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THE FEDERAL HIGH PERFORMANCE COMPUTING PROGRAM

Executive Office of the President
Office of Science and Technology Policy
September 8, 1989

THE FEDERAL HIGH PERFORMANCE COMPUTING PROGRAM

High Performance Computing Systems

- Research for Future Generations
- System Design Tools
- Advanced Prototype Development
- Evaluation of Early Systems

Advanced Software Technology and Algorithms

- Support for Grand Challenges
- Software Components and Tools
- Computational Techniques
- High Performance Computing Research Centers

National Research and Education Network

- Interagency Interim NREN
- Gigabits Research and Development
- Deployment of Gigabits NREN
- Structured Transition to Commercial Service

Basic Research and Human Resources

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

In November 1987, my predecessor, William R. Graham, transmitted to Congress A Research and Development Strategy for High Performance Computing. That report laid out a five-year strategy for federally supported R&D on high performance computing, including hardware for state-of-the-art supercomputers, software, computer networks, and supporting infrastructure. It was written with the assistance of the Committee on Computer Research and Applications under the OSTP Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). This strategy document was to be followed by a detailed program plan.

I am pleased to transmit to Congress that program plan -- the result of an intense interagency effort by a special task force within the Committee on Computer Research and Applications. Following the general organizational structure of the 1987 strategy report, it lays out a broad R&D policy and program plan designed to advance U.S. leadership in high performance computing. This plan calls for a federally coordinated government, industry, and university collaboration to accelerate the development of high speed computer networks and to accelerate the rate at which high performance computing technologies -- both hardware and software -- can be developed, commercialized, and applied to leading-edge problems of national significance.

High performance computing is a vital and strategic technology, exerting strong leverage on the rest of the computer industry and other cutting-edge areas. However, U.S. leadership and diversity in the supercomputer industry itself has declined dramatically; and history shows that a scant 15 years separates the first appearance of a top-of-the-line supercomputer from the appearance of that same computing power in the higher end of the personal computer market. A future national high speed computer network could have the kind of catalytic effect on our society, industries, and universities that the telephone system has had during the twentieth century.

We cannot afford to cede our historical leadership in high performance computing and in its applications. We need to encourage the dynamism of the U.S. computer industry and, hence, our economy. I would ask all of the federal agencies with research programs in high performance computing to work toward implementing the recommendations in this report.


D. Allan Bromley
Director

Foreword

High Performance Computing is a powerful tool to increase productivity in industrial design and manufacturing, scientific research, communications, and information management. It represents the leading edge of a multi-billion dollar world market, in which the U.S. is increasingly being challenged. A strong, fully competitive domestic high performance computer industry contributes to U.S. leadership in critical national security areas and in broad sectors of the civilian economy, including the technical base for many national economic and military security needs. For this reason we are initiating the preliminary planning to address this important U.S. technology.

GOALS

Accordingly, the goals of the Federal High Performance Computing (HPC) Program are to:

- Maintain and extend U.S. leadership in high performance computing, and encourage U.S. sources of production;
- Encourage innovation in high performance computing technologies by increasing their diffusion and assimilation into the U.S. science and engineering communities; and
- Support U.S. economic competitiveness and productivity through greater utilization of networked high performance computing in analysis, design, and manufacturing.

COMPONENTS

The HPC Program is implemented through four complementary, closely coordinated, multidisciplinary Components:

- High Performance Computing Systems;
- Advanced Software Technology and Algorithms;
- The National Research and Education Network; and
- Basic Research and Human Resources.

POLICY

The Federal High Performance Computing (HPC) Program features increased cooperation between business, academia and government. While each of these sectors will retain its current role, the success of this Program will depend in large part on an effective transition from R&D to commercialization—an outcome of successful cooperation among the above sectors.

The measure of success of this Program in the area of R&D will be an increased rate of development of new computing concepts, systems, and architectures. A longer term measure of success will be the rate at which this technological progress shows up in commercialized products. The HPC Program will be consistent with the traditional roles of government, business and academia.

Specifically:

- The government will provide R&D support for HPC and will coordinate R&D among its agencies;
- Business will be the decision maker and source of capital investment for commercialization of HPC technology in response to its assessment of market opportunities; and
- Universities and Federal laboratories will be the primary institutions receiving government funding under this Program.

The government will, in addition, foster a number of mechanisms for increased collaboration and interaction among government, business and universities. Specifically:

- The government will continue to serve as a market for commercial prototypes and for commercial products. This particularly will be the case in the defense sector. These markets will exist in U.S. laboratories, Federal agencies, university centers of excellence and industrially led consortia;
- The government will assist in the development of industrially-led consortia in cases where appropriate (an existing example is SEMATECH); and
- The government will promote centers of excellence, jointly funded and staffed by government, academia, and industry. Technology transfer to industry from government and academia will happen automatically as a result of this ongoing collaboration.

Foreign policy objectives will be supported through existing or future international science and technology agreements. "Symmetry and reciprocity," protection of U.S. proprietary interests, and enforcement of intellectual property rights will continue to be guiding principles.

The Federal High Performance Computing Program will ensure the broadest possible national benefit by addressing:

- Many problems susceptible to computational solution;
- A wide geographic and demographic distribution; and
- The inclusion of government, academia and industry.

STRATEGY

To achieve the policy goals of the HPC Program, our strategy is to:

- Support computational advances through R&D effort to address U.S. scientific and technical challenges;
- Reduce the uncertainties to industry for development and use of this technology through increased cooperation among government, industry and academia and the continued use of government and government-funded facilities as a market for HPC prototypes and commercial products;

- Support the underlying research, network and computational infrastructures on which U.S. high performance computing technology is based; and
- Support the U.S. human resource base to meet needs of industry, academia and government.

ROLE OF FEDERAL, ACADEMIC AND INDUSTRIAL SECTORS

Federal agencies

- Funding for the Program will come from agencies their annual appropriations;
- User agencies will continue to define their respective missions and goals, though guided by the High Performance Computing Program goals and objectives; and
- OSTP, through its Federal Coordinating Council on Science, Engineering, and Technology (FCCSET) Committee on Computer Research and Applications, will assist the agencies as part of its continuing responsibility for coordination and policy guidance. OSTP will also assist by recommending special computational opportunities. However, final priority setting will reside with the respective agencies.

Academia

Universities and colleges will participate in the HPC Program in the following ways:

- Responding to agency program announcements;
- Forming consortia with government and industry;
- Focusing research capabilities on specific areas of computational science;
- Enhancing curricula to take advantage of new generations of computing technologies, attracting additional manpower into various disciplines of computational science; and
- Bringing the Program to the attention of State leaders for potential leveraging of Federal funds.

Industry

- Private industry will develop hardware, software, and networks in response to the Program. Commercialization will be at the initiative and discretion of private industry;
- Industry will join and help finance university or government laboratory R&D activities (at its choosing) to obtain access to expertise and government funded facilities. As a result of these collaborative relationships, the partnership will supply industry with R&D and technology information;
- A broadly representative industry body will assist in making long-range demand and robustness projections for: high capacity research networks; the spectrum of

computer architectures; the adequacy of software development; and the level of the manpower pool. This body will help assure a smooth transition between successive generations of high performance computing systems; and

- Private industry suppliers will provide the network services to Federal agencies in the first two stages of the National Research and Education Network. Industry should plan to operate the NREN fully as soon as feasible.

FUNDING OF THE HPC PROGRAM

The magnitude of the program envisioned by this Program will require major new Federal R&D investment. It is assumed that existing Federal base funding for computer and information science and technology research and development, roughly \$500 million annually, will continue. Preliminary planning estimates suggest that the first year of the program would require an augmentation of \$150 million, which would then grow to an incremented annual level of \$600 million by the fifth year.

MANAGEMENT OF THE HPC PROGRAM

The components of the Program will be managed by existing Federal agencies.

Oversight of the HPC Program will be the responsibility of the Office of Science and Technology Policy with the assistance of the FCCSET Committee on Computer Research and Applications and the help of a High Performance Computing advisory panel which will report to the Director of OSTP:

- The HPC advisory panel will interact regularly with the FCCSET Committee on Computer Research and Applications; and
- The HPC advisory panel will have representation from all sectors and will monitor the progress of the Program for cross-sector balance, breadth of applicability, network security, competitiveness versus international cooperation, and technology transfer effectiveness.

SCOPE OF THIS REPORT

This report is designed for agency-level planning purposes and does not represent the Administration's approval or support of any program not included in the President's budget requests. Programs discussed in this document are subject to budget constraints and Administration approval.

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1. Executive Summary

*High Performance Computing** is a pervasive and powerful technology for industrial design and manufacturing, scientific research, communications, and information management. A strong U.S. high performance computer industry contributes to our leadership in critical national security areas and competitiveness in broad sectors of the civilian economy.

The goals of the High Performance Computing Program are to:

Goals

- Maintain and extend U.S. leadership in high performance computing, and encourage U.S. sources of production;
- Encourage the pace of innovation in high performance computing technologies by increasing their diffusion and assimilation into the U.S. science and engineering communities; and
- Support U.S. economic competitiveness and productivity through greater utilization of networked high performance computing in analysis, design, and manufacturing.

Strategy

These goals will be accomplished through Federally coordinated government, industry, and university collaboration to:

- Support computational advances through a more vigorous R&D effort to expedite solutions to U.S. scientific and technical challenges;
- Reduce the uncertainties to industry for R&D and use of this technology through increased cooperation between government, industry and academia and the continued use of government and government-funded facilities as a market for HPC early commercial products;
- Support the underlying research, network and computational infrastructures on which U.S. high performance computing technology is based; and
- Support the U.S. human resource base to meet needs of industry, academia and government.

* *High performance computing* refers to the full range of advanced computing technologies including existing supercomputer systems, special purpose and experimental systems, and the new generation of large scale parallel systems.

1. Executive Summary

The HPC Program

The Program will consist of four complementary, coordinated components in each of the key areas of high performance computing. The components are planned carefully to produce not only long term results but a succession of intermediate national benefits. Figure 1 shows the relationship of the components of the Program. The High Performance Computing Program will build on those programs already in place, providing additional funds in carefully selected areas to meet its goals. Selected computational challenges, which will have significant effect on national leadership in science and technology, will be used as focal points for these efforts.

High Performance Computing Systems: The United States' leadership in supercomputing is increasingly being challenged. We have developed new, more powerful supercomputing architectures based on innovations. Particularly in parallel processing, we must capitalize on these innovations. To do this, a long range effort involving Federal support will be required for basic research on high performance computing technology and the appropriate transfer of research and technology to U.S. industry, consisting of efforts in the following areas:

- Research for future generations of computing;
- System design tools;
- Advanced prototype development; and
- Evaluation of early systems.

Advanced Software Technology and Algorithms: Historically, software improvements have increased computational performance much more than hardware investments. Yet software productivity is generally poor, and existing software can seldom be re-used without modification. In computing systems for industrial, scientific and military applications, software costs have exceeded those of hardware more than fivefold. Advances in software will be critical to the success of high performance computers with massively parallel architectures. To improve software productivity, an interagency effort will support joint research among government, industry and universities to improve basic software tools, data management, languages, algorithms, and associated computational theory with broad applicability for the *Grand Challenge** problems. These complex problems will require advances in software that have widespread applicability to computational problems in science and technology.

* A *Grand Challenge* is a fundamental problem in science or engineering, with broad economic and scientific impact, that could be advanced by applying high performance computing resources.

1. Executive Summary

Effort in this component focuses on:

- Support for Grand Challenges;
- Software components and tools;
- Computational techniques; and
- High performance computing research centers.

National Research and Education Network: For the past decade technology developed by the U.S. has been available to eliminate distance as a factor in computer access and in collaborations among high technology workers. To maintain our leadership, the U.S. government, together with industry and universities, will jointly develop a high-speed research network to provide a distributed computing capability linking government, industry and higher education communities. This network will serve as a prototype for future commercial networks which will become the basis for a distributed industrial base. This component will consist of:

- An interagency effort to establish an interim National Research and Education Network;
- Research and development for a billions of bits per second (gigabits) network adequate to support national research needs;
- Deployment of the gigabits National Research and Education Network; and
- Structured transition to commercial service.

Basic Research and Human Resources: U.S. universities are not meeting the expanding needs of industry for trained workers in computer technology. There is not an adequate number of high quality computer science departments in this country, and many industrial and Federal laboratories have inadequate research capabilities. Furthermore, existing university, government, and industrial groups do not collaborate effectively enough, and their interdisciplinary activities are too limited. To correct these deficiencies a long term effort to support basic research in computer science and engineering (creating computing systems) will be established by building upon existing programs. This component will also establish industry, university, and government partnerships to improve the training and utilization of personnel and to expand the base of research and development personnel in computational science and technology (using computers).

1. Executive Summary

Organization

Leadership of the Program is the responsibility of the Office of Science and Technology Policy, through the Federal Coordinating Council on Science, Engineering and Technology (FCCSET) Committee on Computer Research and Applications, whose members include representatives of the key agencies that fund R&D in high performance computing. Duties and responsibilities of the Committee include:

- Interagency planning and coordination;
- Technology assessment;
- Policy recommendations to OSTP; and
- Formal annual reports of progress to OSTP.

A High Performance Computing Advisory Panel will be formed, consisting of eminent individuals from government, industry, and academia. Members of the Advisory Panel will be selected by and will report to the Director of OSTP. The Panel will provide the Director and the Committee on Computer Research and Applications with an independent assessment of:

- Progress of the Program in accomplishing its objectives;
- Continued relevance of the Program goals over time;
- Overall balance among the Program Components; and
- Success in strengthening U.S. leadership in high performance computing, and integration of these technologies into the mainstream of U.S. science and industry.

This implementation plan was prepared by the FCCSET Committee on Computer Research and Applications under the leadership of the Office of Science and Technology Policy. It represents a broad spectrum of government, industrial and university interests. The Committee has established subcommittees that will be responsible for planning, organizing, monitoring and coordinating the components of the Program.

SCOPE OF THIS REPORT

This report is designed for agency-level planning purposes and does not represent the Administration's approval or support of any program not included in the President's budget request. Programs discussed in this document are subject to budget constraints and Administration approval.

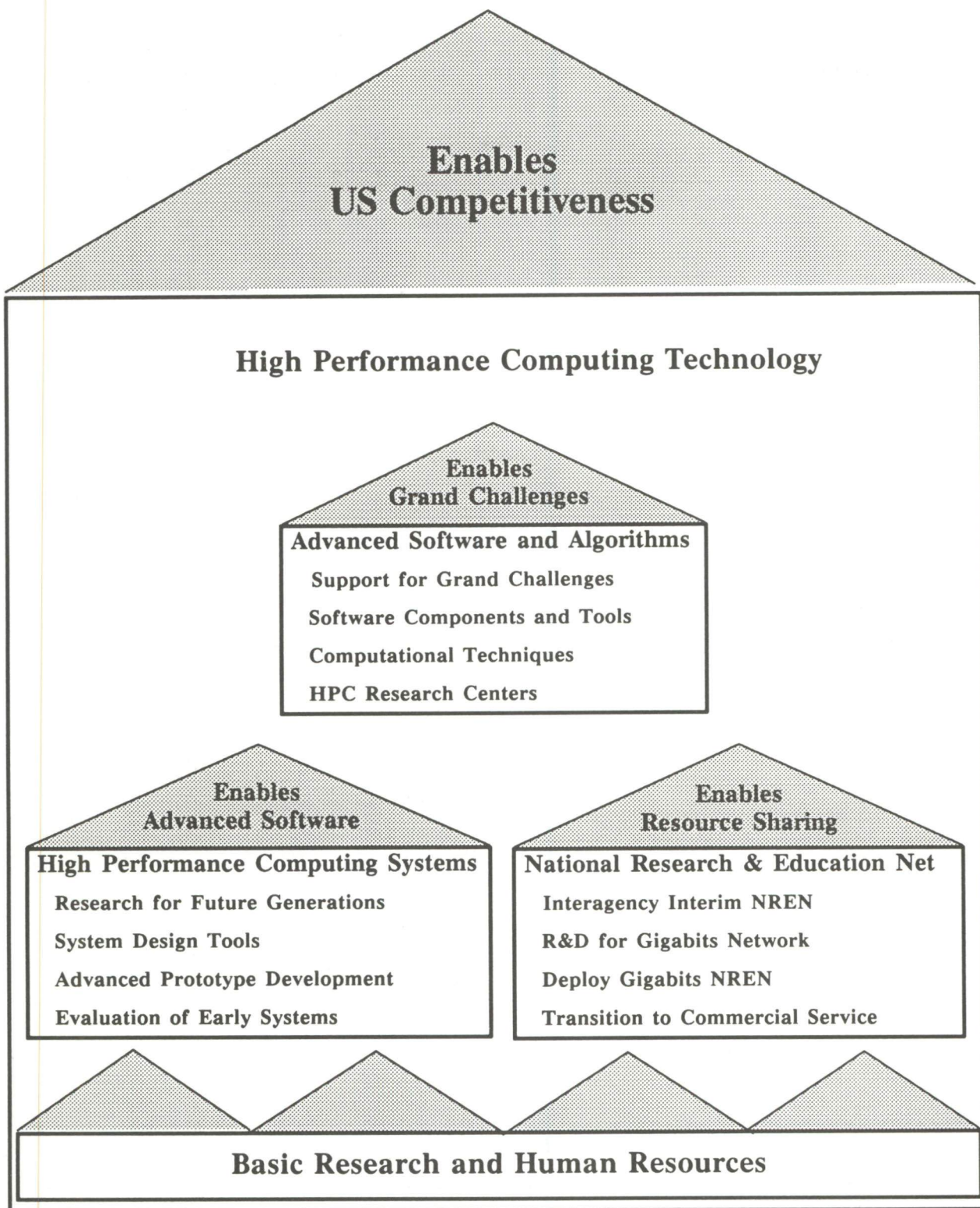


Fig. 1 – Relationship of HPC Program Components

2. Introduction

Purpose and Scope of Report

The purpose of this document is to provide the initial implementation plan for the U.S. High Performance Computing Program. This plan encompasses the first five year period and provides for periodic reviews to be conducted by the Federal Coordinating Council on Science, Engineering and Technology (FCCSET) with the participation of government, industry, and university representatives.

This document discusses:

- National economic and technical issues associated with high performance computing;
- Goals and strategy of this Program;
- Plans for synergistic government, industrial, and university participation;
- Organizational structure to coordinate, manage and review the Program program;
- Economic and technical benefits of the Program; and
- Proposed budget for the first five years of the Program.

This implementation plan was prepared by the FCCSET Committee on Computer Research and Applications under the leadership of the Office of Science and Technology Policy. It represents a broad spectrum of government, industrial, and university interests. This report is designed for agency-level planning purposes and does not represent the Administration's approval or support of any program not included in the President's budget request. Programs discussed in this document are subject to budget constraints and Administration approval.

Background

The Federal Coordinating Council on Science, Engineering and Technology (FCCSET), chartered by the Office of Science and Technology Policy (OSTP), coordinates Federal interagency activities of broad national interest. The FCCSET Committee on Computer Research and Applications serves as the forum for developing a national agenda for computing technology needs, opportunities, and trends.

This FCCSET Committee has examined the scientific, technological and economic effects of high performance computing. The Committee issued reports as early as 1983

2. Introduction

that assessed the status of high performance computing and possible supporting government activities. These studies have consistently demonstrated the need for a strategy to coordinate high performance computing related activities in the government, industrial and university sectors. Dramatic increases in foreign investments in computer related technology have been noted, which challenge the world leadership of the U.S. computing industry. The studies also emphasized that advances in critical areas of national security and broad sectors of the civilian economy depend strongly on high performance computing technology.

The unprecedented power of high performance computing systems has created a new mode of scientific research: computational investigations that complement the traditional modes of experiment and theory. Computational research is being applied to a wide range of scientific and engineering problems called Grand Challenges. *A Grand Challenge is a fundamental problem in science or engineering, with potentially broad economic, political, and/or scientific impact, that could be advanced by applying high performance computing resources.* While the Grand Challenges are already being addressed to some extent using existing supercomputers, progress is often severely limited by current computer speeds and memory capacities. Examples of Grand Challenges are:

- (1) Computational fluid dynamics for the design of hypersonic aircraft or efficient automobile bodies and recovery of oil.
- (2) Computer based weather and climate forecasts, and understanding of global environmental changes.
- (3) Electronic structure calculations for the design of new materials such as chemical catalysts, immunological agents and superconductors.
- (4) Plasma dynamics for fusion energy technology and for safe and efficient military technology.
- (5) Calculations to improve our understanding of the fundamental nature of matter, including quantum chromodynamics and condensed matter theory.
- (6) Machine vision to enable real-time analysis of complex images for control of mechanical systems.

The sample Grand Challenge areas provided in Appendix A are representative of the science and technology areas that will be affected by application of leading edge computational resources and supporting systems. Figure 2 illustrates some of the Grand Challenges that can be adequately addressed through existing high performance computing technology and problems that could be attacked much more successfully with a thousandfold increase in performance.

2. Introduction

Agency Activities: In the early 1980's, Federal agencies initiated programs that provide the basis for the opportunities described in this Program. The NSF established the National Supercomputer Centers to provide high performance computers to the science and engineering community and interconnected them with the research community via the NSFNET. The centers and network have stimulated the development of innovative computational approaches to a wide range of scientific and engineering problems related to the Grand Challenges. NSF also reorganized to create a new Directorate of Computer and Information Science and Engineering (CISE) with increased emphasis and funding for computer and computational disciplines, with a focus on computer networking as a tool for scientific and engineering research.

DARPA initiated the Strategic Computing program to accelerate development of an alternate approach to building high performance computer systems. This program focuses on large scale parallel systems, custom VLSI and associated software, including symbolic processing for the advanced functionality characterized by artificial intelligence. Strategic Computing stimulated the first generation of commercially available scalable parallel computer systems using conservative components and packaging. Early production models of these systems were acquired by several agencies for experimental use. A second generation of these systems is being developed, using custom VLSI. The military services have participated in this program, providing applications focus and technical consultation.

The Office of Naval Research, Air Force Office of Scientific Research, and Army Research Office have separately sponsored important research and development in basic research for advanced computing.

The DOE expanded the National Magnetic Fusion Computer Center and its MFE Network to serve all energy research users in national laboratories, universities, and industry. Several of the National Laboratories have formed computational groups to experiment with novel high performance computers and to develop algorithms that exploit the power of those computers. Special funding was provided to enable university, industry, laboratory collaborations with the national laboratories to acquire parallel computer prototypes to test ideas for advanced high performance computing architectures.

NASA upgraded the computational capability at several of its research and flight centers and established a data network to link them together. At the Ames Research Center, the Numerical Aerodynamics Simulation (NAS) was set up to provide a focused attack on computational aerodynamics employing the highest powered computers available surrounded by data reduction and visualization systems.

HPC Strategy: In 1986 Congress requested that OSTP conduct a study of the critical problems and options for communication networks that support the U.S. high

2. Introduction

performance computing environment. The charter of the FCCSET Committee on Computer Research and Applications was broadened to include the technical aspects of this study. A number of working groups were formed to ensure a perspective that spanned all aspects of the U.S. high performance computing environment. In addition a consortium of government, industry and university experts focused on national infrastructure requirements for high performance computing.* The FCCSET study is documented in "A Research and Development Strategy for High Performance Computing" also known as the *High Performance Computing Strategy (HPC Strategy)*, published by the Office of Science and Technology Policy (included as Appendix B). It provides the foundation for this Program.

The *HPC Strategy* findings were:

- A strong domestic high performance computer industry contributes to maintaining U.S. leadership in critical national security areas and in broad sectors of the civilian economy.
- Research progress and technology transfer in software and applications must keep pace with advances in computing architectures and microelectronics.
- The U.S. faces serious challenges in networking technology which could become a barrier to the advance and use of computing technology in science and engineering.
- Federal research and development funding has established laboratories in universities, industry, and government which have become the major sources of innovation in the development and use of computing technology.

The recommendations of the *HPC Strategy* form the basis for the four components of the High Performance Computing Program.

Four National Research Council reports issued in the period following publication of the *HPC Strategy* have confirmed its findings and emphasized the need to carry out its recommendations: *Toward a National Research Network* (1988), *The National Challenge in Computer Science and Technology* (1988), *Global Trends in Computer Technology and Their Impact on Export Control* (1988), and *Information Technology and the Conduct of Research* (1989).

In December 1988, the Office of Science and Technology Policy charged the FCCSET Committee on Computer Research and Applications to develop this implementation plan for the High Performance Computing Program. The goals, strategy, and actions to implement the Program are discussed in the following sections.

* *A National Computing Initiative*,
Society for Industrial and Applied Mathematics, Philadelphia, PA 1987.

2. Introduction

What is High Performance Computing?

High Performance Computing refers to a productive computing environment that includes high performance components, system and applications software, networking, and the underlying research and human resource infrastructure.

High performance computing systems are those at the forefront of the computing field in terms of computational power, storage capability, input/output bandwidth, and software. These systems include high speed vector and pipeline machines, special purpose and experimental systems, scalable parallel architectures, and associated mass storage systems, input/output units, and systems software. Underlying these advanced systems are microelectronics, optoelectronics, logic devices, and storage technologies.

Advanced software technology and algorithms includes general-purpose operating systems for high performance computer systems and tools and utilities, such as compilers, analysis tools, debuggers, and data management systems. Mathematical algorithms and other general purpose libraries facilitate the use of high performance computers for science and engineering. Software tools will allow high performance computing systems to be embedded transparently in a distributed environment which includes applications specific software and other specialized methods and algorithms. The technology base required to build such environments includes software engineering and data management tools, and basic research in high-level languages and algorithms. Improving these capabilities will greatly enhance scientific and engineering software productivity.

Computer network technology consists of communications and switching capable of providing a very high speed backbone on which the high performance computing environment is distributed. Internetworking and feeder network technology connects local or mid-level high speed networks to the national high speed network. User services such as directories are also essential components of an effective networking environment. Advanced networks will provide improved access to high performance computing systems and increased collaboration opportunities for universities, industry, and government.

Development of high performance computing environments requires a long term, continuing investment in basic research over a wide spectrum of computer and computational science and engineering. A basic infrastructure of knowledge, research, computing facilities, and people are required to create and exploit high performance computing technology.

Why is High Performance Computing Important to the U.S.?

During the last two decades computing has become an important complement to experimental and theoretical research. Computer aided design and engineering

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techniques are replacing manual ones. Computer assisted and automated manufacturing is increasing productivity and improving the value and reliability of industrial products, while reducing the time required for engineering and manufacturing cycles. New knowledge and new industries are increasingly dependent upon computing.

Most of these advances in computing have originated in the United States. However, many of them have been most successfully applied in other countries, where their use has eroded the competitive edge that the U.S. had previously enjoyed. This Program is intended to maintain the U.S. edge by focusing our research advantage in high performance computing toward applications with high value to our economy and national security. Fortunately, current U.S. leadership in high performance computing offers a strategic opportunity to maintain our industrial momentum. The HPC Program provides a way to do this.

The national economic benefits of a strong high performance computing industry are recognized and pursued by other countries. Those nations have formed and funded collaborations between their private and public sectors. Their successes constitute vigorous competition for technological and economic leadership in high performance computing. Foreign computing industries benefit tremendously from government support. To retain our leadership, domestic industrial efforts must be encouraged by a strategy that shares the economic risk of innovation in this capital-intensive field.

National economy: High performance computing is by definition the leading edge of computing technology, which in turn supports many areas of science and technology. Computing constitutes a significant portion of the U.S. economy. For example, in 1988 the U.S. computing industry accounted for 10% of GNP, and almost 10% of all capital investment.* The pace of innovation that it sets pervades the domestic computing industry technology and economics. In terms of capability, today's supercomputer is tomorrow's desk-top workstation and the following day's classroom tool. Thus, U.S. competitive success in the world computing market is supported by leadership in high performance computing.

National security: High performance computing technology is used in critical national security areas. Examples include advanced computer systems architectures, computer network communication technology, and signal processing techniques. Continued acceleration of this technology, including availability of U.S. sources of production, is important to U.S. national security.

Science and technology: High performance computing provides a basis for other innovative scientific and engineering efforts. The pace of rapidly developing technologies, such as robotics, artificial intelligence, communications, high definition

* *The National Challenge in Computer Science and Technology*, National Academy Press, Washington, D.C., 1988, p. 7.

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television (HDTV), campus network applications, semiconductor design, superconductivity, transportation, speech recognition, and data visualization are all dependent on a strong and innovative high performance computing industry.

Manufacturing: High performance computing constitutes an important tool for many industries. Its use in simulation and design improves the productivity of large industries such as aircraft production and automobile manufacturing and is rapidly being extended to other industries. Recent vigorous growth in use of high performance computing in electronics, energy, chemical and pharmaceutical industries illustrates the role of computing in the long term strength of the U.S. economy.

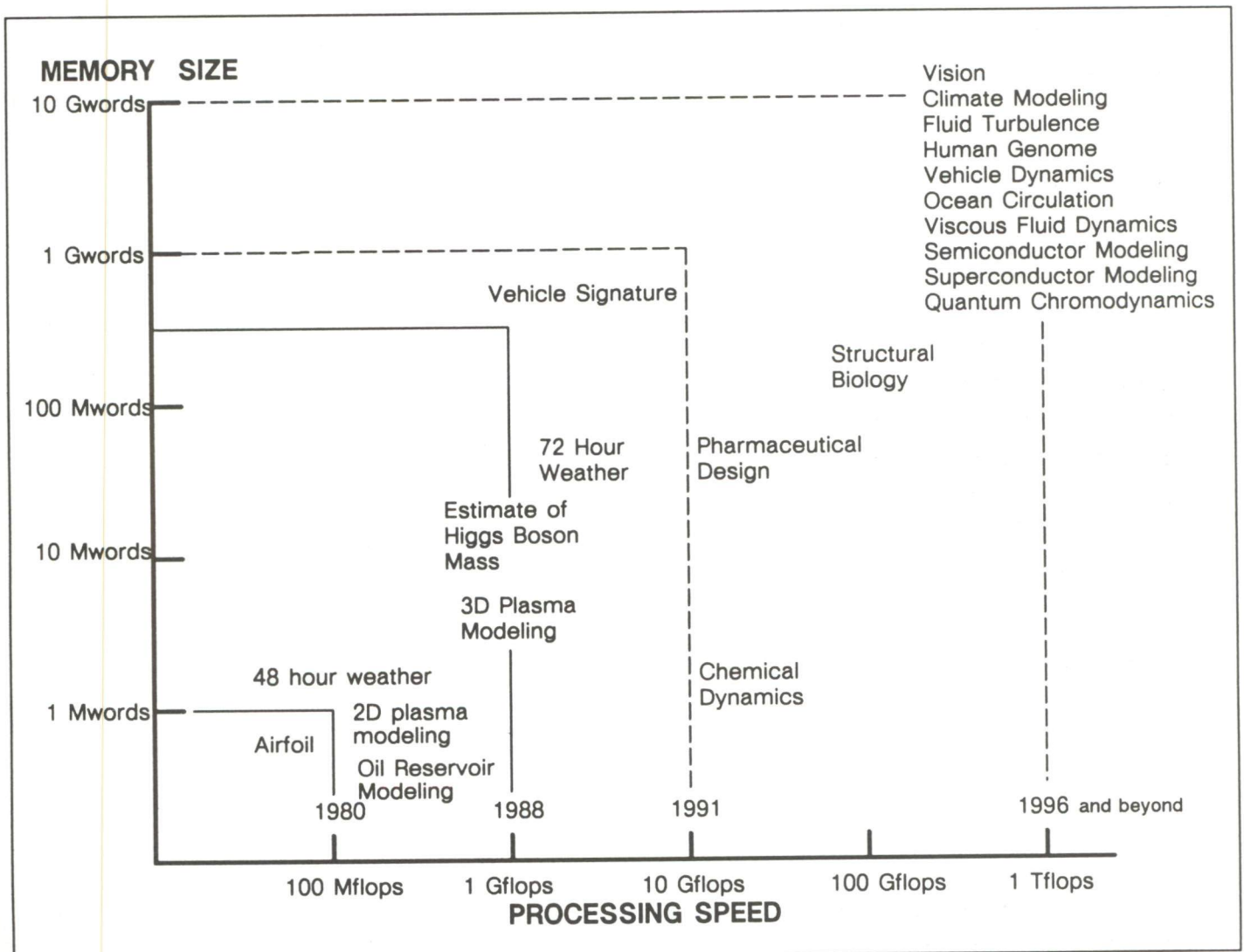


Fig. 2 - Some Grand Challenges and their Projected Computational Requirements

3. Program Plan

3. Program Plan

Introduction

The goals of the High Performance Computing Program are to:

- Maintain and extend U.S. leadership in high performance computing, and encourage U.S. sources of production;
- Encourage innovation in high performance computing technologies by increasing their diffusion and assimilation into the U.S. science and engineering communities; and
- Support U.S. economic competitiveness and productivity through greater utilization of networked high performance computing in analysis, design, and manufacturing.

To achieve these goals, a strategy has been established to:

- Support computational advances through R&D efforts to address U.S. scientific and technical challenges;
- Increase the use of this technology by reducing the uncertainties to industry for R&D and by increasing cooperation among government, industry, and academia;
- Continue use of government and government-funded facilities as a market for HPC early commercial products;
- Support the underlying research, network and computational infrastructures on which U.S. high performance computing technology is based; and
- Support the U.S. human resource base to meet needs of industry, academia and government.

The HPC Program is composed of four coordinated program components: High Performance Computing Systems, Advanced Software Technology and Algorithms, the National Research and Education Network, and Basic Research and Human Resources. Each of the four program components stimulates the development of progressively more advanced products for use throughout computing technology. The four areas build upon each other and upon the existing research base, as illustrated in Figure 1. Each component carries out a recommendation of the November 20, 1987 *HPC Strategy* (see Appendix C.)

Although the program components are described separately, they are interdependent, so that success of the Program depends on balanced support for all of them. For example, the development of high performance computing systems depends on development of advanced software technology and algorithms, because algorithm and software requirements largely determine the corresponding architecture of successful

3. Program Plan

computing systems. Similarly, as the new computing systems become available, new algorithms and software systems are required to take advantage of their capabilities and allow the systems to be used in practical ways.

