions.

Surface treatments provide better finishes and higher quality materials for several industries and applications. Particularly important are ceramic "hot" parts for turbine engines. Surface treatments provide improved military equipment capabilities by creating parts with better finishes and increased durability. Although militarily distinct applications are rare today, some parts of high speed aircraft and submarines require surface treatments different from those available in civilian markets.

The United States and Japan are world leaders in diamond thin-film technology. With products such as diamond tool bits and heat sinks already on the market, both countries are aggressively funding research toward advanced applications such as diamond-based semiconductor devices, integrated circuits, displays, and biomedical coatings. The United States is very strong in some applications, such as military products and diamond windows for infrared transmitting devices. However, Japan has a focused government research program targeting electronics and optical device applications—areas which industry experts predict will eventually account for most of the market for diamond films. While Europe and the rest of the world trail significantly in technology and funding, over two dozen countries worldwide are pursuing basic research. However, given the funding levels in Japan and the United States, Europe and the rest of the world will likely need increased efforts to become competitive.

Ultrapure refining methods

Refining methods which produce ultrapure materials are important for a number of commercial and national defense applications. As feature sizes of integrated circuits get progressively smaller, the purity of the semiconductor materials from which they are fabricated has historically been increasingly important. Development of extremely pure semiconductor crystals is also important for optoelectronic and photonic applications. More recently, chemical vapor deposition and similar thin film techniques have been used to create a pure silicon layer on top of a wafer. That layer is then used to build the actual devices. Consequently, ever increasing the purity of the underlying ingot has become relatively less important to microelectronics. Some processes, such as silicon-on-insulator, even obviate the need for very pure ingots, but the dominant current processes still demand significant purity.

Ultrapure materials are also important for structural applications, since microscopic impurities can cause cracks in ceramics and ceramics-based composites. In general, ultrapure refining methods include micro-gravity and high-pressure fabrication methods which suppress convection currents in the material and allow even distribution of impurities or their elimination.

Internationally, Japan and Germany still lead in the creation of large, pure ingots of semiconductor materials. The ability to create ever larger ingots of pure silicon remains important to advanced microelectronics.

Pollution avoidance

Pollution avoidance technologies are those technologies that "avoid the production of environmentally hazardous substances or alter human activities in ways that minimize damage to the environment. These technologies include equipment, processes, and process sensors and controls designed to prevent or minimize the generation of pollutants, hazardous substances, or other damaging materials, as well as technologies used in product substitution or in recycling and recovery of useful raw materials, products, and energy waste streams. Prevention may include incremental changes to existing manufacturing infrastructure, such as replacing volatile organic compounds with aqueous cleaning systems, using more efficient motors or lighting, or substituting a less hazardous intermediary. But it may also involve substantial changes in industrial infrastructure, such as near net shape casting, no-coke steel making, or entirely redesigned processes (design for environment). Such extensive changes in production processes usually require development of a new attitude toward doing business. They are labeled with different names in various sectors of the economy. Examples in the manufacturing sector are "design for the environment" or "green design." In agriculture, the descriptive phrase is "sustainable agriculture systems."[1]

According to the Environmental Technologies Expert Working Group, process industries such as chemicals, petroleum refining, and pulp/paper, which are large sectors in the U.S. economy and have an international presence, can especially benefit from advances in this area. As worldwide environmental regulation becomes stricter, companies that incorporate pollution prevention technologies into their products and processes will gain competitive advantage. Increased sales of equipment would contribute to job creation in the U.S. A further contribution to economic prosperity is expressed by the contribution of pollution prevention technologies to the success of the PNGV. Sectors of the economy most directly affected are Manufacturing and Transportation and Utilities, Agriculture, Forestry and Fishing, and Mining. Pollution prevention technologies also contribute to the health of the U.S. population by contributing to the security of food and water, and to improvements in environmental quality.

Because of the worldwide focus on the environment, the United States, Japan, and Europe all have a wide range of pollution minimization programs and technologies. There is no clear overall leader. In one important area—developing alternatives to chlorofluorocarbons (CFCs)—Japan, the United States, and to a lesser extent, the United Kingdom have taken the lead. Reductions in manufacturing costs and the development of application-specific products and processes will largely determine competitive position in the next few years. CFC-related research is likely to continue at its present rapid rate or to increase in response to tougher regulations. Japanese and German firms, both with government support, have launched research programs to develop CFC alternatives. Japan, because of its electronics industry, is emphasizing research in solvent technology and has begun to market solvent substitutes and solvent recovery/recycling systems domestically. Germany, is using financial aid and

[1]National Science and Technology Council, pp. 42-43.

technological assistance to promote its hydrocarbon-based domestic refrigeration program.

Predictive process control

Predictive process control involves the ability to monitor and control a continuous materials process in real time. This allows the conditions of the process to be adjusted quickly and responsively, and avoids the delay associated with only monitoring the final product.

Advancing the state of the art in predictive process control requires advances in sensor capability, in data communications and data processing, and in modeling. Improved interfaces with operators, usually via graphic displays, will also provide improved control system performance. The most important class of sensors for this sub-area is non-imaging sensors which can be used to measure a vast range of phenomenology such as temperature, pressure, humidity, radiation, voltage, current, or presence of a particular chemical or biological material. In addition to passive sensors, there are active sensors based usually on lasers. Specialized microsensors can be used to detect particular chemical or biological agents. The information generated by the sensors must be combined and processed using data processing and models specific to the process being monitored.

The potential of this technology sub-area is great, as it can improve the yields and productivity of a wide range of industrial processes. It can also contribute to the reduction in unwanted or polluting side processes.

The United States is a major player in all of the technologies which make up predictive process control. For example, historically Honeywell has had a major presence, having introduced the first distributed control system (the Honeywell TDC 2000) in 1975. Honeywell continues to be a leader, advancing the state of the art with the introduction of the TDC 3000, which incorporates protocols to address modeling errors. Honeywell smart transmitters are available to provide data to the control system. Other U.S. players include Rosemount, Foxboro, Digital, Setpoint, DMCC, and Gensym.

Many other countries are also players in this area, however. In the UK, BNFL has developed the Promass advanced control system, and Predictive Control has developed an advanced controls package called Connoisseur. In Germany, Siemens Industrial Automation, AEG, and Lockner Moeller have been leaders in designing control systems with open architecture. The Japanese company, Yokogawa, is active in the International Fieldbus Consortium. Little information about Japanese work in this field is available in open English-language literature.

At this time one of the more important "battles" in the development of predictive control systems is being waged over the development of standards and protocols to enable communications between field-level devices (such as transducers, actuators, and local controllers) and supervisory controllers. Organizations competing to develop standards include the ISP (InterOperable Systems Project), whose standards are based largely on Profibus (process fieldbus) technology, which is a German national standard, and thus very popular in Europe; the International Fieldbus Consortium, which promotes the IEC Fieldbus; and the widely supported breakaway group WorldFIP, which is a global organization formed to develop an open, universal, fieldbus specification based on the best of both the Factory Information Protocol and emerging versions of the IEC/ISA standard.

Another trend of interest is the recent tendency for companies working in different but interacting areas of advanced control to form strategic alliances, or even outright acquisitions. For example, Honeywell, with expertise in control systems, modeling, and sensor technologies has entered a working agreement with Masonelian, which makes control valves. Usually, the companies are from the same country, such as Honeywell's acquisitions of Profimatics, Inc., and Allied Data Communications, but this is not always the case. Foxboro, for example, has recently signed an agreement with Maihak AG of Germany for reciprocal marketing of analytical products.

MICRO/NANOFABRICATION AND MACHINING

Microfabrication refers to the creation of physical structures with a characteristic scale size of one micron, a millionth of a meter. Nanofabrication refers to the creation of smaller structures, down to the control and arrangement of individual atoms. While grouped together here and bearing some similarities such as the use of vacuum facilities to avoid surface contamination, the techniques used differ dramatically in accordance with the scale involved. Nonetheless, both areas are developing rapidly.

Recently, the production processes used for the fabrication of integrated circuits (chemical etching, material deposition, lithography, etc.) have been used to make mechanical structures. A number of technical problems, such as lubrication, micro batteries, temperature compensation and others, will probably prevent useful applications of microscopic analogs of conventional machines (motors, drills, robot arms, etc.) for the foreseeable future. On the other hand, resonant microbeams are already being used to sense linear and rotational acceleration. The ability to combine these mechanical structures and electronic circuitry on the same piece of silicon is important both economically and militarily.

Microdevice manufacturing technologies

Microdevice manufacturing technologies have the long-term potential to change and influence many areas. Many machine tools can be significantly improved with better sensors and finer control over tiny details. By creating tiny devices, microdevice manufacturing technologies may make possible new classes of much lighter satellites. Many microsensors, including biosensors and chemical sensors, have the potential to be mass produced once the individual steps are created. Thus, microfabrication techniques have become very important to sensor technology as miniaturized, integrated systems have become possible. New instruments, such as ever finer atomic force microscopes and derived instruments, involve such technologies and create improvements to infrastructure for world class science. In the longer term, there is a possibility of creating integrated computers and small machines for a variety of applications. Many of the applications described above would be useful for both commercial and military purposes.

The United States is the world leader in microelectromechanical systems (MEMS)—miniature mechanical devices integrated with microelectronic devices on the same substrate. Japan and Europe (Germany, Switzerland, the Netherlands, and the United Kingdom) all have MEMS R&D programs, with Japan's being the largest. Much of the Japanese research is geared toward medical and industrial microdevice applications. MEMS is not limited to silicon micromachining but may also include metallic and polymeric micromachining technologies as well as other microelectronic fabrication techniques.

Semiconductor manufacturing

Microfabrication remains the basic manufacturing technology of the semiconductor industry. Semiconductor manufacturing technologies are concerned with the creation of smaller structures for semiconductor chips. The methods are based on silicon, and structure the surface of the silicon. Here, the trend continues to ever smaller device sizes using shorter wavelength light in optical systems. At some future point, other technologies, whether x-ray lithography, electron beam lithography, or other ideas, will take over, and such technologies appear as specific technologies in the list. Developing the methods to continue the push to ever smaller device sizes is important to the health of our electronics industry and to the creation of defense systems that rely upon such advanced devices.

Semiconductor manufacturing technologies are essential to the success in production of next-generation integrated circuits. Given the importance of these ICs to the U.S. economy, semiconductor manufacturing technologies make a major contribution to the economic prosperity of the U.S. through job creation in the semiconductor and downstream industries. In addition, these technologies enable harnessing of information technology by creating improved components for computing systems, and by enabling better interface devices for human-computer interactions.

Given the importance of semiconductors in such military applications as computing, simulation, and smart weapons, semiconductor manufacturing technologies make a significant contribution to a number of national security goals. They enable the creation of components for real-time knowledge of the enemy and near-real-time distribution of this knowledge to the fighting forces, contributing to the JCS Top 5 Future Warfighting Capabilities as well.

Although the Japanese dominate the low and medium technology used in semiconductor plastic packages, there is overall parity in the most advanced packaging technologies. Companies from Japan, Europe, South Korea, and the United States have all demonstrated advanced package types, such as multichip modules, although the materials used to make them are produced mostly by Japanese companies. These advanced packages are capable of housing high-density semiconductors—or many semiconductor devices—with increased system performance, reduced space requirements, and lower costs. In some leading-edge areas, the United States has benefited from a more sophisticated military market than exists in Japan. U.S. companies are actively moving this technology into the commercial world.

Semiconductor integration technologies

Semiconductor integration technologies are technologies for combining multiple integrated circuits into efficient modules for performance of complex tasks. Integration technologies are essential for creating economically competitive multi-component systems. They also involve improvements in materials technologies because they involve advanced ceramics and other materials. Semiconductor integration technologies also contribute to harnessing information technology by reducing costs of components for computing systems and by creating multi-chip modules which allow faster movement of electrons between ICs.

Semiconductor integration technologies contribute to national security and warfighting capabilities. By creating smaller and faster equipment with multi-chip systems, semiconductor integration technologies contribute to a capability for real-time knowledge of the enemy and its near-real-term distribution to the fighting forces.

Japan and the United States are roughly comparable across the entire range of semiconductor manufacturing equipment; Europe lags slightly. In one of the single most important areas—optical lithography—firms in Japan, Europe, and the United States all have generally comparable technology, even though Japanese firms have a substantial lead in market share. Companies from each region have leading-edge capability in state-of-the-art, i-line wafer steppers; all are developing successor wafer stepper systems using excimer lasers—rather than mercury arc lamps—to generate deep ultraviolet light for shorter wavelengths. Japanese firms are benefiting from one major U.S. lithography firm going out of business in 1993 and another U.S. firm licensing its advanced technology to Canon. Some observers believe that Japanese firms will eventually pull ahead of their competitors and acquire technology leads as a result of their growing market strength and extensive R&D programs. Japanese and European firms currently have a slight technology lead in R&D for X-ray lithography, the possible next generation of semiconductor lithography equipment. Japan has developed many synchrotron orbital radiation sources for x-ray lithography while the United States has relied on the UK firm, Oxford Instruments, one of the world leaders. Much of the Japanese work has been pushed by the government, with corporate commitment weakening as optical lithography capabilities improve. European R&D is also quite good but less extensive than Japanese efforts. Japan is also strong in other advanced lithography areas, such as ion-beam devices, in which they are only slightly behind the best U.S. work. Neither is likely to be a mainstream production technique for a long time, but could have limited applications in mask production or repair.

Japanese, European, and U.S. firms are generally equal in tester technology. European and U.S. firms improved their position in VLSI logic testers in recent years by shifting to a tester-per-pin technology while their Japanese rivals stayed too long with the older shared-resource technology. A Japanese firm, however, responded by bringing out a VLSI logic tester with tester-per-pin architecture and probably the fastest data rate and largest pin count now available. Each of the major tester areas is led by a company from a different region. Schlumberger, a European company—with its operations based in the United States—leads the logic test sector. Advantest, a Japanese company, leads the memory test sector. Teradyne, a U.S. firm, leads the linear/mixed signal sector. Foreign competitors are likely to slip further in technology. As the semiconductor market shifts more to complex logic devices such as microprocessors, U.S. tester companies will respond to their demands for faster and more capable testers and become stronger competitors to the Japanese and European firms.

Artificial structuring methods

Artificial structuring of materials refers to the ability to layer and combine materials on a microscopic level. This small scale ordering using thin film deposition technologies makes it possible to generate novel properties that could not necessarily be predicted from the initial material constituents, and provide the ability to generate both new materials and on a new scale. The current largest-scale manufacturing efforts rely largely on sputter deposition and spin-on coating technologies. However, the development of new materials is increasingly reliant on more advanced techniques such as chemical vapor deposition and molecular beam epitaxy.

Artificial structuring methods have enabled major advances in a diverse range of industries. Such manufacturing capabilities are the enabling technologies for end products in defense, information technology, manufacturing, energy, and transportation systems. From a commercial perspective, these techniques have produced tremendous growth in microelectronics, high-density data storage, and photonics. The dependence of information and communication technologies on such products highlights the importance of the underlying manufacturing capabilities. Future development of micromechanical systems also depend on the precise control of thin film properties. The evolution of more sophisticated manufacturing techniques is critical to the realization of advanced coatings with enhanced hardness, corrosion-resistance, thermal, and wear characteristics. One of the most exciting candidates is the large-scale production of high-quality diamond thin films because of their hardness, wear-resistance, and very good thermal conductivity at extremely low temperatures. Some of the techniques allow systems of lower dimensionality or very small scale to be created, which, in turn allows examination of fundamental material properties.

Given the increasing dependence of the military on high-technology products, it is apparent that continued investment in artificial structuring methods is essential for sustained security. For example, the manufacture of high-definition displays is dependent, among other things, on advanced thin film techniques. Also, the successful development of diamond coatings has applications ranging from aircraft windshield coatings to high speed electronic components. Artificial structuring methods clearly strengthen the S&T base and the industrial base for defense production, as well as allowing for the creation of products that can be used in new environments and to fulfill new missions

The United States has improved its technology position in several other areas of semiconductor manufacturing equipment in recent years. Japanese and European firms are slightly behind in chemical vapor deposition (CVD) technology as U.S. firms have taken the lead in introducing new high-density plasma CVD systems for 0.35-micron devices. Japanese and European firms are unlikely to gain substantially on U.S. firms in CVD equipment over the next few years, because several U.S. firms have strong technology leads over their rivals. Japanese and European firms also lag U.S. firms in physical vapor deposition (PVD) technology and markets. A U.S. company has pioneered the introduction of technology that has resulted in low particulate contamination levels and excellent and consistent film properties. Japanese firms have also been slow to match U.S. firms which have led the trend toward cluster tools, capable of integrating different semiconductor manufacturing steps. Foreign firms are also substantially behind the United States in ion implantation technology and are likely to continue in this position. One U.S. firm—the market leader—introduced new high-current and medium current ion implantation systems in early 1994. Japanese and European companies also lag U.S. companies in dry-etch equipment. According to some industry observers, the U.S. has taken the lead because the fabrication of such complex logic devices as advanced microprocessors requires more levels of metal—and more dry etching. Japanese firms are working to improve their technology capability in dry etch equipment and are likely to close the gap somewhat. Two Japanese companies, Canon and Anelva, have licensed a U.S. company's plasma source technology.

7. MATERIALS

Materials allow the achievement of a wide range of national goals. Improved materials can help our economic prosperity, our health, our security, and the quality of our lives. A few materials contribute only to a single national goal. For example, our national security is enhanced by new combat aircraft that use stealth materials to help control their signature, but such materials are not at all desirable in use for commercial aircraft which need to be visible and easily identifiable. Such limitation is the exception, not the rule.

The ubiquitous nature of materials, entering into almost every industry and activity, makes materials a key set of enabling technologies for a multitude of goals. Advanced alloys, ceramics, composites, and polymers are enabling technologies for, among other ends, high-performance aerospace and surface transportation. This supports both civil and military systems. Functional materials, such as diamond thin films, can provide enhanced physical and electronic characteristics for a wide range of applications in the manufacturing and electronics industries. In turn, this couples not just to economic goals, but to other goals, from environmental to space exploration. New materials are also key to many manufacturing developments, whether through improving existing products or through creating entirely new possibilities.

The following technology areas are addressed in the Materials category:

Materials
Structures

No single assessment of the performance of the United States could be appropriate across a range as broad as that represented in the technology sub-areas, and indeed, the international position of the United States in Materials is mixed. Although generally leading, there are some areas where the lead is shrinking or a lag has appeared. Some of these assessments are familiar, as the foreign lead in materials for semiconductor manufacturing, or the U. S. lead in polymer matrix composites. Others may be less familiar, as the good U. S. position in ceramic composites, where we do not yet lead the Europeans, but appear better positioned than the competition for the emerging market. Our long concentration on materials science has paid dividends. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 7.1.

Figure 7.1
Materials
Technology Position and 1990-94 Trend

US Technology Position Relative to:
Japan ▷ , ○ , or ◁
Europe ▶ , ● , or ◀

1990–94 Trend
Improved ▷
Declined ◁
Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Materials					
Materials				◁ ●	
alloys				◁ ◀	
ceramics	◁		●		
composites				○ ●	
electronic, photonic		◁ ◀			
high-energy density materials		●*	●	◁	
highway/infrastructure		◁ ◀			
stealth materials				●	○
superconductors		◁		●	
Structures				●	◁
structures—aircraft				●	◁

*Russia

MATERIALS

Alloys

Alloys are a set made up of combinations of metallic elements. The news about alloys is the ability of new material processing techniques to combine hitherto incompatible materials. This has created alloys with new characteristics, such as high temp capabilities unavailable before.

Alloys contribute to job creation and economic growth through efficiencies in production of automobiles and aircraft, in construction, and in other industries where materials can be created for specialized applications. Alloys contribute to enhanced national security by allowing the creation of better quality and less expensive military equipment.

The United States has a slight overall lead in metals technologies, but there are important areas in which foreign firms are equal or slightly ahead. France, the United Kingdom, and Russia, for example, are all about equal to the United States in aluminum-lithium alloy technology. Russia is quite strong with capabilities very close to those of the United States in many areas of advanced metals, including titanium, aluminum, and superalloys. Russian high-strength titanium alloys, if performance claims are true, are equal if not superior to corresponding materials in the United States. France, at the forefront of European aluminum-lithium alloy technology, is being helped by cooperation with Russia. The United States retains a slight technology lead in high-purity titanium alloys, but French research for the next generation of aerospace-grade titanium alloys is approaching U.S. research in terms of goals and achievements. U.S. and European firms, driven primarily by their aerospace industries, have a technology lead in superalloys which are used in a variety of high-temperature and corrosive environments, ranging from jet engines to chemical processing plants. Japan recently completed a national-scale project to develop superalloy capabilities and further research is underway to match U.S. and European capabilities in producing state-of-the-art single-crystal superalloys for aerospace applications. Japan's production capabilities cannot yet match those of U.S. and European firms, but its focus on manufacturing should lead to improvements.

