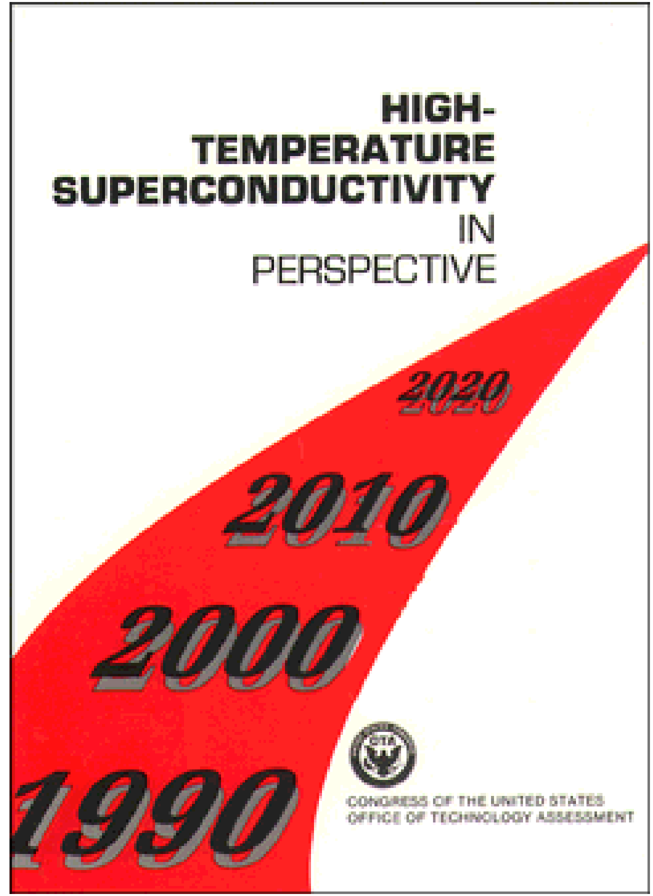
High-Temperature Superconductivity in Perspective

April 1990

OTA-E-440
NTIS order #PB90-253790



Recommended Citation:

U.S. Congress, Office of Technology Assessment, *High-Temperature Superconductivity in Perspective, OTA-E-440* (Washington, DC: U.S. Government Printing Office, April 1990).

*

For sale by the Superintendent of Documents
U.S. Government Printing Office, Washington, DC 20402-9325
(order form can be found in the back of this report)

Outside Reviewers

Alastair Allcock
British Embassy

Takashi Akutsu
International Superconductivity Technology Center

Michel Badia
Embassy of France

Ted Berlincourt
Department of Defense

Larry Blow
General Dynamics

Ian Corbett
Rutherford Appleton Laboratory

Steinar Dale
Oak Ridge National Laboratory

Renee Ford
Harrison, NY

Frank Fradin
Argonne National Laboratory

Robert Gottschall
Department of Energy

Don Gubser
Naval Research Laboratory

Larry Johnson
Argonne National Laboratory

Robert Kamper
National Institute of Standards and Technology

Kemeth Klein
Department of Energy

Tetsuji Kobayashi
International Superconductivity Technology Center

David Larbalestier
University of Wisconsin

Ed Mead
E.I. DuPont de Nemours & Co.

Richard Morrison
National Science Foundation

William Oosterhuis
National Science Foundation

Claudio Orzalesi
Embassy of Italy

John Rowell
Conductus, Inc.

Regine Roy
European Commission
Washington Delegation

Irene Rude
Embassy of the Federal Republic of Germany

Tom Schneider
Electric Power Research Institute

Mike Schuette
University of South Carolina

Lyle Schwartz
National Institute of Standards and Technology

Eugene Stark
Los Alamos National Laboratory

Susumu Tajima
Nikkei Superconductors

Kiyotaka Uyeda
Super-GM

Harold Weinstock
Air Force Office of Scientific Research

Greg Yurek
American Superconductor Corp.

High-Temperature Superconductivity In Perspective
Project Staff

Lionel S. Johns, *Assistant Director,*
OTA Energy, Materials, and International Security Division

Peter D. Blair, *Energy and Materials Program Manager*

Gregory Eyring, *Project Director*

Laurie Evans Gavrin, *Analyst*

Jane A. Alexander, *Analyst*

Administrative *Staff*

Lillian Q. Chapman
Linda L. Lung
Tina Brumfield

Contractors

Advanced Materials Technology
Los Angeles, CA

Granville J. Smith, 11
Smith and Ross Associates
Washington, D.C.

Resource Management International, Inc.
Reston, VA

Technology Management Associates
Chevy Chase, MD

TMAH Consultants
Ridgefield, CT

High-Temperature Superconductivity Assessment Advisory Panel

Paul E. Gray, *Chairman*
President, Massachusetts Institute of Technology

Sidney Alpert
University Patents, Inc.

Malcolm Beasley
Stanford University

H. Kent Bowen
Massachusetts Institute of Technology

Uma Chowdhry
DuPont Experimental Station

Duane Crum
Island Hill Research

Robert C. Dynes
AT&T Bell Laboratories

Simon Foner
Francis Bitter National Magnet Laboratory

Jeffrey Frey
University of Maryland

William J. Gallagher
International Business Machines Corp.

Eric Gregory
IGC Advanced Superconductors, Inc.

William V. Hassenzahl
Lawrence Berkeley Laboratory

Narain Hingorani
Electric Power Research Institute

John K. Hulm
Westinghouse Electric Corp.

Henry Kolm
EML Research Inc.

William D. Manly
Oak Ridge National Laboratory

George McKinney
American Research and Development, Inc.

Michael M. Tinkham
Harvard University

Richard Withers
MIT Lincoln Laboratory

NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

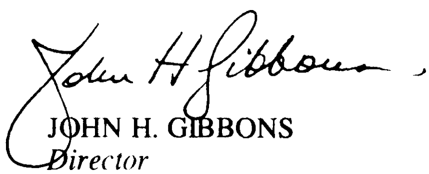
Foreword

This is the second of two OTA assessments on the subject of high-temperature superconductivity (HTS). The first, *Commercializing High-Temperature Superconductivity*, was published in June, 1988. These assessments respond to requests from the State Committees on Governmental Affairs; Energy and Natural Resources; and Commerce Science, and Transportation; as well as the House Committee on Science, Space, and Technology to analyze the opportunities presented by this exciting new technology and to outline Federal policy objectives that are consistent with these opportunities.

This study is complementary to the earlier OTA report. Whereas *Commercializing High-Temperature Superconductivity* considered HTS as a specific case study in the context of broader issues in U.S. industrial competitiveness and technology policy, the present work focuses more on the technology itself and the spectrum of potential applications. A centerpiece of this work is an extensive OTA survey comparing industry investment in superconductivity R&D in the United States and Japan (see Chapter 6). In this regard, OTA gratefully acknowledges the assistance of Japan's International Superconductivity Technology Center for administering the survey in Japan, and of the National Science Foundation for help with the survey design, distribution, and analysis in the United States.

As the title suggests, this study attempts to put HTS in perspective, both in terms of competing technologies (e.g., the more mature low-temperature superconductors), and in terms of the many technical and economic problems that must be overcome before HTS can be widely used. Although it remains a promising field, the full potential of HTS will not be clear for another 10 to 20 years. Thus, HTS is a test case, not of the U.S. ability to commercialize anew technology rapidly, but of its ability to look beyond the immediate future and sustain a consistent R&D effort over the long term. As such, HTS poses a difficult challenge to government policy makers and industry managers alike.

OTA appreciates the assistance provided by the contractors and Advisory Panel, as well as the many reviewers whose comments helped to ensure the accuracy of this report.



JOHN H. GIBBONS
Director

Contents

Chapter 1

Executive Summary

CONTENTS

Figures

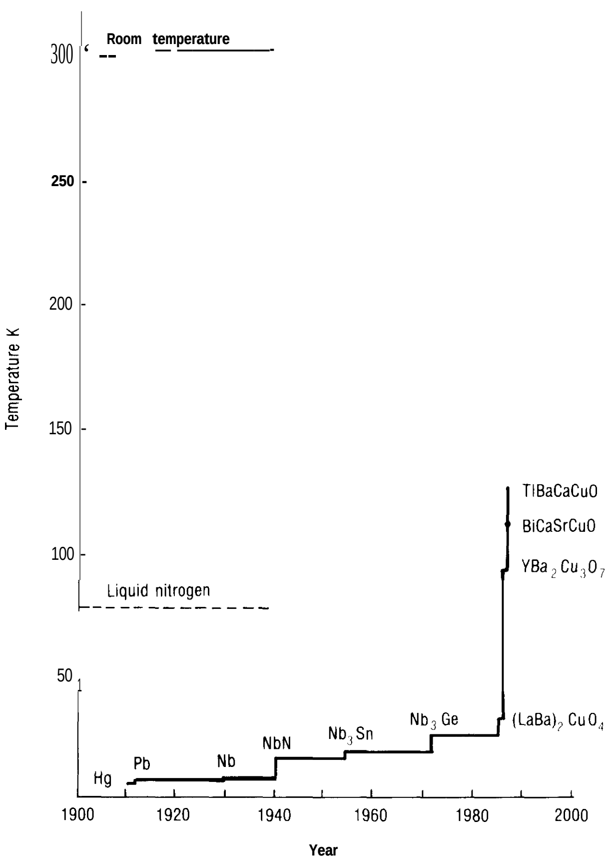
Tables

Executive Summary

Superconductors are materials that lose all resistance to the flow of electricity when cooled below a critical transition temperature (T,). Ordinary conductors such as copper or aluminum present some resistance to the flow of electric current, causing some of the energy to be dissipated as light and heat. This is a useful property in light bulbs and toasters, but leads to undesirable power losses in most applications. By reducing losses, superconductors can make energy production more efficient and computers can be made smaller and more powerful.

The phenomenon of superconductivity was discovered in 1911, but practical superconducting materials were not found until the 1960s. Today, superconducting metals and alloys are being used in a variety of commercial applications in electronics and medicine, but this took many years to come about. One reason for the long gestation period is that in order to function, superconductors had to be cooled to extremely low temperatures—about 4 degrees above absolute zero (4 K)—with liquid helium. The high costs and complexity of liquid helium refrigeration systems tended to confine these low-temperature superconductors (LTS) to a well-controlled, laboratory environment.

Figure l-l-Superconducting Critical Transition Temperature v. Year



SOURCE Office of Technology Assessment, 1990.

In 1986, scientists discovered an entirely new family of ceramic high-temperature superconductors (HTS) with transition temperatures above 30 K—much higher than had previously been thought possible (see figure l-l). Subsequently, related materials were discovered with transition temperatures above the boiling point of liquid nitrogen (77 K). The prospect of cooling with cheaper and more practical liquid nitrogen fueled expectations of widespread commercial applications, and touched off a worldwide race to develop these materials.

OUTLOOK FOR HIGH-TEMPERATURE SUPERCONDUCTIVITY

Over the past 3 years, the intense worldwide research effort on I-ITS has produced remarkable progress. It appears that within the next 5 years, commercial magnetic field sensors and simple microwave devices operating at 77 K are a realistic possibility. But many fundamental questions remain unanswered. There is no theory that explains why these materials exhibit superconductivity, and no one knows whether new materials with even higher T_Cs will be discovered. (So far, the highest reproducible T_C is 125 K, still far below room temperature, which is about 300 K.)

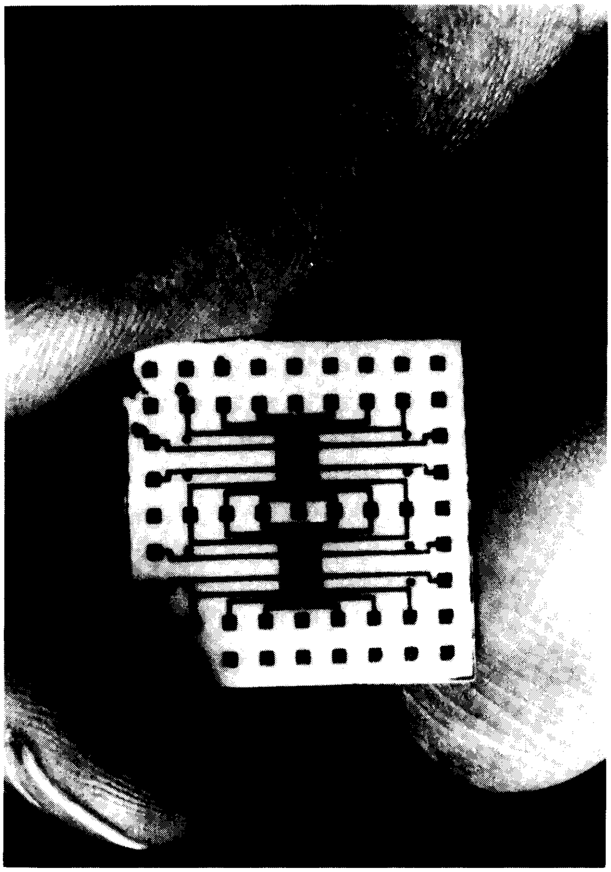


Photo credit: IBM Research

Thin films of HTS material can be used to connect logic and memory chips in computers, making them smaller and faster.

HTS continues to be a promising field where diligence and patience could yield great dividends. But a long-term, basic research effort is needed to avoid wasting large sums on premature development projects. Most observers agree that it will be 10 to 20 years before HTS could be widely used in commercial applications—roughly the same time it took for LTS to move from the laboratory to commercial products. In fact, the commercialization of LTS holds several valuable lessons for HTS.

LESSONS FROM LTS

- The preferred materials for applications are those that are easiest to handle and manufacture, not necessarily the best superconductors or those with the highest T_C.
- Even after a superconducting material with adequate properties is developed, it takes many years to develop a practical conductor from that material and to demonstrate its viability in a commercial prototype.
- Technical difficulties and unanticipated development costs can be expected; nevertheless, it is important to provide sustained, reliable funding through the lifetime of a superconductor R&D project. A successful project that is carefully managed, but over budget, contributes to the store of knowledge; a truncated project is often a total waste of effort.
- Highly reliable, conservative designs are necessary, especially in the commercial sector. While it is tempting for engineers to push a design to the state-of-the-art, reliability is crucial in consolidating a new beachhead.
- It is important to pick targets carefully; i.e., those that are not likely to be "leapfrogged" by a well-entrenched and steadily improving conventional technology. Commercialization of HTS is likely to be most successful in new applications where the technology and designs are fluid.
- It is difficult to predict where the future applications will be. Few could have predicted in 1979 that the largest commercial application of superconductors in 1989 would be in magnetic resonance imaging (MRI) magnets.
- In many applications, lack of commercialization has nothing to do with technical problems with superconductivity; rather, it is due to unfavorable economic conditions. For example, even the discovery of room-temperature superconductivity would not substantially improve the prospects for magnetically levitated transportation systems in the United States, because the costs of such systems are dominated by costs of land acquisition and guideway construction.

PROSPECTS FOR THE COMMERCIALIZATION OF HTS

The lessons above illustrate that commercial applications of superconductivity are not driven

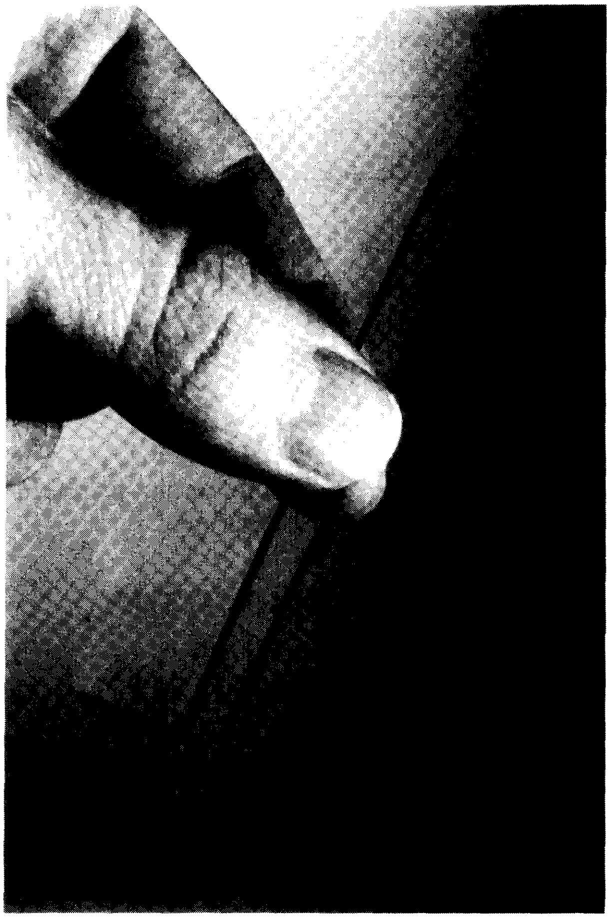


Photo credit: ICI Advanced Materials

This superconducting dipole antenna, fabricated from bulk HTS materials, generates signals four times stronger than a comparable copper antenna at 77 K.

by a high T_c per se. HTS systems will have to demonstrate superior performance, low cost, high reliability, and greater market demand compared with competing technologies. Many uncertainties remain as to how HTS will measure up in each of these areas.

For purposes of analyzing the potential applications of HTS, most studies have assumed that HTS conductors will have the same properties, costs, and design concepts as present LTS conductors, but at an operating temperature of 77 K instead of 4 K. Based on the findings of several of these studies, OTA evaluates the prospects for both HTS and LTS in seven sectors: high-energy physics; electric power; transportation; industrial equipment; medicine; electronics/communications; and defense/space.

The greatest near-term (5 to 10 years) impact of HTS is likely to be in electronics/communications and defense/space. In the medium-term (10 to 15 years), a variety of medical and industrial applications are possible. Significant applications of HTS in the high-energy physics, electric power, and transportation sectors should be considered far-term (>15 years), if they are feasible at all. LTS is likely to remain the only realistic option for large-scale applications such as maglev vehicles, high-field magnets, or electric power generators in the foreseeable future.

It is important to bear in mind that the principal contributions of HTS may well be in applications that cannot be anticipated at this early stage. It could be a conceptual error to force the new ceramic materials into the same mold as the metallic LTS materials. Many observers think that the biggest applications of HTS will be in totally new devices that have not even been considered for LTS.

THE FEDERAL RESPONSE TO HTS

The Federal response to the discovery of HTS illustrates many of the strengths and weaknesses of U.S. R&D policy as it relates to U.S. industrial competitiveness. On the whole, the response has been both substantial and timely. By fiscal year 1990, just 3 years after the discovery of HTS, Federal agency funding for HTS had grown to about $130 million, with a 10 percent increase requested for fiscal year 1991 (see table l-l). This was considerably more than the government funding of any other country (see table 1-2).

The Administration can point to some significant *successes* and even innovations in its approach to HTS. The Defense Advanced Research Projects Agency (DARPA) initiated a unique program emphasizing the processing of HTS materials. Three Department of Energy (DOE) Superconductivity Pilot Centers were established at Argonne, Los Alamos, and Oak

Table I-I—Federal Funding for High-Temperature Superconductivity ($ millions)

Agency	FY 1990 (estimated)		FY 1991 (requested)	
Department of Defense	$ 61.8	(47%)	$ 61.8	(43%)
Department of Energy	34.1	(26%)	43.3	(30%)
National Science Foundation	25.8	(26%)	27.3	(19%)
National Aeronautics and Space Administration	5.9	(5%)	5.9	(4%)
Department of Commerce	2.8	(2%)	4.7	(3%)
Total	$130.4	(100%)	$143.0	(100%)

SOURCE: D. Allan Bromley, Director, Office of Science and Technology Policy, testimony before the Subcommittee on Transportation, Aviation, and Materials, House Committee on Science, space, and Technology, Feb. 21, 1990.

Table 1-2—Estimated National High-Temperature Superconductivity R&D Efforts in Various Countries, 1989

Country	Government HTS budget (millions)	Full-time researchers (all sectors)
United States	$130	1,000
Japan	>70	1,200
West Germany	35	500
France	30	300
United Kingdom	20	200
Italy	>15	200
Netherlands	>2	<100
Soviet Union	—	2,000
China	—	1,000

SOURCE: Office of Technology Assessment, 1990.

Ridge National Laboratories to carry out collaborative research with industry. The Pilot Centers are experimenting with both expedited mechanisms for contracting and greater industry control over intellectual property, and have attracted a large number of prospective collaborators. Mechanisms for rapid exchange of technical information among researchers have been established and appear to be working well.

The Administration's approach also contained much that was familiar to critics of Federal R&D policy. The Department of Defense (DoD) administered the largest HTS budget, and became the principal supporter of U.S. industry programs. Also, much of the Federal budget went to support research in Federal laboratories, which heretofore have not enjoyed a good track record in transferring technology to U.S. industry. And although coordination of HTS R&D programs within each mission agency is good, coordination at the national level is weak. Congress' attempts to address this problem with legislation have met with only limited success.

The Federal response to the advent of HTS is perhaps best characterized as an attempt to broaden the R&D activities of the relevant agencies to address industry needs without fundamentally changing their missions or their relationships to one another. Those who had hoped that the worldwide race to develop HTS might stimulate a serious debate about a new Federal role in meeting the challenge of foreign competition in emerging commercial technologies have clearly been disappointed.

THE U.S. COMPETITIVE POSITION IN SUPERCONDUCTIVITY

Low-Temperature

As a result of Federal support for LTS research during the 1960s and 1970s, U.S. companies today have strong capabilities in LTS wire and cable production, magnet winding technology, superconducting analog electronics, and sensors. Federal support for LTS conductor and magnet development--especially through DOE high-energy physics programs—has enabled U.S. companies to take a leading position in MRI magnets, the largest commercial market for LTS.

But the United States has a weak position in more speculative—but potentially widespread—commercial applications such as digital electronics, rotating electrical equipment, and magnetically levitated (maglev) transportation systems. In these areas, U.S. companies have judged the risks of commercial development to be too high-or the benefits too small-to justify sustained investment. Meanwhile, the Federal Government terminated its support for these programs in the late 1970s and early 1980s, although they were continued in other countries, notably West Germany and Japan.

Interestingly, the discovery of HTS has given a higher visibility to the weak U.S. competitive position in several applications of LTS, especially maglev transportation systems. Several recent reports have recommended restarting these LTS programs, arguing that otherwise, the United States will become dependent on foreign sources for key technologies. But OTA finds that U.S. companies do not appear to have changed their assessment of the risks and benefits. Therefore, if these LTS programs are restarted, the government will have to bear virtually all of the substantial development costs.

High-Temperature

The United States, with the largest national budget for HTS R&D in the world (see table 1-2), has a comprehensive research effort. But there is no reason for complacency. Japan has emerged as the United States' strongest competitor, and has demonstrated superior capabilities in several areas-e. g., synthesis and processing of high-quality materials. Moreover, Japan has shown the ability to sustain long-term investment in materials research, with a strong commitment from its major corporations.

West Germany has a formidable HTS R&D effort underway, with the most extensive industry involvement in Europe. West German companies such as Siemens are stronger competitors in some areas+. g., medical applications of LTS—than are Japanese firms.

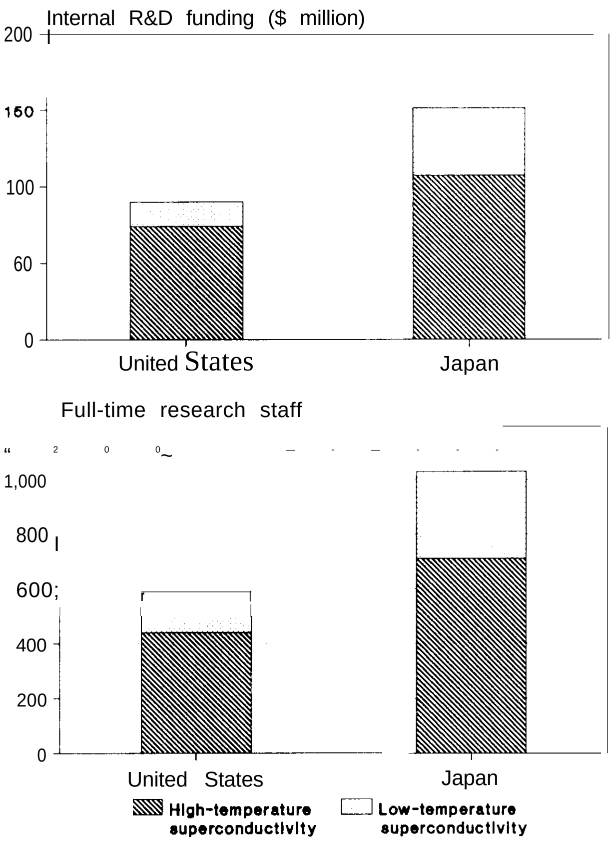
Although the European Community has been slow to organize cooperative research programs in HTS, the 12 member states represent an immense economic and intellectual potential, with more than a million scientists and engineers. In the past, effective collaboration has been hindered by dispersion of resources, isolation of researchers, and poor diffusion of information; but anew era in collaborative R&D could be dawning as the process of unification of European markets proceeds beyond 1992. Taken together, the EC countries represent a bloc of R&D resources and manpower larger than either the United States or Japan alone.

OTA SURVEY RESULTS: U.S. AND JAPANESE INDUSTRY INVESTMENTS IN SUPERCONDUCTIVITY

In late 1988 and early 1989, the Office of Technology Assessment (OTA) conducted a survey of U.S. industrial superconductivity R&D in cooperation with the National Science Foundation (NSF). A parallel survey of Japanese industrial superconductivity R&D was conducted jointly with Japan's International Superconductivity Technology Center (ISTEC). OTA estimates that the survey captured about 90 percent of the U.S. effort, and about 80 percent of the Japanese effort. Among the findings:

- Japanese companies were investing some 50 percent more in HTS R&D (= $107 million) than U.S. companies (= $73 million) in 1988, and their investment in LTS R&D was many times higher than that of U.S. firms (see figure 1-2).
- OTA identified 20 Japanese companies spending more than $1 million of their own funds on HTS, compared with 14 in the United States. In both countries, HTS R&D is heavily concentrated in these firms.
- Among these big spenders, the Japanese companies are more likely to have broader superconductivity programs—both in terms of the variety of materials being developed and the scope of research. Japanese firms reported more resources devoted to basic research than did U.S. firms.
- When asked when their first HTS product would reach the market, Japanese companies projected a later first year-to-market (average year: 2000) than U.S. companies (average year: 1992) in all product categories. The fact that Japanese companies are willing to spend so much on R&D---even though they expect the payoff in commercial products to be at least 10 years away—underscores their strong long-term commitment to HTS. The continuing commitment of Japanese companies to LTS reinforces this conclusion.

Figure 1-2--Comparison of Industrial Superconductivity Research Efforts in the United States and Japan, 1988



In 1988, U.S. industry internal funding for HTS was about $74 million, with 440 full-time researchers, compared with $107 million and 710 full-time researchers in Japan.

NOTE: The data in this figure are adjusted to include OTA's estimate of research efforts not captured by this survey.

SOURCE: Office of Technology Assessment, 1990.

POLICY ISSUES AND OPTIONS

In 1987, shortly after the discovery of HTS, optimism was rampant and room-temperature superconductivity seemed just around the corner. The United States was seen to be engaged in a heated race to commercialize HTS products before its competitors. By 1989, a more realistic view had taken hold: HTS is a test case, not of the U.S. ability to commercialize a new technology rapidly, but of its ability to look beyond the immediate future and sustain a consistent R&D effort over the long term.

The Federal HTS budget grew from $45 million in fiscal year 1987 to an estimated $130 million in fiscal year 1990-substantially more than that of any country in the world. OTA finds that *overall, the United States has an HTS R&D effort that is second to none.* Present funding levels are sufficient to make progress, although perhaps $20 to $30 million more per year could be spent effectively (see table 1-3). But OTA also finds *there are serious reasons to doubt whether U.S. companies will maintain a competitive position in HTS in the future (see key* issues section below). The history of erratic Federal support for LTS programs also raises questions about whether the Federal effort will be sustained over the long term.

Minor Issues

Several issues that were earlier thought to be urgent now appear to be of less importance:

- Adequate supplies of raw materials, chemical precursors, and powders for HTS are not a problem now, nor are they likely to be in the foreseeable future.
- HTS does not appear to raise unmanageable health or safety problems.
- Antitrust restrictions are not a serious inhibitor to U.S. competitiveness in HTS technology.
- Fears that the prolific HTS patenting by Japanese companies could block U.S. companies from participating in major superconductivity markets appear to be exaggerated.

Issues That Bear Watching

There are reasons for concern about several aspects of the U.S. HTS R&D effort, and these could become more serious in the future.

- Federal laboratories may be receiving a disproportionately large share of the HTS R&D budget. In fiscal year 1988, 45 percent of Federal HTS funding went to support research in Federal laboratories. Although these laboratories continue to make important contributions, questions remain about whether they should have such a large share of the HTS budget—especially given the scarcity of resources for universities (see below). Congress could establish a single, independent advisory committee to tour the major laboratories and evaluate the quality and relevance of their HTS research.

- At present, defense and civilian requirements for HTS technology are similar, but this could change as the technology matures. About 47 percent of Federal funding for HTS in fiscal year 1990 comes from DoD-considerably more than comes from any other agency. At the present stage of HTS technology development, OTA finds that military and civilian requirements for these materials are essentially the same, and access to DoD-funded research is not restricted. But as HTS matures and is incorporated into weapons systems, military and commercial R&D priorities are likely to diverge. If DoD funding concentrates on solving problems of primarily military interest, this could hurt U.S. competitiveness in areas such as HTS electronics—widely predicted to be one of the earliest and largest application areas of HTS.
- If progress in HTS technology continues to be incremental, small HTS startup companies could face a critical shortage of capital. Indeed, most small HTS startups report that they have received buyout offers from large foreign companies.
- The importance of active U.S. participation in international superconductivity meetings and programs is growing, while Federal funding to support these activities is stagnant or declining.

Key Issues .

OTA considers the following issues to be especially important (see table 1-3):

- *U.S. companies are investing less than their main foreign competitors in both low-andhigh-temperature superconductivity R&D. This* is by far the most critical issue affecting the future U.S. competitive position in superconductivity, and in many other emerging technologies.
- *University research on HTS merits a higher priority than it presently receives.* University research-specially that performed by individual investigators—has produced important advances in HTS and continues to play a vital role. But in fiscal year 1988, university research received only 30 percent of Federal HTS resources (compared with 45 percent for Federal laboratories), and many innovative research proposals continue to go unfunded. The funding shortage affects young investigators entering the field most severely, but even proven contributors have had difficulty getting adequate support.
- *Coordination of the Federal superconductivity R&D effort can be made more effective at the national level.* The National Superconductivity and Competitiveness Act of 1988 mandated that the Office of Science and Technology Policy (OSTP) produce a 5-year National Action Plan for superconductivity, as well as an annual report on the implementation of the Plan. Although several advisory committees on HTS have been appointed during the past 3 years—including the ''Wise Men' advisory committee established by President Reagan, and the National Commission on Superconductivity established by Congress —these committees were given only a temporary mandate and cannot provide the long-term technology monitoring and analysis called for in the National Superconductivity and Competitiveness Act.

There is one important point that relates to all of the above issues: *funding stability is essential to meaningful progress.* In the past, erratic funding both by Federal agencies and companies has caused disruption of superconductivity programs, and has made it difficult to maintain a pool of U.S. engineering know-how in superconductivity. In contrast, Japan's demonstrated ability to sustain long-term superconductivity

Table 1-3-Superconductivity Policy Issues and Options

Issue / Options	Comments
A. U.S. companies are investing less than their main foreign competitors in both low-and high-temperature superconductivity R&D.	
The key problem is the lack of patient investment capital available to U.S. industry. Policy initiatives that could help would involve meaningful reduction of the Federal budget deficit, and tax policies that encourage higher saving by individuals and businesses.	This problem is fundamental to future U.S. competitiveness in all emerging technologies.
B. University research on HTS merits a higher priority than it presently receives.	
Option 1: Increase NSF's budget for individual investigator grants in HTS at universities by $5 million.	Although NSF's HTS budget has been increased to support the new Science and Technology Center at the University of Illinois, funding for individual investigators has stayed virtually flat, and many innovative proposals are not being funded.
Option 2: Provide $10 million per year for several years to NSF to upgrade university equipment for synthesis, processing, and characterization of advanced materials such as HTS.	U.S. capabilities in such areas as the synthesis of new HTS materials and preparation of large single crystals lag those of its major competitors. Recent studies have underscored the need for greater investment in materials synthesis and processing at universities. Ten million dollars would substantially upgrade the equipment capabilities of perhaps 25 research groups.
Option 3: Provide funding—perhaps through DARPA—to support the participation of universities in a limited number of R&D consortia with companies and government laboratories.	This was the principal recommendation of the President's "Wise Men" Advisory Committee. Properly organized and managed, such consortia can lengthen industry R&D time horizons and spread risks, But it is important to be realistic about what these consortia can be expected to accomplish: they are more likely to enhance generic technology development than to be engines of commercialization.
C. Coordination of the Federal superconductivity R&D effort can be made more effective at the national level.	
Option 1: Give OSTP the additional resources and staff necessary to monitor industry concerns and broker the competing interests of the various funding agencies in superconductivity.	One small step in this direction might be to merge the permanent staff of the National Critical Materials Council with OSTP staff. But without a commitment by the President to give OSTP a leading role in technology policy decisionmaking—a commitment not demonstrated so far—staffing increases at OSTP are unlikely to have any effect.
Option 2: Establish a standing advisory committee on superconductivity reporting to Congress, the Science Adviser, and the President, and give it a mandate of at least 5 years.	Such a long-term advisory committee-perhaps modeled on the now defunct "Wise Men" Advisory Committee-could assist policy makers with tough budgetary choices, e.g., concentrating Federal resources into a limited number of consortia with clearly complementary research objectives. Strong industry representation on the committee would be critical.

KEY: DARPA: Defense Advanced Research Projects Agency
NSF: National Science Foundation
OSTP: Office of Science and Technology Policy

SOURCE: Office of Technology Assessment, 1990.

programs is likely to be a major competitive asset for Japan in the future.

SUPERCONDUCTIVITY IN A BROADER POLICY CONTEXT

The discovery of HTS has come at a time of increasing doubts about the capability of the United States to compete in global high-technology markets. The list of markets in which U.S. industry has slipped badly is growing: e.g., consumer electronics, memory chips, automobiles, and machine tools. Moreover, the U.S. private sector is investing less than its main competitors in a number of emerging technologies such as x-ray lithography, high-definition television, and—as shown by the OTA survey—in HTS and LTS. There is a serious question whether U.S. industry, as it is currently financed and managed, can compete in markets for these technologies in the next century.

The short-term mind set of U.S. R&D managers is not the result of stupidity or ignorance about the importance of R&D to the company's future. Instead, the R&D investment decisions in both the United States and Japan are the product of rational choices made within the prevailing economic and financial environments of the two countries. For decades, Japanese industry has benefited from higher rates of economic growth, lower effective capital costs, higher savings rates, and more stable financial markets than were the case in the United States. All of these factors made it easier for Japanese managers to make long-term investments.

Thus, the challenges associated with HTS research, development, and commercialization should be viewed as a microcosm of broader challenges to the U.S. manufacturing sector in an increasingly competitive world. It is tempting to rely on Federal R&D initiatives-e. g., new federally funded industry consortia, or perhaps creating a new civilian technology agency—to solve the deepening problems. But **such initia**tives, while they may be helpful, do not change the underlying economic and financial pressures on industry that dictate long-term investment decisions. The real solution—increasing the supply of patient capital to U.S. industry-will require politically tough fiscal policy choices that involve trade-offs among military, economic, and social goals. If U.S. competitiveness continues to decline, it will not be because the United States lost the superconductivity race with Japan, but because policymakers failed to address the underlying problems with long-term, private sector investment that HTS helped to bring into the spotlight.

Chapter 2

High-Temperature Superconductivity: A Progress Report

CONTENTS

Boxes

Figures

Tables

Chapter 2

High-Temperature Superconductivity: A Progress Report

No scientific discovery during the 1980s generated more worldwide excitement—and hype—than that of high-temperature superconductivity (HTS) in 1986. Four years later, the hype has died down, but the excitement remains. HTS appears less often in newspaper headlines, and it no longer commands the urgent attention of U.S. policy makers. But during the past several years there have been remarkable advances in HTS research.

This chapter provides a progress report on HTS, and an assessment of the R&D challenges that remain. For readers unfamiliar with the concepts and terminology of superconductivity, a brief primer is provided in appendix 2-A. Additional information on the science of HTS and its applications can be found in several studies[1,2,3] including an earlier OTA report.[4]

PROGRESS REPORT

New HTS Materials

Perhaps the most interesting development that has occurred in the past several years is the realization that HTS is a broader phenomenon than had been first thought. The initial discovery of copper oxides containing lanthanum (T_c = 35 K) in 1986 was followed in 1987 by related compounds containing yttrium (T_c around 93 K) and in 1988 by those containing bismuth (maximum T_c of 110 K) and thallium (maximum T_c of 125 K). Numerous variations on these basic layered copper-oxide compounds have also been found to exhibit superconductivity. This raises the hope that new materials may yet be discovered with even higher T_cs.