The High Performance Computing Program requires an unprecedented level of coordination among agencies of the Federal government that are involved in high performance computing. The agencies involved have already begun cooperation to meet this challenge in order to mount a sufficiently comprehensive program in support of U.S. competitiveness.

The remainder of this section describes the goals for each of the four components of the Program, the actions that will be taken to achieve these goals, and the responsibilities of each of the participating federal agencies. Although the Program builds on the existing research base, its goals extrapolate significantly from those of the base and will require significant additional funding. This funding is presented in Table 1 at the end of the plan, with the funding elements keyed to each component and action of the Program.

3. Program Plan

High Performance Computing Systems

Recommendation: The U.S. Government should establish a long range strategy for Federal support for basic research on high performance computer technology and the appropriate transfer of research and technology to U.S. industry. [*HPC Strategy*, 1987]

Goals

High performance computing systems consist of processors, memory, mass storage, input/output, and associated system software. The systems are characterized in this report by overall sustained performance on large problems. They will be designed so that memory capacities, storage sizes and input/output rates scale to provide sustained performance in proportion to processing.

The goal is to support the development of high performance computing systems which will be capable of sustaining trillions of operations per second on significant problems. The program builds upon present government supported efforts which have established U.S. leadership in developing large scale computer systems and the underlying component technologies. However, achieving and effectively exploiting this thousandfold improvement in performance will require developing a new technology base through a program of research in computer architectures, microelectronics and packaging, and associated systems software .

A primary objective of the plan is to assist the continued viability of domestic sources of high performance computers and their critical components that meet the requirements of U.S. industry and Federal programs, both civil and defense. The plan will focus Federally funded research and promote transfer of results between Federally-funded research programs and U.S. industry. This requires close collaboration of researchers in the nation's universities and government laboratories with industrial scientists and engineers. Government funding will also assist risk reduction in critical areas and will complement private capital in the computer market.

To date Federal investment in high performance computing systems has taken two forms: (1) purchase of early market and production model systems and (2) research and development which has led to commercial high performance systems. In both cases Federal funding has reduced the R&D risk of the high performance computing systems for U.S. manufacturers. Because many foreign computer manufacturers are willing to accept greater R&D risk due to their financial environment, the Federal strategy has been important in maintaining U.S. technical leadership in high performance computing systems.

Early purchase has served several critical functions. It has often provided essential financial assistance and early technical feedback to manufacturers during production of

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their first model of a new high performance computing system. The substantial computational resources provided by these early purchases have maintained the rapid technological advance of the U.S. in both civil and defense sectors, thereby supporting the nation's economic and military security. Early users have devised efficient ways of exploiting the capabilities of new systems, providing a performance characterization of the design. They have also furnished significant new concepts to be incorporated in the designs of succeeding generations. This information has often led to improvements leading to more viable commercial products.

For example, NASA and DOE encouraged industry to develop a more advanced supercomputer to meet their research needs, which resulted in the Cray 2 supercomputer. This powerful new machine with greatly expanded memory might not have achieved market acceptance without the identified high performance computing requirement and subsequent acquisition by these Federal agencies. DOE and NASA acquired the first Cray 2 systems, and their early experience showed the broader market for computational research the importance of memories of hundreds of million words and provided valuable feedback that led to engineering changes for better performance.

Federal research and development investment has facilitated advanced research partnerships between industrial firms and university researchers. Industry provides practical knowledge and advanced manufacturing technology to produce high performance computing systems, while universities have developed new concepts and experimental systems. The results of these partnerships have often been significant in supporting the U.S. economy and national security.

The DARPA Strategic Computing program, DOE, and NASA have funded industry/university partnerships which have established U.S. leadership in scalable, highly parallel, high performance computing systems. Unlike the present generation of supercomputers, the resulting systems employ hundreds to thousands of processors. These architectures are generally scalable to higher levels of parallelism and, in the future, can exploit higher performance components and packaging with corresponding increases in sustained performance. This program has produced very promising results: the first generation of scalable parallel systems are now commercially available and have demonstrated high performance in both numeric and non-numeric applications. The second generation of this class of high performance computers is now emerging and scientific, engineering, defense, and business users are preparing for their arrival. Additional results include enhanced performance for workstations, personal computers, mass storage, graphics and input/output systems.

This Component of the HPC Program will build on recent experience in coordinated funding by different agencies of high performance computing systems research and development. For example, the Strategic Computing program at DARPA invested in R&D for an advanced parallel computer which was subsequently commercialized by

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Thinking Machines Corporation. DARPA then collaborated with DOE and NASA to facilitate early use of this system in their research laboratories. The NSF recently funded a Science and Technology Center at Rice University, California Institute of Technology, Argonne National Laboratory, and Los Alamos National Laboratory which will consider more effective applications of this and other parallel architectures.

Action Plan

The focused high performance computing systems projects in this plan will be undertaken in cooperation with the software development projects. The systems also must be coordinated with advances in networking to ensure that their potential performance is available to remote users via the National Research and Education Network. The advanced research tasks provide excellent training grounds for the next generation of computer and computational scientists and engineers. Collaboration among these components is essential to the success of the Program.

Research for future generations of computing: Research in computer science, scalable parallel computer architectures, high density packaging technology, VLSI technology and optoelectronics will be increased. New packaging and component technologies will be developed together with associated design, analysis, simulation, and testing tools to enable their use in implementing larger scale computer architectures. This includes creating and extending models of computation, together with sufficient efforts in adaptation of fundamental algorithms, operating systems, and programming languages. These systems-specific activities complement the more generic and applications-focused software described in Advanced Software Technology and Algorithms where the emphasis is to develop the full potential of the new architectures.

System design tools: Support for rapid design, prototyping, and integration is essential to reach the capabilities needed for the Program. Progress in research, development and manufacturing of high performance computing systems is presently limited by lack of adequate automated design and analysis tools. A new generation of design tools and techniques will be developed for integrated, computer-assisted design and manufacturing of high performance computing systems from functional specifications through full systems. The tools will be developed so as to provide rapid prototyping in support of research, interfaced with the latest advances in automated manufacturing so as to boost U.S. industrial capabilities in addition to increasing research and development productivity. These facilities will make use of the latest high-density packaging technology which will be required to create systems at the targeted level of performance.

Transfer of technology to stimulate advanced prototypes: Cooperative university/industry high-risk research and development projects will provide rapid technology transfer from research results to working prototypes. Revolutionary concepts

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are emerging from the frontiers of research in computer science and engineering, innovative computer architectures, mass storage systems, input/output systems, high density packaging, Very Large Scale Integration (VLSI) and optoelectronics.

Government funds will be invested where opportunities exist for leverage to accelerate the transfer of the Federally-funded computing technology to American industry and vice versa. Advanced application-specific integrated circuits (ASICs) will be utilized where appropriate in these general purpose high performance computing systems. Joint projects in high risk areas will be pursued on a cost sharing basis with industry in close collaboration with government laboratories and academia. The focus of these projects will be to accelerate transition of high risk, revolutionary concepts from research laboratories into the commercial market while encouraging a domestic means of production for all critical components.

By the mid 1990s, it is expected that commercial advanced prototypes will be capable of sustaining two or three orders of magnitude better performance than today's systems for complex science, engineering, and defense applications, and for other problems of national importance. System software, including operating systems, programming languages, and software analysis tools, will be developed to determine the computational potential of the commercial systems. Performance analysis and measurement tools will be improved to enable the design and configuration of heterogeneous systems.

Evaluation of Early Systems: Evaluation of early production models of new high performance computing systems will be undertaken using representative problems. These systems will be acquired at the smallest scale that can evaluate their potential performance. The resulting evaluations will form a basis for decisions to develop the associated generic software and specific large scale applications in the Advanced Software Technology and Algorithms component. Needs of the Grand Challenges will be considered fully, and some early production models of high performance computers may be utilized in one or more of the Grand Challenges, at the sites performing this research.

This component of the HPC Program does not include acquisition of full scale systems. Some of these will be acquired under the High Performance Computing Research Centers in the Advanced Software Technology and Algorithms component; others will be purchased by Federal agencies to fulfill their missions. This investment will sustain the U.S. competitive edge and must be protected by ensuring appropriate export controls.

Rationale

Improvements in materials and component technology are advancing computer capability rapidly. Memory and logic circuits are continuing to improve in speed and density, but as fundamental physical limits are approached, advances are being sought through improved computer architectures, custom components, and software and

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algorithms. Application-specific integrated circuits, such as for real-time signal processing, are being incorporated into special purpose computing systems. Computer architectures have begun to evolve into large scale parallel systems. Scalable architectures provide a uniform approach that enables a wide range of capacity, from workstations to very high performance computers.

At current performance levels our ability to model many important science, engineering, and economic problems is still limited. Computational models which have been developed for these problems require for realistic solutions speeds of trillions of operations per second and corresponding improvement in memory size, mass storage, and input/output systems. *Achievement of this performance level in the next five years is feasible, based on extrapolations of processor capability, demonstrated architectures, number of processors, and improved software performance.*

Responsibilities

NSF, NASA, DOE and DOD share responsibility for long-range research on the foundations of high performance systems. Within the DOD this responsibility will rest with DARPA, the Army Research Office (ARO), the Office of Naval Research, (ONR) and the Air Force Office of Scientific Research (AFOSR). These agencies have all been involved in this area and have considerable knowledge of the status and opportunities.

DARPA will carry the prime responsibility for high-risk research and development leading to commercialization of highly parallel high performance computing systems and will work with ARO, ONR, and AFOSR to achieve this end. DARPA will also have the lead responsibility for supporting research facilities for rapid design, prototyping, and integration of these systems, using advanced components and packaging. DARPA's unique style of managing high risk, large scale projects is particularly effective for transferring technology in joint university and industrial efforts.

The DOE, NASA and DARPA will continue to acquire first production models of high performance computing systems. The diversity of interests represented by these agencies has been important to the broad range of systems developed by industry in the U.S.. This healthy arrangement will continue.

NIST will expand its program for development of measurement techniques and performance modeling for high performance computer systems, and will support transfer of this technology to industry.

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Advanced Software Technology and Algorithms

Recommendation: The U.S. should take the lead in encouraging joint research with government, industry, and university participation to improve basic tools, languages, algorithms, and associated theory for the scientific Grand Challenges with widespread applicability. [*HPC Strategy*, 1987]

Goals

Sustained improvements in computing hardware performance and sophistication have resulted in a shift from hardware and architecture to software and algorithms as the primary determiners of the power, flexibility, and reliability of major computing systems. Today the ability to exploit computing technology to address scientific and technological problems of competitive and national importance is determined primarily by software capability.

Breakthroughs in software technology enable computer solutions to problems whose scale, complexity or evolving nature previously inhibited any organized approach. Breakthroughs in algorithm design improve problem solving performance by orders of magnitude, making tractable computational solutions in problem areas where previously no solutions of any sort, or only traditional analytical or experimental methods, were available.

The goal for the Software Technology and Algorithms component of the High Performance Computing Program is to develop a base of software technology and algorithms that (1) will enable solution of Grand Challenge application problems in science and engineering, and that (2) will have broad national impact on software productivity and on systems capability and reliability.

The approach taken is to develop the advanced algorithms and software technology required to address applications problems on the scale of Grand Challenges, while ensuring that the generic technology developed can be applied to a broad range of computational problems. This investment may lead to the development of commercial products, but only after the new concepts have been illustrated and their feasibility demonstrated. Therefore, specific investments will be made to reduce the risks associated with the transition and adoption of these advanced technologies.

The U.S. lead in many areas of science and technology will be closely linked to advances made on important fundamental problems identified as Grand Challenges. Grand Challenges come from many fields from basic science to applied technology. Their solutions will have significant, national-level impact across diverse fields of interest to many Federal agencies. Appendix A describes several Grand Challenges and the agencies concerned with their solutions.

Improvements in algorithm design and implementation are as important to total "user realized" system performance as are performance improvements in the computer

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Advanced Software Technology and Algorithms

systems in which these algorithms will be executed. High performance computing offers scientists and engineers the opportunity to simulate conditions that are difficult or impossible to create and measure. This new paradigm of computational science and engineering offers an important complement to traditional theoretical and experimental approaches, and it is already having major impact in many areas. New approaches combining numeric and symbolic methods are emerging. Development of new instruments and data generation methods in fields as diverse as genetics, seismology, and materials is accelerating demand for computational power. As problems grow to the size and complexity of Grand Challenges, and as computer architectures grow more complex in order to provide increased computing power, the software and algorithms challenge becomes significantly greater.

Effective exploitation of the performance potential of the emerging parallel systems poses a special challenge both to software technology and to algorithm design. The required software technology has many dimensions, ranging from systems software, advanced compilers, and languages, to programming environments for developing and adapting software, to large scale distributed data repositories. Also included are techniques for analyzing and constructing software with high reliability and numerical accuracy, design of high performance algorithms for solving generic problems on specific architectures, and development of algorithmic and software architectural approaches specific to solving the Grand Challenges.

Research in fundamental parallel algorithms is needed to provide a sufficient base of algorithms for high performance architectures. The characteristics of the generic algorithms are often strongly dependent on the computational model embodied in a particular machine architecture. Various models of parallelism yield different algorithms, as do heterogeneous systems configurations involving hybrid computational models.

Networking technology will also have significant influence on the design of algorithms for distributed systems. Fundamental algorithms must be specialized and combined to provide application-specific algorithms appropriate for the Grand Challenges. Algorithm design, development, optimization, and validation requires substantial resources and collaboration. Experimental facilities are a critical tool for developing and demonstrating applications and systems software, computer architectures, and networks.

Action Plan

Support for Grand Challenges: A principal focus of activity will be providing advanced software technology support to research groups collaborating to address the Grand Challenges. The purpose of this is not to provide sustaining support for this research, but rather to provide a means to reduce the risks assumed by Grand Challenge researchers when adopting innovative high performance computing technologies.

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Collaborative groups will include scientists and engineers concerned with Grand Challenge areas, software and systems engineers, and algorithm designers. These groups will be supported by shared computational and experimental facilities, including professional software engineering support teams, linked together by the National Research and Education Network. Groups may also create a central administrative base, which can be located anywhere on the network. Experimental facilities, often called testbeds, are included in the network in order to provide real-time access to data streams and support for rapid validation of computational models.

Technical contributions arising from this investment will include development of application-specific codes for innovative high performance computing systems, design and analysis of algorithms for Grand Challenge problems, and architecture and performance assessment as it relates to specific applications.

Agencies will select Grand Challenge applications to be included in this Program on the basis of the national importance of the specific area and the extent of cost-sharing from sources directly concerned with the specific scientific and engineering applications. An additional consideration will be the leveraging potential in other areas, in particular the commercial domain. Investment related to high performance computing will complement the traditional sources of support for Grand Challenge research by enabling exploratory use of advanced computational techniques.

Software components and tools: The Grand Challenge applications groups will have common needs in many areas of software technology including programming environments for code development and adaptation, advanced compiler technology. Also needed will be tools for optimization and parallelization, data management and interoperability, analysis and performance measurement, user interaction and visualization, debugging, and instrumentation. Advances in these generic software technology areas will have broad national impact, beyond the immediate scope of the Grand Challenge applications.

In order to provide these tools in a manner that is responsive to the needs of the applications researchers, collaborative groups will be formed that cut across the Grand Challenge areas in order to coordinate and share supporting software technology. This will enable multiple applications groups to sustain more easily a fast pace of innovation in the underlying software technology. These groups will include industrial, academic, and government researchers. Innovative approaches will be used to provide incentive for industry to participate and share costs.

A major focus of systems design and engineering will be developing advanced software applications that exploit the high capacity of the National Research and Education Network to provide new capabilities to researchers. An important example is a distributed operating system that permits high capacity interactions among programs at multiple network sites. This capability will enable a researcher to develop applications that may involve several high performance computers located at diverse sites to work

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together effectively. Other applications include distributed shared data and program libraries, research report dissemination systems, and advanced user interaction and visualization systems. For example, security support and data interoperability are required to enable distributed databases that exploit the National Research and Education Network.

Computational techniques: Developing software tools and components is basic to fundamental research in computational technology. It is this research that yields the fundamental algorithms, models of computation, new approaches to program analysis, and language approaches that provide fundamental generational advances.

Research in computational techniques includes the areas of parallel algorithms, numerical and mathematical analysis, parallel languages, and program refinement techniques. Also included are models of computation, formal methods for high assurance, theoretical and empirical techniques for algorithm analysis, and related areas.

Results in design and theory of algorithms are as important to breaking down computational scaling barriers as are performance improvements in computing hardware. Algorithm breakthroughs continue to be made on even fundamental problems such as linear algebra that are often assumed to be well understood. Breakthroughs can yield thousandfold speedup factors above and beyond hardware advances, as illustrated in Figure 3.

Parallel computing is the principal source of opportunity to improve computational performance. There are many differences among the models of computation embodied in parallel computers, and all of these differ from the purely sequential model that dominated the first half-century of computing. Algorithm theory has already yielded scalable parallel solutions to many computational problems that were assumed by most practitioners to be inherently sequential. In order to realize the potential for performance and scaling implicit in the parallel computer technology, research in the design of algorithms will be supported.

The evolution of parallel computing technology has also stimulated renewed activity in the area of high level programming languages. Languages that have inherently sequential semantics force programmers to make unnecessary and undesirable computational commitments that must, in any case, be undone by optimizing compilers. Efforts will be funded to develop higher level languages that will enable computational scientists to consider separately the abstract computational problem being solved and the specific implementation approach. This will also enable use of emerging programming tools that integrate program transformation and optimization with analysis to yield implementations with higher assurance and predictable numerical characteristics.

High performance computing research centers: The HPC Program will support deployment of innovative high performance computing architectures to computational

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scientists and engineers working on Grand Challenge applications, and to other computer scientists and engineers. Centers will be established to accelerate transition to new generations of high performance computing technology by enabling researchers to explore applications of this new technology.

Information gained from evaluating prototypes of new architectures as part of the High Performance Computing Systems Component will aid the choice of architectures to support the Grand Challenges. As the risks associated with application of innovative systems diminishes in individual Grand Challenges, the costs associated with the facilities will be transferred to the interested sponsors of the applications research. In this component we include computing hardware, network access to the operating systems of scientific instrumentation, and operational support for the Grand Challenge cooperative groups.

Facilities will also be provided to researchers in computing technology in order to support a more rapid transition to the new technology base. Researchers in areas such as algorithms, software environments, and operating systems require experimental access to new generation hardware. For example, there are a number of theoretical models for parallel computation in general use among algorithm designers, but only through empirical work can these models be adjusted to reflect more faithfully the models embodied in the parallel systems. Crucial systems parameters, for example, the relation of processing time to communications time and memory speed, interact with algorithm design parameters in ways that can best be explored empirically.

It is expected that many of the facilities allocated as part of Advanced Software Technology and Algorithms component will be used to facilitate transition of Grand Challenge applications to the new high performance computing systems. The remaining portion will be provided to computing technology researchers in order to support the development of generic algorithms and software technology. These facilities are in addition to those which will be provided as part of the High Performance Computing Systems component of the Program as a means to accelerate the transition from prototypes into products.

Responsibilities

DOE, NASA, NSF, NOAA and DARPA share responsibility for clearly defining the computational requirements of the Grand Challenges. They will select Grand Challenge applications areas in which collaborative groups are to be formed, and are responsible for providing advanced software technology support to the research groups collaborating to address the Grand Challenges applications in their domains.

NASA will carry lead responsibility for organizing and chairing the Federal Advanced Software, Technology and Algorithms Coordinating Committee. DOE, NSF, DARPA and other DOD research activities will be among the agencies participating in this committee.

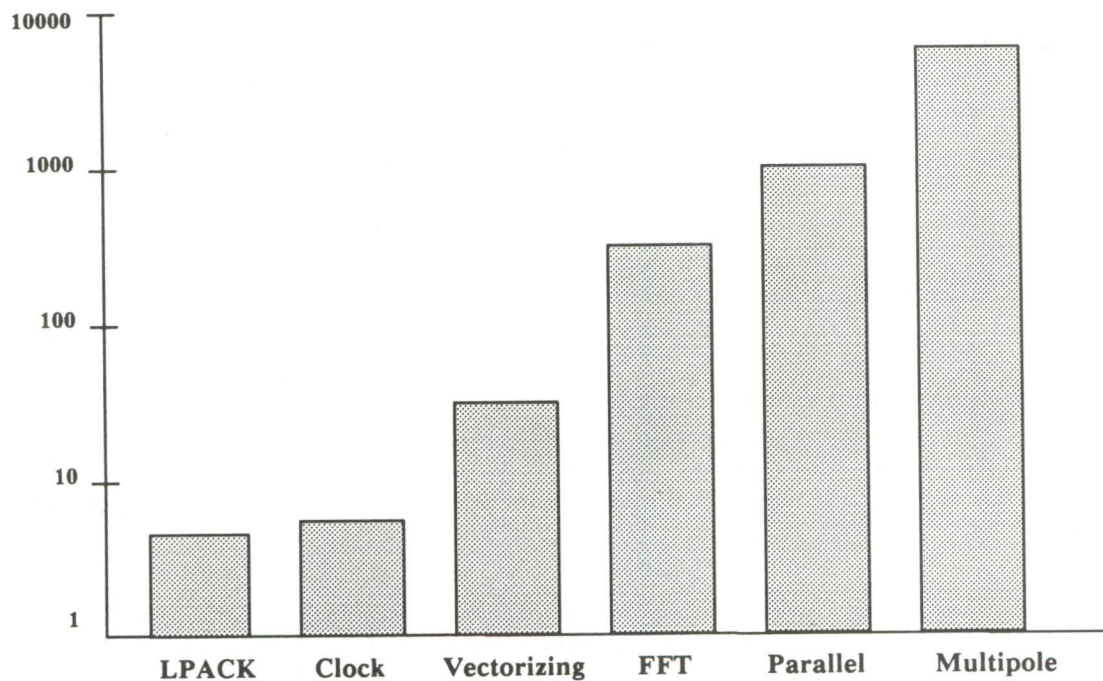
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NASA, DARPA, NSF and DOE will support development of software tools and standard components for use across the spectrum of the Grand Challenges. DOE and NASA share responsibility for exploiting the nearer term potential for commercialization of these software developments.

DOE, NASA, NSF and DARPA will incorporate early production models of the high performance computing systems into high performance computing laboratories. These high performance computing laboratories will include the advanced software tools and components, innovative computational techniques and the application-specific algorithms and experimental code for the Grand Challenges. These facilities will support the required integrated research, and will be available to users through the National Research and Education Network.

NSF, DOE, NOAA and NASA will build on their existing supercomputer centers which will provide the facilities for several high performance computing research centers, accessible to the national research community.

NOAA will be responsible for organizing the coordination of R&D in data management, and will play a lead role in supporting basic research in tools and techniques required for management and analysis of large-scale scientific data bases and distributed data handling.



Factors in Computational Speedup
Examples using vectors of length $n=4096$ (2^{12})

Method	Type	Order	Speedup
LAPACK: BLAS1→BLAS3 {Dongarra, et al.}	Algorithm & Software	constant	4
Hardware Clock Speed {1976 to 1989}	Microelectronics	12ns→2 ns	6
Vectorizing Compilers {CFT, VAST, KAP}	Algorithm & Software	32* scalar	32
Fast Fourier Transform {Cooley and Tukey}	Algorithm	$O(n^2) \rightarrow O[n \cdot \ln(n)]$	340
Parallel Processors {Gustafson, Montry and Benner}	Algorithm & Architecture	Linear in nr. of processors	1000
Fast Multipole Method {Greengard & Rokhlin}	Algorithm	$O(n^2) \rightarrow O(n)$	4000

Fig. 3 – Speedup Due to Advances in Algorithms

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The National Research and Education Network

Recommendation: U.S. Government, industry and universities should coordinate research and development for a research network to provide a distributed computing capability that links the Government, industry, and higher education communities. [HPC Strategy, 1987]

Introduction

The United States must develop a National Research and Education Network (NREN) to support communication between persons and organizations involved in open research and scholarly pursuits in the United States. This need has become increasingly obvious to the research community, especially among those who have experienced the benefits of electronic mail and database access, exchange of files between computers, and remote access to specialized and high-performance computing systems. As networking technology grows in power, network-based collaboration continues to allow substantive improvements in research effectiveness. These themes are well expressed in the recent National Research Council report *Toward a National Research Network* (1988). In developing the plan for this component the growing importance of the interrelationships between the network, the research components of the Program, and the U.S. academic community became increasingly clear. *Education* has been included in the name of the network in explicit recognition of this importance.

Today, all major organizations and government agencies use computer networking to some extent, and those with the most progressive and demanding missions have organized major transcontinental networks. A number of these networks are interconnected, notably those of the National Science Foundation (NSFNET), the Department of Defense (ARPANET and MILNET), the Department of Energy (ESNET), and the National Aeronautics and Space Administration (NASA Science Internet). These and many other commercial and regional networks collectively form the Internet, which currently supports a large portion of the U.S. science and engineering research community.

Today's Internet is far from uniform in the type and quality of service provided, and it does not yet reach the entire research community. Even so, expanding the Internet and enhancing its performance as far as technology allows will fall far short of what can and should be accomplished. The goal of this component is to create a new NREN which operates at rates of gigabits per second nationwide. This tremendous challenge is within the grasp of the United States in the next ten years. A network with this level of performance will provide another major improvement in the effectiveness of the national research community and their resulting ability to contribute to U.S. competitiveness.

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Availability of the NREN will provide an environment which enhances collaboration both for software technology development and for basic research and scholarship nationally. In return the development of the NREN will benefit from advances in software technology, particularly in the area of network services.

The eventual impact of the NREN on national competitiveness may well extend beyond such gains in research productivity. The NREN should be the prototype of a new national information infrastructure which could be available to every home, office and factory. Wherever information is used, from manufacturing to high-definition home video entertainment, and most particularly in education, the country will benefit enormously from deployment of this technology.

Stages of the NREN: The stages of NREN development as articulated in the *HPC Strategy* are:

The *first stage* involves an upgrade of the existing Internet to 1.5 megabit per second trunks. (This process is underway.)

The *second stage* will deliver upgraded network services to 200 to 300 research installations, using a shared backbone network with 45 megabit per second capacity.

The *third stage* will deliver one to three gigabit per second networking service to selected research facilities, and 45 megabit per second networking to approximately 1000 sites nationwide.

The stages of the NREN are illustrated in Figure 4.

Government/Industry/University roles: The Federal government plays a dual role in the development of computer networking. Federal funding has supported networking research and technology development in academic, industrial, and (to a lesser degree) government laboratories. The government also supports operational networks and network services. These are expected eventually to create a commercially viable market whose needs can be supplied by the private sector. In this latter role, the government has supplied networks as value-added services on communication circuits leased from the common carriers, and has subsidized their use by segments of the scholarly and research communities.

Universities play a major research role in advanced networking technology. Whereas most of the improvements in *communications* technology have come from industry, many of the most important *networking* technologies have been developed by universities. Educational institutions are also the primary users of networking nationwide, both for access to high performance computing and for collaboration among themselves and with government and industry.

To date, the role of industry has mostly been to provide communications links and produce equipment for networking. This situation is changing and in fact must be

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radically altered in order to develop the high speed networks of the future. At data rates of gigabits per second the switching elements of the network need to be integrated with the communications links within the facilities of the communications industry. Applications of networks within and between industrial groups should also increase to support a more competitive U.S. industrial posture.

It is anticipated that the government will continue to fund networking research in partnership with academia and industry, and will continue to support parts of the national research networking infrastructure which do not yet have a sizable market. This will be necessary both to build the market for private offerings as well as other commercial goals. It also will be necessary for those government agencies sponsoring development of advanced networking to coordinate the work of multiple government laboratories, industrial, and university groups.

Action Plan

The Federal Research Internet Coordinating Committee (FRICC), a collaboration of the NSF, DARPA, DOE, NASA, and the Department of Health and Human Services (HHS), has begun transforming the present day Internet toward the goal of an NREN. This is being accomplished through sharing communications circuits, network access points, and even entire networks, leading to streamlined operations and reduced costs. The FRICC has established coordinating members in other agencies and national networking organizations and has developed a program plan for implementing the NREN. While these activities have provided a healthy start for the NREN, an additional effort will be necessary to achieve the ultimate goals of the High Performance Computing Program. FRICC, while not formally a part of the FCCSET structure of OSTP, works closely with the Committee on Computer Research and Applications and conducts its activities consistent with the policy guidance of the HPC Program.

Interagency effort to produce an interim NREN. Coordinating an interagency project as large as the NREN will not be easy. It is clear that a unified focus for management is necessary. It is equally clear that the project will not be fully supported by the diverse agencies involved unless they have a decisive role in shaping the project, and are kept in constant, close communication so that the resulting network fills their needs.

In *Stage 1* the agencies will continue to upgrade their networks to 1.5 megabit per second (T1) trunks. This effort is already well underway. In addition, DARPA project known as the *Research Internet Gateway (RIG)* is acquiring a prototype platform for development of "policy-based routing" mechanisms which will allow interconnection of these trunks. Also the FRICC has plans to develop enhanced capabilities such as directory services in support of network users.

As the Internet expands, issues of *network security* have become a source of increasing concern. Recent incidents have demonstrated the vulnerability of computers attached to

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national networks. A significant effort in implementing the NREN will be development and implementation of mechanisms to enhance the security of the connected computing systems, and mechanisms to protect the networks themselves. These mechanisms will rely on policy-based routing capabilities, and also on recent advances in public-key cryptography.

In *Stage 2* the agencies are planning to acquire a common set of 45 megabit per second transcontinental trunks, the *Research Interagency Backbone (RIB)*. The ability to share backbone trunks, resulting in lower costs and improved service for all agencies, will be enabled by gateways with policy-based routing capabilities. When the RIB is fully operational, it will be interconnected with the NSFNET backbone; the result will be the interim NREN. Another equally important result will be the stage 2 technologies, which will provide a base from which commercial providers can offer compatible networking services nationally.

Research and development for billions of bits per second (gigabits) net. The ultimate structure of the *Stage 3* network will not become clear until this research effort is complete. However, it is clear that fiber-optic trunks now being installed by communications carriers will become increasingly important, new switching systems and network protocols must be developed, new high-speed interconnections to workstations and supercomputers will be needed, and some form of interconnection with the Stage 2 network will be needed. An additional goal of stage 3 is to support such advanced capabilities as remote interactive graphics, nationwide data files, and network-based high definition displays for education. Managing the dynamics of these activities will be a major challenge, but the payoff for success in terms of national capabilities will be enormous in terms of research productivity and, subsequently, in the form of technologies and services available from commercial sources.

Deployment of gigabits NREN. Stage 3 culminates in an operational national network with gigabits trunks. Deployment is not expected to begin until the middle to late 1990's.

Structured transition to commercial service: Mid-level networks organized on a regional basis or by other limited constituencies have sprung up indigenously (for example BITNET and several state-funded networks). Other mid-level networks have been formed with seed funding from NSF, NASA, and DARPA. These have become, in varying degrees, part of the existing Internet. They provide an important vehicle for the economic participation of state and local governments and of industry by providing access to the national network and by giving these other sectors a stake in its operation, thus reducing the funding burden on the Federal government. Moreover, each of these networks is typically a private and autonomous (although possibly subsidized) business entity; thus elements of the emerging national network have already become part of the private sector. Continuation of this trend will result in

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opportunities for many companies to become involved in leading-edge data communications.

By the end of Stage 2, it is expected that every university and major laboratory will be connected to the NREN through a mid-level network. Present regional offerings vary widely in reliability and scope. To provide homogeneous and universal networking service, interaction of the Federal government with mid-level networks must increase. It is also to be expected that competition and other market forces will come into play between these networks.

Each of the services developed for the NREN must become available commercially at the earliest practical time. The intention is that networking infrastructure should be a commercial offering nationwide. The government and its contractors would then purchase network connections from companies which would provide service to subscribers in general.

Eventually, computer networking should be as pervasively available as telephone service is today. The corresponding ease of inter-computer communication will then provide the benefits associated with the NREN to the entire nation, improving the productivity of all information-handling activities. To achieve this end, the deployment of the Stage 3 NREN will include a specific, structured process resulting in transition of the network from a government operation to a commercial service.

Agency Responsibilities

NSF will be the lead agency for deploying the operating NREN within the HPC Program. NSF has assumed responsibility for supporting a backbone for the NREN, and will coordinate collaboration among Federal agencies in this area. The NSF role of support and coordination will expand as the NREN grows; NSF will upgrade and extend the operational network, providing advanced network services, and collaboration technology. NSF will also support and participate in the interagency networking testbed.

DARPA will be the lead agency for the Program's advanced networking technology research and development. DARPA's research leading to the advanced networking technology for gigabit speeds (Stage 3) will take place within its Command, Control, and Communications programs as the primary contribution of the Department of Defense to the NREN. DARPA will also create a testbed, jointly funded with other participating agencies, for advanced network technology and inter-agency collaboration.

DOE will provide networking support for the energy research community and participate in the interagency networking testbed.

NASA will provide networking support for the aerospace research community, participate in the interagency testbed, and support research on aerospace applications and technology with a focus on telescience research and development.

3. Program Plan:

The National Research and Education Network

DARPA, NSF, DOE and NASA will continue their active roles in governance of the Internet, and will expand these roles by providing representatives on the council which sets policy for the NREN.

NOAA will provide networking in support of the climate and global change research community and will participate in the interagency testbed.

NIST will participate by establishing networking standards, with particular emphasis on protocols and security standards. NIST will continue its traditional role of coordinating developing technologies such as Broadband ISDN with service providers, computer manufacturers, telecommunication manufacturers, system integrators and end users through the standards process.