The United States was the first country to perform engine tests of intermetallic gas turbine blades and has a clear technology lead. German, French, and Japanese research has been comparable to that performed in the United States, but has generally focused more on research than on near-term applications development. The Japanese have developed an intermetallic for turbine blades, but its overall properties are behind those in the United States. Although the United States currently has the lead, both in technology and production capabilities, Europe and Japan are close enough that many industry observers expect the future market to be evenly split, with each country favoring indigenous production. Russia may have an advantage in its ability to weld advanced alloys, which can help in some applications of those alloys.

Ceramic materials

Ceramics are polycrystalline non-metallic materials. These materials are used in pure form as well as in the form of ceramic matrix composites. (See Composites below.) Ceramics are ideally suited for high-temperature applications, especially in advanced turbine engines, thus increasing engine operating temperatures, making the engine more efficient while lowering overall weight. Ceramics are now being used for many applications that previously involved metals, including cutting tools and automobile engine parts. The problem with ceramics is their brittleness, cost, and difficulty of manufacture. The high brittleness makes ceramic parts extremely prone to impact damage, usually resulting in catastrophic failure. Brittleness might be overcome by using ceramic matrix composites or by new superplastic ceramic technology. The ability of ceramics to be molded allows for the creation of specialized shapes, and the reinforcement of ceramics with composites creates materials of great toughness. Nevertheless, monolithic ceramics will, most likely, see only limited application on advanced turbine engines. One of these applications is the use of ceramics in advanced engine bearings. Significant weight savings over metal bearings will allow engines to achieve higher shaft speeds.

Ceramics contribute to job creation and economic growth in several ways. Their lower heat conduction helps engine efficiency, particularly for diesels, while ceramic coatings reduce friction between automobile engine parts, making automobiles more productive in world markets. In addition, to contributing to efficiency in production, ceramics contribute to improved environmental quality by improving fuel economy and reducing emissions. By reducing friction between parts and lowering the need for lubricants, ceramics also contribute the U.S. national security by reducing the need for logistical support, and thereby improving U.S. global power projection capabilities and effectiveness of warfighting in unconventional conflicts.

The major area of Japanese materials strength is in ceramics. Japanese ceramic fibers and powders are believed by industry experts to be the highest quality in the world. Ube's "Tyranno" fiber and Nippon Carbon's "Nicalon" and "Hi-Nicalon" are considered the best silicon carbide fibers available for use in ceramic composites. Japan currently ranks first in the world in applying monolithic ceramic components such as turbocharger rotors to automotive engines. The willingness of Japanese automakers to incorporate ceramic parts into their production automobiles has given Japan valuable experience in real world applications. Kyocera and NGK Spark Plug, which began introducing ceramic turbochargers for use in Japanese automobiles in the late 1980s, are now mass producing turbochargers and ceramic exhaust valves. Although German companies are developing similar ceramic valves, they have not begun using them on a production scale. Japan has also applied ceramics to machine tool parts such as bearings, rollers, and tool inserts. The technology necessary to produce these components provides Japanese firms with the basic building blocks for eventual production of components for more demanding applications such as cruise missile engines, auxiliary power units, and industrial and aircraft gas turbine engines. Japanese firms benefit from active government support as well as from spin-off capabilities flowing from their dominance of electronic ceramics. Japan's lead in ceramics is directly attributable to a focus on monolithic ceramics, whereas other countries, such as the United States, have allocated more resources to developing ceramic composites for comparable structural applications.

Composites

Composites are materials which are composed of fibers embedded in a matrix. The matrix material in powder or liquid form is combined with reinforcing fibers in a mold, where the combination is subjected to heat and pressure to fuse the part together. Different materials can serve as the matrix, including metals, ceramics, and plastics. The characteristic of composites that makes them most attractive is their ability to provide increased strength and stiffness at smaller weights than would be needed from conventional materials. The weight reduction permits significant improvements in military and civilian applications. As an example, composite materials reduce aircraft empty weights and increase fuel fractions, leading to smaller, lower-cost aircraft that use less fuel to perform a given mission. For airliners, this translates into simple economics, leading to overseas sales—or purchases. For military aircraft composites reduce weight, and therefore life-cycle cost and fuel usage. Also, composite materials lend themselves well to stealth applications. Forty percent of the structural weight of the F-22 will be polymer composites, and it is highly likely that advanced transport aircraft will also make high use of composites. Inspection and repairs of structural composite parts remains a challenge for both civil and military aircraft.

The metal-matrix composites use metal rather than plastic as the matrix. Usually the metal is in the form of a powder which is combined with the reinforcing fibers in a mold, where the combination is subjected to heat and pressure to fuse the part together. Metal matrix composites (MMC's) have advantageous properties of higher strength, stiffness, wear resistance and elevated temperature properties, and are especially applicable for high-temperature uses such as in jet engines. Many metal matrix-composites can be machined on the same apparatus used for traditional metals and some can be welded. Matrix materials include nickel, superalloys, titanium alloys, aluminum alloys, magnesium, copper, intermetallics, and steels. Fibers include, silicon carbide (SiC), refractory metal wires, and carbon fibers, among others.

Metal matrix composites have the potential to significantly affect future propulsion systems, as well as airframes. One metal matrix composite being investigated is fiber-reinforced titanium which is about three times stronger for a given weight than nickel superalloy at temperatures up to 1500°F.

Ceramics are attractive as composite matrix materials in aerospace applications because they offer increased turbine inlet temperatures while lowering overall weight. Unfortunately, at this time ceramics are brittle, costly, and difficult to manufacture. The high brittleness of purely ceramic parts which makes them extremely prone to impact damage may be overcome by using ceramic matrix composites.

There are two types of composites. In one, fibers are uniformly mixed with the matrix and a material with isotropic properties is created. A second type of composite involves aligning fibers in a specific direction in order to create materials with much greater strength in a direction of greatest loads. While composite materials offer numerous advantages in weight and fuel efficiency, their application has been rather limited to date in the commercial world. One reason is that the cost of manufacturing composites remains substantially higher than metals due to the large amount of hand labor, and the weight savings do not always justify their use. However, if the production process were to be more automated, the manufacturing cost of composites could become competitive with metals.

Composites are key to making lighter cars, an important part of meeting the PNGV goals of improved fuel efficiency without sacrificing safety which would make the new generation of U.S. automobiles more competitive on world markets. Composites contribute to the efficiency and competitiveness of the aerospace industry for the same reasons. New composites are already being introduced for surface (non-structural) parts of buildings, and will probably be used for structural elements in the future, contributing to the health of the U.S. construction industry in the U.S. and to competitiveness of U.S. construction companies on world markets. The ability of composites to reduce weight while maintaining strength is a contributor to enhancing national security and warfighting capabilities as well. It allows improvements in global power projection capabilities through the creation of lower-weight equipment.

Europe and Japan are slightly behind the United States in composite technology. European firms lead in developing and using ceramic matrix composites (CMCs), although they rely on the high-quality, low-cost ceramic fibers available from the Japanese. France is the world leader in CMC technology with applications in nozzle flaps for the M-88 gas turbine engine for the Rafale. Japan has focused primarily on monolithic ceramics and is significantly behind European and U.S. efforts in CMCs. Despite the current European lead in CMC research, the United States has excellent long term prospects. Europe's lead is based largely on the R&D efforts of the French firms Societe Europeane Propulsion (SEP) and Aerospatiale on silicon carbide/silicon carbide composites aimed primarily at military and aerospace applications, although they continue to rely on reinforcing fibers from Japan. However, industry estimates predict that the major sectors for CMC applications will be in industrial applications such as radiant burners and heat exchangers. The United States—with CMC programs aimed at developing industrial applications—would gain the most from such a scenario, while France would likely need a substantial redirection of research strategy.

The United States pioneered research in polymer matrix composites (PMCs) in the 1960s and continues to lead the world in this technology. PMCs are attractive for a number of applications—including civil and military aircraft, industrial equipment, and automotive components—due to their excellent strength-to-weight ratios and design flexibility. While manufacturing costs continue to limit the wide-scale introduction of PMCs into advanced applications, industry experts believe a growing acceptance in the automotive and commercial aerospace industries will offset shrinking military markets. The Japanese are ahead in some manufacturing processes, such as co-curing and tooling; and European companies have made important advances in compression moldings and tape-laying processes. Europe is using advanced polymeric composites to a limited degree in primary structural components for new aircraft such as France's

Rafale fighter, Sweden's Gripen fighter, the Euro 2000 fighter, and the Airbus 330/340 civil transport.

The United States, Europe and Japan are all actively developing metal-matrix composites, largely for use in the aerospace industry, and there is currently no clear leader in this field. U.S. and French firms have a slight technological lead in the quality of finished products, but British and Japanese companies have performed notable research on the processing of metal-matrix composites. Currently, the only commercial systems using metal-matrix composites are satellite frames, but these materials have significant potential in turbine disks for jet engines, where they can lower the weight of the engine components by as much as 50 percent. The United States and Britain have led recent efforts to incorporate these materials into jet engines.

The United States and France pioneered carbon-carbon composites research, and remain the technology leaders. Carbon-carbon composites, because of their ability to withstand high temperatures and high stresses, were originally developed for use in missile nozzles and re-entry vehicles, but they are seeing increased application in low-technology applications such as aircraft brakes. Because use has been limited by high processing costs, much of the current research is geared toward developing more efficient processing methods. Although a French team at the Center for Aerospace Studies recently developed a manufacturing method which could reduce the cost of finished materials. Japanese companies are the world leaders in carbon-carbon weaving technology. Germany's efforts have been waning in the past few years, with BASF, one of the largest manufacturers, selling their composites division. U.S. and French firms are likely to maintain their lead in carbon-carbon composites over the Japanese, who perform good research, but lack the applications opportunities that have driven other efforts. Japan has successfully manufactured carbon-carbon products used for the OREX, a materials test bed reentry vehicle for the HOPE space plane, and has manufactured prototype carbon-carbon leading edge, nosecap, and flat panel components also intended for HOPE.

Electronic materials

Electronic materials include various semiconductors whose electronic properties can be easily controlled. Improvements in electronic materials combined with improvements in manufacturing techniques support a variety of civilian and military applications ranging from medical imaging to signal processors for military systems. They are essential to the health of the U.S. electronics industry, as well as to a variety of other industries which now incorporate electronics in their products. Improved electronic materials are essential to the creation of the U.S. national information infrastructure, as well as to the creation of the intelligent vehicle-highway systems, and the creation of "smart buildings." Several industry R&D partnerships are focused on electronics, including improvements in materials and uses. Development of advanced electronic materials is essential to the success of NEMI in invigorating the U.S. electronics manufacturing sector. Because of the military's increasing reliance on smarter platforms and weapons, and more timely information and communications, electronic materials are critical for a variety of defense and warfighting applications.

Foreign firms are generally ahead of the United States in technology for electronic and photonic materials—particularly in technology for producing silicon wafers for microelectronic devices. Japanese and European firms are now producing state-of-the-art eight-inch wafers and are ahead in work on larger-diameters. MITI is funding 70 percent of a seven-year, $180 million project to standardize on a 16-inch wafer for future production. The project includes the nine Japanese companies and two German firms that together control 90 percent of the current world market, and could consolidate foreign control over this technology sector. Firms in other regions, such as Korea and Taiwan are trying to establish independent silicon wafer production facilities and developing wafer technology to support their semiconductor industries. Some larger wafer size will likely become the *de facto* standard.

Japan and Europe are roughly equal to the United States in gallium arsenide (GaAs) wafer technology—the leading alternative to silicon as a semiconductor substrate material. Companies in all three regions are working to improve GaAs wafers by lowering defect densities or forming an insulating layer that could extend applications. GaAs substrates, however, are facing competition from silicon which has a much larger market and is much cheaper. Japan trails the United States and Europe in another alternative material, silicon germanium.

Photonic materials

Photonic materials are largely varieties of special electronic materials. The specific technologies under photonic materials include semiconductor lasers, laser arrays, and detectors. These comprise the transmitters or sources and receivers used in any optical system. The interoperability of information technologies with photonic materials and optoelectronic devices in general is critical for the entire communications industry. Thus, the sub-technology areas of telecommunication/data routing, photonic materials, and optoelectronics should be considered jointly.

There are two basic classes of photonic materials: electronic materials with controllable and appropriate optical properties for optical-electronic transducers (GaAs and GaAlAs), and silica glasses for long-distance transmission of optical signals. Because they allow faster computing and transmission of information over wider bandwidths, photonic materials make a particularly important contribution to harnessing information technology by allowing distributed access to information ranging from multi-media entertainment to medical diagnostics.

Photonic materials are also widely used for military applications. These include: communication and navigation, laser radar, electronic warfare, guidance and control of smart weapon systems and unmanned vehicles, sensors (including: sonar, gyro, and focal plane arrays), and simulation and training. In all of these applications the key components involve sensors and detectors, laser arrays, and communication networks.

High energy-density materials

High energy-density materials include explosives, munitions, and improved propellants. Advanced propellants increase performance of rocket boosters and help reduce visible plume signatures under certain atmospheric conditions, thereby decreasing the potential for in-flight detection. New very powerful explosives can significantly increase the effectiveness of precision-guided munitions, such as missiles and torpedoes, against hard targets. New fuel-air explosives and advanced explosives could lead to improved conventional weapons that would be more effective against their intended targets. While main applications of high energy-density materials are military, there may also be some applications to space launch since the U.S. needs a higher ISP solid rocket.

Russia is the world leader in advanced propellants, with work in advanced oxidizers and other key technologies taking place earlier than similar work in the United States. The French possess equivalent technology to that of the United States in high-energy density solid rocket propellant capabilities having produced comparable motor case materials, nozzles, and propellants. The French have an impressive R&D effort, which has produced energetic propellants and composite motor case materials, both of which are now being used on new generations of weapons systems. However, the French—paralleling similar decisions by both the United States and Japan—have chosen to use older technology in the development of the Ariane 5 boosters. The technology used for these boosters was developed from solid rocket motors on the Ariane 3 and 4 and on French ballistic missiles. Japan is several years behind the United States in solid rocket technology, primarily in motor case materials and propellants. Japan developed and manufactured HTPB binders and propellants approximately eight to ten years after the United States based on original technology for composite propellants obtained under license from the U.S. company, Morton Thiokol. Currently, the performance that the Japanese obtain from their HTPB propellant is comparable to similar products in the United States. The Japanese prefer the reliability of HTPB-based propellants and probably will not pursue more energetic propellants for boosters because of the associated hazards.

Highway and infrastructure materials

Highway and infrastructure materials include new pavings made from recycled asphalt and such familiar materials as cement. In addition to materials that are being created specifically for infrastructure applications, older materials, such as cement, are being improved through a better understanding of their structure and the incorporation of microscopic fibers forming a composite structure. These new materials, many of which are already used overseas, would make a significant contribution to the improvement in the physical transportation infrastructure. The effect on job creation and economic growth would be both direct, through the creation of jobs in the transportation sector, and indirect, through the creation of jobs in other sectors which rely on the availability of better and more economical transportation. These materials would also contribute to enhancing infrastructure survival characteristics in earthquakes and other natural disasters.

The United States has been a leader in the development of and use of high performance concrete (HPC), with compressive strengths above 10 ksi. Several other countries are moving aggressively to exploit HPC technology, including Canada, France, Japan, Norway and Sweden. In France, for example, designers routinely use HPC with strengths from 8 to 14 ksi in bridges and buildings. In addition to HPC, several countries, including Britain, France, Germany and Sweden are making significant advances in chemical-resistant concrete and high-precision concrete construction. Strengths to 100 ksi may soon be possible and are currently being studied in France.

In France, high performance surface dressing for asphalt pavements is being used, and requires special equipment for its placement. High-performance asphalt (HPA) is also the focus of interest in Germany where hot-mixed rubberized asphalt and reclaimed asphalt pavements are widely being used. Work in Sweden and Britain is producing pavers and blocks utilizing fly ash that may prove commercially viable.

Although the United States established an early lead in the development and introduction of high-performance steel (HPS) with yield points up to 100 ksi, the rest of the world has recently caught up and taken the lead. In catching up, steel makers in Japan and Europe have used new technology to overcome two of the major problems in manufacturing the new class of quenched and tempered steels: high energy consumption because of repeated heating, cooling and reheating; and fabrication requiring great care so that welded joints have the same desirable properties as the parent material. Japan is currently the world leader in weldable and fire-resistant HPSs. Over the past few years, Japanese and European producers have reported significantly improved mechanical properties for steels produced using special thermomechanical controlled processing (TMCP), and they have installed the facilities to produce these steels. In the United States the first production facility will not be installed at least until 1995.

Currently, the United States enjoys a leading role in advanced-composites technology, essentially based upon defense work. Large scale research efforts in Europe and Japan are now being accelerated and threaten to undercut the United States' leading role within the next decade. There is a large potential market for advanced composite materials (ACM) in the rehabilitation of our highway infrastructure, but ACM are not economically viable in most civil applications at current cost levels. New, more affordable processes for manufacturing composite structures for civilian infrastructure are being developed in the United States and several are being funded, in part, by ARPA. Unlike the United States there are a number of composite bridges in England, Europe and Japan. Japan is far ahead of the United States in the development of this new market.

Biocompatible materials

Biocompatible materials are discussed in detail in Living Systems/Medical Technologies.

Stealth materials

Stealth using low-observable materials enables the control or reduction of signatures of weapon systems. This is only possible in conjunction with a sophisticated design process that incorporates signature as an important operating parameter. The emphasis to date has been on the radar signature, and thus radar-absorbing materials have been the focus of development. The continual challenge is to develop new, lighter materials that are more easily integrated into military systems. A particular challenge will always be near turbine engines where the demands of high-temperature behavior meets demands for radar properties. Stealth materials include special coatings and materials which can be shaped in special ways.

Signatures are those characteristics by which these systems may be detected, recognized, and engaged. The modification of these signatures can improve survivability of military systems, leading to improved effectiveness and reduced casualties as demonstrated in the Persian Gulf conflict.

Europe and Japan are behind in applied stealth technology as evidenced by U.S. aircraft programs such as the F-22, B-2, and F-117A. Most of the applied foreign low-observable work involves basic shaping, material coating techniques, and signature testing requirements. Europe has been led by France, Sweden, Germany, and the United Kingdom in various types and levels of low-observable applications. Applications on fighter aircraft have generally been at fundamental applied levels, primarily using absorbent coatings, limited structural shaping, and absorbent structure. Applications seem to be limited to the areas with highest signature return rather than application to an entire airframe. European firms are also working on stealth technology applications to cruise missiles and unmanned aerodynamic vehicles. Advanced Japanese fighters, like the FS-X, could deploy low-observable technology, but Japanese firms are probably better positioned as materials suppliers than as users.

Superconductors

Superconductors are materials that conduct electricity without loss. Such materials are used for high-field magnets in several applications, such as high-energy physics and high-resolution nuclear magnetic resonance imaging machines. They are also used to construct sensitive instruments for measuring changes in magnetic fields, and are then used in medical instruments and in geological exploration. These applications are all based on the existing technology of low temperature superconductors, a well-established industry.

High-temperature superconductors are a relatively recent discovery. Providing the theoretical understanding of these materials could contribute to the goal of achieving world leadership in materials science. The losses in electric transmission could be reduced if high-temperature superconducting transmission lines became practical, providing less expensive power for job creation and economic growth. When the materials become commercially viable, their effects could also include cheaper magnetic levitation transportation systems, and better scientific infrastructure for those fields that use superconducting magnets.

Japan probably has a slight edge over the United States in superconductors based on a large and diverse research program emphasizing power as well as medical and electronics applications. Both are about equal in low-temperature superconductors (LTS) magnet technology, but each country has different areas of emphasis. Japan is ahead in applying LTS magnets to transportation applications such as magnetic levitation vehicles and magneto-hydrodynamic ship propulsion, whereas the United States has focused on magnets for high-energy physics including fusion research. Although LTS applications continue to be the mainstay of superconductor research, efforts on high-temperature superconductors (HTS) have continued and the development of wires, microwave devices, and magnetic field detectors is nearing the applications stage. Europe, led by Germany, trails the leaders by a few years. Russia has some capability, particularly in LTS for manufacturing wires and magnets. Much of this strength probably derives from work on fusion devices and particle accelerators.

STRUCTURES

Aircraft structures

Aircraft structures are a particular example of combining design tools, fabrication techniques, and specific materials to create more highly optimized physical structures. Structural technology has always been a key driver for aircraft advancement. The use by Chanute and the Wright Brothers of the braced box concept instead of the earlier, bird-like structural design approach was one of the factors that made manned flight possible, and the use of stressed-skin metal construction (such as the DC-3) made the commercial transport a viable economic proposition. Structural technology has a primary influence on aircraft empty weight, which directly drives purchase price and operating cost, as well as influencing range and payload.