Room-Temperature Superconductivity

A superconductor operating at room temperature would be revolutionary. Provided that suitable manufacturing processes were available, and costs were comparable to ordinary conductors, room-temperature superconductors could replace normal conductors in virtually all devices involving electricity or magnetism. Over the past 2 years, there have been occasional reports of observations of room-temperature superconductivity, though none has been confirmed.[5]

No one knows yet whether room-temperature superconductivity is possible. At this writing, there are no accepted theoretical limitations on T_c. But even if a room-temperature superconductor is possible, practical applications may be difficult:

- To obtain critical fields and currents at levels high enough to be useful, superconductors are typically operated at temperatures substantially below T_c. For practical room-temperature (300 K) operation, a T, of 400 to 600 K (261 -621 'F) would be required (well above the temperature of boiling water).
- At elevated temperatures, vortex lattice pinning (see app. 2-A) becomes much more difficult, due to the higher ambient thermal energy. This could make it impossible for the room-temperature superconductor to carry useful currents even in small magnetic fields.

The search for new material with higher T_cs remains an important quest, along with research aimed at understanding the fundamental limitations of the performance of present materials. In this connection, further research on novel superconductors --e.g., organics--could lead to new insights.

Progress in Improving HTS Properties

Thin Films

Films of superconductor, usually between 30 angstroms and 1 micrometer in thickness, can be deposited on a base material (called a substrate) to yield conductors used in a wide variety of sensors and electronic circuits. Several of the techniques for depositing the films-e. g., sputtering, molecular beam epitaxy, electron beam evaporation, and chemical vapor deposition—have much in common with

[1] Alan M. Wolsky et al., "The New Superconductors: Prospects and Applications," *Scientific American*, vol. 260, No. 2, February 1989, p. 61.

[2] National Academy of Sciences Committee on Science, Engineering, and Public Policy, *Research Briefing on High-Temperature Superconductivity* (Washington, DC: National Academy Press, 1987).

[3] C.P. Poole, T. Datta, and H.A. Farach, *Copper Oxide Superconductors* (New York, NY: John Wiley Interscience, 1988).

[4] U.S. Congress, Office of Technology Assessment, *Commercializing High-Temperature Superconductivity*, OTA-ITE-388 (Washington, DC: U.S. Government Printing Office, June 1988).

[5] "Room T_C Reports Fail Verification," *Superconductor Week*, vol. 3, No. 4, Jan. 23, 1989, p. 1.

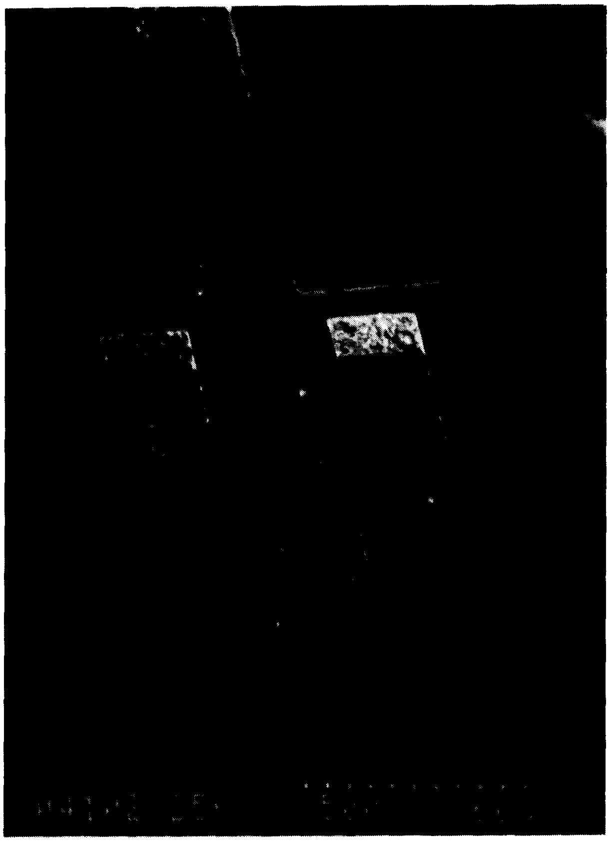


Photo credit: IBM Research

Electron micrograph of an edge-junction superconducting quantum interference device (SQUID) fabricated from $YBa_2Cu_3O_7$ thin films.

the techniques used in semiconductor manufacturing. New processes—e.g., laser ablation—are also being developed. These techniques permit control over the growth of the film, some down to a single atomic layer.

Progress in improving the properties of thin films has occurred considerably faster than in bulk materials. This is apparently because the films grow as single crystals or as polycrystals having good alignment between their copper-oxygen planes, and because the vortex pinning strength is quite high. Already, critical current densities (J_c) above 1,000,000 Amps/cm^2 have been measured at 77 K in a magnetic field of 1 tesla—a level suitable for many electronics applications. Progress has also been made in producing films at temperatures below 600 °C (processing temperatures below about 500 °C are required to be compatible with manufacture of multilayer semiconductor devices) and in developing new substrate materials that are less expensive and more practical.

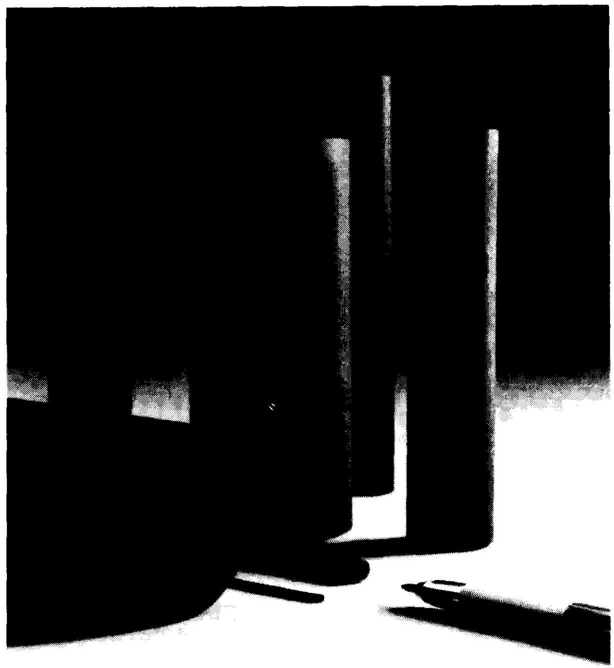


Photo credit: ICI Advanced Materials

Tubes fabricated from bulk high-temperature superconductors can be used for radio-frequency cavities and conductors.

Bulk Superconductors

Bulk materials include thick films (>1 micrometer), wires, tapes, and three-dimensional shapes. Bulk conductor forms are used in large-scale applications, such as magnetic resonance imaging (MRI), maglev vehicles, etc. They are made by techniques common in metallurgy or ceramics: extrusion, tape casting, pressing, etc. Typically, they involve compaction and shaping of nonsuperconducting powders or precursors, followed by firing in an oven to consolidate the material and create the superconductor. This yields a polycrystalline material consisting of partially oriented crystalline grains separated by grain boundaries.

HTS bulk conductors have generally exhibited lower critical current densities than thin films, thought to be caused by weakened superconductivity at the grain boundaries. The critical current also falls off more rapidly with applied magnetic field than is the case with thin films. But recent advances in processing have raised the critical currents in short wires to several tens of thousands of Amps/cm^2

Table 2-I—HTS R&D Challenges

Topic	Comment
Basic *Research*	
Theory/Mechanism of HTS	Abetter understanding will point the way to new materials, improvements in existing materials, and perhaps to new applications.
Search for New Materials	Synthesis and characterization of new HTS materials have been of tremendous value in guiding theory development, and will continue to be so. Further investigation of novel superconductors-e. g., organics-could provide important insights.
Structure/Property Relationships	Understanding properties such as critical current behavior is vital for virtually all applications. It involves not only basic physics issues but also the full complexity of the microstructure.
Appy *Research*	
Processing Science	Understanding the relationships among process variables, microstructure, and properties is critical for making better materials reproducibly. New, cheaper processes also need to be developed.
Thin Film Processes	Key goals include: reducing process temperatures below 500 °C so as to be compatible with semiconductor processing; finding suitable substrates and deposition processes-especially enabling deposition on semiconductors; developing processes for making films with extremely clean surfaces and strong superconductivity all the way up to the surface.
Bulk Processes	Key goals include: finding techniques for improving the superconductivity connection between adjacent crystal grains; introducing strong pinning sites for the magnetic vortex lattice; reducing alternating current (AC) losses; and making extremeiy thin filaments (several micrometers in diameter).
Applied Research-continued	
Chemical Stability	Some HTS materials are prone to react with atmospheric water and carbon dioxide, as well as with cladding and substrate materials. Some also readily lose oxygen from the crystal lattice. These reactions impair the superconductivity, and raise concerns about long-term stability. New approaches are needed to protect the materials and prevent these reactions.
Mechanical Properties	Mechanical properties such as brittleness, strength, and fatigue have received less attention than superconducting properties, but improvements are critical to reduce costs and increase reliability in actual applications.
Device Engineering R&D	
Thin Film Devices	Key goals include: demonstration of practical Josephson Junctions (JJs); development of a three-terminal device; patterning of multiiayer structures; developing low-resistance electrical contacts.
Bulk Devices	Key goals inciude: demonstration of long, flexible wires with 100,000 $Amps/cm^2$ in a magnetic fieid of 5 tesla; braiding and stabilization of composite cable; low-resistance electrical contacts and splicing of sections.
Manufacturing R&D	Includes making large numbers of JJs with uniform switching and threshold characteristics on a chip with high yield; long lengths of wire with reproducible properties; cost-effective nondestructive evaluation techniques.
Systems Development	Superconducting components have to be integrated into fully engineered systems, with refrigeration, auxiliary electronics, mechanical support, etc.

SOURCE: Office of Technology Assessment, 1990.

at 77 K—within a factor of 10 of levels required for most applications. It should be noted, however, that these have been realized only in small samples of test material; reproducing them in long wires poses major engineering challenges.

R&D CHALLENGES

While there has been considerable progress over the past several years, there remains along way to go before HTS can be widely used in practical applications. Table 2-1 gives examples of key remaining R&D challenges for both thin film and bulk HTS materials. These are grouped in five R&D categories: basic research; applied research; device engineering; manufacturing research; and systems development. They involve improving properties and processes, as well as integrating the superconducting components into larger systems.

A strong, ongoing basic research effort is essential to support cost- effective development of applications. At this writing, there is no commonly accepted theory of HTS. Thus, there is no way of predicting which materials should exhibit high critical temperatures, currents, or magnetic fields. Theory can also predict new phenomena. The Josephson effect, the basis of the device used in superconducting electronics, was predicted first by theory and later observed by experiment. If new phenomena are occurring in HTS, then new types of devices may be possible.

Basic research is also needed to establish the relationships among composition, microstructure, and properties-especially critical current density. In some cases, HTS presents new problems that

Box 2-A—Superconducting Magnets

A superconducting magnet's major assets are its very high field strength, its ability to produce spatially uniform and temporally stable fields, its low power consumption, and its reliability. While a conventional electromagnet with an iron core can produce continuous fields up to around 2 tesla, superconducting magnets can routinely produce fields in excess of 12 tesla. A superconducting magnet consumes very little power except for refrigeration, while a nonsuperconducting magnet requires a large power source and extensive cooling.[1]

The superconductor used in magnets is much more than just a simple winding of wire. Typically, multifilamentary conductors are needed, with filament diameters of a few microns. These filaments are embedded in a normal metal matrix or tape, which stabilizes the superconductor and provides mechanical strength. If a section of the superconductor goes normal, then the current will be carried by the matrix, which has a lower resistivity than the superconductor in its normal state. Without the matrix, the normal spot would heat, causing adjacent areas of superconductor to go normal. The disturbance would propagate, causing the whole magnet to quench.

More than 20 years of R&D went into learning how to manufacture appropriate conductors from LTS materials that are mechanically strong, flexible enough to be wound into a magnet, low-loss for AC currents[2], capable of high current densities, and stable against thermal, electrical, and magnetic fluctuations. Wire-drawing techniques are sufficient to produce thin filaments from ductile materials like niobium-titanium. But with more brittle materials such as niobium-tin, the process is trickier.[3] Because HTS materials are more brittle yet, fabrication of a suitable conductor will be a big challenge.[4]

Brittleness is also a concern for the reliability of a magnet. When a magnet is energized, the magnetic field exerts a force that tends to push the coils outward. This puts the coil materials in tension. Brittle materials like HTS tend to form cracks under tension. Therefore, HTS conductors will have to be supported by stiff structural materials designed so that the stresses on the superconductor fall within acceptable limits.

There are several other major problems with HTS composite conductors for magnets. The problem of low critical currents in HTS bulk conductors—especially in the presence of strong magnetic fields—has been mentioned in the text. HTS materials also react chemically with nearly all metals other than gold and silver, thus complicating the development of a good matrix/superconductor match. Finally, the layered structure of HTS materials can lead to differential thermal contraction, causing cracking during warm-up and cool-down cycles of the magnet.

As a result of these challenges, high-field HTS magnets should be considered to be long-term. A DOE report on the possibility of HTS accelerator magnets[5] estimates a minimum time of twelve years with a dedicated program to develop a multifilamentary conductor and winding technique, and to demonstrate a magnet. It notes that "a more aggressive program than assumed, while capable of reducing development risk, would not necessarily compress the schedule significantly." A commercial application requires development of auxiliary electronics and components, followed by testing and reliability demonstration. After the demonstration of the magnet, several years may be required for market acceptance.

---

[1]Comparing power requirements for an industrial high-gradient magnetic separator used in clay processing, the conventional version requires 270 kilowatts (kW) to produce the field and 30 additional kW for cooling, while the low-temperature superconducting magnet uses only 0.007 kW to produce the field and 60 kW for cooling. Argonne National Laboratory, *Advances in Applied Superconductivity: A Preliminary Evaluation of Goals and Impacts*, Report ANL/CNSV-64, January 1988.

[2]The AC losses are due to hysteresis, eddy currents, and resistance.

[3]The problem of brittleness of niobium-tin, a low-temperature superconductor, is avoided by using a ductile precursor form of niobium and tin for the wire-drawing and magnet winding steps. Only after all steps that require ductility and flexibility are completed is the wire heat-treated to react the niobium and tin to form the superconductor. The danger is that heat treatment after winding can cause breakdown of the insulator between conductors, thus causing a short circuit in the magnet.

[4]A process similar to that used for niobium-titanium (cf., footnote 3) is being tried with HTS materials by American Superconductor Corp. This startup company is forming ribbons of the metallic constituents and then oxidizing them to form the superconductor.

[5]Basic Energy Sciences Advisory Committee Report to U.S. Department of Energy, *Panel on High T_c Superconducting Magnet Applications in Particle Physics*, December 1987.

never had to be faced with LTS. For instance, the performance of HTS materials is far more sensitive to impurities or minute changes in composition at surfaces and grain boundaries than is the case with LTS materials. This means that fabrication processes for HTS must be able to control the properties of these surfaces to a much higher degree.

To some extent, research in applied areas can be carried out in parallel with basic research. For

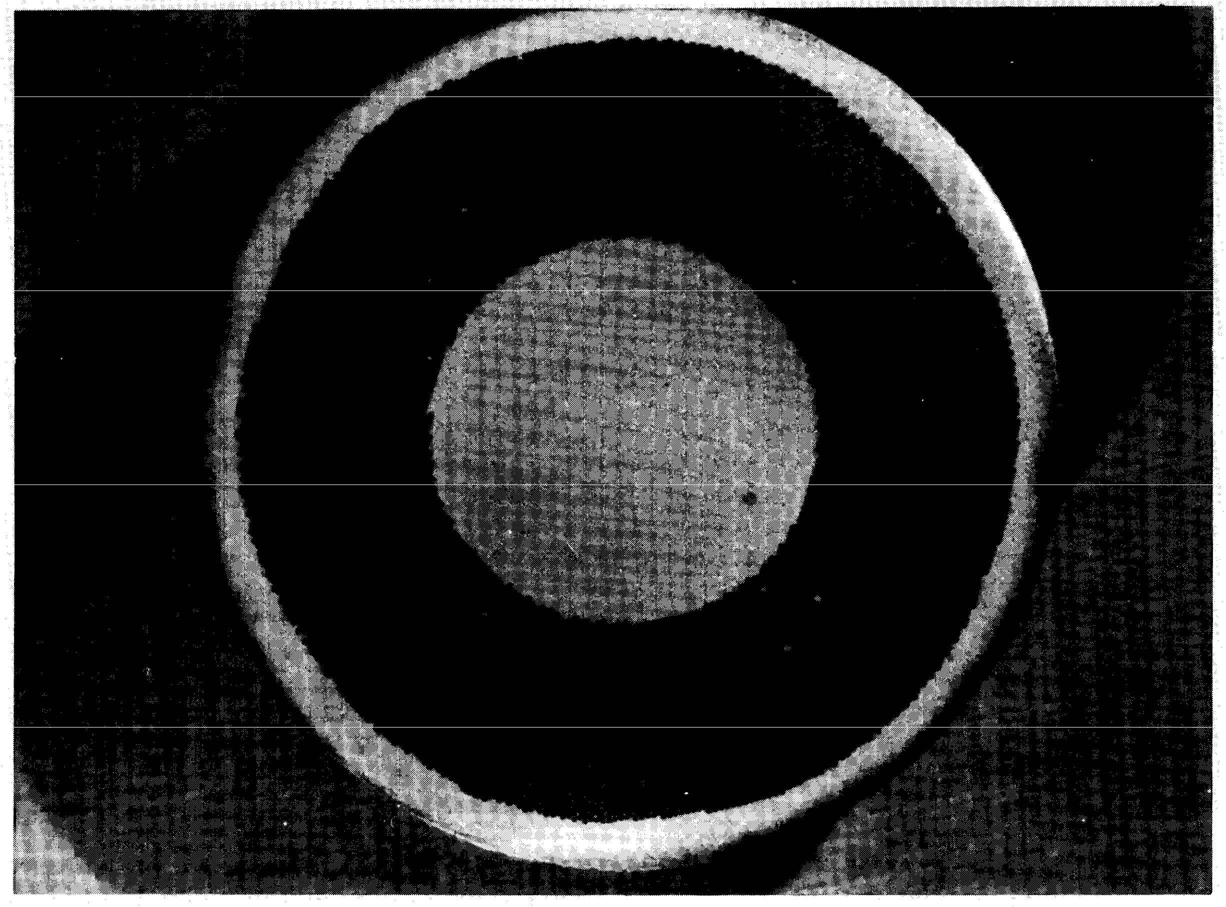


Photo credit: Supercon, Inc.

Prototype composite superconductor containing 11,000 niobium-titanium filaments, designed for use in the Superconducting Super Collider.

example, the critical current can be improved empirically (applied research) without having fully characterized the material (basic research). Similarly, the full system has parts that can be designed, built, and tested without the superconducting component. For instance, the refrigeration requirements can be approximated early, and developed before the superconducting component is completed.

But until the basic parameters of the technology—e.g., the pinning mechanism—are understood, early resources spent on manufacturing technology and systems development may turn out to have been wasted in light of new developments. No amount of research on vacuum tube technology would have produced a supercomputer; it awaited the discovery of the transistor and of integrated circuits.

A better feel for all of the requirements that must be satisfied for HTS to be used in commercial applications can be gained by considering two key applications of LTS: high-field magnets and Josephson Junctions (JJs). These are the "building blocks' of many present superconductivity applications. JJs illustrate the challenges associated with thin film technology, while magnets illustrate the challenges of fabricating devices from bulk materials. These are discussed in boxes 2-A and 2-B.

Box 2-B—Josephson Junctions

A Josephson Junction (JJ) is the basic building block of superconducting computers, digital electronics, and sensors. A JJ consists of two superconductors separated by a thin barrier layer of nonsuperconductor (see figure 2-1). As long as the current is not too large, pairs of superconducting electrons can tunnel through the barrier without any resistance; at some threshold current, however, the junction switches to a resistive state, with a resulting voltage across the barrier.

A JJ can be switched from the "off" (zero voltage) state to the "on" (finite voltage) state extremely rapidly (in about 1 picosecond) and with 100 times less power than a corresponding semiconductor transistor. The technology for producing JJs has been intensively developed using LTS films, and today LTS JJs are used in a variety of research instruments for astronomy, voltage measurement, and fast data sampling circuits. In principle, JJs could enable superconducting computers to be much smaller and faster than semiconductor-based computers. But although there has been extensive research on JJ computer components—first in the United States and more recently in Japan—the introduction of a general purpose computer using JJs does not appear to be imminent (see ch. 3).

HTS materials do exhibit the Josephson effect. In fact, polycrystalline HTS materials can be thought of as strongly superconducting grains coupled by weak Josephson links at the grain boundaries. These weak links appear to be the cause of the relatively low critical current densities observed to date in bulk materials.

Individual weak link junctions can be isolated relatively easily—simply by forming a narrow constriction in a thin film. These natural grain boundary JJs may be suitable for simple devices using one or two junctions, e.g., SQUIDS (see ch. 3). But for devices such as logic gates, that require many JJs be used together, more reproducible, deliberately fabricated junctions (e.g., the tunnel junction illustrated in figure 2-1) will be required.

The fabrication of large numbers of reproducible junctions was a major challenge with LTS, and could prove to be even more difficult with HTS. HTS junctions are likely to be 10 times more sensitive to imperfections at the superconductor-barrier interface than is the case with LTS materials, requiring far more precise control over the surface quality. The barriers must also be able to withstand the high processing temperatures required for HTS materials. These challenges guarantee that devices requiring large-scale integration of HTS JJs are many years away.

NEW OPPORTUNITIES

HTS materials are unique in having extremely high values of upper critical magnetic field (H_{c2}). At 0 K, H_{c2} for $YBa_2Cu_3O_7$ is estimated to be many hundreds of tesla,[6] compared with around 14 tesla for niobium-titanium, the LTS material used most often in superconducting magnets. If the critical current density of HTS bulk conductors can be improved, the high H_{c2} could enable an HTS magnet to operate as an insert inside another magnet, thus boosting the maximum field in the core.[7] [8] Use of HTS would also allow such magnets to operate at higher temperatures than present LTS magnets.

Another unique feature of HTS derives from the fact that the superconducting electron pairs are bound together more tightly than is the case for LTS (larger energy gap). Because the high frequency response of superconductors is limited to frequencies that do not disrupt the electron pairing, the stronger pairing could enable HTS 'devices to operate at frequencies up to 10 times higher than LTS devices. This could revolutionize the communications industry, making tens of thousands of new satellite broadcast channels available, and result in correspondingly higher rates of signal transmission and processing.

It is even possible that some of the "disadvantages of HTS materials could be turned into advantages. The sensitivity of the superconducting properties to oxygen content, crystal direction, and applied magnetic field could someday be the basis for new devices.

[6]For the magnetic field H parallel to the copper-oxygen planes. This estimate is only approximate, since it is based on extrapolation from measurements near 90 K.

[7]The highest continuous fields currently available are achieved using this type of hybrid magnet. They involve inserting a conventional water-cooled magnet inside a superconducting magnet.

[8]Explosive techniques, which destroy the magnet and sample, have reached fields of 100 to 1,000 tesla for a fraction of a second. However, the highest field strengths that are generally available at the Francis Bitter National Magnet Laboratory are 31.8 tesla continuous, and up to 68.4 tesla pulsed. Higher static and pulsed fields are available in Japan.

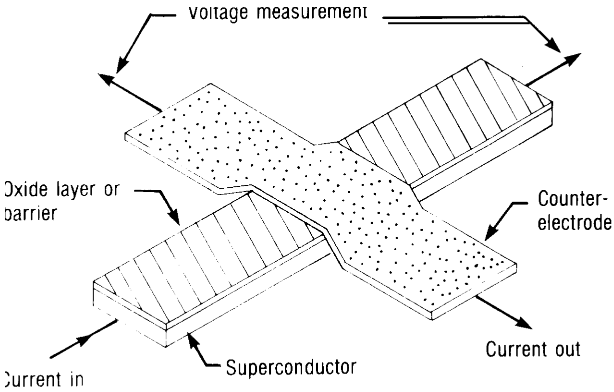
A particularly exciting prospect is the possibility of designing hybrid, layered devices that would combine different HTS materials with semiconductors, optoelectronic materials, and other superconductors to yield novel performance.

CONCLUSION

In spite of some recent press reports that describe the new HTS materials as disappointing,[9] the past 3 years have seen rapid progress both in improving the superconducting properties of known materials and in finding new materials. Many observers remain optimistic that present problems can be solved and that both familiar applications and entirely new ones will occur—although the time scale for many of these is not short.

Experience gained from previous research on LTS—in processing techniques, characterization of materials, and design of integrated systems—will come in handy, though. And these problems are being addressed by large numbers of researchers around the world; since its discovery in 1986, more than 12,000 papers have been published on HTS. HTS is an area where continued diligence and patience could yield great dividends.

Figure 2-l--Schematic of a Tunnel (or Josephson) Junction



SOURCE ***Business Technology Research,*** "Superconductive Materials and Devices," 1988.

[9]See, for example, Robert Pool, "Superconductivity: Is the Party Over?" *Science*, vol. 244, No. 4907, May 26, 1989, p. 914.

APPENDIX 2-A: SUPERCONDUCTOR PRIMER

As the temperature of a superconductor is lowered, a critical temperature T_c is reached at which the material undergoes a transition from the normal state to the superconducting state (figure 2-2). The superconducting state is defined by two characteristics: the ability to conduct an electric current without loss; and the expulsion of magnetic field from the interior of the material (Meissner effect).

Zero Resistance

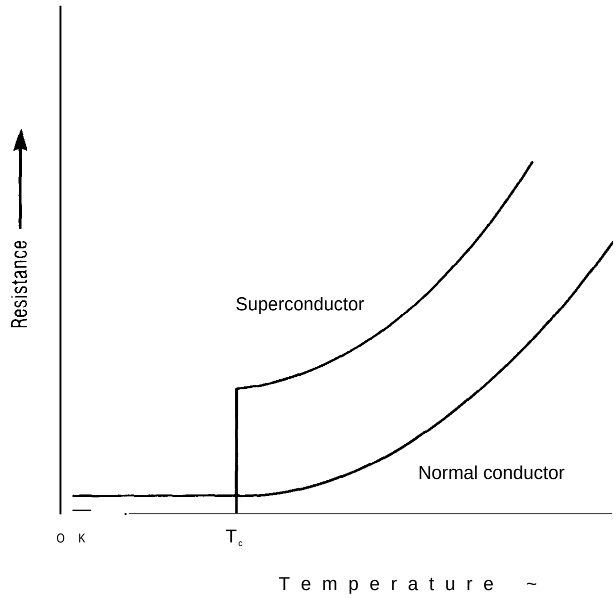
Ordinary conductors such as copper or aluminum present some resistance to the flow of electric current, causing some of the energy in the current to be dissipated into light and heat. Resistance is a useful property in light bulbs and toasters, but not for transmitting electricity from a power generating station to a factory. With zero electrical resistance, superconducting systems do not require a continuous supply of power to make up for losses. This has far-reaching consequences, enabling higher currents to be carried through wires, higher fields in magnets, and further miniaturization of computers.

Strictly speaking, the property of *zero* resistance obtains only under special conditions of direct (DC) currents. For alternating (AC) currents, such as the 60 cycle currents available from household wall outlets, superconductors do exhibit a small resistance. In general, this resistance is still lower than that of other common conductors such as copper and aluminum. However, the resistance of these metals decreases with temperature, dropping by roughly a factor of 6 between room temperature (300 K) and liquid nitrogen temperature (77 K). Thus, the advantage of a superconductor over a normal metal for a given application depends on how the superconductor's losses compare to those of normal wires at the relevant frequency and temperature.

Meissner Effect

A superconductor expels magnetic fields from its interior by generating electrical currents on the surface. This property, known as the Meissner effect, is what causes a small magnet to float above a superconductor, and can be exploited, e.g., to produce frictionless bearings. This screening property also makes superconductors useful as magnetic shields; e.g., electronics can be shielded against electromagnetic interference from other nearby equipment. Although zero resistance is the property exploited in most superconductivity applications, the Meissner effect is considered the *sine qua non* of superconductivity; for while a drop in electrical resistance to a low value can occur in nonsuperconductors, the Meissner effect is unique to the superconducting state.

Figure 2-2—Temperature Dependence of the Resistance of a Normal Conductor and a Superconductor (schematic)



At T_c, the resistance of a superconductor drops to zero.

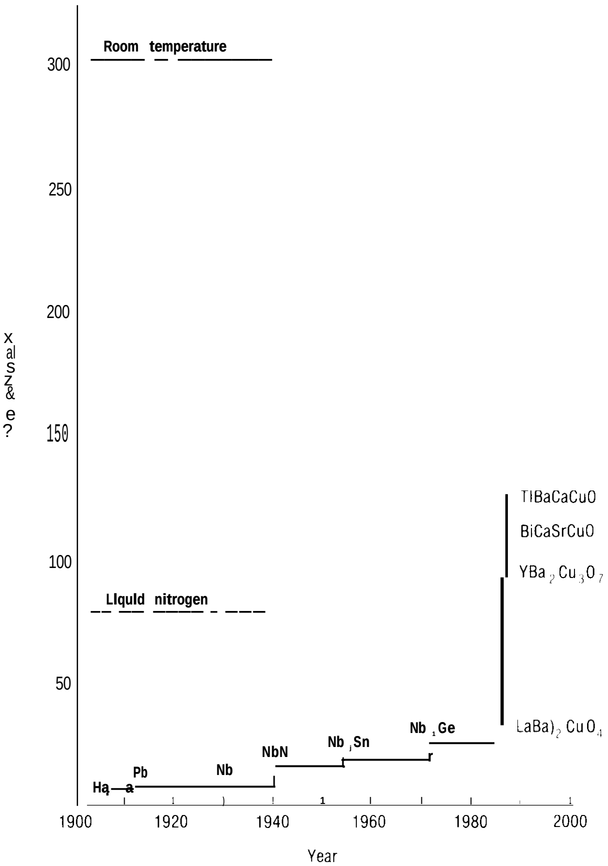
SOURCE: Office of Technology Assessment, 1990.

High-Temperature Superconductors

In 1986, superconductivity was discovered in a new class of ceramic materials having the chemical composition $(La,Ba)_2CuO_4$ at 35 K (-396 °F). Prior to 1986, the highest known transition temperature was 23 K (–418 °F) for niobium-germanium (see figure 2-3). The transition temperature of the most commonly used LTS material—an alloy of niobium and titanium—is 9 K (–443 °F). These low-temperature superconductors (LTS) must be cooled with liquid helium at 4 K (–452 °F), which is expensive and difficult to work with. This is one reason why LTS materials have not been used widely in commercial applications.

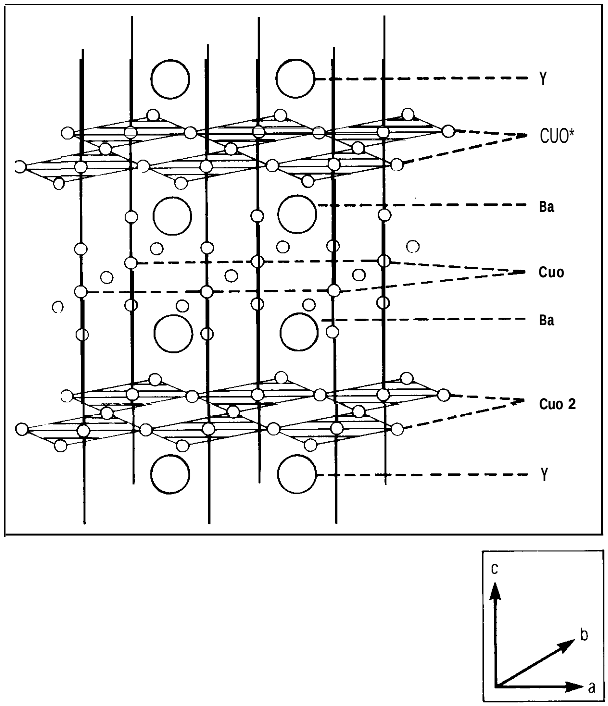
There are now three main types of superconducting compounds with transition temperatures above the boiling point of liquid nitrogen (77 K or –321 °F). In 1987, $YBa_2Cu_3O_7$ was discovered with T_c = 92 K (–294 °F). In 1988, $Bi_2Sr_2Ca_nCu_{1+n}O_{2(3+n)}$ with n = 1 (T_c = 85 K or –306 °F) and n = 2 (T_c = 110 K or –261 °F) and $Tl_2Ba_2Ca_nCu_{1+n}O_{2(3+n)}$ with n = 0 (T_c = 80 K or –315 °F), n = 1 (T_c = 110 K or -261 °F), and n = 2 (T_c = 125 K or –234 °F) were discovered. Numerous variations on these compounds have been found to be superconductors, all based on a layered, copper-oxygen structure (see

Figure 2-3--Superconducting Critical Transition Temperature v. Year



SOURCE: Office of Technology Assessment, 1990.

Figure 2-4—Structure of $YBa_2Cu_3O_7$ Showing Successive Stacking Planes Along the C-axis



The supercurrent is carried primarily in the CuO_2 planes.

SOURCE: Adapted from T.H. Geballe and J.K. Hulm, "Superconductivity—The State That Came In From the Cold," Science, vol. 239, No. 4838, Jan. 22, 1988, p. 370.

figure 2-4). At this writing, the thallium compound $Tl_2Ba_2Ca_2Cu_3O_{10}$ has the highest reproducible transition temperature (125 K).

The discovery of HTS materials with transition temperatures above the boiling point of liquid nitrogen aroused such great excitement because liquid nitrogen is cheaper, easier to handle, and has a higher cooling capacity than liquid helium. By operating at 77 K, both the system design and the refrigerator design can be simplified, and in principle, both capital and operating costs can be reduced. This revived hopes of widespread commercial applications of superconductivity.

History of Superconductivity

Highlights of the history of superconductivity are shown in table 2-2. Superconductivity was first discovered in 1911 by Heike Kammerlingh Onnes in Leiden, The Netherlands. The Onnes group discovered that mercury lost all resistance to direct electric current flow when cooled to 4 K (-452 oF). This occurred soon after the successful liquefaction of helium, which allowed such very low temperatures to be reached.

Although the Leiden group immediately saw many applications for a lossless conductor, the superconductors they had found could only carry high current densities at low magnetic fields; as the fields were increased, they reverted to normal metals. This made them technologically useless.

Over the years, more than 6,000 elements, compounds, and alloys have been found to be superconductors. But for many years no one understood how to get the current-carrying capacity at high magnetic fields up into a useful range. The first materials capable of carrying high currents in high magnetic fields ("type II" materials—see below) were discovered in the Soviet Union in the 1950s.

It was not until 1957 that a theoretical understanding of superconductivity was achieved.[1] Using this theory, the Josephson Junction—a superconducting switching de-

[1] J. Bardeen, L.N. Cooper, and J.R. Schrieffer, *Physical Review B* vol. 106, p. 162 (1957); ibid., vol. 108, p. 1175 (1957).

Photo credit: Argonne National Laboratory

Electron micrograph of the grain boundary between crystals of HTS. Striations reflect the stacking of copper-oxygen planes. Because the supercurrent is carried primarily in the copper-oxygen planes, this kind of misalignment greatly reduces the current flow across the grain boundaries in the bulk material.

vice useful in electronic circuits and computers—was predicted and fabricated in 1962.[2] In 1955, the first practical supermagnet was produced at the University of Illinois, and in 1960 significant supermagnet advances were made at Bell laboratories. During the 1960s, commercial superconducting wire became available, and was soon used in large superconducting magnets for particle accelerators and nuclear fision experiments.

During the 1960s and 1970s, supermagnets largely displaced electromagnets for research, but it was not until superconductors appeared in magnetic field sensors in the 1970s and in MRI magnets in the early 1980s that they began to move out of a research environment. Since then, superconductors have slowly been making their way into commercial applications such as magnetic separators for removing impurities from kaolin clay and fast electronics for high-speed oscilloscopes (see ch. 3).

LTS is nearly 80 years old, while HTS is barely 3. The period between the discovery of LTS and the development of the first practical conductors (''type II' materials) was 50 years; it was another 20 years after that before LTS began to be used outside of a laboratory environment. This suggests that the widespread commercialization of HTS may take decades. To be sure, much has been learned from the development of LTS that may be applicable to HTS. But, as discussed below, HTS also presents some new challenges that will require real breakthroughs to solve—not just hard work.

Table 2-2—Important Dates in the History of Superconductivity

Year	Event
1911	... Superconductivity discovered (Onnes)
1933	... Meissner effect discovered (Meissner)
1934	... Phenomenological theory (London)
1950	... Macroscopic quantum theory (Ginzburg-Landau)
1957	... Prediction of type II materials (Abrikosov)
1957	... Microscopic quantum theory (Bardeen-Cooper-Schrieffer)
1950s	.. "A-15" materials (e.g., Nb_3Sn) discovered (Matthias et al.)
1961	... High-field, high-current properties developed (Kunzler)
1962	... Josephson effect predicted and discovered (Josephson)
1986	... HTS (T_c = 35 K) discovered (Bednorz-Mueller)
1987	... HTS (T_c = 93 K) discovered (Chu et al.)
1988	... HTS (T_c = 110 - 125 K) discovered (Maeda, Hermannn et al.)

SOURCE: Off Ice of Technology Assessment, 1990.

Superconductivity Theory

In 1957, Bardeen, Cooper, and Schreiffer, who received the Nobel prize for their theory (known as the "BCS" theory), proposed that electrons form pairs (known as Cooper pairs) in the superconductor and that these pairs are able to carry currents without loss. In the superconducting state, the electrons-which are normally repelled from one another due to their same electric charge-feel a net attraction through interaction with vibrations of the crystal lattice, resulting in the formation of Cooper pairs. BCS theory has proven applicable to all known low-temperature superconductors with only minor modifications. As yet, it is not clear whether BCS theory can be adapted to explain the new HTS materials.