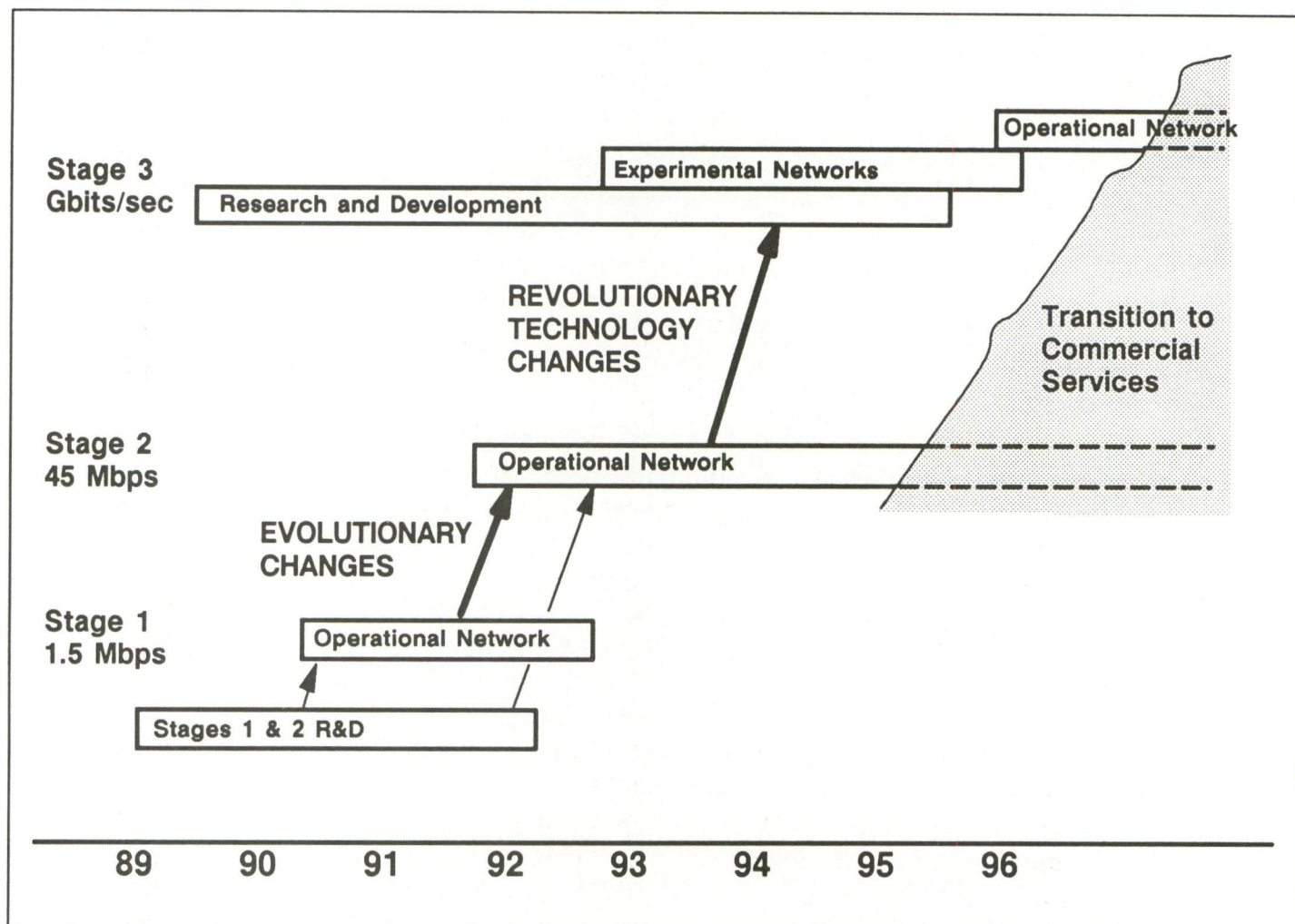


Fig. 4 - Timetable for the National Research and Education Network

3. Program Plan

Basic Research and Human Resources

Recommendation: Long term support for basic research in computer science should be increased within available resources. Government, industry, and universities should work together to improve the training and utilization of personnel to expand the base of research and development in computational science and technology. [*HPC Strategy*, 1987]

Goals

This component of the High Performance Computing Program addresses longer term national needs for high performance computing. The rapid growth of computing technology and computational science and engineering has created extraordinary demands for more rapid innovation, significantly increased manpower, and accelerated transfer of technology. The basic research community plays a major role in addressing these needs.

We must sustain a rapid pace of innovation in computer science and in computational science by investing in long term basic research.

Proprietary control is difficult to retain in an industry that is characterized by periodic major structural innovations, such as the shift now in progress from central timeshared computing to distributed networked workstations. Because of this, industry has little incentive to invest in long term approaches unless costs and risks are shared. For this reason, most of the major breakthroughs in computing have been the result of basic research activity. Examples include timesharing, local and national networks, VLSI design technology, personal computing, parallel computing, artificial intelligence, and many others. Each of these breakthroughs has had an enormous impact in the marketplace.

Increased numbers of qualified people are needed both in computational science and engineering, and in computer science and engineering. Universities are beginning to create new academic programs in areas of computational science and engineering that develop skills in both computer technology and in specific areas of science and engineering. The rapid evolution of this technology requires practitioners with a broad range of generic skills.

There is a need to reduce risk to industry in adapting and applying new technology. Technology is transferred rapidly from research into practice when the research community is an active participant in the process and when there is consensus in the research community on basic technical issues. The diversity of parallel computing models and algorithmic approaches now emerging provides unusual opportunity for application. The rapid pace of technology development in computing and computational science demands active participation of basic researchers in accomplishing transfer of the emerging technologies.

3. Program Plan: Basic Research and Human Resources

Support for basic research must be supported in several respects. The High Performance Computing Program addresses this need through direct basic research support, improved infrastructure to increase research productivity, and facilitation of collaboration. The goals of this component of the Program are:

- **Basic research.** Ensure an adequate level of basic research activity to produce the next generation of innovative results in computing technology.
- **Human resources.** Support basic research, education, and training in order to meet the needs of research, personnel, and transition support in both computing technology and in computational science and engineering.
- **Support for collaboration.** Promote collaborations involving the basic research community, industry, and government to allow attacks on larger scale problems and accelerate dissemination of results.
- **Infrastructure.** Support the effectiveness of the research community by providing facilities and research infrastructure, including experimental high performance computers, networks, associated systems software, and applications software components.

The Basic Research Enterprise. Basic research programs already underway and supported by current Federal funding provide a base from which many computing applications goals can be achieved, but this base is already under great pressure even without the demands of important new thrusts¹. The pace of expansion of computing technology and its applications greatly exceeds the rate of expansion of basic research, with consequent strain on the basic research community².

Effectively integrating new high performance computing technology into the US technological and scientific mainstream will require sustained research effort across the spectrum of computing technology. Some examples are microsystems component technology and packaging, computer architecture, fundamental algorithms and complexity, software engineering languages and tools, networking and distributed computing, artificial intelligence, numerical algorithms, and applications-specific algorithms.

Human Resources. Several studies in the past 10 years have documented the human resources challenges to the continued development and exploitation of computer technology³. A particular focus of these studies has been the severe undersupply of computer scientists and computer engineers at advanced degree levels. Computational scientists and engineers are in even shorter supply.

1. *The National Challenge in Computer Science and Technology*, Computer Science and Technology Board of the National Research Council, National Academy Press, Washington, 1988.

2. Gries, D., et al. *Imbalance Between Growth and Funding in Academic Computer Science: Two Trends Colliding*, Communications of the Association for Computing Machinery, 29(9), Sept 1986.

3. Program Plan: Basic Research and Human Resources

Addressing the Grand Challenge applications requires large scale collaborative effort involving diverse groups of scientists, engineers, and mathematicians. The manpower shortage in computing technology and in computational science and engineering is hindering progress in these areas.

Collaboration. Interactions among multiple research teams and potential technology recipients contribute significantly to reducing the risks associated with transfer of major technologies into production. Collaboration can be facilitated in the basic research community by ensuring a high level of access to the network applications software based on the National Research and Education Network and by involving basic research groups in Grand Challenge applications.

The network support software will include capabilities for activities such as rapid distribution and sharing of research results, software distribution and configuration management support mechanisms, high-capacity interaction support for remote computers, access to instrumentation in remote experimental laboratories, rapid search and retrieval in distributed library databases, and so on.

Infrastructure. Scarcity of funds in computing technology research has hindered modernization of university computing research and education facilities. A rapid pace of technological innovation requires aggressive investment to ensure that universities remain at the forefront. Networked access to high performance computing with advanced software support is important for training computational scientists and engineers. The potential for using networks to disseminate results and conduct collaborative research at all educational levels is just beginning to be realized.

Basic infrastructure for computer research has been a concern for some years. Several agencies have programs that support the needs of the HPC Program. The Institutional Infrastructure Program at NSF has helped to equip approximately 25 computer science and computer engineering departments in the past eight years. DARPA for many years has been instrumental in building a core research base at major universities. The University Research Instrumentation program of the Department of Defense has provided important equipment and research support. The DOE research program has provided modern parallel computer facilities to several of its national laboratories and universities to promote basic research in high performance computing and to provide training facilities for graduate students and young faculty in all the disciplines involved in computational sciences. NASA maintains several research institutes and centers of excellence to interface with universities.

3. Gries, *op. cit.*; Feldman, Jerome A. and William R. Sutherland. *Rejuvenating Experimental Computer Science*. Comm. ACM 22, 9 (Sept. 1979), 497-502.; Kosaraju, S. Rao., et al. *Meeting the Basic-Research Needs of Computer Science*, Study report of the NSF CCR Advisory Committee, December, 1986; *Profiles -- Computer Science: Human Resources and Funding*, National Science Foundation report 88-324, February, 1989.

3. Program Plan: **Basic Research and Human Resources**

Action Plan

Several specific approaches are taken to address the goals. These approaches will, in most cases, be implemented as possible expansions of existing research funding programs.

Expand basic research. Increase basic research activity in computing technology areas that influence high performance computing, including algorithms, software languages and tools, architectures, systems software, microsystems, networks, distributed computing, and symbolic processing.

Attain a level of 1000 computer science Ph.D.s per year by 1995. Strengthen the human resource infrastructure for basic research. Support university risk investment in computational science and engineering degree programs. This should be done by expanding the number of universities capable of providing high quality advanced education in computer and computational science and engineering.

Promote at least 10 computational science and engineering degree programs. Sponsor interdisciplinary programs in universities to accelerate the maturing of computational science and engineering subdisciplines.

Upgrade 10 university computer science departments toward the standards of current 10 best. Include facilities for research in high performance computing. Also, upgrade an additional 25 computer science departments to nationally competitive quality.

Provide National Research and Education Network access for every U.S. university and major laboratory. Every university and major laboratory will be connected to the National Research and Education Network through a mid-level network.

Improve facilities available to support basic research and advanced education. High performance computing facilities currently available to researchers are in such demand that there is only limited availability for educational usage in computational science and engineering degree programs. The effective introduction of computational science and engineering techniques into industry requires students to receive exposure to high-performance machines.

Improve ties between computing technology and other disciplines. Many breakthroughs in computational science and engineering applications result from interactions with computer scientists. Correspondingly, computer science, through exposure to the needs of computational science and engineering, is producing technology to address future needs. Funding will be directed to promote these interactions.

Provide access to professional engineering support. Professional engineering staff should be available to basic research groups for assistance in construction and maintenance of large scale prototype systems, including software and hardware. This

3. Program Plan: **Basic Research and Human Resources**

can be accomplished through industrial collaborations or through placement of professional staff in university laboratories.

Responsibilities

Federal agencies historically have supported activities which advance basic research by developing and improving infrastructure for the nation's knowledge and human resource base in computing. The HPC Program will exploit existing mechanisms to meet needs in these areas.

The DOE has established advanced computational science research facilities at several national laboratories and universities. Although the DOE labs already maintain a strong university cooperation program, more needs to be done to provide closer ties with the academic computational science community below the top echelon. For example, an expansion of the summer program for high school students using national facilities would be beneficial in providing interested and trained students to the universities.

The national laboratories are ideal training centers for graduate students in the sciences because of the wealth of experience in solving real world problems. This environment makes a valuable addition to the training of new scientists and should be made available to many more senior graduate students, post-doctoral fellows and young faculty than is currently possible.

The NSF's primary mission is broad support of basic research and human resources in science and engineering. NSF recently reorganized to support a new research directorate, Computer and Information Science and Engineering (CISE), to focus resources on computing as a strategic research area. CISE supports research grants for academic institutional improvement as well as research. The research community supported by CISE will be primary participants in this Program.

Several NSF Centers (Science and Technology Centers, Engineering Research Centers, and Supercomputer Centers) focus on topics central to the HPC Program. These Centers illustrate the type of university-industry and interagency programs which can be employed directly as testbeds and sources of high performance computing technology.

The five NSF National Supercomputer Centers, for example, have provided advanced hardware and software to advance the utility of computational science across an entire spectrum of researchers. More than 11,000 scientists at some 300 institutions have used these facilities during the past few years. The research facilities and advanced experimental systems developed under the Program can be made available broadly to the entire U.S. research community through the National Research and Education Network.

NASA supports leading-edge applications of high performance computing technology. It also supports development of computational science programs in universities.

3. Program Plan:

Basic Research and Human Resources

NASA Institutes (ICASE, RIACS, ICOMP, CESDIS) and Centers of Excellence (CASIS, ICLASS) provide settings at NASA Centers or at Universities where computer scientists and computational scientists can work together using state of the art equipment on a permanent or temporary basis (summers, sabbaticals, etc.) These programs would be for undergraduates, graduate students, postdoctorals, university faculty, and researchers from industry and government.

NASA has supercomputer facilities at several of its field centers (Ames, Goddard, Langley, Lewis, and Marshall). NASA has also established the Numerical Aerodynamics Simulation (NAS) Facility, which is a national facility for aerospace applications which operates not only state-of-the-art supercomputers, but advanced parallel computers like the Connection Machine. NASA has also established a significant Artificial Intelligence Laboratory in the Information Sciences Division at ARC. These facilities are used for a wide range of mathematical, algorithm, systems software, and computer architectural research. These facilities are available to NASA centers, institutes, and grantees, and to the aerospace community. Under this program NASA facilities will be expanded to include scalable testbeds to support interdisciplinary research which combines mathematics, algorithms, systems software, and computer architecture.

NOAA has supercomputer facilities, and has also created generic, broad spectrum workstation design facilities to support the Program for Regional Observing and Forecasting Systems (PROFS). Under this Component, NOAA will expand the opportunities for collaborative research at its facilities for development of algorithms and techniques for large scientific data bases, use of artificial intelligence in data management, and development of climate prediction models.

DARPA provides high performance computing systems for research community use on two scales: small-scale for experimentation, software and algorithm development by computer and computational science research groups, and medium-scale for shared-use facilities intended for access by dozens of groups via the National Research and Education Network. DARPA funding also supports key university and industrial labs for research and advanced development in computer and network architecture, network protocols and management, microsystems design and prototyping, advanced components and packaging, software tools and parallel algorithms.

4. Organization

Leadership of the HPC Program is the responsibility of the Office of Science and Technology Policy. It will be coordinated through the FCCSET Committee on Computer Research and Applications, whose members include representatives of the key agencies. The Committee will work closely with the President's Science Advisor and the various government funding agencies to ensure the continuing success of the Program. The components of the program that implement the Program will be executed by the cognizant agencies. Duties and responsibilities of the Committee include:

- Interagency planning and coordination;
- Policy development and technology assessment;
- Liaison with the industrial and university sectors; and
- Annual reporting of progress to the Office of Scientific and Technology Policy.

A High Performance Computing Advisory Panel will be formed, consisting of eminent individuals from government, industry, and academia. Members of the Advisory Panel will be selected by and will report to the Director of OSTP. The Panel will provide the Director and the Committee with an independent assessment of:

- Progress of the Program in accomplishing its objectives;
- Continued relevance of the Program goals over time;
- Overall balance among the Program components; and
- Success in strengthening U.S. leadership in high performance computing, and integration of these technologies into the mainstream of U.S. science and industry.

A broadly representative industry body will assist in making long-range demand and robustness projections for: high capacity research networks; the spectrum of computer architectures; the adequacy of software development; and the level of the manpower pool. This body will help assure a smooth transition between successive generations of high performance computing systems.

The FCCSET Committee on Computer Research and Applications has established subcommittees that will be responsible for planning, organizing, monitoring and coordinating the components of this Program. This includes liaison with the industrial and academic sectors, and published annual reports.

5. Budget

Budgets for the Program are presented in Table 1. Each budget element corresponds to a key activity in one of the four components of the HPC Program. The activities are described for each component in Section 3 of this plan. The yearly additional funding requested for this Program corresponds to the estimate given in the *HPC Strategy*, with some adjustment to yearly funding levels as a result of more detailed planning and inflation. Significant portions of the Program's funding will be allocated in each of the three participating sectors: universities, industry, and government laboratories.

Currently, the four principal funding agencies are spending about \$500 Million per year on research and development for high performance computing. It is important that this funding continue with coordination by the FCCSET Committee as discussed in this plan, because the ability of the Program to achieve its goals depends upon maintenance of the broad base of computational and computer science and engineering research presently funded by the Federal government.

Preliminary planning estimates suggest that the first year of the program would require an augmentation of \$150 million, which would then grow to an incremental annual level of \$600 million by the fifth year.

Special attention has been devoted to the subcomponents "Early Systems for Evaluation" and "High Performance Computing Research Centers". There is an explicit strategy for investment in emerging high performance computing systems (including associated software) in these activities, to ensure that adequate funding is available. It is intended that the Early Systems for Evaluation budget sustain acquisition of the smallest scale systems which will allow characterization of their potential performance. For systems which prove to have good performance potential, the High Performance Computing Research Centers budget will support scaling these systems up, to demonstrate that potential in the Grand Challenges or other advanced applications. This will reduce risk to both producers of the systems and researchers using them, to provide the necessary incentive for early deployment in the most advanced applications.

The Basic Research and Human Resources component also requires special discussion, because it is funded in two ways. First, ten percent of the Program funding is set aside for this component. Second, it is intended that an additional fifteen percent of the total Program funding in the other three components will consist of basic research, carried out largely in Universities, which will also support the Program goals in Basic Research and Human Resources. Integrating this research with the rest of the Program allows a smooth flow of research from basic ideas through to applications.

Summary of Additional Funds

(Millions of Dollars)

Reference Page	Component	Year 1	Year 2	Year 3	Year 4	Year 5
17	High Performance Computing Systems	55	91	141	179	216
19	Research for Future Generations	11	17	24	32	37
19	System Design Tools	10	18	21	25	25
19	Advanced Prototype Development	22	36	65	86	116
20	Evaluation of Early Systems	12	20	31	36	38
23	Advanced Software Technology and Algorithms	51	90	137	172	212
24	Support for Grand Challenges	9	19	34	43	48
25	Software Components and Tools	15	30	41	60	78
26	Computational Techniques	6	10	18	19	31
26	High Performance Computing Research Centers	21	31	44	50	55
31	National Research and Education Network	30	50	95	105	110
33	Interagency Interim NREN	14	23	55	50	50
34	Gigabits Research and Development	16	27	40	55	60
34	Deployment of Gigabits NREN			(Funding begins after Year 5)		
34	Structured Transition to Commercial Service			(Funding begins after Year 5)		
37	Basic Research and Human Resources	15	25	38	46	59
	NOTE:					
						15% of the other three Components is also committed to this general area
	TOTAL High Performance Computing Program	151	256	411	502	597

Table 1 - Budget Summary by Program Component

ACKNOWLEDGMENTS

Office of Science and Technology Policy guidance was provided by William R. Graham, Tom Rona, Robert Post, and Paul Huray. The Plan Drafting Committee was chaired by David B. Nelson from the Department of Energy; and included J. Mark Pullen, William L. Scherlis, and Stephen L. Squires from the Defense Advanced Research Projects Agency; Donald Austin, Daniel Hitchcock, Thomas Kitchens, and Norman H. Kreisman from the Department of Energy; Paul H. Smith from National Aeronautics and Space Administration; and Melvyn Ciment, Peter Freeman, and Stephen Wolff from the National Science Foundation. Special thanks are due to Sandy Merola and Dennis Hall from the Lawrence Berkeley Laboratory, for editing and production assistance.

APPENDIX A: SUMMARY OF GRAND CHALLENGES FOR WHICH SOLUTION IS LIKELY TO BE POSSIBLE USING SYSTEMS DEVELOPED UNDER THIS INITIATIVE

PREDICTION OF WEATHER, CLIMATE, AND GLOBAL CHANGE. The aim is to understand the coupled atmosphere, ocean, biosphere system in enough detail to be able to make long range predictions about its behavior. Applications include understanding CO₂ dynamics in the atmosphere, ozone depletion, climatological perturbations due to man made releases of chemicals or energy into one of the component systems, and detailed predictions of conditions in support of military missions.

Agencies: DOE, DOD, NASA, NSF, NOAA

CHALLENGES IN MATERIALS SCIENCES. High performance computing has provided invaluable assistance in improving our understanding of the atomic nature of materials. These have an enormous impact on our national economy. A selected list of such materials includes: semiconductors, such as silicon and gallium arsenide and superconductors such as the high T_c copper oxide ceramics that have been shown recently to conduct electricity at about 100 degrees Kelvin.

Agencies: DOD, DOE, NSF, NASA

SEMICONDUCTOR DESIGN. As intrinsically faster materials, such as gallium arsenide are used, a fundamental understanding is required of how they operate and how to change their characteristics. Essential understanding of overlay formation, trapped structural defects, and the effect of lattice mismatch on properties are needed. Currently, it is possible to simulate electronic properties for simple regular systems, however, materials with defects and mixed atomic constituents are beyond present capabilities.

Agencies: DOD, DOE, NSF

SUPERCONDUCTIVITY. The discovery of high temperature superconductivity in 1986 has provided the potential of spectacular energy-efficient power transmission technologies, ultra sensitive instrumentation, and devices using phenomena unique to superconductivity. The materials supporting high temperature superconductivity are difficult to form, stabilize, and use, and the basic properties of the superconductor must be elucidated through a vigorous fundamental research program.

Agencies: DOE, NSF, DOD

STRUCTURAL BIOLOGY. The function of biologically important molecules can be simulated by computationally intensive Monte Carlo methods in combination with NMR of crystallographic data. Molecular dynamics methods are required for the time dependent behavior of such macromolecules. The determination, visualization, and analysis of these 3D structures is essential to the understanding of the mechanisms of enzymic catalysis, recognition of nucleic acids by proteins, antibody/antigen binding, and many other dynamic events central to cell biology.

Agencies: DOE, HHS, NSF

DESIGN OF DRUGS. Predictions of the folded conformation of proteins and of RNA molecules, by computer simulation is rapidly becoming accepted as a useful, and sometimes primary tool in understanding the properties required in drug design.

Agencies: DOE, HHS, NSF

HUMAN GENOME. Comparison of normal and pathological molecular sequences is our current most revealing computational method for understanding genomes, and the molecular basis for disease. To benefit from the entire sequence of a single human will require capabilities for more than three billion subgenomic units, as contrasted with the ten to two hundred thousand units of typical viruses.

Agencies: DOE, HHS, NSF

QUANTUM CHROMODYNAMICS. In high energy theoretical physics, computer simulations of QCD are yielding first principle calculations of the properties of strongly interacting elementary particles. New phenomena have been predicted including; the existence of a new phase of matter, and the quark-gluon plasma. Properties under the conditions of the first microsecond of the big bang, and in the cores of the largest stars have been calculated by simulation methods. Beyond the range of present experimental capabilities, computer simulations of grand unified "theories of everything" have been devised using QCD (Lattice Gauge Theory).

Agencies: DOE, NSF

ASTRONOMY. Data volumes generated by Very Large Array (VLA) or Very Long Baseline Array (VLBA) radio telescopes currently overwhelms the available computational resources. Greater computational power will significantly enhance their usefulness in

SUMMARY OF GRAND CHALLENGES

exploring important problems in radio astronomy, resulting in better return on a major national investment.

Agencies: NASA, NSF

CHALLENGES IN TRANSPORTATION. In the nearer term, substantial contributions to vehicle performance can be made using more approximate physical modeling and reducing the amount of interdisciplinary coupling. Examples include, modeling of fluid dynamical behavior for three dimensional flow-fields about complete aircraft geometries, flow inside of engine turbomachinery, duct flow, and flow about ship hulls.

Agencies: NASA, DOD, DOE, NSF, DOT

VEHICLE SIGNATURE. Reduction of vehicle signature (acoustic and electromagnetic, and thermal characteristics) is critical for low detection military vehicles.

Agencies: NASA, DOD

TURBULENCE. Turbulence in fluid flows impacts the stability and control, thermal characteristics, and fuel performance of virtually all aerospace vehicles. Understanding the fundamental physics of turbulence is requisite to reliably modeling flow turbulence for the analysis of realistic vehicle configuration.

Agencies: NASA, DOD, DOE, NSF, NOAA

VEHICLE DYNAMICS. Analysis of the aeroelastic behavior of vehicles, as well as the stability and ride analysis of vehicles are critical assessments of land and air vehicle performance and life-cycle.

Agencies: NASA, DOD, DOT

NUCLEAR FUSION. Development of controlled nuclear fusion requires understanding the behavior of fully ionized gasses at very high temperatures under the influence of strong magnetic fields in complex three dimensional geometries.

Agencies: DOE, NASA, DOD

EFFICIENCY OF COMBUSTION SYSTEMS. To attain significant improvements in combustion efficiencies requires understanding the interplay between the flows of the various substances involved and the quantum chemistry which causes those substances to react. In some complicated cases the quantum chemistry required to understand the reactions is beyond the reach of current supercomputers.

Agencies: DOE NASA, DOD

ENHANCED OIL AND GAS RECOVERY. This challenge has two parts: to locate as much of the estimated 300 billion barrels of oil reserves

in the US and then to devise economic ways of extracting as much of this as possible. Thus improved seismic analysis techniques as well as improved understanding of fluid flow through geological structures is required.

Agencies: DOE

COMPUTATIONAL OCEAN SCIENCES. The objective is to develop a global ocean prediction model incorporating temperature, chemical composition, circulation, and coupling to the atmosphere and other oceanographic features. This will couple to models of the atmosphere in the effort on global weather as well as having specific implications for physical oceanography.

Agencies: DOD, NASA, NSF, NOAA

SPEECH. Speech research is aimed at providing a communications interface with computers based on spoken language. Automatic speech understanding by computer is a large modeling and search problem in which billions of computations are required to evaluate the many possibilities of what a person might have said within a particular context.

Agencies: NASA, DOD, NSF

VISION. The challenge is to develop human-level visual capabilities for computers and robots. Machine vision requires image signal processing, texture and color modeling, geometric processing and reasoning, as well as object modeling. A competent vision system will likely involve the integration of all of these processes with close coupling

Agencies: NSF, DARPA, NASA

UNDERSEA SURVEILLANCE FOR ASW. The Navy faces a severe problem in maintaining a viable anti-submarine warfare (ASW) capability in the face of quantum improvements in Soviet submarine technology, which are projected to be so substantial that evolutionary improvements in detection systems will not restore sufficient capability to counter their advantages. An attractive solution to this problem involves revolutionary improvements in long-range undersea surveillance which are possible using very high gain acoustic arrays and active acoustic sources for ASW surveillance. These methods will be computationally intensive; even taking advantage of inherent parallelism and judicious design of algorithms, computational demands for the projected post-2000 era submarine threat mandate achieving signal processing computation rates of in excess of a trillion operations per second.

Agencies: DOD

APPENDIX B: GLOSSARY

bits– binary digits (the smallest units of digital information); also an abbreviation for “bits per second”

broadband ISDN (BISDN)– broadband integrated services data network, an evolving standard commercial communications offering which will provide data rates of hundreds of megabits per second

byte– one character of computer storage

common carrier– a regulated commercial company which offers communication services in an open market

flops– abbreviation for floating-point operations per second, a unit which characterizes the performance of a computer for certain scientific and engineering calculations

giga– prefix meaning billion, e.g. “gigaops” means “billion operations per second” and “gigabits” means “billion bits per second”

links– long-distance communications circuits, also known as “trunks”

mega– prefix meaning million, e.g. “megaops” means “millions operations per second” and “megabytes” means “million characters of storage”

mid-level network– a computer network with scope which falls between a nationwide network and a local network, such as one of the state or regional networks

ops– abbreviation for “operations per second”, a general measurement of computer performance

policy-based routing– a computer network function which treats data packets in different ways depending on some policy, for example certain packets may be given high priority, certain others may be rejected as not authorized to use some portion of the network

telescience– science practiced at a distance, using telecommunications

tera– prefix meaning trillion, e.g. “teraops” means “trillion operations per second”

testbed– an configuration intended to allow experimentation with systems in an application environment

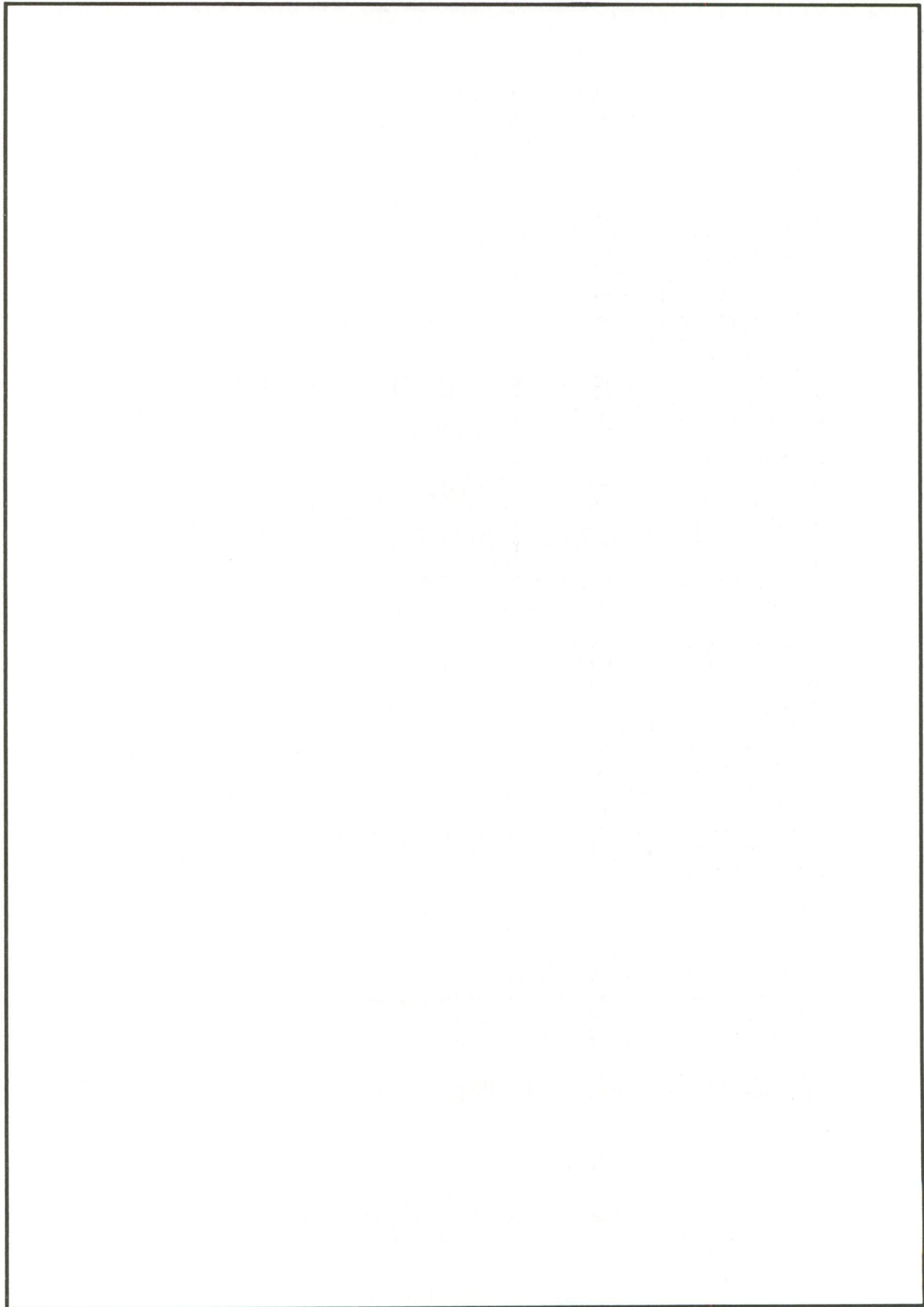
trunks– long-distance communications circuits, also known as “links”

value-added services– services provided in addition to basic communication links (and at extra cost); for example, computer networking using communications provided by a common carrier

**A RESEARCH AND DEVELOPMENT
STRATEGY
FOR
HIGH PERFORMANCE COMPUTING**

Executive Office of the President
Office of Science and Technology Policy
November 20, 1987

APPENDIX C: *HPC Strategy* REPRINT



APPENDIX C: HPC Strategy REPRINT

EXECUTIVE OFFICE OF THE PRESIDENT OFFICE OF SCIENCE AND TECHNOLOGY POLICY WASHINGTON, D.C. 20506

This year the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) Committee on Computer Research and Applications began a systematic review of the status and directions of high performance computing and its relationship to federal research and development. The Committee held a series of workshops involving hundreds of computer scientists and technologists from academia, industry, and government. A result of this effort is the report that follows, containing findings and recommendations concerning this critical issue. It has been sent to the appropriate committees of Congress for their review.

A consistent theme in this report is the need for industry, academia, and government to collaborate and exchange information on future R&D efforts. Partners need to give one another signals as to their intent for future activities, and this report is a necessary first step in that process. The vision it represents must continue to grow. For that reason, I have asked the Committee to initiate the appropriate forums for discussing it further with the computing community.