Aircraft structures are essential to competitiveness in the aerospace industry, with impact on both commercial and military segments. The fibers of polymer matrix composites can be aligned, forming a material with anisotropic properties. If carefully designed for an application, such materials allow a lighter, smaller structure to replace larger, usually metal ones. So far, the application of such structures has been limited to those demanding the highest performance. These have usually been in the aerospace industry, frequently in military systems. Part of this limitation comes from the difficulty in fabricating complex structures from the materials. In the example of polymer matrix composites, this has been manifested as a difficulty in arranging the fibers in the pattern needed; the usual solution is expensive, because it is labor-intensive. For many applications, these problems are compounded by the difficulty of optimally designing with such materials.

Aircraft structures make a contribution to meeting job creation and economic growth by contributing to the success and competitiveness of the U.S. aircraft industry. They also contribute to meeting the U.S. warfighting capabilities by enhancing performance of military aircraft.

Japan lags Europe and the United States in computational structural mechanics for aircraft applications, and has relied heavily on Western-developed computational mechanical analysis tools to support most of its advanced aircraft structures programs. In the commercial sector, Mitsubishi Heavy Industries, Fuji Heavy Industries and Kawasaki Heavy Industries all use Dassault's CATIA 3-dimensional structural modeler. Japanese development of commercial codes is limited; integrated aero-structural-controls analysis and optimization approaches are still being explored at the research level. Although the major aircraft design and manufacturing firms are familiar with recent international development in the multidisciplinary optimization field, most of the interest is in obtaining and using U.S. and European techniques and software, including NASTRAN and CATIA.

The European aircraft production industry is slightly behind the innovative developments now entering applied engineering in the most advanced U.S. fighter and commercial aircraft acquisition programs. European aircraft computational mechanics activities have applied efforts of sophisticated technology in both military and commercial aircraft programs. Computer-aided engineering and manufacturing can permit designers and manufacturing engineers to meet in the preliminary design phase to integrate requirements and technology limitations early in the design cycle as well as throughout the development process. The result is an airframe optimized to the respective key performance specifications, whether as a military fighter or a commercial passenger aircraft. The benefits are avoidance of costly delivery delays and re-engineering work during the fabrication phase. The Eurofighter 2000 and the French Rafale have extensively used both U.S. and indigenous developed finite element analysis (FEA) and structural optimization software to advanced the airframe technology to state-of-the-art relative to mechanical performance and physical characteristics. The French have been using Dassault's CATIA design software package coupled with ELFINI FEA that has a demonstrated capability to handle the "paperless" design and prototype engineering tasks without requiring physical articles. In the commercial sector, Airbus Industrie also employs a host of U.S. and European commercial software products. Airbus Industrie is reported to have moved from physical prototype design process to a full paperless design process with its A330 and A340 aircraft.

Europe is behind the United States in hot structure airframe designs and materials for components for the extreme thermal, mechanical, and acoustic loads in many projected applications. Despite some impressive growth in the past five years, recent economic pressures have slowed or stopped several key programs. The European Space Agency's (ESA) and its membership continue to look for piecemeal applications of individual sub-technologies of the troubled HERMES space plane Program. Most European hypersonic flight vehicle programs have been drastically reduced or stopped. Examples include the financially troubled ESA FESTIP study and the now defunct German Hypersonic Technology Program (formerly Sanger Program). Overall, the Europeans apparently are trying to maintain hot structure technology programs while attempting to find new applications to sustain advanced development.

Japan is also behind the United States in hot structure design, test, and production. Japan has closely studied and attempted to duplicate or commercially acquire many aspects of the hot structure production process. Their National Aeronautics and Space Development Agency (NASDA) and the National Aerospace Laboratory (NAL) have managed government-funded programs in single-stage and two-stage space transportation concept development and associated design and materials development. These efforts will impact future high-speed civil aircraft and hypersonic aircraft initiatives under study. Japanese funding to establish and improve indigenous capabilities in advanced material processing, lightweight thermal structure manufacturing and test facility infrastructure have been well reported. Although their general capabilities in hot structures have grown recently, Japanese firms still lag the United States in critical engineering and technology areas, including aerothermal and structural analysis codes, test facilities, and materials development.

The United States has a substantial lead in actively cooled structures. Europe is still generally conducting fundamental research on structural materials, coolant design and function, and thermal-aerodynamic cooling phenomena characterization. The European leader, France, does have some near-term applications of actively-cooled structures, primarily because of its military-funded requirements in hypersonic flight vehicles (i.e., aircraft and missiles). The French have done extensive work in computational models for hypersonic flow condition and boundary layer interface. This effort could help an actively-cooled structure designer to evaluate this concept before expensive prototype development and tests occur. Some work has also been done by Germany, but future activities may cease with the official demise of the national hypersonic program. Japan's actively cooled structures technology also remains behind that in the United States. The bright spot is the amount of funding still potentially available to develop actively cooled structure in applied high-speed flight vehicles. Some aircraft and space plane programs being managed by NAL include structure concepts that will require the levels of thermal-mechanical performance that actively cooled structures are best suited to perform. NASDA's HOPE vehicle does not drive structure requirements to include actively cooled structures. This explains why Japanese research and development efforts have not aggressively attacked this area yet. Further maturation of NAL's single-stage space plane or a hypersonic passenger aircraft could accelerate the current pace of development.

applications of actively-cooled structures, primarily because of the [illegible] in hypersonic flight vehicle [illegible]. The [illegible] HOPE [illegible] thermal-protection and [illegible] layer [illegible] cooled structure designs to evaluate the concept [illegible] development [illegible] which has also been done by Germany, but future activities may [illegible] national hypersonic program. Japan currently [illegible] technology [illegible] behind in the United States [illegible] available [illegible] actively cooled [illegible] vehicle. Some [illegible] plane program [illegible] first [illegible] require [illegible] performance that actively cooled structures achieve [illegible] HOPE vehicle does not drive structure requirements to include actively cooled structures. The [illegible] were [illegible] not [illegible] space plane or any [illegible] or development.

8. TRANSPORTATION

The following technology areas are addressed in the Transportation category:

- Aerodynamics
- Avionics and Controls
- Propulsion and Power
- Systems Integration
- Human Interface

At a more specific technology level, the report discusses aircraft and surface vehicle aerodynamics, aircraft and spacecraft avionics, surface transportation controls, aircraft turbines and spacecraft power systems. At the level of systems integration and human-machine interface, the report discusses intelligent transportation systems, spacecraft and aircraft integration, human factors engineering (as it relates to transportation systems) and spacecraft life support systems.

The area of intelligent transportation systems is one where the U.S., Western Europe, and Japan are all engaged in various private and public efforts to develop more effective and efficient surface transportation systems. This area will ultimately involve radical changes in both vehicular technology and infrastructure that have the capacity to alter the American transportation system by better incorporating modern information technology into virtually every phase of passenger and freight transportation including its intermodal elements.

The U.S. has preeminence in most transportation areas, except for Western European developments in commercial aircraft technology, the leadership of France, Germany and Japan in fielding high speed rail systems, and German and Japanese advances in mag-lev technology. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 8.1.

AERODYNAMICS

Aircraft aerodynamics

Aerodynamic efficiency is one of the key parameters that determines the weight and cost of an aircraft. Roughly speaking, an aircraft's range is directly proportional to its aerodynamic efficiency without any increase in fuel usage. Such fairly-recent aerodynamic technologies as supercritical airfoils and winglets have already provided substantial increases in aerodynamic efficiency over first-generation jet transports, and there are many emerging aerodynamics technologies worthy of development and implementation. One of the most

Figure 8.1
Transportation
Technology Position and 1990-94 Trend

US Technology Position Relative to:
Japan ▷, ○, or ◁
Europe ▶, ●, or ◀

1990–94 Trend
Improved ▷
Declined ◁
Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Transportation					
Aerodynamics				●	◁
aircraft aerodynamics				●	◁
surface vehicle aerodynamics (?)				○ ●	
Avionics & Controls				◀	◁
aircraft and spacecraft avionics				◀	◁
surface transport controls					
Propulsion & Power				◁ ●	
aircraft turbines				●	◁
spacecraft power systems				○ ●	
electrically powered vehicles			○	●	
Systems Integration				●	○
intelligent transportation systems					
spacecraft and aircraft integration				●	○
Human Interface					
human factors engineering					○ ●
spacecraft life support				●*	▷ ▶

*Russia (?) based on limited information

promising, especially for improving efficiency in jet transports, is laminar flow control.

Improved aerodynamics is critical to both commercial and military aircraft, including rotary wing aircraft. For commercial aircraft, improved aerodynamics reduces operating costs, thereby making the aircraft more competitive on international markets. It also significantly contributes to the national security by improving efficiency and performance of military aircraft.

Europe—primarily Germany, France, and the United Kingdom—is only slightly behind the United States in aircraft aerodynamics. Europe's hypersonic programs have been slowed significantly for economic reasons, but the test infrastructure continues to advance. European aerospace firms are investigating laminar flow airfoil technology to improve the competitiveness of their commercial aircraft. Current R&D efforts include the multinational European Laminar Flow Investigation (ELFIN) project which involves evolutionary improvements in and optimization of airfoil geometry as well as hybrid laminar flow techniques (HLFTs). Europe is conducting HLFT tests on the tail fin of an A320 and planning wingtip-to-wingtip tests on an A340. In addition, France's Dassault began HLFT tests in early 1993 on its Falcon 900 business jet. Airbus has also done extensive testing of riblets—originally developed by NASA and U.S. companies—on an A320 and A340 to create laminar flow over large regions of the aircraft's surface.

Japanese firms are substantially behind firms in both Europe and the United States, but joint work on the FS-X has allowed an infusion of U.S. aerodynamic technology that is improving their capabilities. Japanese research in laminar flow control has been limited by the lack of domestic commercial aircraft programs. Russia generally is behind the leaders in computational capability and advanced computational fluid dynamics codes for hypersonics and progress is slowing because of political and economic uncertainties. The United States also has a slight lead in technology for surface vehicle aerodynamics, based in large part on capabilities derived from the aerospace industry.

Surface vehicle aerodynamics

Surface vehicle aerodynamics provide the scientific foundations for developing lower drag shapes for automobiles, buses, trucks, and trains. As vehicle speed increases, aerodynamic drag becomes a major contributor to vehicle inefficiency and increased fuel consumption. The same phenomena that lead to increased drag-airflow separation and unsteady eddy formation-also lead to higher levels of flow noise and vehicle control problems. Aerodynamically designed vehicles can be both quiet and more efficient than existing vehicles, although current vehicles already incorporate efficient aerodynamic shapes. Given that drag reduction translates into reduced energy consumption, more efficient vehicles and ultimately lower demand for foreign oil.

AVIONICS AND CONTROLS

The United States is the world leader in most avionics and controls technology and is likely to maintain but not increase its edge over the next several years. Two European firms, France's Sextant Avionique and the UK's General Electric Company (GEC), are challenging traditional U.S. leaders across a wide range of avionics products but with the current downturn in military budgets, commercial developments will be slowed as few companies will be willing to risk large investments solely for the commercial market. Fewer new programs will make it difficult for foreign countries to decrease the gap or for the United States to increase it.

Aircraft and spacecraft avionics

Several goals drive development of fly-by-light (FBL) control systems: increased resistance to electromagnetic interference (EMI), increased bandwidth, and weight reductions. The increasing use of composite materials in aircraft structures has decreased EMI shielding previously provided by metal structures. Consequently, electrical cables used in fly-by-wire (FBW) systems are subjected to greater electrical interference which can degrade performance. In contrast to traditional electrical data busses, optical pulses transmitted by FBL systems are unaffected by the much lower frequency electromagnetic waves that characterize the EMI threat. FBL systems also provide better protection against lightning strikes. Moreover, fiber-optic cables can carry vast amounts of data and offer potential weight advantages. FBL technology will probably not be used in commercial transports until the 21st century, as the first production applications of fully FBL technology will probably be in military helicopters because of their extensive use of composite airframe structures.

During the 1980s, ring laser gyroscopes (RLGs)—first produced by U.S. firms for commercial aircraft—began replacing mechanical gyros in inertial navigation systems. During this same period, fiber-optic gyroscopes (FOGs) were also developed. Although FOGs initially promised equivalent performance to RLGs at lower cost, they have not yet met these expectations. Industry experts believe that FOGs are competitive in some low-to-medium-accuracy applications—such as attitude and heading indicators—but have not yet challenged RLGs in the high accuracy market. FOG systems—updated by global positioning system satellites—offer some long-term promise, particularly if FOG drift rate reduction programs are successful.

Avionics technologies have a huge impact on military aircraft, and leadership in areas such as radar, fire-control, countermeasures, stealth, and command and control must be maintained for the implementation of national security policy and strategy. Avionics technologies also have a large effect on commercial aircraft, and this impact will grow in future years. Active controls technologies as pioneered by U.S. aircraft such as the F-16 are now providing reduced fuel consumption and maintenance costs for the European Airbus and other foreign competitors to U.S. commercial aircraft. Advanced cockpit displays and controls, such as the "glass cockpit" reduce crew expenses and increase safety. Rotocraft are also likely to benefit from advances in avionics leading to improved safety and efficiency. Upcoming advancements in air traffic technologies should permit increased airspace usage with greater safety. Integration of aircraft and air traffic control systems of the future will be key to reducing delays and increasing capacity.

Advanced avionics make a direct contribution to the competitiveness of U.S. aircraft on world markets. They certainly play an important role in the U.S. ability to meet its national security and warfighting objectives.

European firms are at parity with U.S. firms in fly-by-wire (FBW) technology and ahead in its application to commercial aircraft. Although FBW systems have been in use on military aircraft since the mid-1970s, they were not introduced on commercial transports until the mid-1980s. Operating costs and safety considerations drive commercial FBW applications through reduced weight, improved fuel efficiency, increased reliability, and less unscheduled maintenance. European success can be attributed to two factors —aggressive application of military flight control technology to commercial aircraft and a wave of consolidation within the avionics industries. Although FBW technology was originally developed by U.S. firms for military aircraft, European firms—Britain's GEC and France's Sextant—were the first to apply the technology to a commercial aircraft, the Airbus A320. In late 1990, GEC won the contract to supply the FBW system for the Boeing 777—the first U.S.-produced commercial aircraft to incorporate FBW technology. Because new commercial transport programs like the Boeing 777 are launched so infrequently, GEC is gaining a significant advantage over U.S. firms in the commercial application of FBW technology. Japan, by contrast, has only a basic capability in FBW technology, through the FSX fighter program, and currently lacks a commercial program to gain experience.

U.S. firms—led by McDonnell Douglas—appear to have the lead in fly-by-light (FBL) developments. Much of the impetus for the U.S. developments comes from ARPA's technology reinvestment program. Limited reporting indicates that GEC and France's Dassault lead the Europeans in FBL development. GEC gained important experience through the FBL system it built for a dirigible. Japan has shown interest in FBL, but has allocated relatively small budgets for its development. Further development in FBL technology will likely require an appropriate military program and will give the country sponsoring the effort a significant advantage in FBL technology. NASA AST FBL program is also a major contributor to this technology development for the civil sector.

The United States is the leader in ring laser gyro (RLG) technology but several foreign firms have developed strong RLG capabilities. British Aerospace and the French firms SAGEM and Sextant are producing RLGs with long-term drift rates adequate for aircraft navigation. Foreign firms, however, lag U.S. firms in reducing gyro size while maintaining high accuracy. Foreign firms also remain secondary players in the RLG market because they are not cost competitive with U.S. firms. As Sextant's RLG production technology matures, the firm may attempt to win navigation contracts for Airbus aircraft—currently supplied by Honeywell. Japan Aviation Electronics originally based its development of RLG technology on licenses from a U.S. firm but now has an independent capability in the technology. Future foreign RLG developments will depend on whether those firms continue to fund RLG research or change their focus to fiber optic gyroscope or the Global Positioning System (GPS). The United States has a slight lead in fiber optic gyroscopes—an alternative technology for aircraft inertial-grade accuracy. Foreign efforts include work by the French firm, Photonetics, and Japan Aviation Electronics. U.S. manufacturers retain a lead in global positioning systems (GPS) receivers and processing equipment, largely because of their experience developing the satellite system. Europeans and Japanese each have a number of firms working on GPS receivers, but industry experts predict the U.S. will maintain its position over the next several years.

Japanese firms do not have strong technical capabilities across broad product lines but are strong in avionics display technologies. Japanese firms such as Hosiden, Sharp, Hitachi, NEC, and Toshiba have very high production yields and account for 95 percent of the world's active matrix liquid crystal displays—the technology of choice for most high-performance flat panel display (FPD) applications. Cockpit displays have evolved over the last decade from complex electromechanical instruments to electronic multifunction displays. The most advanced current commercial aircraft have displays based on cathode ray tubes, but FPDs are lighter, take up less space, consume less power, and offer increased display areas. Japanese firms were the first to achieve FPD sizes large enough for aircraft, and are now selling them on the commercial market (Boeing 777). Japan's FPD producers have only limited interest in producing FPDs for avionics applications, primarily because production runs are very small relative to the large FPD orders for computer and consumer electronic applications. Over the next several years, the United States could close the technology gap with Japan, based on government support for FPD and manufacturing technology development.

Spacecraft avionics currently involves issues of reliability, space certification, miniaturization, reduced power consumption, and "black box" modularity. Spacecraft control systems, on-board navigation systems, and precise engine throttling would all benefit from further improvements in this area. There is a growing trend towards the standardization and assembly of building block components to achieve a number of different functions and in this way to avoid a requirement to develop a large quantity of special purpose systems.

Surface transportation controls

Surface transportation controls span such applications as microprocessor based emissions control systems for monitoring and controlling engine performance to reduce emissions and optimize engine performance to the myriad components that would be essential to attain an intelligent vehicle highway system. A critical examination of the emissions control application suggests that these systems may operate effectively for much of a vehicles useful life, but ultimately, many of these systems may degrade and exhibit highly variable behavior that is accompanied by gross emissions of hydrocarbons, CO, and NOx. Thus, the issue is not to develop systems whose performance when new is exemplary. Rather, it is to develop reliable maintenance free emission control systems that will operate at close to new car levels when a vehicle is well past 100,000 miles and into its third, fourth, or fifth level of ownership. This remains a major challenge, particularly if years of neglect and poor maintenance are considered. In general, it seems plausible to think that reliable emission control systems for exhaust and evaporative emissions hold the key to reducing urban emissions and ozone formation in many areas, particularly in California, where 40 percent of vehicles have more than 100,000 miles on their odometer. The U.S. is pre-eminent in this technology area, driven by our commitment to clean air.

PROPULSION AND POWER

Propulsion technologies are important to both national security and economic prosperity because better engines improve fuel economy and reduce maintenance costs, and also allow designing a smaller, cheaper aircraft to perform some required mission. The interaction of propulsion and aerodynamics is essential for developing powered lift vehicles.

Aircraft turbines

For the turbojet engine, a key objective of the last 40 years has been to increase combustion temperatures for better efficiency and reduced fuel consumption, without burning up the turbine blades. This is done by better materials such as the ceramics mentioned elsewhere, better cooling approaches, and by better computational analysis methods. Reduced emissions and reduced noise are also becoming extremely important for the civil sector. Performance improvements in core engine technology have historically been driven by military programs, and commercial engine development will continue to benefit from military research efforts. Hot section advances are most directly linked to materials development and innovation in cooling techniques. Improved transmissions would be instrumental in moving forward with advanced rotocraft designs, such as the next generation of the tilt-rotor.

Efficiency of aircraft turbines significantly affects purchase price and operating costs of aircraft. Improved engines contribute to job creation in the aerospace sector, as well as to the competitiveness of the U.S. aerospace industry, because the U.S. is a major player in international aerospace markets. They also contribute to improvements in environmental quality by reducing emissions from aircraft engines and reduced energy consumption. Greater efficiency of aircraft engines also contributes to the warfighting capability of rapid global power projection.

The United States has the overall lead in aircraft turbine engine technology, based on its superior military technology, but shares the lead in commercial propulsion systems technology with the UK's Rolls Royce. Europe has an edge in facilities for propulsion/airframe integration testing of large models at high Reynolds Numbers. They may also have an edge in technologies for noise reduction. Second-tier manufacturers in France, Germany, and Japan have seen their capabilities increase through international joint ventures and European military development programs. This general pattern is likely to continue with France (likely to become more competitive with the United States over the next five years as they assume responsibilities for a greater percentage of engine designs and component manufacturing) leading the way and Japan bringing up the rear. While Japan will likely become a more attractive joint venture partner—almost certainly the country's prime goal—technology transfer is unlikely to be enough to significantly alter capabilities relative to the world leaders over the next several years.