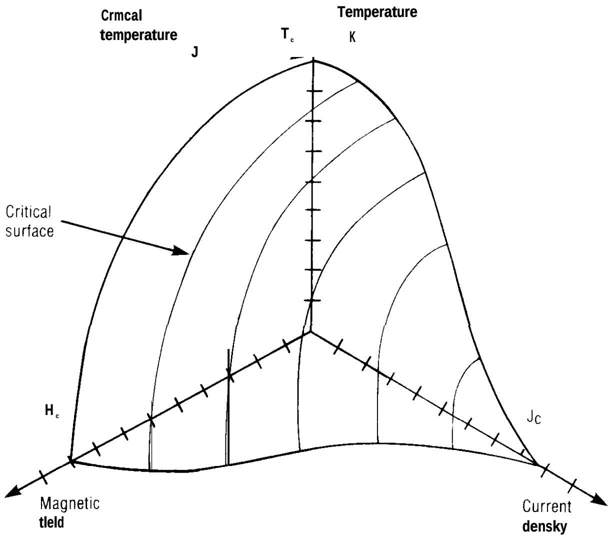
Critical Properties

A transition from the superconducting state back to the normal state can occur in any of three independent ways: by raising the temperature above the critical transition temperature (T_c); by raising the current flow above the critical current density (J_c); or by raising the applied magnetic field above the critical magnetic field strength (H_{c2}). Alternatively, lesser changes in these variables can cause the transition if they occur in combination.

For a typical superconducting material, the parameters T_c, J_c, and H_{c2} define the boundaries within which the material if in the superconducting state, and outside of which the material is in its normal resistive state (see figure 2-5). In general, the actual values of these parameters depend not only on the type of material, but also on its processing history, impurities, etc. For a given superconducting material, an application is only feasible if the operating temperature, current, and magnetic field fall well within these boundaries. To obtain usefully high

[2] B.D. Josephson, ''Possible New Effects in Superconductive Tunneling,'' *Physical Review Letters*, vol. 1, July 1962, pp. 251-253.

Figure 2-5—Superconducting State Boundaries Defined by Temperature, Field, and Current

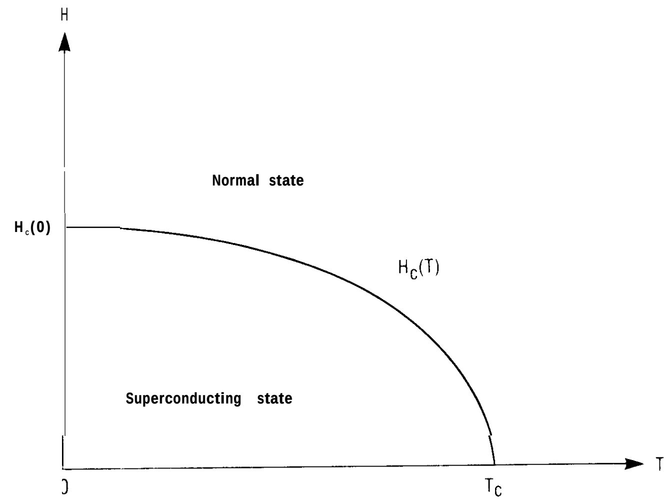


Material must be maintained below the "critical surface" to remain superconducting.

SOURCE: *Business Technology Research, "Superconductive Materials* and Devices," 1988.

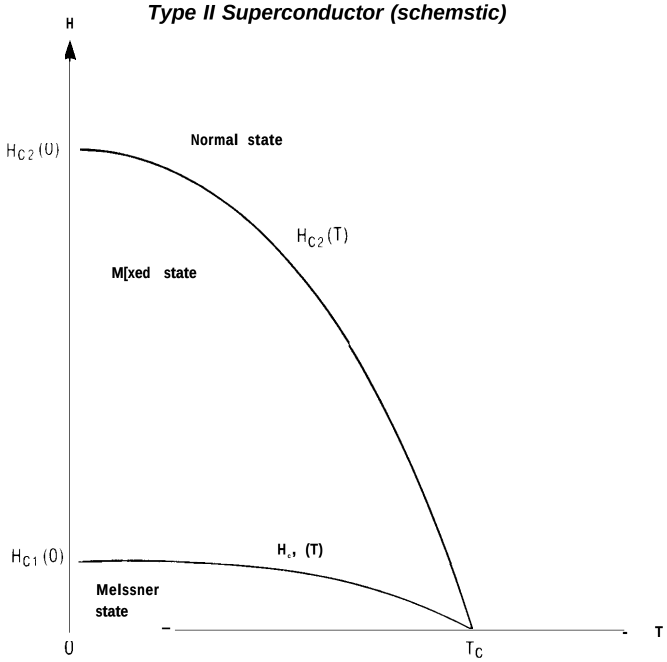
Figure 2-6—Critical Magnetic Field (H) v. Temperature Boundary

Type I Superconductor



Material must beat afield and temperature below the $H_c(T)$ line to remain superconducting.

Type II Superconductor (schemstic)



Magnetic flux lines enter the material for fields above $H_{c1}(T)$. Material remains superconducting below upper critical field $H_{c2}(T)$.

SOURCE: *Business Technology Research*, "Superconductive Materials and Devices," 1988.

values of current and magnetic field, superconductors are generally operated well below TC—ideally below about $1/_2 T$. Thus, for operation at 77 K, a T_C of approximately 150 ~ is desirable, higher than the T_C of any presently known material. Accordingly, room-temperature operation would require a T_C around 600 K, about 621 oF.

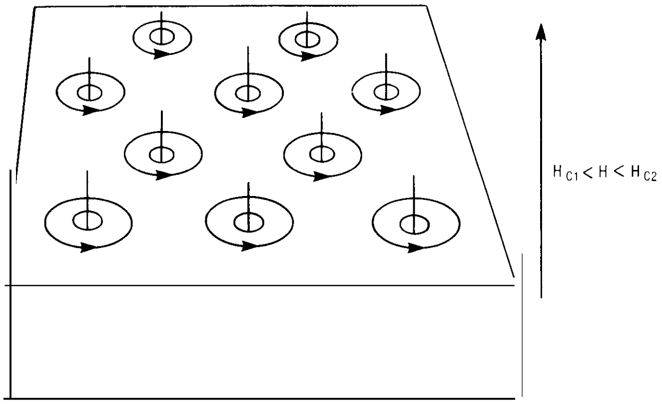
Behavior of Superconductors in a Magnetic Field

Superconductors are classified in two types according to their behavior in an applied magnetic field (see figure 2-6). Type I superconductors, which include most pure metal superconductors, exclude magnetic flux until a maximum field (H_C) is exceeded at which point the material loses its superconductivity. In general, type I superconductors are not technologically important because H_C is very low—100 to 1,000 gauss (0.01 to 0.1 tesla).[3] By comparison, the field of a typical magnet used in an MRI system is around 15,000 gauss. None of the type I superconductors remains superconducting in such a high field.

Virtually all superconductors of technological importance are type II, including the new HTS materials. Type II superconductors have two critical fields, H_{C1} and H_{C2}. They behave like type I materials at low magnetic fields, below H_{C1}. At fields above H_{C2}, the superconductor is driven into its normal state. For fields between H_{c1} and H_{c2}, the magnetic field penetrates the superconductor,

[3]One tesla (T) equals 10,000 gauss (G). The Earth's magnetic field at Washington, DC, is 0.57 gauss.

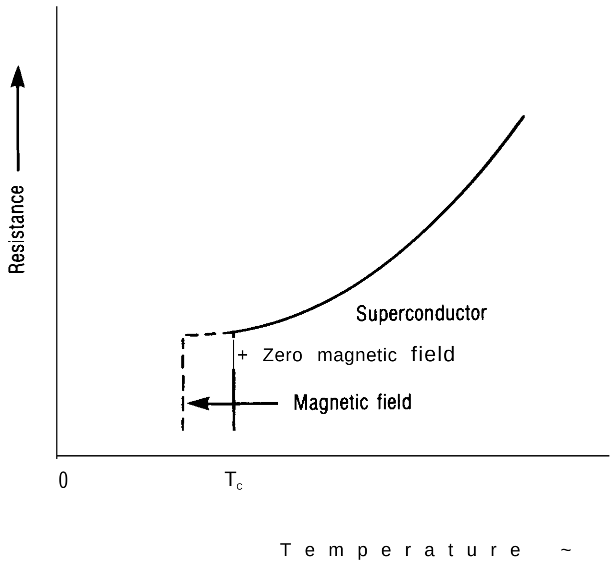
Figure 2-7--Schematic Representation of Flux Vortices in a Type II Superconductor



When the applied magnetic field is between H_{c1} and H_{c2}, lines of magnetic flux penetrate the superconductor, surrounded by supercurrent "whirlpools." As long as these flux lines remain "pinned" at fixed sites, the superconductivity is not impaired.

SOURCE: *Business Technology Research*, "Superconductive Materials and Devices," 1988.

Figure 2-8-Effect of Magnetic Field on Superconducting Transition (schematic)



An applied magnetic field causes resistance to appear in HTS materials below T_c.

SOURCE: Office of Technology Assessment, 1990.

forming a lattice of vortices or supercurrent 'whirlpools' (see figure 2-7). These vortices repel one another, and arrange themselves in a regular array so as to be as far from one another as possible. As the magnetic field increases toward H_{c2}, more vortices are formed, the lattice spacing is decreased, until at H_{cz}, the superconductivity disappears.

HTS materials are unusual in having much higher values of H_{c2} than LTS materials. For instance, at 4 K, H_{c2} for Nb_3Sn is about 20 tesla, compared with an extrapolated value for $YBa_2Cu_3O_7$ of around 200 tesla. It is not yet clear how these higher values of H_{c2} may be exploited.

Critical Current Density

The current density is defined as the amount of electric current passing through a unit cross section of conductor. In many applications—e.g., magnets—superconductors have to be able to sustain high current densities (typically 10^5 to 10^6 Amps/cm^2). Even on electronic circuit boards, where the absolute currents are only on the order of milliamps, the current density is high because the cross section of the conductors carrying the current is so small. The maximum current density that a superconductor can carry, the critical current density (J_c), depends not only on the composition of the material, but also on details of the microstructure, such as the presence of impurities and defects in the crystal lattice.

There is a theoretical limit on the amount of current that can be carried by any superconductor.[4] But, in practice, type II superconductors in a magnetic field typically exhibit J_cs that are a factor of 10 below this theoretical limit. The reason is that the flow of electric current exerts a force (Lorentz force) on the vortex lattice, and this force gets stronger as the electric current increases. Resistance appears when this force becomes strong enough to dislodge the vortex lattice from the pinning sites to which it is attached.

A significant fraction of the vortices are pinned in place by defects, grain boundaries, and other points of weakened superconductivity. Also, because of their mutual repulsion, the unpinned vortices are locked in place. Collectively, this local site pinning and the lattice locking are known as the pinning force in the superconductor. At the critical current the Lorentz force overcomes the pinning force and vortices begin to move. This movement constitutes resistance, and eventually quenches the superconductivity. An understanding of how to fabricate LTS conductors with the strongest possible pinning forces has been reached only after 20 years of research.

Increasing temperature can also act to disrupt the superconductivity in type 11 materials. At low temperatures (around 4 K), the ambient thermal energy is not large

[4]The thermodynamic critical current is the amount of current that will produce a magnetic field that exceeds the thermodynamic critical field locally. The thermodynamic critical current causes depairing of the Cooper pairs, thus destroying the superconductivity.

enough to dislodge pinned vortices. Therefore, thermally activated vortex movement has not been a problem with LTS materials. At higher temperatures, though, the higher thermal energy in the crystal can overcome the pinning forces, causing vortices to jump from one site to another (flux creep).

In the presence of a magnetic field, HTS materials exhibit a small residual resistivity at temperatures considerably *below* T_c (see figure 2-8). This phenomenon is not observed in LTS, and may require HTS materials to be operated substantially below T_c for applications in a magnetic field, i.e., at temperatures of 20 to 30 K rather than 77 K. This residual resistivity is due both to poor coupling between individual grains of HTS and to weak vortex pinning vis-a-vis thermal energy. Better processing techniques will eventually lead to improved intergranular coupling. New and stronger pinning mechanisms will have to be found to counteract the higher thermal energy at higher operating temperatures. Some hope may be derived from the fact that *thin* films of HTS exhibit far higher critical currents in the presence of magnetic fields than do bulk single crystals. This suggests that the low critical currents in bulk materials may not be intrinsic, but may be improved by creating microstructure similar to those in thin films. In any case, materials with higher T_c do not necessarily have higher pinning strength, and therefore are not necessarily more attractive for practical applications.

Chapter 3

Applications of Superconductivity

CONTENTS

Boxes

Tables

Chapter 3

Applications of Superconductivity

INTRODUCTION

The purpose of this chapter is to assess the significance of high-temperature superconductors (HTS) to the U.S. economy and to forecast the timing of potential markets. Accordingly, it examines the major present and potential applications of superconductors in seven different sectors: high-energy physics, electric power, transportation, industrial equipment, medicine, electronics/communications, and defense/space.

OTA has made no attempt to carry out an independent analysis of the feasibility of using superconductors in various applications. Rather, this chapter draws on numerous reviews published over the past several years. Nor is this discussion exhaustive; instead, the intent is to survey some of the noteworthy factors that will determine the potential for HTS in the different economic sectors cited above. In most applications, HTS competes with low-temperature superconductors (LTS) as well as with steadily improving nonsuperconducting technologies; therefore, the prospects for LTS—a far more mature technology—are considered in parallel with those of HTS.

Following the discussion of applications is a section on the lessons for HTS that can be gleaned from nearly 80 years' experience with LTS. The chapter concludes with a discussion of the significance of a higher critical transition temperature (T_c) in the context of the broader requirements that must be met by any viable commercial technology.

APPLICATIONS

High-Energy Physics

From its inception until the coming of age of magnetic resonance imaging (MRI) in the mid-1980s, the U.S. superconducting wire industry was almost entirely dependent on wire procurements by Federal laboratories. This wire was primarily used in particle accelerator magnets for high-energy physics (HEP) research.[1]

Accelerators require huge amounts of superconducting wire. The Superconducting Super Collider will require an estimated 2,000 tons of NbTi wire, worth several hundred million dollars.[2] Accelerators represent by far the largest market for superconducting wire, dwarfing commercial markets such as MRI,

Superconductors are used in magnets that bend and focus the particle beam, as well as in detectors that separate the collision fragments in the target area. (Superconducting radio frequency cavities are also used to accelerate the particles in linear accelerators.) The magnets typically operate at high fields (around 5 tesla); the higher the operating fields, the higher the particle energies that can be achieved, and the smaller the size of the accelerator needed. Superconducting magnets are essential because they have low losses and enable higher magnetic fields; without them, power requirements and construction costs would be prohibitive. The low operating temperature of LTS magnets also helps to minimize scattering of the beam.

Superconducting Super Collider (SSC)

The SSC is a racetrack-shaped collider that is expected to extend particle physics research to a higher level of energy—about 20 TeV—than has ever been achieved before.[3] Sited in central Texas, the SSC is to be 54 miles in circumference—lo times the size of the Fermilab Tevatron—and may cost as much as $7.2 billion.[4] The superconducting magnets, which have experienced development problems, are expected to account for about one-third of the total SSC construction cost. In fiscal 1990,$225 million was appropriated to continue development and begin construction of the SSC. The project is expected to be completed in 10 years.

[1] Particle accelerators can be used to study the internal structure of atomic nuclei and to produce intense beams of radiation in the ultraviolet and x-ray regions of the electromagnetic spectrum.

[2] Business Technology Research, ''Superconductive Materials and Devices,'' 1988, p. 57.

[3] The previous high, at the Fermilab Tevatron, approaches 1 TeV (1 TeV = 10^{12} electron volts). At the higher energies, physicists hope to observe the ''top'' quark, which would confirm the predictions of the Standard Model, and the Higg's Boson, posited by unified field theory.

[4] Irwin Goodwin, ''Trying Times: Cost of Remodeling SSC Causes Texans To Circle Their Wagons,'' *Physics Today*, vol. 43, No. 1, January 1990, p. 45.

Photo credit: Fermi National Accelerator Laboratory

Completed superconducting dipole magnets for Fermilab's Tevatron, stacked awaiting installation in the 4-mile accelerator.

With the discovery of superconductivity above liquid nitrogen temperature, the possibility arose of delaying construction of the SSC in order to be able to use HTS for the magnets. Potential savings were anticipated in either of two areas: by operating at higher temperatures and thus reducing the refrigeration costs, or by operating at higher fields and thus permitting a reduction in the size of the ring. But studies have shown that-even if suitable HTS magnets were available today—neither of these savings would amount to much.[5,6,7]

In any case, analysts have estimated that it would take at least 12 years to demonstrate an accelerator dipole magnet made from an I-ITS material.[8] Furthermore, physicists have learned from bitter experience that it is better to be cautious in pushing the state-of-the-art in accelerator magnet technology.[9]

Although primary reliance on HTS is ruled out for the SSC, there maybe niche applications that could help to bootstrap HTS into the next generation of machines. One possible use of HTS would be in electrical leads that supply power between the liquid nitrogen cooling jacket and the LTS magnets at liquid helium temperature, thereby reducing the heat load on the refrigeration system. But in the foreseeable future, LTS wire will continue to be the material of choice for the critical magnets used in HEP research.

Electric Power

Several applications of superconductivity in the electric power sector have undergone extensive evaluation and even prototype development: e.g., fusion magnets, generators, superconducting magnetic energy storage (SMES), and AC transmission lines. An overview of the impact of superconductivity on these applications is provided in table 3-1. Other applications not discussed here include magnetohydrodynamic power generation, transformers, motors, and power conditioning electronics.

Fusion Magnets

Magnetic fusion requires confinement of a heated plasma in a magnetic field long enough to get it to ignite—about 1 second. *O Superconducting magnets are considered essential for the continuous, high-field operation that would be necessary for a commercial fusion reactor.

Like particle accelerator magnets, Federal fusion magnet programs have provided a significant government market that has driven the development of

---

[5] U.S. Department of Energy, Office of Energy Research DOE/ER -0358, Panel on High-T_c Superconducting Magnet Applications in Particle Physics, *Report of the Basic Energy Sciences Advisory Committee*, December 1987.

[6] M.S. McAshan and P. VanderArend, *A Liquid Nitrogen Temperature SSC*, SSC Central Design Group, SSC-127, April 1987.

[7] R. Meuser, T. Elioff, N. Travis, and J. Zelver, *Potential Effect of the New High-Temperature Superconductor on SSC Costs*, SSC Central Design Group, SSC-N-347, May 1987.

[8] U.S. Department of Energy, op. cit., footnote 5, p. 6.

[9] This was the lesson of Isabelle, a disastrous accelerator project undertaken in the 1970s and early 1980s at Brookhaven National Laboratory. Based on the superior performance of one prototype magnet, the decision was made to upgrade the design to double the total energy. But for years the performance of the prototype magnet could not be reproduced consistently. By the time this was accomplished, it was too late: in 1983, the high-energy physics community decided that the window of opportunity for Isabelle had passed due to the superior progress in Europe on an accelerator in the same energy range. Isabelle was halted, having expended $150 million and requiring $150 to 200 million more to be completed. The U.S. high-energy physics community decided to put their efforts into a request for a higher-energy-range accelerator (the SSC).

[10] For a review of fusion technology, see U.S. Congress, Office of Technology Assessment, *Starpower: The U.S. and the International Quest for Fusion Energy*, OTA-E-338 (Washington, DC: U.S. Government Printing Office, October 1987).

superconducting magnet technology.[11] As a result, there are no major unsolved technical problems in the fabrication of large fusion magnets. 12 The lack of follow through on these programs can be attributed to technical, economic, and political issues affecting fusion technology. Because magnet refrigeration costs are less than 1 percent of total construction costs, the advent of HTS is not expected to change the outlook for fusion.[13]

Superconducting Generators

Superconducting generators enjoy three potential benefits over conventional generators. They offer better system stability against frequency changes due to transients on the grid. Because they can operate at higher magnetic fields (5 to 6 tesla), the size can be reduced up to 50 percent; this in turn could reduce capital costs significantly. Finally, efficiency could be increased by 0.5 percent (a reduction in losses of around 50 percent). Even this small efficiency increase could result in fuel savings that would pay back the capital costs of the generator over its lifetime.[14]

Although several prototype superconducting generators were designed and constructed at the Massachusetts Institute of Technology, General Electric Co., and Westinghouse Electric Corp. during the 1960s to the early 1980s,[15] these were never commercialized because there was no perceived demand for new generating capacity.[16] Today, the United States has no significant ongoing commercial LTS generator program, although programs are continuing in West Germany, Japan, and the Soviet Union. Siemens in West Germany is proceeding with plans for an 850 megawatt (MW) commercial system, and tests of prototype components are expected to begin in 1990.[17] A consortium of Japanese companies is developing a 200 MW generator for the late 1990s (the "Super-GM" project, see ch. 5).

Most studies indicate that LTS generators are only competitive with conventional generators at very high power ratings (500 to 1,000 MW). But with low load growth in the 1980s and continuing uncertainties about demand in the 1990s, there appears to be little enthusiasm among U.S. firms to put up their own cash for R&D on such large machines.[18] In principle, use of HTS could make smaller machines more competitive, but estimates differ on how much. The refrigeration system would be much simpler, and this would lead to greater reliability and maintainability. But the application involves a high-field, high-current, wire-wound magnet, spinning at high speed, under large centrifugal stresses. HTS wires would have to carry current densities on the order of 100,000 Amps/cm^2 in a 5 tesla magnetic

11The Mirror Fusion Test Facility (MFTF) at Lawrence Livermore National Laboratory was the most ambitious superconducting magnet program ever undertaken. Begun in 1974 and continuing for 12 years, it involved construction of 42 huge magnets of different types, costing over $100 million and using 583,400 pounds of superconductor. Although the magnets did operate to specifications, the project was mothballed in 1986 due to lack of funds.

12In 1976, the Energy Research and Development Administration initiated a program to address the need for superconductive coil technology in the Tokamak program. It was called the Large Coil Program (LCP), and was based at Oak Ridge National Laboratory (ORNL). Originally, LCP was intended to be a domestic program involving the fabrication of three coils by industry contractors and a test facility at ORNL. Because of growing international interest in fusion coil technology, the program was expanded under the auspices of the International Energy Agency (and renamed the Large Coil Task, or LCT) to six coils, three contributed by the United States, and one each from Switzerland, EURATOM, and Japan. This international collaboration ran from 1977 to 1987, and concluded with testing of the six coils at ORNL. Although the LCT was considerably more costly and time-consuming than initially estimated—final costs were $78 million, more than twice the initial estimates of $33.5 million—it was a technical success and was a model of close international cooperation. But at the conclusion, funding was reduced so that the Tokamak program could not afford to purchase the new magnets.

13F. Schauer et al., "Assessment of Potential Advantages of High T_C Superconductors for Technical Application of Superconductivity," Kernforschungszentrum Karlsruhe, KfK 4308, September 1987, p. 6.

14Electric Power Research Institute, "The New Superconductors," 1988, p. 22.

15TMAH Consultants, "Lessons From Low-Temperature Superconductors," a contractor report prepared for the Office of Technology Assessment, November 1988, p. 17.

16By 1983, U.S. utilities had for the most part stopped adding new generating capacity; those few new generators being ordered were small (200 to 300 megawatts). Utilities (particularly those in the industrial Midwest) had overbuilt generator capacity based on overoptimistic market growth estimates from the early 1970s. Consequently, during the 1980s utilities experienced slow demand which left planned capacity underutilized. Only at the end of the decade has demand increased to the point where new capacity is beginning to be needed.

17D. Lambrecht, "Development of SC Generators by Siemens KWU," in the Proceedings of the International Energy Agency's Second Experts' Meeting, Sorrento, Italy, May 11-12, 1989, p. 75.

18From 1987 to 1992 utilities were expected to bring online only about 29,700 MW of capacity from all sources. (Total capacity in 1987 was 718,056 MW.) U.S. Congress, Office of Technology Assessment, *Electric Power Wheeling and Dealing: Technological Considerations for Increasing Competition*, OTA-E-409 (Washington, DC: U.S. Government Printing Office, May 1989), p. 45.

Table 3-1-Applications in the Electric Power Sector

Application	Impact of superconductivity	Comments
Fusion magnets	Technical feasibility demonstrated with LTS, unlikely with HTS.	Superconducting magnets are essential, but fusion is limited by technical problems unrelated to superconductivity.
Magnetohydrodynamics (MHD) magnets	Technical feasibility demonstrated for LTS, unlikely for HTS.	Similar to fusion situation.
Generators	Technical feasibility of rotors demonstrated with LTS, possible with HTS.	Superconducting designs only economic at high power ratings, for which demand is limited. HTS could make smaller generators more attractive, but faces extreme technical challenges. Virtually no active programs in U. S., despite continuing development programs abroad.
Superconducting Magnetic Energy Storage (SMES)	Technical feasibility demonstrated with LTS, possible with HTS.	Similar to generator situation, although U.S. has an active program due to potential for military applications.
Transmission lines	Technical feasibility demonstrated with LTS, potentially attractive with HTS.	Must be placed underground, making capital costs high. Superconducting designs only economic at high power ratings, though HTS could make lower capacity lines more attractive. Market outlook discouraging.
Auxiliary equipment: Current limiters Switches Fuses Power leads	Minor with LTS, promising for HTS.	May provide an early opportunity to demonstrate performance of HTS in a utility setting.

SOURCE: Office of Technology Assessment, 1990.

field to realize the large decrease in size possible. These requirements make the generator one of the most difficult applications for HTS.

Beyond the turn of the century, there will be a market for new generators, both to replace older equipment and to accommodate growth in demand.[19] The share of superconducting generators in this market is uncertain. But one thing is clear. Because it is likely to take at least 15 years to demonstrate a commercial system, the United States is effectively conceding this market to its competitors unless it restarts its LTS generator programs immediate y.

Superconducting Magnetic Energy Storage (SMES)

In an SMES system, electric power is stored in the magnetic field of a large superconducting magnet, and can be retrieved efficiently at short notice. Power conditioning systems are required to convert the DC power in the magnet to AC for the grid when discharging the SMES, and vice versa when recharging. SMES has several potential applications in electric utilities. Large units (above 1 GW-hr capacity) could be used for diurnal storage and load leveling. Smaller units may provide a number of operating benefits: e.g., spinning reserve, automatic generation control, black start capability, and improved system stability.

SMES is also of interest to the military because it can deliver large quantities of pulsed power to weapon systems such as ground-based lasers for ballistic missile defense. The Strategic Defense Initiative Organization (SDIO) is presently supporting the development of a 20 MW-hr/400 MW engineering test model (ETM), which could begin tests by 1993.[20] Because the military design and the utility design are similar except for the power conditioning system (weapons must receive large amounts of power quickly and may drain the SMES in a very short time; utilities must have a constant reliable supply from which smaller amounts of power are withdrawn on a daily basis), utilities are

[19] The export market could provide opportunities sooner than the domestic market.

[20] The project, currently in the design phase, is being carried out by two contractor teams—one headed by Bechtel National, Inc. and one by Ebasco Services, Inc. The entire project was originally planned to cost $80 to $90 million over 5 years; it has already experienced stretchouts due to optimistic initial development estimates, as well as subsequent shortages of SDIO funds. The cost is now expected to approach $200 million, with construction delayed until fiscal year 1992.

providing a small percentage of the funding through the Electric Power Research Institute.

Utilities have experimented with several methods of storing energy, including pumping water uphill to a reservoir, compressing air, and charging batteries and capacitors. SMES has several advantages over other types of energy storage systems. For load leveling, it offers a higher efficiency than any other storage technology—90 to 93 percent,[21] compared to 70 to 75 percent for pumped hydro-and can switch back and forth between charging mode and discharging mode in a matter of milliseconds. This quick response time means that it can contribute to the stability of the utility system against transient disturbances.[22]

The SMES concept has undergone extensive evaluation in the United States since the early 1970s.[23] Most studies indicate that SMES for load leveling is only cost-effective at very large storage capacities, around 5000 MW-hr.[24] Such an SMES would be physically very large, perhaps 1,000 meters in diarneter.[25] To contain the magnetic forces on the coils, the SMES must be buried in bedrock, with total construction costs estimated to be around $1 billion.[2b]

I-ITS does not appear to offer dramatic reductions in capital or operating costs for SMES. With excellent HTS materials (comparable in cost and properties to NbTi, except with higher critical temperature), one could reduce capital costs by 3 to 8 percent.[27] HTS would provide only marginal improvements in the efficiency of the system, since only 2 percent of the power is consumed by refrigeration (this decreases with increasing SMES capacity), and 3 to 4 percent of the power is lost in the power conversion electrical system, the main determinant of efficiency. The high electric currents required could be another stumbling block for HTS. To reduce capital costs of the conductors, high critical current densities are required-in excess of 300,000 Amps/cm^2. The best present HTS wires are only capable of some tens of thousands of Arnps/cm^2 at 77 K, and this decreases in increasing magnetic fields. HTS materials could, however, be a good choice for the power leads connecting the liquid nitrogen jacket to the liquid helium temperature SMES coil.

In the present economic environment, utilities find such a large SMES unattractive compared with supplementary gas turbines. Before investing in such a large project, utilities will require that the technical feasibility and economic assumptions be demonstrated in smaller SMES systems such as the SDIO ETM mentioned above. Small SMES units (less than 100 MW-hr) are also undergoing evaluation for industrial or residential use in Japan.

Power Transmission Lines

Interest in superconducting power transmission lines dates back to the 1960s, when demand for electricity was doubling every 10 years. There was great concern about where large new power plants could be sited safely--specially nuclear plants—and about how such large amounts of power could be transmitted to users without disrupting the environment. Overhead lines often cut swathes through wooded areas and spoil scenery. Underground lines, a solution to environmental concerns, have other problems. Conventional underground cables are about 10 times more expensive than overhead lines, and consequently account for only 1 percent of the transmission lines in the United States. Moreover, because of heat dissipation and line impedance problems, these lines are limited to small capacities and short distances.

[21] A.M. Wolsky et al., *Advances in Applied Superconductivity: Goals and Impacts*, A Preliminary Evaluation of Argonne National Laboratory, ANL/CNSV-64, January 1988, p. 103.

[22] A prototype SMES was demonstrated by the Bonneville Power Authority to stabilize oscillations on a long intertie connecting southern California to the Pacific Northwest. A 30 MJ SMES was built by GA Technologies under contract to Los Alamos; it was 13 feet in diameter and 9 feet high. Connected to the intertie for about 1 year (1983), it turned out to have a lower efficiency than expected (86 percent) and to have some problems with refrigeration. Overall, the system was judged moderately successful.

[23] TMAH Consultants, op. cit., footnote 15, p. 23.

[24] A.M. Wolsky et. al., op. cit., footnote 21, p. 105.

[25] There are also environmental concerns that could add significantly to the cost and difficulty of siting the SMES. The magnetic field of a SMES is not confined to the interior of the coil, but extends both laterally and up above the system. These fields could interfere with heart pacemakers, communications systems, and the navigational mechanisms of birds. Thus, a utility SMES may require a fenced exclusion zone over the area where the field exceeds 10 gauss, perhaps several square miles.

[26] W.V. Hassenzahl, R.B. Shainker, and T.M. Peterson, "Superconducting Magnetic Energy Storage for Utility Applications," draft paper prepared for the Electric Power Research Institute, to be published, 1990.

[27] A.M. Wolsky et al., op. cit., footnote 21, p. 107.

Superconducting lines promised to address these problems: since their current-carrying capacity is not limited by heat dissipation they are able to carry large amounts of power at relatively low voltage. After the oil embargo of 1973, the emphasis shifted to the conservation potential of superconducting transmission. On average, about 4 percent of the electric power carried by a transmission line is lost due to resistance.[28] In principle, most of these losses could be avoided through the use of superconducting transmission lines.[29]

Superconducting transmission lines could carry either direct current (DC) or alternating current (AC). DC lines are used to carry large blocks of power from one point to another. A superconducting DC cable could carry very high currents with no resistive losses. But because the cost of DC lines is dominated by the conversion to AC at either end, a superconducting line would have to be extremely long (perhaps several hundred miles) to be economically competitive with cheaper overhead lines. Such cables are unlikely to be used except where alternatives are not available (e.g., for undersea power transmission), and are not considered further here.

During the 1970s, there were several important studies of AC superconducting transmission lines.[30] Three major projects were initiated in the United States, the most extensive of which was at Brookhaven National Laboratory. The Brookhaven project produced two 115 meter, 80 kilovolt (kV), one-phase lines made from Nb_3Sn. The project met all of its original design objectives, and, through continuous contact and collaboration with the utilities, maintained its relevance through its 14-year life span. But by the time it was completed in 1986, the economic landscape had changed.

Power consumption is no longer doubling every 10 years, and the near-term demand for new transmission lines of any type appears to be minimal, going hand-in-hand with the low demand for new generating capacity. There is evidence that existing transmission capacity is almost fully utilized. But at present, utilities prefer to build small power plants close to the end users rather than large plants far away.[31] EPRI has estimated that a liquid helium-cooled line would have to carry more than 5,000 megavolt-amps (MVA) to be cost-competitive.[32] This is much larger than a typical conventional line, rated at 1,000 to 3,000 MVA, and most utilities today are interested in smaller lines in the 200 to 1,000 MVA range.[33]

Transmission lines appear to be one of the few electric power applications where the incremental advantage of HTS at 77 K over LTS is very significant. This is because the long lengths involved make the cost of cooling with liquid helium extremely high, and the demands made on the conductor performance are relatively low. By some estimates, HTS could reduce costs by as much as 30 percent compared with LTS. EPRI has estimated that, using HTS conductors, lines with capacities as low as 500 MVA may be economically feasible.[34,35] It is ironic that in this one electric power application for which HTS technology seems potentially suitable, the projected demand is lacking.[36]

Current Limiters, Switches, and Fuses

These devices are used to control power flows, especially during short circuit conditions in the electric power system, and thus also reduce the short circuit capacity required of other components, such as cables, transmission lines, generators, and transformers.

Superconducting versions of these devices generally rely on controlling currents by switching the conductor from the nonresistive superconducting state to the normal resistive state. Compared with their conventional analogs, these superconducting components offer the advantage that they introduce

28 The Electric Power Research Institute, op. cit., footnote 14, p. 16.

29 There are conventional alternatives. For instance, losses could be reduced by using conventional conductors having a larger cross section, though this would increase conductor weight and require somewhat higher capital investment for towers, etc.

30 TMAH Consultants, op. cit., footnote 15, p. 11.

31 Office of Technology Assessment, op. cit., footnote 18, p. 20.

32 EPRI, op. cit., footnote 14. 1988, p. 18.

33 Ibid., p.18.

34 Ibid., p. 18.

35 A recent EPRI report concludes that present materials are still far from technical feasibility, though. Electric Power Research Institute, Assessment *of Higher-Temperature Superconductors for Utility Applications*, EPRI ER-6399, Project 2898-3 Final Report, May 1989.

36 This demand Picture, thou@, could change rapidly in the future due to environmental or Other site-specific considerations.

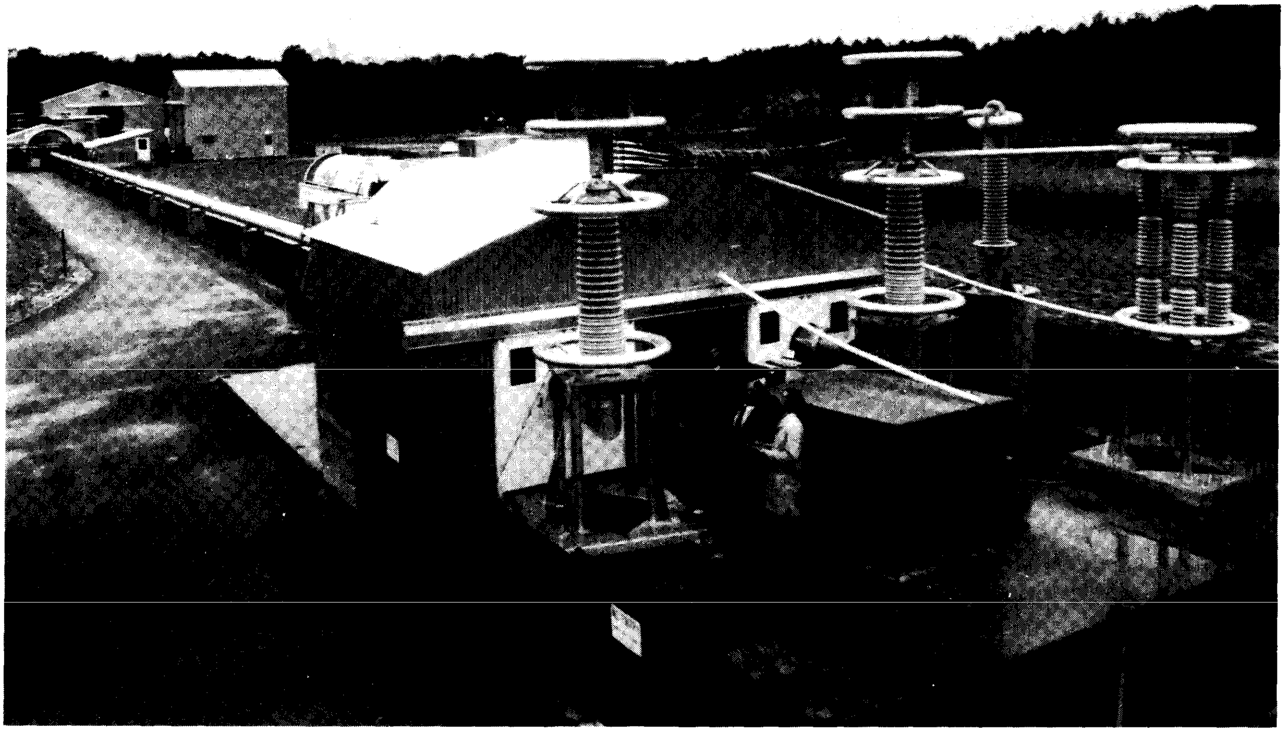


Photo credit: Brookhaven National Laboratory

Power Transmission Project's test facility at Brookhaven National Laboratory. Two 430-foot-long cables made of niobium-tin were successfully tested in a single cryogenic enclosure (long white pipe in background).

no losses into the system during normal operation, and switching times can be reduced from 1 to 2 cycles (about 20 milliseconds) to less than 1 millisecond.