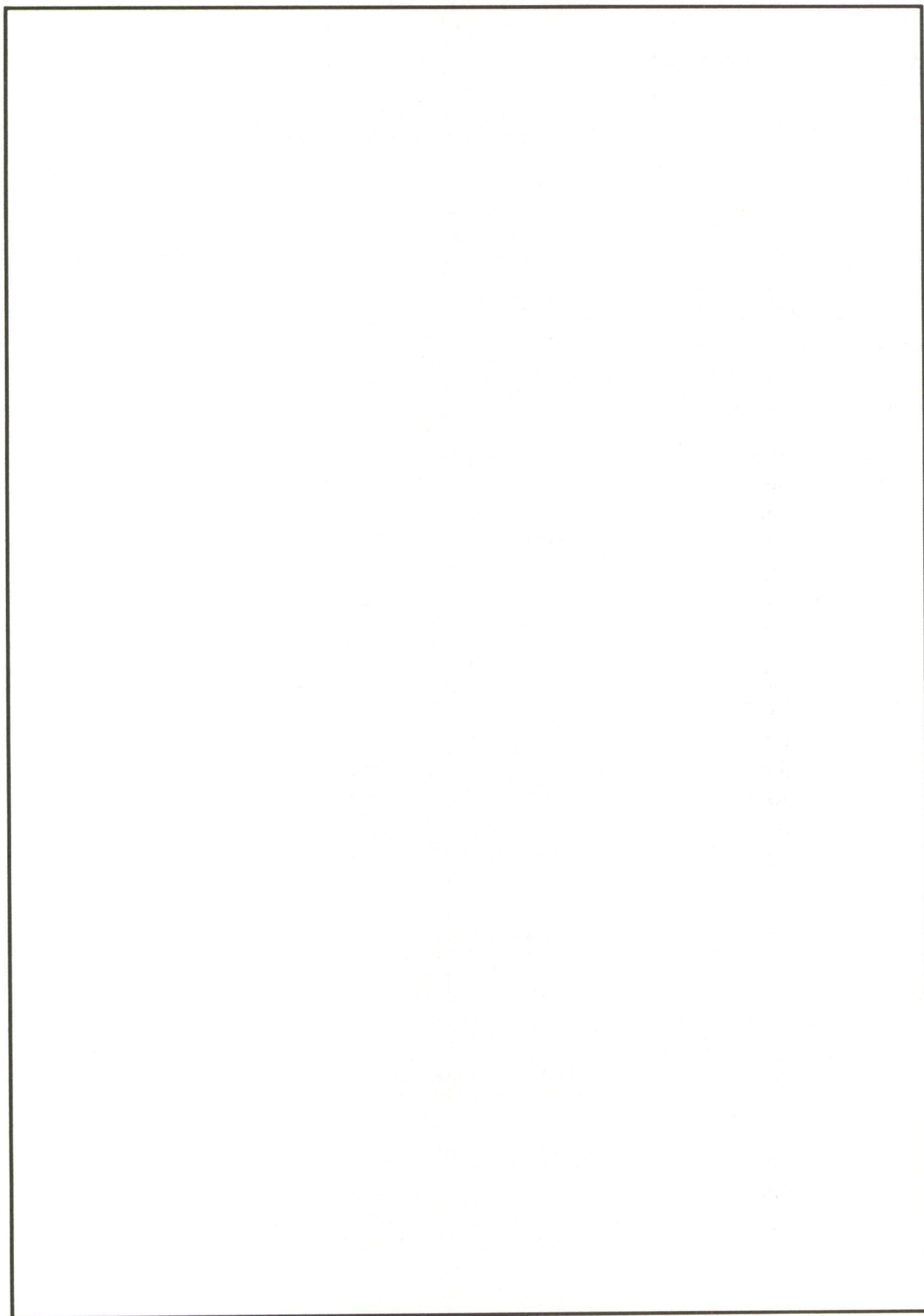
Another theme has come out of this report: within four decades, the field of computer science has moved from a service discipline to a pervasive technology with a rigorous scientific basis. Computer science has become important to our national security and to our industrial productivity, and as such it provides the United States with many opportunities and challenges. Three of those opportunities are addressed in the report's findings and recommendations: High Performance Computers, Software Technology and Algorithms, and Networking. The fourth recommendation involves the Basic Research and Human Resources that will be required to conduct the other initiatives.

One thing is clear: the competition in an increasingly competitive global market cannot be ignored. The portion of our balance of trade supported by our high performance computing capability is becoming more important to the nation. In short, the United States must continue to have a strong, competitive supercomputing capability if it is to remain at the forefront of advanced technology. For that reason the Office of Science and Technology Policy is encouraging activities among the federal agencies together with the academic community and the private sector.



William R. Graham
Science Adviser to the President and
Director, Office of Science and Technology Policy

APPENDIX C: *HPC Strategy* REPRINT



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SUMMARY OF FINDINGS ON COMPUTER RESEARCH AND APPLICATIONS

1. HIGH PERFORMANCE COMPUTERS: A strong domestic high performance computer industry is essential for maintaining U.S. leadership in critical national security areas and in broad sectors of the civilian economy.

- U.S. high performance computer industry leadership is challenged by government supported research and development in Japan and Europe.
- U.S. leadership in developing new component technology and applying large scale parallel architectures are key ingredients for maintaining high performance computing leadership. The first generation of scalable parallel systems is now commercially available from U.S. vendors. Application-specific integrated circuits have become less expensive and more readily available and are beginning to be integrated into high performance computers.

2. SOFTWARE TECHNOLOGY AND ALGORITHMS: Research progress and technology transfer in software and applications must keep pace with advances in computing architecture and microelectronics.

- Progress in software and algorithms is required to more fully exploit the opportunity offered by parallel systems.
- Computational methods have emerged as indispensable and enabling tools for a diverse spectrum of science, engineering, design, and research applications.
- Interdisciplinary research is required to develop and maintain a base of applications software that exploits advances in high performance computing and algorithm design in order to address the "grand challenges" of science and engineering.

3. NETWORKING: The U.S. faces serious challenges in networking technology which could become a barrier to the advance and use of computing technology in science and engineering.

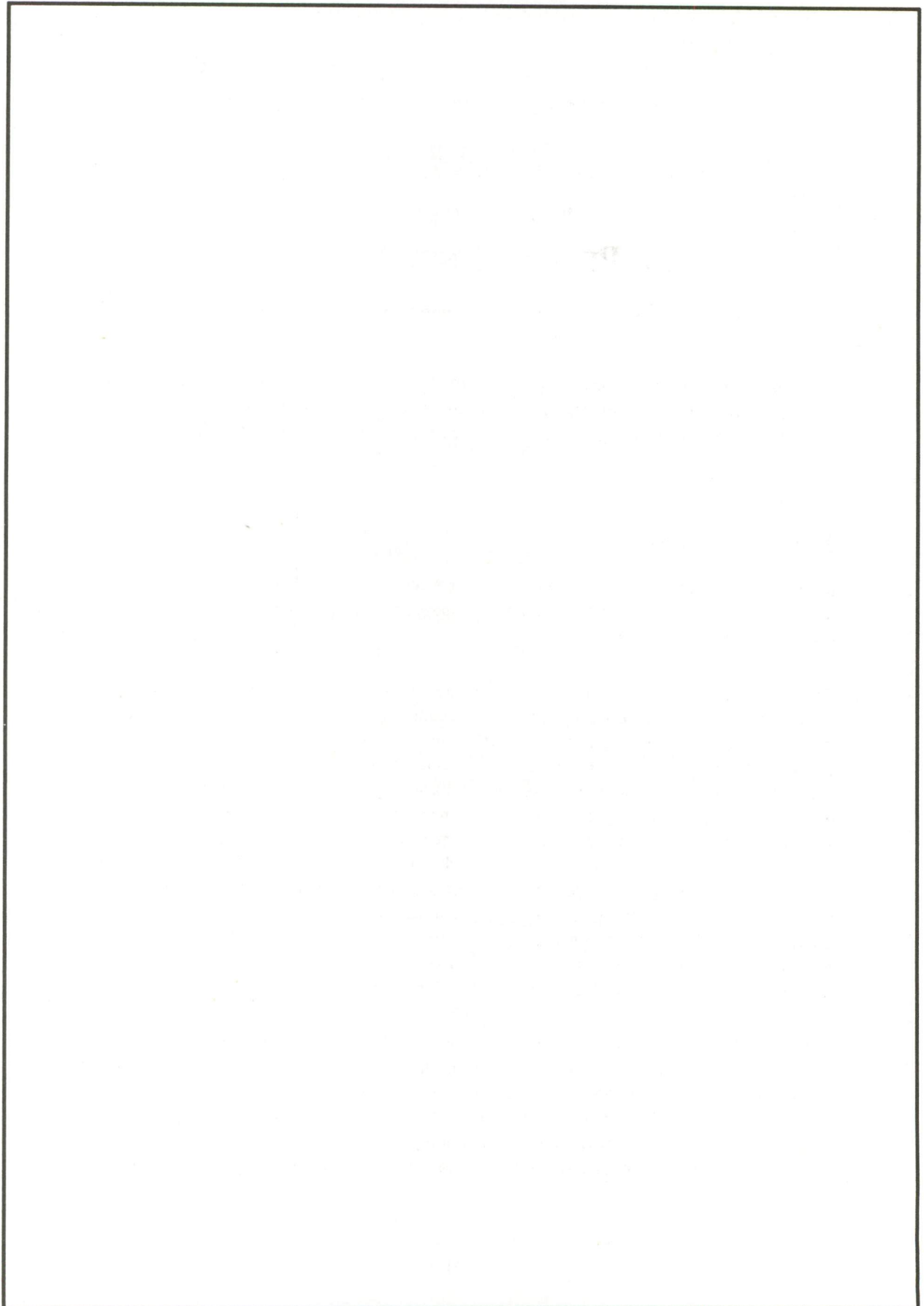
- Current network technology does not adequately support scientific collaboration or access to unique scientific resources. At this time, U.S. commercial and government sponsored networks are not coordinated, do not have sufficient capacity, do not interoperate effectively, and do not ensure privacy.
- Europe and Japan are aggressively moving ahead of the U.S. in a variety of networking areas with the support of concentrated government and industry research and implementation programs.

4. BASIC RESEARCH AND HUMAN RESOURCES: Federal research and development funding has established laboratories in universities, industry, and government which have become the major sources of innovation in the development and use of computing technology.

SUMMARY OF RECOMMENDATIONS FOR A NATIONAL HIGH PERFORMANCE COMPUTING STRATEGY

1. **HIGH PERFORMANCE COMPUTERS:** The U.S. Government should establish a long range strategy for Federal support for basic research on high performance computer technology and the appropriate transfer of research and technology to U.S. industry.
2. **SOFTWARE TECHNOLOGY AND ALGORITHMS:** The U.S. should take the lead in encouraging joint research with government, industry, and university participation to improve basic tools, languages, algorithms, and associated theory for the scientific "grand challenges" with widespread applicability.
3. **NETWORKING:** U.S. government, industry, and universities should coordinate research and development for a research network to provide a distributed computing capability that links the government, industry, and higher education communities.
4. **BASIC RESEARCH AND HUMAN RESOURCES:** Long term support for basic research in computer science should be increased within available resources. Industry, universities, and government should work together to improve the training and utilization of personnel to expand the base of research and development in computational science and technology.

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A RESEARCH AND DEVELOPMENT STRATEGY FOR HIGH PERFORMANCE COMPUTING

High performance computing refers to the full range of supercomputing activities including existing supercomputer systems, special purpose and experimental systems, and the new generation of large scale parallel architectures.

THE CHALLENGE

In the span of four decades, computing has become one of the most pervasive and powerful technologies for information management, communications, design, manufacturing, and scientific progress.

The U.S. currently leads the world in the development and use of high performance computing for national security, industrial productivity, and science and engineering, but that lead is being challenged. Through an increased foreign industrial capability, the U.S. technology lead in computing has diminished considerably in recent years, but the U.S. continues to maintain strength in basic science and technology. The technology is changing rapidly and the downstream rewards for leadership are great. Progress in computing can be accelerated through the continued pioneering of new hardware, software, algorithms, and network technology and the effective transition of that technology to the marketplace. A shared computing research and development vision is needed to provide to government, industry, and academia a basis for cooperative action. The successful implementation of a strategy to attain this vision and a balanced plan for transition from one generation of technology to the next can result in continued strength and leadership in the forthcoming decades.

High performance computing technology has also become essential to progress in science and engineering. A **grand challenge** is a fundamental problem in science or engineering, with broad applications, whose solution would be enabled by the application of the high performance computing resources that could become available in the near future. Examples of grand challenges are: (1) Computational fluid dynamics for the design of hypersonic aircraft, efficient automobile bodies, and

extremely quiet submarines, for weather forecasting for short and long term effects, efficient recovery of oil, and for many other applications; (2) Electronic structure calculations for the design of new materials such as chemical catalysts, immunological agents, and superconductors; (3) Plasma dynamics for fusion energy technology and for safe and efficient military technology; (4) Calculations to understand the fundamental nature of matter, including quantum chromodynamics and condensed matter theory; (5) Symbolic computations including speech recognition, computer vision, natural language understanding, automated reasoning, and tools for design, manufacturing, and simulation of complex systems. Many of these could be considerably advanced by the use of computer systems capable of trillions of operations per second.

THE STRATEGY

A **High Performance Computing Strategy**, involving close coordination of existing programs and augmented effort, is required to address this national challenge. This strategy involves the coordinated pursuit of computing technology goals through joint efforts of government, industry, and academia. The strategy will have impact in clarifying and focusing the direction of Federally-funded computing research, which continues to be the major source of innovation for computing technology and a primary catalyst for industrial development. Government support should be highly leveraged with resources provided by industry participants. To be effective, the strategy should also be defined and continually updated in cooperation with industry and academia by making them participants in developing and implementing a shared vision of the future to ensure continued U.S. leadership.

The high performance computing strategy is designed to sustain and focus basic Federally-funded research and promote the transfer of basic science from the laboratory to U.S. industrial development and finally to the marketplace. Technology development will be encouraged as appropriate to meet immediate needs as well as to create a foundation for long term leadership. Strong emphasis will be placed on continued transfer of the results of government funded R&D to industry and on cooperation with industry to insure the continued strength of American high technology trade in the international marketplace.

The basic elements of the strategy are research and development programs in high performance computer architecture, in custom hardware, in software and algorithms, and in networking technology, all supported by a basic research foundation. In each of these areas, major opportunities exist that require coordinated support and management, building on existing government programs. Access to high performance computing is essential for providing scientists and engineers at research institutions throughout the country with the ability to use the most advanced computers for their work. The strategy needs to concurrently address the appropriate Federal role in each

of the basic elements of the R&D process—basic research, applied research, and industrial development—in order to meet long term, intermediate, and short term technology development goals. Explicit attention must be directed to the flow of technology from basic to applied areas and to the marketplace, as well as back into the research community to create the next generation of computing infrastructure, achieving a cumulative effect. Technology developments within individual element areas will contribute extensively to other activities. Simultaneous and coordinated pursuit of the areas is therefore an important element of the strategy.

CURRENT STATUS AND TRENDS

- **High performance computing systems.** Improvements in materials and component technology are rapidly advancing computer capability. Memory and logic circuits are continuing to improve in speed and density, but as fundamental physical limits are approached, advances are being sought through improved computer architectures, custom hardware, and software. Computer architecture has begun to evolve into large scale multiple processor systems, and in the past four years a first generation of scalable parallel systems has progressed from the research laboratory to the marketplace. Scalable architectures provide a uniform approach that enables a wide range of capacity, from workstations to very high performance computers. Application-specific integrated circuits, such as for real-time signal processing, are being incorporated into special purpose computers.

At current performance levels our ability to model many important science, engineering, and economic problems is still limited. Formulations of computational models presently exist that for realistic solutions would require speeds of teraflops (trillions of floating point operations per second) and equivalent improvement in memory size, mass storage, and input/output systems. In addition, symbolic processing is complementing and enhancing numeric approaches. Achievement of this performance level in the next 5 years appears to be a feasible goal, based on credible extrapolations of processor capability, number of processors, and software sophistication. In developing the new architectural approaches, however, careful collaboration will be required with the applications community to assess the various approaches and to achieve transition to the new approaches where appropriate. As transitions are made, the high performance computing industry should strive to maintain its continued leadership and competitiveness.

- **Software technology and algorithms.** As high performance computing systems evolve and become more critical in science, engineering, and other applications domains, software technology becomes an increasingly central concern. As experienced in many U.S. space and defense programs, for example, software can become the dominant computational cost element in large systems because of the need to support evolution throughout the system life cycle from design and

development to long term maintenance and transition to the next generation. Future software environments and tools should support the development of trustworthy systems capable of evolution, while increasing productivity of developers and users of the systems. Effective exploitation of the performance potential of the emerging parallel systems poses a special challenge both to software and to algorithm design.

High performance computing offers scientists and engineers the opportunity to use computer models to simulate conditions difficult or impossible to create and measure in the laboratory. This new paradigm of computational science and engineering offers an important complement to traditional theoretical and experimental approaches, and it is already having major impact in many areas. New approaches combining numeric and symbolic methods are emerging. The development of new instruments and data generation methods in fields as diverse as genetics, seismology, and materials accelerates demand for computational power. In addition, the opportunity is created to coordinate and focus effort on important grand challenges, such as computational fluid dynamics, weather forecasting, plasma dynamics, and other areas.

- **Computer network technology.** A modern high speed research network is one of the elements needed to provide high performance distributed computation and communication support for research and technology development in government, academia, and industry. A coordinated research network based on very high bandwidth links would enable the creation of large-scale geographically distributed heterogeneous systems that link multiple high performance workstations, databases, data generation sources, and extremely high performance servers as required, in order to provide rapid and responsive service to scientists and engineers distributed across the country. The existing national network is a collection of loosely coupled networks, called an internet, based on concepts pioneered in the U.S.

Technical issues being addressed include utilization of fiber optics to improve performance for the entire research and higher education enterprise of the nation. An additional issue of pressing concern, particularly within the governmental and industrial sectors, is that of computer and network security to ensure privacy and trustworthiness in a heterogeneous network environment. At present, responsibility for privacy and the assurance of trust are vested principally in the computers and switching nodes on the network. Further research, already actively underway, is urgently needed to develop models, methodology, algorithms and software appropriate to the scale of a coordinated research network.

● **Basic research and human resources in Computer and Computational Science.** Federal funding has historically been, and will likely remain, a major source of support for important new ideas in computing technology. Carefully managed and stable funding is required to maintain vigorous research in computer and computational science and sufficient growth in computer science manpower. It is important to maintain the strength of the existing major research centers and to develop new research activity to support the growth in computer and computational science. Interactions should be fostered among academia, industry, and national laboratories to address large problems and to promote transfer of technology. In the longer term, enhancement of the computing technology base will have significant impact in productivity, efficiency, and effectiveness of government, industry, and the research community.

IMPACT

Computing technology is vital to national security. Advanced computer systems and software are now integral components in most major defense, intelligence, and aerospace systems. Computing technology has a central role in energy research, oil exploration, weapons research, aircraft design, and other national security technology areas.

Major advances in science and engineering have also accrued from recent improvements in supercomputing capability. The existence of machines with hundred megaflop (hundreds of millions of floating point operations per second) speed and multimillion word memories has allowed, for the first time, accurate treatment of important problems in weather prediction, hydrodynamics, plasma physics, stress analysis, atomic and molecular structure, and other areas. The emerging machines with 1 to 10 gigaflop (billions of flops) speed and 100 to 300 million word memories are expected to produce comparable advances in solving numeric and symbolic problems.

Many of these advances in science and engineering are the result of the application of high performance computing to execute computational simulations based on mathematical models. This approach to science and engineering is becoming an important addition to traditional experimental and theoretical approaches. In applications such as the National Aerospace Plane, supercomputing provides the best means to analyze and develop strategies to overcome technical obstacles that determine whether the hypersonic vehicle can fly beyond speeds of Mach seven, where wind tunnels reach their maximum capability. The list of applications for which supercomputing plays this kind of role is extensive, and includes nearly all high-technology industries. The extent of its usage makes supercomputing an important element in maintaining national competitiveness in many high technology industries.

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The high performance computing strategy will have impact in many sectors of the economy. Nearly all sectors of advanced industry are dependent on computing infrastructure. Any improvement in computing capability will have substantial leveraged impact in broad sectors, particularly as applications software increases in power and sophistication.

The computer hardware industry alone amounted to \$65 billion in 1986, and U.S. technical market dominance, long taken for granted, is now challenged in this and other critical areas, including networking, microsystems and custom high-performance integrated circuit technology. Foreign investment in computing research and technology has grown considerably in the last decade.

As stated in the report of the White House Science Council, *Research in Very High Performance Computing*, November 1985, "The bottom line is that any country which seeks to control its future must effectively exploit high performance computing. A country which aspires to military leadership must dominate, if not control, high performance computing. A country seeking economic strength in the information age must lead in the development and application of high performance computing in industry and research."

BACKGROUND

The Federal Coordinating Council on Science, Engineering and Technology (FCCSET) was established by Congress under the Office of Science and Technology Policy (OSTP) to catalyze interagency consideration of broad national issues and to coordinate various programs of the Federal government. The FCCSET in turn, established a series of committees, with interagency participation to assess and recommend action for national science and technology issues. The committees have become recognized as focal points for interagency coordination activity, addressing issues that have been identified by direct requests through the OSTP and indirect requests by member agencies (such as the NSF requirement to provide an update to the Lax Report on Large Scale Computing in Science and Engineering). These studies have enabled the FCCSET Committee on Computer Research and Applications to develop a national view of computing technology needs, opportunities, and trends.

From its inception, the FCCSET Committee on Supercomputing (the original name of this committee) was chartered to examine the status of high performance computing in the U.S. and to recommend what role the Federal Government should play regarding this technology. The committee issued two reports in 1983 that provided an integrated assessment of the status of the supercomputer industry and recommended government actions. The FCCSET Committee on Computer Research and Applications concluded that it would be proper to include an update of the earlier reports to address the changes that have occurred in the intervening period as a complement to the technical

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reports. The review was based upon periodic meetings with and site visits to supercomputer manufacturers and consultation with experts in high performance scientific computing. White papers were contributed to this report by industry leaders and supercomputer experts. The report was completed in September 1987 and its findings and recommendations are incorporated in the body of this report.

In developing the recommendations presented in this report, the FCCSET Committee reviewed findings and recommendations from a variety of sources, including those mentioned above. A related activity has been the preparation by the White House Science Council (WHSC) Committee on Research in Very High Performance Computing of the report *Research in Very High Performance Computing*, November 1985. The WHSC Committee, composed of respected individuals from academia, industry, and government, made recommendations related to the issues more recently addressed by the FCCSET Committee. In the areas addressed by both committees, there is a significant consistency of recommendations, and, indeed, progress in recent months further strengthens the case for the recommendations. The convergence of views expressed in the many reports, the strong interest in many sectors of government in developing a policy, the dramatic increase in foreign investment and competitiveness in computing and network technology, and the considerable progress in computing technology development worldwide are all indicators of the urgency of developing and implementing a strategy for nationwide coordination of high performance computing under the auspices of the government.

One of the of the direct requests that this report responds to is in Public Law 99-383, August 21, 1986, in which Congress charged the Office of Science and Technology Policy to conduct a study of critical problems and of current and future options regarding communications networks for research computers, including supercomputers, at universities and federal research facilities in the United States. The legislation asked that requirements for supercomputers be addressed within one year and requirements for all research computers be addressed within two years. Dr. William R. Graham, Director of the Office of Science and Technology Policy, subsequently charged the Federal Coordinating Council on Science Engineering and Technology (FCCSET) Committee on Computer Research and Applications to carry out the technical aspects of the study for OSTP.

It was recognized by the FCCSET Committee on Computer Research and Applications that networking technology needs to be addressed in the context of the applications of computing and the sources of computing power that are interconnected using the network technology. This report, therefore, presents an integrated set of findings and recommendations related to Federal support for computer and related research.

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Three subcommittees carried out the work. Each of these committees contributed to the Findings and Recommendations contained in this report. The result is an integrated set of recommendations that addresses the technical areas.

- **The Subcommittee on Computer Networking, Infrastructure, and Digital Communications** invited experts in government, industry and academia to write white papers on networking trends, requirements, concepts applications, and plans. A workshop involving nearly 100 researchers, network users, network suppliers, and policy officials was held in San Diego, California in February 1987 to discuss the white papers and to develop the foundation for the report. Workshop leaders and other experts later met in Washington to summarize the workshop discussions and focused on six topics: access requirements and future alternatives, special requirements for supercomputer networks, internet concepts, future standards and services requirements, security issues, and the government role in networking. As a result of this work, the participants recommended that no distinction should be made between networks for supercomputers and other research computers and that the final report to the Congress should address networks generally. The requirements for both supercomputers and for other research computers are, therefore, addressed in this report.
- **The Subcommittee on Science and Engineering Computing** assessed computing needs related to computational science and engineering. The committee focused its deliberations on requirements for high performance computing, on networking and access issues, and on software technology and algorithms. Under the auspices of the Society for Industrial and Applied Mathematics (SIAM), and with the support of NSF and DOE, a workshop involving 38 recognized leaders from industry, academia, and national laboratories was held at Leesburg, Virginia in February 1987 on research issues in large-scale computational science and engineering. This workshop focused on advanced systems, parallel computing and applications. As a result of the workshop report, recommendations were made related to the role of computing technology in science and engineering applications.
- **The Subcommittee on Computer Research and Development** assessed the role of basic research, the development of high performance computing technology, and issues related to software technology. Contributing to this activity were two workshops. The National Science Foundation (NSF) Advisory Committee for Computer Research reviewed the field and produced an Initiatives Report in May 1987. This report recommended investment in three areas, including parallel systems and software technology. In September 1987, the Defense Advanced Research Projects Agency (DARPA) held a workshop on advanced computing technology in Gaithersburg, Maryland involving 200 researchers from academia, industry, and government. The workshop focused on large-scale parallel systems and software approaches to achieving high performance computing.

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An important result of the activity of the FCCSET Committee on Computer Research and Applications and its subcommittees is that increased coordination among the Government elements is necessary to implement a strategy for high performance computing. The findings and recommendations presented here represent a consensus reached among the subcommittees and convey the powerful and compelling vision that emerged. As a result of this process, the next step would be for the members of the Committee on Computer Research and Applications to develop a plan to help ensure that the vision is shared between government, academia, and American industry. Subsequently, the Committee should develop an implementation plan for Federal government activities, including a detailed discussion of overall priorities.

1. HIGH PERFORMANCE COMPUTERS

- **FINDING:** A strong domestic high performance computer industry is essential for maintaining U.S. leadership in critical national security areas and in broad sectors of the civilian economy.

U.S. prominence in technology critical to national defense and industrial competitiveness has been based on leadership in developing and exploiting high performance computers. This preeminence could be challenged by dependency upon other countries for state of the art computers. Supercomputer capability has contributed for many years to military superiority. In addition, industrial applications now constitute more than half of the supercomputer market and are an important factor in U.S. industrial competitiveness. However, continued progress in computational science and engineering will depend in large part on the development of computers with 100 to 1000 times current capability for important defense, scientific, and industrial applications. These applications are represented by the grand challenges.

- U.S. high performance computer industry leadership is challenged by government supported research and development in Japan and Europe.

The U.S. currently leads the world in research, development, and use of supercomputers. However, this leadership faces a formidable challenge from abroad, primarily from the Japanese. The 1983 FCCSET report stated that "The Japanese have begun a major effort to become the world leader in supercomputer technology, marketing, and applications." Most of the analyses and projections advanced in support of that statement have proven to be accurate.

Japanese supercomputers have entered the marketplace with better performance than expected. Japanese supercomputer manufacturers have attained a high level of excellence in high speed, high density logic and memory microcircuits required for advanced supercomputers. As a result, some U.S. computer manufacturers are dependent on their Japanese competitors for sole supply of critical microcircuits. Japanese manufacturers, universities, and government have demonstrated the ability to cooperate in developing and marketing supercomputers as well as in advancing high performance computing. Recent successes in dominating related high-technology markets underscore their financial, technical, and marketing capability.

- U.S. leadership in developing new component technology and applying large scale parallel architectures are key ingredients for maintaining high performance computing leadership. The first generation of scalable parallel systems is now commercially available from U.S. vendors. Application-specific integrated circuits have become less expensive and more readily available and are beginning to be integrated into high performance computers.

The current generation of supercomputers achieve their performance through the use of the fastest possible individual components, but with relatively conservative computer architectures. While these computers currently employ up to eight parallel processors, their specific architectures cannot be scaled up significantly. Large scale parallel processing, in which the computational workload is shared among many processors, is considered to be the most promising approach to producing significantly faster supercomputers. The U.S. is currently the leader in developing new technology as well as components. However, exploiting these techniques effectively presents significant challenges. Major effort will be required to develop parallel processing hardware, algorithms, and software to the point where it can be applied successfully to a broad spectrum of scientific and engineering problems.

Government funded R&D in universities and industry has focused on an approach to large-scale parallelism that is based on aggressive computer architecture designs and on high levels of circuit integration, albeit with somewhat slower individual components. Unlike current supercomputers, the resulting systems employ 100s to 10,000s of processors. Equally important, these architectures are scalable to higher levels of parallelism with corresponding increase in potential performance.

The first generation of scalable parallel systems is now commercially available from U.S. vendors. These systems have demonstrated high performance for both numeric and non-numeric, including symbolic processing. Comparable systems do not yet exist outside the U.S. The second generation, with higher speed individual components and more parallelism, is already in development here. Experience with these systems has shown that, even with existing software, they are effective for certain classes of problems. New approaches to software for these large-scale parallel systems are in the process of emerging. These approaches suggest that parallel architecture may be effective for wide classes of scientific and engineering problems. An important benefit of the scalable architectures is that a single design, with its attendant components and software, may prove to be useful and efficient over a performance range of 10 to 100 or more. This allows one design to be used for a family of workstations, mini-supercomputers, and supercomputers.

- **RECOMMENDATION:** The U.S. Government should establish a long range strategy for Federal support for basic research on high performance computer technology and the appropriate transfer of research and technology to U.S. industry.

The program should build upon existing government supported efforts. However, government funding should not be viewed as a substitute for private capital in the high performance computer marketplace. A primary objective is to ensure continued availability of domestic sources for high performance computers that are required for Federal programs, both civilian and defense. These actions should include:

- Government should support, when appropriate for mission requirements, the acquisition of prototype or early production models of new high performance computers that offer potential for improving research productivity in mission areas. These computers could be placed in centers of expertise in order to allow sophisticated users to share initial experiences with manufacturers and other users, and to develop software to complement the vendor's initial offerings. These initial acquisitions should not require the vendor to supply mature operating systems and applications software typical of production computers. However, a criterion for acquisition should be that the hardware designs reflect a sensitivity to software issues, and that the computer has the potential for sustained performance in practical applications that approaches the peak hardware performance.
- Government agencies should seek opportunities to cooperate with industry in jointly funded R&D projects, concentrating especially on those technologies that appear scalable to performance levels of trillions of operations per second (teraops) for complex science, engineering, and other problems of national importance. Systems are needed for both numeric and symbolic computations.

However, since government mission requirements typically exceed those of industrial applications, cooperating with industry in R&D for computers to meet these missions will help to assure that the necessary computers are available. It will also drive supercomputer development at a faster pace than would be sustained by commercial forces alone, an important factor retaining and increasing U.S. leadership in this area.

- Government agencies should fund basic research to lay the foundation for future generations of high performance computers. Steps should be taken to ensure that development of state-of-the-art computers continues to be monitored for appropriate export controls.

2. SOFTWARE TECHNOLOGY AND ALGORITHMS

- **FINDING:** Research progress and technology transfer in software and applications must keep pace with advances in computing architecture and microelectronics.

- Progress in software and algorithms is required to more fully exploit the opportunity offered by parallel systems.
- Computational methods have emerged as indispensable and enabling tools for a diverse spectrum of science, engineering, and design research and applications.
- Interdisciplinary research is required to develop and maintain a base of applications software that exploits advances in high performance computing and algorithm design in order to address the "grand challenges" of science and engineering.

A **grand challenge** is a fundamental problem in science and engineering, with broad application, whose solution will be enabled by the application of the high performance computing resources that could become available in the near future.

As high performance computing systems evolve and are applied to more challenging problems, it is becoming increasingly clear that advances in software technology and applications are essential to realize the full performance potential of these systems. Software development, analysis, and adaptation remain difficult and costly for traditional sequential systems. Large scale complex systems including parallel systems pose even greater challenges. Market pressures for the early release of new computing system products have created a tradition of weak systems software and inadequate programming tools for new computers.

Current approaches to software development provide only limited capabilities for flexible, adaptable, and reusable systems that are capable of sustained and graceful growth. Most existing software is developed to satisfy nearer term needs for performance at the expense of these longer term needs. This is particularly the case for applications in which specific architectural features of computers have been used to obtain maximum performance through low level programming techniques. The lack of portability of these programs significantly raises the cost of transition to newer architectural approaches in many applications areas. Approaches are beginning to emerge in the research community that have a potential to address the reuse and portability problems.

Experiments with parallel computers have demonstrated that computation speeds can increase almost in direct proportion to the number of processors in certain applications. Although it is not yet possible to determine in general the most

efficient distribution of tasks among processors, important progress has nonetheless been made in the development of computational models and parallel algorithms for many key problem areas.

Access to advanced computing systems is an important element in addressing this problem. Experience has shown that the quality of systems and applications software increases rapidly as computing systems are made more available. Initial generic operating systems and extensions to existing programming languages can provide access through coupling high performance computers with existing workstations using either direct or network connections. However, in order to achieve the full potential impact of large scale parallel computing on applications, major new conceptual developments in algorithms and software are required.

The U.S. leads in many areas of software development. The Japanese, however, also recognize the need for high quality software capability and support in order to develop and market advanced machines. They have demonstrated the ability to effectively compete, for example in the area of sophisticated vectorizing compilers.

The U.S. will need to encourage the collaboration of computer scientists, mathematicians, and the scientists in critical areas of computing applications in order to bring to bear the proper mix of expertise on the software systems problem. Such collaboration will be enhanced by network technology, which will enable geographically dispersed groups of researchers to effectively collaborate on "grand challenges." Critical computer applications include problems in fluid dynamics, plasma physics, elucidation of atomic and molecular structure, weather prediction, engineering design and manufacturing, computer vision, speech understanding, automated reasoning, and a variety of national security problems.

- **RECOMMENDATION:** The U.S. should take the lead in encouraging joint research with government, industry, and university participation to improve basic tools, languages, algorithms, and associated theory for the scientific “grand challenges” with widespread applicability.

Software research should be initiated with specific focus on key scientific areas and on technology issues with widespread applicability. This research is intended to accelerate software and algorithm development for advanced architectures by increased early user access to prototype machines. It would also provide settings for developing advanced applications for production machines. Software technology needs to be developed in real problem contexts to facilitate the development of large complex and distributed systems and to enable transition of emerging parallel systems technology into the computing research community and into the scientific and engineering applications communities.

As part of a mixed strategy, longer term and more basic software problems of reliability and trust, adaptability, and programmer productivity must continue to be addressed. Languages and standards must be promoted that permit development of systems that are portable without sacrificing performance.