Because of the trend towards higher thrust engines, in concert with the trend towards larger aircraft, by the year 2000, deliveries of engines with greater than 45,000 lb thrust are forecast to be more than 50 percent of the market by value. The trend towards higher-thrust engines has two general consequences for the competitiveness of engine manufacturers. The higher costs associated with development of these large engines have led to more joint international programs and transfer of technology to second-tier manufacturers. Secondly, with the attention of the technology leaders focused at the high-thrust end of the market, second-tier manufacturers are increasing their roles in the development of smaller engines. This is particularly true of the French firm SNECMA, which has recently announced its intention to lead the development of a new turbofan for civil applications based around the core of its latest fighter engine.

Performance improvements in propulsion systems are driven by core technology advances in engine component technologies, manufacturing capabilities, and systems integration. Europe continues to lag in turbine-blade technologies, but is keeping pace with U.S. developments. The United Kingdom and France are slightly behind the U.S., but have introduced some technologies first. For example, the United Kingdom was the first to introduce hollow fan blades, instrumental for reducing engine weight. France is a leader in advanced composite materials and has introduced silicon carbide nozzle flaps for their M88 engine.

Wide-chord fans—which do not require part-span shrouds and are therefore more efficient—are quickly being adopted industry-wide. Some operators of engines with wide-chord fans have also claimed that the fan blades' ability to flex makes them more resistant to birdstrike damage. Next generation engines will likely also incorporate swept aerodynamics in both fans and compressors to provide additional increases in efficiency. High strength-to-weight compressor materials are being developed to permit increased rotational speeds that—along with the adoption of low aspect ratio blade shapes—will enable reductions in the number of airfoils required.

Rolls Royce's development of the wide-chord fan gave it a technology lead in this area, but U.S. firms reacted quickly to close the gap and are likely to move ahead over the next several years, as composite fan blades are introduced on the GE90 and Pratt and Whitney's Advanced Ducted Prop engine. Research and development of active compressor stability control and high strength-to-weight ratio materials—including metal matrix composites—proposed by the European Aero-Engine Industry Group parallel U.S. efforts. Japan's responsibility within the IAE consortium for the fan and low pressure compressor is its first major share of a commercial engine program. Although the fan was derived from an existing Rolls Royce design, it is worth noting that the V2500 passed every ingestion and fan-blade-off test the first time the engine was tested. Despite this improvement, problems experienced on other indigenous efforts suggest that Japan still has a substantial technology lag.

Rolls Royce combustor technology is at parity with that of U.S. manufacturers; however, the company slightly lags in the application of turbine technology to commercial engines. Its latest civil engine offering—the Trent—still uses directionally solidified high-pressure turbine blades. While Rolls Royce and the UK Ministry of Defense are jointly funding high-pressure turbine design research, improvements resulting from this program will likely be offset by advances already achieved in a similar U.S. effort. Japan's responsibility for the low-pressure turbine on the GE90 program complements its role in the IAE consortium.

Rolls Royce now uses full authority digital engine controls (FADECs) on all of its engines and France has demonstrated improvement through production of a FADEC for SNECMA's latest military engine and controls components for the CFM56 and CF6-80. Japan has an indigenously developed FADEC that has reportedly been successfully ground and flight tested. However, the system is intended for use on the FSX fighter and has yet to be validated in service.

Spacecraft power systems

Spacecraft power systems provide power for spacecraft mission, communications, and housekeeping functions. In the case of lunar or planetary missions that involve instrumented or human landings, surface power systems must also be provided. Efficiency, power density, reliability, environmental risk, safety, shielding, etc. must all be considered in any power system. The following issues are important for space or surface power systems.

- Power generation (the energy source) Possible options include solar (photovoltaic, thermoelectric, thermionic, or dynamic), batteries and fuel cells, nuclear (radioisotopes, fission, fusion), other (antimatter, winds, chemical)
- Energy storage, with options such as batteries, fuel cells, flywheels, capacitors, and superconducting rings
- Power handling, including conditioning, control, packaging, enhancement, and conversion

- Thermal management, as a means of handling system heat including heat transfer rejection or storage as well as thermodynamic, thermoelectric, and thermionic cycles
- Power transmission, using laser, microwave, or millimeter waves over long distances, or perhaps cables and/or fiber optics for connecting components on lunar or planetary surfaces.

Space power systems are relevant to both economic progress and national security. They contribute to sustainable economic growth through promoting efficient energy production and utilization technology, and help the environmental monitoring and assessment function through their ability to provide long term power for environmental monitoring satellites. They contribute to national security through their ability to provide energy sources for military surveillance systems.

The U.S. is preeminent in spacecraft power systems, based largely on the relative scale and sophistication of its space effort. Only the U.S. and Russia are manufacturing radioisotope thermal generators (RTGs) essential for the space mission to the planets, but there is a possibility that the U.S. will abandon research in this technology.

Electrically powered vehicles

The relevant electrically-powered vehicle technologies are discussed under "Energy."

SYSTEMS INTEGRATION

Systems integration refers to the ability to design, produce, test, and implement large-scale complex systems whose individual elements often utilize advanced technology components. The most widely cited example is manned space flight, particularly the Apollo program, that assembled, integrated, and tested new and existing systems to achieve its mission. Many aerospace companies define their activities as system integrators rather than as technology developers. Although systems integration is particularly important in space and missile defense system applications, we concentrate on two main sub-areas that offer considerable potential. One area, Intelligent Transportation Systems, is a recent generalization of the Intelligent Vehicle Highway Systems (IVHS), that could literally transform the U.S. surface transportation system. The other area, space and aircraft integration, reflects a virtual revolution in our ability to design spacecraft and aircraft.

Intelligent transportation systems

Intelligent transportation systems (ITS) utilize advanced computers, sensors, electronics, communications, and other technologies to improve the safety and efficiency of all modes of surface transportation for people and goods, including intermodal transfers.

The following areas are currently being emphasized in ITS research:

1. Travel and Transportation Management includes real time information about routes and services for motor vehicles operators, traffic control and management of highway incidents, and on-board emissions testing.

2. Travel Demand Management includes travel information, ride matching and reservations, perhaps using interactive media—to assist travelers to optimize their overall origin-to-destination journey in terms of time and cost, and across various transportation modalities and to assist transportation system operators to better tailor their services via demand matching.

3. Public Transportation Operations include improved management of transit systems, en-route transit information for individual vehicles (vehicle locators), personalized public transit (dial-a-ride), and public travel security. The goals are to improve operational performance of transit systems and to improve the user-friendliness of public transit to attract non-traditional users.

4. Commercial Vehicle Operations enhancements, such as electronic document clearance and fee payment, roadside and on-board safety and weight monitoring, vehicle locator systems, etc. would improve commercial fleet management of freight trucks and rail cars, and reduce administrative costs. Another safety related enhancement would be to develop systems to prevent collisions at highway-rail grade crossings.

5. Emergency Management would involve detecting, predicting, and avoiding possible emergencies. Systems that trip an automatic distress alert when an airbag opens, that alert distracted or dozing drivers to their erratic driving behavior, that warn of imminent danger ahead, perhaps due to weather or other upcoming hazard, would be particularly useful by helping to prevent accidents and by reacting quickly to those that do occur. This is particularly important in rural settings where 60 percent of traffic fatalities occur. Several low technology approaches for assessing the utility of wireless or kiosk-based road and weather information delivery systems are under investigation in many states.

6. Vehicle Control and Safety Systems that would eventually culminate in an automated highway system, include different types of collision avoidance systems, vision enhancement, improved safety readiness, and pre-crash restraint deployment. On some stretches of highway, automatic platooning of

vehicles that are controlled electronically could increase lane capacity by factors of three or four.

In addition to these six major areas, electronic payment services would improve convenience and efficiency, for toll collection, personal vehicle use, interstate tracking, and for public transit users who might rely on "smart" fare cards. Some of these systems are already fielded around the country.

Forecasts suggest that traffic fatalities, accidents and congestion would markedly decrease when ITS becomes operational. In fact, successful deployment of ITS has the potential to vastly improve surface transport in the U.S. while improving energy efficiency and reducing pollution from transportation. Although much of ITS progress thus far has targeted private and commercial motor vehicles, it is expected that rail system and public transportation operations will also benefit. Although the major benefits would promote health, safety, and economic security, important national security benefits would stem from more efficient use of existing highways in times of crisis or war.

There seems to be no clear leader in intelligent transportation systems technologies since the U.S., Western Europe, and Japan are all pursuing active programs involving both private and public resources.

Spacecraft and aircraft integration

Complete integration of an aircraft or spacecraft, as opposed to mere component design, requires broad experience, a complete understanding of all component technologies, and a design infrastructure including methods, tools, and people. The added complexity of making many sub-systems operate simultaneously without interference with each other requires a special set of skills which are different from skills required to design and build an individual component.

One emerging tool for enhanced systems integration is multidisciplinary design optimization. It is an emerging computational technique which has high promise for the overall improvement of design quality and resulting aircraft efficiency. It includes several numerical techniques for finding an optimal system solution across numerous functional disciplines such as aerodynamics, structures, and controls. While this has always been a goal, attacked by such time-honored techniques as the carpet plot, it has been virtually impossible to simultaneously optimize any complex system due to the number of variables required.

Multidisciplinary Optimization techniques such as "Decomposition" hope to break this logjam and allow complex system optimization of hundreds or thousands of variables. This will find more-optimal solutions resulting in lower aircraft weight and cost. Lower weight and cost will, in turn, improve the competitiveness of U.S. aircraft on world markets, and will result in aircraft which are more friendly to the environment because they will use less fuel and producing fewer emissions. In addition, multidisciplinary aircraft design will allow designers to produce better military aircraft, contributing to national security and warfighting capabilities.

Europe is slightly behind the United States in overall systems integration capability for civil and military aerospace systems. With the development of the Boeing 777, the United States took the lead in the design and manufacture of commercial aircraft. Boeing used an integrated approach through fully digital product definition with all parts created by CATIA CAD/CAM systems. Airbus has not yet used this approach and may not for the next several years. However, Europe does have the capability to integrate increasingly complex aircraft systems as demonstrated in a host of commercial and military aircraft. Japan, on the other hand, has not yet led a major commercial development and has had difficulty with systems integration on its military programs. Japanese firms, although members of Boeing's design team, have not independently designed and manufactured their own modern commercial aircraft. Japan also trails the United States and Europe in spacecraft systems integration capability, including satellites and launch vehicles.

HUMAN INTERFACE

A human interface is an essential element in the successful design and safe, reliable operation of any transportation system. The field of study that leads to proper design focuses on human capabilities, limitations, behavior and performance while interacting with complex engineered systems and environments. The role of the human operator in the control loop has changed greatly—from driving, navigation, and piloting as traditionally conceived to the control of complex systems in relatively infrequent off-nominal, potentially high risk situations. In the case of commercial aircraft, human factors involves both crew-machine and behavioral interactions on the flight deck to improve effectiveness and safety. For military pilots, it involves improving pilot function and situational awareness under conditions of fatigue and/or physical stress including high "g" associated with maneuvers and acceleration/deceleration. For the surface vehicle driver, it may involve ergonomic design, and integration with systems that are likely to be part of the intelligent transportation system of the future. For space flight, human factors involve issues of human performance and behavior in stressful, isolated, confined environments for extended periods.

The willingness to use and perhaps depend on technology is a cultural phenomena not simply bounded by the basic technology. A primary case in point is the degree of automation entailed in the Airbus flight control systems. As automation becomes more capable, the degree of keeping humans in the control loop and the ability to over-ride the control system will become more of an issue. In the case of highly unstable, non-linear control regimens where computer control is the only option, operator training and operator acceptance pose difficult problems - particularly as to the judgment of when and how to over-ride.

Human factors engineering

As the limits of human capabilities are becoming an important factor is safe and effective operation of transportation systems, several technologies are being used to extend or obviate these limits. In order to significantly increase the data analysis and response capabilities of drivers and flight crews, a modern "glass cockpit" is being designed to enhance readability and minimize the possibility for inappropriate interpretation of displays or activation of systems.

For the surface vehicle driver, creating a good interface may involve ergonomic design, and integration with systems that are likely to be part of the intelligent transportation system of the future. As part of an initiative to improve the safety and efficiency of the nations highways, work has been done to provide in-vehicle signing information and safety warning systems, sensory systems which provide extended line of sight during reduced visibility conditions, and obstacle detection and avoidance systems. This is intended to lead up to a fully automated highway system.

High "g" loads experienced by military pilots reduce the availability of well oxygenated blood to the retina, resulting in gray out and a tunneling of vision, and eventually loss of blood flow to the brain resulting in loss of consciousness. Countermeasures using small ultrasonic transducers are able to sense the reversal of blood flow at high "g" and used to control the pressure in a lower body garment intended to restrict the pooling of blood in the lower abdomen and legs. Lessons learned from the deterioration of the visual field under high "g" loads have also been applied to instrument design, head-up-displays, and alarm systems intended to catch a pilots attention even in a high noise, high stimulus environment.

Meaningful analog studies on Earth and in space are required for long duration flights. Ongoing work using the Antarctic as an analog has been quite productive. Another challenge facing crews in remote, isolated situations is that abnormal maladaptive behavior due to exposure to toxic substances may be indistinguishable from psychosis. Senior observers of military and exploration efforts have pointed out that human factors were responsible for mission failure more often than equipment factors. As in most complex systems, habitability and ergonomics also require more support and integration into spacecraft systems design.

Research, development and testing of human factors and the underlying assessment technologies based on physiological measurements has been conducted by the U.S. national laboratories, and their associated universities and contractors. Individual private corporations have conducted little work in this area beyond noise reduction and seating design; focusing more on appealing to consumer interest than in functional design issues. Automotive manufacturers here and abroad have demonstrated many concept vehicles with alternative interior and gauge designs; but these tend to driven more on visual graphic impact than meaningful contributions to improved human performance or control. Ergonomics has been most extensively studied and reduced to practice in the past by the Europeans, but as its value for differentiating consumer products has been more widely acknowledged in the past few years, manufacturers are beginning to draw on the established data bases.

The U.S. has a clear-cut lead in anti-g countermeasures in high performance aircraft, and even cockpit display and instrumentation. As the pressure suits universally worn by fighter pilots are capable of being pressurized, it is more of a deployment decision rather than one of underlying technology. The ultrasonic Doppler flow techniques for assessing individual pilot status during high-g have been more fully evaluated, control algorithms refined and reduced to practice in the U.S.

Spacecraft life support

Spacecraft life support involves issues of reliable, closed, physical-chemical, and/or bioregenerative systems. The goal is an integrated, stable ecosystem with greater simplification, minimal resupply, and greater degrees of closure. Current baseline designs for the space station depend entirely on reliable resupply of air and water consumables from the ground. The mass costs are unacceptable for any extended-duration manned missions, either on the Lunar surface or for Mars transit and exploration. While the Russians believe they could simply stock supplies for a two-year mission, serious long-term exploration requires a commitment to bioregenerative, closed, ecological life support systems. These systems must be capable of recycling and providing air, water, and food, while controlling toxics and bacterial or viral contamination. Stable, robust life support systems are essential to reducing remote outpost dependencies on resupply missions. In order of complexity, partially closed physical-chemical systems would be first, followed by closed physical-chemical systems.

In the broader perspective of the many sub-systems which comprise an integrated life support system, the Space Shuttle Extended Duration Orbiters provide an example at the 14 to 17 day end of the scale, with the pending Space Station exemplifying low development risk systems which can be ready evolved once the basic operational platform is in orbit. The critical areas include atmosphere control and supply, atmosphere revitalization, potable and wash water systems, waste management systems, temperature and humidity control, water recovery and management, microbial and toxics decontamination, and fire detection and suppression. All of these sub-systems are designed to evolve during the lifetime of the station, with eventual closure of the air, water, and potentially even the food loop as goals for long duration space flight. As designed, the base-lined filtration systems will be swapped out every 30 days with a 90 day resupply cycle from the ground. Water and CO_2 scrubber systems now in development could have their mass significantly reduced but with a corresponding increase in their power requirement.

Pilot plant evaluation, scale-up, and in-space validation must be performed under actual operating conditions, in zero gravity or on the Lunar surface. Lunar validation of such systems should precede any situation of long-term dependency. Advances in this area would contribute to maintaining leadership of the U.S. in science, mathematics, and engineering by improving our ability to facilitate long term space flight and by facilitating closed loop processing of materials with minimal environmental impact.

As the Russian "Mir" is the only permanently manned platform currently in space, it provides an example of the capabilities of water recycling and CO_2 removal but with total dependency on ground based resupply of oxygen. The Russians systems which have been of particular interest, water recycling and CO_2 removal, are the subject of a contractual relationship between Hamilton-Standard (one of the U.S. companies with a long-term involvement in this area) and the Russia groups. Several studies have been performed to assess the utility of the Russian work for early Station configurations.

9. ACTIVITIES RELATED TO CRITICAL TECHNOLOGIES

A large number of programs and development plans for technologies designated here as National Critical Technologies already exists in government and the private sector. Given the breadth of technologies covered by the list, it is impossible to describe or even list most of these here. This section discusses the areas in which different agencies perform R&D relevant to critical technologies, and provides some examples of specific programs in each technology category. It also provides some examples of government-private sector partnerships and non-government initiatives.

FEDERAL GOVERNMENT ACTIVITIES

A significant proportion of the approximately $70 billion devoted annually by the federal government to the support of R&D directly involves the development of critical technologies. Two other categories of R&D activities account for the remainder of the federal R&D budget.

The first encompasses the approximately $14 billion spent annually by the federal government on the conduct of "basic research." This portion of the federal R&D budget is not considered directly relevant to critical technologies because these monies involve the pursuit of greater knowledge or understanding without a specific technological application in mind. As a result, all activities falling within DOD's Budget Category 6.1 (Basic Research) are excluded, as is the "basic research" of all other federal agencies. The only notable exceptions involve the Department of Health and Human Services and the National Science Foundation, both of which are agencies with the preponderance of their R&D activities officially constituting "basic research," but which also are centrally involved in key areas on the Critical Technologies list (i.e., Biotechnology and most areas of Information and Communication, respectively).

Also excluded from R&D directly relevant to critical technologies are the activities of DOD that involve the demonstration and validation of integrated military technologies (6.4), engineering and manufacturing development for military use (6.5), miltary R&D management support (6.6), and military operational systems development (6.7). While activities within these categories (i.e., 6.4 and 6.5) clearly involve the advanced development and application of critical technologies, it is impossible to separate these from the overall missions of programs, and as a result, the approximately $26 billion spent annually within these four DOD Budget Activity categories is not generally included among the resource totals relevant to critical technologies.

Consequently, the "core" of federal R&D budget—the "applied research" and "development" as these terms are generally defined for all federal agencies—also forms the foundation for the nation's critical technology R&D. In the case of the Department of Defense, this includes those activities which fall within DOD's Budget Activities 6.2 (Exploratory Development) and 6.3 (Advanced Development). Similarly, for other agencies, it includes those activities that do not generally constitute "basic research" (note exception described above). Below are brief descriptions of the critical technology areas in which R&D activities of the major agencies are concentrated.

Activities by agency

Department of Defense

The Department of Defense is a major contributor to work in virtually every area of critical technologies. The critical technology most dominated by work housed within DOD involves Sensors within Information and Communication. Among these programs are ones involving signal processing, night vision, signal verification, guidance assistance, and the detection of various substances and movements. DOD also dominates efforts to develop technology for education and training focusing on simulation.

National Aeronautics and Space Administration

The National Aeronautical and Space Administration's R&D work focuses mostly in three major critical technologies areas: transportation, aeronautics and communications. The remainder of NASA's critical technology work reflects the importance of flight-worthy spacecraft, lower cost space launch, and reliable communications in all space missions. In addition, Mission to Planet Earth Program focuses on monitoring and assessment of the quality of the environment. The Space Station Program is concerned with systems integration. NASA is also an important contributor to the work on human factors engineering and human-machine interface.

Department of Energy

While DOE has a presence in every critical technology area, its major programs in Fossil Fuels, Nuclear Energy, Fusion Energy, and Solar Energy constitute virtually the entirety of the Federal Government's R&D efforts to improve the generation of energy. Similarly, DOE's activities dominate the government-wide R&D efforts in environmental remediation and restoration and energy efficiency. The DOE's Los Alamos National Laboratory is leading the Human Genome project, the most significant effort in human genetic mapping in the world.

Department of Health and Human Services

While the majority of R&D activities of the Department of Health and Human Services involve "basic research," over half of all on-going work in technologies critical to living systems is performed by its National Institutes of Health. Augmenting the work of these institutes in this critical technology area is work by the Centers for Disease Control and Prevention in vaccines and infectious diseases and the Food and Drug Administration in the promotion of food safety and medical devices. In addition, work at NIH in the critical technology area of Information and Communication has broken new ground for scope and imagination (i.e., the National Library of Medicine's enormous project on the visible man).