These applications may be especially attractive for HTS compared with LTS. The new ceramics have comparatively high resistivity in the normal state, and liquid nitrogen is a far more efficient coolant than liquid helium. Moreover, these devices need operate only in small magnetic fields, and are subjected to small mechanical forces. Such small-scale applications could provide an early opportunity to gain experience with HTS in a utility setting.

Transportation

Applications of superconductivity in transportation include: magnets for levitation, propulsion, and guidance of high-speed ground vehicles ("maglev"); motors and generators for use in ships, aircraft, locomotives, and other ground vehicles; energy storage and propulsion systems for cars; and magnets for ship propulsion. An overview of the impact of superconductivity on these applications is given in table 3-2. Of these, maglev systems are the most extensively developed, and have received the most attention.

Maglev Systems

Airports and highways are becoming more and more congested, resulting not only in costly time delays, but in serious smog problems in heavily traveled corridors. Community resistance to new roads and airports compounds the difficulties of expanding these to fill travel demand. Transportation petroleum consumption alone exceeds domestic oil production, and oil supplies will continue to diminish as travel demand increases. 37 High-speed maglev vehicle systems offer one solution to these problems.

There are two principal levitation concepts for maglev vehicles: attractive-force and repulsive-force, Attractive maglev uses nonsuperconducting electromagnets mounted on the vehicle that are

37 A.M. Wolsky et al., op. cit., footnote '21, p. 169.

Table 3-2—Applications in the Transportation Sector

Application	Impact of superconductivity	Comments
Maglev systems	Technical feasibility demonstrated with LTS, minor with HTS.	Superconducting designs offer some advantages over conventional (attractive) maglev, but oosts are dominated by land acquisition and guideway construction.
Automobiles	Negligible unless room-temperature superconductors are discovered.	Cryogenic systems would be costly and inconvenient.
Ships:		
Electric drive	Technical feasibility demonstrated with LTS, possible with HTS.	May be most attractive in military ships where space and flexibility of hull design are at a premium,
Electromagnetic thrust	Possible with LTS, unlikely for HTS.	Technical and economic feasibility have yet to be proven in oceangoing vessels; requires large, high-field magnets.

SOURCE: Office of Technology Assessment, 1990.

attracted to the underside of steel rails. This concept was invented in West Germany and is also called ‘‘electromagnetic maglev. One disadvantage of this design is that the suspension gap between the rails and the car is less than one-half inch, placing strict demands on track alignment. The system is dynamically unstable and requires precise real-time feedback to control the suspension height. The vehicles are also very heavy (the latest weighs 102 tons), and require a massive support structure. Nevertheless, full-scale development of this system, called the Transrapid, is now underway in West Germany, with commercial operation scheduled to begin in the mid-1990s.[38]

Repulsive-force maglev, also called “electrodynamics, ’ uses vehicles levitated by superconducting magnets that induce repulsive currents in a guideway containing aluminum sheets or coils. Vehicles are levitated 6 to 10 inches above the guideway. This concept, invented in the United States,[39] was developed into scale models in the early 1970s, with support from the Federal Railroad Administration, the National Science Foundation, and private companies.

Support for all high-speed ground transportation research in the United States terminated in 1975, however. Meanwhile, the Japanese have actively continued developing a superconducting maglev system based on the U.S. “null flux” levitation and propulsion scheme, and a full-scale model has been undergoing tests on a 4.3-mile test track in Miyazaki, Japan for several years.[41]

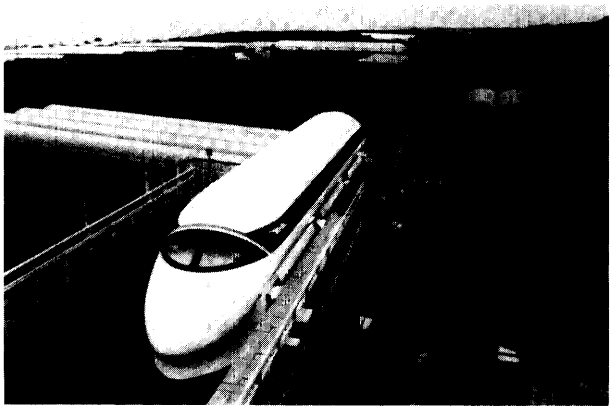


Photo credit: Japan External Trade Organization

Japan’s prototype linear motor car, a magnetically levitated train.

Conceptually, the West German and Japanese maglev systems are railroad systems, in which the maglev suspension is substituted for steel wheels. Viewed as a railroad technology, maglev trains offer several advantages over steel wheel trains. Maglev is capable of higher speeds (circa 300 mph) than steel-on-steel (circa 185 mph, with potential for over 200 mph). Maglevs are quieter, operable in a greater range of weather conditions, and are less polluting than diesel trains (although equivalent to electric trains). They have fewer moving parts, resulting in

38 The first commercial route is expected to connect the airports of Bonn and Essen.

39 G.R. Danby and J.R. Powell, ‘‘A 300 MPH Magnetically-Suspended Train, ’ *Mechanical Engineering, vol. 89,* November 1%7, pp. 30-35,

40 S.J. Thompson, Congressional Research Service, “High Speed Ground Transportation (HGST): Prospects and Public Policy,” Apr. 6, 1989, p. 5.

41 Construction of a new 27-mile test track has also been approved for the Yamanashi prefecture.

less wear and tear, and are less likely to derail because of the close coupling between train and track.

Notable disadvantages of maglev center around development and construction costs. Development costs for the West German Transrapid system have exceeded $1 billion, $800 million of which has been subsidized by the West German government.[42] Development costs of the Japanese system have also exceeded $1 billion, and construction costs for the new 27-mile Japanese system are expected to be around $56 million per mile (not counting tunneling costs).[43] Development of a U.S. system is estimated to cost $780 million[a] plus $15 million per mile for construction.[45]

Maglev is being evaluated along with other high-speed ground transportation options for several corridors in Florida, Nevada/California, Texas, and Ohio. Given the lack of domestic maglev technology in the United States, the West German and Japanese systems are being considered.[46] Florida has begun a process that could initiate construction of a maglev line (using the West German Transrapid technology) between Orlando Airport and Disney World/Epcott Center as early as 1990.[47] Although the United States was a world leader in maglev R&D in the mid- 1970s, there are no ongoing development programs.[48] However, it remains unclear whether these "train-like" maglev systems will be broadly applicable in the United States, given the relatively lower demand for train travel compared with Europe and Japan.

Going Beyond Railroads—There are other ways of viewing maglev technology than as a simple replacement for existing rail transportation. In one concept, lightweight individual vehicles follow one another closely along the guideway, each programmed to pull off and stop only at its destination.[49] Unlike railroads, this system could be installed along existing interstate highways, and indeed, conceptually resembles an elevated, high-speed freeway lane.

Recent studies have also suggested that maglev may more usefully be viewed as an airline technology, rather than a railroad technology.[50] Maglev could be integrated into the Nation's air transportation system as a substitute for less profitable (and inefficient) short-haul airline flights (those of less than 600 miles). Using small maglev systems for these distances would free up limited gate space as well as take-off and landing slots for more profitable long distance flights. Maglev lines could be installed as spokes radiating from major airports that have sizable populations within a limited radius.

Role of Superconductivity—Superconducting magnets are essential to repulsive maglev technology; however, the magnets and refrigeration systems together account for only 1 to 2 percent of total costs; the major system cost is in construction of the guideway (60 to 90 percent of total system cost).[51] If high-speed maglev systems are judged to be politically and economically desirable, present LTS magnet technology is adequate to the task; thus, superconductivity technology is not a bottleneck to the development of maglev. The discovery of HTS does not change this analysis. Although the vehicles could be made somewhat lighter with HTS magnets,

42 "Perspective," *Business Month*, November 1988, p. 11.

43 NationaJ Technical Information Service, *Foreign Technology*, vol. 89, No. 38, Sept. 19. 1989, P. iv.

44 See Maglev Technology Advisory Committee, *Benefits of Magnetically-Leviated High Speed Transportation for the United States*, Executive Report published by Grurnman Corp. for the Senate Committee on Environment and Public Works, June 1989, p. 30.

45 L.R. Johnson et al., Maglev Vehicles and Superconductor Technology: fntegratwn *of High-Speed Ground* Transportation *into the Air Travel System, Argonne* National Laboratory Center for Transportation Research, CNSV-67, April 1989, p. 5.

46 See Maglev Technology Advisory Committee, op. cit., footnote 44, p. 30.

47 Paul H Reistrup, President of the Monongahela Railway Co., testimony at hearings before the Surface Transportation Subcommittee, Senate Committee on Commerce, Science, and Transportation, Oct. 17, 1989.

48 Several bills were introduced in the 101st Congress (S-220 and S-221, H. Con. Res. 232) supporting us. maglev programs. The Bush Administration has requested about $10 million in the fiscal year 1991 budget for maglev feasibility studies.

49 H.H. Kolm and R.D. Thornton, "The Magneplane: Guided Electromagnetic Flight, ' *Proceedings of the Applied Superconductivity Conference*, Annapolis, MD, May 1-3, 1972.

50 L. R. Johnson et al., op. cit., footnote 45.

51 Larry Johnson, Director, Center for Transportation Research, Argonne National Laboratory, written testimony at hearings before the Senate Committee on Environment and Public Works, Subcommittee on Water Resources, Transportation and Infrastructure, Feb. 26, 1988, p. 4.

the overall gains would be no more than a few percent.[52]

Automobiles

Proposed auto applications include SMES devices to supply short bursts of power for starting or accelerating vehicles (allowing use of a smaller motor for the steady speed operation of the car), and linear induction motors that would receive power from conducting strips in the roadway (similar to the propulsion system in maglev). Superconducting motors for cars are also possible. But most analysts agree that neither LTS at 4 K nor HTS at 77 K appears to have significant applications in automobiles in the foreseeable future.

Batteries are far superior to SMES devices in automobiles because of their comparatively larger energy storage density, and would be cheaper as well, due to the inconvenience and cost of cooling the SMES. And a superconducting linear induction propulsion system would require not only an entirely new vehicle design, but a new infrastructure of power strips in millions of miles of roadways and a corresponding number of power distribution substations. According to U.S. auto industry experts, superconductors will not be used widely in cars unless they can operate at ambient temperatures.[53]

Ship Propulsion

Electric Drive-Present ship drive designs rely on mechanical power transfer—i.e., a long drive shaft and extensive gearing between the power plant and the propeller. All parts of the mechanical propulsion system must be in fixed locations, leaving little design flexibility. Moreover, since all power transfer is mechanical, the system is extremely noisy, with considerable vibration that can be easily detected—an undesirable feature for military craft such as submarines.

Electric drive consists of a turbine/generator system coupled electrically to the motor/propeller system. This provides greater design flexibility, since the two can be located independently, accommodating unusual hull shapes. It also offers operational flexibility, e.g., lower inertia in the drive system and reduced noise.[54]

Superconductors can be used in both the generator system and the motor system. Although superconductors can provide somewhat higher efficiency than conventional generators and motors, the principal advantage on ships appears to be the potential for reduced size and weight. This is especially important in smaller craft-e. g., destroyers and submarines—where hull space is restricted. Thus, electric drive ship propulsion in the United States is mostly of interest to the Navy. A superconducting DC homopolar generator and motor prototype system has been constructed and tested on a 65 foot ship at the David Taylor Research Center in Annapolis, Maryland.[f5]

While LTS materials offer considerable size reduction over conventional technologies, HTS materials appear to offer little advantage over LTS for this application. An HTS motor and an LTS motor (both 10 to 15 Tesla, with the same rpm and horsepower) would have approximately the same weight and diarneter.[5b] HTS materials may also be unable to support adequate current densities at the high magnetic fields required.

Electromagnetic Thrust Propulsion—131ectromagnetic thrust drive systems (sometimes called magnetohydrodymamic (MHD) drives), rely on seawater flowing through a channel in the hull where a DC electric current is passed through it. This current interacts with a field applied by a large magnet, resulting in a backward force on the water that propels the ship forward.

The propulsion force is proportional to the magnitudes of the current and the magnetic field strength. However, the current is limited by the amount that can be passed through seawater without causing excessive power losses due to heating. Thus, the thrust depends on the strength of the magnetic field. It has been estimated that a magnet of 10

[52] 1bid.

52 Superconductor *Week,* **vol.** 2, No. 45, Nov. 21, l988, p. 6.

53 Business Technology Research, op. cit., footnote 2, 1988, p. 106.

55 Although such a supconducting DC motor may offer advantages on board small military ships, this may be a niche application only. The market for DC motors has been shrinking for years due to replacement by variable speed AC motors (see discussion of motors in industrial section below).

56 M1chael J. SuperCYnSkl, David Taylor Research Center, in **a presentation at the Conference** on Military **Developments sponsored by Superconductor** *Week,* Washington, DC, Oct. 31 to Nov. 1, 1988.

tesla is needed for a commercial system to be economic .57

Superconducting magnets are the only practical option for achieving such large fields. However, large-bore magnets having such high fields would be extremely massive (not to say expensive), reducing propulsion efficiency. For the same reasons discussed above for large, high-field magnets, this is not a promising application for HTS. MHD propulsion has been considered for use on submarines because it eliminates the detectable vibrations associated with the propeller and generator, although it may not be acceptable for this application because the leakage magnetic field and various gases generated might make the submarine too vulnerable to detection.[58]

The MHD drive concept was fust developed in the United States in the 1950s, but the United States currently has no active development programs. The Japanese Foundation for Shipbuilding Advancement (an industry association) is building a prototype MHD-propelled ship scheduled for completion in 1990.[59]

Industrial Applications

There are many potential applications of superconductivity in industrial equipment. A partial list includes sensors for process and quality control; magnets for separation of solid, liquid, and gaseous mixtures; magnets for processing and shaping materials; accelerator magnets for x-ray lithography of microelectronic chips; and windings for industrial motors. In several of these applications, e.g., magnetic separation and compact accelerators, the feasibility has been demonstrated with LTS. The likely impact of superconductivity in some illustrative applications is indicated in table 3-3.

Sensors

Industrial sensor applications of superconductors have been discussed by several authors[m] and include applications both inside and outside the factory: for example, inspection of raw materials, monitoring of manufacturing functions such as the positioning of the work piece and tool, nondestructive inspection in finished parts, detection of corrosion in bridges, or exploration for mineral and oil deposits, etc.

The most commonly discussed superconducting sensors are Superconducting Quantum Interference Devices (SQUIDs),[61] which are capable of detecting extremely small magnetic fields; however, superconducting sensors can also be configured to measure small currents, voltages, temperature changes, and electromagnetic radiation emissions. Of course, there are numerous options for sensors using more conventional technologies: optical, chemical, ultrasonic, etc., and superconducting sensors may offer advantages only in certain niches.

Heretofore, LTS SQUIDS have not found application in industrial settings because their sensitivity typically far exceeds the ambient magnetic field noise levels, and because of the difficulty of working with liquid helium. Although HTS SQUIDS operating at 77 K are inherently more noisy than LTS SQUIDS operating at 4 K, their sensitivity is likely to be more than adequate for the industrial environment, and they would be far easier to maintain and transport.

While sensor markets for HTS are not likely to be large in terms of volume of material, there appears to be a number of possible niches. One example might be an array of HTS SQUIDS for improved detection of concealed weapons at security checkpoints. Because sensors are not especially demanding in terms of the superconductor material properties, present HTS materials may be adequate, and commercial HTS SQUIDS could be introduced within a few years. The United States appears to be

57 D.L. Mitchell and D.U. Gubser, "Magnetohydroynamic" Ship Propulsion With Superconducting Magnets, " **Journal of** Superconductivity, vol. 1, No. 4, 1988, p. 349.

58 Frank Hutchison, DARPA, personal communication, September 1988.

59 The "Yamato l," 38 meters long and 10 meters across, is the product of a 6-year, $350 million effort begun in 1985. The vessel will be built at Mitsubishi's Kobe plant. Superconductor *Week, vol. 4, No. 5,* Jan. 29, 1990, p. 5.

60 See, for example, Thomas P. Sheahan, Industrial Superconductivity, a report to the. Office of Industrial Programs, U.S. Department of Energy! October 1987.

61 For an introduction to SQUIDS and their applications, see R. Fagaly, "SQUID instrumentation and Applications, " *Superconductor Industry,* vol. 2, No. 4, Winter 1989, p. 24.

Table 3-3-Applications in the Industrial Sector

Application	Impact of superconductivity	Comments
Sensors: Processing Quality control	Minor for LTS, significant for HTS.	Operation at 77 K could offer greater reliability and maintainability in the industrial environment.
Magnetic separation	Significant for LTS, potentially promising for HTS.	Reliability and performance with LTS have already been demonstrated in kaolin clay purification.
Materials processing and shaping	Moderate for LTS, minor for HTS.	Will face strong mmpetition from conventional electromagnets.
Compact accelerators	Moderate for LTS, minor for HTS.	High magnetic fields and high mechanical strength are essential.
Motors	Minor for LTS, possible for HTS.	LTS only economic for the largest sizes (above 10,000 hp). HTS motors could reduce the economic break-even point, but the conductor must have extremely high performance.

SOURCE: Office of Technology Assessment, 1990.

well-positioned to participate in the early markets for HTS SQUIDs.[62]

Magnetic Separation

A strong magnetic field can be used to separate a mixture of magnetic and nonmagnetic materials. Conventional magnets are presently used in a variety of industrial separation processes, especially for the separation of strongly magnetic metals from other solids. Compared with other industrial separation techniques (e.g., distillation, filtration, chemical methods, and membranes), magnetic separation methods are not widely used, however.

The use of iron cores in conventional electromagnets limits the attainable fields in magnetic separators to around 2 tesla, and limits the magnetic field volume due to the sheer weight of the iron. With superconducting magnets, a 2-telsa field can be produced in a larger volume, or continuous fields of 5 tesla and above can be produced in a smaller volume. The use of higher fields permits a higher process throughput, and makes it possible to separate smaller particles having weaker magnetism.

Superconducting magnetic separation systems have recently been demonstrated commercially in several countries for separation of discoloring impurities from white kaolin clay, a material widely used in the paper industry (see box 3-A). Superconducting magnets could also be used for removal of environmentally harmful materials from municipal solid waste and wastewater streams, removal of sulfur from coal, and pretreatment of water to reduce carbonate scale formation in pipes and fixtures.[63]

A promising possibility for the future could be the combination of chemical and magnetic separation techniques. Selective chemical attachment of magnetic tags to specific molecules in a mixture could facilitate their separation by magnetic methods.

In principle, HTS magnetic separator systems would offer significantly lower capital and operating costs than LTS systems, since the scale of these systems is small enough that the 4 K cryogenic systems constitute a significant fraction of overall system costs. In addition, HTS magnets operating at 77 K would be easier to maintain and require shorter times for warmup and cool down. Unknown factors are whether HTS materials can achieve high enough current densities in the ambient magnetic fields, whether they will be sufficiently flexible to be wound into magnets, whether they will be sufficiently strong to withstand the powerful reaction forces of the generated fields, and whether they will be sufficiently reliable and stable in the industrial environment.

Materials Processing

Recent laboratory work suggests that magnetic fields below 2 tesla applied during processing can have a pronounced effect on the final microstructure of various materials: e.g., the sintering of ceramics,

62 Federal laboratories such as the National Institute of Standards and Technology and firms such as IBM have announced Progress in developing HTS SQUID technology.

63 S.J. Dale et. al., summary report for RP8009-2, Electric Power Research Institute ER-6682, January 1990.

Box *3-A--Magnetic Separation of Impurities From Kaolin* Clay[1]

Kaolin clay is a naturally occurring white mineral that is used to fill and whiten paper products. It also is used in china and ceramics. Magnetic separation can improve the whiteness and brightness of low-grade kaolin clay by removing iron-containing magnetic impurities that stain the clay, thus increasing the clay's value and utility. Magnetic impurities are trapped in the tnagnetic field of the separator, while the kaolin passes through unaffected. 1n 1987, U.S. production of kaolin totaled 8,827,000 short tons, valued at approximately $540 million. The Bureau of Mines projects U.S. demand to be greater than 12 million short tons in the year 2000.[2]

In 1%7, J.M. Huber Corp., a producer of kaolin clay, sought methods for improving the low-grade clay available in Georgia. Based on research conducted at the Massachusetts Institute of Technology National Magnet Laboratory under the National Science Foundation's Research Applied to National Needs program, the process of High Gradient Magnetic Separation (HGMS) was developed, and the first HGMS separators-using both conventional and superconducting magnets—were built by Magnetic Engineering Associates, a small Cambridge, Massachusetts firm. Eventually, the technology was licensed to the clay industry worldwide, as well as to the tacortite (a low-grade iron ore) and water purification industries.

By 1973, commercially available magnetic separators for kaolin (using conventional electromagnets) could process 60 tons/hr, Since that time, the magnetic separator has become the standard industry method for producing high-quality kaolin clay from low-grade sources.

In May 1986, Huber introduced the first low-temperature superconducting version of the kaolin magnetic separator, with a phenomenal 99 percent uptime in its first year, In the superconducting magnetic separator, the conventional electromagnet is replaced by a superconducting one. In addition, the energizing and de-energizing of the magnet are computer controlled. Huber contracted with Eriez Magnetics to build the superconducting version, at a cost of around $2 million, including the refrigeration equipment. It processes 20 tons of kaolin per hour, with a 90 percent reduction in the amount of electricity required compared to a conventional unit. Part of the success of this superconducting magnetic separator is due to its conservative design. Its liquid helium refrigeration capacity is twice what is needed for normal operation. In addition, there is a reservoir of liquid helium sufficient to keep the system running for over a week in the event of a total failure of the refrigerator. The design life is l@ cycles, which is over 50 years use for 2 cycles/hour, 24 hours a day. Huber ordered a second, larger unit, and placed it in operation in March 1989.

There are five companies worldwide that have taken superconducting magnetic separators beyond the laboratory: KHD Humboldt Wedag {West Germany), Cryogenic Consultants Limited (United Kingdom), Eriez Magnetics (U.S.A.), Czechoslovakia Kaolin Works, and Oxford Instruments Limited (United Kingdom). Two of these companies, Eriez and Czechoslovakia Kaolin Works, make superconducting magnetic separators for kaolin clay. The Czech system produces 15 tons of purified kaolin per hour.

The market for superconducting magnetic separators for kaolin clay is limited, even though demand for kaolin is expected to continue to grow. There are probably less than 20 large kaolin magnetic separators, conventional and superconducting, currently operating in the United States. However, the experience with superconducting magnetic separators in this application has important lessons far other applications of magnetic separation.

Magnetic separators in the industrial environment must have high reliability and operating simplicity. Conventional wisdom said that a dirty industrial environment was incompatible with liquid helium use. But the high reliability of the first commercial superconducting magnetic separator-due to its extremely conservative design-proved that LTS equipment can work well in an industrial environment.

Also, as demonstrated in the case of conventional kaolin magnetic separation, once economic viability and reliability are demonstrated by one company, competitors will be forced to follow. And the demonstrated operating efficiency of the kaolin superconducting magnetic separator indicates that there may be other impure raw materials-e.g., iron ores previously thought to be too poor a grade-that could be economically produced using this technology.

---

1 This box draws heavily on the contractor report report from TMAHConsultants, "Lessons From Low-Temperature Superconductors," prepared for the Office of Technology Assessment, November 1988.

2 U.S. Department of the Interior, Bureau of Mines, *Mineral Facts and Problems,* 1985 edition; and U.S. Department of the Interior, Bureau of Mines, Mineral Commodity Summaries *1989.*

polymerization of plastics, and the crystal growth of metals.[64] It is even likely that the course of chemical reactions-especially those involving colloidal mixtures or precipitation of solids-could be manipulated with powerful magnetic fields. These effects, which could be very significant, have not received serious study.

Strong magnetic fields on the order of 40 tesla can also be used for industrial shaping of metals and other conductors. This comes about because a magnet can exert powerful forces on a conductor moving through its magnetic field. These forces are developed without the mechanical friction that accompanies conventional shaping processes such as drawing of wire or press-molding sheets.[65] As a result, costly tool wear would be virtually eliminated. Continuous fields of this magnitude would involve hybrid magnets, and considerable engineering development would be required to overcome the problem of mechanical stresses on the magnet itself under such high fields. The critical current and magnetic field limitations of present HTS materials are serious barriers to their use in high-field magnets.

Compact Accelerators

As discussed earlier in this chapter, the large particle accelerators used in high-energy physics research depend on superconducting magnets and cavities to accelerate, direct, and focus the particle beams. Smaller versions of these machines (dimensions in the tens of square meters) could find application in industry settings; notably, in compact synchrotrons that would generate intense x-ray beams for lithography of microelectronic chips. Use of x-rays could permit the feature sizes of microelectronic circuits to be reduced to about 0.1 micrometer, compared with the current state-of-the-art of about 0.5 micrometer.[66] This capability could usher in a new generation of smaller, more powerful computers and electronics.

Several significant efforts are underway around the world to produce compact synchrotrons for x-ray lithography. In Japan, government and industry have invested an estimated $700 million in seven synchrotrons projects for x-ray lithography, and may spend $1 billion more to devise manufacturing systems.[67] West Germany, a member of the Joint European Submicron Silicon project (JEW), is building a $210 million institute to develop x-ray technology for chip manufacture.[68] In the United States, IBM has invested some $130 million on R&D and has contracted with the United Kingdom's Oxford Instruments to build a compact synchrotrons, scheduled for completion in 1992. But Federal support for R&D has been very modest (DARPA supports a $30 million program on x-ray lithography research) and other U.S. companies have been reluctant to get involved.

Compact synchrotrons technology presents a dilemma for U.S. companies. On the one hand, it could make existing chip fabrication technologies obsolete. On the other hand, capital costs of even compact synchrotrons systems are extremely high (perhaps $16 to $20 million), and cheaper competing technologies based on ultraviolet lasers or electron beam steppers continue to offer smaller feature sizes (perhaps down to 0.3 micrometers), thus narrowing the potential advantage of synchrotrons.

Superconducting magnets are the only practical alternative for producing synchrotrons rings smaller than about 5 meters in diameter. Present Japanese prototypes using LTS magnet technology have diameters of about 3 meters, If present LTS prototypes are successful, and these designs are commercialized, the industry emphasis on reliability and familiarity with the technology may mean that LTS will be preferred over HTS. Furthermore, if compact synchrotrons turn out to be an enabling technology for a new generation of microchips, it appears that the breadth and depth of commitment in Japan will guarantee that Japanese companies will take the early lead in the commercialization of this technology

64 Ibid. p.70.

65 Ibid.

66 Brian Santo, ''X-ray Lithography: The Best Is Yet to Come, ' *IEEE Spectrtun, February 1989, p. 49.*

67 Mark Crawford, ' 'The Silicon Chip Race Advances Into X-rays, " *Science, vol. 246, No. 4936,* Dec. 15, 1989, p. 1382.

68 Ibid.

Table 3-4-Applications in the Medical Sector

Application	Impact of superconductivity	Comments
MRI magnets	Successful application of LTS; minor for HTS.	An HTS magnet would lead to savings of only $10 per $700 scan.
Biomagnetics:		
SQUIDS	Demonstrated for LTS; possible for HTS, especially in applications not requiring the highest sensitivity.	Thermal noise at 77 K is inherently 20 times higher than at 4 K, although present commercial SQUIDS are generally not operated at their inherent noise limits.
Pickup coils for MEG	Demonstrated for LTS; promising for HTS.	A 77 K coil could be placed closer to patient's skull, for a stronger signal.
Room shielding	Not feasible for LTS: minor for HTS.	Competing technologies, including improved electronic noise discrimination, could be preferable.
Research magnets	Successful application of LTS; minor for HTS.	Since the technology is in hand, LTS magnets will be preferable for fields less than about 20 tesla.

KEY: MEG = magnetoencephalography; MRI = magnetic resonance Imaging; SQUID = Superconducting Quantum Interference Dewe.

SOURCE: Office of Technology Assessment, 1990.

Motors

The potential for superconductors in motor applications has been reviewed recently.[69] [70] In principle, superconductors can lead to higher efficiency (50 percent reduction in losses) and reduced size and weight (20 percent reduction in diameter, 60 percent in length, up to 60 percent in weight). Technically, superconducting motors share many of the same performance requirements as superconducting generators, but motors may be somewhat less attractive.

As with generators, AC superconducting motors are only cost-effective in the largest size ranges—above 2,000 horsepower (hp), a tiny fraction of all motors. EPRI has estimated that, because of the cost of liquid helium cooling, LTS motors would only be competitive above 10,000 hp, though HTS with liquid nitrogen cooling could reduce the threshold of economic feasibility to 5,000-10,000 hp.[71] [72]

Because they are similar rotating machinery, AC superconducting motors and generators share many of the same technical difficulties: AC losses, large mechanical stresses, and cryogenic seals for rotating shafts. But motors have a few additional problems: during startup and load variations, motors may experience heating and vibrations. Also, a large torque is needed to start a motor and its associated load, exerting large forces on motor components.

For HTS to succeed in AC motors, filaments having critical current density of 100,000 $Amps/cm^2$ in a magnetic field of 4 to 5 tesla, greatly reduced AC losses, and a high-strength composite conductors will be required—all major challenges for present HTS materials, as discussed in chapter 2.

Medical Applications

Medical applications of superconductivity are relatively recent, having their origins in research conducted during the 1970s. Examples are magnetic resonance imaging and magnetoencephalography. The feasibility of using superconductivity in these areas has been demonstrated in LTS, and indeed, superconducting MR1 magnets are now well established commercially and constitute the largest non-government market for superconducting wire and cable. However, the prospects for penetration of present HTS materials into these markets do not appear very promising, as indicated in table 3-4.

Magnetic Resonance Imaging

Each of the various body tissues, e.g., blood, organs, vessels, and bone, exhibits a slightly different chemical environment for the hydrogen atoms contained in its constituent molecules. When a strong magnetic field is applied to the body, these chemical environments can be readily distinguished.

69 A. M. Wolsky et al., op. cit., footnote 21, p. 111.

70 S.J. Dale et al., op. cit., footnote 63.

71 The Electric Power Research Institute, op. cit., footnote 14, p. 23.

72 A recent report (S.J. Dale et al., op. cit., footnote 63) indicates that DC HTS motors as smallas 100 hp could be economical with an open liquid nitrogen cooling system, but this is a hopeful forecast that assumes dramatic improvements in materials properties.

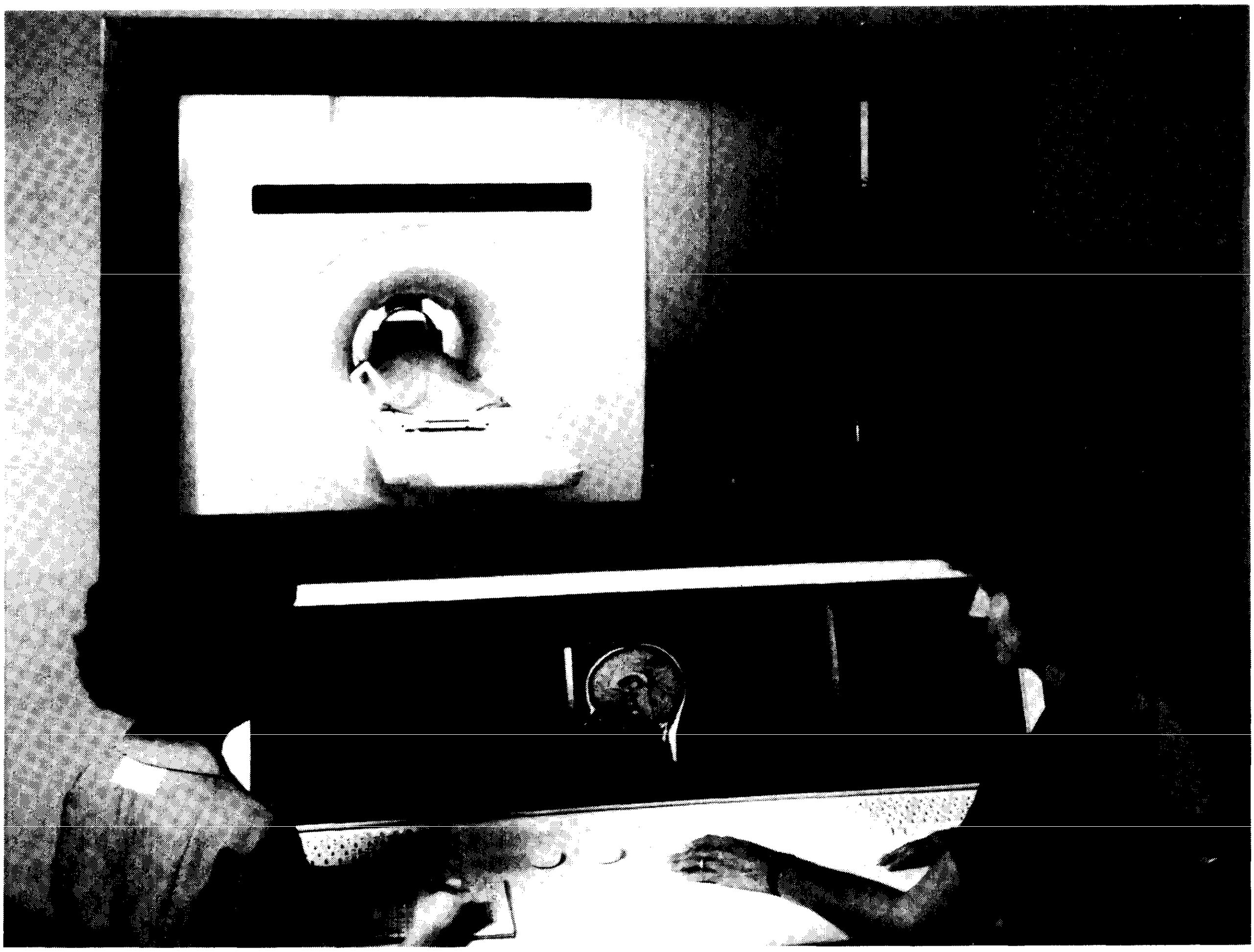


Photo credit: General Electric Medical Systems

Magnetic resonance imaging (M RI) system, the largest commercial application for superconducting magnets.

MRI takes advantage of this fact to produce pictures of cross-sectional slices of the body in which the various tissues (especially soft tissues containing a large percentage of water) and their associated disorders can be identified. MRI provides a powerful tool for diagnosis of a variety of internal disorders, obviating the need in many cases for invasive procedures such as exploratory surgery or excessive exposure to x-rays.

The MRI technique can be generalized beyond static cross-sectional pictures of body organs. As scanning speeds and data processing speeds increase, real time pictures of dynamic body processes will be possible. At higher fields, MRI of paramagnetic nuclei other than hydrogen, especially sodium and phosphorus, could give new insights into the body's chemical processes, e.g., metabolism.

MRI is notable because it is virtually the only successful commercial application of superconductivity (see box 3-B). Although MRI is more expensive (costing about $700 per scan) than competing imaging technologies such as ultrasound and x-ray CT scanning, it has secured a stable market niche because of its superior image quality for soft tissues. Further, for the high magnetic field strength and stability needed for good image quality, superconducting magnets far outshine conventional copper magnets.

The current market for MRI is about 500 machines (about $1 billion) per year, with prospects for steady growth into the 1990s. LTS MRI magnets have become a mature and highly reliable technology, both for stationary and mobile facilities. However, the cost savings of replacing the LTS

Box 3-B--Magnetic Resonance Imaging

MRl **has its origins** in research in Great Britain and the United States in the mid 1970s. The first prototype scanner was **built** by EMI (Great Britain), **and the first superconducting** model was introduced just 2 years later, As late as 1982, experts were predicting that--due to problems with reliability of the cryogenics and high cost-superconducting magnets would not be attractive for MM systems.[1] Although there were some initial problems with cryostat **design (especially for mobile units), these problems were overcome, and present MRl** systems are considered extremely reliable. Most high-resoiution MRI systems today operate at a magnetic field strength around 1.5 telsa, a regime that requires the use of superconducting magnets. (Power dissipation of conventional resistive magnets *becomes* prohibitive above **about 0.2 telsa) Today,** superconductive magnets have captured more than 95 percent of the MN magnet market.