In applications areas including computational science and engineering, technology should be developed to support a smooth transition from the current software practice to new approaches based on more powerful languages, optimizing compilers, and tools supported by algorithm libraries. The potential of combining symbolic and numeric approaches should be explored. Progress in these areas will have significant impact on addressing the “grand challenges” in computational science and engineering. Although there are many pressing near term needs in software technology, direct investment in approaches with longer term impact must be sustained if there is to be significant progress on the major challenges for software technology while achieving adequate system performance.

Applications include (1) distributed access to very large databases of scientific, engineering, and other data, (2) high bandwidth access to and linking among shared computational resources, (3) high bandwidth access to shared data generation resources, (4) high bandwidth access to shared data analysis resources, such as workstations supporting advanced visualization techniques.

3. NETWORKING

- **FINDING:** The U.S. faces serious challenges in networking technology which could become a barrier to the advance and use of computing technology in science and engineering.
 - Current network technology does not adequately support scientific collaboration or access to unique scientific resources. U.S. commercial and government sponsored networks presently are not coordinated, do not have sufficient capacity, do not interoperate effectively, and do not ensure privacy.
 - Europe and Japan are aggressively moving ahead of the U.S. in a variety of networking areas with the support of concentrated government and industry research and implementation programs.

Computer network technology provides the means to develop large scale distributed approaches to the collaborative solution of computational problems in science, engineering, and other applications areas. Today, researchers sharing a local area network are able to exploit nearly instantaneous communication and sharing of data, creating an effect of linking their workstations and high performance servers into a single large scale heterogeneous computing facility. This kind of capability is now appearing in larger scale campus-wide computer networks, enabling new forms of collaboration. National networks, on the other hand, have low capacity, are overloaded, and fail to interoperate successfully. These have been expanded to increase the number of users and connections but the performance of the underlying network technology has not kept pace with the increased demands. Therefore, the networks which in the 1970s had significant impact in enabling collaboration, are now barriers. Only the simplest capabilities, such as electronic mail and small file transfers, are now usable. Capacity, for example, is orders of magnitude less than the rates required, even if the network is used only for graphics.

Other countries have recognized the value of national computing networks, and, following the early U.S. lead, have developed and installed national networks using current technology. As a result, these countries are now much better prepared to exploit the new opportunities provided by distributed collaborative computing than the U.S. is at the present time. The basic technologies for later generations are also being developed in the U.S., but there have been no major efforts to apply them to address the needs.

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A longer term goal is the creation of large scale geographically distributed heterogeneous systems that link multiple superworkstations and high performance supercomputers to provide service to scientists and engineers distributed across the country. A well-coordinated national network could link these resources together when required on an *ad hoc* basis to provide rapid response to computational needs as they arise. This could reduce the number of sites needed for the physical presence of supercomputers. Present access to computer networks by researchers is dependent upon individual funding or location. There is unnecessary duplication in the links from various agencies to each campus. The development of improved networking facilities could greatly stimulate U.S. research and provide equitable access to resources.

Many scientific research facilities in the U.S. consist of a single, large, and costly installation such as a synchrotron light source, a supercomputer, a wind tunnel, a particle accelerator, or a unique database. These facilities provide the experimental apparatus for groups of scientific collaborators located throughout the country. Wide area networks are the logical mechanism for making data from such facilities more easily accessible nationwide. An important issue is that of computer and network security to ensure privacy and trustworthiness in a heterogeneous network environment. At present, responsibility for privacy and the assurance of trust are vested principally in the computers and switching nodes on the network.

Existing government-supported wide-area networks include ARPANET, HEPNET, MFENET, NSFNET, NASNET, MILNET, and SPAN, as well as private and commercial facilities such as TYMNET, TELENET, BITNET, and lines leased from the communication carriers. Longer-range estimates vary, but it is expected that by the year 1995 the nation's research community will be able to make effective use of a high capacity national network with capacity measured in billions of bits per second. Without improved networks, speed of data transmission will be a limiting factor in the ability of researchers to carry out complex analyses. The digital circuits most widely available today with transmission speeds of 56 kilobits per second (kb/s) are impediments to leading edge research and to optimal remote high performance computer use.

Point-to-point connections require interconnects through multiple vendors with cumulative costs. Greater network speed can reduce the time required to perform a given experiment and increase both the volume of data and the amount of detail that can be seen by researchers. Scientists accessing supercomputers would benefit because access speed is often critical in their work. Improved functionality frees scientists to concentrate directly on their experimental results rather than on operational details of the network. Increased network size extends these opportunities to thousands of individuals at smaller academic institutions throughout the nation. These modernization measures would significantly enhance the nation's position in scientific research. A national network would help maintain the U.S. leadership position in computer architectures,

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microprocessors, data management, software engineering, and innovative networking facilities, and promote the development of international networking standards based on U.S. technology.

Integrated Systems Digital Networks (ISDN—voice and data) have been installed abroad on a national or regional scale. Research abroad is being conducted on service up to 1 Gb/s. Within the next five years, Integrated Services Digital Network (ISDN) circuits ranging from 64 kb/s to 1.5 Mb/s will be available in the larger metropolitan areas of the U.S. However, these services will fall short of the requirements for computer networks. By 1988 more than fifty Campus Area Networks will be operational at speeds approaching 100 Mb/s. Wide area networks operating at 1.5 Mb/s or less will not be able to handle the data volume expected.

Japan and Europe have extensive efforts with experimental nets in intermediate (40Mb) and high (gigabit) range. Japan is studying operational aspects of fiber nets using their national research network as a testbed, which includes exploring the feasibility of fiber optic services to residences.

To estimate the network bandwidth needed to support research at a major installation, the kinds and volume of traffic that would be used have been estimated at a representative campus, extrapolated ten years into the future. Three models were used to compute three independent estimates of the requirements for bandwidth needed by type of work, information needs by type of user, and information flowing at the installation boundary. In each model, the peak bandwidth was estimated for each type of service. For example, in the Task model, the need is dominated by that of at least one researcher to receive full color and full-motion high resolution images. A high-resolution color image contains about 30 megabits of information, so that a display rate of 30 frames per second requires a bandwidth of nearly one gigabit per second (Gb/s). In the User model, a research university with 35,000 students and 3,000 faculty and research staff using a mix of bandwidths again requires an aggregate bandwidth of approximately one Gb/s. In the Edge of the Installation model, bandwidth is estimated by the types of remote facilities being accessed and the expected number of simultaneous users; typical facilities include particle accelerators, supercomputers, and centers for imaging and/or animation. The aggregate bandwidth needed is one Gb/s. Thus three independent means of estimating bandwidth arrive at nearly the same requirement for a large research installation, and one Gb/s can confidently be used as a lower bound on the bandwidth of a national research network.

- **RECOMMENDATION:** U.S. government, industry, and universities should coordinate research and development for a research network to provide a distributed computing capability that links the government, industry, and higher education communities.

A research network should be established in a staged approach that supports the upgrade of current facilities and development of needed new capabilities. Achievement of this goal would foster and enhance the U.S. position of world leadership in computer networking as well as provide infrastructure for collaborative research. The FCCSET Committee on Computer Research and Applications should provide a forum for interagency cooperations. Elements of the plan should include:

- *Stage 1.* Upgrade existing facilities in support of a transition plan to the new network through a cooperative effort among major government users. The current interagency collaboration in expanding the Internet system originated by DARPA should be accelerated so that the networks supported by the agencies are interconnected over the next two years.
- *Stage 2.* The nation's existing networks that support scientific research should be upgraded and expanded to achieve data communications at 1.5 Mb/sec for 200 to 300 U.S. research institutions.
- *Stage 3.* Develop a system architecture for a national research network to support distributed collaborative computation through a strong program of research and development. A long-term program is needed to advance the technology of computer networking in order to achieve data communication and switching capabilities to support transmission of three billion bits per second (3 Gb/s) with deployment within fifteen years.
- Develop policy for long term support and upgrading of current high performance facilities, including timetables for backbone and connection development, industry participation, access, agency funding, tariff schedules, network management and administration. Support should be given to the development of standards and their harmonization in the international arena.

Until the national research network can replace the current system, existing networks should be maintained and modified as they join the national network. Remedial action should be initiated as soon as possible. Upgrading the backbone to at least 1.5 Mb/s should be accomplished by 1990. This will ensure that the new generation of high performance computing can be effectively interconnected.

Industry should be encouraged to participate in research, development, and deployment of the national research network. Telecommunication tariff schedules

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which have been set for voice transmission should be reviewed in light of the requirements for transmission of data through computer networking.

Prompt effective coordination is needed to increase user participation in the standards development process, to get requirements for standards expressed early in the development process, and to speed the implementation of standards in commercial off-the-shelf products. It is essential that standards development be carried out within the framework of overall systems requirements to achieve interoperability, common user interfaces to systems, and enhanced security.

4. BASIC RESEARCH AND HUMAN RESOURCES

- **FINDING:** Federal research and development funding has established laboratories in universities, industry, and government which have become the major sources of innovation in the development and use of computing technology.

Many of the advances in computer science and technology in the U.S. were made possible by Federal programs of research support to universities and industry. For example, the advances that have occurred since 1983 in the area of parallel computing are the direct result of Federal research investment through agencies including DARPA and NSF. In the area of application of supercomputers to science and engineering, the majority of this investment came from the NSF Advanced Scientific Computing centers. In the area of parallel architectures, the major investment came from the DARPA Strategic Computing Program. Programs sponsored by DOE, NASA, and Defense to support critical mission needs have been a major source of investment in computational applications research. In industry, support for basic research is only a small fraction of industry research most of which is focused on nearer term product development. This can be attributed in part to the long term and high risk nature of basic research, but a more significant inhibitor of investment is the difficulty in the computer industry of maintaining proprietary protection for certain kinds of key fundamental advances.

- **RECOMMENDATION:** Long term support for basic research in computer science should be increased within available resources. Industry, universities, and government should work together to improve the training and utilization of personnel to expand the base of research and development in computational science and technology.

Maintain vigorous research in Computer Science and sufficient growth of computer science manpower to support the scientific/technological basis of the computer field. Foster interactions among academia, industry, and national laboratories by creating interdisciplinary teams to address large scale problems. Extend the technology base to attain significant impact on competitiveness and industrial productivity.

Innovative very high performance computing systems should be made available to universities and basic research laboratories in order to assist in the evaluation and exploitation of new technology and new industrial innovations.

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Continue the following successful approaches to basic research and development: (1) The practice of loosely coordinated and flexible basic research supported through various federal sectors and applied to a diversity of institutions, (2) The mixed strategy of peer review to support a broad range of exploratory basic research throughout the academic community and the complementary technical program management approach of larger scale experimental systems programs which exploit new opportunities as they emerge, (3) Support for individuals and small groups in theoretical areas, (4) The practice of supporting the relevant basic research as part of larger experimental systems projects.

IMPLEMENTATION

Success of the National High Performance Computing Strategy will require an attitude of cooperation in which academia, industry and government work effectively together in developing and assessing new technology and in achieving the transition of promising new ideas into the marketplace. The rapid pace of developments in computing technology creates a number of implementation challenges that must be addressed explicitly if the Strategy is to have maximum impact.

The FCCSET Committee on Computer Research and Applications provides an appropriate forum for coordination of Federal agency programs. Specifically:

- The subcommittee on Computer Networking, Infrastructure, and Digital Communications will develop a coordinated implementation plan for the national research network.
- The subcommittee on Science and Engineering Computing will review the *grand challenges* through the use of high performance computing systems, including the research that will be involved.
- The subcommittee on Computer Research and Development will review the need for advanced software, algorithms, and hardware for future high performance computing systems.

All of the subcommittees will consider appropriate action to secure a foundation of basic research and human resources. In all three subcommittees we expect some overlap of responsibility and interchange of ideas to be compatible with success.

As has been firmly stated, the full cooperation through a shared vision between government, industry and the research community will be a necessary ingredient for the successful implementation of this strategy. The FCCSET Committee on Computer Research and Applications therefore calls for timely consideration of the vision and strategy by representative bodies of the research community and industry.

It is essential, however, that implementation of the strategy be undertaken in a timely manner. There is a need to follow through on the breakthroughs that occurred partially as a result of federal investment in the early 1980s. The fast pace of development dictates that appropriate Federal efforts are needed to help ensure continued excellence in high speed networking technology and leadership in high performance computing. Foreign investment in technology development in these key areas has increased dramatically. The prudent strategy is to maintain a consistent strong lead in research and to transfer the results as quickly as possible to American industry.

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COST ESTIMATES

Many of the basic elements of the high performance computing strategy are already being implemented as part of ongoing agency programs at DOE, DARPA, NSF, NASA, and other Federal agencies, and important progress is being made. The FCCSET Committee activity has contributed to achieving a shared vision, and early coordination is already occurring in anticipation of implementation of the strategy. Implementation of the strategy involves three principal funding components, including the national research network, joint research to address the "grand challenges," and basic research in high performance computing architecture, custom hardware design, software, algorithms, and supporting technologies. Multiple agencies are involved in the implementation and funding of each of these components.

The funds that would be associated with each of these components are described below. Obviously, any incremental funding must be evaluated and approved within the context of current activities and research needs in other high priority fields. Currently, the Federal government is spending about \$500M per year on all aspects of high

Summary of Additional Funds
(Millions of Dollars)

Current Funds		Yr 1	Yr 2	Yr 3	Yr 4	Yr 5
50 ^a	National Research Network	5 5 40	5 5 40	5 55 40	0 55 40	0 55 40
150 ^b	Joint Research in Computational Science and Engineering	30	60	90	120	150
300	Basic Research in Computer Science and High Performance Computing	60	120	180	240	300
500	TOTAL (above current funds)	140	230	370	455	545
Funding Increase by Year (noncumulative)		140	90	140	85	90

a Estimated network research and support in grants and contracts.

b Estimated operating costs for existing computational science facilities.

performance computing. Funding for the activities recommended in this report would increase this base by \$140M in additional resources for the first year, growing to an additional \$545M per year in 5 years.

National Research Network. Current operating costs for the present collection of research-support networks operated by DARPA, NSF, DOE, and NASA is approximately \$50M per year; the figure is uncertain because many subnetworks are funded by increments on research grants and contracts, rather than being centrally supported. Currently the interconnection of existing agencies' networks is planned within existing budgets. A significant increase in investment is needed to achieve the required capability. This investment could occur in three concurrent stages.

The *first stage* activity would involve an immediate upgrade to 1.5 Mbit/sec of the existing research-support networks. This would cost \$15M over three years.

The *second stage* would expand upgraded network services (45Mbit/sec) to 200 to 300 research installations, using primarily fiber-optic trunk facilities. Development costs for this stage would be \$5M per year of additional funding. Operation of the upgraded network would commence in three to five years, with operating costs of approximately \$50M per year. Since the transition from the first stage to the second stage network could not be instantaneous, initially the full operating cost of the second stage network would necessitate additional funding; that requirement will diminish to the extent that the first stage network is phased out.

The goal of the *third stage* would be to deliver one to three Gbit/sec to selected research facilities, and 45 Mbit/sec to approximately 1000 research sites. Research and development costs for this project are estimated at \$400M of new funds, spent over ten years; after ten years, operating costs would be about \$200M per year unless some tariff relief is achieved.

Joint Research in Computational Science and Engineering. Current operating costs for existing computational science laboratory facilities is approximately \$150M per year. Additional investment would be required to upgrade the existing facilities and/or to establish additional joint research activities, with government, industry, and university participation, to address approximately specific problem areas, including selected *grand challenges*. Many of these joint research efforts will involve multiple physical sites connected by the research network. The investment in these research activities supports pursuit of the grand challenges. This includes personnel to develop computational approaches in terms of theory, algorithms, and software, and the acquisition of modern computing equipment. Estimated Federal costs average \$15M per year to establish and sustain each grand challenge. The joint research activities would be introduced at the rate of two per year. Overall investment will be approximately \$30M per year initially, increasing to \$150M per year in five years as new grand challenges are added.

Basic Research in Computer Science and High Performance Computing. Current Federal investment in advanced computer research is estimated at \$300M in FY88. Over the past four years, investment in these areas has grown at 15% per year. The rate of increase appears to be declining, however, at a time when increased investment appears to be needed. Sufficient resources should continue to be allocated to take full advantage of the high performance computing opportunities that now exist including design and prototype development of systems capable of trillions of operations per second. A second important element is stable funding, which is required to preserve the long-term strength of the research community.

Other countries are also devoting considerable resources in this area. For example, the Japanese government supports two projects which directly address supercomputer development: The Fifth Generation Project and the Superspeed Project. Support for each of these is estimated to be in excess of \$100M per year. In addition to this government support, Japanese industry is investing considerably more to develop high performance computers. Japanese government and industry are also investing amounts comparable to those recommended here to develop high bandwidth research networks.

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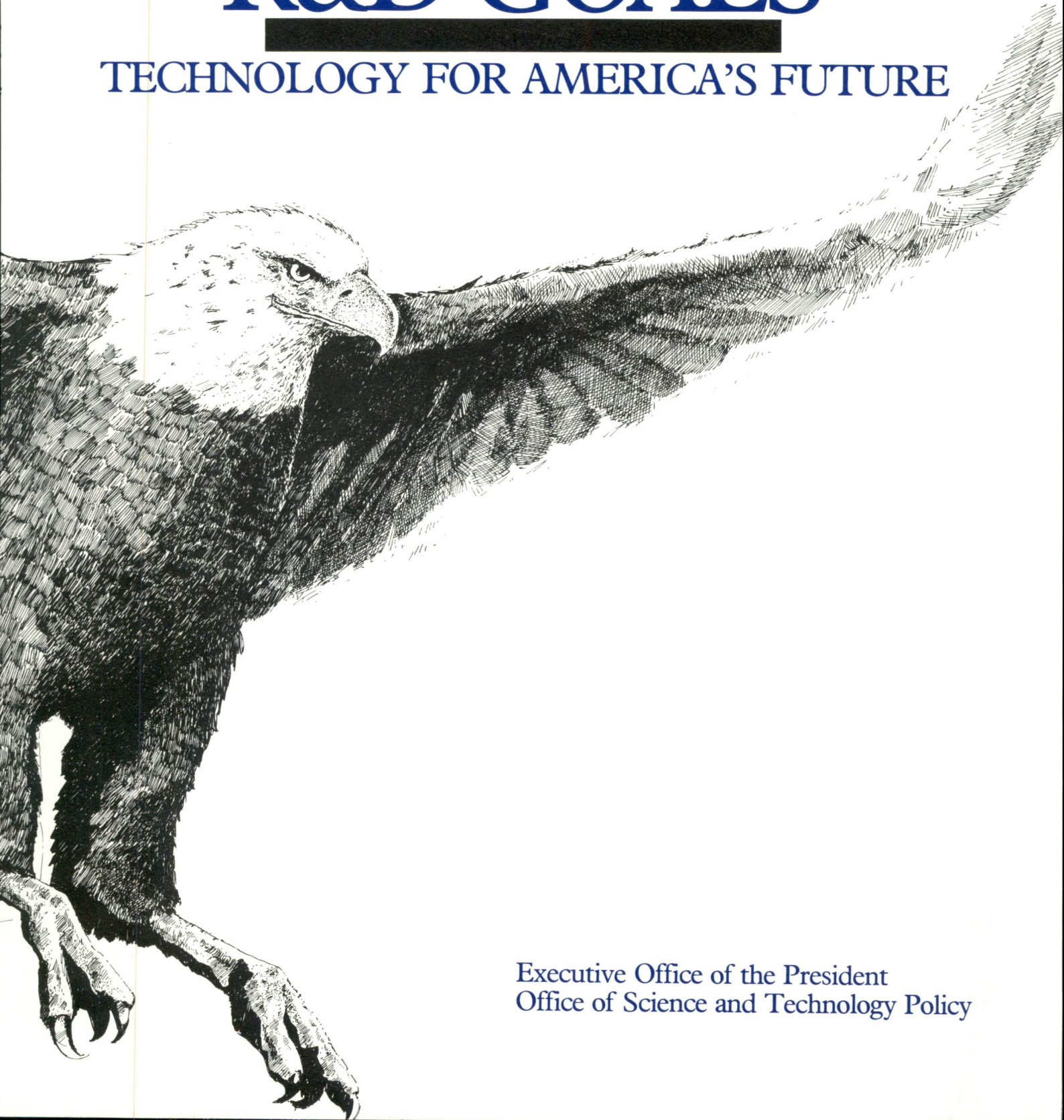
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NATIONAL AERONAUTICAL R&D GOALS

TECHNOLOGY FOR AMERICA'S FUTURE



Executive Office of the President
Office of Science and Technology Policy

FOREWORD

In November of 1982 an interagency working group, under the direction of the White House Office of Science and Technology Policy, issued a comprehensive report analyzing the state of aeronautics research and the role of the Federal Government in supporting that research. Among its conclusions were that there are possible today monumental advances in aircraft performance. Due to the nature of the benefits, both military and commercial, the Federal Government and industry must unite to realize that potential.

As a result of that report, I established an Aeronautical Policy Review Committee, composed of government, industry, and academic experts, for the purpose of keeping track of the implementation of the recommendations in the first report. This second report by the Committee points out that, like other industries that rest on strong technological bases, American aeronautics faces tremendous challenges from abroad as well as tremendous opportunities for advances and leadership now and in the future.

The report is comprehensive and addresses specific goals in three areas—subsonics, supersonics, and transatmospherics—that we should be focusing on. It gives clear direction for the Administration's commitment to maintaining and extending our leadership in this field. If the goals are pursued vigorously by industry, academia, and government, U.S. aeronautics, in both the civil and defense sectors, will be able to sustain its preeminence into the next century.

G.A. Keyworth, II
Science Advisor to the President, and
Director, Office of Science and Technology Policy

March 1985

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EXECUTIVE SUMMARY

Challenges and Opportunities

U.S. aeronautics is and will remain a decisively forceful influence on the long-term economic and military security of the nation. The technical margins that have long defined U.S. aeronautical preeminence have narrowed significantly in recent years as foreign competition has increased. This trend, if allowed to continue, will evolve into major national weaknesses substantially increasing the vulnerability of America's position in world affairs. Because aeronautics is so integral to our national interest, U.S. national aeronautical policy now stipulates that the nation cannot and will not allow leadership erosion.

Lasting U.S. aeronautical leadership will only be secured by the vigorous renewal of America's traditional strength: pioneering new technology. Aeronautical opportunities are known today which, if actively pursued, would result in 21st century U.S. civil and military aircraft of clear-cut supe-

riority. Their technical excellence and cost advantages could more than overcome foreign competitive approaches.

Strategy and Goals for U.S. Aeronautics

The high-technology payoffs that result from advances in aeronautics are important national benefits that must be maximized by American enterprise. This maximization requires both government and industry to combine their efforts toward aggressive technological goals with potential for broad future application. In this pursuit, early

"Lasting leadership will only be secured by the vigorous renewal of America's traditional strength: pioneering new technology."

"America's future in aeronautics demands much more than a 'business as usual' attitude."

applications can help generate the national resources and experience needed to capitalize on the opportunities that will follow. This strategy also supports the more definitive objectives for technically superior U.S. military aircraft.

The Committee proposes three national goals to clarify and focus the direction for U.S. aeronautical R&D. Successful attainment of these goals will challenge American creativity. Within the next 10 years the U.S. must build its research and technology momentum and achieve a trans-century renewal of the nation's total aeronautics capacity. Work must proceed concurrently on all three goals, with early emphasis on the first. The goals are presented here in time-phased order of attainment:

Subsonics Goal: To Build Trans-Century Renewal

- Envisions technology for an entirely new generation of fuel-efficient, affordable U.S. aircraft operating in a modernized National Airspace System.
- Captures immense civil aircraft market opportunities by technologically superseding foreign competitive challenges.
- Supports development of advanced military aircraft capabilities.
- Requires acceleration of key technology advances for 1995 readiness target. Applications well into the next century.

Supersonics Goal: To Attain Long-Distance Efficiency

- Develops pacing technologies for sustained supersonic cruise capability.
- Enables linking of farthest reaches of Pacific Rim in four to five hours. Recognizes growing U.S. strategic and economic interests with partnership potential.
- Provides military with enhancements in basing flexibility, long-distance responsiveness, and survivability.
- Applications through much of the next century.

Transatmospherics Goal: To Secure Future Options

- Pursues research toward capability to routinely cruise and maneuver into and out of the atmosphere with takeoff and landing from conventional runways.

- Builds on progressive subsonic, supersonic, and hypersonic advancements in aeronautics technology as well as Space Shuttle experience.
- Influences long-range options for both aeronautics and space.
- Significant to military and civil 21st century leadership.

Collectively, these goals will focus national energies and creativity on new frontiers and opportunities that are vital for the future success and leadership of America.

Implementation Challenges

America's future in aeronautics demands much more than a "business as usual" attitude. U.S. industrial companies must work with one another, and with government agencies, to increase *accomplishment* and enhance *affordability*.

Historically, a number of barriers have impeded technological advancement in both the public and private sectors. The current environment amplifies the impact of many of these impediments on achieving technology readiness. Appropriate corrective actions exist, and should be pursued without delay:

- Federal contracting procedures should be restructured to reflect a greater distinction between the procurement of research and technology and the procurement of hardware.
- Regulatory policy should encourage cooperative efforts for technology development among U.S. companies (as is now ongoing between U.S. and offshore companies).
- Federal tax legislation should adequately stimulate private investment in timely technology development.
- All branches of the Government with relevant oversight and/or management responsibilities should strive to maintain the continuity of research and technology development activities.

Planning, Priorities, and Policies For Action

Technical plans for implementing these goals must be developed in close conjunction with the reordering of national R&D priorities and policies. This task challenges both public and private sector creativity to gain real growth in aeronautical technology development. It also challenges government leadership to reconcile policies inhibiting R&D progress and affordability. Toward this national purpose, the Executive Offices and mission-oriented agencies of government must work closely with Congress to ensure that the rich potential in aeronautics is nurtured, encouraged, and firmly secured as an American reality.

INTRODUCTION

U.S. Aeronautics in a Global Context

U.S. aircraft have long dominated in civil aircraft markets and in weapon system technical superiority, but there is no guarantee that U.S. leadership in aeronautics will be retained even in the short term. In fact, the U.S. can no longer assume its leadership is secure on any high technology front. Very clearly, the intensity of global competition in high technology poses a serious challenge to U.S. aeronautical preeminence, a situation which also brings into question the economic and strategic future of the United States. Aeronautics has a crucial role both in America's defense capabilities and in the employment, transportation, and exports which strengthen our national economy.

In aeronautics, the U.S. system of private enterprise has developed a unique base of national synergy which affects key parts of the nation's overall competitiveness. Aircraft provide a challenging product focus that stimulates high technology innovation from a broad array of contributing companies and industrial sectors. The success of this aspect of America's aeronautical infrastructure has not gone unnoticed by other nations, and aircraft capacities have become favored targets for foreign technological and industrial expansion over much of the past decade.

While U.S. aircraft still maintain a broad base of technological advantage, the margin of that advantage has narrowed dramatically in recent years. In a growing number of aircraft-related areas, foreign technical capabilities are now comparable, if not superior, to those of the U.S. This is particularly evident for smaller aircraft, where the entry threshold has been within the financial and technical reach of an increasing number of smaller nations or multinational consortia. Foreign military aircraft capacities are now showing a similar trend. Coupled with this, military and civilian aircraft technologies and products have become a politically sensitive aspect of international negotiations and trade. In this respect, the erosion of American preeminence implies major negative consequences for the position of U.S. leadership in global security as well as for the vitality of U.S. industry in a changing global economy.

An Expanding Perspective

All these factors were recognized in the Administration's 1982 Aeronautical R&T Policy, which established challenging national goals for furthering all aspects of U.S. aeronautical preeminence. Following one of these policy recommendations, the President's Science Advisor formed a senior executive-level committee to review (from a national perspective) the Government's long-range aeronautical plans for consistency with the policy objectives. This is the second report submitted by that policy review committee.

The Committee's first report, submitted to the Executive Office of the President in November

1983, included a number of recommendations to encourage a more aggressive and farsighted national outlook for aeronautics. During 1984, the U.S. aeronautical community reexamined opportunities for technological advancement that could be achieved by the end of this century. This crucial evaluation was conducted with a view toward vehicle concepts that reached beyond the arbitrary time horizon of the turn of the century. The results presented to the Committee both confirmed and expanded many earlier assessments. Very high-leverage payoffs can be expected from interdisciplinary efforts in propulsion, materials, aerodynamics, structures, and avionics. Aggressive technological readiness can produce either a distinct U.S. advantage or, conversely, an advantage to foreign civil and military competitors, depending on where the greatest effort and commitment are made. In considering this dynamic situation, several important factors should be borne in mind:

- Leapfrog advancements are definitely possible which would make obsolete virtually all significant civil and military aircraft operational today (both fixed and rotary wing).
- The range of high-payoff R&T opportunities impacts all classes of aircraft and will far exceed resources available for investment.

"Very clearly, the intensity of global competition in high technology poses a very serious challenge to U.S. aeronautical preeminence"

NATIONAL AERONAUTICAL R&D GOALS

"While payoffs will be time-phased in their realization, it is important that work toward all three goals proceed concurrently."

Three long-range goals are proposed to address all these challenges and opportunities. The Committee believes that the highest potential for revitalizing U.S. competitiveness lies in America's traditional area of strength: the pioneering of new technology. The three goals proposed here are aligned to form a strategy aimed at a decisive strengthening of the U.S. technological foundation and leadership position in world markets and relative to our military adversaries.

The goals are time-phased, with the first goal (subsonics) being crucial as an enabling goal. It must serve to reenergize American R&D momentum, because the product technologies it fosters must generate private sector resources necessary for exploitation of ensuing opportunities in supersonic and transatmospheric flight. While payoffs will be time-phased in their realization, it is important that work toward all three goals proceed concurrently. Emphasis over near-term years, however, must necessarily be focused on the first goal.

Subsonics Goal: To Build Trans-Century Renewal

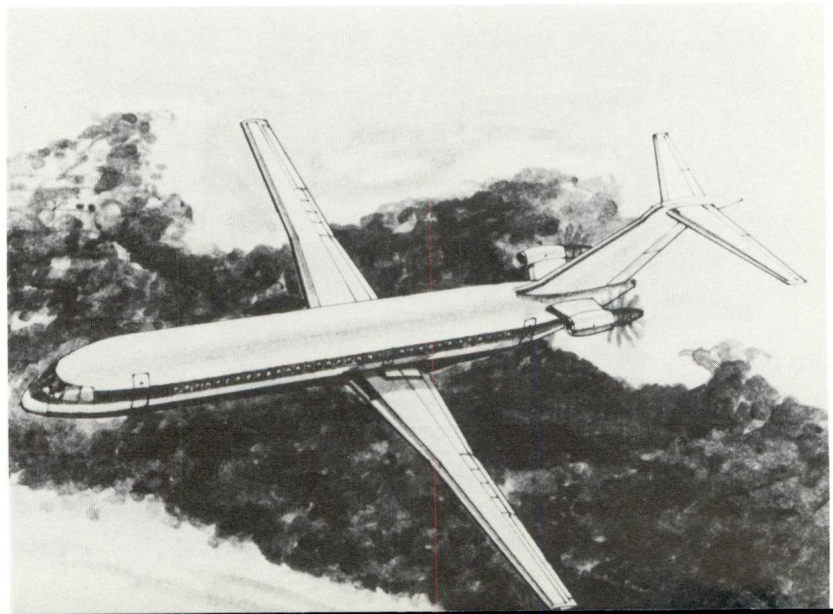
Advancing technology for a new generation of U.S. subsonic aircraft

The past 15 years have seen mostly evolutionary advancements in subsonic aircraft technology, but future possibilities for truly revolutionary advancements far exceed all these. Subsonic opportunities can establish a firm U.S. foundation for technically superior aircraft to carry U.S. aeronautical leadership into the next century. The subsonics goal envisions this with an entirely new generation of fuel-efficient U.S. aircraft operating in a flexible and modernized National Airspace System. Simply stated, its aim is a safe, congestion-free U.S. aeronautical interstate system, offering superior air transportation at half its current cost. The subsonics goal also envisions the development of advanced military airlift capabilities, long endurance aircraft, low observables, rotorcraft, and other spin-off military requirements that are anticipated for the same general time frame.

Accelerating subsonic technology can leverage unique advantages for the United States, by capitalizing on the pioneering efforts in airspace modernization and deregulation already in the national agenda. It also promotes domestic supply for the very large U.S. civil aircraft markets. In this respect, subsonic aircraft also dominate in world market projections, with a variety of requirements extending well into the next century. This immense civil opportunity is the cornerstone for sustaining American aircraft capacities, since civil work generates 60 percent of the total aircraft production business for the 15,000-company supplier base which supports both U.S. civil and military needs. Foreign competition has already placed serious technology readiness pressures on the U.S. supply base, particularly with respect to smaller classes of aircraft (commuters, business aircraft, and rotorcraft) where the position of U.S. products is most endangered today.

Significant national research and technology development is already in progress. However, key subsonic advances contributing to new trans-century aircraft must be accelerated and readied by the mid-1990's to meet crucial competitive applications that will affect U.S. aeronautical momentum into the next century. Technologies that are integral to the development of these subsonic aircraft include: laminar flow control advancements that substantially reduce aircraft drag; all composite high-strain structures; a new generation of super bypass and propfan engines; and fully integrated flight controls and operating systems that interface with National Airspace System modernization. It is essential for the National Airspace System Plan to maintain cohesiveness and flexibility to accommodate and keep pace with these future aircraft technologies. Advanced computational capability is key for both aircraft and air system objectives.

New aircraft in the system will more than double today's best fuel efficiency, as well as being substantially more efficient in operation. U.S. general aviation, rotorcraft, commuters, and transport aircraft that decisively reduce acquisition and operating costs will dominate established world



markets and the new air service expansions of developing nations. U.S. helicopters and V/STOL aircraft will also become increasingly important in both these market areas. Advanced aircraft of this type can reduce congestion in U.S. airports and provide transportation infrastructure unique to the specialized requirements of developing nations.

Achievements of this magnitude could also produce a U.S. advantage in the eventual formation of a globally compatible air system, as well as leadership in other areas of international aviation. This in turn could leverage significant U.S. strategic and economic advantage for other important world agendas, particularly in the developing Pacific region.