Department of Agriculture

Virtually all work in advancing sustainable agricultural production is housed in the Department of Agriculture, shared relatively equally by its bureaus—the Agricultural Research Service and the Cooperative State Research Service. The remainder of USDA's critical technology activity focuses primarily on the monitoring and assessment of environmental quality and is housed in the Forest Service.

Environmental Protection Agency

The EPA's R&D focuses intensely on monitoring and assessment activities to preserve and improve the quality of our environment. The EPA has research programs in air quality, water quality, drinking water, pesticides, hazardous waste, toxic substances radiation, and multimedia research, as well as the lesser volume work in pollution control.

While the EPA is the recipient of record for the R&D funding associated with Superfund activities, a large portion of the money actually ends up at the National Institute of Environmental Health Sciences in the National Institutes of Health at the Department of Health and Human Services. The primary focus of this program is remediation and restoration.

National Science Foundation

The vast majority of the R&D conducted by the National Science Foundation is "basic research" and so outside the scope of the Critical Technologies Report. The two notable exceptions to this are the work of NSF's Directorate of Computer and Information Science and Engineering (CISE) and Directorate of Engineering. The work of NSF in Information and Communications is dominated by CISE; the work of the Engineering Directorate is in the areas of Manufacturing and Materials. In addition, the work of the Directorate of Geosciences is of major importance to the monitoring and assessment of environmental quality.

Department of Interior

The R&D activities of the Department of Labor's Geological Survey and National Biological Survey (still resident in the Fish and Wildlife Service in FY 1993), comprise a notable portion of the nation's effort to monitor and assess the quality of our environment.

Department of Commerce

The critical technology activities of the Department of Commerce are split between its two bureaus—the National Oceanic and Atmospheric Administration and the National Institute of Standards and Technology. The entirety of NOAA's Office of Oceanic and Atmospheric Research and the National Environmental Satellite, Data, and Information Service are devoted to monitoring and assessing the quality of our environment. In addition, the National Marine Fisheries Service within NOAA is a principal promoter of technology to advance the commercial fishing industry.

That portion of R&D conducted by NIST that does not concentrate on metrics and calibration is central to the advancement of critical technologies in Manufacturing, Materials, and Information and Communication, albeit the effort is modest when compared in scale to the resources devoted to these activities by larger agencies. A notable portion of NIST's critical technology work is accounted for by the activities of its Advanced Technology Program.

Department of Transportation

As an amalgam of "administrations" regulating the various modes of transportation, the Department of Transportation's R&D efforts emphasize matters of prevention and safety. As a result, DOT, especially the Federal Aviation Administration, contributes to work in the critical technology area of Information and Communication to ensure the safe operation of both commercial and non-commercial aircraft.

Examples of programs

The government programs which comprise the R&D expenditures described above are many and varied. They include the Technology Reinvestment Project (TRP) used to stimulate the transition from separate defense and civilian industrial bases to a "growing, integrated, national industrial capability,"[1] the Advanced Technology Program which works with industry to share the cost of developing high-risk but powerful enabling technologies for commercial applications, and others. In order to provide a "flavor" for the breadth of the federal R&D enterprise, selected programs and the primary technical challenges which they address are discussed below.

Wind turbines

The primary technical challenge in improving wind-energy efficiency is to develop a turbine which can operate efficiently and reliably under conditions of wide fluctuations in wind velocity, with low maintenance and low capital costs. Improvements in blade design and development of variable-speed turbine

[1]Technology for Economic Growth, p. 12.

systems combined with power-handling electronics are the focus of research programs in the U.S. and Europe.

The stall-controlled turbine is one of two competing conceptual designs being developed in the U.S. under funding from the Department of Energy. Variable-speed wind turbines utilize power-handling electronics to enable the rotor to rotate at variable speeds. This increases annual energy output, improves power supply quality to the grid, and reduces structural loads. Power -handling electronics serve to suppress harmonic currents and reduce transmission losses by controlling the power factor when current and voltage are not in phase. Controls can also be introduced to reduce structural dynamic load (reducing the stress on structural interaction, as that between the rotor and the tower, when rotor angular velocity is variable).

Environmental quality

It was estimated that the federal government has spent approximately $550 million for research, development, and demonstration of remediation technologies in 1994. These expenditures represent approximately 15 percent of the total federal investment in research, development, and demonstration for all environmental technologies.

DOE programs, which fund more than 40 percent of the work in this area, include remediation of high-level waste tanks; contaminant plume containment and remediation; contaminated solids and buried waste; mixed waste characterization, treatment, and disposal; and facility transition, decommissioning, and final disposal. DOE, along with DOD, have a particular interest in remediation and restoration technologies because of their sizable tasks involved in cleaning up toxic contamination at their facilities. The USDA also has a substantial program that includes technologies to improve degraded lands and develop biological means to generate wood pulp and degrade wood preservatives. At EPA, resources are used for research in areas such as bioremediation technologies for clean up toxic wastes. The EPA also administers the SITE (Superfund Innovative Technology Evaluation) program, which provides an opportunity for technology developers to demonstrate capabilities to successfully remediate Superfund waste. SITE programs have looked at techniques as varied as photocatalytic oxidation, in-situ vapor extraction, and biological degradation in immobilized cell bioreactors.

In 1991, the Western Governors Association, the Departments of Defense, Energy, and Interior, and the Environmental Protection Agency signed a memorandum of understanding to create a state-federal partnership to test ways to expedite testing of innovative clean-up technologies. In 1992, the Western Governors and the four federal agencies established the Federal Advisory Committee to Develop On-Site Innovative Technologies (DOIT) to oversee the development of new approaches to remediation technology development, deployment and commercialization. The DOIT committee activities are ongoing.

State governments are also starting to become players in the environmental technology arena, often out of fear that technologies to remediate wastes in their states will not be available when needed. For example, the new Center for Evaluation of New Environmental Technologies is a joint effort of the California Department of Toxic Substances Control and the University of California Davis. This joint state government-academic center has picked five commercially developed technologies for evaluation and demonstration, starting in 1994.

The U.S. government has begun coordinating research and development work in environmental technologies through the National Science and Technology Council (NSTC) joint-subcommittee on environmental technologies (JSET), which is derived from the committees on Civilian Industrial Technology and Environmental and Natural Resources. In addition, the National Science and Technology Council and the White House Office of Science and Technology Policy are developing a strategy for promoting environmental technologies to achieve sustainable development.

In the FY94 Technology Reinvestment Program (TRP) awards, there were several in the sensors area that are relevant to environmental monitoring, site characterization, or other detection of hazardous agents. These include:

- The E-SMART System for In-Situ Detection of Environmental Contaminants (General Atomics, Air Force/Armstrong Laboratory, Georgia Tech Research Institute, Isco, Inc., Photonic Sensor Systems, Inc., Science & Engineering Analysis Corporation, $5.4 million, 24 months)

- Volatile Organic Compound (VOC) Sensors, Communications, Processing, and Display (Hughes Aircraft Company, AAI-ABTECH, GM Hughes Electronics Research Laboratories, University of Pennsylvania, $2.5 million, 24 months)

- UV DIAL Lidar (OCA Applied Optics, Los Alamos Science, $2.0 million, 12 months)

- Field-Deployable, Continuous Monitoring Mass Spectrometer (Teledyne Electronic Technologies; DOE/Oak Ridge National Laboratory/MMES; Monsanto Company; Phillips Petroleum Company, Scientific Services Div.; Scientific Instrument Services, Inc.; Synergist, Inc., $6.9 million, 24 months)

- IMAS: An Intelligent Modular-Array System for the Monitoring of VOCs in the Environment (Tektronix, Inc.; Battelle, Pacific Northwest Laboratories; DOE/Sandia National Laboratories; Sawtek Inc., $2.1 million, 23 months)

<u>Flat panel displays</u>

The DOD's flat-panel display initiative is a five year, $587 million program to provide Defense with early, assured, and affordable access to advanced flat panel display technology by supporting domestic investments in dual use display capability. The prerequisite industry matching funds should bring the total investment to $1.2 billion.

A major element of the initiative is a focused R&D competition for next generation display technologies limited to firms that demonstrate commitment to produce current generation displays to meet defense needs. The R&D program will be conducted on a cost-shared basis to ensure that the participating firms have commitment to bring the technology developments into application. The DOD is planning to have four such competitions over the next five years. International companies are eligible to participate based on criteria of the Technology Reinvestment Project. Each of these competitions is designed to be neutral regarding any specific display technology and judged on the quality of the proposed research and development, the soundness of the technical plan, the adequacy and appropriateness of the proposed cost sharing, and demonstration of commitment to production of current generation displays.

The DOD' flat panel display initiative is the largest government initiative for advanced displays systems. Other smaller efforts include support for the development of generic technologies through ARPA and NIST. The Clinton administration has also established a link between the National Information Infrastructure and advanced displays. The administration favors letting private industry build the NII but is willing to fund high-risk R&D for overcoming technological obstacles. Advanced displays have been designated as one of the primary obstacles to the success of NII.

Software

The time, expense, and great uncertainty involved in all large-scale software development projects is the greatest software-related problem. Projects routinely run 50% to 200% over budget and beyond schedule, and are sometimes abandoned in midstream. One continuing hope is that a science of "rapid prototyping" will evolve to allow early risk reduction through iterative test and evaluation of critical components, user interfaces, and designs at a stage where changes can be made easily before major design commitments are made. Other research thrusts in software engineering involve the attempt to "manufacture" software from standard modules and with standard procedures, to emulate other engineering and production disciplines that are able to predict costs and schedule for development. To better assess the state of U.S. software engineering and promote effective practices, the Software Engineering Institute (SEI) was established as a Federally Funded Research and Development Center (FFRDC) in 1984 by DOD through the Advanced Research Projects Agency (ARPA). It is located in Pittsburgh PA, in association with Carnegie-Mellon University.

One focus of rapid software development is the use of object technology to create libraries of reusable code modules based on object oriented software. The U.S.

FY94 Technology Reinvestment Program (TRP) awarded three contracts in this area:

- Object Technology for Rapid Software Development and Delivery (Anderson Consulting, CoGenTex Inc, Expersoft Corporation, Raytheon Company's Missile Systems Division); $24.5 million, 24 months

- LEGOS: Object-based Software Components for Mission-Critical Systems (I-Kinetics Inc., Heuristicrats Research Inc, Iona Technologies Ltd, Navy/Naval Sea Command Inc, SunSoft, UTC Pratt & Whitney, Government Engines & Space Propulsion); $8 million, 24 months

- Object Technology for Rapid Software Development and Delivery (Template Software Inc, Honeywell Technology Center, IBM Corporation, ISX Corporation); $12 million, 24 months

The NIST Advanced Technology Program is also investing in software development. One of its major thrusts, a 5-year $150 million Component Based Software Program, is an effort to help industry create fine-grained software components and specialized high-performance tools. The aim is to enable semantic-based software creation in which systematically reusable software components can be automatically assembled into a broad array of application specific systems.

<u>Recombinant DNA technologies</u>

The Human Genome project is an international effort to locate and catalog every gene, changing our understanding of human biology at its most basic level and revolutionizing the practice of medicine. Genetic susceptibilities have been implicated in many major disabling and fatal diseases including heart disease, stroke, diabetes, and several kinds of cancers. As the genetic mechanisms of inherited disease are determined, it will provide the ability to identify people who have or carry genetic disease. The identification of these genes and their proteins will pave the way for more effective preventative measures and therapies. Indentification will inevitably occur before treatments are developed, so that each success in the gene-mapping project will create new ethical and social policy dilemmas. The potential presymptomatic diagnosis of disease will present substantial challenges related to individual privacy and insurability.

A major component of the Human Genome Project is the development of automated sequencing technology that is faster, more sensitive, accurate and economical. The present gel-based equipment can sequence only 50,000 to 100,000 bases per year at a cost of $1 to $2 per base. The current goal is to develop technology capable of 100,000 or more bases per day at a cost of $.50 per base, with subsequent technologies offering a further factor of 10 reduction in processing costs. High voltage capillary and ultrathin electrophoresis to increase separation rate and the use of resonance ionization spectroscopy to detect stable isotope labels look promising. Third generation gel-less sequencing technologies include (1) enhanced fluoresce detection of individual labeled bases in flow cytometry, (2) direct reading of the base sequence on a DNA strand with the use of scanning tunneling or atomic force microscopies, (3) enhanced mass spectroscopic analysis of DNA sequences, and (4) sequencing by hybridization to short panels of nucleotides of known sequence.

Electronic data management and publishing systems are increasingly essential components of genome reearch as the on-going projects are generating volumes of information that cannot be readily incorporated by traditional publishing. Correlating mapping data from different laboratories has been a problem because of different methods of generating, isolating and mapping DNA fragments. In addition to laboratory methods, the emerging field of Genetic Informatics is making a significant contribution to the ability to constucting and searching the maps and sequences in order to find specific genes. Major databases are globally distributed (U.S., Germany, France, Italy, Australia, Japan, Israel, Switzerland) and accessible via the InterNet.

National Institute of Standards (NIST) has announced the Tools for DNA Diagnostics Program which focuses of the development of low-cost, integrated, miniaturized, high throughput, parallelizable, automated systems that can be used to obtain DNA sequence information efficiently and accurately. The largest award under the program, $31.5 million, went to a joint venture between Affymetrix Inc. and Molecular Dynamics Inc which are developing a device that will diagnose diseases by analyzing a patient's DNA on the surface of a silicon microchip that is read by a laser scanner. Another award, $14.7 million, went to the C. Everett Koop institute for a project to help the health care industry take advantage of the information superhighway.

<u>Vaccines</u>

It is currently estimated that over 20 federal agencies play a role in the development, testing, distribution, and use of vaccines in the U.S. From 14 U.S. companies in 1980, only four remain largely because of problems related to liability and profitability. The entire global vaccine market is estimated by a recent UNICEF study to be about $3 billion. NIH spent an estimated $300 million on vaccine research and the CDC spent another $528 million on vaccine purchase, research, and testing. DOD is responsible for military vaccine needs and global emergencies.

The development of a vaccine for AIDS continues to be elusive. It is estimated that expenditures are about $160M worldwide, with industry spending about $25 million globally and the U.S. government spending about $111 million. The perception is that most of this work is done in the smaller biotechnology companies.

Manufacturing

Government support has long been associated with developments in manufacturing. Much of NIST's industrial research has supported the development of standards. In the Department of Defense, support has come through programs like MANTECH. What is new today is the promise of the "lean manufacturing" paradigm, which has also been supported in the Department of Defense. In some industries, transformation to lean manufacturing is being promoted by the federal government, as in the Department of Defense "lean" aircraft initiative, a collaborative effort involving industrial firms, the Air Force, and the Massachusetts Institute of Technologies.

In addition to developing specific manufacturing technologies, the federal government is also involved in helping diffuse best manufacturing practices through the NIST Manufacturing Extension Partnership. MEP centers, located throughout the country, help small and medium-size businesses adopt modern equipment and manufacturing and management techniques in order to become more competitive in domestic and international markets.

Here is one specific example. The evolution of more sophisticated manufacturing techniques is critical to the realization of advanced coatings with enhanced hardness, corrosion-resistance, thermal, and wear characteristics. One of the most exciting candidates is the large-scale production of high quality diamond thin films.

Given the increasing dependence of the military on high technology products, it is apparent that continued investment in artificial structuring methods is essential for sustained security. For example, the Department of Defense is presently the largest customer of high definition displays, and the manufacture of these displays is dependent, among other things, on advanced thin film techniques. Also, the successful development of diamond coatings has applications ranging from aircraft windshield coatings to high speed electronic components.

Research funding for thin film manufacturing techniques is shared by federal and private sector sources. The DOD has significant investments through ARPA and other bureaus. In particular, it is estimated that $100 million annually is invested by private companies and the government on research into producing diamond films with the largest spender being DOD. Much of this funding has stemmed from the former Strategic Defense Initiative Office, now renamed Ballistic Missile Defense Office (BMDO). Additional funding of thin film deposition research originates in the Departments of Commerce, Energy and the National Science Foundation. DOE also sustains research efforts itself and has worked to establish joint ventures with industry in this field.

While the United States is not the industry leader in many of the applications reliant on artificial structuring manufacturing methods, it is competitively positioned in thin film deposition technologies. However, there are major challenges for the advancement of existing techniques as well as for the development of emerging manufacturing capabilities. The key technological challenge for new techniques is the transfer of laboratory successes into large scale production. The primary impediment is that growth rates are severely limited for many of these new technologies and materials. For example, molecular beam epitaxy has demonstrated the ability to fabricate unique structures but is primarily a research tool for this reason.

The development of these technologies is also capital intensive. Diamond thin films are a dramatic example of a major investment without any, as yet, marked returns. As a result, commercial activities often view ease of manufacture as the primary requirement for a technology. Consequently, research investment efforts often focus on manufacturability.

Materials

The federal government has long promoted the development of new materials. This effort started under the old Federal Coordinating Council for Science, Engineering, and Technology as the Advanced Materials and Processing Program. As we note in a discussion of composite materials below, the interrelation of materials to material processing is still an important factor that should shape any program. The federal attention to materials is now continuing under the Civilian Industrial Technology Committee of the National Science and Technology Council.

A coordinating mechanism for materials research has proved useful in the past, because of the spread of research on materials across agencies. The Departments of Commerce, Energy, Defense, the Interior, Transportation, Health and Human Services, and Agriculture all support important programs, as does the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Science Foundation. Avoiding duplication while assuring important leads are followed requires coordination.

The diversity of supporting agencies is driven by the ubiquitous effects of materials. Each agency has important applications or classes of materials that are uniquely theirs. Each agency also understands the demands of its applications very well, whether that is a low observable material for the Department of Defense or a new paving repair product for the Department of Transportation. Keeping the material development connected to this understanding is important in quickly tapping new opportunities. As materials develop, though, new applications become interesting, such as the use of wood fiber to reinforce cement. Making the other interested agencies aware of such developments is the other major function and benefit of high-level coordination.

The current coordination of materials development led by the NSTC has focused material developments on the priorities of the government. Among others, emphases have been created on the automotive sector, supporting the PNGV; the building and construction sector as well as the built infrastructure of roads and bridges; the electronics industry; and the aerospace industry. These areas have been supported, in part, through programs like the ATP.

Another important aspect of this coordination is the maintenance of the user facilities. The federal government is the provider of most important user facilities. These facilities are important to the development and characterization of many new materials. They are spread across a range of agencies, reflecting the range of interests in materials. There are many such facilities. A selection illustrating their variety follows:

- Cold Neutron Research Facility (supported by the National Institute of Standards and Technology of the Department of Commerce) and the associated Center for High Resolution Neutron Scattering (supported by the National Science Foundation)

- Cornell High Energy Synchrotron Source (supported by the National Science Foundation)

- National Synchroton Light Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Stanford Synchroton Radiation Laboratory (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Advanced Light Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Advanced Photon Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- High Flux Beam Reactor (supported by the Office of Basic Energy Sciences of the Department of Energy)

- High Flux Isotope Reactor (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Intense Pulsed Neutron Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Manual Lujan Jr. Neutron Scattering Center (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Center for High Resolution Electron Microscopy (supported by the National Science Foundation)

- Francis Bitter National Magnet Laboratory (supported by the National Science Foundation)
- National High Magnetic Field Laboratory (supported by the National Science Foundation)
- National Nanofabrication Users Network (supported by the National Science Foundation)

Most user facilities have been developed to meet specific needs of researchers in materials across all sectors of our society. They differ in important details, such as the energy of the electrons in the synchrotrons, and thus in the wavelength of the emitted light. This allows each facility to probe a different aspect of a material, or a different property. The facilities also support non-materials work, including fundamental science, but the core of their work remains materials characterization. The need for many of these facilities has been validated by several studies from the National Research Council, and some of the facilities themselves are being duplicated in both Europe and Japan, where their importance is apparent.

Composites

The metal-matrix composites use metal rather than plastic as the matrix. Usually the metal is in the form of a powder which is combined with the reinforcing fibers in a mold, where the combination is subjected to heat and pressure to fuse the part together. Metal matrix composites (MMC's) have advantageous properties of higher strength, stiffness, wear resistance and elevated temperature properties, and are especially applicable for high-temperature uses such as in jet engines. Many metal matrix-composites can be machined on the same apparatus used for traditional metals and some can be welded. NASA is currently validating their use up to a temperature of 2300° F. Matrix materials include nickel, superalloys, titanium alloys, aluminum alloys, magnesium, copper, intermetallics, and steels. Fibers include, silicon carbide (SiC), refractory metal wires, and carbon fibers, among others.

Metal matrix composites have the potential to significantly affect future propulsion systems, as well as airframes. One metal matrix composite being investigated is fiber-reinforced titanium which is about three times stronger for a given weight than nickel superalloy at temperatures up to 1500° F. Compressor discs of SiC reinforced titanium have been manufactured by Textron. For the IHPTET (Integrated High Performance Turbine Engine Technology) program Allison Gas Turbines tested a compressor fabricated with metal matrix composites. It achieved an 80% reduction in weight over a conventional compressor stage.