MR1 was a godsend to U.S. superconducting wire and magnet manufacturers, coming as it did at a time when the Federal Government was scaling back or concluding many of its large-scaie superconductivity programs. From only two systems in the United States in 1980, growth has been such that the 1,000th superconductive MRI magnet was shippd in 1987,[2] Current sales in the United States are around 500 units per year. Major integrated MRI producers **(manufacturing both** magnets and total systems) are General Electric and Siemens (West Germany), who control over half of the MRI market. About 44 percent of the market is shared by the wire and magnet vendors-Qxford Superconducting Technology, Intermagnetics General Corp., and Applied SuperConetics.[3] U.S.-based companies thus have a strong competitive position in the MRI market.

Although MRI has seen significant growth during the past decade, and is now the only successful large-scale commercial application of superconductivity, growth rates have fallen far short of many early predictions. The most important reason is its relatively high cost. A typical MRI system costs about $2 million, plus siting and installation costs. Of this, the superconductingm agnet accounts for perhaps $350,000. Installation costs, especially for magnetic shielding, can be nearly as high as those of the system itself.[4] A typicai MRIscan costs about $700, **about 100** times more than ultrasound, and 3 to 5 times more than a computer-aided tomography (CAT) x+ray scan. Use of CAT, which had been predicted by some to be displaced by MRI, actually grew by 20 percent in 1988. CAT's lower cost and faster scanning time (2 seconds per body cross-section, compared with 10 to 15 minutes for MRI), togetherwith its superior images for bone, make it preferred for scans of the chest abdomen, or entire body.[5] MRI provides superior images of soft tissues.

Why Was MRI Successful?

Why has MRI become a successful commercial application of superconducting magnets? Industry analysts suggest several reasons. One is that the medical diagnostics' industry is inherently a technology-oriented market accustomed to incorporating technologies recently developed in the laboratory. A1though costs are high, the value to the patient of an accurate, early diagnosis-for example, early detection of a tumor-is even higher. Furthermore, these costs are spread through the health insurance system.

Superconducting magnets have demonstrated clear performance advantages over conventional resistive magnets fur MRI, providing higher fields over larger volumes, and superior field uniformity and stability. These advantages are directly translated into higher image quaiity and greater speed. Also, initial operating experience with superconducting MRI magnets was favorable; startup problems were no more serious than had been anticipated.

Finally, superconductivity was introduced early into the life cycle of MRI, with the first imager built in 1978, and the first superconducting system introduced only 2 years 1ater. Superconductive magnets did not have to displace a well-established technology that had been optimized over decades. Further, due to prior Federal programs aimed at development of high-performance superconducting wire and cable, there was a match between the needs of the new industry and the capabilities of wire and cable manufacturers. Product development began almost

1 ITMAH Consultants, "Lessoms From Low-Temperature Superconductors," contractorr report prepared for the Office of Technology Assessment, November 1988.

2 Business Technology Research, "Superconductive **Materials** and Devices," 1988, p. 39.

3 Ibid., p. 49.

41bid., p. 154.

5 Karen Fitzgerald "Medical Electronics," *IEEE Spectrum,* January 1989 p. 68.

{continuedonnextpage)

Box 3-B—Magitetic Resonance Imaging--Continued

immediatly, without the need for extensive applied research and engineering expenditures; this lowered the from-end costs to the manufacturers. The favorable timing also ensured that magnet design and system design evolved together, making the integration of the superconducting magnet into the overall system easy.

Lessons **for HTS**

What lessons for HTS can be drawn from the MRI experience? First, no one could have predicted when modern superconductor wires were developed 20 years ago that MRI would be the major commercial application of superconductivity today. MRI technology depended not only on the availability of high-field superconducting magnets, but also on the development of nuclear magnetic resonance (NMR) spectroscopy as well as imaging concepts and fast computer signal processing. This makes quite plausible the claim-barely 3 years after the discovery of HTS--that the biggest future applications of HTS have not yet been thought of.

Second, the penetration of a new technology like HTS is fastest in wholly new areas or early in a new product life cycle. If there are well-established competitors, the new technology must offer dramatically superior performance or lower cost—not just a minor improvement—in order to compete. In fact this conclusion militates against the penetration of the MRI market by HTS magnets, even if they were available today,

Third, the first applications of new technologies like HTS are likely to be in specialized, high-technology markets where high performance is the purchase criterion, not low cost. This has also been the pattern in other advanced materials, which found early applications in medicine, upscale sporting goods and, almost universally, defense applications.

There are broader policy implications as well. In MRI, U.S. companies have shown that they can seize and maintain a strong market position over a long period in a highly competitive world market. But this would not have been possible without the preceding Department of Energy-funded programs that supported the development of superconducting wire and magnets. Especially notable was a DOE-funded collaboration between the University of Wisconsin arid vendor companies that led to dramatic improvements in the performance of NbTi conductors from 1981 to 1988. This illustrated the important role that universities can play in making U.S. industry more competitive.

magnet with an HTS magnet have been estimated at only about 5 percent,[73] largely because the magnet and refrigeration costs amount to only a minor fraction of the overall system costs. Clearly, if HTS magnets with performance and cost at 77 K comparable to those of present MRI magnets at 4 K were available, they would be used. But the MRI market per se is not large enough to drive the additional R&D investments necessary to develop such magnets.

Biomagnetic Applications

The human body produces a variety of magnetic fields, from both passive and active sources. Passive sources are typically magnetic particles, e.g., particles from the environment trapped in the lungs, or iron stored in the liver. Active sources are the electrical currents that accompany body processes, for instance the beating heart, or neuronal activity in the brain. The currents produce magnetic fields that, although weak, can be detected by SQUID sensors without the need for attached electrodes.

Magnetoencephalography (MEG)—MEG is considered one of the most promising applications of superconductivity to disease detection. First demonstrated in 1968, MEG shows potential for locating sources of epilepsy deep within the brain without the need for inserted electrodes; it couId potentiality be used in the diagnosis of a variety of brain disorders, including Alzheimer’s disease, Parkinson’s disease, and head injuries. MEG has also shown the potential to study normal brain activity during the process of muscle action.

Because the magnetic fields produced by the brain are very weak, they are usually measured in a magnetically shielded room. Magnetic noise amplitudes in a typical hospital may be 10 nanoteslas, many orders of magnitude larger than the brain’s signal. The measurement is made using sensitive pickup coils placed as close as possible to the

[73]Business Technology Research, op. cit., footnote 2, p. 155.

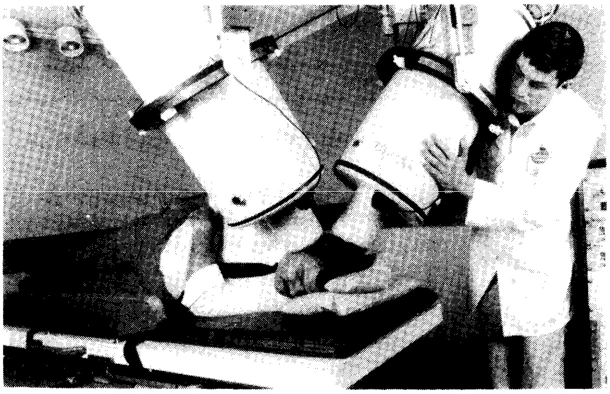


Photo credit: Biomagnetic Technologies, Inc.

Magnetic fields produced by the brain can be mapped by superconducting sensors in magnetoencephalography (MEG).

patient's head.[74] Considerable development will still be required before the technology can begin to make its way into diagnostic use. Japan's Ministry of International Trade and Industry has recently announced the formation of a consortium of 10 companies to develop MEG.

Due to their higher thermal noise levels, it appears that HTS SQUIDS will not readily replace LTS SQUIDS in the growing markets for biomagnetic sensors requiring high sensitivity. However, prospects for HTS maybe considerably better in passive system elements, such as 77 K pickup coils, which could be placed closer to the patient's skull. More speculatively, it may be possible to build magnetically shielded rooms using HTS, but here HTS will have to compete with conventional magnetic shields of mu-metal (high nickel alloy steel).

Electronics and Communications

Superconducting circuits offer several advantages over conventional semiconducting devices, including higher switching speeds, lower power dissipation, extreme detection sensitivity, and minimal signal distortion. There has been a long history of LTS R&Din electronic devices in the United States, primarily sponsored by the Department of Defense with some support from the National Bureau of Standards (now the National Institute of Standards and Technology). As a result of this effort, several LTS electronic devices are now readily available, including SQUID magnetometers, Josephson voltage standards, millimeter wave mixers, and fast data sampling circuits.

Table 3-5 provides OTA's estimate of the impact of superconductivity on several existing or potential electronic devices. The opportunities and barriers associated with these applications are discussed in somewhat more detail below.

Digital Devices and Computers

Digital devices are those that manipulate information with discrete levels (' 1's or O's") rather than over a continuous range, as does an analog device. Present superconducting digital circuits rely on the on/off switching of Josephson Junctions (JJs) to create these discrete levels, unlike semiconductor digital circuits, which use transistors. Development of a practical superconducting transistor remains a major research goal, but such a device has not yet been invented.

Computer applications of superconductors include logic gates, memories, and interconnects. In principle, a computer based on JJs could be several times faster and 100 times smaller than present computers, though this application is somewhat speculative (see below). Meanwhile, the same devices required for JJ computer circuits can also be used in less demanding, smaller scale applications, e.g., fast analog-to-digital converters, shift registers, and memories, as well as circuits to perform arithmetic operations.

Whereas the United States scaled back its efforts in superconducting digital devices in 1983, several Japanese laboratories continued their programs, and now have produced digital integrated circuits having as many as 24,000 JJs on a single chip. A prototype Japanese Josephson microprocessor was recently shown to operate at a clock speed 10 times higher, and a power dissipation 500 times lower, than a comparable gallium arsenide microprocessor.[75]

Experts are divided, though, as to where such devices will find application. Because many problems remain with large-scale integration of JJ circuits—particularly for high-density memory—semiconductor researchers interviewed by OTA question whether LTS JJ technology will ever be

[74] One prototype system manufactured by Biomagnetic Technologies Inc. uses a multichannel array of 37 pickup coils and SQUIDs that can localize brain signals without having to be rotated around the skull, as is necessary with present commercial systems having only 7 channels.

[75] S. Hasuo and T. Imamura, "Digital Logic Circuits," *Proceedings of the IEEE*, vol. 77, No. 8, August 1989, p. 1190.

Table 3-5-Applications in the Electronics and Communications Sectors

Application	Impact of superconductivity	Comments
Digital circuits:		
A-D converters, shift registers, memories, etc.	Demonstrated with LTS; possible for HTS.	Many technical challenges remain in HTS JJ technology.
Computers	LTS JJs may be suitable for logic and cache memory, but high-density memory still a problem. HTS/semiconductor hybrid systems are possible.	May be more useful for specialized defense computing needs than for general purpose computing. Higher power dissipation with HTS a problem for LSI.
Analog circuits:		
SQUIDS	Successful application of LTS; significant for HTS if noise problems can be overcome.	HTS would make use of SQUIDS more common in many applications not requiring the highest sensitivity.
Signal processing:		
Amplifiers, oscillators, etc.	LTS performance already impressive. Moderate for HTS, if high-quality tunnel junctions can be fabricated, and if high-frequency losses can be reduced further.	Conventional systems do not yet require extremely high frequencies; may be especially important for military applications and in space.
Passive devices:		
Computer wiring, interconnects	Silicon-based machines do not operate at LTS temperatures. Moderate for HTS at chip and board level at 77 K.	Line resistance often is not the limiting factor. Copper at 77 K provides a low-cost alternative.
Antennae, filters, delay lines, etc.	Demonstrated with LTS; promising for HTS.	HTS likely to see first use in military/space applications.
Communications	LTS circuits already demonstrated at microwave frequencies (1 to 30 GHz); could open up new regions of the electromagnetic spectrum at even higher frequencies. HTS could extend this up to the TH_z range.	Could revolutionize satellite broadcasting. Initially, will be useful primarily for military/space applications.
New *devices*	If new phenomena are responsible for HTS, then new devices may be possible.	HTS could be combined with semiconductors or optical materials to create novel hybrid devices. If a true superconducting transistor with power gain can be developed, this would find widespread applications.

KEY: A-D = Analog to digital; GHz = Gigahertz; J = Josephson Junction; LSI = Large-scale integration; THz = Terahertz.

SOURCE: Office of Technology Assessment, 1990.

suitable for a general purpose computer (though they acknowledge that it could find application in specialized military applications).

These semiconductor experts consider semiconductor devices and processes as the "technology to beat" for the foreseeable future, not superconducting JJ computers. U.S. managers have been reluctant to make the large up-fi-ont R&D investments required to overcome the remaining problems in view of steadily improving semiconductor systems. They note, however, that the development of a true superconducting transistor with power gain, and fabricated with existing semiconductor processes, could dramatically improve the outlook for superconducting computers.[76]

Advocates of stronger U.S. programs in digital superconducting electronics have a different view. They argue that remarkable progress has already been made at a level of effort dwarfed by that expended on semiconductor electronics. In the long term, they say, the future of computers, whether superconducting or semiconducting, will be at low temperatures, and the speed and efficiency of superconducting electronics is likely to win out. Moreover, the stakes are high. In dropping its digital LTS programs, the United States risks not only losing its edge in specialized military applications, but also losing its supercomputer and mainframe computer industries. Even if the technology goes nowhere, these advocates argue, the most the United States stands to lose is a few tens of millions of

[76]A typical semiconductor transistor is a three-terminal device that uses a small input current or voltage to control a much larger output current or voltage, thus producing power gain. Josephson Junctions are two-terminal devices that do not exhibit power gain. This makes circuit design with JJs considerably different from semiconductor circuit design.

dollars-a small price to pay considering the stakes involved.

There is general agreement among analysts that there are opportunities for mixed superconductor/semiconductor computer systems—for example, fast superconducting JJ logic gates coupled to dense semiconductor memory in the same system. Mixed LTS/semiconductor systems are feasible, but difficult, since most silicon devices stop functioning around 40 K, and so require that the LTS and semiconducting components be kept at different temperatures.[77] However, silicon devices function very well at 77 K, and indeed the trend in circuits using Complementary Metal Oxide Semiconductor (CMOS) technology will be to cool them to liquid nitrogen temperature. Thus, there appears to be some potential for a marriage between HTS and evolving semiconductor computer technology.

Recent research indicates that HTS Josephson devices may have speeds comparable to LTS devices, but because of the larger energy gap in HTS, the Josephson devices dissipate about 100 times more energy when the junction switches from the "off' to the "on' state.[78] This suggests that HTS may be more appropriate for fast, small-scale circuits than for large-scale integrated JJ circuits.

Many observers feel that the first applications of HTS in computers will be in passive elements, such as interconnects, signal transmission lines, or board-level wiring. In transmission lines, superconductors offer lower attenuation and distortion, for a clearer signal. Superconducting lines could be made extremely narrow (perhaps 1 micrometer wide for signal lines and 10 micrometers for power distribution), thus simplifying the design of the system.[79] Such passive elements are also attractive because they would be relatively easy to fabricate and make relatively small demands on the superconductivity properties, With micrometer feature sizes, though, operating current densities above 1 million Amps/c m^2 will be required on the chip.[80] Moreover, superconducting interconnects must compete with copper lines, whose resistance at 77 K is six to seven times lower than at room temperature, presenting a cheap and reliable alternative.

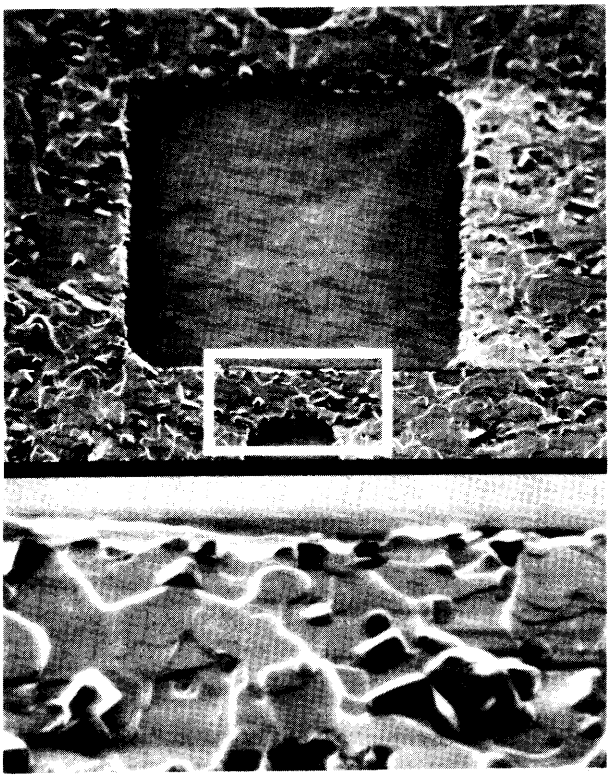


Photo credit: IBM Research

The first HTS SQUID with noise low enough to be useful. Highlighted area shows the polycrystalline microstructure of the material.

Thus, a role for HTS in computers is possible in the future, but it is somewhat uncertain. Much depends on the development of technologies for controlling the properties of surfaces and junctions, which are still fairly primitive for HTS.

Analog Devices

Analog circuits provide a continuous range of signal level, in contrast to the discrete nature of digital circuits. Analog devices that have already been fabricated with LTS include SQUIDS, microwave and millimeter wave components for detection, amplification, and processing of signals in the 10 to 200 GHz range, voltage standards, and infrared detectors.

[77]Gallium arsenide (GaAs) devices do work well at 4 K, though commercial large-scale integrated circuits with GaAs do not yet exist.

[78]S. Hasuo and T. Imamura, op. cit., footnote 75, p. 1191.

[79]U.S. Department of Defense, *Superconductivity Research and Development Options*, July 1987, p. 63.

[80]Business Technology Research, op. cit., footnote 2, p. 122.

SQUIDS are considered to be one of the most promising HTS devices in the near term. Magnetic field sensors based on SQUIDS potentially have wide applications in several sectors covered in this chapter, e.g., medicine, industrial equipment, and defense. Currently available LTS SQUIDS operating at 4 K provide magnetic field sensitivity and noise levels near the quantum limit.

Although early SQUIDS fabricated with HTS showed very high noise levels, these levels were reduced as processing technology improved. At this writing, IBM had produced an HTS SQUID using polycrystalline thallium-based material that showed a noise level at 77 K comparable to that of commercially available LTS SQUIDs.[81] HTS SQUIDS could have a big impact in applications not requiring sensitivity at the quantum limit, or in sensors operating in remote locations, tightly constrained environments, or in instruments requiring portability where a liquid helium cryostat is not practical.

Because individual SQUIDS place few demands on the superconducting material and are relatively easy to fabricate, they are likely to be one of the first commercial applications of I-ITS. Several companies, both in Japan and in the United States, view HTS SQUIDS as good “test products” for gaining expertise in fabricating HTS materials and devices. But manufacturing HTS SQUIDS in large numbers with uniform switching thresholds (required for large-scale digital integrated circuits) remains a difficult challenge.

Passive Devices

Passive devices are those that do not require connection to an external power source in order to perform their circuit function. Examples discussed above under ‘‘computers are superconducting interconnects and power distribution lines. Also included in this category are delay line signal processors, high-efficiency waveguides and filters for microwave circuits, antennae for sending and receiving radio frequency signals, and shielding for stray magnetic fields. The feasibility of superconducting analog signal processors, which exhibit more than 10 times the processing capability of the competing conventional technology, has been demonstrated with LTS.[82] In the near term, such devices will be of primary interest to the military, perhaps in high-speed communications and radar systems.

The higher binding energy of the superconducting electron pairs in HTS offers the potential for higher frequency operation than in the equivalent LTS device. Early samples of HTS showed a high frequency surface resistance that negated this theoretical advantage. But considerable progress has been made in this area: at this writing, the surface resistance of the best HTS materials was 10 times lower than that of any metal at 77 K (though still not as good as niobium at 4 K). These developments are considered very encouraging.

Communications

Presently, television, radar, radio, and telephone communications are limited to a fairly narrow frequency range in the electromagnetic spectrum. Increasing demand for a limited number of frequency slots has led to conflicts among commercial broadcasters. Superconductivity offers the potential to make tens of thousands of new satellite broadcast channels available by opening up the millimeter and submillimeter regions of the electromagnetic spectrum.[83] Specific applications include switches, correlators, transmission lines, filters, parametric amplifiers, antennae, shielding, and other receiver parts.

HTS promises to extend the available frequency range even higher—perhaps into the terahertz (10^{11} to 10^{12} hertz) range, and to do so in a temperature regime where efficient refrigeration is available. Development of terahertz frequency components for space communications and imaging applications is one of the major thrusts of the Strategic Defense Initiative Organization superconductivity R&D program (see ch. 4). One benefit for civilian technology might be to increase dramatically the resolution of radar systems.

---

[81] This comparison is not quite fair because the high-temperature SQUID lacks the input coupling device required for practical applications, which will increase noise levels. Because noise levels are proportional to operating temperature, HTS SQUIDs at 77 K will ultimately be about 20 times less sensitive than the equivalent LTS SQUIDs at 4 K. William Gallagher, IBM, personal communication, November 1989.

[82] Business Technology Research, op. cit., footnote 2, p. 123.

[83] R. Simon and A. Smith, ‘‘Fast, Quiet, and Precise: Superconductive Electronics,’’ *Supercurrents*, vol. 8, March 1989, p. 49.

Table 3-6-Applications in the Defense and Space ectors

Application	Impact of superconductivity	Comments
Defense:		
Sensors Submarine detection Infrared detectors Mine detection	Possible with LTS; promising for HTS.	HTS offers ruggedness, easier maintenance, lower power requirements.
Electronics	Significant for LTS; potentially significant for HTS.	LTS offers higher speed computer logic useful for cryptography, synthetic aperture radar, acoustic array processing, and other computation-limited uses; higher bandgap of HTS could permit higher resolution radar, higher speed communications, etc.
Pulse power	Demonstrated for LTS; possible for HTS.	See energy storage section above. HTS warm-to-cold current leads possible.
Kinetic energy weapons	Possible for LTS, minor for HTS.	Superconductors are essential in some designs, but very high current densities are required.
Free electron lasers	Possible for LTS; minor for HTS.	Superconducting magnets could reduce the size of the accelerator needed at the front end oft he free electron laser.
Ship propulsion	Electric drive demonstrated for LTS, minor for HTS.	See *Transportation section.*
Space:		
Sensors	Demonstrated with LTS; HTS could offer greater sensitivity.	One example is a blometer for planetary observation.
Satellite electronics	HTS could enable greater flexibility of design and greater mission capabilities.	Low launch weight, low power, and reduced cooling requirements are a major plus.
Radiation shield	Possible for HTS.	Superconducting loops could provide shielding against high-energy charged particles on long-term manned flights.
Electromagnetic launch	Possible for LTS, doubtful for HTS.	Could substitute for first stage rocket in sending cargo (not people) into space more cheaply from Earth.
Magnetic bearings	Possible for HTS.	Would eliminate need for lubrication and problem of surfaces seizing up in a vacuum.

SOURCE: Office of Technology Assessment, 1990.

Defense and Space Applications

Many of the applications discussed in previous sections have defense and space analogs: e.g., motor/generator sets for ship propulsion; SMES to power ground-based lasers; antennae and filters for ultrasensitive receivers; and high-frequency electronics for high-resolution radar and burst and spread-spectrum communications. These and other military/space applications have been reviewed in several recent studies,[84] and are not covered in detail here (see table 3-6).

Defense and space applications are grouped together because they have a strong overlap, not only in design-e. g., railgun weapons and electromagnetic launchers—but in their cost and performance criteria as well. Performance is the primary purchase criterion, with less emphasis on capital or operating costs. These systems are not designed for mass production; rather, the superconducting components are optimized for specific applications.

Often, defense and space applications of superconductivity have much in common with their commercial analogs. However, the defense versions of these applications must be designed with several additional factors in mind: light weight, ruggedness, low power requirements, low maintenance, radiation hardness, and the capacity to operate in a wide variety of environments. In the long run, these additional requirements could cause a divergence

[84] Defense Superconductivity Research and Development Working Group, U.S. Department of Defense, "Superconductivity Research and Development Options," July 1987; Defense Science Board, "Military System Applications of Superconductors," Office of the Under Secretary of Defense for Acquisition, Washington, DC, October 1988; Defense Advanced Research Projects Agency, "High-Temperature Superconductors," February 1989.

between the military and commercial goals and priorities for applied superconductivity R&D.

The higher operating temperatures available with HTS can provide solutions to the unique challenges associated with the military/space environment:

- *Light weight.* The potential for reducing the size and weight of superconducting equipment, such as generators and motors, provides greater flexibility and mission capability of the vehicles on which they are deployed. In space, the reduced launch weight—made possible by eliminating bulky liquid helium refrigeration systems—is a major plus.
- *Ruggedness.* The superconducting equipment must be rugged enough to survive the acceleration, vibration, and other stresses of space launch. The military is concerned that the systems continue to operate during battle conditions in the field-pitch and roll of naval ships, vibrations and jolts of land vehicles, and sharp accelerations of aircraft. The greater simplicity of HTS refrigeration systems would make them more reliable under these conditions.
- *Low power.* Power consumption is an important constraint for both space and military field applications, since in both cases, available power is limited. Space systems presently depend on battery, solar, or nuclear power; mobile military applications depend on on-board power systems. In addition to limited power available, cooling must be provided for the power dissipated. Passive radiative cooling in space can be used to maintain temperatures around 80 K if the heat load is small enough. For larger heat loads, refrigeration can be combined with passive radiative cooling. This combination cooling would take less power to maintain for HTS than for LTS.
- *Maintainability,* Generally, both military and space applications are designed for minimum maintenance. In space, human mechanics are not available to keep a system continuously tuned, and in the military, sophisticated maintenance is only available far from the battle lines. A system that requires delivery of liquid cryogen is not as desirable as one that can make the cryogen from the air or that uses a closed-cycle refrigerator. The military is concerned with not having to maintain supply lines. Low maintenance also means the system is more likely to be available for use (high readiness).

  A related issue is the working lifetime—how long the system will last in space with the given stored power and cryogen. Useful lifetime of a satellite may be determined by the above factors, rather than the decay of the orbit. For the military, the useful lifetime of SQUID sensors used for antisubmarine patrol could be limited by the time it takes for all the cryogen to evaporate. These mission capabilities could be dramatically enhanced with HTS.
- *Radiation hardness.* Some form of radiation hardness is needed for space and military applications. Space craft do not have the protective layer of the Earth's atmosphere to absorb the damaging radiation from solar flares and cosmic rays. Without radiation hardening, system lifetime can be extremely short; especially for electronics, in which minute changes can destroy individual components. Although not enough is known about the radiation hardness of HTS, preliminary indications are that HTS components maybe no more susceptible to disruption by external radiation than LTS components.[85]

New Applications

Virtually all of the recent assessments of the potential for HTS involve considering the incremental benefits that HTS could bring to applications already known for LTS. For purposes of analysis, they assume that HTS conductors will be essentially identical to LTS conductors, but with a higher operating temperature. While this kind of analysis is a natural first step, it assumes that the new ceramic materials can be put into the same conceptual mold as the older metal alloys.

Many observers think that the biggest future applications for HTS will have nothing to do with present LTS devices, These applications will not involve a simple substitution of HTS into a known LTS design; rather, they will take advantage of the unique properties of HTS. A particularly exciting prospect is the possibility of designing hybrid, layered devices that would combine different HTS materials with semiconductors, optoelectronic materials, and other ceramics to yield novel performance. Given the great variety of materials that exhibit

[85] D.U. Gubser, Naval Research Laboratory, personal communication, October 1989

HTS--e.g., some that conduct the supercurrent with holes and some with electrons-the variety of possible devices can only be glimpsed at the present time.

While it is difficult to justify significant investment in HTS on the basis of applications that have not yet *been* conceived, it is also true that optimism is often essential for success in R&D. If there is a natural tendency to underestimate the difficulty of solving the immediate problems, there is also a tendency to underestimate the long-term possibilities.

LESSONS FROM LTS

Nearly 30 years after the development of practical LTS materials, LTS has moved out of the laboratory to gain a foothold in commercial applications. This process has not been easy, though, and it offers a number of lessons that should be considered in forecasting the evolution of HTS technologies.

- *The preferred materials for applications are those that are easiest to handle and manufacture, not necessarily the best superconductors or those with the highest T_c.* Although Nb_3Sn is a superior superconductor in terms of critical transition temperature, critical current density, and upper critical magnetic field, it is brittle and difficult to fabricate, and is consequently rarely used. Due to its ductility and workability, NbTi has become the workhorse material for LTS magnet applications, even though its cooling requirements are more stringent. This suggests that factors such as processability and brittleness may ultimately weigh as heavily as T_c or even J_c in determining the feasibility of using certain HTS materials.
- *Even after a practical superconducting material is developed, it may take many years to develop a practical conductor from that material and then to demonstrate its viability in a commercial protype.* Although relatively high performance was achieved with NbTi alloys within a year of their discovery, some 10 years elapsed before a sophisticated NbTi cable conductor was developed. A practical superconducting cable involves a tremendous amount of engineering, including drawing fine filaments of superconductor to reduce AC losses, stabilization with normal conductors for quench protection, channels for coolant flow, dielectric insulation, etc. Moreover, scaling up from small sections to long lengths in prototype applications requires significant additional time. These phases of development are basically serial, and cannot proceed in parallel. This suggests that even if the superconducting properties of bulk HTS materials can be brought up to the level of present LTS materials, it will still be many years before practical tapes or cables for large-scale HTS applications will be available.
- *Highly reliable, conservative designs are necessary, especially in the commercial sector.* While it is tempting for engineers to push a design to the state-of-the-art, reliability is crucial in establishing a new beachhead. Even after LTS has been successfully demonstrated in some commercial applications, it may be necessary to conduct extensive demonstrations of HTS (perhaps by insertion into the existing LTS design) to convince commercial customers of the reliability of HTS.

  It is important to pick targets carefully; i.e., those that are not likely to be "leapfrogged' by a well-entrenched and steadily improving conventional technology. The principal reason why IBM researchers dropped their Josephson Junction computer effort in 1983 was because they projected that by the time the technical problems of a JJ computer could be worked out, conventional semiconductor machines would improve to the point that the advantage of a JJ machine would be minimal. Commercialization of HTS will be most successful in new applications where the technology and designs are fluid. The most promising applications of HTS will probably be those that are enabled by the unique properties of I-ITS, rather than those in which LTS is already successful.
- *It is impossible to predict with certainty where the future applications will be.* In the late *1970s*, for example, no one could have predicted that the largest commercial market for LTS 10 years later would be in MRI systems.
- *In many applications, lack of commercialization has nothing to do with technological problems related to superconductivity; rather, it is due to unfavorable economic conditions or changing political circumstances.* This lesson applies primarily to large-scale applications where the cost of the superconducting component is only a small fraction of the capital costs

of the overall system. For example, even the discovery of room-temperature super-conductivity would not substantially change the prospects for magnetically levitated trains in the United States.

- *While it is often impossible to anticipate precisely how much time and money it will take to overcome the scientific and technical obstacles confronting a new technology such as HTS, it is important to provide sustained, reliable funding through the lifetime of the project.* A successfully completed project-even if it costs more and takes longer than expected— contributes to the store of knowledge; a truncated project is often effort lost forever. This lesson, which seems no more than common sense, has been repeatedly ignored in the funding history of Federal LTS programs. The lesson has not been ignored in Japan (see ch. 5), and remains an important policy objective for HTS if the United States hopes to be competitive, as discussed in chapter 7.

FACTORS THAT WILL DETERMINE THE PACE OF HTS COMMERCIALIZATION

The discovery of superconductivity above liquid nitrogen temperatures is certainly an exciting development. As yet, however, HTS remains largely in the realm of the scientific laboratory, not practical technology. Moreover, commercial applications are not driven by a higher T_c per se. The superconducting transition temperature is only one contributing element to four distinct but interrelated factors that will determine the commercial potential of HTS in actual applications: superior performance; low cost; high reliability; and strong market demand. After 3 years of HTS development, there remains tremendous uncertainty in each of these categories.

Performance

Thin film HTS materials do appear to offer some potential performance advantages over LTS and conventional technologies: e.g., higher frequency operation for electronic circuits, or hybrid superconductor/semiconductor devices. At 77 K, the performance of bulk HTS materials has been improving steadily, but is still significantly worse than LTS materials at 4 K-especially their capacity to carry high currents in a magnetic field. These properties will undoubtedly improve as the relationships among chemical composition, microstructure, and performance become better understood through continued basic research.

In the meantime, the identification of HTS with 77 K operation has perhaps been overemphasized. There may be significant opportunities in both electronic applications and in power applications for HTS in the 20 to 30 K range, where there is no competition from LTS. Cooling in this temperature range would be considerably simpler than at 4 K, and would probably be done with flowing helium gas.

In those applications where superconductivity offers a clear advantage over conventional technology, it should not be assumed that HTS will eventually be preferred to LTS. Each type of superconductor may find its own niches. For instance, LTS may continue to be preferred in cases where greater ductility, low electronic noise, or high vacuum are important, whereas HTS may be preferred where light weight or low maintenance are essential.

cost

There are two principal cost issues: first, the cost of the superconducting system compared with a competing conventional system; and second, the incremental cost savings obtained by using HTS instead of LTS.

Typically, a superconducting design has a higher capital cost, but a lower operating cost than a conventional design. The requirement for cooling with liquid helium usually means that LTS systems are only cost-competitive with conventional systems at the largest sizes. While HTS can reduce the economic breakeven point by simplifying the design and reducing operating costs, savings are generally small, usually a few percent. This is because the cost of the superconducting component and refrigeration system is often only a small percentage of the overall cost. These cost estimates are generally made assuming that HTS conductors would have the same cost and performance as LTS conductors, but at 77 K. But actual HTS conductor costs could end up being much higher-depending, for instance, on the cost of compensating for any deficiencies in HTS properties (such as low strength due to brittleness) and the cost of ensuring reliability.

Reliability

Although the superconducting properties of various HTS materials are undergoing intense study, very little is known about the long-term reliability of these materials under actual operating conditions. In other ceramic materials, reliability has been a serious issue that has often prevented their use in applications that require predictable performance over long periods. Much more will have to be learned about effects such as thermal and mechanical cycling, chemical stability, residual stresses, etc., before designers will feel confident about specifying these materials for applications sensitive to materials failure.

Potentially, reliability could become an advantage for HTS. The dependence of LTS systems on complex liquid helium cryogenic refrigeration technology has caused reliability concerns in the past. Although liquid helium refrigeration technology has matured substantially, the freedom HTS allows to operate above 4 K—whether in the 20 to 30 K range using flowing helium, or at 77 K with liquid nitrogen—would simplify the designs greatly and increase reliability still further.

Market Demand

In many large-scale applications (e.g., maglev, SMES, or electric power generators), superconductivity technology is not the bottleneck to commercialization. Instead, high capital costs and uncertainty in the market value of the benefits are the principal barriers. In the present high cost-of-capital environment, companies often find themselves unable to foot the bill for R&D and prototype demonstration, even though they may have a strong interest in the technology. Government will have to pay these costs if these applications are to go forward. Because HTS typically has only a marginal impact on the costs and benefits in these applications, it is unlikely to change this situation.

FORECASTING THE COMMERCIALIZATION OF HTS

Notwithstanding the many remaining uncertainties, these four factors do provide some broad perspectives on the likely pace of commercialization of HTS in the seven economic sectors discussed above. Below, these sectors are grouped according to the timing of significant use of HTS: near-term (5 to 10 years), medium-term (10 to 15 years), and long-term (more than 15 years). This analysis assumes incremental improvements in materials operating in the neighborhood of 77 K. If superconductors capable of operating at room temperature were to be discovered, many applications would become far more attractive, e.g., superconducting overhead transmission lines, applications in automobiles, etc., and entirely new markets for superconductors would open up, e.g., consumer products and household items.

Near-Term: Defense/Space and Electronics/ Communications

These sectors, which have a large overlap, are driven primarily by high performance considerations. High cost can be tolerated if the materials provide unique mission capabilities. The potential for higher frequency and larger bandwidth of HTS compared with LTS makes HTS attractive for military and space applications. And the potential for hybrid superconductor/semiconductor systems operating at liquid nitrogen temperature makes HTS attractive in electronics. Market demand is not a problem with military applications, and the large, high-turnover market for electronics provides many possible niches for new devices, Early applications for HTS could be in sensors and passive microwave devices. Most of these applications will use thin films, where technical progress with HTS has been most rapid.

Medium-Term: Medicine, Industry

For superconductivity applications in these sectors, the capital and operating costs associated with liquid helium refrigeration are often a significant fraction of overall costs; therefore, even if HTS does not offer performance advantages over LTS systems, it may offer lower costs. Early opportunities for HTS could come in industrial sensors, pickup coils for MEG, and perhaps low-field magnets. Many applications in this category need high-field magnets, which will require bulk HTS conductors with high-current capacity in high magnetic fields-the area in which HTS progress has been slowest. Because reliability is so important, HTS may require long demonstration periods, and could have difficulty displacing a well-entrenched LTS system.

21-216 - 90 - 3 : QL 3

Long-Term: High Energy Physics, Electric Power, Transportation

In these large-scale applications, the costs of the superconducting components are generally a small fraction of the overall system construction costs; therefore, the cost advantage of HTS over LTS is generally small. The use of superconductors is driven by market demand for the entire system, not by advances in superconductor technology. HTS could find early application in niches such as current limiters or warm-to-cold power leads, but designers cannot afford to use an unproven technology in critical components of a multibillion dollar system. Reliability is paramount, and the consequences of superconductor failure could be disastrous and even life-threatening. Thus, the more mature LTS technology may be preferred, even if HTS materials with comparable properties can be developed. In most cases, HTS would have to displace well-entrenched conventional or LTS technologies. Finally, these applications have stringent requirements for the superconductor---e.g., high critical currents and high magnetic fields-the areas where technical progress with HTS has been slowest.