Stepping up national research momentum and efficiency is a vital part of this far-reaching goal. In view of this, a broad, trans-century strategy is proposed later in this report that places particular emphasis on revitalizing the nation's capacities for aeronautical innovation over the next decade.

Supersonics Goal: To Attain Long-Distance Efficiency

Developing technology for efficient, long-distance supersonic cruise

Gaining sustained supersonic cruise capability is of very high priority for future military aircraft survivability, long-distance responsiveness, and basing flexibility. However, this military capability is also aligned with highly constructive civil opportunities that could benefit the U.S. in important non-military areas as well. Supersonic advancement offers the added potential for welding long-term bonds between the U.S. and Pacific partners through possible joint development of the pacing technologies for a new generation of supersonic transports. The key technologies underlying this objective (propulsion, structures, materials, and aerodynamics) are largely generic to future military needs.

Strategically and economically, United States trade and alliances in the Pacific have major implications for the future. The region's dynamic

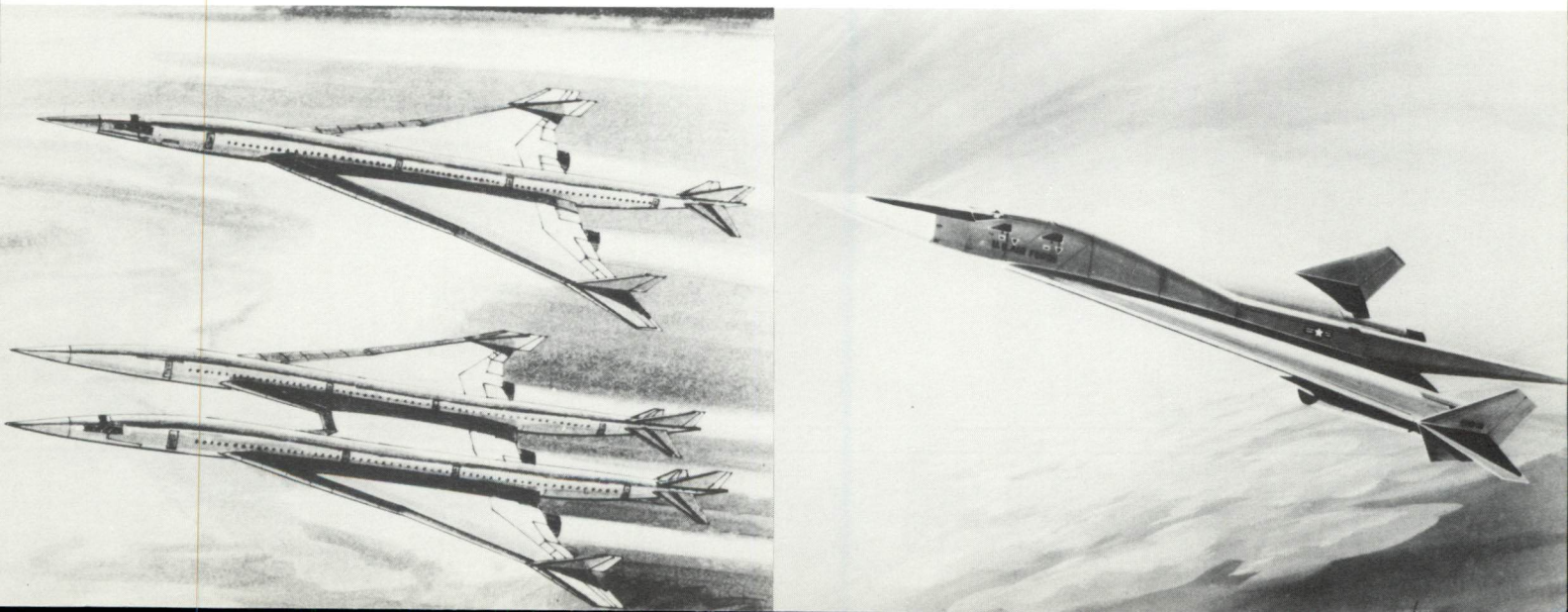
growth and vast potential for development should continue to be influenced and encouraged by American policy and enterprise. U.S. trade with the Pacific community has increased over 75 percent within the last six years, accelerating well beyond the volume of trade with Europe. Mutual security bonds are also of increasing significance in light of a potential major Soviet military buildup in the region. From both the strategic and economic perspectives, the vast Pacific area is constrained by distance, a factor adding significance to a U.S. supersonic goal . . . and contributing to the potential for Pacific Rim development by increasing cooperation and understanding among the nations and peoples of this important region.

The key technologies for advancing supersonic cruise capability have not been aggressively pursued by the U.S. since the 1971 demise of the U.S. Supersonic Transport program. However, the NASA-funded Supersonic Cruise Research program, which ended in 1981, established a constructive base for further advancement. The development of single crystal turbine blades, better coatings, advanced cooling methods, and improved internal aerodynamics has allowed significant improvements in military engine thrust-to-weight ratios. The application of these technologies to a variable cycle engine with reduced noise, and much improved specific fuel consumption over the entire speed regime, forms a starting basis for the Pacific Supersonic Transport.

The application of powder metallurgy technology and superplastic forming techniques to load-carrying structure, along with new thermoplastics, carbon-carbon, and metal matrix materials, will also have significant benefit for all classes of military and civilian supersonic aircraft. Additionally, fault-tolerant computers that provide load alleviation and dynamic damping, coupled with the cooler structure allowed by supersonic laminar flow, will significantly reduce the aircraft weight per pound of payload as compared with earlier supersonic transports.

The advent of powerful computer systems will allow the computation of complex flows and the

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optimization of configurations that extend the regions of supersonic laminar flow. A complete understanding and verification of the potential for supersonic laminar flow is critical for sustained cruise speeds that would allow both military and civil aircraft operations at triple the fuel efficiency of today's supersonic technologies. Combined with other supersonic advances, it can also substantially reduce the overpressures contributing to sonic booms.

Creative integration of these technologies could provide the U.S. and its Pacific allies with a transportation system linking the farthest reaches of the area in four to five hours, while providing the military with vitally needed mission enhancements in basing, long-distance responsiveness, and survivability.

Transatmospherics Goal: To Secure Future Options

Exploiting the growing convergence of aeronautics and space technology

U.S. aeronautics and space endeavors share in related constraints and unexploited opportunities in the transatmospheric regime. The capability to routinely cruise and maneuver into and out of the atmosphere, to gain rapid responsiveness for low earth orbit missions (manned or unmanned), or to attain very rapid transport services between earth destinations from conventional runways must be viewed as aerospace options with global importance for the future.

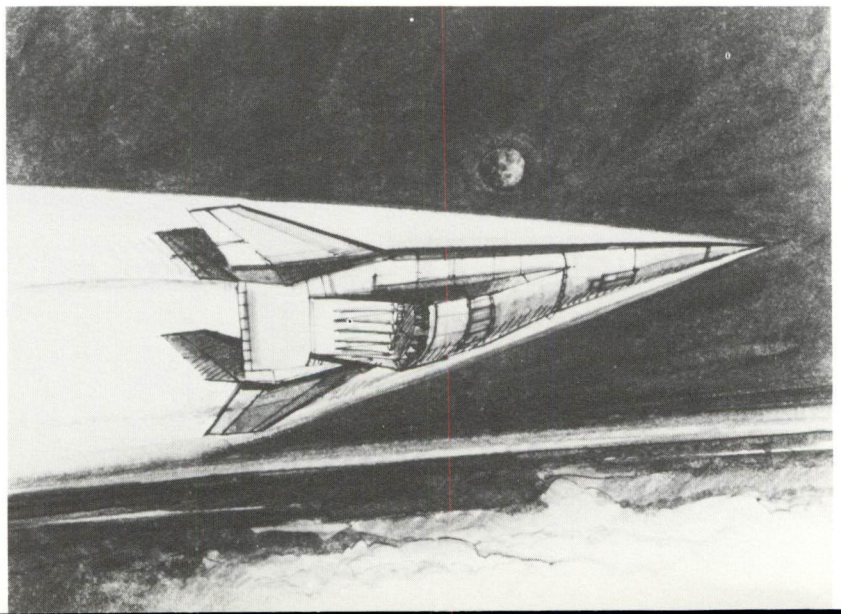
The importance of these capabilities to the U.S. must be underscored, since all these possibilities are also open to foreign military or civil initiatives in either aeronautics or space. The U.S. has largely viewed the transatmosphere as a technical boundary . . . used to define the separate responsibilities between U.S. aeronautics and space. This is a view foreign competitors may not hold, since aeronautics and space technologies are rapidly converging.

This convergence makes it vital for the U.S. to establish a long-range goal for understanding and

better exploiting this important bridging regime. Increased understanding of the transatmospheric environment and its relationship to maneuvering vehicle requirements must be gained within the near term. This knowledge will be highly significant to the selection of high-payoff developments in propulsion, fuels, materials, system concepts, and other areas which may influence future national options in space and/or aeronautics.

Much of the flight vehicle technology base is expected to develop from the progressive subsonic, supersonic, and hypersonic advancements in aeronautics as well as from Space Shuttle experience. Follow-on advancements in lightweight structural and thermal protection concepts involving new materials systems, artificial intelligence advancements, and blended body aerodynamics are also part of the progressive technology development scenario. Hybrid air-breathing propulsion systems, the truly pacing technology for conventional and routine operations from earth, are now viewed as feasible over the long term. Major fuel system/propulsion advancements may also be possible that would extend vehicle capabilities to high earth orbit missions.

The U.S. must seriously consider that the proliferation of world space activities will eventually call for more conventional forms of transport having the earth-based flexibility possible with transatmospheric flight. There are also very important future military options possible. The extreme altitude and speed capabilities this technology makes possible could enhance military survivability in lethal environments and provide flexible basing for global range weapons delivery, reconnaissance, or space support missions.



REVITALIZATION STRATEGY

If the vital goals outlined here are to be met, research momentum and efficiency must be energized on a national scale. Toward that end, a strategy is proposed that places primary emphasis on efforts that will revitalize the nation's capacities for aeronautical innovation over the next decade.

Emphasize Basic Research and Technology

A broad-based national program of basic R&T must be supported and sustained to produce the new concepts and ideas essential to technological advancement. A continuous flow of fundamental knowledge from both public and private research is vital if new advances and breakthroughs are to occur.

Universities

Much of the nation's basic research, as well as the training of scientific and engineering manpower, is performed within the American university system. A significant expansion of industry and government sponsorship of basic research at the university level is needed to encourage and sustain the important university contribution to America's knowledge and skill base. In particular, increased aeronautical research relationships between industry and the university system will provide valuable impetus for overall aeronautical momentum.

Government and Industry

On another level, highly important aeronautical programs are conducted directly by government and private industry. Basic research and technology at this level forms the bedrock for future technology progress. Government and industry research furthers physical phenomena understandings and the generic technology evolutions that lead to important new aeronautical advances. A continuity of effort on all these fronts — government, industry, and university — must be stressed to maximize the effects of this highly important aspect of trans-century revitalization.

Time Frame for Progress

A decisive trans-century momentum in national achievement must be established within the next 10 years. This becomes patently clear in view of the fact that only some 25 years elapsed between the DC-3 technology era and the advent of America's first generation of commercial jet transports. By all indications, future leaps in aeronautics technology will be achieved within much shorter time frames. We can also anticipate, from past aeronautical experience, that the acceleration of technology advancement will lead American society into new frontiers of opportunity. America must be fully prepared to take advantage of these opportunities.

Address the Issue of Affordability

Sustained preeminence will require both cost and *technical* superiority from U.S. aeronautics. Affordability, or the cost of acquisition, is a major problem confronting both military and civil aircraft programs today. The Committee believes that cost will remain a major impediment to national progress and competitiveness until more concrete steps toward solution are taken.

Partial solutions can be realized in the technologies directly affecting the product level. Advanced manufacturing and product management concepts are all-important in this respect, but partial solutions are not the answer.

Energizing the R&T Chain

Product costs are highly influenced by the degree of continuity and effort employed at the early stages of research and technology. The most critical area is technology validation, the mid-phase in the R&T chain. This phase takes potentials identified from basic research (the first phase) and advances them into risk-acceptable readiness; the final phase then entails product application and production. National policies and implementing procedures that influence or direct technology have driven unintended barriers into this critical mid-phase of R&T, causing this vital link in the innovation chain for aeronautics to be short-circuited.

There is no question that achieving technology validation and readiness of high-payoff potentials is the most costly and time-consuming aspect of research and development. It requires more time and more money than many persons in program advocacy positions are prepared to recognize or admit to. In truth, significant accomplishment is required before specific system needs are known or program commitments made. It is seldom fully recognized that production failures, program delays, or cost overruns may have been preordained because the risks in critical technologies were not sufficiently understood, and not reduced by appropriate feasibility demonstration experiments, before program commitments were made.

Civil and Military Synergy

There are highly constructive synergies that can be brought into play to affect affordability. For example, military advancements stress performance; on the other hand, commercial developments tend to emphasize lowered production costs, vehicle operating efficiency, and high availability with low

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"In the Committee's view, the question is not whether these advances will be made . . . only when they will be achieved and by whom."

maintenance . . . all of which are attributes vital to reducing military costs.

At the production level, the civil industry becomes crucially important, because commercial endeavors provide both continuity and private sector funding to sustain industrial innovation. The 15,000 companies supporting both military and civil aircraft programs depend on civil work for about 60 percent of their aircraft production business. This close interrelation of civil and military enterprise should be viewed and utilized as a strong positive force for aeronautical progress and particularly for the achievement of affordability.

Strategy for Improvement

To correct problems that have historically impeded technological development, the following actions should be vigorously pursued:

- Federal contracting procedures should be restructured to reflect a greater distinction between the procurement of research and technology and the procurement of hardware.
- Regulatory policy should encourage cooperative efforts for technology developments among U.S. companies (as is now ongoing between U.S. and offshore companies).
- Federal tax legislation should adequately stimulate private investment in timely technology development.
- All branches of the Government with relevant oversight and/or management responsibilities should strive to maintain the continuity of research and technology development activities.

The competitiveness of future U.S. civil and military aircraft will call for all these measures. But it will take more than aggressive government and industry funding at the validation readiness level. It will require smart money and cohesive policies to create a dynamic and flexible capacity to exploit the full circle of synergies that surrounds U.S. aeronautics.

SUMMARY

The Challenge for Preeminence

The Committee believes that the single most crucial challenge facing U.S. aeronautics is that much of the nation's leadership, both in government and in industry, underestimates the depth of foreign aeronautical commitment and resolve. U.S. preeminence can be maintained only by focusing a more aggressive national effort on attainment of the proposed national goals for aeronautical R&D. This U.S. strategy would simultaneously produce both a strengthened defense capability and a position of clear-cut product superiority in the international marketplace.

In the Committee's view, the question is not whether these advances will be made . . . only when they will be achieved and by whom. The benefits are too valuable to remain untapped by competitors and adversaries for long. At the present time, the magnitude of world opportunity, and the extent of technology readiness required to decisively exploit this richness, appear to be largely underestimated in the policies and plans affecting U.S. aeronautics.

The Agenda for Achievement

The agenda for implementing these goals must create real national growth in R&D. Technical plans must reflect this, and the agenda must also emphasize the major issue for today — affordability. Traditional strengths can and must be utilized more cohesively. Affordability *should* challenge U.S. aeronautics to remove costly compartmentalizations from efforts that ready multi-use technologies important to long-term national goals. We must reshape our policies and procedures and posture our efforts toward working more effectively, if the nation is to compete more decisively. National affordability should *again* challenge U.S. aeronautics with the hard fact that military affordability is implicitly linked to the vitality of civil exploitations of technology. In view of this, and in the face of high payoffs and growing dual-use trends, the massive control of critical technologies must be questioned.

The greatest challenge confronting the American realization of the potentials implicit within these goals may be that of redirecting the force of American will into specific, cohesive, and bold steps toward the future.

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**THE NATIONAL
ACTION PLAN
ON SUPERCONDUCTIVITY
RESEARCH AND DEVELOPMENT**

WITH A BACKGROUND REPORT BY
THE OSTP TASK FORCE FOR
THE NATIONAL ACTION PLAN
ON SUPERCONDUCTIVITY
RESEARCH AND DEVELOPMENT

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

DECEMBER 1989

**THE NATIONAL
ACTION PLAN
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December 1989

THE ACTION PLAN
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INTRODUCTION

This document presents the Superconductivity Action Plan pursuant to the Superconductivity and Competitiveness Act of 1988. Development of the Plan was coordinated by the Office of Science and Technology Policy (OSTP) with consultation from the staff of the National Critical Materials Council (NCMC). The Plan draws upon contributions from leaders in the technical community of the Federal Government responsible for superconductivity research and development programs, as well as from the report of the Committee to Advise the President on Superconductivity. Input from leaders in the private sector was obtained during the formulation and review of the Plan.

While the future development of technology related to superconductivity will be determined by a broad range of actions in both the public and private sectors, this Plan focuses on three areas where there is opportunity for the Federal Government to promote development and commercialization. These are:

Coordination -- The Office of Science and Technology Policy will provide leadership in the national superconductivity effort. OSTP will coordinate an on-going assessment of our national status in superconductivity and will serve as a point of contact for leaders of the public and private sectors to register their viewpoints and recommendations for action as the needs change over the coming years.

Technical -- Federal funding is the largest consolidated source of support for superconductivity research and development. Seven generic areas of research and development are identified as main thrusts of the U.S. effort.

Policies -- Government policies ultimately affect the economic and business climates in which superconductor technology will evolve. Five policy areas are identified in which potential future actions will directly or indirectly affect superconductor technology.

This Plan is founded on the precept that as long as the potential for applications based on superconductivity remains high, we as a Nation must be at the forefront of that technology and be ready to translate basic scientific knowledge into viable applications. Superconductivity already has important commercial and humanitarian impact (e.g. Magnetic Resonance Imaging (MRI) & instrumentation and magnetic materials separation). With certain breakthroughs, it could become an enabling technology leading to an even broader range of new products. The current state of knowledge is, however, inadequate to predict if or when these breakthroughs will be achieved. Over the next five years, then, the Plan must necessarily be flexible if it is to be effective and responsive to changing needs and progress during the period. Key to our success is a clear understanding of our current position, where we are headed, and the mechanisms to coordinate our efforts.

COORDINATION OF THE PLAN

The Assistant to the President for Science and Technology, who is also the Director of the Office of Science and Technology Policy, will assume the responsibility for coordinating the Plan with both private and public sectors. The Plan must be based on a realistic understanding of the resources available for material science research in the Administration's programs and therefore must also be coordinated with other top Administration budget and policy officials.

The Subcommittee on Superconductivity of the Committee on Materials (COMAT), under the OSTP Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), is an important resource and is expected to play a major role in the coordination of public sector activities. The Subcommittee is comprised of the program managers from all agencies overseeing the Government's research and development (R&D) efforts in superconductivity.

Although there is inter-agency coordination through the COMAT Subcommittee on Superconductivity and several topical ad-hoc instances of agency cooperation, this effort does not materially impact technical coordination and cooperation among the Federal laboratories, nor between them and the university and industry performers of government-supported R&D on superconductivity. This latter cooperation is, however, an important element in rapid U.S. scientific and technological progress in this area. The Federal Laboratory Consortium (FLC) will be asked to institute a program to develop closer collaboration and cooperation among these performers of Federal superconductivity R&D (including Federal laboratories, universities, industries, and consortia) and to designate a liaison with the Subcommittee on Superconductivity.

Annual Reports and Ongoing Analysis of Funding

Public Law 100-697 calls for an annual report by OSTP, with the assistance of NCMC, "setting forth and evaluating the progress of the Superconductivity Action Plan." As also stated in the legislation, this review "shall include a description of the amount of funds expended in the previous year by all Federal departments and agencies involved with superconductivity." This review will be carried out jointly by OSTP, with the aid of

COMAT, and the Office of Management and Budget. The first such budget cross-cut is expected to be part of the President's Fiscal Year 1991 budget submission to Congress in January 1990. The first action to be undertaken in this regard will be development of a consistent format for interpretation and reporting of budgets, so that cross-agency comparisons can be made by technical research category. This format will yield what amounts to a superconductivity budget planning matrix similar to that which is presented in Table 1 of Chapter II of the Background Report. The cross-cutting analysis this affords will assure that the allocation of resources by topic is consistent with the continuing goals and priorities developed for advancing this technology.

The annual reports to Congress will also include an ongoing assessment of the technical programs, potential applications, and goals described in this Plan and accompanying Background Report. The assessment will emphasize progress in superconductivity R&D, especially technical breakthroughs. Chapter III of the Background Report identifies a number of potential future applications for superconductivity, the development of which in the long term will be dependent to a large extent on the level and consistency of funding provided by the Government, particularly in the near term. Therefore, the strengths and weaknesses of the U.S. program will be assessed in relationship to our competitors in Japan and Europe so that areas can be considered for increased emphasis.

The OSTP Director, working with NCMC, the President's Council of Advisors on Science and Technology (PCAST), and other relevant groups, will also consider any additional steps as needed to address technical or policy needs. The OSTP Director will work to assure that all parts of the Government program form a coherent whole, well balanced between basic research and applications. And, he will coordinate with the private

sector as appropriate, so that the U.S. program - public and private - will be effective. To this end, he will encourage the formation of industry-university-Government laboratory consortia as recommended by the Committee to Advise the President on Superconductivity.

TECHNICAL AREAS

The perspective on our current position in superconductivity science and appropriate directions for the future were established by convening a task force of experts and program managers from the Federal agencies. The accompanying report, "Background for the Superconductivity Action Plan," presents a profile of the current status of the technical work underway, as well as potential future applications which will heavily influence the fundamental research in the near term. The match between the two identifies where actions are warranted.

It should be emphasized that the field of high-temperature superconductivity (HTS) is still in its infancy. This is evidenced by the myriad of materials problems encountered in the search for practical applications as well as in the development of fundamental understanding. Using the historical development of semiconductors, optical communication, or genetic engineering as a guide, the full potential of HTS technology will take time to achieve. Therefore, stability and continuity of funding consistent with continuing progress, are indispensable for its success. To be able to provide HTS support of this nature, the technical goals of Federal agencies need to be generic rather than specific in terms of HTS products. Presented below are the initial technical goals, identification of responsible agencies, and recommendations for action in generic technical areas.

HTS Materials in General

Continuing research is needed to find and characterize superior HTS materials. Superior refers not only to higher transition temperature, and higher current density, but also to higher critical magnetic field, easier fabrication, improved compatibility with other materials in terms of processing parameters and chemical stability, increased flexibility, and reduced cost. In addition, there may be other parameters which are specific to potential applications. There is good reason to believe that the best low-temperature superconducting (LTS) materials have already been discovered, but there is considerable promise that many new HTS materials with interesting properties are yet to be discovered.

Another important goal is the development of a theory of HTS, since a sound theoretical understanding is essential to facilitate engineering applications of these materials. The understanding of Josephson-junction behavior, flux dynamics and ac and rf losses, are examples of the information to be garnered from all agencies' materials programs to support the development of such theory. A support element in development of these materials will be the preparation of accurate phase diagrams and maintenance of this information for use by Government, industry, and universities.

Continuing Federal support for fundamental research in HTS materials is warranted and needed throughout the next five years. The Department of Energy (DOE), the Department of Defense (DOD), the Department of Commerce (DOC) through the National Institute of Standards and Technology (NIST), and the National Aeronautics and Space Administration (NASA) fund substantial research programs in their laboratories and in the private sector. It is recommended that these agencies maintain support for materials research programs, stressing stability and continuity of funding in areas of continuing

progress. In addition to DOD and DOE, the National Science Foundation (NSF) is a primary means for directing Government funding into universities for HTS materials research. The President has proposed increased support for NSF in his February 1989 report, "Building a Better America." Strengthening the NSF role will benefit both individual university investigators and future Science and Technology (S&T) Centers focusing on materials research.

HTS Films for Sensors and Electronics

Technology for the production of high quality HTS films capable of supporting adequate critical current densities with low surface resistance and low background noise is needed for use in planar sensors and electronics applications. Efforts in this area have been particularly successful. Current densities achieved are fully adequate for signal and power bus interconnects in superconductor sensor and electronic circuits and in semiconductor microelectronic chips. However, full processing compatibility with semiconductor technology has not yet been achieved. Indeed, that represents a considerable challenge and may rely upon as-yet-undiscovered HTS materials which have more compatible processing parameters.

Another goal is the development of technology for preparing stable and reproducible electron tunneling junctions, both Josephson-type (pair) and Giaever-type (quasi-particle), for use in a variety of superconducting sensor and electronics applications. There have been a few reports of successful HTS tunneling junctions. Clearly we are now at an embryonic state of HTS device technology, both in terms of concepts and in fabricating reproducible junctions. But the potential for truly significant advances in speed and device

density makes that more of an opportunity than a barrier to progress.

The primary funding agency for research on HTS films is the DOD, although much of the actual research is performed in the DOC(NIST) and DOE laboratories, as well as NSF-supported single investigator projects in this area. In addition, a significant portion of the NASA effort is dedicated to this area because of the potential impact on submillimeter-wave astronomy, Earth observation technology, and space communications applications. It is recommended that the DOD be given primary responsibility for promoting advancements in these technologies because of the many potential applications in defense systems. The DOC (NIST) also has a responsibility for considering commercial applications (per the Technology Transfer Act) for these technologies.

Magnets

An exceptionally important goal is that of achieving high critical current density at high temperatures and high magnetic fields in HTS conductor configurations suitable for fabricating superconducting magnets to satisfy the myriad potential applications. There are currently no HTS high-current-density conductors suitable for superconducting magnet fabrication. Contributing to the challenges of utilizing the HTS materials for superconducting magnets are their brittle microcrack-prone nature, their short superconducting coherence lengths, their anisotropies, and their sensitivities to chemical attack.

The DOE and DOD are both major sources for research on superconducting magnets and applications. It is recommended that the two agencies establish an arrangement for bi-lateral coordination and share responsibility for promoting advancement in the technology.

Large-Area HTS Films

Development of high-quality, large-area HTS films for use in magnetic and electromagnetic shielding applications and in high frequency cavity resonator applications is another goal. Progress to date suggests that useful films can be prepared for dc and low-frequency ac shielding applications in low to moderate intensity fields, provided the magnetic field is parallel to a preferred HTS film surface. In high-frequency cavity-resonator applications, where ac loss considerations dominate, the requirements on film quality are more stringent. To date, the observed high-frequency properties of HTS films at liquid nitrogen temperatures are approximately an order of magnitude better than those for pure copper at the same temperature. For example, NASA has recently demonstrated operation of an HTS device at millimeter wavelengths which exhibited loss characteristics reduced by a factor of two when compared to the same device fabricated from metallic films at 77 Kelvin (K). For HTS film cavity resonators to be useful in particle beam accelerator applications, further improvement is required and will call for considerable developmental effort. For the shielding applications, and especially for the compound-curvature cavity-resonator surfaces, the very large anisotropies typical of the superconducting properties of HTS materials pose difficult challenges. Accordingly, there is considerable incentive to continue the search for additional HTS materials in hopes that not all such materials exhibit such anisotropy, and to develop methods for texturing the present materials.

It is recommended that the DOD maintain its ongoing programs to develop large-area electronics applications and shielding for electric motors to underpin the development of technology in this area.

Bulk Conductors

Materials that can carry large currents for power and magnet applications appear to pose the greatest challenge. To be useful, these materials must have much better physical and mechanical properties than present materials; critical current, critical magnetic field, flexibility, and ductility all must be improved. Specific goals would include: developing an understanding of flux creep and lattice melting with prototype approaches to flux pinning to improve operating regimes; demonstration of a reproducible, controlled process for the production of thick films, as a stepping stone between thin films and bulk materials; in the longer term, development of a reproducible HTS conductor, carrying 100 amps in a 2 Tesla (T) magnetic field, at a current density of 10,000 amps per square centimeter; and demonstration of polycrystalline bulk materials achieving 100,000 amps per square centimeter at 10T and 77K. It is recommended that the DOE should continue supporting this area of R&D. It is also recommended that NASA continue research on bulk materials for advanced cryocooler technology.

Materials Production and Processing Technology

Materials production and processing technology is a key area that will underpin our ability to compete in HTS internationally. Experience to date with the extreme sensitivity of HTS materials performance to process parameters, and the need for real-time in-situ sensors (e.g. chemical) beyond current state-of-the-art physical sensors, call for a concerted effort to develop this supporting process technology. Although the "best" HTS materials may, as yet, be undiscovered, the process technology developed for present materials could help accelerate adaptation to new materials. It is recommended that the DOE, DOD, NASA, and NIST pursue cooperative programs involving their laboratories, universities, and industry.

Materials and Coolant Supply

Large increases may eventually develop in the demand for the materials from which superconductors are fabricated or for the coolants which provide the necessary temperatures. Thallium, for example, is a byproduct of copper, lead, and zinc refining; world reserves are estimated at 415 short tons. The Bureau of Mines monitors these materials and should periodically assess the supply/demand outlook.

POLICY AREAS

The Government has a continuing responsibility for fostering economic and business climates that will encourage commercialization of technologies, like superconductivity, which have the promise of long-term benefits to the economy and to society. It also has the opportunity to meet its own particular needs in defense, energy, space, etc. by encouraging development of new technologies such as HTS.

This component of the Plan presents the various policy strategies, which have been identified as having a strong bearing on technologies such as superconductivity. They provide a basis for consistent and stable research in the private sector, exchange of information across international boundaries, a consistent basis for Government R&D, and protection of the environment. The risks and uncertainties inherent in the development of new technologies may well be disincentives to investment by industry. Government can foster more long-term industrial investment in technology development by pursuing policies which help to lessen these investment risks.

Research and Experimentation Tax Credit

The Research and Experimentation (R&E) Tax Credit is a mechanism designed to increase private sector investment in R&D of new technologies, such as superconductivity. This in turn enhances the innovative qualities and efficiency of the U.S. economy. The tax credit was due to expire in 1985, but was extended first by the Tax Reform Act of 1986 (TRA) for two years in order to enable Congress to evaluate the operation of the credit. The Technical and Miscellaneous Revenue Act of 1988 (TAMRA) extended the credit for an additional year--until December 31, 1989, but with a fifty-percent reduction in allowable R&E expensing. While this action kept the credit from expiring it did not eliminate uncertainty about the credit's future and further reduced the value of the credit to firms performing research.

The current tax credit provision provides only limited encouragement to new enterprise centered on superconductivity or other new fields since it rewards only absolute increases in R&E spending, and restricts creditable expenditures to those incurred "in carrying on" a trade or business. This contrasts with another provision, Section 174, Internal Revenue Code (I.R.C.), which allows R&E expenses to be deducted currently when incurred "in connection with" a trade or business.

Administration initiatives in support of tax credit law reform will aid the commercialization of superconductivity. The President has proposed changes to the present tax credit to encourage U.S. industry to invest in long-range research. These changes include: making the R&E tax credit permanent, thereby providing some degree of certainty in making long-term commitments; extending the credit to cover expenditures by startup firms, which will help encourage venture investment in these

enterprises; and establishment of a two-tier structure for the tax credit, thus encouraging both rapid growth in R&E expenditures as well as sustained commitments. It is strongly recommended that the President's proposal be adopted.

Capital Gains Tax Differential

A lower rate for long-term capital gains will reduce the cost of capital in the United States and create incentives for investment in the long-term productive capacity of American industry. Investment in new production capacity is necessary to bring products incorporating new technologies to the market. The initiatives to lower capital gains tax contained in President Bush's economic program will help stimulate the commercialization of superconductivity.

International Cooperation

While the normal functioning of science bodies provides for information exchange between investigators, it is appropriate for the U.S. Government to establish close contact with basic research efforts in the rest of the world, particularly Japan and Europe.

The U.S.-Japan Agreement on Cooperation in Science and Technology, for example, provides a framework for new relationships for cooperation on superconductivity research and development in coming years. The agreement incorporates provisions to establish a more balanced and reciprocal partnership in joint undertakings to assure comparable access to facilities and activities, and provides provision for the adequate and effective protection of intellectual property rights. The NSF,

through a variety of Japan programs, is encouraging U.S. scientists and engineers to participate in R&D efforts in Japan and to take Japanese language training.

Science and Technology Base

Developing and maintaining a base in enabling technologies such as superconductivity is vital to the future of our Nation. In order to maintain this technology base, steady, predictable support is needed rather than sporadic crisis-response budgeting. A more stable research environment would be created by multi-year authorization and two-year appropriations cycles. Such an approach would help researchers in superconductivity, as well as other key technologies, devote more of their time to research, and less of their time to satisfying paperwork requirements.

The development of superconductive products requires that basic research exist in parallel with commercialization efforts. In order to accomplish this the public and private sectors must work cooperatively, each pursuing their legitimate roles. This method will, if successful, shorten the cycle of innovation which is the key to competing in international markets.

Environment, Health, and Safety

Careful attention to environmental and health and safety concerns is an important factor that distinguishes the U.S. economy from those of some major trading competitor nations. The present high-temperature superconductors contain toxic elements, e.g. barium, thallium, bismuth and lead. Rapid commercialization of these superconductors will, therefore, require both development of standards for

environmental release, and occupational health and safety, as well as, giving early attention to these issues in each agency's R&D program.

It is recommended that, as appropriate, the Environmental Protection Agency and the Occupational Health and Safety Administration develop any necessary new standards for use by the public and private sectors and that all agencies involved in this area incorporate into their R&D programs explicit long-range planning to anticipate issues and to comply with this national policy.

BACKGROUND FOR THE SUPERCONDUCTIVITY ACTION PLAN

**OSTP Task Force For the National
Action Plan on Superconductivity
Research and Development**

December 1989

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CHAPTER I INTRODUCTION

This report provides background information for the Action Plan. This chapter provides a brief history and overview of the government responses leading up to this Plan. Chapter II reviews the current status of our national efforts in superconductivity. Current status is defined at the programmatic, technical, and policy levels. Chapter III presents potential applications which could be possible in the long term. The scenario for such a future could be greatly affected by major breakthroughs or setbacks and is, therefore, highly speculative. But, by matching the baseline account given in Chapter II against the scenario of possible future applications, we can come to a better understanding of where we need to assign responsibilities over the next five years. This Plan, derived from the collective wisdom of experts in both the Government and the private sector, is based on the information presented in this report. The Plan is dynamic and through the feedback provided by readers in the technical and policy communities it will evolve to encompass their collective wisdom.