The basic limitation for metal matrix composites is cost. SiC fiber costs $2500/lb, however this is due to the relatively low volume at which SiC is produced. It is estimated that cost could drop to $100-200/lb with production of 40,000 lbs a year. Textron Specialty Materials will demonstrate the production of SiC in a titanium metal matrix this year under a contract from the Air Force (NASP funding). The experiment will attempt to automate the production process and demonstrate the ability to produce the material at lower cost. New intermetallic compounds (titanium aluminide, nickel aluminide, iron aluminide), when used as a matrix material, will further improve the high-temperature properties of metal matrix composites. Incomplete information on property data and fabrication techniques are two limitations that exist at this time. These limitations are being addressed and are not nearly as much of a concern as cost.

Another type of composite is ceramic matrix composite. Ceramics offer increased turbine inlet temperatures while lowering overall weight. The problem with ceramics is their brittleness, cost, and difficulty of manufacture. The high brittleness makes the ceramic parts extremely prone to impact damage, usually resulting in catastrophic failure. Brittleness might be overcome by using ceramic matrix composites or by new superplastic ceramic technology. Monolithic ceramics will, most likely, see only limited application on advanced turbine engines. One of these applications is the use of ceramics in advanced engine bearings. Significant weight savings over metal bearings will allow engines to achieve higher shaft speeds. There are several companies involved in the research and development of advanced ceramic materials including, Eaton, GTE, Norton, and TRW. The Department of Energy is also sponsoring a research program called the Advanced Turbine Technology Applications Project (ATTAP) at Garrett Turbine Engine and Allison Gas Turbine Division.

<u>Structures</u>

Today's most advanced fighter aircraft such as the F-22 and EF-2000 make extensive use of composite materials in primary structure such as wing and fuselage. Transport aircraft are using them already in less-critical structural areas, but will undoubtedly incorporate them soon in primary structure for greater weight and cost savings. In the future, the use of composites will be expanded and optimized for weight and producibility through better manufacturing approaches and large scale integration, and even newer technologies such as smart structures and adaptive structures will become reality. These are described below.

Large-scale integration, or co-cured composite structures offer the potential of very large reductions in structural manufacturing costs. This technology, in development for many years, involves the lay-up and simultaneous cure ("cocure") of entire structural elements such as the wing box, rather than separately curing small parts then fastening them together. The elimination of conventional fasteners from the skin of an aircraft reduces drag and complexity, as well as weight and fuel leakage problems. Problems remain, however, with repairability (because the structure cannot be disassembled), quality control, inspection, and scrap costs.

Research in these areas is under way at numerous industry and government facilities. NASA's Advanced Composites Technology (ACT) program is developing technologies that will further the introduction of composites into the primary structures of future commercial transportation aircraft. Research is also being conducted at NASA Langley, as well as Boeing, McDonnell Douglas, Lockheed, and 12 other companies.

A more-exotic structural concept is the "smart structure". A smart structure is one that is "aware" of its state, through embedded sensors and intelligent computer systems. On composite structures the sensors might be optical fibers embedded in the matrix, whereas conventional airframes would have strain gauges or optical fibers bonded to the airframe. If the structure also has the ability to make corrections and adjustments based on measurements from sensors embedded in the structure then it is considered to be an "adaptive smart structure". For example, the sensors in the structure would inform the pilot about the extent of damage incurred in a battle, or it might tailor the control surfaces for greater aerodynamic efficiency based on flight conditions, or it might suppress vibration during flight.

Smart structures have the potential to revolutionize operational cost. Typically, the required intervals for repairs or inspections are statistical evaluations of aircraft life, with much conservatism to ensure that the "worst" airframe is inspected and serviced often enough for safety. Using the smart structure concept, airframe fatigue and other life-related problems would be measured and calculated on-board the aircraft. With appropriate changes in civil regulations, this could permit a safe reduction in inspection and regular maintenance costs with substantial impact on the economics of commercial transports.

Research in this area is being conducted by the Air Force (primarily at Wright Laboratories), Navy, DARPA, and NASA, as well as on the contractor level. Boeing, United Technologies, and McDonnell Douglas have been conducting tests on flight articles. NASA is flight testing an F-15, as part of the HIDEC program, which eventually will sense control surface damage and then reconfigure the flight control system to land the aircraft safely.

Propulsion

Several U.S. programs are in place to promote research into advanced aircraft engine technologies including IHPTET (Integrated High Performance Turbine Engine Technology), HITEMP (High Temperature Engine Materials Program), ATTAP (Advanced Turbine Technology Applications Project), and EPM (Enabling Propulsion Materials Project). IHPTET, the most prominent of the programs, is a comprehensive propulsion technology program managed by the Aero Propulsion Laboratory, which is part of the USAF's Wright Laboratories. The program has as its goal the doubling of gas turbine performance by the end of the century. Also, the Air Force is funding the Advanced Turbine Engine Gas Generator (ATEGG) program and the Joint Technology Demonstrator Engines

(JTDE - also funded by the Navy). Allison and Pratt & Whitney have tested ATEGG engines while GE and Pratt & Whitney have tested JTDE engines. Finally, the considerable ongoing investment in the development of the engines for the F-22 can be expected to have a vast "spin-off" for advanced commercial and military aircraft.

GOVERNMENT-INDUSTRY PARTNERSHIPS

An increasing number of programs, especially ones with potential commercial applications, are being funded and performed by partnerships between the government and the private sector. Such partnerships are characterized by substantial financial contributions from member-companies and the government, as well as by arrangements for joint decision-making with regard to the direction of R&D.

Partnerships allow the government to leverage its resources in the days of tight R&D budgets by funding technologies and applications which may be risky for industry but essential for the nation's future. At the same time, substantial financial contributions made by the private sector partners assure that these companies have a stake in the successful outcome and commercialization of the R&D. Several examples of industry-government partnerships are discussed below.

Advanced batteries

In 1991, Chrysler, Ford, General Motors, the Electric Power Research Institute, and the U.S. Department of Energy created the U.S. Advanced Battery Consortium (USABC), to fund advanced battery research and development. USABC set performance goals for medium-term batteries which would "result in mass production of electric vehicle batteries potentially in this decade" and far-term batteries which will provide electric vehicle performance competitive with today's internal combustion engines. While there are no clear winners yet, a number of battery technologies appear capable of meeting USABC goals.

Extensive re-engineering of lead-acid battery technology has produced several systems which exceed the USABC medium-term goals for cycle life and cost, far exceed the power goal, and come within about 75% of the energy storage goal. Nickel-metal-hydride battery technologies have received approximately $20 million of USABC funding. Extensive re-engineering of lead-acid battery technology for commercial transportation applications has produced several systems which exceed the USABC medium-term goals for cycle life and cost, far exceed the power goal, and come within about 75% of the energy storage goal. For instance, a lead-acid battery produced by the Optima Corp is currently used in a commercially available, four-passenger electric car which a range of over 100 miles and high performance acceleration of 0 to 60 mph in 6 seconds. However, current lead-acid batteries are inadequate for military applications such as battlefield vehicles due to their low specific energy. The need for compactness and mobility makes advanced batteries with long-life and high specific energy density more important for military vehicles than commercial vehicles. A battery developed by the Ovonics Battery Company is projected to achieve all USABC requirements except for cost, though the power density of current designs still falls short. A sodium-nickel-chloride battery developed by AEG Corporation is projected to meet all USABC mid-term goals except cost. The technology is currently being tested in European vehicle demonstrations and is available for automobile manufacturers for testing. AEG is currently developing a pilot plant and is working to remedy problems of low power densities at low charge states for the battery.

The far-term USABC goals are most likely to be met by lithium polymer battery technology. The lithium-iron-disulfide battery offers high power and energy densities, and possibly low-cost manufacturing via thin films. Currently Westinghouse has developed a monopolar form of this battery for use in electric lawnmowers.

Partnership for the New Generation of Vehicles

On September 29, 1993, President Clinton, Vice President Gore and the chief executives of the Big Three automakers announced the formation of a government-industry Partnership for the New Generation of Vehicles (PNGV). The goals of the partnership are to significantly improve national manufacturing technology, including adoption of agile and flexible manufacturing; to implement commercially viable innovation from ongoing research on conventional vehicles; and to develop a vehicle to achieve up to three times fuel efficiency of today's comparable vehicles without loss of quality performance and utility. The goals are interrelated, focused both on the near-term and the longer term.

Because an automobile involves many different technologies, the success of the PNGV will involve improvements in many different technical areas, many of them on the National Critical Technologies List. Included are lightweight materials, advanced catalysts, aerodynamics, and energy storage technologies. A number of different administrative and program mechanisms will be used as well, ranging from TRP to take advantage of technologies being developed by the DOD, to NSF grants, to contracts under the ATP, to DOE CRADAs. In addition to the Big Three automakers, program participants will include suppliers, universities, and other consortia which can contribute relevant knowledge.

U.S. Display Consortium

The ARPA HDS program began in 1988 and focused on underlying technologies required for the production of advanced displays. It was established with a dual-use strategy. The Clinton Administration increased the funding allocated to the program. By February of 1993, 85 projects had been funded with a total cost of

$70 million. Both universities and private firms have been supported. Research on AMLCD was combined with field emission displays, color electroluminescent, and color plasma, which are the four major competing technologies underlying advanced displays. Support is continuing through the DOD initiative and through NIST.

The ARPA program has now transformed into a program that involves a large consortium of companies. In July of 1993 the U.S. Display Consortium (USDC) was established by ARPA, AT&T, Xerox, Tektronix, and a number of smaller display manufacturers. The mission of USDC is to "develop the U.S. manufacturing infrastructure required to support a world-class U.S. based production capability for high definition flat-panel displays." The consortium is open to display manufacturers, the manufacturer equipment makers, and to companies that use displays in their products. By pooling the cost for R&D expenditures the overall economic barriers for high volume production of advanced displays should be significantly lowered. Since this is an ARPA led project the majority of the funds that have been spent on smaller research programs will now be invested in the USDC.

National Electronics Manufacturing Initiative (NEMI)

The National Electronics Manufacturing Initiative (NEMI) is a project designed by both industry and government electronics research managers to better coordinate important research in critical electronics technologies. NEMI grew out of the Electronics Subcommittee of the National Science and Technology Council (NSTC), a subcommittee that provides Federal interagency coordination for technical planning, budgeting, reporting, and evaluation of Federal programs in electronics science and technology, and supports two-way communications on these programs within the government and with the private sector.
The goal of the NEMI is to promote joint industry/government development of the underlying technology and infrastructure required to enable and encourage manufacture in the United States of new, high technology electronics products, such as the hardware for accessing the Information Superhighway. NEMI aims at coordinating R&D in enabling technologies, improving the manufacturing infrastructure for specific electronics technologies, demonstrating projects in support of National priorities and to meet specific government agency missions, and to develop recommendations on improving the U.S. business environment for electronics manufacturing. The technologies that NEMI has targeted for specific attention are:

- microelectronics
- human interface technology
- low-cost integrated packaging
- mass memory
- power management
- precision mechanical parts and assembly

- design and manufacture for mass-customization
- computer-based design and manufacturing
- information access technologies
- advanced materials

Photonics and optoelectronics

Currently many government R&D funding programs for photonics research require a consortium of companies to work together or companies to work with the government labs. Companies and government labs working together to share information on manufacturing problems are intended to help the photonics industry to reach a consensus on standards that are critical to the development of platform processes. The alliance model among companies in the private sector is becoming more and more common, since the cost to develop flexible standardized platforms for manufacturing photonic devices is extraordinarily high. Nevertheless, the lack of consensus and the current competitive atmosphere in the photonics arena prevent the quick development of these essential standard platforms. The government programs are helping to lower the high initial investment for individual companies and are beginning to consolidate research studies which could ultimately lead to a consensus on certain platform technologies.

There is considerable federal investment in the optical computing area. The Advanced Research Projects Agency (ARPA) is sponsoring a consortium in Optoelectronic Module Technology (OETC). The principle investigators in this project are Martin Marietta Electronics Laboratory, AT&T Bell Laboratories, Honeywell Technology Center, and IBM T. J. Watson Research Center. The purpose of OETC is to expedite the development of high bandwidth and high density optical interconnect components and to facilitate the implementation and proliferation of the developed products. This project's ultimate goal is to position the U.S. as the world leader in optical interconnect technology. Four out of seven technology areas chosen for the ARPA Technology Reinvestment Project (TRP) for fiscal year 1994 will involve photonics or optoelectronics. These include: high density data storage systems, high definition systems manufacturing, uncooled infrared sensors, and environmental sensors. There are also several other government initiatives for continued research in photonics and optoelectronics manufacturing research through the National Institute of Standards and Technology.

$11 million of TRP money has been also been invested in a university-industrial consortium to develop a rewritable optical storage system, exploiting blue/green lasers, that will store up to 10 Gigabytes in a single 5.25" optical disc. This effort is expected to result in a factor of 5-10 increase in storage capacity of the state-of-the-art commercial systems today.

NON-GOVERNMENT INITIATIVES

In addition to their participation in various consortia and government programs, companies, universities, and non-profit organizations have programs of their own which are relevant to technologies on the National Critical Technologies list. Several of these initiatives are expressed as development roadmaps which specify technical goals to be achieved by specific dates, and strategies for achieving these goals. Many of the roadmaps include a description of roles expected by all participants in the industry: companies, government, universities. They also bring together in a holistic way various technologies necessary for the achievement of advances in an industry.

Environmental quality

Less than 10 percent of all U.S. investment in environmental technology innovation is directly attributable to federal and state agencies, although this figure may be expected to be somewhat higher specifically in the remediation area. Joint efforts between government, industry, and academe account for a significant additional share of investment, but private investment by U.S. firms also abounds. These investments in environmental technology tend not to be as part of large-scale technology initiatives in the private sector, however, but tend rather to be small-to-medium size efforts by individual or small groups of firms. For example, private sector remediation technology development reported in just one recent issue of *Environmental Business Journal* include a vitrification system for radioactive waste being developed by Numatec, Inc., a funnel and gate system designed to contain contaminated groundwater plumes and channel them to in-situ bioreactors for treatment being developed by the Waterloo Center for Groundwater Research, a biofiltration system to process the vapors produced by soil vacuum extraction systems being developed by EG&G, Inc., a photocatalytic oxidation system for treatment of organic pollutants in water being developed by Solarchem Environmental Systems, and a fluidized bed bioreactor to break down pentachlorophenol used in wood preservatives being developed by Warzyn, Inc.

High-density data storage

There is considerable activity in the data storage area at the present time, since the requirements for ever-increasing storage in any level of the computing industry continue to grow. At the high end, the development of processors that can address larger and larger amounts of memory, and the construction of multiprocessor machines, often with separate memories for each processor, has led to increasing expectations on primary memory size from the user community. Increasing amounts of data from various sensors has led to requirements for larger secondary and tertiary memories. Requirements for terabytes of storage are becoming increasingly common. At the consumer end of the market, similar growths in storage requirements are evident. Recent software offerings from companies such as Microsoft require as much as 16 megabytes of

RAM for optimal performance, and require increasing amounts of mass storage for programs — for example, modern word processors can take tens of megabytes of storage if all options are installed. The memory industry has responded by producing increasingly higher capacity products at lower unit prices, lower power consumption and smaller form factors. For example, the price for a megabyte of magnetic disk storage is now below 50 cents, whereas only a few years ago, it was tens of dollars. Small factor disks for laptops (for example in the popular PCMCIA II format) have recently been announced in capacities of more than 100 megabytes. Other technologies in the developmental stage offer storage capacities many times these numbers in similar sized packages.

At the present time, U.S. companies dominate the magnetic disk market, and are usually the first to produce larger capacity products. In particular, U.S.-developed improvements in recording head technology will shortly lead to another round of capacity enhancements. Competition is very severe, however, with disk prices falling by half every year at the present time. The major U.S. players, including Conner Peripherals, Maxtor, Seagate Technology and Western Digital, spend of the order of 10% of their revenues on research and development, essentially all in-house, to keep up with the competition. The goals are obvious: to increase capacity per unit volume, decrease cost per megabyte, and increase reliability. $20 million of TRP funds have also been awarded to a consortium of seven other companies to develop high density magnetic disk storage for portable information systems.

Until recently, the Japanese led in the RAM market. However, at the present time, the playing field is more equally balanced between Japanese, Korean, European and U.S. producers, although the Japanese still have the leading market share. More importantly, the costs of building a leading-edge RAM manufacturing facility have risen to the billion dollar level, forcing individual companies to form global partnerships in this area in order to share the cost. Such partnerships include IBM, Siemens and Toshiba, Hitachi and Goldstar (South Korea), and Hitachi and Texas Instruments. As a result, there is a global sharing of information on the production of such components. This trend will continue unless cheaper fabrication methods are developed.

The value of the RAM market to U.S. companies is of the order of $30 to $40 billion annually. Essentially all research is done by the companies themselves, with limited cooperation from university research centers.

RAM for optimal performance, and supporting vast amounts of space storage for programs – for example, modern word processors can take tens of megabytes of storage. All options ... [illegible] ... speeds ... [illegible] ... However ... [illegible] ... megabytes ... [illegible] ... years ago ... [illegible] ... the popular PC/XT ... [illegible] ... more than ... [illegible] ... single-chip ... [illegible]

At the present time, U.S. companies dominate the magnetic disk market, and are usually the first to produce larger capacity products. In particular, ... developed improvements in recording head technology will shortly lead to another round of capacity enhancements. Competition is very severe. However, with ... [illegible] ... players, including Conner Peripherals, ... [illegible] ... DRAM ... [illegible] ... development ... [illegible] ... technology and innovation ... [illegible] ... and ... [illegible] ... of ... [illegible] ... development of portable information systems.

Unlike ... [illegible] ... the RAM market ... [illegible] ... the ... [illegible] ... Japanese. ... [illegible] ... European ... [illegible] ... manufacturing facility of the order of a billion dollars ... [illegible] ... companies to form global partnerships in this area in order to ... [illegible] ... Such partnerships include IBM, Siemens and Toshiba ... [illegible] ... South Korea and Hitachi and Texas Instruments. Associated with these is a global sharing of information on the production of such components. This trend will continue unless cheaper fabrication methods are developed.

The value of the RAM market to U.S. companies is of the order of $50 to $60 billion annually. ... [illegible] ... done by ... [illegible] ... with limited ... [illegible] ... research ... [illegible]

10. CONCLUSIONS

As shown by the analysis presented in this report, the United States is well positioned in those technologies which are deemed to be critical to the nation's economic prosperity or national security. Although we do not lead in every specific technology, our technological capabilities are either better than or on par with the best in the world in all 27 critical technology areas, as shown in Figure 10.1. That is an accomplishment of which the nation can be proud.

Nevertheless, given the rapid nature of technological progress and the increasing intensity of global competition, we must continue to improve both our development efforts and our efforts to diffuse advanced technology widely into the economy and into systems and components used by the military to protect the nation's security. The trends in Figure 10.1 indicate that the size of the U.S. lead has either declined or remained constant, which argues for continued U.S. investment in technology development if the U.S. position is to be preserved. In times of constrained resources we must do these things more efficiently, as well.

The cabinet-level National Science and Technology Council (NSTC) is an important instrument for assuring the nation's continuing technological leadership. The NSTC's principal purposes are: to establish clear national goals for federal S&T investments, to ensure that policies and programs are developed and implemented to support those goals; and harness S&T to improve quality of life and long-term economic strength of the United States. The NSTC provides a formal mechanism by which the vast Federal R&D enterprise can be coordinated, priorities can be explicitly set, and unnecessary duplication of effort can be eliminated.

In addition to increased coordination of the Federal R&D enterprise, the Administration has placed an emphasis on coordinating federal R&D programs with the private sector and on forming collaborative programs and partnerships. The private sector is given an opportunity to provide its input in a variety of ways, ranging from the advice given by the President's Committee of Advisors on Science and Technology (PCAST), to workshops and white papers to help identify technology areas for investment by the Advanced Technology Program, to joint funding and direction of programs like the Partnership for the New Generation Vehicle. This collaborative relationship will help assure the long-term health of the U.S. technology base and the nation's ability to take full advantage of the products, processes and information it creates.

While the National Critical Technologies are not the only technologies important to the long-term economic health or national security of the United States, they are those which have the greatest impact. The process of identifying these technologies has been one part of the continuing effort to use technology to assure a brighter future for the nation.