CONCLUSIONS

Based on the discussion above, OTA draws several conclusions:

- The continuing technical progress in HTS, as well as the range of potential applications of superconductivity in the seven sectors reviewed (also new applications), justifies a strong, continuing Federal effort in both LTS and HTS.
- LTS will remain the technology of choice in many applications, and will be preferred in large-scale applications such as high-field magnets in the foreseeable future.
- From several points of view, small-scale applications of HTS are most promising in the near term, while large-scale applications are probably 20 years away, if feasible at all.
- Due to government markets and funding in high-energy physics, fusion research, analog electronics, and other defense applications of LTS, the United States has a strong position in these technologies; expertise gained in these technologies has also enabled U.S. firms to take a strong position in spinoff medical applications such as MRI and MEG, and in superconducting magnets for industrial processing. The United States has a relatively weak position in more speculative—but potentially widespread—commercial applications such as digital electronics, rotating electrical equipment, and magnetically levitated vehicles.

The policy implications of these conclusions are taken up in chapter 7.

Chapter 4

The U.S. Response to High-Temperature Superconductivity

CONTENTS

Tables

Chapter 4

The U.S. Response to High-Temperature Superconductivity

This chapter begins with a description of the Federal response to the advent of HTS. This is followed by a brief critique. An evaluation of the adequacy of this response, as well as that of U.S. industry, is presented in chapter 7.

FEDERAL POLICY

The sense of excitement in the scientific community that came with the discovery of new, high-critical-transition-temperature (T_c) superconductors was quickly transmitted to the policymaking community in Washington. To scientists, the discovery was the breaking of a long-assumed temperature barrier, which cast doubts on the validity of a widely accepted theory. To policy makers, the opportunities of HTS represented a test case of the United States' ability to quickly transfer the technology out of the laboratory and into commercial applications.

The President's Superconductivity Initiative

In July 1987, President Reagan addressed an audience of more than 1,000 at the Federal Conference on Superconductivity. In his speech, the President presented an 1 l-point agenda to promote cooperative research, to move scientific achievements more rapidly into the commercial realm, and to protect the intellectual property rights of scientists and engineers involved in superconductivity research. A list of these proposals and what has happened to them since 1987 is given in table 4-1.[1]

The legislative part of President Reagan's package, consisting of three initiatives, went to Congress in February of 1988. The first initiative proposed to relax the antitrust restrictions on joint production ventures among companies. Similar proposals have been made to promote U.S. competitiveness in several other technologies, e.g., high-definition television and semiconductor memory chips; but at this writing, the Bush Administration is still considering its position on the matter.

The second initiative proposed extending patent protection for process patents, and this was passed as part of the (Omnibus Trade and Competitiveness Act of 1988. The third initiative, which did not result in any legislation, proposed authorizing Federal agencies to withhold commercially valuable scientific and technical information from release under the Freedom of Information Act. None of these three legislative proposals was specific to HTS.

The remaining eight administrative initiatives have all been implemented in some form. Perhaps the most influential from a policy point of view was the establishment of the "Wise Men" Advisory Committee on Superconductivity (formally, the Committee to Advise the President on High Temperature Superconductivity) operating under the White House office of Science and Technology Policy. This seven-member council was comprised of experts in superconductivity from academia, industry, and government. Their report was released in December 1988.[2]

The Wise Men recommended an increase in funding of a few million dollars' to strengthen the scientific effort at universities, and the establishment of tour to six superconductivity consortia, each involving a major research university, a government laboratory, and several private industry members. These consortia are to be focused on applied HTS research. and are thereby distinguished from the more basic research-oriented consortia supported by the National Science Foundation. Since the report was published, the debate over HTS and U.S. competitiveness has largely been framed in terms of the need for one kind of consortium or another.[3]

Congressional Initiatives

Omnibus Trade and Competitiveness Act (Public Law 100-418)

As noted above, only one of the President's three legislative initiatives has been passed into law: in Title IX of the Omnibus Trade and Competitiveness

[1]A private body, the Council on Superconductivity for American Competitiveness, has published a brief analysis of this initiative, called *A Progress Report and Critique of the President's Superconductivity Initiative*, November 1988.

[2]The Committee to Advise the President on High Temperature Superconductivity. *High Temperature Superconductivity: Perseverance and Cooperation on the Road to Commercialization*, December 1988.

[3]A consortium to develop superconducting electronic devices—involving MIT, Lincoln Labs, IBM, and AT&T—was announced in April 1989 that closely follows the Wise Men's model.

Table 4-l-President's 1987 Superconductivity Initiatives

Proposal	Action
Legislative:	
Amend the National Cooperative Research Act to permit joint production ventures.	Did not result in any legislation. New proposals presently under consideration at the Justice Department.
Amend patent laws to increase process patent protection.	Passed as part of the Omnibus Trade and Competitiveness Act of 1988.
Exempt commercially valuable information developed at Federal laboratories from disclosure under the Freedom of Information Act.	No action; this was deemed politically impractical.
Administrative:	
Establish "Wise Men" advisory group (President's Advisory Council on Superconductivity).	Formed in February 1988; reported to the President and disbanded December 1988. Recommended establishment of four to six superconductivity consortia involving major research universities, companies, and government laboratories.
Establish Superconductivity Research Centers at Federal laboratories.	Four centers established, three at DOE's Argonne, Lawrence Berkeley, and Ames laboratories, and one for electronic applications of HTS at NIST/Boulder.
Accelerate implementation of Executive Order 12591 on technology transfer from Federal laboratories and cooperative research.	Ongoing; three Superconductivity Pilot Centers established in 1988 at Argonne, Oak Ridge, and Los Alamos to conduct joint research with industry.
Accelerate processing of patent applications.	Patent "fast track" established at the Office of Patents and Trademarks, but only 10 to 15 percent of HTS patent applications were submitted under this procedure.
NIST to accelerate standards development for HTS.	Ongoing, but small effort.
Reprogram fiscal year 1987 funds into superconductivity R&D; place high priority on superconductivity for fiscal years 1988 and 1989.	Virtually the entire HTS budget is reprogrammed money; to make funds available, programs in LTS, advanced ceramics, and other materials R&D were cut.
Accelerate military development of electronics and sensor applications, including prototype devices.	Ongoing; DARPA and SDIO have applications-oriented HTS development programs in place.
Seek reciprocal opportunities to participate in joint R&D programs with Japan under the Agreement on Cooperation in Science and Technology.	At this writing, a variety of joint projects are under negotiation.

KEY: DARPA: Defense Advanced Research Projects Agency
DOE: Department of Energy
NIST: National Institute of Standards and Technology
SDIO: Strategic Defense Initiative Organization

SOURCE: Office of Technology Assessment, 1990.

Act, patent coverage was extended to process patents. Title V also has a number of provisions affecting superconductivity, including the establishment of a National Commission on Superconductivity. Table 4-2 presents the sections of the Omnibus Trade and Competitiveness Act that are relevant to superconductivity, and to technology generally.

National Superconductivity and Competitiveness Act of 1988 (Public Law 100-697)

Passed in the waning hours of the l00th Congress, the National Superconductivity and Competitiveness Act of 1988 called for a 5-year National Action Plan for Superconductivity—to be presented to Congress in August 1989—that would define national goals for HTS and delegate responsibilities to the various Federal agencies to achieve them. This Act stresses the importance of a long-term commitment to developing superconductor applications, since these are seen to be 10 to 20 years away. The Office of Science and Technology Policy (OSTP) was given responsibility for coordinating the Plan with the National Critical Materials Council (NCMC) and the National Commission on Superconductivity (the same Commission mandated in the Omnibus Trade Act). A yearly report is required by Congress detailing the implementation of the Plan, as well as a program of international cooperation in superconductivity.

But the preparation of the Action Plan did not work out as Congress intended. The National Commission was appointed, but had no formal charter, and so did not participate in the drafting of the Plan. The National Critical Materials Council had no active members. The 'Plan' that emerged in

Table 4-2—Provisions of the Omnibus Trade and Competitiveness Act of 1988

	Requirement	Action by the Administration
On superconductivity:		
Report of the President	President must submit budget proposals regarding advanced materials with FY90 budget request.	No action.
National Commission on Superconductivity	To form, report, and disband by December 1989. Report to include: the state of U.S. competitiveness in superconductivity, foreign activities, impacts *on* U.S. national security of potential dependence on foreign procurement, options for tax incentives, possible benefits of exemptions from antitrust laws.	Formal charter delayed; first meeting Oct. 19, 1989.
National Critical Materials Council (NCMC)	Mandates staff increase; continues funding.	No active members during 1988 and 1989.
On technology generally:		
Intellectual property rights	Strengthens existing protections of intellectual property rights.	None required.
National Institute of Standards and Technology	Renames the National Bureau of Standards; increases responsibility for aiding U.S. industry in competing in manufacturing, creates a new post within the Commerce Department for technology policy.	Renaming occurred; technology policy appointment remains unfilled as of March 1990.
Technology extension centers	Requires NIST to assist in establishing regional technology transfer centers.	Three extension centers created.
Clearinghouses	Commerce Department is mandated to develop a clearinghouse of State and local initiatives for transferring Federal technology; second clearinghouse of State and local initiatives to enhance U.S. competitiveness.	Plan awaiting approval.
Competitiveness Policy Council	To advise the President on long-term strategies for U.S. competitiveness.	Council created, chaired by Vice President,
National Academy of Sciences	To review strengths and limitations of existing collaborations where the Federal Government is a partner.	In planning stages.
Education and training	Establish foreign language assistance programs, awards in technology education,	NSF program for language training under development.

KEY: NCMC: National Critical Materials Council
NIST: National Institute of Standards and Technology
NSF: National Science Foundation

SOURCE: Office of Technology Assessment, 1990.

December 1989 explicitly recognized the need for greater Federal coordination and for a cross-agency budgetary analysis of spending in various research areas; but it did not contain budget recommendations, nor the 5-year perspective that Congress wanted.[4]

FEDERAL GOVERNMENT PROGRAMS

The Federal Superconductivity Budget

Federal funding for HTS R&D rose from $45 million in fiscal year 1987 to an estimated $129 million in fiscal year 1989. In fiscal year 1990, funding stayed virtually constant (see table 4-3). From 1987 to 1989, LTS R&D funding rose from $40 million to $58 million.[5] Thus, in 1989, about two-thirds of government superconductivity R&D funding went to HTS.

Although the Department of Energy (DOE) and the Department of Defense (DoD) spent about the same amount on superconductivity overall in 1989, (both HTS and LTS), DoD had the biggest budget for HTS R&D, with a 45 percent share. DOE was second with 30 percent, and about 20 percent was allocated by the National Science Foundation (NSF). The National Aeronautics and Space Administration (NASA) and the Department of Commerce (through the National Institute of Standards and Technology, NIST) made up most of the rest, with the Department of the Interior and the Department of Transportation each spending less than 1 percent.

[4] "The National Action Plan on Superconductivity Research and Development," Executive Office of the President, Office of Science and Technology Policy, December 1989.

[5] Report compiled by the Federal Coordinating Committee on Science, Engineering, and Technology/Committee on Materials/Subcommittee on Superconductivity, "Federal Research Programs in Superconductivity," March 1989.

Table 4-3-Federal R&D in Superconductivity ($ thousands)[a]

	Fiscal year 1988[b]	Fiscal year 1989b (estimate)	Fiscal year 1 990' (estimate)
High-temperature:			
DoD	43,700	58,000	61,800
DOE	26,238	38,493	34,100
NSF	16,600	22,400	25,800
NASA	3,300	4,900	5,900
DOC (NIST)	2,800	4,800	2,800
DOT	50	150	—
DOI	100	100	—
Total HTS	92,788	128.843	130,400
Low-temperature:			
DoD	16,100	15,000	13,200
DOE	28,627	36,073	79,300[d]
NSF	3,800	3,800	3,000
NASA	2,650	3,050	2,000
DOC (NIST)	570	470	470
DOT	0	0	0
DOI	0	0	0
Total LTS	51,747	58,393	98,000
Total HTS+LTS	**144,535**	**187,226**	**228,400**

[a]Does not include funding for procurement of superconducting wire, magnets, and devices or funding of the superconductivity projects in the Small Business Innovation Research program.

[b]Federal Coordinating Committee on Science, Engineering, and Technology/ Committee on Materials/Subcommittee on Superconductivity, "Federal Research Programs in Superconductivity," March 1989.

[c]D. Allan Bromley, Director, Office of Science and Technology Policy, testimony before the Subcommittee on Transportation, Aviation, and Materials, House Committee on Science, Space, and Technology, Feb. 21, 1990.

[d]The large increase over 1989 is due to development problems with the SSC magnets, which required redesign.

KEY: DOC: Department of Commerce
DoD: Department of Defense
DOE: Department of Energy
DOI: Department of the Interior
DOT: Department of Transportation
NASA: National Aeronautics and Space Administration
NIST: National Institute of Standards and Technology
NSF: National Science Foundation

SOURCE: Compiled by the Office of Technology Assessment, 1990.

Table 4-4 gives a breakdown of where this HTS research was performed in fiscal year 1988. About 45 percent was performed in Federal laboratories, 30 percent in universities, and 25 percent in industry.[6] The wisdom of allocating more HTS R&D resources to Federal laboratories than to all of the Nation's universities is discussed in chapter 7.

Key Superconductivity Programs

Department of Defense (DoD)

The various defense agencies have had a long history of support for superconductivity. DoD began funding superconductivity research in the late 1940s, with the establishment of the Office of Naval Research at the end of World War 11.[7] Subsequently, the Air Force has supported research in sensors, airborne generators and signal processing, and the Navy in magnetic and electromagnetic/infrared (EM/ IR) detectors and ship propulsion research, among other projects. Most of the defense agencies have supported some type of superconducting electronics research, and often were the only Federal agencies to do so. Nevertheless, most of the defense programs in LTS had been completed or scaled back before the discovery of HTS.[8]9 After the discovery of HTS, many new programs were initiated to explore its potential for defense applications. Table 4-5 highlights some ongoing programs within DoD.

The Defense Advanced Research Projects Agency (DARPA) program, which accounted for over 40 percent of DoD's HTS R&D in fiscal year 1989, deserves special mention because it is unique in focusing on HTS materials processing and prototype applications development. [10]DARPA supports some 40 contractor teams working on dual-use projects (i.e., those with civilian as well as military applications).

Department of Energy (DOE)

DOE sponsored many programs in LTS prior to the discovery of HTS (see ch. 3); DOE also sponsored LTS conductor development for particle accelerator magnets such as those at Fermilab, and

[6]This breakdown can be used to estimate how many full-time-equivalent researchers were conducting HTS research in these institutions in 1988. Dividing each agency's funding totals by its average funding per senior-level researcher yields an estimate of 430 researchers working full-time on HTS in Federal labs, and 220 full-time-equivalent researchers in universities (not including graduate students). See Technology Management Associates, *The Federal Sector Effort in Superconductivity*, contractor report prepared for the Office of Technology Assessment, Nov. 15, 1988, p. 29.

[7]Kenneth Flamm, "Government's Role in Computers and Superconductors," contractor report prepared for the Office of Technology Assessment, March 1988, pp. 43-47.

[8]Congressional Research Service contractor report for Congress, "Commercialization of Technology and Issues in the Competitiveness of Selected U.S. Industries: Semiconductors, Biotechnology, and Superconductors," 88-486 SPR, June 1988.

[9]One exception is the Strategic Defense Initiative Organization Superconducting Magnetic Energy Storage (SMES) program, designed to provide power to ground-based lasers for ballistic missile defense (see ch. 3). If this program proceeds on schedule to produce a prototype SMES system by 1994, it will comprise a significant fraction of the Department of Defense superconductivity budget in the early 1990s.

[10]For a description of the DARPA program, see Defense Advanced Research Projects Agency, *High-Temperature Superconductors*, a report on the DARPA High-Temperature Superconducting Ceramic (HTSC) Technology Program, February 1989.

Table 4-4-Performers of HTS Research-Summary by Agency (Fiscal Year 1988)

	HTS budget outlavs ($ millions)	Performed by		
		Federal lab	University	Industry
Department of Energy				
Energy research	15.3	12.2	3.1	0.0
Conservation and renewable energy	4.9	4.9	0.0	0.0
Fossil energy	0.3	0.3	0.0	0.0
Defense programs	7.2	7.2	0.0	0.0
Total	$27.7			
Department of Defense				
Air Force	7.0	2.0	4.5	0.5
Navy	9.0	3.9	3.0	2.1
Army	2.0	2.0	0.0	0.0
Strategic Defense Initiative Organization	12.0	3.0	1.0	8.0
Defense Advanced Research Projects Agency	18.0	2.5	2.5	13.0
Total	48.0			
Department of Commerce (National institute of Standards and Technology)				
institute of Materials Science and Engineering	1.0	1.0	0.0	0.0
National Engineering Laboratory	1.1	1.1	0.0	0.0
National Measurement Laboratory	0.7	0.7	0.0	0.0
Total	2.8			
National Aeronautics and Space Administration				
Office of Aeronautics and Space Technology	2.6	1.6	0.5	0.5
Commercialization	0.5	0.5	0.0	0.0
Total	3.1			
National Science Foundation	14.5	0.0	14.5	0.0
Department of the Interior	0.1	0.1	0.0	0.0
Department of Transportation	0.0	0.0	0.0	0.0
National Institutes of Health	0.0	0.0	0.0	0.0
Total HTS	96.2 (loo%)	43.0 (45%)	29.1 (30%)	24.1 (25%)

NOTE: These estimates were made before the more precise figures in table 4-3 became available, but are accurate to within 5 percent.

SOURCE: Technology Management Associates, "The Federal Effort in Superconductivity," contractor report prepared for the Office of Technology Assessment, Nov. 15, 1988, p. 27

more recently, the Superconducting Super Collider. See table 4-6 for a descnption of the more important DOE superconductivity programs.

Superconductivity Research Centers—Inaccordance with President Reagan's Superconductivity Initiative, DOE's Office of Basic Energy Sciences established three HTS Research Centers, at Argonne National Lab, Lawrence Berkeley Lab, and Ames Lab. A fourth center for electronics applications was established at NIST/Boulder. These Research Centers were assigned complementary missions for I-ITS: Argonne concentrates on bulk materials for wires and cables; Lawrence Berkeley focuses on theory and on fabrication of thin films for electronic devices; and Ames concentrates on basic materials research and has responsibility for gathering and disseminating information on HTS. These Research Centers have also formed research teams with other national laboratories; e.g., Argonne works with Ames and Brookhaven labs on bulk applications. The Argonne Center involves about 50 researchers, and has links to both the State of Illinois Institute for Superconductivity and the National Science Foundation Science & Technology Center (see below), making it one of the largest concentrations of HTS expertise in the world. The Research Centers continue to be supported by funds reprogrammed from other areas,

Superconductivity Pilot Centers—In September 1988, DOE's Office of Conservation and Renewable Energy announced the establishment of three Superconductivity Pilot Centers, at Argonne, Oak Ridge, and Los Alamos National Laboratories. The Pilot Centers are intended to bring the enormous expertise

Table 4-5-Department of Defense Superconductivity Programs

Agency	Estimated fiscal year 1989 funds ($ millions)	Comments
High-temperature:		
DARPA	25.0	43% of DoD HTS R&D. A unique program focusing on HTS materials processing. Most of the funding goes to small firms.
SDIO	14.1	24% of DoD HTS R&D. Highly applications-oriented; includes radar, radio frequency cavities, antennae, and shielding.
Navy	9.7	17% of DoD HTS R&D. Abroad-based R&D program, built around a 5-yearplan.
Air Force	7.0	12% of DoD HTS R&D. A broad-based R&D program including processing and characterization. Applications include sensors, communications.
Army	2.2	4% of DoD HTS R&D. A broad-based R&D program including processing, theory, and characterization. Applications include sensors and electromagnetic launchers.
Total HTS	58.0	
Low-temperature:		
DARPA	6[a]	R&D on compact synchrotrons for x-ray lithography.
SDIO	8.0	53% of DoD LTS R&D.
	(11.4[a])	Superconducting Magnetic Energy Storage engineering test model: design competition.
Navy	4.7	31% of DoD LTS R&D. Historically the main DoD LTS supporter,
Air Force	1	Includes superconducting airborne generator project.
Army	0	No LTS R&D.
NSA	1.3	Superconducting electronics.
Total LTS	15.0	
Total LTS & HTS	73.0	

[a]Not in budget total.

KEY: DARPA: Defense Advanced Research Projects Agency
DoD: Department of Defense
NSA: National Security Agency
SDIO: Strategic Defense Initiative Organization

SOURCE: Report compiled by the Federal Coordinating Committee on Science, Engineering, and Technology/Committee on Materials/Subcommittee on Superconductivity, "Federal Research Programs in Superconductivity," March 1989.

and unique facilities of these National Laboratories to bear on problems of interest to commercial industry. Funded at a level of $6 million in fiscal years 1989 and 1990,[11] the Pilot Centers are supporting joint research projects with industry—generally on a 50-50 basis. They differ from the Research Centers in that they are intended to develop stronger ties to industry, to provide a gateway to the other laboratories' programs in superconductivity, and to be a testing ground for new experiments in technology transfer.

In the past, U.S. companies have been reluctant to work with Federal laboratories, because of the enormous amount of red tape involved. The Pilot Centers are structured so as to avoid these problems, offering expedited contracting procedures, greater protection of intellectual property, easier access to patents, and exclusive licenses for jointly developed technologies. At this writing all three Pilot Centers have signed agreements with major U.S. companies involved in HTS research.

National Science Foundation (NSF)

In addition to its individual grant programs, NSF sponsors various collaborative superconductivity research efforts including: Materials Research Laboratories, Materials Research Groups, the Bitter National Magnet Laboratory, the Wisconsin and Cornell synchrotrons centers, and a new supercon-

[1]The Bush Administration has slated the Pilot Centers for an increase to $15 million in its FY 91 budget request.

Table 4-6---Department of Energy Superconductivity Programs

Programs	Estimated fiscal year 1989 funds ($ millions)	Comments
High-temperature: [a]		
Basic Energy Sciences	16.8	44% of total DOE HTS R&D. Focused on basic research; DOE's largest HTS program.
Energy Storage & Distribution	12.9	34% of total HTS R&D. Includes funding for Pilot Centers.
All other HTS R&D	8.8	Mostly defense programs.
Total HTS	38.5	
Low-temperature: [b]		
High Energy and Nuclear Physics	27.4	76% of DOE LTS R&D. Includes wire, magnet, and materials projects.
All other LTS R&D	8.7	Mostly fusion magnets.
Total LTS	36.1	
Total HTS & LTS	**74.6**	

[a]Not including Small Business Innovation Research grants (SBIRs)
[b]Not including procurements or SBIRs

SOURCE: Federal Coordinating Committee on Science, Engineering, and Technology/Committee on Materials/Subcommittee on Superconductivity, "Federal Research Programs in Superconductivity," March 1989.

ductivity Science and Technology Center at the University of Illinois (see table 4-7.)[12]

Although total NSF funding for HTS R&D has increased steadily, virtually all of these increases have gone to support research at large centers such as S&T Center at the University of Illinois. Funding for individual investigator grants appears to have remained static, despite an increasing number of outstanding research proposals. This situation is discussed further in chapter 7.

Department of Commerce

All of the Department of Commerce efforts in superconductivity take place within the National Institute of Standards and Technology (NIST). NIST (formerly the National Bureau of Standards) has provided U.S. superconductivity standards since 1969, and developed the standard volt based on an array of 19,000 LTS Josephson Junctions, among other projects. The main standards research is carried out at the Boulder, Colorado facility. Though modest in size, this program provides the crucial function of improving the quality of reported superconductivity data, enabling meaningful comparisons of data among different researchers and organizations. NIST has a small but well-regarded superconducting electronic devices program and was designated a Superconductivity Research Center for Electronic Applications in President Reagan's initiative. Table 4-8 provides a breakdown for the NIST superconductivity budget for ‘fiscal year 1988 as well as totals for fiscal year 1989.[13]

Coordination Within Federal Agencies

Department of Defense (DoD)

The Department of Defense has devoted greater attention to coordination of its HTS programs than any other agency. The Defense Superconductivity Research and Development (DSRD) Working Group, chaired through the Office of the Secretary of Defense (OSD), is the formal DoD-wide coordinating committee. In 1987, the DSRD Working Group prepared a study of possible uses for HTS in military applications.[14] This study included approxirnations of the costs of research projects in each of the applications. According to the OSD, the report

[12]The objective of the S&T Centers is to take advantage of opportunities in science and technology that are too complex or too demanding of resources to be carried out by any one organization. They are structured to include a Federal laboratory and several industry partners, and are managed by a university. Besides the University of Illinois, the Superconductivity S&T Center also includes Northwestern University, the University of Chicago, and Argonne National Lab. It is to be funded at $24.5 million over 5 years. In fiscal year 1989, two new Materials Research Groups in superconductivity were begun at the Universities of Wisconsin and Minnesota at a total cost of about $900,000 per year.

[13]A breakdown was not available for fiscal year 1989 data.

[14]Department of Defense, DSRD Working Group, "Superconductivity Research and Development Options," July 1987.

Table 4-7-National Science Foundation Superconductivity Programs

Special programs	Estimated fiscal year 1989 funds ($ millions)	Comments
High-temperature:		
Individual grants	9	
Young Investigators program	1	Superconductivity R&D theory/experiment.
Science and Technology Center (STC)	4.3	Cooperative HTS R&D.
Materials Research Labs and Groups	5.4	MIT, Stanford, U. Illinois, Northwestern, U. Chicago, Harvard, Cornell, U. Minnesota, U. Wisconsin.
User facilities	3.5	Bitter National Magnet Lab, synchrotrons facilities.
Total HTS	23.2	
Low-temperature:		
Individual grants	2.3	
Materials Research Labs and Groups	0.2	
User facilities and instrumentation	0.5	
Total LTS	3.0	
Total LTS + HTS	**26.2**	

SOURCE: Willlam Oosterhuls, National Science foundation, personal communication, February 1990.

served its initial coordination function well and now needs updating.

The Navy, which has the largest superconductivity program of the three services, also has the most extensive coordination mechanisms.[15] A Naval Consortium for Superconductivity has been established to coordinate R&D efforts, and in 1989 the Navy developed a 5-year plan for superconductivity.[16]

Department of Energy (DOE)

The main DOE coordinating body for materials is the Energy and Materials Coordinating Committee; its Subcommittee on Superconductivity is charged with the internal coordination of superconductor R&D in DOE. At Ames Laboratory, the Center for Basic Scientific Information distributes a widely read biweekly newsletter, High-T_C Update, including a bibliography of the latest HTS preprints. The DOE National Laboratories have held a series of conferences broadcast nationally by satellite that have made the latest HTS results available to other researchers. At DOE's Office of Scientific and Technical Information, located in Oak Ridge, Tennessee, a computer database has been established to provide up-to-date technical information on superconductivity to U.S. industry. Called the 'Superconductivity Information System," it offers a bulletin board, electronic mail, a database of work in progress, a preprints database, a database of all DOE-sponsored research, and printed copy of database searches.

Coordination of HTS activities also takes place under the auspices of the Superconductivity Coordinating Committee on Electric Power. This group is made up of the Electric Power Research Institute, various electric utilities, and numerous Federal agencies, including DOE, NSF, and NIST.

National Aeronautics and Space Administration (NASA)

Internal coordination of both HTS and LTS research programs is provided through the NASA Superconductivity Working Group, chaired out of the Office of Aeronautics and Space Technology and the Information Sciences and Human Factors Division. Contacts with the larger industrial and scientific community are maintained through the Space Systems Technical Advisory Committee, a review team for HTS, with members from industry and universities as well as other governmental organiza-

[15]These include the Naval Research Advisory Council (a body of industry experts that reviews the overall Navy R&D program annually); an extensive workshop program through the Office of Naval Research (ONR) for potential contractors; and coordination with the Strategic Defense Initiative Organization and DARPA.

[16]The plan, called the ''Navy Superconductivity Program,'' was prepared by the Naval Consortium for Superconductivity, the Office of Naval Research, and the Office of Naval Technology, and released on May 15, 1989.

Table 4-8--National Institute of Standards and Technology Superconductivity Programs

Programs	Fiscal year 1988 funds[a] ($ millions)	Comments
High-temperature:		
Materials preparation	0.5	Includes phase diagrams.
Structure determination and characterization	0.7	Includes neutron scattering.
Property measurements	0.9	Includes standards and electronic structure measurements.
Fabrication and devices	0.7	Includes thin films and electronics.
Total HTS	2.8[a]	
Low-temperature:		
Total LTS	0.5	Includes JJs, SQUIDS, standard volt, and measurement standards.
Total HTS and LTS	**3.3**	

[a]There was a 1-year increase of $2 million for HTS in fiscal year 1989 (giving an overall total of $5.3 million for superconductivity), but a large part of these funds was spent to repair damage from a fire in a clean room used to fabricate superconducting electronics.

KEY JJ: Josephson Junction; SQUID: Superconducting Quantum interference Device

SOURCE: Federal Coordinating Committee on Science, Engineering, and Technology/Committee on Materials/Subcommittee on Superconductivity, "Federal Research Programs in Superconductivity," March 1989:

tions. NASA's Technology Utilization division is in the process of forming a NASA consortium (open to any U.S. entity) for research on superconductivity and technology transfer to the private sector. It will be located at the Jet Propulsion Laboratory in Pasadena California, and is expected to begin operations in 1990.

Coordination at the National Level

The Office of Science and Technology Policy (OSTP) has been the focus of efforts to coordinate Federal HTS programs. As noted above, OSTP had responsibility for the National Action Plan on Superconductivity R&D, released in December 1989.

Committee on Materials (COMAT)

One body under the auspices of OSTP, the Committee on Materials (COMAT), has played a valuable role.[17] COMAT was instituted to coordinate materials policy among the various Federal agencies, and all agencies with significant interests in materials R&D are represented. In 1988 and 1989, the Superconductivity Subcommittee of COMAT published a comprehensive review of all Federal agency programs and budgets for both HTS and LTS R&D.[18] It has also taken a leading role in defining options for future international collaboration in HTS.

COMAT has been viewed by the Administration as the preferred body for coordinating materials policy among all of the relevant agencies. Its actual function, though, is best described as information exchange, rather than active coordination, since it does not set an overall agenda for materials R&D, has no control over agency budgets, and does not monitor or guide individual agency programs. The need for national coordination going beyond the activities of COMAT is recognized in OSTP's Action Plan.[19]

National Critical Materials Council (NCMC)

NCMC, established in 1984,[20] is charged by Congress with responsibility for overseeing the formulation of policies for "advanced" and "critical' materials. It was intended by Congress to be an active oversight body for coordinating all Federal agencies on materials policy issues. The Reagan Administration saw NCMC as redundant with existing agencies-especially COMAT—and neglected it entirely.[21] During most of 1988 and 1989, the

[17]COMAT is formally under FCCSET (Federal Coordinating Committee on Science, Engineering and Technology), established in 1976 by the National Science and Technology Policy, Organization, and Priorities Act to facilitate coordination of science and technology policy.

[18]"Federal Research Programs in Superconductivity," op. cit., footnote 5.

[19]"The National Plan on Superconductivity Research and Development," op. cit., footnote 4, p. 3.

[20]The National Critical Materials Act of 1984, Public Law 98-373.

[21]U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design: New Structural Materials Technologies,* OTA-E-351 (Washington, DC: U.S. Government Printing Office, June 1988), p. 307.

Council had no active members, although its staff assisted in the preparation of the Action Plan.[22]

Coordination Among State and Federal Agencies

Many States have seen opportunities in HTS for improving local economic competitiveness. Several provide funding (generally less than $1 million) for HTS research, most of which goes to the main State universities. Often, these funds are provided within the context of broader advanced technology programs; one example is the Ben Franklin Program in Pennsylvania, which now supports several superconductivity projects. A few States have developed new programs dedicated to HTS R&D. The largest State efforts in superconductivity are in Illinois, Texas, and New York (programs in several States are outlined in table 4-9). These generally involve some cost sharing with the Federal Government. For example, the Illinois efforts complement the Federal programs awarded over the past 2 years, including the NSF S&T Center at the University of Illinois and the DOE Pilot Center at Argonne National Laboratory.

Industry Consortia

In the 1980s, the R&D consortium has become one of the most popular technology policy tools in the United States aimed at regaining lost markets and exploring new technologies. The privately sponsored Microelectronics and Computer Technology Corporation (MCC) and the more recent industry/government-sponsored Sematech have been notable examples of this trend. Inevitably, a variety of consortia have also been proposed as a means of accelerating the commercialization of HTS by U.S. firms. Since the release of the Wise Men's' Report (see above), which recommended the establishment of four to six HTS consortia focusing on applications, the number of consortia either established or planned for HTS development has skyrocketed. A partial list is given in table 4-10.

Most of these consortia are directed toward development of HTS electronic devices, and virtually all seek Federal funding. This proliferation of HTS consortia-all working in similar R&D areas—raises concerns about whether the U.S. effort will be diluted in a hodgepodge of small consortia, each below "critical mass" in size, and whether Federal funds will be wasted on duplicative research. Critics of this situation point to Japan's International Superconductivity Technology Center, a single HTS R&D consortium involving all of the major superconductivity companies under the auspices of the Ministry of International Trade and Industry (see ch. 5).

In fact, there is a kind of informal coordination taking place among the U.S. consortia. Often, for instance, members of one consortium are on the planning board of another, and researchers associated with different constellations of labs have frequent opportunities to exchange information. Ultimately, market forces and the limitations of the Federal budget will sort out which consortia will survive and which will not, but there may be a Federal role in making this process more orderly, Options to address this question are taken up in chapter 7.

International Cooperation

Many laboratories around the world have capabilities in superconductivity research comparable to those in the United States, and past international collaborative programs in LTS such as the Large Coil Task (see ch. 3) have proven to be extremely valuable.[23] Other examples include: the annual U.S.-Japan Workshop on High-Field Superconductors, which met for the sixth time in 1989; the Versailles Agreement on Advanced Materials and Standards, which has an active program for international comparisons of measurements of critical currents and alternating current losses; and the International Electrochemical Commission, which has established a Technical Committee on Superconductivity to develop international standards.

U.S. superconductivity researchers have long had informal, one-to-one collaboration with their foreign colleagues. For instance, NSF has had a bilateral agreement with Japan in place for 28 years that promotes researcher-directed collaborations in basic science. In 1987, NSF initiated a new program that is jointly funded by the United States and Japan to

[22] On Feb. 21, 1990, D. Allan Bromley, Director of OSTP, announced the appointment of three Council members, including himself as chairman.

[23] Negotiations are continuing on foreign participation in DOE's Superconducting Super Collider Program.

Table 4-0-State Government Support for Superconductivity

State	Description of program
California	The State Department of Commerce has a program of grant awards for technology transfer of university research to commercial entities, called the Competitive Technology Program. This program receives matching private sector funds. Superconductivity project awards total $1.8 million, for a superconductivity applications center, HTS high-frequency electronic devices, and SQUID development.
Florida	The State has established the Florida Initiative, a consortium composed of 7 State universities, involving 55 principal investigators. It receives funds from a pool of $25 million provided by DARPA to the State of Florida for microelectronics research. Of this $25 million, $6.4 million goes to superconductivity R&D. Florida has shown significant interest in magnetically levitated train technology. The potential Tampa-Orlando-Miami maglev train project has been canceled; however, a short maglev line from the Orlando airport to Disney World/EPCOT Center is still under discussion.
Illinois	Illinois is home to several large federally sponsored superconductivity programs, many at Argonne National Lab. The University of Illinois is the principal site of the new NSF Science and Technology Center for Superconductivity. Some State funds are used to leverage Federal and industrial funds at Argonne and the S&T Center, but most of the funding comes from the Federal Government.
Maryland	The University of Maryland (College Park) established a Center for Superconductivity Research intended eventually to have approximately 20 full-time researchers (six faculty members). State funding is $1 million for the first year (beginning July 1988); $2 million for the second year; and $3 million for the third. Collaboration with industry is expected; negotiations are underway with utilities (for wire fabrication research), and a chemical company (for materials characterization).
New Jersey	The New Jersey Science and Technology Commission's Governor's Roundtable issued a report recommending the development of a New Jersey superconductivity program, focused on high-field magnet fabrication. The Commission recommends a State funding level of $1-2 million per year to be matched at least one-to-one by non-State sources. The State has seed funding for a fellowship program in which college seniors and first year graduate students can work in academic and industrial labs on superconductivity research.
New York	The New York State Institute for Superconductivity (NYSIS) at SUNY Buffalo was established in June 1987. Its focus is on transferring HTS technology into practical applications. It is to have 27 faculty members and over 100 graduate students and postdocs. New York State funding is $10 million and this is expected to be leveraged by Federal funds. Of this, $5 million is to be used for lab equipment and construction; $2.2 million for awards for external researchers; and $2.2 million for researchers within the Center. At this writing, 31 awards have been made, totaling $1.4 million; 16 of these have gone to SUNY Buffalo researchers, and 15 to other New York universities and businesses.
Texas	Of the several consortia located in Texas, most receive no State funding. The Microelectronics and Computer Corporation (MCC) entered into a joint superconductivity research program with the Texas Center for Superconductivity at the University of Houston (TCSUH) in 1988. TCSUH is funded at a level of $30 million over 3 years, receiving $6.5 million from the State of Texas and other funding from DARPA and Du Pont.