Because of the close relationship between the high- and low-temperature superconductivity sciences, it is not practical to address only high-temperature programs in the Plan. While research on high-temperature materials is underway, development of applications with low-temperature materials will lay essential groundwork for the later adaptation of high-temperature materials where they offer advantages. Thus, in the sections that follow, the combined programs are addressed, distinguishing high- from low-temperature activities where appropriate.

HISTORY

In 1911, Heike Kamerlingh Onnes and his graduate student discovered that mercury, when cooled to 4 degrees on the Kelvin (K) scale, lost its electrical resistance, a phenomenon known as superconductivity. Tin and lead were also observed to be superconductors at 3.7K and 7K respectively, and although they could be fashioned into wires, they could not transport electrical currents at magnetic fields large enough to be useful. Not until 50 years later was it discovered that niobium-3-tin compounds and alloys of niobium-titanium could carry the needed currents, but with transition temperatures of 18K and 10K respectively. However, even at these low temperatures, which required liquid helium cooling systems, some applications were developed. These so-called "low-temperature superconductors" (LTS) have found commercial application in fields where the cost of generating magnetic fields using conventional copper conductors would be prohibitive. Such an application is magnetic resonance equipment used in medical imaging. The LTS systems have also played a very important role in basic science when employed, for example, in particle accelerators.

In 1986, after several years of experimenting with nickel oxides, K. Alex Mueller and J. Georg Bednorz discovered a compound of barium-lanthanum-copper oxide which exhibited superconducting properties at a transition temperature of 30 K. This was higher than the maximum transition temperature achieved with intermetallic alloys (23 K), and much higher than what had previously been achieved with oxides. Several months later, Paul Chu at the University of Houston developed an yttrium-barium-copper oxide compound that exhibited superconducting characteristics at 95 K. This was significant because a temperature above that of liquid nitrogen (77 K) greatly diminishes refrigeration costs.

This 1-2-3 compound, named after the relative proportions of the constituents, was the first of the "high-temperature superconductors" (HTS) which have generated so much interest and activity in recent years. In early 1988, bismuth and thallium compounds were discovered which exhibited superconducting characteristics at 105K and 125K respectively.

HTS offers a number of potential advantages for commercial applications over LTS systems resulting from direct or indirect reductions in refrigeration costs. First, liquid nitrogen costs considerably less than liquid helium. Also, the reduced complexity of the refrigeration system leads to simpler operation, maintenance, and related training. Reduced weight of the refrigeration system, increased holding time for liquid nitrogen compared to helium coolant, and the possibility of producing much more compact systems due to the decreased insulation requirements also add to the advantages of HTS. In applications where refrigeration costs are a significant fraction of total cost -- such as in superconducting power transmission -- HTS systems offer the potential for lower operating costs.

GOVERNMENT RESPONSES

The Federal Government historically has been an advocate and major source of support for superconductivity research and development. Federal involvement has been largely driven by the basic science that characterizes superconducting phenomena and the resulting scientific exploration made possible by this technology. Long before the discovery of HTS materials, LTS materials were playing an important role in the advancement of science. Superconducting magnets and superconducting sensors made possible new techniques in physics and medicine which have forever changed those sciences. High-energy particle accelerators, magnetic resonance imaging systems and superconducting

quantum-interference devices are just a few of the applications that have been built on the technology of LTS. These applications for LTS will undoubtedly remain important well into the future.

More recently, superconductivity has emerged as a technology of potential importance to national defense, the economy, and the welfare of our citizens. Upon discovery of HTS, this field of science received unusual attention throughout the world. Much of the publicity focused on applications that could become economically feasible with nitrogen-based cooling systems. In addition, since a new set of materials had been discovered, hopes have been raised that new materials in this class with even higher superconducting temperatures will be discovered. The potential for further significant breakthroughs have attracted new worldwide support for the science. It has been recognized that those first to commercialize such a technology could well gain an insurmountable advantage in the world marketplace.

The Federal Government responded rapidly to meet the new challenges of HTS. At the time of the discovery, the Federal Government was spending approximately \$55 million annually on all aspects of superconductivity. A portion of this was redirected to research on high-temperature phenomena within the first year after the discovery. The goals embraced by the Executive branch of the Government at the time were reflected in the President's Superconductivity Initiative, issued at the Federal Conference on Commercial Applications of Superconductivity, on July 28, 1987, which stated:

"The President's initiative reflects his belief that it is critical that the U.S. translate our leadership in science into leadership in commerce. While the

U.S. private sector must take the lead, the Administration is taking important actions to facilitate and speed the process, including increasing funding for basic research and removing impediments to procompetitive collaboration on generic research and production and to the swift transfer of technology and technical information from the Government to the private sector."

These goals set the direction for a number of actions within the Federal establishment that shaped the current programs for research, development, and commercialization of superconductivity that are described below. Among the more important actions directed specifically to superconductivity was the establishment of superconductivity research centers at several Federal laboratories, encouragement of Government-industry-university cooperation in research, and the formation of a "Wisemen's Group" to advise the President on actions to promote commercialization of superconductivity.

Recommendations of the Committee to Advise the President on High Temperature Superconductivity

The Committee to Advise the President on High-Temperature Superconductivity, which was formed under President Reagan's Superconductivity Initiative, assessed the competitive position of the United States regarding the potential commercialization of HTS. In general it found that the main deficiency in the U.S. position was the absence of groups uniting scientific and applications knowledge. The committee made two primary recommendations. The first emphasized the importance of continuing support for individual

investigators and urged increasing support from funding agencies to utilize more fully existing talent. The second recommended creation of a small number (4 to 6) of Superconductivity Consortia (SC's) to address the deficiency identified above. The Advisory Committee recommended that each consortium (in the most basic form) consist of a research university, a national laboratory, and industries engaged in superconductivity research. In addition to these "primary" members other "secondary" members could participate at a lower level.

The Office of Technology Assessment Report

In 1988 the Office of Technology Assessment (OTA) completed an assessment of U.S. competitiveness in high-temperature superconductivity presenting its findings to the Congress in a report entitled "Commercializing High-Temperature Superconductivity." The report identifies three possible response scenarios through which the Federal Government might foster commercialization of HTS. In the first--the flexible response--things remain as they are, with strong support for basic research and for mission-oriented technology development, and little in the way of support for direct commercial technology development. The second scenario, an "aggressive response," argues for (1) more money for NSF to make available for HTS research, (2) Federal sharing in the costs of some private R&D ventures in the hopes of encouraging industry to take a more long-term approach to HTS research, and (3) formation of a working group of experts from industry, universities, and Government to decide the merits of various collaborative proposals and policy options. A third scenario would involve the formation of a Federal technology agency--a proposal which goes beyond the specific needs of HTS. The OTA report suggests that the more

aggressive approach "could substantially improve prospects for rapid commercialization of HTS in the United States at relatively modest cost."

Legislative Actions

Several pieces of legislation came out of Congress in 1988 which added to the governmental focus on superconductivity issues. The Omnibus Trade Bill contained a provision which created the National Commission on Superconductivity charged with reviewing and reporting on the status of superconductivity in the United States vis-a-vis the rest of the world. The National Superconductivity and Competitiveness Act of 1988 called for the development of The National Action Plan on Superconductivity Research and Development. This document is the first response to the mandate for that Plan. In addition, a budget crosscut for superconductivity will be forwarded to Congress in connection with the submission of the President's budget proposal to Congress for FY 1991. It will describe each mission agency's programs in superconductivity and contain estimates of funding for these agencies to continue supporting research in this area.

President Bush's Administration

President Bush re-affirmed the national commitment to commercialization of superconductivity in his April 5, 1989 Message to the Congress Transmitting the Annual Report on International Activities in Science and Technology. In that message he stated:

"Believing that the R&D of today is the goods and services of tomorrow, and believing that further discoveries in superconductivity hold enormous potential for applications, President Reagan signed into law on November 19, 1988, the National

Superconductivity and Competitiveness Act of 1988, which establishes a framework for a national program in superconductivity. ...Our goal as a nation is to lead the world in superconductivity R&D and in translating this new technology into useful products."

The Federal actions which have shaped the Nation's current position in HTS have been guided by prevailing viewpoints of the proper roles of the Government in research, development, and commercialization. The general consensus is that the Government should provide:

- Direct funding support for basic research at the precompetitive stages,
- Direct support for development of products for which the Federal Government is the major market, particularly for defense systems,
- Laws and a regulatory environment favorable to commercialization of new products, and
- Measurement standards, methods, and reference data needed by industry and Government laboratories to effectively characterize new technologies.

In the case of superconductivity the Government can act as a catalyst in bringing together the expertise of the national laboratories, universities, and industry in partnership. This new catalytic role derives from the very nature of this technology. Today, more than ever before, advanced industrial nations are collectively challenged by opportunities afforded by rapid scientific advances and the emergence of a number of highly flexible enabling technologies like superconductivity. These technologies have the potential to generate a wide array of applications substantially impacting the future of many industrial

sectors and product/service lines. In so doing, they could substantially improve the way we live, go about our business, and produce goods and services.

Superconductivity, along with other enabling technologies like advanced materials, digital imaging, microelectronics, flexible computer integrated manufacturing, genetic engineering, optoelectronics, and high performance computing, will not be industry specific and, thus, warrants assistance where feasible and appropriate from the Government. The multidisciplinary nature of the technology and the fact that the benefits from commercialization will accrue over such a long term may make it difficult for individual firms to justify capitalizing the basic R&D expenses required for commercialization. Generic technical advances cut across industrial sectors and markets. With fierce international competition, time will be critical in transferring the technology into marketable products -- with successful commercialization dependent on concurrent research, design, manufacturing, and marketing. The vertically integrated industrial entities that can spread the costs of R&D investments have a strategic advantage in capturing future markets. Finally, a Government effort to foster the technology is also important because of its potential uses in national security.

Because of the time pressure for concurrent effort across the spectrum from research to applications, and the diversity of industries involved, the management challenge is great. The Nation's success in commercializing superconductivity ultimately depends on the private sector, which must make the critical decisions on how much capital, time, and effort to invest. Yet, the challenges are so large and the potential is so great that Federal vision, leadership, and support are warranted to ensure our Nation's stake in the outcome.

Most importantly, the Federal Government must provide stability and continuity for the long-term effort that will be required for the scientific community to solve the large problems inherent in developing commercial applications for these materials. To meet these challenges, the Government, universities, and industry should work in a cooperative and synergistic fashion to capitalize on the greatest strengths of each.

CHAPTER II THE CURRENT STATUS OF TECHNICAL RESEARCH, FEDERAL PROGRAMS, AND POLICIES

TECHNICAL STATUS OF ADVANCED SUPERCONDUCTIVITY RESEARCH

Important properties of any superconducting material are its critical transition temperature (the temperature below which the resistance becomes zero) T_c , its critical magnetic field (the field below which the resistance is zero) H_c , and its critical current density (the current density below which the resistance is zero) J_c . For conventional or low-temperature superconducting (LTS) materials H_c and J_c were large enough to support a growing technology based on the unique properties of superconductivity. The one difficulty with superconductivity using LTS materials is that for them to be operative, temperatures must be maintained near 4.2 K. (The highest T_c prior to 1986 was 23 K, but most materials used for commercial technologies had T_c below 10 K.) This fact has limited development of superconductivity, although in many applications the cost of refrigeration is negligible in comparison with the costs of attempting to achieve the same result with non-superconducting technology.

The Nobel Prize-winning discovery by Bednorz and Mueller in 1986, unleashed tremendous scientific and technological excitement for several reasons. First, the discovery was totally unexpected. Scientists did not predict the superconducting properties of the material and indeed still do not understand the fundamental mechanism for its existence. Secondly, the discovery provided the promise of greatly lessened refrigeration requirements compared with lower T_c materials. Several other factors contributed to this excitement. One was that the potential value of superconductivity was well known to the scientific and

technological community prior to the discovery. Applications and uses were there if the right material came along. Another was that the new high-temperature superconducting (HTS) materials were easily made (in very rudimentary form) thereby permitting many groups, laboratories, and industries to begin research efforts almost overnight after hearing of the discovery. Although, as will be shown later, the complexity of producing materials of suitable quality can be an inhibition to proper scientific experimentation. A final reason for its great excitement was that the discovery came at a time when the country was experiencing a perceived technology gap with other industrialized nations. Superconductivity was viewed by the Government of the United States as a technology in which the United States must lead.

Today, three years after the discovery of HTS materials, superconductivity has become a well known phenomenon worldwide with continuing visibility at the national level. There has been a prodigious outpouring of both scientific and popular articles and news releases. New methods of conducting and managing research are evolving as a result of the desire to develop science and technology together. New partnerships are being formed. A focus on the key issues is emerging. The quality of research and consistency of data are improving as the rush to be first is subsiding. People and laboratories with experience and expertise are leading the research and development (R&D) efforts. These are very promising signs of developing program maturity. Where we are today as far as the "state of the art in superconductivity" will be addressed in three parts: theory, materials, and applications.

Theory

The traditional microscopic theory of superconductivity proposed by J. Bardeen, L.N. Cooper, and J.R. Schrieffer (widely known as the BCS theory), developed in 1957 and subsequently refined, had been adequate to explain the properties of known superconductors--until the discovery of the new oxide superconductors. This theory is based on the physical notion that pairs of electrons are coupled with an interaction determined by the atomic vibrations of the underlying lattice (the so-called electron-phonon interaction) and that these "Cooper pairs" condense into a resistanceless phase at low temperatures. A result of this theory, confirmed by experiment, is that the superconducting electron pairs have a charge of twice that of an electron. All of the other properties of previously known superconductors could be understood in terms of the BCS theory, and quantitative first-principles calculations of these properties were highly successful. The electron-phonon interaction was considered the fundamental mechanism of all known superconductors.

Although the theory of superconductivity for the conventional or low T_c ($T_c < 25$ K) materials is well established, it did not lead to the prediction of HTS materials. In fact, the theory often was used to argue against the possibility of HTS. At this stage, we still do not have an adequate theory to explain HTS. There are many new and revitalized theories around today but most make qualitative predictions--not quantitative--and hence are difficult to confirm or deny. In fact, definitive experiments have not yet been determined that would prove or disprove a given theory. There are, however, truly exciting challenges to be solved by the theorist in superconductivity today. Indeed, many of these challenges do not necessarily involve superconductivity per se, because there are so many other unexplained properties of the new oxide materials. For instance, metal insulator transitions

occur in these materials. Various types of magnetic behavior are observed when the materials are not superconducting. Indeed, the fundamental nature of the electronic behavior of these materials may be different from anything we have observed and described to date.

The theorist faces a challenge. Not only are the materials complex in atomic structure, but by virtue of being so complex they are difficult to prepare in quality forms necessary to do careful experiments to guide the theorists. Indeed, experimental data are difficult to assess, often in error, and change with time as sample quality improves. It is extremely important that theoretical and experimental studies be closely coupled if rapid progress is to be made. Carefully made and well characterized samples must be used in these studies.

Materials

There are more than 6000 elements, alloys, and compounds that are known superconductors. Up until the discovery of the new HTS materials, most superconducting materials were metallic with moderately good electrical conductivities (organic, polymeric, and a few ceramic superconductors did exist). The alloy used in most magnet applications of superconductivity today is NbTi, which becomes superconducting at 10 K. This alloy is preferred because of its ductility and its ability to carry large amounts of current at high magnetic fields and still retain its superconducting properties. Brittle compounds with intrinsically superior superconducting properties are also being developed for magnet applications. The most promising of these compounds are Nb₃Sn, V₃Ga, Nb₃Ge, Nb₃Al, and NbN, which have higher T_c (15 to 23 K) and higher critical currents at high magnetic

fields than NbTi. Development of reliable processing methods for forming wires and magnets of these brittle materials remains an issue.

Electronic applications of superconductivity use different materials. Development began using Pb or Nb (T_c of 7-9 K) in bulk form, but later emphasis switched to materials deposited in thin film form. PbIn and PbAu alloys became preferred over pure Pb films because they are more stable. Improved vacuum deposition systems eventually led to the use of pure Nb films because they, in turn, were more stable than Pb alloy films. Recent developments in thin film synthesis techniques are leading to the use of the refractory compound NbN (T_c of 15 K) in electronic applications. NbN is very stable and possesses a higher T_c than either Pb or Nb. New HTS materials are highly complex ceramic oxide materials based on a cubic perovskite-type structure. La-Ba-Cu-O was the first discovered at 30 K, Y-Ba-Cu-O was discovered soon thereafter at 94 K. About a year later, discoveries of Bi-Sr-Ca-Cu-O at 110 K and Tl-Ba-Ca-Cu-O at 125 K were announced. All these superconductors with T_c above 35 K have some basic similarities. They contain a Cu-O planar structure and most contain divalent alkaline metals. T_c increases as the number of layers increases to 3 or 4 (peak 125 K) and then appears to fall as more planar Cu-O layers are added. Indeed a material with very large numbers of Cu-O planes becomes insulating. Qualitative arguments are being put forth to explain this peak in T_c near 125 K based on the ability to increase the electronic charge in the layer. If these qualitative arguments hold up, one may expect that T_c in these Cu-O layer compounds to remain below 150 K. Hence, in these materials, room temperature superconductors may not be feasible. (But because the theory has not been developed, such a statement is certainly contestable.) These HTS materials remain superconducting in very high magnetic fields

(i.e. H_{c2} is probably over 1 megagauss) but magnetic flux enters the interior of the superconductor at very low values of magnetic field (i.e. H_{c1} is probably lower than 50 gauss). Large H_{c2} is important for DC and low-frequency power applications, but large H_{c1} is important for high-frequency power applications. At present the small H_{c1} may constrain high-frequency power applications.

One of the most important parameters for useful application of this technology is the critical current value J_c , which depends on both temperature and magnetic field. At low magnetic field, the critical current varies from 10^6 amp/cm² at 77 K to 10^8 amp/cm² at 4 K for high quality films. Thus, for those applications that do not require high magnetic fields, the new HTS materials look very promising. On the other hand, the critical current in a 3 Tesla (T) magnetic field is much smaller, and even the best reported values (10^5 amp/cm²) are being questioned due to interpretation and criteria problems. The fundamental physics of how superconducting materials carry large currents in high fields suggest that the ability to carry high current at high fields may not be easily achieved in HTS materials. There are several problems with the preparation of these materials. They are structurally highly complex and require high-temperature anneals or heat treatments (which create reaction problems with materials that make contact during annealing). Because of these difficulties, reproducibility is poor and chemical stability is uncertain. In sum, commercial, production-scale quantity, high-quality samples of HTS materials, needed to support a growing technology, do not exist yet. However, there are many manufacturers trying to fill this gap and most research groups are trying to develop new fabrication techniques. Materials R&D remains the number one issue in our progress on HTS mater-

ials. It should be stressed that there are no fundamental issues that limit uses, but that tremendous materials development is required.

Applications

There are many potential applications of superconducting materials. Most have been known for years and have been evaluated and tested by using the older, LTS materials that operate at temperatures near 4 K and require the use of liquid helium. For example, the International Voltage Standard is defined worldwide by using the superconducting properties in circuits cooled to 4 K. Ultra-sensitive microwave and millimeter-wave receivers that use superconducting detectors cooled to 4 K or below are used by radio astronomers in their very large antennas to study the cosmic background. Superconducting magnets operating at 4 K are crucial and integral components of magnetic resonance imaging systems. Superconducting magnetometers capable of detecting minute magnetic field emanations from the body are used as clinical tools in medical diagnostic work. Very large superconducting magnets are used in fusion research systems. Magnetically levitated trains supported by superconducting magnets have operated at speeds up to 300 MPH and are under evaluation. Superconducting magnets and microwave cavities are in use in many state-of-the-art particle accelerators worldwide. Many potential applications also interest the military. Electronic applications include magnetic detectors for antisubmarine warfare and mine warfare; very sensitive and very compact receiving antennas for submarine communications systems; very low noise, wide signal bandwidth microwave and millimeter-wave surveillance and communications receivers; and very large bandwidth, high-resolution analog and digital signal-processing circuits.

Thin superconducting films have been made into extremely sensitive detectors of electromagnetic radiation. These films have been made into sensors for detecting infrared radiation, i.e. for night vision and detecting missiles by the heat they emit. In the area of large power applications, superconducting electrical motors and generators have been developed using LTS materials and have been used to propel experimental Navy ships. This has the potential for yielding significant advantages in engine size and weight. In the longer term, HTS materials may enable magnetohydrodynamic propulsion. Superconducting coils are under development for use in pulsed-energy weapon systems.

Thus, for specific applications where there are stringent performance requirements, superconducting technology, even at 4 K, has been in extensive use despite the inconvenience of the refrigeration required for operation at this temperature.

INDUSTRY EFFORTS

Some large industrial concerns have made substantial efforts in superconducting technology development, with examples being IBM, AT&T, DuPont, Bellcore, Allied Signal, TRW, General Electric, Westinghouse, W.R. Grace, United Technologies and Hughes. Other industrial firms with significant efforts include Hypres, Babcock and Wilcox, Varian, Micrilor, BTI, IGC, Honeywell, Raytheon, Corning, General Dynamics, General Electric, COMSAT, Boeing, Eastman Kodak, General Atomics, Lockheed, Rockwell, Hewlett Packard, Ceracon, American Magnetics, and Foster-Miller. Additionally, several start-up companies with superconductivity as their major focus have been formed, including: CPS Superconductor, Superconductor Technologies Inc., Conductus, American

Superconductor, Superconductive Components, and the planned creation of the Superchip Corporation.

CONSORTIA

There are many consortia cropping up in the superconductivity field. It would be beyond the scope of this report to do them all justice here. However, it is instructive to present some of the larger efforts.

Presently, the largest HTS Consortium in the United States is the Texas Center for Superconductivity at the University of Houston (TCSUH)/Microelectronics and Computer Technology Corporation (MCC) consortium which currently consists of several industrial members: Bellcore, Boeing, DEC, DuPont, 3M, Motorola, and Westinghouse. The annual budget at TCSUH is about \$10 million, mainly from the Defense Advanced Research Projects Agency (DARPA), the State of Texas, the National Science Foundation (NSF), and private sources, while the budget of MCC is \$1.1 million from industry. Recently, the TCSUH/MCC consortium has also signed research cooperation agreements with the three Department of Energy (DOE) Superconductivity Pilot Centers at Argonne, Los Alamos, and Oak Ridge National Laboratories, and actively exchanges information with them on several levels. Other state consortia include one at the State University of New York - Buffalo and the Consortium on Superconducting Ceramics at Lehigh University in Pennsylvania.

In concord with recommendations of the White House Superconductivity Advisory Committee, IBM, and AT&T, have formed a consortium with the Massachusetts Institute of Technology's (MIT) Lincoln Labs to accelerate the development of superconducting

electronics. DuPont and Hewlett-Packard and the Los Alamos National Laboratory have also announced the intent to form a consortium to pursue electronic applications.

The National Aeronautics and Space Administration's (NASA) Lewis Research Center has recently signed a Memorandum of Agreement with Argonne National Laboratory to jointly pursue HTS research of mutual interest. Other NASA collaborative efforts are also discussed under the agency description section.

The NSF has established a Science and Technology Center for High-Temperature Superconductivity which involves the Universities of Illinois and Chicago, Northwestern University, and Argonne National Laboratory.

It should be noted that most of the consortia exist only on paper or are in very early stages of development. The future of these efforts is unclear.

FEDERAL AGENCY PROGRAMS

The advent of HTS in late 1986 benefitted the field as a whole. The HTS breakthrough revived interest in low-temperature work to provide an enhanced, low-temperature technology base for future use in high-temperature technology. President Reagan's 11-point initiative helped to stir U.S. Government research forces into action. Large funding levels were earmarked for superconductivity. However, the majority of the Federal money awarded to these programs was reprogrammed from other important research efforts.

While approximately \$100 million has been devoted to superconductivity by the various industrial concerns for fiscal year 1989, the U.S. Government has earmarked almost twice that amount for its own efforts. The Federal agencies supplying the majority of

funds are DOE, Department of Defense (DOD), NSF, NASA and Department of Commerce (DOC) through the National Institute of Standards (NIST). The Department of Transportation (DOT), the Department of the Interior (DOI), and the Federal Emergency Management Agency (FEMA) also actively follow the technology. Detailed descriptions of the current goals and priorities, key responsibilities, and participation with industry and universities have been provided by each Government agency and will be included in the budget cross-cut. Additional sources of information concerning Federal programs include: "Federal Research Programs in Superconductivity," compiled by the OSTP Committee on Materials (COMAT) Subcommittee on Superconductivity; and "Commercializing High-Temperature Superconductivity," produced by the Office of Technology Assessment.

Department of Energy

The DOE has had a long-standing interest in superconductivity because of its potential use in high energy physics, fusion, and in a variety of other energy systems such as electrical transmission, generation, and storage. Since the days of the Atomic Energy Commission, a predecessor to the Department, support of superconductivity research and procurement of superconducting devices by the DOE have had a major positive impact on the economic viability of the small U.S. superconductor industry. For example, the Department's Fermi National Accelerator Laboratory completed the world's largest superconducting project, the superconducting Tevatron accelerator, which contains 1,000 magnets using 60 tons of niobium-titanium superconductor supplied by industry. The Department's involvement in the development of superconductors has been and will

continue to be substantial, as will its contributions to the development of a U.S. superconductor industry.

The major programs in HTS are in the Office of Energy Research, the Office of Conservation and Renewable Energy, and the Office of Defense Programs. Within the Office of Energy Research, the Office of Basic Energy Sciences is responsible for basic research. In the Office of Conservation and Renewable Energy, the goal of the Office of Energy Storage and Distribution is technology development for applications in electric power (utility-sized) systems. These systems include generators, transformers, transmission/distribution lines, and magnetic energy storage. The goal of the Office of Energy Utilization Research (OEUR) is to support R&D aimed at understanding processes that underlie a variety of energy systems and end-use applications. The OEUR Division of Energy Conversion and Utilization technologies (ECUT) has two goals--to develop generic enabling technologies for advanced energy conservation concepts and to understand the physical processes underlying these technologies to broaden their applicability. The Office of Defense Programs focuses on nuclear weapon applications. The major programs in low-temperature superconductivity are in the Office of Fusion Energy and High Energy and Nuclear Physics.

High Temperature Superconductivity

Research in the Office of Basic Energy Sciences addresses synthesis, understanding the crystalline structure, theory, physical and chemical properties, processing to make bulk materials, and mechanical properties. This research program deals with fundamental questions regarding the mechanism by which these materials become superconducting, the

fundamental parameters of critical temperature, critical magnetic field and critical currents, and synthesis of new materials to expand the range of these parameters. The research program also addresses the scientific understanding of processing needed to make reliable forms such as films, wires, and tapes with optimum superconducting properties. As called for in the Superconductivity Initiative, the Office of Basic Energy Sciences has established three Superconductivity Research Centers to act as information sources on specific superconductivity areas, including Argonne (conductor applications), Lawrence Berkeley (electronic devices), and Ames (fundamental and generic properties).

The Office of Energy Storage and Distribution has the responsibility of developing HTS technology for large-scale applications requiring high current in magnetic fields. The applied research will provide a technology base for industry to develop a wide range of commercial products including electric motors, generators, transmission/distribution lines and storage magnets. This includes responsibility for the development of processing and fabrication, technical/economic studies to determine the most appropriate initial application focus or focuses, and device development.

The goals of the DOE Superconducting Technology for Electric Power Systems (STEPS) applied research program are to advance the knowledge of HTS technology and to apply that knowledge to large-scale applications in the U.S. electric power industry. STEPS activities are performed by nine national laboratories and their industrial and university partners. These developmental programs are enhanced by strong interactions with the ongoing superconductivity basic research efforts and with the technology transfer programs already underway in the national laboratories. The program strategy is to

develop HTS coils and cables in parallel with a secondary emphasis on device investigations and application studies.

Former DOE Secretary Herrington established superconductivity pilot centers at three of its national laboratories: Argonne, Oak Ridge, and Los Alamos. They are experiments designed to work with industry in accelerating the enabling technologies for the development of commercial HTS products by making national laboratory resources more readily available to industry and university researchers. Key elements addressed in the two year pilot center experiment are: intellectual property rights for cost-sharing arrangements with private companies, expedited contracting features, and the protection of data from competing companies. The experiment emphasizes the collaborative role of industry in developing the work agenda of the pilot centers. Fifteen collaborative agreements between industrial organizations and the three national laboratories have been signed under pilot center auspices, and the program is currently oversubscribed in terms of expressed industrial interest.

The goal of the ECUT Program (see page II-12) is to develop proof-of-concept HTS components and devices (e.g., motors, magnetics, sensors, and magnetic field shielding) generic to energy conservation concepts. Efforts focus on applications where existing HTS materials exhibit nearly satisfactory current density and magnetic field stability.

The Office of Defense Programs is responsible for R&D in HTS for nuclear weapons applications which include: switches, radio frequency (RF) cavities, co-axial lines, microwave generators, energy storage, infrared (IR) generators and detectors, magnetic anomaly detectors, and RF shielding and guides.

Low Temperature Superconductivity

The Office of Fusion Energy supports the development of large, high-field, steady-state, and pulsed superconducting magnet systems that are needed for fusion reactor systems. The R&D efforts are concentrated on the utilization of low-temperature niobium-tin superconductors to fabricate the large 10 to 15 T magnets that are needed. The improvement of niobium-tin superconductor performance and development and characterization of the properties of structural and electrical insulator materials at 4 K are an integral part of the program.

The Division of High Energy Physics directly supports the development of the conductor technology needed to advance the performance of accelerators and detectors used in experimental high-energy physics. R&D on conventional, LTS materials includes a large effort on the dipole magnets for the Superconducting Super Collider, special focusing magnets for the Stanford Linear Collider, solenoids, large detectors, and a generic program to improve the characteristics of niobium-titanium superconductor materials.

The Division of Nuclear Physics supports development of magnets for a Relativistic Heavy Ion Collider at Brookhaven National Laboratory and work on superconducting RF cavities at several other sites. The Continuous Electron Beam Accelerator Facility (CEBAF) will use 1.5 GHz RF cavities that operate at about 2 K, reducing the power requirements for acceleration of the beam by about a factor of 100 compared to normal RF cavities. At CEBAF, there is also activity under way in the design of superconducting magnets for spectrometers. Other nuclear physics facilities actively developing RF cavities are the ATLAS heavy ion research facility at Argonne National Laboratory and the Nuclear Physics Laboratory at the University of Washington.

Department of Defense

The DOD effort is divided among the Army, Navy, Air Force, DARPA, Strategic Defense Initiatives Organization (SDIO), and National Security Agency (NSA). The Army effort is still in the early stages and limited in-house and contractual resources have been set aside for superconductivity research. The Navy has provided continuous support for superconductivity since 1946, both at in-house laboratories and through contract research with universities and industries. Following the discovery of HTS, the Navy re-examined and enhanced its support for superconductivity. It formed a Naval Consortium for superconductivity which monitors the various Navy programs, and developed a 5-year plan for R&D for superconductivity. The Navy plan includes both HTS and LTS programs. It has a significant component devoted to fundamental studies of HTS materials, as well as development programs aimed at Superconducting Quantum Interference Device (SQUID) magnetometry for Navy sensors (mostly LTS), electronics for signal processing and radiation detection (HTS and LTS), power application with emphasis on ship propulsion (LTS), and space applications (HTS).

The Air Force conducts modest in-house efforts together with a major contract program, and, has placed great emphasis on materials research (both LTS and HTS) for electronics applications. Its primary focus is in thin film processing and quantum tunneling structures. In 1988, it helped to establish (1) the Stanford University Center for Research in Superconductivity and Superconducting Electronics and (2) the Boston-area Superconductive Electronics Consortium with integrated materials and electronics activities at Lincoln Laboratories, MIT, and the Rome Air Development Center (RADC) directorates at Hanscom Air Force Base to foster their efforts in superconducting electronics. Additional-

ly, the Air Force funds significant thin film programs at the University of Minnesota and the Westinghouse R&D Center.

The DARPA and SDIO programs are implemented through a variety of Government, industry, and university contracts, as neither organization has in-house materials research capabilities. DARPA has established superconducting research centers at the University of Houston, at state universities in Florida, and has formed industrial consortia with Superconductor Applications, Inc. and the Superchip Corporation. The DARPA program is broad in technology scope, including power, electronic, and magnetic applications, but narrow in materials scope as it includes only HTS materials. The SDIO effort is also broad in focus, including sensor and electronics applications as well as a very large-scale LTS magnetic energy storage system. Both HTS and LTS technology are being actively pursued. Its primary emphasis is on near-term applications including IR focal plane array sensors, millimeter wave components for radar and communications, rf accelerator cavities, and high-power, high-current downloads for superconducting magnetic energy storage systems.

Finally, the NSA is interested in data acquisition and processing for electronics applications, but at a modest funding level.

The National Science Foundation

The majority of NSF funding in superconductivity is university-based, concentrating on fundamental research into theory, experimental properties, structure, synthesis, and processing of the HTS materials. Several NSF-supported facilities offer current and potential benefits to superconductivity researchers in Government, industry, and universities. These include the National Magnet Lab at MIT (which provides the highest fields available

to test and characterize superconductors), the synchrotron radiation facilities at Wisconsin and Cornell, and the Center for High Resolution Electron Microscopy at Arizona State University. The NSF has recently established a Science and Technology Center for HTS research at Illinois. This center involves the University of Chicago, Northwestern, Argonne National Lab, and the University of Illinois as the four major partners. NSF also supports significant thrust efforts in HTS in the Materials Research Labs at MIT, Stanford, Northwestern, and Illinois. The Division of Materials Research of NSF started 2 new Materials Research Groups at the University of Wisconsin and the University of Minnesota in FY 1989. NSF support for single investigators is also important in training the workforce that will be available to work on applications of HTS.