Figure 10.1
National Critical Technologies
Technology Position and 1990-1994 Trend

US Technology Position Relative to:
- Japan ▷ , ○ , or ◁
- Europe ▶ , ● , or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Energy					
Energy Efficiency			▶	○	
Storage, Conditioning, Distribution, and Transmission			●	○	
Improved Generation			●	○	
Environmental Quality					
Monitoring and Assessment				◁ ◀	
Pollution Control			○ ●		
Remediation and Restoration			◀	◁	
Information and Communication					
Components			▷	●	
Communications				●	◁
Computing Systems				●	◁
Information Management					▷
Intelligent Complex Adaptive Systems*			○	◀	
Sensors			▷ ▶		
Software and Toolkits				●	▷
Living Systems					
Biotechnology				○ ▶	
Medical Technologies				▷ ●	
Agriculture and Food Technologies				◁ ▶	
Human Systems				▶	▷
Manufacturing					
Discrete Product Manufacturing				○ ●	
Continuous Materials Processing*			○ ●		
Micro/Nanofabrication and Machining			▷	●	
Materials					
Materials				◁ ●	
Structures				●	◁
Transportation					
Aerodynamics				●	◁
Avionics & Controls				◀	◁
Propulsion & Power				◁ ●	
Systems Integration				●	○
Human Interface*					▷ ▶

*based on limited information

APPENDIX A

NATIONAL CRITICAL TECHNOLOGIES LIST

The section provides the definition of critical technologies and then discusses the structure of the list. The complete list is presented in Table A.2.

WHAT IS A "CRITICAL TECHNOLOGY"?

The precedence for identifying select goods as "critical" arose in the 1920s when dependence on foreign imports of certain materials was judged to be a vulnerability for the U.S. military. Accordingly, Congress required that the U.S. maintain a strategic reserve of such "critical materials" in order to ensure readiness in case of military conflict. An extension of the same idea, i.e., that some technologies are critical for military readiness but also as fuel for economic growth, informed the Congress's use of the term in PL 101-189. In this legislation mandating a critical technologies report, Congress defined "critical technologies" as "essential for the United States to develop to further the long-term national security or economic prosperity of the United States."[1] The phrase "critical technologies" as used in the legislation implies that some technologies are so fundamental to national security or so highly enabling of economic growth that the capability to produce these technologies must be retained or developed in the United States.

Since the requirement for a National Critical Technologies report was established in the 1990 Defense Appropriations Act, several critical technologies lists have come into existence. Various departments and agencies of the Federal government have carried out or publish critical technology assessments, including the Department of Defense, the Department of Commerce, and the National Aeronautics and Space Administration. Additionally, a number of private sector lists have been generated. Other industrialized countries have also identified national critical technologies. For example, both Germany and Japan engage in a formal Delphi process involving government, industry and academia to evaluate the importance and status of a broad set of technologies.

This list-making activity should not be seen as redundant. Different lists are generated for different purposes, and the technologies on these lists are selected for their potential to aid in achieving specific goals. That is, the technologies on different lists are "critical" for different reasons. In the case of the critical technologies activities of the Department of Defense, for example, technologies are examined in relation to five Future Joint Warfighting Capabilities most needed by the U.S. Combatant Commands. The Commerce Department's emerging technologies list, published in 1990, was based on market potential dictated by the department's mission to promote and improve commerce.

---

[1] US Code, Title 42, Section 6683.

Differing criteria, purposes and legislative references aside, many observers have noted strong similarities between the critical technology lists.[2] In a highly interdependent economy with substantial overlap between civilian and defense applications, this similarity is not surprising. Integrating various critical technologies lists and capturing the similarities—which reveal complex relationships within the economy and between sets of national and sub-national goals—in a consistently aggregated, rationally organized way was the first important task in producing this report.

Because the U.S. economy is broad and technologically advanced, many technologies are important to some aspect of economic prosperity or national security. Choosing those that are "critical" on the national level requires some careful thinking about definitions. The first necessary definition is that of "technologies" since "critical technologies" are a subset of the larger group. Technology involves knowledge. In order to differentiate technology from other forms of knowledge, this report defines technology as knowledge that has the following characteristics:

- Systematized and practical, based on experimentation and/or scientific theory
- May involve new discoveries, current knowledge, or a combination of both
- Directed toward application or achieving a goal rather than only toward understanding
- Involves direct manipulation of materials or biological systems, or the implementation of mathematical algorithms
- Is reproducible and transferable

This definition excludes much basic science which is directed at pure understanding of natural phenomena. However, the definition is broad enough to include knowledge built on scientific understanding and knowledge acquired through experimentation or accident.

Once the realm of "technologies" is defined, it is necessary to define what we mean by "critical." The definition in this National Critical Technologies report assumes that the criticality of a technology is determined by the importance of the application to which the technology is put. That is,

criticality is derived from the importance of the outputs of the system of which the technology is a constituent part, as well as from the significance the technology has for enabling that system

---

[2]Comparisons of various critical technology lists may be found in Mogee, Mary Ellen, *Technology Policy and Critical Technologies: A Summary of Recent Reports*, The Manufacturing Forum, National Academy Press, Washington, D.C., December 1991 and in Knezo, Genevieve J., *Critical Technologies: Legislative and Executive Branch Activities*, Congressional Research Service 93-734 SPR, Washington, D.C., 5 August 1993.

This definition explicitly answers the question "Critical for what?" thereby helping to link policy objectives to choices of technologies. For example, since improvements in education at all levels are considered essential to the future economic prosperity and national security of the United States, education and training software which enables advanced education and training methods and systems is a critical technology that meets the definition above.

CLASSIFICATION AND AGGREGATION METHODOLOGY

The National Critical Technologies Report defines "criticality" in the broadest possible way—to "develop and further the long-term national security or economic prosperity of the United States." Thus, this list must be *integrative* in a fundamental sense, incorporating the diverse concerns and objectives which comprise ideas of security and prosperity and which drive much of the other list-making activity. It must also identify areas not captured in extant lists because they span the concerns or responsibilities of several different agencies or groups.

The 1995 National Critical Technologies list was created through a process of input from multiple constituencies in a traceable and reproducible manner, described in greater detail in Appendix B. The process began with a candidate list which included technologies appearing in the first Report of the National Critical Technologies Panel (March 1991), as well as the lists published by the Department of Commerce, Department of Defense, Department of Energy and by NASA. A four-level hierarchical structure was used to integrate lists based on different organizational schemes and levels of aggregation. Sample or illustrative applications to which the technologies contributed were also included, although the list of applications was not expected to be exhaustive. Technology experts were utilized to include knowledge of specific technologies and applications where existing lists did not contain a sufficient level of detail. In addition, the candidate list indicated whether each specific technology contributed primarily to economic prosperity, national security, or both.

The six major technology categories in the 1991 list[3] were changed to seven. The descriptions of the seven categories are shown in Table A.1. The candidate list classified technologies according to the nature of the skills and problems involved in their development, not by the technologies' applications. This focus on underlying technologies rather than applications streamlined the list. Many technologies support multiple applications, so an application-based taxonomy complicates a technology list by forcing the same technology to be placed in multiple categories. Technology focus was also deemed to be more helpful to users because it allowed them to see the breadth of influence of a technology and to determine whether a technology meets their requirements for criticality based on applications it supports.

[3]The 1993 Panel did not re-write or alter the 1991 list.

Table A.1
Description of technology categories

Technology Category	Description
Materials	Substance of physical objects
Manufacturing	Producing physical objects
Information and Communications	Producing, storing, manipulating, and moving information
Transportation	Physically moving people and objects
Living Systems	Creating and modifying biological processes
Energy	Powering the other categories
Environmental Quality	Dealing with environmental consequences of past, present, and future activities

Table A.2

National Critical Technologies List

Energy

Energy Efficiency
Energy Storage, Conditioning, Distribution and Transmission
Improved Generation

Energy

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Energy Efficiency	building technologies	"superwindows"	•		
		modular utility components	•		reduced demand growth in energy sector by increasing energy efficiency of buildings, industry
		energy efficient lighting, appliances	•		
		advanced building management	•		
	non-IC propulsion systems		•		improved combustion systems for automobiles
Energy Storage, Conditioning, Distribution and Transmission	advanced batteries	lead-acid, lithium, aluminum-iron	•	•	power sources for electric vehicles w/consumer appeal
		sodium metal chloride, sodium sulfur	•	•	"even-out" intermittent renewables generation for greater feasibility, appeal
		zinc-bromine, iron-air, zinc chloride	•	•	area and frequency regulation, spinning reserve, peak shaving, and power quality
		iron-chromium, zinc-ferrocyanide, Li-Fe-S	•	•	
	power electronics	high-power solid state switches	•	•	greater stability, lower losses, faster switching of electric grid, conditioning of
		utility electronics	•		current from non phase-locked intermittent sources (renewables),
					high voltage direct current converter stations and real time systems control
	capacitors		•	•	EV energy storage ("ultracapacitor"), high pulse repetition frequency syst (eg, elec guns)

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Improved Generation	gas turbines	combuster design	•		highly efficient energy generation with minimum pollution
		high-temperature materials (see "Materials)	•		
	fuel cells	proton exchange membrane	•		commercial development of fuel cell technology for distributed generation, transport using hydrogen and hydrocarbon fuels
		phophoric acid fuel cells	•		
		molten carbonate fuel cells	•		
		solid oxide fuel cells	•		
	next generation nuclear reactors	light-water	•		increased safety margines, reduced relative costs through passive response to non-normal conditions, simplified systems, inherently improved thermal management, tolerance
		inherently stable reactor technology	•		
	power supplies	high energy density, low mass supplies	•	•	improved weapons systems/reconnaissance vehicles, electronic warfare systems
		pulse supplies		•	simulating nuclear weapons effects
	renewable energy	solar thermal power technologies	•		mass production of devices for direct sunlight conversion and competitive prices
		photovoltaics	•		
		wind turbines	•		improved performance in a wider range of wind resource sites
		biomass fuels	•		conversion to synthesis gas or oil for production of electric power, liquid/gasseous fuels

Environmental Quality

Monitoring and Assessment
Pollution Control
Remediation and Restoration

Environmental Quality

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Monitoring and Assessment	integrated environ monitoring	sensors (see "Info. and Comm.")	•	•	global climate/ocean observing systems; battlefield identification of dangerous chemical and biological agents; proliferation monitoring
		software (see "Info. and Comm.")	•	•	
		networking (see "Info. and Comm.")	•	•	
		simulation (see "Info. and Comm.")	•	•	
	remote assessment of biosysten	ground truth biomarkers and pattern recognition	•	•	forestry and fisheries management, crop yield prediction
Pollution Control	pollution control	physical separation	•		increase fraction of waste stream recovered for recycling and reuse by increasing efficiency and lowering cost with which components of stream can be separated
		component separation	•		
		chemical transformation	•		
		biological agent separaton	•		
		waste elimination	•		
Remediation and Restoration	remediation and restoration	soil washing	•		increase efficiency of, reduce cost and cycles required to remediate sites, especially those with multiple contaminants, habitat restoration
		thermal desorption	•		
		composting	•		
		electrochemical separation	•		
		super-critical water oxidation	•		
		recovery of spilled oil and other hazardous subst.	•		
	bioremediation	microbal metabolism of organic pollutants	•		
		sequestration of heavy materials	•		
	nuclear wastes storage/disposal	storage	•	•	increased safety/decreased uncertainty for storage and containment of nuclear waste
		treatment	•	•	
		separation	•	•	

EP= Economic Prosperity; NS = National Security

Information and Communication

Components
Communications
Computer Systems
Information Management
Intelligent Complex Adaptive Systems
Sensors
Software and Toolkits

Information and Communication

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Components	high-density data storage	thin-film recording head transducers	•		1-gigabyte micro-floppies
		recording media	•		storgage requirements for high-definition displays, high-performance computing
		high-density RAM	•	•	
		format compatibility/standards for optical storage	•		long-term commercial viability of media, storage requirements for high-def displays
		magneto-optical storage	•		eraseable data storage w/ conventional optical disk data density
		holographic optical elements	•		improved access time, reduced weight, cost
		parallel data storage controllers	•	•	meet storage requirements of massively parallel computers
	high definition displays	lithography (see Micro/Nano Fabrication)	•	•	competitive high-definition display manufacturing capability supporting
		circuitry patterning	•	•	(eg) flat panel, HDTV, military systems
		glass sheet production	•	•	
		thin-film techniques	•	•	
		holographic displays	•	•	displays for military and commercial systems
	high-resolution scanning techs	high yield detector arrays (see Sensors)	•	•	search engines on optical storage
Communications	data compression	chaotic graphics compression	•	•	high data-transfer requirement applications, eg HDTV
	signal conditioning and validation		•	•	support high-performance, arrayed/multi-spectral sensor applications: target recognition, munitions guidance, CIM, environmental monitoring
	telecom/data routing	broadband switching	•		full utilization of fibre-optic capacity especially in support of NII
		programmable radios		•	all-spectrum/format radios for military interoperability, reduced costs
		wireless communic tech	•	•	improved economics, technical characteristics to support maximum access to NII and robust military comm system
		cable	•	•	
		fibre	•	•	
		satellite-ground communic protocols	•	•	improved space-ground interoperability.
		mobile computing systems	•	•	
Computer Systems	interoperability	data interchange standards	•	•	full standardized multi-media data exchange on NII or other systems
		product data exchange	•	•	full exchange of product characteristic data between systems
	parallel processing	MIMD (Multiple Instruct, Mult Data Stream)	•	•	parallel-processing hardware and software to support high-performance
		SIMD (Single Instruction, Multiple Data Stream)	•	•	computing activities in: prediction and analysis of complex systems,
		VLIW (Very Large Instruction Word)	•	•	management, simulation and design of complex systems/processes
		systolic arrays	•	•	
		specialized parallel coprocessors	•	•	
		hypercubes	•	•	
		parallel data storage architecture	•	•	

EP= Economic Prosperity; NS = National Security

Information Management	data fusion	multi-spectral data processing	•	•	advanced targeting and guidance, environmental monitoring, machine vision,
		distributed array processing	•	•	intelligence capabilities, anti-stealth techniques
	large-scale info. systems	very large database management tools	•	•	finanancial systems, electrical power grids, battlefield surveillance systems,
		real-time large scale info retrieval tools	•	•	fusion of global ocean and climate observing data
	health systems and services	integrated systems of electronic patient records and decision support systems	•	•	patient management and outcome studies, telemedicine, virtual medical groups, evaluation of preventive interventions, health resource allocation
		user interfaces	•	•	
	integrated nav. systems	electronic charts data information systems	•	•	improved ship navigation capabilities, navigation systems for
		on-the-fly DGPS positioning	•	•	air traffic control, intelligent transportation systems
		real-time environmental info. systems	•	•	
Intelligent Complex Adaptive Systems	autonomous robotic devices	sensors	•	•	automatic sentries, hazardous materials handling, mine detection & removal,
		signal processing	•	•	counterterrorist ops, law enforcement, environ. remediation, public disaster responses
		software	•	•	
		robotics	•	•	
	artificial intelligence	knowledge representation	•	•	AI systems for military and commercial/manufacturing use
		comp-based reasoning methods	•	•	
		machine learning methods	•	•	
Sensors	physical devices	microsensors	•	•	integrated sensing/signal processing, expanded in-situ monitoring, integrated systems
		biosensors	•	•	diagnostics, environ/exposure monitoring, nano-controls, biological weapons use detec
		chemical sensors	•	•	process control, environmental monitoring, chemical weapons use detection
		passive thermal imagers	•	•	battlefield night vision, medical diagnostics
		IRST systems (point source passive thermal imag)		•	passive targeting systems, identification, kill assessment
		high yield, high-density photo/IR detectors	•	•	HDTV, scanning, medical imaging, environmental monitoring, night vision systems,
		multi-spectral integrated sensors	•	•	machine vision, advanced targeting and precision-guided munitions
	integrated signal processing	IR/radar sensors	•	•	improved miniaturized sensors w/ sensor and processing circuitry on same chip

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Software and Toolkits	education/training software	military training--see "simulation software"		•	battle simulation and training
		multi-media authoring tools	•	•	more effective education and life-long training
	network and system software	navigation and resource discovery tools	•		high utility, easy-access NII via tools for organizing and finding information
		directories	•		
		registries	•		
		transparent embedding software	•	•	integrated heterogenous concurrently operating systems in distributed env
		operating systems	•	•	
		run-time execution systems	•	•	
		programming languages	•	•	
		interpreters	•	•	
		compilers	•	•	
	modeling and simulation software	virtual battlefields & weapons systems		•	improved effectiveness, economics of training, "virtual prototyping"
		atmospheric and global systems	•	•	improved prediction of weather, knowledge of global change phenomena
		computational fluid dynamics	•	•	better aero/hydro-dynamic design, combustion and industrial process design
		agriculture	•		sustainable agric practices, optimized yields
		cellular/biomolecular function	•		
		computational physics	•	•	
		computational chemistry	•	•	rational design of new chemicals and pharmaceuticals; countermeasures against bio. wa
		economic systems	•		
		numerical control simulation	•	•	visualization of machining process: design for min waste, CIM
		manufacturing	•	•	"virtual CIM" of products: allow rapid prototyping, reduced startup costs
	software engineering tools	CASE (Computer-Aided Software Engineering) too	•	•	increased efficiency of software authoring, better software maintainability
		user interface design tools	•	•	contain software costs
		software testing tools	•	•	increased reliability, reduced cost of software, especially in complex systems
		IC design tools	•	•	improved design capabilities for complex ICs
	pattern recognition	virtual reality software	•	•	
		natural language recognition (speech, handwriting)	•	•	
		multi-media operating systems	•	•	
	software production	rapid prototyping	•	•	reduced development costs, fewer development cycle iterations
		modular/object-oriented programming	•	•	

Living Systems

Biotechnology
Medical Technologies
Agriculture and Food Technologies
Human Systems

Living Systems

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Biotechnology	bioprocessing	drug, chemical, enzyme production	•		full commercialization of biotech by increased efficiency,
		mineral extraction	•		reduced cost of cell bioreactors/bioprocessing; aquaculture
	monoclonal antibody production	diagnostics	•	•	improved diagnostic capability for diseases and disorders
		therapeutics	•	•	improved treatment of variety of diseases
		separation processes	•		
		enzyme-like catalysts	•		cheaper, more effective processing of certain materials
	protein engineering	protein sequencing	•	•	site specific binding/blocking
		protein folding	•	•	achieving the right shape, not just the right sequence
		rationally designed drugs	•	•	improved potency and specificity
		structural biology	•		shaping molecules
		tailored protein catalysts	•		high selectivity and specificity catalysts: more effic synthesis (lower cost, waste m
		molecular electronics	•	•	ultra-high density/low-power memories
		biomolecular materials	•		
		molecular motors	•	•	
	recombinant DNA technologies	gene mapping/sequencing	•		diagnostics, prevention and therapy for diseases in humans,
		gene therapy/replacement	•		identification/manipulation of specific genes in plants and animals
		antisense	•		turning off specific protein production
		agricultural species modification	•		plant and livestock species with designed traits, plant pest/pathogen resistance
		transgenic cell cultures	•		modified cells to act as bioreactors
		therapeutic agents (see Vaccines)	•	•	
	vaccines	infectious disease	•	•	enhanced immunogenicity
		AIDS vaccine	•	•	contain spread of AIDs virus
		cancer (tumor type specific)	•		
Medical Technologies	health info systems/services	See "Information and Communication"	•	•	
	biocompatible materials	microcapsules	•		slow, targeted release of medication
		replacement materials	•	•	more durable, more effective materials for replacement of natural tissue or bone
		material surface characteristics	•	•	implantable devices, sensors, and electrodes
		tailoring immune system response	•	•	artificial blood, skin, tendons and ligaments
		tissue engineering	•	•	

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Medical Technologies, cont'd	functional diagnostic imaging	high-field spectroscopic MRI	•	•	electronic biopsy
		optical coherence tomography	•	•	biochemical functional assessment
		AI diagnostic support systems	•	•	
	bacterial/viral detect/screening	detection/ID at different concentrations, media, environments	•	•	food and water quality assurance, antibiotic selection, infection control
		epidemioloy statistical techniques	•	•	surveillance of new disease and spread of disease
	medical devices and equipment	patient monitoring equipment	•	•	
		biosensors	•	•	pressure, electrophysiology, blood chemistry
		functional electrical stimulation devices	•	•	functional restoration, including hearing, breathing, contenance and mobility
		critical care instrumentation	•	•	cardio-pulmonary bypass pumps, repirators
		blood chemistry auto-analyzers	•	•	
		de-contamination and sterilization	•	•	
		endoscopic/laporascopic surgical equipment	•	•	
Agriculture and Food Technologies	sustainable agri. produciton	genetic resource ID, preservation and utilizatior	•		improved bio. efficiency of agricultural organisms, bio. pest control, sustainable agricultual systems, soil and water conservation
		biological and engineering criteria	•		
		ecosystem management	•		
	food safety assurance	pathogen detection, isolation, reduction/ elimination	•	•	food safety, comprehensive HACCP
		drug and residue detection	•	•	
		waste management	•		byproduct recover and value-added product development
	aquaculture and fisheries		•	•	sustained population management and production, food quality assurance
Human Systems	advanced human-machine interfaces	psychophysiology of learning	•	•	education, training, performance enhancement
		mental workload assessment	•	•	
		neurotechnologies	•	•	
		software for AHCI/ see software	•	•	human-machine interfaces more accurately simulating natural experience for increased ease-of-use and utility
		sensors	•	•	
		signal processing	•	•	