KEY: DARPA=Defense Advanced Research Projects Agency; MCC.Microelectroncs and Computer Corp.; NYSIS=New York State Institute on Superconductivity; SQUID= Superconducting Quantum Interference Device; SUNY. State University of New York; TCSUH=Texas Center for Superconductivity at the University of Houston

SOURCE: Office of Technology Assessment, 1990

get more U.S. researchers into Japanese laboratories.[24] Through this program, Japanese laboratories formerly closed to foreign researchers are now actively seeking foreign scientists. So far, though, this program is undersubscribed by U.S. researchers.[25]

The discovery of HTS has stimulated several international efforts to explore the potential for this technology. Examples include a series of international meetings on electric power applications of superconductivity held by the International Energy Agency,[26] and specific mention of HTS in the United States-Japan Agreement on Cooperation in Science and Technology. At this writing, several joint superconductivity projects were being negotiated under the Agreement.

Such international programs are likely to become even more important in the future. Yet Federal agency budgets to support these activities are static

[24]This program consists of three parts: the Science and Technology Agency fellowships for long-term (6 to 15 months) postdoctoral visits to Japanese government labs in which 20 spaces are reserved for National Science Foundation-chosen researchers; a similar agreement with the Ministry of Education for 20 fellowships in Japanese university labs; and a blanket $4.8 million grant from Japan to NSF for general support for the program, including initial survey visits and language training. This money could also be used to send U.S. researchers to Japanese industrial labs.

[25]Shahid S. Siddiqui, "Too Few Foreign Scientists in Japan," *Nature*, vol. 340, No. 6232, Aug. 3, 1989, p. 337.

[26]U.S. liaison is through the Department of Energy's Office of Conservation and Renewable Energy

Table 4-10--A Partial List of HTS Consortia

Consortium type	Major partners	Comments
Industrial:		
MCC Austin, TX	Bellcore, Boeing, DEC, Du Pont, Motorola, 3M, Westinghouse.	Merged in 1988 with the Texas Center for Superconductivity at the University of Houston (TCSUH, see below).
SuperChip Washington, DC	Tektronix, others to be announced.	Under the auspices of the Council on Superconductivity for American Competitiveness (CSAC); has sought $1 billion in loan guarantees from the Federal Government; has received seed money from DARPA.
Superconductor Applications, Inc. Princeton, NJ	To be announced.	To be based at David Sarnoff Laboratory under the direction of Stanford Research Institute; has received seed money from DARPA.
University-based:		
Consortium for Superconducting Electronics Cambridge, MA	AT&T, IBM, Lincoln Labs, MIT.	Most closely resembles the model proposed by the “Wise Men”; seeking up to $5 million from DARPA.
TCSUH Houston, TX	Du Pont, plus joint membership of MCC partners.	Formed in 1987 with $2.5 million from State of Texas; received $4 million from DARPA in 1988.
NSF S&T Center Urbana, IL	University of Illinois, Northwestern University, University of Chicago, Argonne National Lab.	Funded by NSF at a rate of $24.5 million over 5 years.
Lehigh University Consortium for Superconducting Ceramics Bethlehem, PA	AT&T Bell Labs, BOC Group, U.S. Navy.	12 full-time researchers.
NY State Institute on Superconductivity Buffalo, NY	SUNY Buffalo plus partners to be announced.	Initial funding of $10 million from the State of New York; expected to be supplemented with Federal funding.
National lab-based:		
Argonne Argonne, IL	Beldon Wire, Du Pont, GE, MagneTek, United Technologies.	Location of DOE Pilot Center ($2 million funding); HTS funding lab-wide is $10-12 million.
Los Alamos Los Alamos, NM	American Superconductor, AMP, Hewlett Packard, Du Pent, Rockwell.	Location of DOE Pilot Center ($2 million funding); HTS funding lab-wide is$11 million.
Oak Ridge Oak Ridge, TN	Corning Glass, Du Pent, FMC, IBM, GE, Westinghouse.	Location of DOE Pilot Center ($2 million funding); HTS funding is $6 million.
Jet Propulsion Lab Pasadena, CA	To be announced.	Under the auspices of NASA; expected to begin operations in 1990.

KEY: CSAC=Council on Superconductivity for American Competitiveness; DARPA=Defense Advanced Research Projects Agency; DOE= Department of Energy; MCC=Microelectronics and Computer Corp.; NASA=National Aeronautics and Space Administration; NSF= National Science Foundation; SUNY= State University of New York; TCSUH=Texas Center for Superconductivity and the Unversity of Houston.

SOURCE: Office of Technology Assessment, 1990.

or declining. This issue is discussed further in chapter 7.

CONCLUSIONS

The Federal response to the discovery of HTS illustrates many of the strengths and weaknesses of U.S. R&D policy as it relates to U.S. industrial competitiveness. On the whole, the response has been both substantial and timely. By fiscal year 1989, 2 years after the breakthrough, the Federal budget for HTS had grown to nearly $130 million—about the same as the budget for all other advanced ceramics R&D combined.

The Administration can point to some significant successes and even innovations. The mission agencies moved quickly to redeploy resources and researchers to HTS. The DARPA program emphasizing HTS processing is unique. The DOE Pilot Centers are experimenting with expedited mechanisms for contracting with industry and for disposition of intellectual property, and they have received positive initial reviews from prospective industry collaborators. Mechanisms for rapid exchange of technical information among researchers have been established and appear to be working well.

The Administration's approach also contains much that is familiar to critics of Federal R&D policy. DoD allocates the largest budget, and has become the principal supporter of U.S. industry programs. Much of the Federal budget goes to support research in Federal laboratories, which heretofore have not had a good track record in transferring technology to U.S. industry. And although coordination of HTS R&D programs within the mission agencies is strong, coordination at the national level is weak. Congress attempts to address this problem with legislation have met with little success.

The Federal response to the advent of HTS is perhaps best characterized as an attempt to broaden the R&D activities of the relevant agencies to address industry needs without fundamentally changing their missions or their relationships to one another. Those who had hoped that the worldwide race to develop HTS might stimulate a serious debate about a new Federal role in meeting the challenge of foreign competition in commercial technologies have clearly been disappointed.

Is the present Federal response adequate to ensure future U.S. competitiveness in HTS? This question is taken up in chapter 7, following an examination of foreign HTS programs in the next chapter, and those of private industry in chapter 6.

Chapter 5

High-Temperature Superconductivity Programs in Other Countries

CONTENTS

Boxes

Tables

Chapter 5

High-Temperature Superconductivity Programs in Other Countries

How do U.S. and foreign efforts compare in high-temperature superconductivity (HTS)? This chapter briefly assesses foreign programs in superconductivity, focusing primarily on government programs.[1]

JAPAN

History of Japanese Superconductivity Programs

Unlike the case of HTS, where Japanese researchers have made major advances, the Japanese made few contributions to the initial development of low-temperature superconductors (LTS). LTS research in Japan began in the early 1960s, and for many years Japanese researchers followed closely the LTS developments in the United States. It was nearly a decade before the Japanese began to catch up. During the 1970s, though, the Japanese Government initiated a number of collaborative LTS programs, featuring long-term commitment from its national laboratories, universities, and companies, that allowed Japan to surpass U.S. capabilities in several areas----e. g., Josephson Junction (JJ) technology,[2] maglev transportation, and superconducting rotating machinery. The principal Japanese Government programs are outlined in table 5-1.

Several observations can be made about these programs. First, their goal was and is to develop commercial-not military-technologies. Second, they were long-term programs, typically lasting 8 to 10 years. Their funding was sustained at a relatively constant level, in contrast to the erratic funding of corresponding U.S. programs over this period. Third, they featured strong emphasis on national laboratory facilities and personnel, although a large part (often 50 percent) of the funding and research were provided by the participating Japanese companies. Since the discovery of HTS, considerable thought has been given to how HTS can be integrated with ongoing LTS programs. Today, the Japanese Government is funding a mix of LTS and HTS programs in parallel, with the intent of incorporating HTS materials into more mature LTS projects as soon as the new materials can satisfy the necessary requirements.

The Japanese HTS Budget

Table 5-2 gives a budget breakdown for the principal Japanese agencies involved in superconductivity R&D. Major funding comes from the Ministry of International Trade and Industry (MITI), the Science and Technology Agency (STA), and the Ministry of Education (MOE). In 1989, HTS R&D accounted for slightly less than half of superconductivity R&D budget, compared with two-thirds in the United States. Japanese agency budget figures typically do not include salaries and overhead. When adjusted to include these costs, the nominal HTS total of $43 million in 1989 scales to over $70 million[3]—still considerably less than total HTS spending of the U.S. Government ($129 million) in 1989. Counting researchers in universities, national laboratories, and industry, OTA estimates that around 1,200 researchers are active in HTS R&D in Japan, compared with perhaps 1,000 in the United States.[4]

The most important new thrusts in superconductivity are given in table 5-3. These have been described in detail previously.[5] Programs especially well-known outside Japan are the International Superconductivity Technology Center (ISTEC) and the Superconductive Generation Equipment and Materials (Super-GM) program (see boxes 5-A and 5-B). Overall, OTA finds that there is a rough parity between Japan and the United States in HTS R&D. This parity does not extend to all technical areas, though: one recent report notes that Japan surpasses

[1]A comparison of U.S. and Japanese industry programs is presented in the next chapter

[2]U.S. Congress, Office of Technology Assessment, *Commercializing High-Temperature Superconductivity*, OTA-ITE-388 (Washington, DC: U.S. Government Printing Office, June 1988), pp. 71-72.

[3]International Superconductivity Technology Center estimate, October 1989.

[4]In 1988, Japanese industry had about 700 full-time researchers in HTS (see next chapter).

[5]U.S. Congress, Office of Technology Assessment, op. cit., footnote 2, p. 51.

Table 5-l—History of Japanese LTS Programs

Project	Supporting agency, R&D laboratory	Duration	Results	Comments
MHD power generation	MITI:ETL various companies	1966-1975	Mark V supermagnet.	Matching funds from companies, which gained experience in LTS magnet construction.
High-energy physics	MoE:KEK various companies	1971 -present	60-Gev collider (TRISTAN) including superconducting magnets for beam control, detection; also rf cavities and refrigeration systems.	Minor funding from companies.
Supermagnets for fusion research	STA:JAERI Nagoya U., Kyushu U Nihon U Osaka U,, MoE	Early 1970s-present	Large Coil Task coil tested 1987. J-60 Experimental Reactor. Toroidal and poloidal coils for new Fusion Experimental Reactor.	Program is expected to continue at present levels. No specific clans to incorporate HTS.
Maglev tram	MOT.JNR (now7 regional JR compames)	1970-present	44-seat test vehicle; 7km test guideway; 375km/hr manned test.	New50km test guideway planned. Funding IS 95 percent from private sources. No serious plan to incorporate HTS.
Electromagnetic ship propulsion	Ad-hoc group, Japan Foundation for Shipbuildmg Advancement (organized 1985) various companies	1970-present	Model vessel tests (1970 to 1979) Design for 22-meter, 150-ton oceangoing vessel for 1990 ("Yamato") miniature model tested in 1986. Total cost est. 40 million dollars.	Efficiency is low, requires very high magnetic field (>1 O tesla).
Basic technology for superconductivity and refrigeration	STA.NRIM various companies	1982-1986	Advancement of basic technology related to LTS and refrigeration.	Researchers became core of the New Superconducting Materials Forum and Multicore Project of STA.
Superconducting magnetic energy storage (SMES)	MIT I various companies	1986-?	Feasibility studies.	Candidate for new national R&D project. Designs for smaller, toroidal SMES being considered by electric utility industry (as opposed to larger, solenoid designs under study in the United States).
Superconductive generation equipment and materials (Super GM) (See box 5-B)	MIT I (NEDO) various companies	1988-1995	Design and construct 70 MW model generator Design components for 200 MW pilot generator.	Culmination of many years of research and engineering experience with superconducting magnets and prototype generators, beginning with MHD program HTS materials being developed.
Superconducting quantum electronics	MoE unversitles	1979-1981	Advances in fabrication methods for JJs and devices.	Provided experience base in unversities now being tapped for HTS-based electronics R&D.
Josephson Junction Devices	MIT I:ETL NTT, various companies	1982-1989	989 Prototype large-scale i containing thousands computer based on 1€ microprocessor and 2 possible by 1990.	Program continued after U.S. effort stopped in 1983. Japanese companies now have a strong base for future thrusts in superconducting electronics, including HTS.
New superconducting materials	MoE universities	1984-1986	986 Training for university at development of higt	Predated discovery of HTS but served as a springboard for rapid Japanese involvement. Program extended 1 year after discovery of HTS.

KEY: ETL: Electrotechnical Laboratory; JAERI: Japan Atomic Energy Research Institute; JJ: Josephson Junction; JNR: Japan National Railroad (now broken up into 7 regional companies); KEK: National High-Energy Physics Laboratory; MHD: Magnetohydrodynamics; MITI: Ministry of International Trade and Industry; MOE: Ministry of Education; MOT: Ministry of Transportation; MW: Megawatt; NEDO: New Energy and Industrial Technology Development Organization; NRIM: National Research Institute for Metals; NTT: Nippon Telephone and Telegraph; STA: Science and Technology Agency

SOURCE: Advanced Materials Technology, "Assessment Study of the History of Japanese Superconductivity Efforts," contractor report prepared for the Office of Technology Assessment, November 1988.

Table 5-2-Japanese Government Fiscal 1989[a] Superconductivity Budget ($ millions)

Agency	HTS	LTS	Total
Ministry of International Trade & Industry	10.6	24.0	34.6
Science & Technology Agency	24.3	6.8	31.1
Ministry of Education	7.2	8.7	15.9
Ministry of Transportation	0.0	7.0	7.0
Ministry of Posts& Telecommunications	0.5	0.0	0.5
Total	42.6[b]	46.5	89.1

aDraft budget. The Japanese fiscal year begins April 1.
bCannot be compared directly to U.S. figures because Agency budgets often do not include salaries and overhead. When these are included, the total is estimated to beat least $70 million.

SOURCE: Adapted from *Superconductor Week*, vol. 3, No. 8, Feb. 20, 1989, p. 6.

Table 5-3-Recent Japanese Government High-Temperature Superconductor R&D Programs

Agencyl Program	Comments
Ministry of International Trade and Industry:	
Superconducting materials and process technologies	10-year program beginning 1988, includes funding for ISTEC and national laboratories.
Superconducting electron devices	10-year program beginning 1988, about half going to the private sector, focusing on development of HTS transistors.
Superconducting generator (Super-GM)	8-year program beginning 1988, primarily LTS; includes parallel HTS research component.
Science and Technology Agency:	
Multi-Core project	Coordinated effort of nine STA-funded national laboratories participating in HTS R&Din four "core" areas: theory/ database, processing, characterization, and technology transfer.
New superconducting materials forum	Professional forum on HTS development with 135 member companies and research associations. Interfaces between Multi-Core project and private industry efforts.
Ministry of Education:	
Mechanism of superconductivity	3-year program beginning 1988 involving some 100 researchers under the direction of Prof. Y. Muto, Tohoku University.
Chemical design and processing of new oxide superconductors	3-year program beginning 1989 under the direction of Prof. K. Fueki, Science University of Tokyo.
Development of electronics with new superconducting materials	3-year program beginning 1989 involving three research groups under the direction of Prof. K. Hara, Chiba Institute of Technology.
Special research project on new superconductors	3-year program beginning 1987 involving four research groups under the direction of Prof. S. Tanaka, University of Tokyo.
Ministry of Posts and Telecommunications	
Development of HTS mixer at terahertz frequencies	
HTS characterization and thin films for infrared detectors	Carried out at NIT laboratories.

ISTEC: International Superconductivity Technology Center

SOURCE: Office of Technology Assessment, 1990.

the United States in synthesis and processing of HTS materials, and in organic superconductor research.[6]

Japanese HTS programs are well integrated with previous LTS efforts, both in terms of personnel and research goals. For example, the core participants in STA'S New Superconducting Materials Forum and Multi-Core Project (table 5-3) also participated in a previous 5-year STA-sponsored LTS project on Basic Technology for Superconductivity and Refrigeration (table 5-1). In Japan's fiscal year 1988, MITI also initiated a new 10-year program to develop practical HTS transistors, following on the conclusion of an 8-year program to develop niobium JJs.

One common belief about Japanese companies is that they have become successful competitors because of their ability to work together in consortia organized by the Japanese Government. ISTEC, a single consortium of most major companies involved in HTS R&D that was organized under the auspices of MITI, is often held up as a trump card that will put Japanese companies ahead in the race to commercialize HTS. But although the formation of ISTEC is an impressive achievement, *its agenda is deliberately focused at a basic research level--+-e., materials development—similar to the research program of a university or national laboratory in the United States.* Members' motives for joining ISTEC are complex, but typically do not include the expectation that research at ISTEC will lead directly to commercial applications. For that, the member companies are relying on the major efforts underway at their own R&D laboratories, and the accumulated expertise built up over years of experience with LTS, semiconductor processing, and ceramics technology.

EUROPEAN COOPERATIVE PROGRAMS

The two most important existing European cooperative programs that sponsor HTS projects are Framework, an EC activity, and the EUREKA

[6]Japanese Technology Evaluation Center Superconductivity Panel, "High-Temperature Superconductivity in Japan," a report for the National Science Foundation, NTIS PB 90-123126, November 1989.

Box 5-A—Intm#ationd Supereonductivity Technology Center (ISTEC)

ISTEC is a consortium of companies organized under the auspices of MITI. Established in January 1988, its laboratory facilities, located in a building leased from Tokyo Gas, were officially opened in October 1988. ISTEC was established to pursue several activities related to superconductivity: conduct basic R&D on HTS and processing technology; review research progress and feasibility of various applications; organize international symposia, seminars, and workshops; promote international exchange of scientists; and disseminate information.

Resources

ISTEC has 111 members, under two kinds of memberships: associate and full. Full members participate in the laboratory and can send one or two researchers each. Full members give an additional one-time donation of 100 million yen (about $800,000) and pay an additional annual fee of 12 million yen (about $100,000) to support the laboratory. Companies pay the salaries of the researchers they send, and a lo-year commitment is expected. Most companies-viewing ISTEC as a training opportunity-are sending relatively young researchers, rather than their seasoned superconductivity veterans.

Associate members may participate in the seminars and receive the publications, but do not participate in the actual research or intellectual property rights. (However, associate members may share some benefits such as reduced royalty payments for licenses.) Associate memberships require an initial donation of 1 to 2 million yen (about $8,000 to $16,000) and a 0.5 to 2 million yen annual fee. A listing of ISTEC membership as of June 1989 is given in appendix 5-A.

At that time, 46 companies had joined as full members, yielding an initial capitalization of about $34 million. In addition, they contributed about $4.2 million in *operating* expenses. As of October 1989, there were 89 research staff, **including 77** dispatched from the member companies.

In Japan's fiscal year 1988, MITI's contribution was 440 million yen *($3.4 million), which incresed to 890* million yen ($6.4 million) in Japan's fiscal year 1989. These figures do not include salaries. According to one estimate, ISTEC'S operating budget if salaries are included, comes to about $17 million per year; thus, in Japan's fiscal year 1989, ISTEC received about one-third of its support from MITLl

Research organization

The research at ISTEC laboratory is organized according to seven groups as follows:

1) Characterization and analysis of fundamental properties of superconductors; 2) HTS oxides and search for new superconducting ceramics; 3) Research on organic superconductors. 4) Fundamental research on chemical processing; 5) Fundamental research on physical processing; 6) Organization of an HTS database; and 7) Research on high-critical-current density superconductors {presently at the Japan Fine Ceramics Center in Nagoya).

Each group is headed by a leading expert drawn from a major university or national laboratory, and when fully staffed, will have 10 to 22 members. Research is expected to remain at a very basic level, not directed toward particular applications, since competing companies are involved.

ISTEC's policies on intellectual property were finalized in March 1989.[2] In general, patent rights are shared between ISTEC and the company that dispatched the researcher who did the work.

International Aspects

ISTEC has actively encouraged foreign companies (and individual researchers) to join the laboratory. At this writing, though, only four U.S. companies had joined as associate members (DuPont-Japan, Rockwell, IBM-Japan, and Intermagnetics General), plus the Electric Power Research Institute (EPRI) (see app. 5-A). There are two European associate members, British Telecom and Rhone-Poulenc Japan; there are no non-Japanese full members. Given the substantial investment involved (perhaps $1.5 million the first year and $400,000 per year thereafer-to cover salaries and expenses for two researchers), most U.S. firms would apparently rather invest their external R&D dollars in domestic collaborations where there is no language barrer, where it is easier for researchers to make the necessary career adjustments, and where U.S. companies have more control over the R&D agenda.

---

1 According to ISTEC management sources.

2 Takashi Akutsu, "The Establishment of the 'Guideline on Handling of Intellectual Property Rights,' of ISTEC," *ISTEC Journal*, vol. 2, No. 2, July 1989, p. 38.

SOURCE: Office of Technology Assessment, 1990.

initiative, a European-based program with close ties to the European Community.[7] While the budgets of EUREKA and Framework are relatively small compared with the overall R&D efforts of the national member States, these cooperative programs are considered by European observers to be important for a number of reasons: they allow organizations with different strengths to combine R&D resources necessary to maintain competitiveness; they are focused on commercial applications of high technologies; and they help to lower legal and regulatory barriers within Europe.

Framework

The Framework program of the Commission of the European Communities, as its name implies, provides an overall strategy, structure, and financial package through which specific R&D programs operate. Three EC programs within Framework support HTS research: ESPRIT II, Stimulation of Science (now in its second phase, called Science) and BRITE/EURAM. ESPRIT is a basic/applied research program in information technologies. BRITE/EURAM (1989-1992) is a recent industrial research program that builds on the successful activities of two previously separate programs covering research in industrial technologies (BRITE) and advanced materials (EURAM). "Science" was established to address three goals: better mobility of researchers, large facilities and projects, and a more integrated, multidisciplinary approach to research.

Several EC projects on HTS research were launched in May, 1988. A budget of about $16 million has been approved for HTS through 1989.[8] Nearly all of the HTS budget is expected to support collaborative industrial applied research within the member countries, with matching funds to be supplied by industry. A standing committee of representatives of key research institutions in the member countries has been established to provide information on national HTS programs, staff exchanges, and scientific meetings.

Eureka

EUREKA is a product of the French concern that the United States' Strategic Defense Initiative would vastly add to the U.S. storehouse of commercial technologies, and represents a civilian attempt by Western European countries to keep up with this expected U.S. technology development. It is a $1 billion, industry-led program directed independently of the EC. The EUREKA program hosts two LTS superconductor projects.[9]

FEDERAL REPUBLIC OF GERMANY

West Germany has supported superconductivity research consistently for the past 20 years. Most of the government funding is provided by the Ministry for Research and Technology (BMFT), which has supported LTS R&Din three principal areas: generic technology development (materials, magnets, cryogenics, devices); energy research (primarily superconducting generators); and medical technology (magnetic resonance imaging, biomagnetic measurements). As a result, West German firms have capabilities comparable to those of U.S. firms in large-scale applications, and are stronger competitors in some emerging commercial applications of LTS-e.g., magnetoencephalography (see ch. 3)—than are Japanese firms.

In 1988, BMFT HTS project funding was about $10 million, 90 percent of which went to research institutes, The remaining 10 percent went to support industrial research, and was matched by the recipient companies. In subsequent years, BMFT funding has grown, and is expected to reach some $33 million.

Some 90 research teams, with a total of about 500 research personnel, are estimated to be active in HTS at West German institutes and industrial laboratories. Information exchange and coordination among these groups is excellent, and is carried out under the auspices of BMFT

Private industry investment in HTS is higher in West Germany than in any other European country. Major investors include Siemens, Hoechst, Daimler-Benz, Degussa, Dornier, and Villeroy & Boch. Hoechst is concentrating on materials research; Siemens and Daimler-Benz have more of an applications focus (Siemens is developing an LTS generator, for example). However, there appears to be an informal agreement in effect among these compa-

[7]EUREKA was created in 1985 by 19 European countries and the Commission of the European Communities.

[8]For comparison, the combined budgets for ESPRIT II, Science, and BRITE/EURAM are about $3.8 billion over 3 years.

[9]"Two European Projects Receive Funding Approval," *Superconductor Week*, vol. 1, No. 11, Oct. 12, 1987, p. 6.

Box 5-B-Superconductive Generation Equipment and Materials (Super-GM)

Super-GM is an engineering research association that provides an excellent example of a Japanese demonstration project in action.

Goals

Super-GM is an 8-year (Japanese fiscal years 1988 to 1995), $200 million MITI "Moonlight Project" program aimed at producing a 70-MW class LTS generator scale model, and the basic design of a 200-MW class machine. It is expected to be succeeded by a program to develop a 200-MW class prototype machine. The initial 7-MW class size is considered to be small enough to facilitate construction and transport, and at the same time large enough (about one-third scale) that no unexpected scale-up problems to 200-MW class are anticipated.

History

In 1983, the Japan Electric Council looked into the feasibility of various superconductor applications in the power sector, and classified them in order of priority. Transformers and generators were the two applications that survived this review. However, the efficiency of existing transformers is already very good, and superconducting wires with low alternating current losses are difficult to make, so priority went to the generator. A consensus was reached in 1985-86 that superconducting generators were going to be important in the 21st century. Generators now in service are expected to require replacement by the year 2000, and smaller machines will be needed. The advantages of superconducting generators were considered to be improved efficiency (by 0.5 to 1.0 percent) and increased system stability. Therefore, a 2-year feasibility study was initiated by MITI.

After the feasibility study, MITI called for the formation of an industry research association and for proposals from prospective members. MITI then chose the participants and created the vertically integrated structure of Super-GM (see table 5-4),

Organization

Super-GM consists of 16 member companies and organizations. Membership consists of end users, system and subsystem manufacturers, superconductor material manufacturers, and associated organizations.

The end users will provide test and evaluation facilities for the various generator designs being pursued in parallel by the systems manufacturers. There is a loose vertical organization to the companies along competing design lines (similar to the competition between the Bechtel and Ebasco teams on the SMES program in the United States), but there is also some horizontal overlap among projects, particularly at the level of the cable/component manufacturers.

About 90 percent of Super-GM's 1988 funding of $12.2 million came from MITI's Agency for Industrial Science and Technology (its research coordinating arm) via NEDO (New Energy and Industral Technology Development Organization). Industry is responsible for the remainder, which is actually raised through rate hikes by the nine utilities.[1] The research is not centralized, although there is a central administrative facility in Osaka: each participating company sends 1 to 2 people to the facility, but conducts its own research in-house. Super-GM has about 200 researchers total.

Operation

In all, three different kinds of superconducting rotors will be prepared using NbTi conductors. Hitachi and Mitsubishi are working on two rotors that are appropriate to somewhat cheaper, smaller (circa 300 MW) generators, and the overall technology is fairly well in hand. Both companies have built and tested experimental LTS generators in the past and are planning to produce for the commercial market after the year 2000. Mitsubishi is also collaborating with Fujikura and Furukawa to develop rotors using Nb_3Sn conductors.

Toshiba is winking on a third design that would be appropriate to a larger (over 1,000 MW), more expensive system, and Toshiba is considered to be "challenging the technology" in a more aggressive fashion. Toshiba has already built and tested a 3MW prototype to verify its design studies.

There are also two competing refrigeration systems being developed, one by Mayekawa and one by Ishikawajima-Harima Heavy Industries. There is a loose coupling between these two efforts.

At the end of 1991, there will be an interim evaluation of the progress of all projects, and some winnowing of the options will take place. In 1995, choices will be made among the three main designs, and another follow-up program will be started to develop the prototype 200-MW class machine.

---

[1]Edward Overell, "Japan Embarks on $200 Million Superconducting Generator Program," *New Technology Week*, vol. 1, No. 26, Nov. 23, 1987, p. 12.

Rote of HTS

Six companies--Mitsubishi, Hitachi, Toshiba, Furukawa, Sumitomo, and Fujikura-plus the Japan Fine Ceramics Center---am pursuing seven research projects to develop HTS materials specifically for generators and other electric power applications. Super-GM managers are reluctant to predict when HTS wire will be available, saying only that it is important to stay "flexible" with regard to the insertion of HTS.

Given the fact that LTS conductor technology is so much more mature, the HTS portion of Super-GM may most accurately be viewed as a good opportunity to pursue HTS materials development and explore new applications in the electric power sector, rather than as a serious effort to incorporate HTS into the generator design. However, Super-GM managers are delighted that HTS came along when it did, and note that "HTS fever" has given a shot in the arm to the whole superconducting generator program.

SOURCE: Office of Technology Assessment, 1990.

Table 5-4-Membership of Japan's Super-GM Project

End users:
Chubu Electric Power Co., Inc.
Kansai Electric Power Co., Inc.
Tokyo Electric Power Co., Inc.
System/subsystem manufacturers:
Hitachi, Ltd.
Ishikawajima-Harima Heavy Industries Co., Ltd.
Mayekawa Mfg. Co., Ltd.
Mitsubishi Electric Corp.
Toshiba Corp.
SC material/cable/component manufacturers:
Fujikura, Ltd.
Furukawa Electric Co., Ltd.
Kobe Steel, Ltd.
Showa Electric Wire and Cable Co., Ltd.
Hitachi Cable, Ltd.
Sumitomo Electric Industries, Ltd.
Associated organizations:
Central Research Institute of the Electric Power Industry
Japan Fine Ceramics Center

SOURCE: Super-GM, 1989.

nies not to publicize industry research results in HTS.[10]

FRANCE

French Government laboratories responded quickly to the discovery of HTS. In 1987, the Government supported some 240 researchers in HTS at the Centre de l'Energie Atomique, Centre National de la Recherche Scientifique (CNRS), Centre National d'Etudes des Telecommunications, and universities, at a cost of about $28 million.

A new $1 million HTS research center ($2.4 million operating budget) has been built at Caen that involves more than 70 full-time researchers working to develop superconductor applications. The center is supported by the largest French companies, French national agencies, and several European companies outside of France.

In the summer of 1987, the Ministry of Research announced a 2-year, $8.6 million program to promote cooperative government/industry research projects in HTS, with industry providing matching funds. A 2-year follow-on program is now under discussion.

In contrast to the rapid response of the French Government, French industry has been slower to get involved. In 1987, an estimated 60 full-time and 40 part-time researchers were active in HTS. This research is concentrated in just a few companies, chiefly Compagnie Generale d'Electricity (CGE), Thomson-CSF, and Rhone-Poulenc. CGE and Rhone-Poulenc have taken a leading role in a collaboration with CNRS and French universities to improve the performance of bulk HTS materials for energy applications. Thomson-CSF is the industrial leader in France for applications in the field of superconducting electronics, and employs some 20 full-time researchers working to develop HTS electronic devices.

UNITED KINGDOM

The United Kingdom has a modest, though well-coordinated, national HTS program. National coordination is achieved through a joint committee of the Department of Trade and Industry (DTI), and the Science and Engineering Research Council (SERC), The centerpiece of the SERC HTS effort is the Interdisciplinary Research Center for Supercon-

[10]For example, Hoechst had quietly filed for patents in the United States, Japan, and West Germany for the first high-temperature bismuth-based material 2 months before it was discovered independently at Japan's National Research Institute for Metals. "Hoechst AG Filed Bismuth Patent Last November," *Superconductor Week*, vol. 2, No. 15, Apr. 18, 1988, p. 1.

ductivity at Cambridge University, funded at a guaranteed minimum of $9 million over 6 years. Complementary research projects are being funded with a separate budget of $3.5 million at other universities. DTI has made an additional $12.9 million available for joint projects with industry on a matching basis. The Ministry of Defence has a small intramural program with links to universities, bringing the U.K. annual total to about $18 million.

Industry response to HTS has been mixed. Although U.K. companies have developed a strong technology base in LTS magnets, the technology base for superconducting electronics is relatively weak (and mainly military), as have been the links between academia and industry. Active research projects under the DTI program have now started, such as the one at Harwell, where six British companies have become members of Harwell's HTS Superconductivity Club (consortium). Member companies are: Air Products, BICC, Ford of Britain, Johnson Matthey, Oxford Instruments, and BOC International. Several universities are also involved. The Club has planned a 3-year research program costing about $6.8 million, half of which will be provided by DTI. Overall, up to 100 researchers are estimated to be active in industry; key individual companies include General Electric Co. (GEC), Plessey, British Aerospace, Imperial Chemical Industries (ICI), Cooksons, and Oxford Instruments.

ITALY

Italy has had many projects in energy-related areas of LTS technology, including motor/generator sets, cables and magnet technologies for fusion, particle accelerators, and magnetohydrodynamics (MHD). Italy has a broad-based research program in HTS, including: thin-film processing, cables, magnetic storage, magnetic separation, shields, cavities, and motors.

Italian researchers quickly reproduced the YBaCuO results of the Universities of Houston and Alabama, and hosted several early international meetings on HTS. In 1989, Italy's National Research Council budgeted some $10 million to $15 million for HTS, and overall the national effort involves perhaps 200 researchers. A consortium of 27 universities has been established at the Superconductivity Applications Development Center in Genoa, including about 100 research positions. Italy's major superconductivity research centers are at the University of Genoa and the University of Salerno, near Naples.

Although little industrial research on HTS has been published, leading companies appear to be Ansaldo, Montedison, Pirelli, and Florence Industrial Metals. Ansaldo is a subcontractor on the Bechtel team designing the U.S. Superconducting Magnetic Energy Storage system and is currently developing a prototype HTS motor, jointly with the University of Genoa. Ansaldo is also a primary manufacturer of LTS magnets for the European Hadron Electron Ring Accelerator and for fusion energy projects.

THE NETHERLANDS

The Netherlands has a small-scale government program in HTS scheduled to run through 1991. It is dominated by Philips, which has enormous technical and financial clout. The government is providing about $4.5 million; another $4.5 million comes from private sources. Philips' work is coordinated with several university laboratories, especially Eindhoven [University of Technology. Consistent with Philips' main business areas, the effort is focused on superconducting electronics, with only a small part devoted to energy applications. Other Dutch institutions cooperating in the effort include the Universities of Amsterdam, Leiden, Nijmegen, and Twente, and the Netherlands Energy Research Foundation. Akzo is another Netherlands-based company active in HTS R&D.

SWEDEN

Sweden's HTS effort consists of a small government/university/industry joint program in applications research. ASEA-Brown-Boveri (ABB), Ericsson, the Swedish Defense Research Establishment, and seven Swedish universities are participating.[11] Although the Swedish program in HTS is very small (about $2.5 million over 2 years), the main player, ABB, has substantial superconductivity experience and is considered by U.S. company representatives to be a formidable competitor in potential electric power applications, i.e., generators, transmission lines, and power conditioning equipment.

[11] High-T_C Update, vol. 3, No. 5, Mar. 1, 1989, p. 9.

SOVIET UNION

It is difficult to obtain reliable estimates of the Soviet effort in HTS. The budget for the Soviet Academy of Sciences has been estimated at several hundred million rubles, plus about $40 million in hard currency for purchase of foreign equipment.[12] Estimates for the overall number of Soviet HTS researchers put the figure at about 2,000. However, these researchers often do not have access to state-of-the-art equipment that is available to U.S. researchers.

Soviet publications suggest that a broad range of HTS research is being conducted, including research in thin films for electronics and bulk materials for large-scale applications. 13 These publications also indicate a continuing commitment to LTS research, particularly in superconducting sensors and electronics, in magnetohydrodynamic (MHD) electric power production, and in fusion energy.

The Soviet Union has had a stronger program to develop MHD power plants than any other country. A 500 megawatt (MW) demonstration MHD power plant is being built at Ryasan. The Soviets are thought to have a 10-year lead in MHD, but the program has experienced some delays due to problems with winding the superconducting magnets and is in danger of being canceled.[14] The Soviet Union has also developed a 300-MW generator based on LTS, similar to U.S.-developed LTS generators.

While Western observers rate the quality of Soviet theoretical work as first-rate, its experimental work has received mixed reviews. Moreover, the level of coordination and information exchange among Soviet institutes is often poor. Many observers consider the Soviet system to be too bureaucratic to exploit HTS breakthroughs rapidly on a worldwide commercial scale, although this situation could improve as present restructuring programs move forward.

PEOPLE'S REPUBLIC OF CHINA (PRC)

Since the early 1960s, China has conducted a broad research program in LTS materials, large-scale magnets, generators, magnetic separators, and Josephson Junction devices.[15] In recent years, it has produced some of the highest performing multifilamentary NbTi conductors. *G

China has responded to the discovery of HTS with an intensive research program, and it has hosted several international meetings on HTS. The work is being conducted in a wide variety of research institutes and universities both inside the country and by visiting Chinese scientists doing joint research in foreign laboratories. China has large reserves of rare earths and is the world's largest producer of yttrium and other rare earths used in some HTS materials.

As part of an overall program to increase R&D in the People's Republic, the National Natural Science Foundation of China (a counterpart of the U.S. National Science Foundation) has planned to spend $5.5 million per year (not including salaries) on HTS research in universities, out of a $3 billion per year research budget.[17]

The scope of the Chinese work is broad, and the PRC appears to have allowed researchers to publish freely, often in English journals. Some 1,000 researchers appear to be involved in HTS. *8 Despite a geographically dispersed effort, there appears to be little duplication of research, suggesting a coordinated program.[19]

Although the Chinese work is prolific, it is judged by Western observers to be somewhat uneven in quality, due in part to a lack of first-rate equipment.[20] As yet there is little indication that an industrial effort is underway to exploit fully the results of the

[12]''Interview with Academician Yurii Ossipyan,'' *Supercurrents*, February 1988, p. 8.