The National Aeronautics and Space Administration

NASA is investigating the potential applications of HTS materials for aeronautics and space and actively pursuing research and development to exploit both HTS thin and bulk materials technology. Current areas of agency emphasis include: components for satellite and deep-space communication and data systems, sensors and associated cryogenic systems for radiometry and spectroscopy, propulsion and power transmission, magnetic energy storage for space applications, and developing HTS materials that will be stable in the space environment. NASA has achieved a breakthrough in high-frequency HTS device technology by producing a material which retains its superconducting characteristics at millimeter wavelengths. The existing significant effort includes both in-house and university grant activities. To date, support for this program has been secured almost exclusively through reprogrammed funds and center discretionary funds. A national

consortium is being structured which will be centered at the NASA Jet Propulsion Laboratory and involve participation from industry, government, and academia as well as considerable support from the State of California Department of Commerce. In addition, a Memorandum of Agreement has been established between the NASA Lewis Research Center and the DOE Argonne National Laboratory to jointly pursue HTS research of mutual interest.

Department of Commerce

The National Institute of Standards and Technology (NIST) has two areas of activity in HTS. NIST is providing basic measurement and standards support to U.S. organizations, including: measurement of fundamental data on materials physics and chemistry; development of measurement methods and verified data characterizing the superconducting properties of new materials; and measurement support for materials process control. NIST also houses the Superconductivity Research Center for Electronic Applications, established by the President's Superconductivity Initiative.

Department of Transportation

The DOT has a strong interest in the application of superconducting materials. The DOT's interest covers a broad range of potential applications of advanced superconductivity including sensing for weapons detections, propulsion for ships and high-speed ground transportation, as well as improvements in all electrical systems in vehicles as well as electrification. The special marine propulsion applications that are under study in Japan in the form of propeller-less drive systems are of interest to DOT. The magnetic levitation

technology for high-speed trains is another area of current interest. There are under consideration at least six defined corridors in the United States.

Department of the Interior

The DOI has been engaged, through the Bureau of Mines, both in materials research and in acquiring data on commodity materials production, to analyze those data, and to disseminate them by means of periodicals and special reports. Since superconducting materials require relatively rare byproduct elements with limited world reserves, the Bureau will continue to monitor technical developments in the superconductor arena. The Bureau's ceramics research on superconductivity is conducted at its Tuscalusa (Alabama) Research Center and metal research at its Albany (Oregon) Research Center. The Bureau is interested in the potential of superconducting magnets for mineral and materials processing as well as in mining operations.

Federal Emergency Management Agency

FEMA's interest in HTS is integral with developing options to improve our industrial base responsiveness capability for defense and essential civilian needs. In terms of specific HTS applicability to industrial manufacturing; FEMA is interested in five areas: 1) Energy Systems - especially Extra-High Voltage Electric Power; 2) Telecommunications Systems - specifically telephone, broadcast and command and control; 3) Financial Systems - specifically electronic funds transfer; 4) Defense Manufacturing Systems - specifically laser-based machinery and electro-mechanical technologies; and 5) Transportation Systems - all modes.

Table II-1 summarizes the current technical programs by agency.

TABLE II-1
SUMMARY OF AGENCY
SUPERCONDUCTIVITY PROGRAMS
FOR FY 1989 BY APPLICATION CATEGORY

<u>AGENCY</u>	<u>SENSORS</u>	<u>ELECTRONICS</u>	<u>POWER & PROPULSION</u>	<u>PARTICLE ACCELERATORS</u>	<u>OTHER</u>	<u>TOTAL IN \$000</u>
NIST	LTS: SQUIDS, IR Radiometer, Microwave power standard, HTS: IR Detector	LTS: A/D Converter	Materials R&D	Materials characterizations	Superconductor Standards, Josephson Volt Standard	5,300
DOE	Industrial Sensors and Controls	Electronics for nuclear weapons program applications	Power Generation, Magnetic Energy Storage, Mo-Transmission, Motors, Material separators	Dipole magnets for SSC, rf cavities	Theory, generic enabling technologies, materials processing and properties	75,000
DOD						
ARMY	Magnetic/EM/IR Sensors, Mine Countermeasures	Signal Processors	EM Launchers		HTS: Theory, Proximity effect extrapolation, materials characterization and processing	2,200
NAVY	Magnetic sensors for ASW and mine counter-measures, EM/IR/Sensors	Signal processors, logic, memory, surveillance, communication, antennas, mm-wave generators	Electric ship drive, energy storage, E&M launchers		Occurrence, Theory, Materials Characterization, processing, environmental stability	14,400

<u>AGENCY</u>	<u>SENSORS</u>	<u>ELECTRONICS</u>	<u>POWER & PROPULSION</u>	<u>PARTICLE ACCELERATORS</u>	<u>OTHER</u>	<u>TOTAL IN \$000</u>
AIR FORCE	LTS: Inertial Sen- sors, HTS: Sensors	LTS: signal proc- essing, HTS: signal processing, antennas			Occurrence, Mater- ials Characterization, Processing	8,000
SDIO	LTS: EM/IR Sen- sors, HTS: Focal Plane Arrays	LTS: Signal Process- ors, HTS: signal process- ing, microwave and mm-wave systems, antennas, radar	LTS: EM Launchers, SMES Design Com- petition HTS: power systems	HTS: RF Cavities, Magnetic Shielding		33,500
DARPA	HTS Sensors	HTS: Interconnects, Signal processors, A/D converters, an- tennas	HTS: Motors, Gener- ators, EM Launchers, pulsed power		Synthesis, Processing	25,000
NSA		LTS: electronics, cross-bar switches				400

<u>AGENCY</u>	<u>SENSORS</u>	<u>ELECTRONICS</u>	<u>POWER & PROPULSION</u>	<u>PARTICLE ACCELERATORS</u>	<u>OTHER</u>	<u>TOTAL IN \$000</u>
NASA	LTS: SQUID Magnetometers, Gravity Gradiometers, HTS: Sensors and associated cryogenics	HTS: Microwave Components, Switches	HTS: Bearings, Thrusters, Magnetic Energy Storage, and Power Transmission		Space Materials Technology	7,000
DHHS	Nuclear Magnetic Resonance Spectroscopy and Imaging, Magnetoencephalography (MEG)					3,300
NSF					Support for individual scientists, support for centers and groups, and support for user facilities, training of graduate students and post-docs in HTS	26,000
TOTAL FOR ALL AGENCY PROGRAMS						200,100

CURRENT POLICIES TO ENCOURAGE COMMERCIALIZATION

A number of legislative and executive actions have occurred in recent years that either directly or indirectly affect the policy climate for the development and commercialization of superconductivity. These actions are listed below in decreasing order of their direct relationship to superconductivity research, development, and commercialization.

The President's Superconductivity Initiative

In July 1987 President Reagan issued a directive to bring focus to the Federal actions in support of superconductivity. The Initiative consisted of eleven (11) points--three legislative and eight administrative in nature.

1. A proposal to expand the National Cooperative Research Act (NCRA) to include some types of joint production ventures.
2. A proposal to amend U.S. patent laws to increase protection for manufacturing process patents, a part of which was enacted in the Omnibus Trade Act.
3. Proposed legislation to authorize withholding the release of commercially valuable scientific and technical information under the Freedom of Information Act that would harm U.S. economic competitiveness.
4. Establishment of an advisory group to the President under the auspices of the White House Science Council. This Superconductivity Advisory Committee produced a report at the end of 1988, the recommendations of which are given later.
5. The establishment of a number of Superconductivity Research Centers. Specific assignments for these centers were given to the departments of Energy and Commerce. Also, the National Aeronautics and Space Administration established a

coordinating group on superconductivity, the National Science Foundation augmented support for HTS research at three materials research labs, and the Department of Defense is developing a multi-year plan to ensure the most immediate use of superconductivity technologies in military systems--all in response to the Initiative.

6. Urging all Federal agencies to implement quickly the steps outlined in Executive Order 12591 designed to encourage technology transfer and research cooperation among Federal, university, and industry organizations. The agencies are in various stages of implementing this request.

7. Directing the Patent and Trademark Office to accelerate the processing of patent applications and adjudication of disputes involving superconductivity technologies when requested by the applicants to do so. As described later in this report, this action has been taken.

8. Directing the National Institute of Standards and Technology to accelerate its efforts to develop and coordinate common standards related to superconductivity. This effort is under way.

9. Encouraging the reallocation of Federal agency monies towards superconductivity research. The agencies have complied.

10. Requesting that DOD accelerate prototype work in sensor, electronic, and superconducting magnet-based military applications and that the Department of Commerce accelerate development of prototype devices in detection and measurement of weak magnetic fields. These programs have been accelerated.

11. Taking advantage of the opportunity presented by the U.S.-Japan Science and Technology Agreement to seek reciprocal U.S. opportunities to participate in Japanese government supported research and development, including superconductivity. Bilateral discussions have begun on this topic.

National Superconductivity and Competitiveness Act of 1988

This act directs the Federal agencies to promote collaborative arrangements in and with industry and to promote development of manufacturing and processing technologies for superconductivity. The Action Plan is required by the act. In addition it directs specific agencies to work in a wide range of superconductivity technologies and applications. It also reinforces technology transfer mandates to the agencies and laboratories. The Director of OSTP and the Secretaries of Commerce and Energy are asked to identify Federal policies and regulations that may impede long-term industry investment in areas such as the commercialization of superconductivity.

Omnibus Trade and Competitiveness Act of 1988

The Act established the National Commission on Superconductivity and required that the Commission review various areas including: incentives; regulatory changes; research emphasis; coordination and data dissemination; and foreign competition. The Commission provides a forum in which eminent members of the Government and the private sector can address impediments to commercialization of superconductivity and present their views to the President and Congress.

The National Cooperative Research Act of 1984

This Act encourages collaborative R&D by groups of companies. Over 125 R&D consortia have been registered under the Act, which modifies the operation of antitrust laws to reduce the incentive for third party civil suits. The Act contains three provisions:

1. Clarification that joint research and development is to be analyzed under a "rule of reason" standard that takes full account of its competitive benefits and may not be held unlawful per se.
2. The limitation of what a third party could obtain when filing for recovery. This limitation applies to any of the antitrust acts when filing against persons engaged in joint research and development who have registered under the Act. The claimant is limited to damages plus reasonable legal fees, as opposed to the treble damages which have been previously been allowed.
3. A provision for the payment from the claimant to the defendant of attorney's fees and other costs of the suit if the claim is judged to be frivolous, unreasonable, without foundation, or in bad faith.

Together, these three provisions remove a major barrier to collaborative R&D. For many companies, large and small, the financial risks associated with long-term research programs devoted to superconductivity would be too great to assume alone. This Act provides means to distribute that risk more broadly among U.S. industries.

Federal Technology Transfer Act (1986) amending the Stevenson-Wydler Act (1980)

The Federal Technology Transfer Act of 1986 created a national policy and legal framework for the management and commercialization of technology developed with Federal resources. Specifically, the Act allows federally owned and operated laboratories to perform cooperative research projects with the private sector and negotiate ownership arrangements for resulting inventions. This decentralized approach has significantly increased proprietary cooperation between the labs and U.S. industry.

The law also provides financial incentives for technology transfer and commercialization within the private sector. Laboratories are allowed to keep the majority of resulting royalties (the parent agency can award a percentage to other labs if desired), and share at least 15 percent of the total royalty return with government inventors. Before approving cooperative arrangements with foreign companies under these authorities, agencies must determine that U.S. companies have equal access to R&D opportunities in the country in question.

Antitrust Enforcement Guidelines for International Operations

These 1988 guidelines detail a sympathetic enforcement policy that acknowledges the globalization of markets and the precompetitive benefits of joint ventures. The benefit of these guidelines to superconductivity is to clarify the conditions under which industries can conduct joint research and development with minimal risk of antitrust violations.

Facilitating Access to Science and Technology

Executive Order 12591 (April 1987) reinforces implementation of earlier legislation to improve the access of Federal laboratory technology, expertise, and facilities to the private sector, as well as to state and local governments and universities. The order provides several very specific requirements intended to make this process of "technology transfer" work in a businesslike fashion, including patent licensing, the negotiation of simple collaborative R&D agreements between these laboratories and other organizations, and participation in consortia.

The University and Small Business Patent Procedure Act (1980) (amended by the Trademark Clarification Act (1984))

These acts give universities and small businesses the right to elect title to patents developed with Federal funding, including those developed under their operation of Government-owned laboratories (with some exceptions). By vesting intellectual property rights with non-governmental organizations the probability for successful commercialization is greatly increased.

Patent Law and Intellectual Property Rights

In accordance with the President's Initiative on Superconductivity, the Patent and Trademark Office (PTO) will, on applicant's request, accord "Special" status to all patent applications for inventions involving superconductive materials, manufacture, and use. This

special status places the application on a tracking procedure which assures timely examination and processing.

The U.S. Patent System is functioning well. The increased confidence of the public in the patent system is demonstrated by the steady increase in patent application filings. In 1981, filings were 107,000 and in 1989 the filings are expected to reach 152,000 applications. The creation of the Court of Appeals for the Federal Circuit (CAFC) in the early 1980's provided consistency in patent decisions which also increased public confidence in the U.S. Patent System. Over the last four years the Patent and Trademark Office has recruited and trained over 1000 examiners to maintain its quality examination level.

The Patent and Trademark Office is employing a modern Automated Patent system (APS) to maintain and improve quality examination. All 1400 examiners have electronic access to search approximately 1 million U.S. patents issued since 1975. A test of the utilization of a full image file in one of the PTO's examining groups has been successfully completed. Procedures are underway to expand this utilization to another examining group.

United States business community, academic institutions, and inventors endeavoring to develop and commercialize superconductivity inventions will benefit from the overall United States Government efforts to strengthen both the United States and foreign patent systems. These efforts include Special 301, the General Agreement on Tariffs and Trade (GATT), and the harmonization of patent laws between nations.

The Small Business Innovation Development Act (1984)

Through FY 1989, \$1.35 billion in research grants have been made to small businesses under the Small Business Innovative Research (SBIR) program. The program is intended to stimulate technological innovation, use small businesses to meet Federal R&D needs, increase private sector commercialization of innovations derived from Federal R&D, and foster and encourage participation by minority and disadvantaged persons in technological innovation. The SBIR program adds to the diversity of ways in which financial support can be obtained from the Government for innovative approaches to the problems in superconductivity. The program is designed to provide seed funding from the Government to launch innovations which have short-term prospects for commercialization.

The program is divided into three phases. Phase I contracts (or grants depending on the agency), limited to \$50,000, are designed to explore the scientific and technical feasibility of a proposed idea. Phase II projects, limited to \$500,000, develop the idea's potential to meet specific agency program needs. Phase III is directed toward commercialization of the technology with no Federal funds involved.

In 1983, 10 SBIR Phase I projects relating to superconductivity were funded. By 1987 this number had jumped to 34 Phase I awards and 7 Phase II awards. In 1988, 58 SBIR Phase I projects were funded and 14 Phase II projects were funded. Thus, the number of SBIR projects involving superconductivity has increased dramatically in the last two years. Two factors may account for this increase--either agencies are expanding the number of superconductivity topics in their SBIR solicitations, or more high quality proposals on superconductivity topics are being received by the participating agencies. Agencies may fund more than one proposal on each topic in their SBIR solicitation or may

choose to fund no proposals for a particular topic. These decisions are made by the agency after technical review of the SBIR proposals is completed. In this way, current agency research priorities are integrated into the SBIR award process.

Title V Report, April 1989

This report of the President on international activities in science and technology indicated the initiation of numerous bilateral and multilateral dialogues on the benefits of effective, equitable intellectual property rights. The advances in international protection of intellectual property rights for U.S. interests exemplified by the U.S.-Japan Agreement on Cooperation in Science and Technology signed in 1988 improves the competitive environment for U.S. companies working on superconductor technology.

Council on Competitiveness

The Vice President chairs this council of cabinet secretaries, reviewing competitiveness issues at the request of the President. The Council provides a potential mechanism whereby impediments to commercialization of superconductivity can receive high-level attention.

Economic Council Working Group on Research, Development, Technology, and Innovation

In recognition of the importance of R&D and technological competitiveness, President Bush established a new Working Group under the Economic Policy Council chaired by the Secretary of Commerce to develop options to improve the innovation process and the commercialization of technology.

CHAPTER III

POTENTIAL FUTURE APPLICATIONS FOR SUPERCONDUCTIVITY

The basis for the Action Plan must be grounded in a vision of the possible applications of superconductivity over the long term. Of course, different technologies will or will not emerge based on the long-term level of support for R&D, economic benefits of superconductivity, and the actual rate of technical progress on superconductivity. Potentially, there are many possible areas for applications, but the realization of this potential will depend largely on future technical progress. While it is difficult or impossible to predict with confidence how widespread the commercial applications of superconductivity will be in, say, 20 years, these applications will steadily grow, and may prove to be extremely significant in the long term.

LARGE-SCALE APPLICATIONS

Typical large-scale applications are those for which large dissipationless current densities must be sustained at high magnetic fields in bulk conductors suitable for fabrication of supermagnets. Included in large-scale applications are electric power devices (generators, motors, transformers, cables, and magnetic storage) in which large critical current densities are required with varying levels of magnetic field strengths.

Magnetic Resonance Imaging

Perhaps the largest area of commercial application of superconductivity over the next decades may well be in medical magnetic resonance imaging (MRI) systems. The more advanced of these systems could be capable of resolving features as small as a tenth of millimeter in size, an improvement of a factor of ten over that which is typical today.

With advances in cooling systems, the cost of refrigeration would provide a modest incentive to the introduction of HTS magnets for MRI systems, all other things being equal. However, the LTS systems may offer advantages in low-temperature stability and reduced system noise which outweigh the benefits of reduced refrigeration costs from operating at the higher temperatures.

While at present the United States is the world's major supplier of MRI systems, Great Britain is the dominant supplier of the LTS magnets for such systems. As the MRI market develops, there will surely be greater competition from Japan and West Germany, as well as Great Britain.

Electric Utility Applications

Energy conservation measures which followed the energy price increases of the 70's and early 80's have temporarily stopped expansion of electric generating capacity, virtually decimating electric generator manufacturing operations in the United States and reducing the volume in much of the rest of the world. Nonetheless, in the next 20 years or so, significant expansion of generating capacity will be needed, and many older generators will have exceeded their useful lifetimes and will require replacement. In the long term, there is the possibility that conventional generators will give way to superconducting generators. However, this transformation, if it occurs, would be driven primarily by factors other than the efficiency gains of superconducting generators, which amount at most to no more than half a percent. Much more significant is that the higher magnetic fields attainable with superconducting field windings allow total machine volume and weight reductions of a factor of three to eight. This translates into lower capital costs both for the generators

themselves and for the plants which house them. Another very significant advantage is that such relatively high power density generators would interact more effectively with their associated power grids under certain abnormal operating conditions, and they are apt to show higher transient stability margins.

The DOE applied HTS research program, Superconducting Technology for Electric Power Systems (STEPS) is developing the knowledge of HTS technology for large-scale applications in the U.S. electric power industry. The program strategy is to develop HTS coils and cables since these are the generic building blocks for a wide range of power devices, including small motors and magnets as well as large power equipment. Device investigations and application studies are also a part of the STEPS program. It must be emphasized, however, that such applications would require considerable future technical progress in HTS.

Another conceivable electric utility application for superconductivity is magnetic energy storage. In this application, excess generating capacity is pumped into a large superconducting magnet energy storage system (SMES) during periods of low demand. During periods of high demand the stored energy is withdrawn and fed back into the power grid. Such a system is particularly attractive, because round trip energy losses are estimated to be only 3-5% of the energy stored, in contrast to losses of greater than 35% for alternate approaches such as pumped water, batteries, or compressed air. A SMES offers the further advantage that it can provide unique stability for the utility grid, improving system reliability.

SMES is being considered for a dual application--power grid use and military use. For the latter, it can provide the brief burst of very high energy needed to power certain

defensive weapons, such as the free-electron laser, used in a strategic defense system. These experiments, when completed, will provide information necessary to make a technological and economic determination of the feasibility of commercial and military applications. These initial SMES systems will incorporate LTS materials in their high-stress windings, as this is the only technology available for this purpose in the near term. Refrigeration economies might be realized through the use of HTS materials for the low-strain SMES input and output leads in the transition region from liquid helium temperature to liquid nitrogen temperature.

When the SDIO engineering design competition is completed, the United States will be well-positioned in large-scale SMES technology. A more modest, but high quality, effort is underway in Japan. SMES technology may eventually become an important component of the electric power industry in the 21st century and may assume considerable commercial significance in incorporating both large- and small-scale units in the electric grid.

The new HTS materials have rekindled interest in superconducting electric power transmission cables. The long lengths (one to hundreds of miles) of power transmission cables leads to nearly prohibitive refrigeration demands for LTS power lines; these demands are significantly reduced (but may still prove economically impractical) for the much higher operating temperatures of the HTS case.

Superconductivity has potential application in magnetic confinement of controlled thermonuclear fusion. LTS supermagnets will continue to fulfill critical roles in this quest. There will be incentives for ultimate conversion to HTS magnets, the timing of which will

depend on technological developments and the evolution of controlled thermonuclear technology.

Levitated Trains

The economic viability of Maglev trains will depend more on the costs of right-of-way and "track" construction than the availability of technology for levitation and propulsion. Thus, market development will be largely independent of advances in superconductivity. It is also pertinent that there exists competing West German activity which utilizes non-superconducting magnetic technology.

The use of supermagnets for the propulsion and levitation of trains (Maglev) has already been demonstrated by Japan with LTS supermagnets and appears to have significant advantages over non-superconducting magnets. The levitation allows operation at speeds above that possible with steel-wheel trains and therefore fills the perceived need for a high-speed ground transportation system. Consideration is also being given to levitated-train transportation in several areas of the United States, and in parts of Europe.

Propulsion

Superconducting rotating electrical machinery may play a significant role in ship propulsion and possibly in tank and even helicopter propulsion. In all cases, a prime power source (e.g. a gas or steam turbine) turning at very high speed, drives a superconducting generator, which supplies current to a low-speed superconducting motor driving the propeller or rotor. The generator and motor combined take the place of heavier and less efficient reduction gears. For surface ships, advantages will be realized in areas such as

speed, range, payload, and space utilization. In Navy ships, superconducting drive offers higher survivability and the capability to switch power rapidly between propulsion and protective systems such as electromagnetic weapons. In submarine applications, further advantages will stem from the greatly reduced noise, which will enhance capabilities for covert operations.

The United States Navy has carried out pioneering work in this area and is well positioned to pursue it to fruition. Current primary Navy emphasis is on conventional, as opposed to superconducting, electric drives. However, recognizing further advantages offered by superconductivity, the U.S. Navy is continuing research and development on superconducting machinery exploring the technology for large scale (3,000 to 30,000 HP) machines.

An alternate approach to ship propulsion makes use of magnetohydrodynamic (MHD) forces. In this approach a supermagnet on board a ship or submarine exerts a force on sea water when an electric current is caused to flow through the water. The pioneering analytical studies of MHD ship propulsion were performed in the U.S., but only modest activity continues today. Japan is currently developing a 150 ton MHD-propelled surface ship scheduled for completion in the early 1990's. However, the advantages of MHD propulsion in general over conventional propulsion are unproven.

Finally, superconductors have propulsion applications in the area of electromagnetic launchers. Among all types of electromagnetic launchers, including rail guns, one stands out for its simplicity and efficiency, and it is uniquely superconducting. It is the so-called "superconducting quench gun." The gun is remarkable in that, except for modest transient field losses in the superconducting windings, essentially all of the energy stored in a series

of persistent current superconducting magnets is transferred to the kinetic energy of a projectile. There appears to be the possibility of attaining hypersonic projectile velocities with consequent extreme penetrating capabilities against armor. However, it must be emphasized that the concept has not yet been subjected to rigorous overall systems analysis. Army, Navy, DARPA, SDIO, and DOE all have experience and interests in electromagnetic launchers and could be teamed in this endeavor.

Particle Accelerators

Superconductivity is already widely employed in particle accelerators used in medical radiation therapy, industrial radiation processing, developmental military weapons, and basic particle physics investigations. Superconductive materials permit greater economy and higher performance in particle beam-bending and focusing electromagnets and for resonant cavity structures.

Over the next several decades, it is possible that particle accelerators will develop into a significant market segment for HTS material applications in the modest size magnets required for medical therapy and industrial processing. HTS materials may also prove attractive for space-borne neutral-particle-beam resonant-cavity accelerators in the SDI program, because of the potential for using passive radiation cooling in the space environment.

The United States has consistently maintained strong capabilities in all aspects of particle accelerator technology, and the Nation is in a good position to advance applications on all fronts, despite competition from European, Soviet, and Japanese interests.

Microwave and Millimeter-Wave Generating Tubes

Microwave and millimeter-wave sources are of importance in communications and radar systems and as a means for heating plasmas in controlled thermonuclear reaction experiments. Such sources, like the gyrotron, require high magnetic fields for their operation. The higher the operating frequency, the higher the required magnetic field. Accordingly, as both civilian and defense communication and surveillance systems have sought the greater bandwidths and other attributes of higher frequencies, they have required the higher magnetic fields conveniently attainable only with supermagnets. The scope of such applications can be expanded even further if HTS magnets can be substituted for the current LTS magnets. For space applications, in which radiative cooling may suffice, the incentive for transition to HTS magnets is particularly high.

Although the high-frequency end of the microwave and millimeter-wave generating tube market is not large at present, it is growing and will have exceptionally important leverage on military systems. Moreover, it is an area in which the Soviets have demonstrated high accomplishment, and the United States may expect lively competition.

SMALL-SCALE APPLICATIONS

Small-scale applications of superconductivity are typically based on film technology. Small-scale applications include interconnects (both low- and high-current), passive circuit elements, small antennas, sensors, oscillators, mixers, switches, and amplifiers to name but a few. The rich diversity and novelty of superconducting phenomena make possible a realm of electronics technology that already competes effectively with semiconductor electronics in some areas (e.g. electromagnetic field detectors) and shows every indication

of continued growth. The determining factors will be considerations such as speed, sensitivity, noise characteristics, spectral coverage, low attenuation, low dispersion, and low power requirements. Still another area for exploitation is that of hybrid devices and circuits, in which superconducting and semiconducting materials are combined to yield novel devices and circuits.

The various electronic technologies discussed above are in different stages of development. The full spectrum of circuit elements can be fabricated at this time from LTS materials, and LTS electronics technology will continue to evolve. In comparison, small-scale electronics technology with HTS materials is in an early stage of development. A strong capability in LTS electronics technology will assist the attainment of a strong position in HTS electronics.

Semiconductor-superconductor hybrid electronics technology is also in an embryonic state. Modeling with semiconductor-LTS hybrid structures should be a useful prologue for HTS endeavors.

Sensors

Superconducting sensors are the most-sensitive, lowest-noise sensors known for large regions of the electromagnetic spectrum. As magnetic field detectors they are opening new areas of medical diagnostics, sensing the magnetic fields of the heart and brain. They are employed in studies of geomagnetism, and they find use in developmental magnetic detection systems for mines and for submarines. As electromagnetic field detectors, superconducting sensors offer unparalleled performance for ELF wavelengths, through radio frequencies, through microwave and millimeter-wave frequencies, and well into the infrared

region of the spectrum. They may find wide application in military and civilian communication and surveillance systems and have for many years been the detectors of choice in radio astronomy.

LTS sensor technology is relatively mature and will continue well into the next century to fulfill the highest-sensitivity, lowest-noise applications. HTS sensor technology is in its infancy, but offers to greatly extend the useful temperature and spectral ranges of superconducting sensors. The overall processing and fabrication challenges for HTS sensors appear at this time to be less stringent than those for semiconductor electromagnetic wave sensors, and so in the long term, it would appear that HTS sensors could enjoy an economic advantage over semiconductor technology.

Analog Electronics

Superconducting analog electronics embraces both passive and active circuit elements which receive information from sensors and perform analog processing up to and including analog-to-digital (A/D) conversion. Included in addition to A/D converters are antennas, transmission lines, delay lines, filters, mixers, oscillators, and amplifiers. Many of these components are unique and have no semiconductor equivalent.

LTS analog electronics technology has been extensively developed and decisive performance superiority over semiconductor technology has been demonstrated for many components and sub-systems. A number of the LTS analog electronics devices and systems could displace or augment semiconductor technology. There are incentives to execute as many of these components and systems as possible in HTS technology.

Conversion should be relatively straightforward for analog electronic components, except those requiring Josephson and Giaever junctions.

The United States possesses a substantial lead in LTS analog electronics technology at present. Maintaining this lead and transferring it to HTS analog electronics technology will require consistent funding and perseverance.

Digital Electronics

The civil and military sectors both need ultra-high-speed digital electronic processors (computers). In the former there are requirements for supercomputers to address the grand challenges of computing, such as global weather modeling, computational fluid dynamics, medical imaging, electric power system control and protection, and other areas. In the military arena there are requirements for ultra-high-speed digital electronics processors to take full advantage of the myriad signals from a variety of radar, infrared, and sonar surveillance systems. Such processors are also key to handling complex battle-management situations, cryptographic problems, and other matters of military interest.

The ultimate in such digital microelectronics technology must involve:

- o ultra-fast switches with delay time negligible relative to the system's longest-path transit delay,
- o ultra-small switches, closely packable to minimize the the system's transit delay,
- o low-resistance, low dispersion interconnects to handle ultra-short-pulse digital information without distortion,
- o ultra-low switching and sustaining energy, to reduce power

- requirements and minimize heat removal problems,
- o a quantum-level switching phenomenon, which is the ultimate in low switching energy, and
 - o low-temperature operation, so as to avoid thermal upset at the low switching levels of the quantum phenomenon.

At this time it appears that all of these requirements are best fulfilled by superconductivity, it is also possible that they may be fulfilled equally well or better by some combination of superconductivity with single-electron charging phenomena and or semiconductor quantum-size-effect phenomena. To assure a strong competitive position in the critical arena of ultra-high-speed computing, all such promising approaches should be vigorously pursued.

Although modern superconducting digital electronics technology was pioneered in the United States, largely by the IBM Corporation, this technology has not been aggressively pursued in this country since 1983. In contrast, it has been very actively developed in Japan, where progress has been made in the fabrication of very-high-performance LTS superconducting processors with up to 30,000 Josephson junctions. In the most likely course of development of digital superconducting electronics, the necessary device invention and systems architecture will be accomplished with LTS materials, such as niobium and niobium nitride, for which relatively mature processing technologies already exist. As processing capabilities for HTS materials mature, some of these devices and systems architectures will be executed in HTS materials. Also, the extreme anisotropies of the HTS materials may be the basis for novel devices and architectures not anticipated in the LTS arena. In any event, for reasons outlined above, some of the highest-performance HTS digital electronics systems may well also need to be operated at relatively low temperatures, not at the limits of the superconducting transition temperatures.

GLOSSARY OF TECHNICAL TERMS

AC - Alternating Current, descriptive of a signal which varies periodically in amplitude as a function of time.

A/D Converter - Analog to digital converter, an electronic device which translates an analog signal from a sensor, for example, to a set of corresponding discrete signals intelligible to a computer.

Bolometer - A sensitive detector operated in a transition region between superconducting and normal states capable of sensing certain forms of radiation.

Bulk Material - Superconducting material which is synthesized and processed so that it can be shaped or molded to form bearings, magnets, wires, tapes, etc., by techniques such as chemical precipitation.

Cavity - An electromagnetic resonator useful for generating or amplifying very high frequency signals, as in a gyrotron for example.

DC - Direct Current, an electric current which maintains constant amplitude over time.

EM Launcher - Electromagnetic Launcher, a structure capable of accelerating large masses, such as projectiles or vehicles, to high velocities (see rail gun).

Flux Creep - Movement in lines of magnetic flux induced by electric current or magnetic field which is sufficient to decrease the performance of superconductors.

Flux Pinning - A superconducting phenomenon characterized by lines of magnetic flux being confined or localized in bulk material, which is potentially useful for enhancing current carrying capacity.

Focal Plane Array - A dense set of detectors of, for example, infrared radiation, used in sensitive image detection and analysis.

Free Electron Laser - A wavelength-selectable source of laser light using an accelerated electron beam as its energy source. A technology under development for medical applications and for the Strategic Defense Initiative.

Giaever Junction - A device similar to the Josephson Junction but consisting of two superconductors with different energy gaps (incident radiation with energy exceeding this "gap" level eliminates superconductivity).

Gyrotron - A cavity vacuum tube device capable of generating extremely high power levels at millimeter wavelengths (MMW) which requires magnetic fields of several T, necessitating cryogenic magnets.

H_c - Symbol for critical magnetic field measured in Tesla, above which material is not superconducting.

HP - Horsepower, a measure of power equivalent to 746 watts.

HTS - High-Temperature Superconductivity, generally referring to ceramic materials which exhibit superconducting properties above 77 K, the boiling point of nitrogen.

IR - Infrared, a range of the electromagnetic spectrum between millimeter-waves and visible light.

J_c - Symbol for critical current density, above which the material is no longer superconducting. A J_c of from 100,000 to 1,000,000 amps/cm² is required by integrated circuit interconnections.

Josephson Junction - A device consisting of an extremely thin insulating barrier sandwiched between two superconductors which is capable of extremely fast switching speeds.

K - Kelvin, a temperature scale for which 0 K corresponds to -459 degrees Fahrenheit (absolute zero) and room temperature is approximately 300 K.

LTS - Low Temperature Superconductivity, implying conventional metallic materials which exhibit superconductivity at temperatures near absolute zero (about 4 K).

Maglev - Abbreviated form of magnetically levitated (train), an evolving mode of transportation which uses high field magnets to suspend and propel a vehicle to speeds in excess of 300 miles per hour.

Magnetometer - A device which exploits Josephson Junction technology and is capable of detecting extremely small magnetic fields, especially promising for anti-submarine warfare and basic scientific research.

MHD Magnetohydrodynamic - The technology for converting the kinetic energy in a moving fluid (e.g. a plasma) into electrical energy by applying a magnetic field.

Magnetoplasmadynamic - An engine principle which uses a magnetic field to direct plasma through a nozzle, capable of high efficiency and low thrust which is useful for interplanetary travel, for example.

Microwave - A range in the electromagnetic spectrum above one gigahertz and through millimeter-waves.

Mixer - An electronic device which combines two electromagnetic signals together and produces a signal which is the difference of the original inputs, an essential component in communications systems.

MMW - Millimeter wave, referring to a portion of the electromagnetic (frequency) spectrum between 30 gigahertz and 300 gigahertz.

MRI - Magnetic Resonance Imaging, a medical diagnostic technique which measures weak radio frequency signals emitted by certain nuclei in soft body tissues responding to applied magnetic fields.