Manufacturing

Discrete Product Manufacturing
Continuous Process Manufacturing
Micro/Nano Fabrication and Machining

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Discrete Product Manufacturing	CIM support software	CAD (Computer-Aided Design)	•	•	improved solid-object representation design
		CAE (Computer-Aided Engineering)	•	•	improved interactive design/performance analysis of product
		process, machine performance databases	•	•	ensure consistency with high skills production and work systems
	equipment interoperability	group technology	•	•	improved factory, production efficiency, by IDing job/item similarities
		CAPP (Computer-Aided Process Planning)	•	•	optimized factory routing, production lead times with variant, generative CAPP
		data-driven management info systems	•	•	capabilities to effectively design, manage CIM
		factory scheduling tools	•	•	enhanced forecasting and scheduling capabilities for improved efficiency
	intelligent processing equipm	sensors (see Info & Communications/Sensors)	•	•	process monitoring and control; automated design of large-scale ICs
		next generation controller (see Info&Comm/softwr)	•	•	
	robotics		•	•	automated construction; de-mining
	auto. systems for facilities ops.	computer-aided production cycle management	•		
		building automation systems	•		
	net shape processing	hot isostatic pressing	•	•	more economic/technically feasible finishing of non-traditional materials
		metal injection molding	•	•	e.g.,ceramics, super-alloys
		superplastic forming	•	•	
		liquid transfer molding of polymer matrix composite	•	•	low cost manufacturing of large parts
	rapid solidification processing	spray forming	•	•	uniform microstructure alloys, esp for hard to shape alloys
		gas atomization	•	•	

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Continuous Materials Processing	catalysts	tailored protein catalysts	•		
		shape slective catalysts	•		fules and chemical production
		catalysts by design	•		increased efficiency thermal processing, pollution control catalysts
		biomimetic catalysts	•		carbon dioxide utilization
	surface treatments	laser hardening	•	•	selective surface hardening in: medical implants, high-perf bearings, extrusion dies
		thin films (see "artificial structuring methods")	•	•	
		grinding and machining of ceramics	•	•	reduced cost and increased reliability of parts
		ceramic coatings (see "ceramics")	•	•	
	ultrapure refining methods	various refining methods (non-specified)	•	•	OEICs, stronger polymer matrix composites and ceramics
		electron beam processing	•	•	high-purity alloys for jet turbines
	pollution avoidance	process design strategies	•		achieve lower levels of environmental loading
		improved processes	•		increase resource efficiency of process industries, e.g., petroleum refining, metals, etc.
		design for the environment	•		life-cycle approach to design of products and processes
		industrial ecology	•		multidimensional production and recycling/reuse systems
	predictive process control	sensors	•	•	
		data processing	•	•	
Micro/Nano Fabrication and Machining	microdevice manufacturing techs	silicon machining	•	•	better quality, expanded capability, lower-cost micro-machines for sensors, controls
	semiconductor manufacturing	x-ray lithography	•	•	miniaturization and cost containment for chip manufacture
		microwave plasma processing	•	•	
		electron/ion micro-beams	•	•	
		artificially structured materials	•	•	
		laser-assisted processing	•	•	
		metrology	•	•	
		design testing	•	•	
	semiconductor integration techs	integrated packaging	•		easier/lower cost integration/interconnection of multiple chips
		multichip modules	•		
	artificial structuring methods	chemical vapor & sputter deposition	•	•	thin films, high-speed microelectronics, OEICs
		molecular and chemical beam expitaxy	•	•	high performance alloys, ceramics, coatings (eg diamond) for improved wear, thermal,
		spin-on deposition	•	•	and radiation-resistance characteristics
		vaccum evaporation	•	•	

Materials

Materials
Structures

Materials

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Materials	alloys	light weight structural alloys	•	•	lighter, stiffer airframes, automobile frames
		intermetallic alloys (Ti/Ni/Fe aluminides)	•	•	high-temp structural applications in aerospace
	ceramic materials	ceramic IC packaging	•		improved interconnection/data rates for multi-IC assemblies
		ceramic matrix composites (see "composites")	•	•	
		ceramic coatings	•	•	improved wear characteristics in high-speed moving parts: turbine engines, cutting tools
	composites	polymer matrix composities	•	•	economical, bulk PMCs for jet engines, automobiles, high-T aerodynamic surf
		ceramic matrix composites	•	•	high-perf aircraft engines, automobile engines, advanced armor
		metal-matrix composites	•	•	space applic. for null-outgassing, rad-resist important, hypersonic aircraft, HSCT, armor
		carbon-carbon composites	•	•	ultra-high temperature aerospace applications (rocket nozzles, thermal surfaces)
		molecular-scale composites	•	•	
	electronic materials	GaAs	•	•	superior, economic GaAs-based ICs (faster and/or hardened electronics)
		thin-film dielectric materials	•	•	miniaturization of microwave communication devices
	photonic materials	semiconductor lasers/laser arrays	•	•	laser/detector techs to support communications
		advanced detectors	•	•	and optical data processing, with eventual goal of OEICs
	high energy-density materials	advanced solid and liquid propellants		•	space launch vehicles, longer-range artillery
		explosives		•	improved conventional weapons
	highway/infrastructure materials	paving	•		higher-durability, more economical materials to maintain surface transport infrastructure
		repair materials	•		
		polymer matrix composites	•		retrofit reinforcement for earthquake damage prevension
	biocompatible materials		•	•	See "Living Systems"
	stealth materials	radar-absorbing materials/coatings		•	increased abilities for military aircraft to operate unobserved by radar
	superconductors	high temperature superconductors	•	•	sensors, low-power electronics, power transmission, energy storage,
		advanced low-temp superconductors	•	•	powerful magnets for research, medical diagnostics, maglev technology

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Structures	aircraft structures	computational structural mechanics	•	•	enhance productivity of prototype development
		hot structures	•	•	hypersonic cruise/reentry functions
		actively cooled structures	•	•	
		materials life behavior prediction	•	•	improved safety, design for lifecycle
		life extension technologies	•	•	
		stealth structures		•	enhanced survivability, effectiveness of military aircract through reduced observability
		infrastructure materials		•	

Transportation

Aerodynamics
Avionics and Controls
Propulsion and Power
Systems Integration
Human Interface

Transportation

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Aerodynamics	aircraft aerodynamics	turbulence prediction and control	•	•	engine efficiency, aircraft stability improvements
		laminar flow control	•	•	
		noise control	•	•	reduced environmental impact aircraft, low-observable aircraft
		hypersonic/aero-assist/wave-rider designs	•	•	long-range, high-speed aircraft
	surface vehicles aerodynamics	low-drag designs	•		more efficient, lower-emissions vehicles
Avionics & Controls	aircraft/spacecraft avionics	glass cockpit techs	•	•	reduce pilot workload
		foul-weather flying systems	•	•	
		fly-by-light techs	•	•	reduced weight, increased reliability and stability control
		power-by-wire techs	•	•	
		highly integrated engine/airframe controls	•	•	high-speed (>m=3) applications
		space-qualifed computers	•	•	better performance, autonomous operations, improved reliability
	surface transport controls	advanced engine controls	•		more efficient, lower-emissions engines
Propulsion & Power	aircraft turbines	high-thrust turbines		•	sustained supersonic cruise w/out afterburners
		high-efficiency turbines	•	•	better specific fuel consumption
		multi-fuel/hybrid engines	•		develop more powerful engines w/ better fuel economy and lower NOx emissions
		advanced engine components	•	•	increased safety, quality assurance, lower manufacturing cost
	spacecraft power systems	high-efficiency solar cells	•	•	lower spacecraft weight
		high power compact sources	•	•	deep space mission requirements
		remote power transmission	•	•	in space/space to ground power transmission
		batteries (See "Energy")	•	•	lower spacecraft weight
	electrically powered vehicles	energy storage techs (see "Energy")	•		reduce emissions/secondary pollutant concentrations in urban areas

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Systems Integration	intelligent transportation syst	sensors	•		add information and control infrastructure to existing physical transport infrastructure to increase safety, capacity, driver convenience & reduce emissions, fuel consumption, congestion.
		networks	•		
		software	•		
		satellite navigation	•	•	
	aircraft/spacecraft integration	satellite assembly	•	•	industry-wide, common interface standards
		advanced fabrication, lay-up and joining techs	•	•	successful adaptation to new materials, reduced costs of design, prototyping
		multi-displinary aircraft design techniques	•	•	
Human Interface	human factors engineering	ergonomics	•		improved automobile control
		long-duration flight countermeasures	•	•	improve safety and situational awareness/counter aircrew fatigue
		high-g countermeasures		•	improve pilot function under high-g maneuvers
	spacecraft life support	closed/mostly closed extended life support sys	•		reduced space logistics costs

APPENDIX B
TECHNOLOGY SELECTION AND ANALYSIS

This appendix discusses the process for the selection and analysis of National Critical Technologies. It starts with the discussion of the legislative mandate for creating the National Critical Technologies Report. It then details the process by which particular technologies were selected for inclusion. Finally, it discusses the methodologies used for analysis and assessment.

LEGISLATIVE MANDATE

The National Critical Technologies Report is prepared biennially at the direction of the 101st U.S. Congress in Public Law 101-189. This law charges a panel of public and private sector officials with identifying no more than 30 national critical technologies "essential... to develop and further the long-term national security or economic prosperity of the United States." The current report is the third in the series.

NATIONAL CRITICAL TECHNOLOGIES REVIEW AND SELECTION PROCESS

Review and approval

The National Critical Technologies Review Group that approved the 1995 National Critical Technologies Report includes members of the President's Committee of Advisors on Science and Technology (PCAST) senior government officials. The government officials applinted by the Director of OSTP included the Associate Director of OSTP for Technology and the Associate Director of OSTP for National Security and International Affairs.

In addition to the National Critical Technologies Review Group, the 1995 Report was prepared with the participation from the committees of the National Science and Technology Council (NSTC). All relevant federal agencies that participate in NSTC committees had the opportunity to review and comment on the National Critical Technologies list, although the Committee on Civilian Industrial Technology and the Committee on National Security had the lead roles in the process. The primary focus of the content reviews by the agencies was to reflect current status and relative importance of various technologies, to fill in gaps, and to assure that the most important potential applications were included.

Following the NSTC review, the list was presented for review and approval to the National Critical Technologies Review Group. The report itself went through a similar process of review and approval, ensuring that all inputs and comments on earlier versions were addressed.

Selection criteria

As described in Appendix A, the process began with a candidate list. Technologies from this candidate list were selected for the final list if they met one or more of the following criteria.

Economic Prosperity

1. Directly and substantially supports major S&T goal(s) of the Administration as documented in the Memorandum on 1996 Research and Development (R&D) Priorities, dated May 6, 1994, as shown in Table B.1.

2. Directly and substantially contributes to the S&T base essential for maintaining or promoting a globally competitive position for one or more U.S. industries.

3. Meets tests of potential economic importance in the near-term for technologies of incremental change, and in the longer term for breakthrough technologies.

4. Has a high rate of discovery (i.e., will impact fast-moving technology intensive industries, such as telecommunications infrastructure and devices).

5. Meets a test that despite recognition of an industry need, sufficient R&D investments by the private sector will not occur without Federal support due to the magnitude or protracted payback period for the required investment, riskiness of the technological development, or generic nature of a technology in which no single company could expect to recover its R&D investment (the latter is a "commons" test).

National Security

1. Makes an essential contribution to enabling or advancing the future warfighting requirements, as shown in Table B.2.

2. Makes an essential contribution to mission areas under the administration national security priority R&D as stated in the Memorandum on 1996 Research and Development (R&D) Priorities, dated May 6, 1994 (Goal 6, Enhancing National Security)

3. Is essential to meeting other Defense requirements that are traceable through the 1994 Defense Science and Technology plan.

METHODOLOGICAL NOTES

International benchmarking

Assessments of foreign position and trends for the critical technology areas are based on analysis of specific technology sub-areas. Sub-area assessments are aggregated, based on analytical judgments regarding relative weighting or importance, to obtain assessments of each area. Assessments in some areas, e.g., biotechnology or predictive process control, are difficult because much of the overseas research and process development take place in corporate rather than academic environments, the work is considered proprietary, and there is little incentive to publish or to reveal the state of development to anyone who might be considered a potential competitor.

Other methodological points include:

- *Geographic regions.* Europe and Japan are the focus of this assessment, but other countries are considered when they are at or near the leading edge. Europe is treated as an aggregate and assessments are based on the best demonstrated capability in any European country rather than on an average across countries.

- *Technical vs. non-technical measures.* Assessments of current position and five-year trends are based on technical performance rather than on market success, competitiveness, government policy, corporate spending, or any other non-technical factor. In some cases, assessments are complicated by the need to separate design trade-offs from significant differences in technology capabilities. For example, telecommunications vendors are pursuing alternative R&D strategies for asynchronous transmission mode switches. Assessments must take into account the fact that alternative R&D strategies could reflect real differences in capability, such as weakness in software, or could simply be a result of different perceptions as to the best technical path.

- *Research vs. embedded technology.* The entire technology spectrum is considered, but with differing emphases depending on which technology is being assessed. For example, assessments of biotechnology stress the research portion of the innovation spectrum, whereas aircraft propulsion evaluations focus more heavily on what is actually in service.

Table B.1
Research and Development (R&D) Priorities

Goal areas	Priorities for research and development
1. A Healthy, Educated Citizenry	• Biomedical research, health promotion and disease and injury prevention research • Food production, safety and security research • Health systems and services research • Basic research on learning and cognitive processes • New models to evaluate learning productivity • Technology development for high-quality, affordable learning tools • Demonstration of innovative technology and networking applications • Systemic mathematics and science education curricular reform
2. Job Creation and Economic Growth	• Industry-initiated competitive cost-shared R&D partnerships • The Partnership for a New Generation of Vehicles • The National Electronics Manufacturing Initiative • Construction and building • Manufacturing infrastructure • Materials technology • Biotechnologies • Transportation system assessment • Physical infrastructure for transportation • Information infrastructure for transportation • Aeronautics • Energy Production and utilization technologies • Space launch
3. World Leadership in Science, Mathematics and Engineering	• Strengthening fundamental science • Human resources policy for science and technology • Strengthening U.S. S&T capacity through physical infrastructure
4. Improved Environmental Quality	• Scientific basis for integrated ecosystem management • Socioeconomic dimensions of environmental change • Development of science policy tools • Observations, and information and data management • Environmental technologies
5. Harnessing Information Technology	• Computing systems • Networking and communications • Software, algorithms and basic research • Information infrastructure services • Human-computer interaction • Computing and communications applications
6. Enhanced National Security	• Support our military strategy • S&T applications to new post-cold-war missions • Weapons of mass destruction

Table B.2
Future Joint Warfighting Capabilities

1. To maintain near perfect real-time knowledge of the enemy and communicate that to all forces in near-real time.

2. To engage regional forces promptly in decisive combat, on a global basis.

3. To employ a range of capabilities more suitable to actions at the lower end of the full range of military operations which alow achievement of military objectives with minimum casualties and collateral damage.

4. To control the use of space.

5. To counter the threat of weapons of mass destruction and future ballistic and cruise missiles to mthe CONUS and deployed forces.

Source: *Defense Science and Technology Strategy*, September 1994.

ACRONYMS AND ABBREVIATIONS

ACM	Advanced Composite Materials
ACT	Advanced Composites Technology
AHCI	Advanced Human-Computer Intervace
AI	Artificial Intelligence
AMLCD	Active Matrix Liquid Crystal Displays
ARPA	Advanced Research Projects Agency
ATEGG	Advanced Turbine Engine Gas Generator
ATM	Asynchronous Transfer Mode
ATP	Advanced Technology Program
ATTAP	Advanced Turbine Technology Applications Project
BMDO	Ballistic Missile Defense Office
CAD	Computer Aided Design
CADAM	Computer Aided Design and Manufacturing
CAM	Computer Aided Manufacturing
CASE	Computer-Aided Software Engineering
CCD	Charge-Coupled Devices
CD-ROM	Compact Disk Read-Only Memory
CFC	Chlorofluorocarbons
CIM	Computer Integrated Manufacturing
CMC	Ceramic Matrix Composites
CNC	Computer Numerical Controls
CONUS	Continental United States
COTS	Commercially Available Off-The-Shelf
CRADA	Cooperative Research and Development Agreement
CVD	Chemical Vapor Deposition
DARPA	Defense Advanced Research Projects Agency
DMSO	Defense Modeling and Simulation Office
DOD	Department of Defense
DOE	Department of Energy
DOIT	Develop On-Site Innovative Technologies
DOS	Disk Operating System
DRAM	Digital Random Access Memory
DSP	Digital Signal Processing
ELFIN	European Laminar Flow Investigation
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EPA	Environmental Protection Agency
EPM	Enabling Propulsion Materials Project

EPRI	Electric Power Research Institute
ESA	European Space Agency
EV	Electric Vehicle
FADEC	Full Authority Digital Engine Control
FBL	Fly-By-Light
FBW	Fly-By-Wire
FEA	Finite Eleme nt Analysis
FES	Functional Electrical Stimulation
FFRDC	Federally Funded Research and Development Center
FOG	Fiber-Optic Gyroscope
FPD	Flat Panel Display
GaAlAs	Gallium Aluminum Arsenide
GaAs	Gallium Arsenide
GATT	General Agreement on Tarrifs and Trade
GEC	General Electric Company
GPS	Global Positioning System
HDTV	High Definition Television
HITEMP	High Temperature Engin Materials Program
HLFT	Hybrid Laminar Flow Technique
HPA	High Performance Asphalt
HPC	High Performance Concrete
HPCC	High Performance Computing and Communication
HPM	High-Power Microwave
HPS	High Performance Steel
HTS	High-Temperature Superconductors
IC	Internal Combustion
IHPTET	Integrated High Performance Turbine Engine Technology
IMAS	Intelligent Modular-Array System
ITS	Intelligent Transportation System
IVHS	Intelligent Vehicle Highway Systems
JSET	Joint-Subcommittee on Environmental Techn ologies
JTDE	Joint Technology Demonstrator Engine
LAN	Local Area Network
LTS	Low-Temperature Superconductors
MAN	Metropolitan Area Network
MANTECH	MANufacturing TECHnology Program
MEMS	Microelectromechanical Systems
MEP	Manufacturing Extension Partnership
MIMD	Multiple Instruction, Multiple Data Stream

MITI	Ministry of International Trade and Industry (Japan)
MMC	Metal Matrix Composites
MPP	Massively Parallel Processors
MRP	Materials Requirements Planning
MRP II	Manufacturing Resource Planning
MW	Megawatts
NAFTA	North American Free Trade Area
NAL	Natonal Aerospace Laboratory
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Aeronautics and Space Development Agency (Japan)
NASP	National Aerospace Plane
NEMI	National Electronics Manufacturing Initiative
Ni-Cd	Nickel-Cadmium
Ni-H_2	Nickel-Hydrogen
NIH	National Institutes of Health
NiH	Nickel-Hydrogen
NII	National Information Infrastructure
NiMH	Nickel-Metal-Hydride
NIST	National Institure of Standards
NSF	National Science Foundation
NSTC	National Science and Technology Council
OETC	Optoelectronic Module Technology
OTA	Office of Technology Assessment
PCR	Polymerize Chain Reaction
PMC	Polymer Matrix Composite
PNGV	Partnership for the New Generation of Vehicles
PURPA	Public Utilities Regulatory Policies Act
PV	Photovoltaic
PVD	Physical Vapor Deposition
R&D	Research & Development
RAM	Random Access Memory
RFW	Radio -Frequency Weapons
RLG	Ring Laser Gyroscope
S&T	Science and Technology
SAFT	Societe des KAccumulateurs Fixes et de Traction
SAR	Synthetic Aperture Radar
SDH	Synchronous Digital Hierarchy
SE	Software Engineering
SEI	Software Engineering Institute
SEP	Societe Europeane Propulsion
SiC	Silicon Carbide
SITE	Superfund Innovative Technology Evaluation

SOF	Special Operations Forces
SPF	Superplastic Forming
STEP	Standard for the Exchange of Product Model Data
TMCP	Thermomechanical Controlled Processing
TRP	Technology Reinvestment Project
USABC	United States Advanced Battery Consortium
USDA	United States Department of Agriculture
USDC	United States Display Consortium
VOC	Volatile Organic Compound
WAN	Wide Area Network