[13]The DOE/Ames Laboratory publication *Hi-T_C Update* contains a bibliography of recent Soviet publications in HTS.

[14]Paul Kemezis, ''Superconducting Magnets Baffle Soviet Scientists,'' *New Technology Week*, vol. 2, No. 26, June 27, 1988, p. 1.

[15]NATO Advanced Study Institutes Series, *Superconductor Materials Science*, Simon Foner and Brian B. Schwartz (eds.), vol. B68, 1981, p. 813.

[16]TMAH Consultants, ''Lessons From Low-Temperature Superconductors,'' contractor report prepared for the Office of Technology Assessment, Nov. 18, 1988, p. 8.

[17]Edward Overell, ''China Undertaking Massive R&D Effort,'' *New Technology Week*, vol. 1, No. 28, Dec. 7, 1987, p. 1.

[18]''Zhao: 1000 Chinese Scientists Are Working on High T_C Materials,'' *Superconductor Week*, vol. 2, No. 17, May 22, 1988, p. 1.

[19]Resource Management International, Inc., ''Superconductivity in Western Europe and Other Selected Countries,'' contractor report prepared for the Office of Technology Assessment, Sept. 19, 1988.

[20]''Aggressive Chinese Program Keeps Pace With Discoveries,'' *Superconductor Week*, vol. 2, No. 17, May 2, 1989, p. 8.

research, and no indication of the future status of the government and university programs.

CONCLUSIONS

While many foreign nations have ongoing HTS research efforts, it is apparent that the Japanese will be the strongest competitors of the United States in exploiting the potential of new HTS materials, both because of their solid foundation of LTS development and because of their strong commitment of resources to HTS research. The Federal Republic of Germany will also be a strong competitor; it produces some of the best LTS materials, and West German companies have a stronger position in some emerging areas-e. g., biomagnetic devices—than do the Japanese.

While OTA finds a rough parity between the quality of U.S. and Japanese HTS R&D, there are several areas where Japan has superior capabilities, and there are noteworthy differences in Japan's approach to superconductivity. Historically, funding for LTS programs has been sustained over a long period in Japan, and commitments to new commercially oriented LTS projects (e.g., computer electronics, maglev, and electric power generators) are being made where funding has long since been cut off in the United States. The new HTS programs in Japan have drawn heavily on the expertise accumulated during these LTS programs, and are being designed to capitalize on previous LTS research results.

Based on visits to numerous Japanese laboratories involved in superconductivity, OTA finds that National laboratories like MITI's Electrotechnical Laboratory, and STA'S National Institute for Research on Inorganic Materials and National Research Institute for Metals, as well as universities in Tokyo, Osaka, and Kyoto, Sendai, and others, are conducting first-rate research in HTS and have much to offer to U.S. visiting scientists.[21] Unfortunately, the quality of this work is not fully appreciated by U.S. researchers, who tend to focus primarily on the work in Japanese industry laboratories.

Several European countries have substantial HTS programs led by the research efforts of a few large multinational companies including Philips (the Netherlands), Siemens (West Germany), Asea-Brown-Boveri (Sweden/Switzerland), GEC (United Kingdom), Thomson (France), and Ansaldo (Italy). These companies have considerable financial and technical resources as well as a strong interest in HTS, and are already formidable competitors of U.S. firms in LTS applications.

Joint research programs in HTS within the European Community are as yet quite small, but are growing. The planned unification of the European market in 1992 is likely to strengthen the European competitive position in HTS. The combined HTS R&D budgets of the EC member countries are already considerably larger than those of the United States or Japan alone.

Both the Soviet Union and the People's Republic of China have major efforts underway in HTS, but these efforts are hampered by a lack of state-of-the-art equipment and unwieldy bureaucracies. Neither country appears to have the industrial muscle to compete effective y in early commercial markets for HTS, but this assessment could change in the long term.

[21] For a discussion of specific projects, see Robert J. Gottschall, ''Basic Research in Superconductor, Ceramic, and Semiconductor Sciences at Selected Japanese Laboratories,'' U.S. Department of Energy DOE/ER-0410, February 1989.

APPENDIX 5-A—MEMBERSHIP OF JAPAN'S INTERNATIONAL SUPERCONDUCTIVITY TECHNOLOGY CENTER (JUNE 1, 1989)[1]

Anelva Corp.
• Asahi Glass Co., Ltd.
British Telecom
Central Japan Railway Co., Ltd.
• Central Research Institute of the Electric Power Industry
Chiyoda Corp.
• Chubu Electric Power Co., Inc.
• The Chugoku Electric Power Co., Inc.
The Dai-ichi Kangyo Bank, Ltd.
The Dai-Tokyo Fire& Marine Insurance Co., Ltd.
Daido Steel Co., Ltd.
The Daiwa Bank, Ltd.
Dentsu, Inc.
Du Pont Japan, Ltd.
East Japan Railway Co., Ltd.
• Electric Power Development Co., Ltd.
Electric Power Research Institute (EPRl)
Fuji Electric Co., Ltd.
Fujikin International, Inc.
• Fujikura, Ltd.
• Fujitsu, Ltd.
• Furukawa Electric Co., Ltd.
Hazama-Gumi, Ltd.
• Hitachi Cable, Ltd.
Hitachi Chemical Co., Ltd.
Hitachi Metals, Ltd.
• Hitachi, Ltd.
• The Hokkaido Electric Power Co., Inc.
• The Hokuriku Electric Power Co., Inc.
Honda Research and Development Co., Ltd.
IBM Japan, Ltd.
INES Corp.
Intermagnetics General Corp.
• Ishikawajima-Harima Heavy Industries Co., Ltd.
Japan Air Lines Co., Ltd.
Japan Fine Ceramics Center
JEOL, Ltd.
Kajima Corp.
Kandenko Co., Ltd.
• The Kansai Electric Power Co., Inc.
• Kawasaki Heavy Industries, Ltd.
• Kawasaki Steel Corp.
• Kobe Steel, Ltd.
Kumagai Gumi Co., Ltd.
• Kyocera Corp.
• Kyushu Electric Power Co., Inc.
Marubun Corp.
• Matsushita Electric Industrial Co., Ltd.
• Mayekawa Manufacturing Co., Ltd.
Mazda Motor Corp.
The Mitsubishi Bank, Ltd.
• Mitsubishi Cable Industries, Ltd.
Mitsubishi Corp.
• Mitsubishi Electric Corp.
• Mitsubishi Heavy Industries, Ltd.
• Mitsubishi Metal Corp.
Mitsui & Co., Ltd.
The Mitsui Bank, Ltd.
Mitsui Mining & Smelting Co., Ltd.
Murata Manufacturing Co., Ltd.
• NEC Corp..
• NGK Insulators, Ltd.
• NGK Spark Plug Co., Ltd
• Nippon Mining Co., Ltd.
Nippon Sanso K.K.
• Nippon Steel Corp.
Nippon Telegraph and Telephone Corp.
• Nissan Motor Co., Ltd.
Nisshin Steel Co., Ltd.
NKK Corp..
Ohbayashi Corp.
• Oki Electric Industry Co., Ltd.
Okinawa Electric Power Co., Ltd.
Osaka Gas Co., Ltd.
• Railway Technical Research Institute
Rhone-Poulenc Japan
Rinnai Co.
Rockwell International Corp.
Saibu Gas co. Ltd.
Sakaguchi Electric Heaters Co., Ltd.
• Sanyo Electric Co., Ltd.
Sato Kogyo CO., Ltd.
• Sharp Corp.
• Shikoku Electric Power Co., Inc.
Shimizu Corp.
• Showa Electric Wire & Cable Co., Ltd.
Sony Corp.
The Sumitomo Bank, Ltd.
Sumitomo Chemical Co., Ltd.
Sumitomo Corp.
• Sumitomo Electric Industries, Ltd.
Sumitomo Heavy Industries, Ltd.
• Sumitomo Metal Industries, Ltd.
Taikisha, Ltd.
Taisei Corp.
Takaoka Electric Manufacturing Co., Ltd.
Takenaka Komuten Co., Ltd.
Toda Construction Co., Ltd.
Toho Gas Co. Ltd.
• Tohoku Electric Power Co., Inc.
The Tokai Bank, Ltd.
Tokai Electric Construction Co., Ltd.
Tokyo Cryogenic Industries Co., Ltd.
• The Tokyo Electric Power Co., Inc.
Tokyo Gas Co., Ltd.
Tokyu Construction Co., Ltd.
• Toshiba Corp.
• Tosoh Corp.
• Toyota Motor Corp.
• Ube Industries, Ltd.
• Ulvac Corp.

• Indicates special supporting members
[1]International Superconductivity Technology Center, 1989.

Chapter 6

Comparison of Industrial Superconductivity R&D Efforts in the United States and Japan: An OTA Survey

CONTENTS

Figures

Tables

Chapter 6

Comparison of Industrial Superconductivity R&D Efforts in the United States and Japan: An OTA Survey

INTRODUCTION

In late 1988 and early 1989, the Office of Technology Assessment (OTA) conducted a survey of U.S. industrial superconductivity R&D in cooperation with the National Science Foundation (NSF). A parallel survey of Japanese industrial superconductivity R&D was conducted jointly with the International Superconductivity Technology Center (ISTEC), a consortium of Japanese firms organized under the auspices of the Ministry of International Trade and Industry.

In the United States, OTA/NSF attempted to capture all companies involved in superconductivity R&D. Surveys were received from 360 U.S. companies, of which 217 reported either in-house or collaborative superconductivity R&D.[1,2] OTA estimates that the research at these companies represents about 90 percent of the U.S. industrial effort.[3] In Japan, OTA/ISTEC attempted to capture only the major superconductivity R&D-performing companies.[4] Surveys were received from 92 Japanese companies, of which 71 reported either in-house or collaborative superconductivity R&D. OTA and ISTEC estimate that about 80 percent of Japanese industrial research was captured by the survey. Unless specifically indicated, the data reported in this chapter are not adjusted for these different capture rates. For a more accurate comparison of funding levels and numbers of researchers, it is necessary to increase the U.S. data by about 11 percent and the Japanese data by about 25 percent.

R&D spending figures quoted throughout this chapter represent only the companies' own funds unless otherwise specified. Government funding for research performed by industry is considered separately, This highlights what in OTA's view is the best measure of a company's commitment to superconductivity —the investment of its own cash.

For simplicity, this chapter focuses primarily on HTS survey results. Additional survey data relating to LTS are provided in appendix 6-A. The OTA survey form used in the United States is included as appendix 6-B (a Japanese translation with slight modifications was sent to the Japanese companies).

OVERALL TOTALS: UNITED STATES AND JAPAN

Figure 6-1 shows OTA's estimate of the total industry effort in the United States and Japan, measured in both millions of dollars[5] and numbers of full-time researchers.[6] These data *are adjusted* according to OTA's estimate of the efforts not captured in each country. In 1988, Japanese industrial spending on in-house HTS R&D is estimated to be about $107 million—some 50 percent greater than the estimated total of $74 million in the United States.[7,8] Japanese firms also spent about $44

[1]Nine of the 217 U.S.-based companies are 50 percent or more foreign-owned, but the research they reported took place in U.S. facilities.

[2]Some companies chose to answer only selected questions. The response rate on the data presented here was over 90 percent unless otherwise indicated.

[3]This estimate is based on those companies known by OTA to have superconductivity R&D efforts that did not return a survey.

[4]Because the survey coverage in the United States was more comprehensive, the U.S. sample contains a long "tail" of small efforts that were not captured in the truncated Japanese sample (see figure 6-5). Thus, some caution is appropriate in comparing U.S. and Japanese survey results.

[5]Internal funding only; Japanese companies were asked for funding totals in yen; conversions used were: 144.6 yen per dollar for 1987 and 128.2 for 1988.

[6]Researchers spending more than 50 percent of their time on superconductivity. No distinction is made here between industry researchers paid with government funds and those paid with internal funds. Thus, the number of researchers reflects the total R&D performed in industry, regardless of funding source.

[7]Some Japanese companies reported low ratios of funding to research staff (less than $50,000 per researcher). This may mean that actual Japanese spending totals are even higher.

[8]In 1988, Japanese firms reported spending an additional $29 million for HTS collaborative research outside their own firms, e.g., to establish the ISTEC research center, which will conduct research primarily on HTS. By comparison, U.S. firms surveyed spent an additional $8 million on HTS collaborative R&D performed outside their own firms.

million on in-house LTS R&D compared with $16 million by U.S. firms.[9]

These differences are also reflected in the R&D staff totals in the two countries. As of October 1988, OTA estimates that some 440 U.S. industry researchers were spending greater than 50 percent of their time on HTS, compared with some 710 in Japan.[10]

Figure 6-2 shows the increase in industry R&D efforts (as captured in the survey) over time. When corrected for changes in yen/dollar exchange rates,[11] HTS funding grew by about 40 percent and LTS funding by about 20 percent in both countries from 1987 to 1988. The corresponding R&D staff data, taken at three points in time, suggest that the industrial effort began to level off in both countries during 1988. This impression was confirmed by spokesmen for several key companies interviewed by OTA.

Figure 6-3 gives a breakdown of funding sources for HTS research performed by industry in the United States and Japan. In the aggregate, companies in both countries spend more of their own internal funds than they receive from outside sources, by at least 4 to 1.[12] Compared with Japan, the U.S. Government is funding about twice as much of the I-ITS R&D performed by industry .13

Comparable data for LTS are shown in figure 6-4. In the United States, 56 percent of the LTS industrial research was funded by the Federal Government, while in Japan, only 9 percent was funded by the Japanese Government. This demonstrates the far greater commitment of Japanese companies to LTS.

CHARACTERIZING THE SURVEYED COMPANIES

In both countries, HTS R&D is heavily concentrated in a few firms. As shown in figure 6-5, the top five U.S. firms put up 55 percent of the R&D dollars, while in Japan the top five firms paid for 42 percent. The major Japanese companies tended to have more HTS researched; 9 companies had 20 or more full-time researchers (comprising 60 percent of all full-time Japanese researchers captured), compared with just 3 companies with 20 or more in the United States. In the United States, one-quarter of all full-time researchers work in companies employing three or fewer I-ITS research staff.

Company Size

With few exceptions, the big HTS spenders are large companies, but not all large companies in the survey have big HTS programs. In the United States, 73 percent of all internal HTS funding came from 61 companies with sales of over $1 billion. But 36 out of 61 were investing less than $300,000 in HTS; i.e., less than the cost of 2 full-time researchers.[14]

Small companies are sometimes viewed as the ''secret weapon' of U.S. competitiveness. Of the 217 U.S. companies captured in the OTA survey, 121 are small companies;[15] of these, 53 are startups in the last 5 years. Two of these startups have internal HTS R&D programs of over $1 million per year. Small companies as a group put up only 9 percent of total industry funding for HTS, but receive 44 percent of all Federal funding. (In Japan, just 10 large firms receive 100 percent of government funding.) Interestingly, small companies in the United States account for a much larger fraction of LTS R&D—57 percent—a reflection of the reluctance of most large U.S. companies to spend their own money on LTS R&D. No small Japanese

[9]The U.S. Government provides far more funding to U.S. companies for LTS R&D than the Japanese Government provides to its companies. Total industrial LTS R&D *performed* is estimated to be $48 million in Japan and about $40 million in the United States in 1988.

[10]Interestingly, the number of researchers spending at least a *part* of their time on HTS (when adjusted for efforts not captured in the survey) was larger in the United States (about 1,170) than in Japan (about 1,070). This suggests that a large number of firms in the United States continue to monitor developments, but are reluctant to make full-time staff commitments.

[11]The stronger yen in 1988 exaggerates the R&D growth in Japan, measured in dollars, cf. footnote 5.

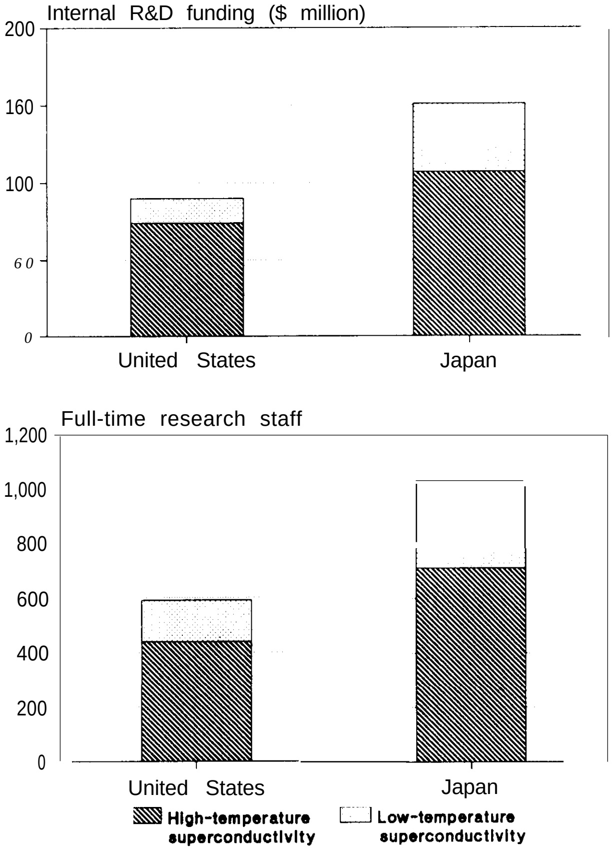
[12]In the United States, Federal agencies reported budgeting about $24 million for industry HTS R&D in 1988, whereas the companies captured in the survey reported receiving only about $12 million. This discrepancy may have been due to a problem of timing; funding may have been obligated by the agencies in 1988 that had not yet been spent at the time of the survey.

[13]The U.S. sample included 17 companies classified as ''dependent'' efforts; that is, they spend none of their own funds, but receive R&D funding from outside sources. These dependent efforts account for 7 percent of the captured government funds. There were no dependent efforts captured in Japan.

[14]On average, companies in the U.S. database spend about $170,000 per full-time-equivalent HTS researcher, compared with about $150,000 in Japan.

[15]Defined here as those companies having 500 or fewer employees.

Figure 6-l-Comparison of Industrial Superconductivity Research Efforts in the United States and Japan, 1988

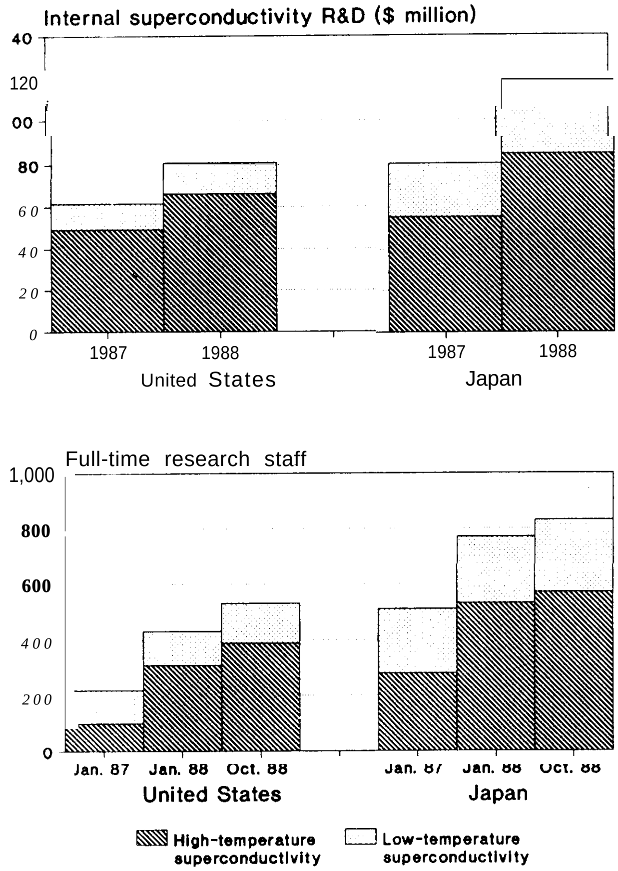


n 1988, U.S. industry internal funding for HTS was about $74 million, with 440 full-time researchers, compared with $107 million and 710 full-time researchers in Japan.

NOTE: The data in this figure are adjusted to include OTA's estimate of research efforts not captured by this survey.

SOURCE: Office of Technology Assessment, 1990.

Figure 6-2—Increase in Industrial Superconductivity in the United States and Japan, 1987-1988



Industry funding and research staff dedicated to HTS grew substantially from January 1987 to January 1988 in both the United States and Japan. The relatively small increase in research staff from January 1988 to October 1988 suggests that this growth was leveling off in both countries.

SOURCE: Office of Technology Assessment, 1990.

companies were captured in the survey database, reflecting the different sampling method used in Japan (see above).

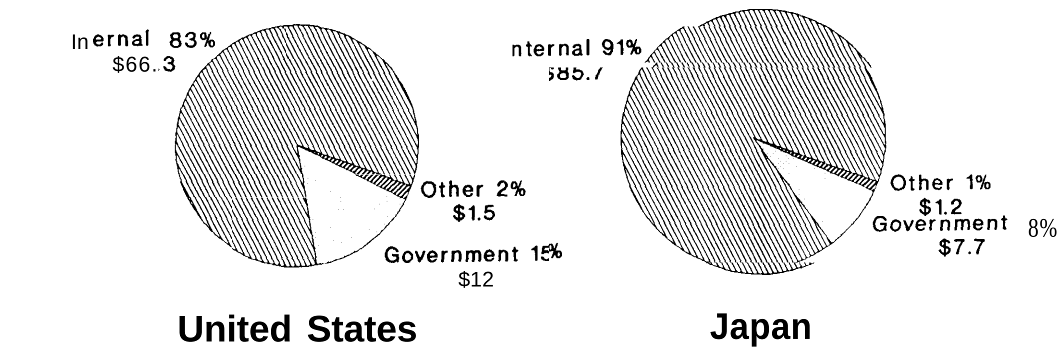
As a group, small companies spent more on applied research and development work than on basic research. (Basic research was heavily concentrated in a few large firms.) Small companies tended to be more optimistic, predicting their first HTS product an average of 3 years earlier than large companies.

Main Business Areas

The main business areas of companies involved in HTS R&Din the United States and Japan are shown in figure 6-6. In both countries, the largest category is ''electronics, ' defined here to include companies in computers and telecommunications.[16] The second largest category could be called "advanced materials. In the United States, companies in the advanced materials category are primarily chemical companies, while in Japan they are primarily metals

[16]In the United States, those companies describing their main business areas as ''electronics'' or ''electrical equipment'' tend to be different companies, whereas in Japan they are the same. This difference is reflected in figure 6-6, and emphasizes the greater tendency toward horizontal integration in Japan. Since electronics applications will generally require HTS thin films, and electrical equipment will generally require bulk materials, (e.g., wires), it follows that the fraction of companies conducting both thin film and bulk R&D is higher in Japan; cf. figure 6-8.

Figure 6-3-Funding Sources for HTS Research Performed by Industry in the United States and Japan ($ million)

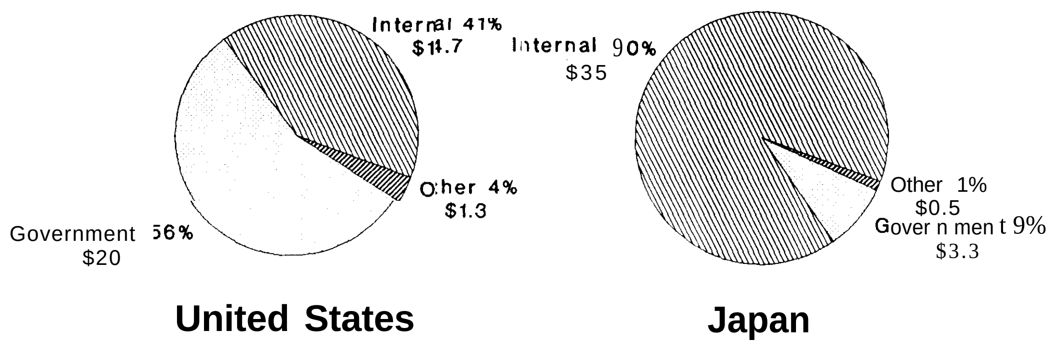


In both countries, the bulk of HTS R&D performed by companies is supported by internal funds. The U.S. Government supports nearly twice as much industry HTS R&D as does the Japanese Government.

NOTE: "Government" funding refers to national government funding only. "Internal" funding refers to companies' own funds; "Other" funding includes State and local government funding, and funding from other companies.

SOURCE: Office of Technology Assessment, 1990.

Figure 64-Funding Sources for LTS Research Performed by Industry in the United States and Japan ($ million)



U.S. and Japanese industry perform about the same amount of LTS R&D. But in the United States, funding comes predominantly from the Federal Government, while in Japan, it comes from internal sources.

NOTE: "Government" funding refers to national government funding only. "Internal" funding refers to companies' own funds; "Other" funding includes State and local government funding, and funding from other companies.

SOURCE: Office of Technology Assessment, 1990.

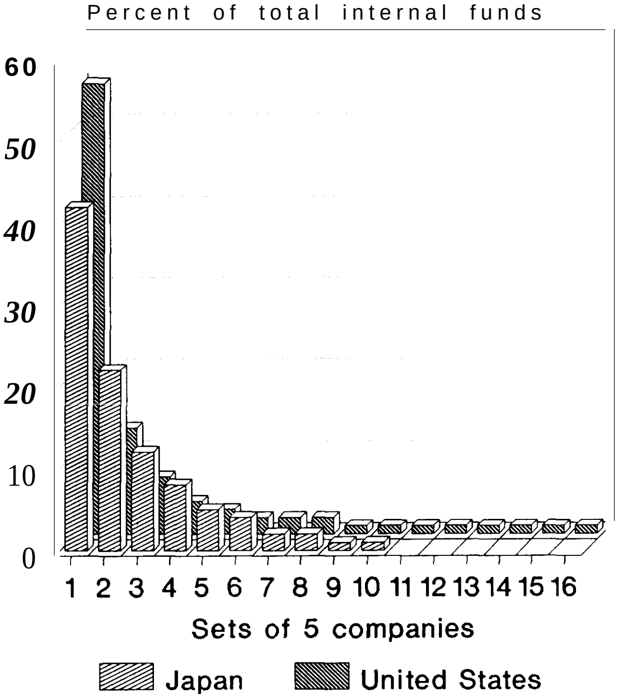
companies. In the United States, aircraft/defense companies invest much more than their counterparts in Japan. Conversely, Japanese electric utilities invest far more than their U.S. counterparts.

Reliance on Defense Markets

In Japan, the companies receiving government funding for HTS are oriented toward commercial markets. Only one company in the Japanese sample depended on the Defense Agency for over one-quarter of its sales, and it did not receive any government HTS funds. In the United States, 63 firms active in HTS were dependent on the Department of Defense for more than one-quarter of their sales. Thirty companies in this group received 58 percent of all Federal HTS funds.[17] Virtually all of the Federal HTS funding for industry in the United States comes from the Department of Defense, while the primary government funding source in Japan is the Ministry of International Trade and Industry (MITI).

[17] An additional seven U.S. companies, which receive 21 percent of all Federal funding, declined to answer the question on defense markets.

Figure 6-5-Distribution of Industry HTS Research in the United States and Japan



Each block represents total internal R&D funding of five companies, ranked according to size of R&D program. In both countries, the bulk of HTS research is concentrated in a few companies. In the left-most block, the five companies with the highest internal HTS R&D expenditures account for around 55 percent of all internal industrial HTS R&D in the United States, and around 42 percent in Japan.

SOURCE: Office of Technology Assessment, 1990.

Type of Research

Companies were asked to break down their superconductivity R&D (HTS and LTS) into three categories: basic, applied, and development.[18] The results, shown in figure 6-7, do not support the contention that Japanese firms simply appropriate the basic research of the United States and concentrate on developing applications. On the contrary, Japanese companies reported spending a larger fraction of their budgets on "basic" research-as defined by OTA—than did U.S. companies (by a margin of 37 percent to 28 percent). This suggests that much of the basic research undertaken in U.S. universities or national laboratories is performed in Japan by companies.

Companies were also asked to characterize whether their HTS research is directed toward thin films or bulk forms. The results are shown in figure 6-8. In both countries, the majority of companies are funding research on thin films. This is consistent with the predominance in both countries of companies with main business areas related to electronics—the field in which thin films are likely to find their broadest applications. But in Japan the fraction of companies with research in both thin film and bulk materials was considerably greater; U.S. companies were more likely to specialize in one or the other. *9

Collaborations

Most U.S. companies performing superconductivity R&D are involved in collaborations with at least one outside organization. Of the 217 companies supporting superconductivity R&D, 183 (84 percent) are either engaged in or plan to engage in some type of collaboration outside their own firm. Similarly, 96 percent of the Japanese firms reported some collaborative R&D.

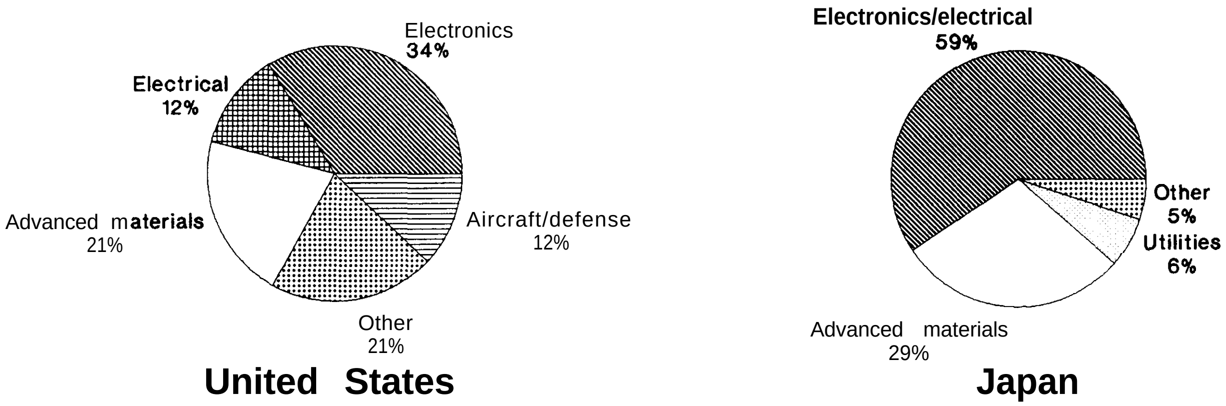
The relative popularity of various collaborative partners in 1988 is shown in figure 6-9. Most of the Japanese companies surveyed are members of the MITI-sponsored consortium ISTEC; thus, 91 percent reported membership in an industry consortium, compared with just 22 percent in the United States. *(J Apart from this, the collaborative behavior in the two countries is similar. Universities were more popular partners than national laboratories in both countries, although Japanese firms were somewhat more likely to be collaborating with a national laboratory than U.S. firms. The popularity of collaborating with other individual firms was about the same in the two samples. Japanese firms moved more quickly than U.S. firms to establish collaborative arrangements, as evidenced by the comparatively large number of U.S. firms in the "plans to collaborate" category as of late 1988.

[18] Companies were asked to check various categories of research that OTA grouped under these headings; see App. 6-B for details.

[19] To some extent, this result is exaggerated by the different sampling methods used in the two countries. Presumably, the Japanese companies with small programs (not captured in the sample) would have been more specialized. But the overall trend toward greater overlap between thin film and bulk research in Japan is also seen when only the large programs are compared (see the section on *Major HTS Programs* below).

[20] Given that ISTEC—itself a consortium—selected the Japanese companies to be surveyed, the results are skewed toward higher rates of collaboration than would be true of the general population of Japanese companies. Nevertheless, almost all major Japanese players in HTS are members of ISTEC.

Figure 6-6-Main Businsss Areas of Companies Performing HTS R&D in the United States and Japan



In both countries, companies with the largest efforts tended to have main business areas in electronics or electrical equipment. (These were distinct categories in the United States, but were inseparable in Japan.) In the United States, aircraft/defense companies play a significant role, whereas in Japan the electric utilities are more heavily involved.

SOURCE: Office of Technology Assessment, 1990.

In 1988, U.S. companies spent about $8 million on collaborative HTS R&D performed outside of the company, compared with a total of $29 million in Japan. However, these dollar figures may not accurately reflect the actual amount of collaboration going on. In both countries, companies often engage in informal collaborative relationships that may involve interchange of personnel or samples, but do not require exchange of funds. In fact, 67 U.S. companies and 14 Japanese companies report ongoing collaborations, but no outside expenditures.

BREAKDOWN OF HTS R&D FUNDING BY SIZE OF RESEARCH PROGRAM

To compare the structure of the U.S. and Japanese superconductivity industries more effectively, company programs were classified into three categories according to their level of internal funding. This breakdown for the United States and Japan is summarized in tables 6-1 and 6-2, respectively (comparable data for LTS are given in appendix 6-A). "Major" HTS R&D efforts are those with $1 million or more of internal funding. ''Midrange" efforts are those in the $100,000 to $1 million range. "Minor" efforts are those less than $100,000 per year.

Although these categories are somewhat arbitrary, OTA thinks they convey a qualitative implication for future competitiveness: companies with sustained annual R&D investments of $1 million or more can be expected to be major players in HTS; companies in the $100,000 to $1 million range are considered serious; and companies investing less than $100,000 are basically "watchers."

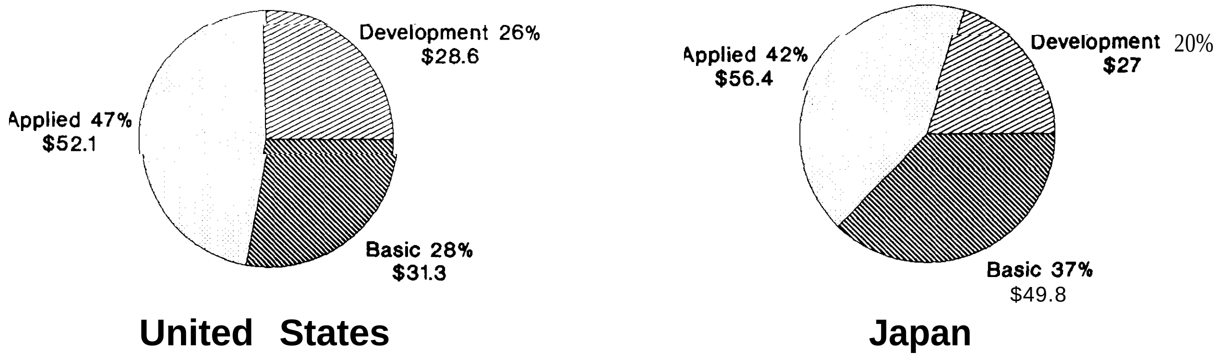
Major HTS Programs

Companies with internal HTS R&D programs of at least $1 million are likely to be in the competitive forefront in superconductivity in the 1990s. In both countries, these companies account for 75 percent or more of the total internal funding for HTS. There are 14 such companies captured in the United States, compared with 20 in Japan.

In the United States, this group of large HTS spenders included 10 large companies (sales over $1 billion), 2 medium-sized companies, and 2 small startup companies. Their dependence on Federal funding varied widely. Of the 14, 7 reported receiving no Federal funds; the other 7 received 42 percent of all Federal funds--on average $714,000 per company—but this was small in comparison with the average amount that the company was putting up: $3.5 million.

In Japan, all 20 of the big HTS spenders had annual sales of over $1 billion. Government funding was concentrated in this group. Although 13 of 20 companies did not report receiving any government

Figure 6-7--Characterization of Industry Superconductivity Research in the United States and Japan ($

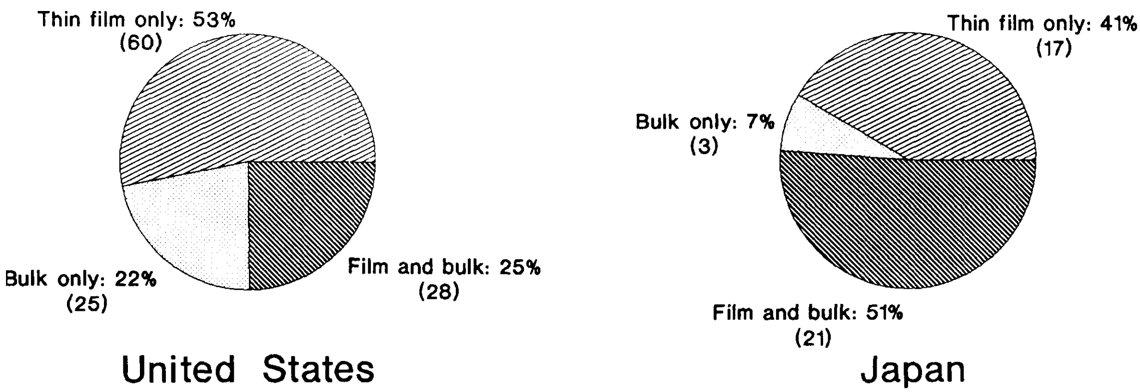


Japanese companies reported performing more “basic” superconductivity research than did U.S. companies,

NOTE: This data includes total HTS and LTS R&D performed.

SOURCE: Office of Technology Assessment, 1990.

Figure 6-8-HTS Thin Film and Bulk Processing R&Din the United States and Japan (number of compa



In both countries, the majority of companies are performing research on processing HTS thin films. However, in Japan, companies are more likely to be conducting both thin film and bulk processing R&D.

NOTE: Each pie represents the set of all companies with some thin film or bulk processing R&D.

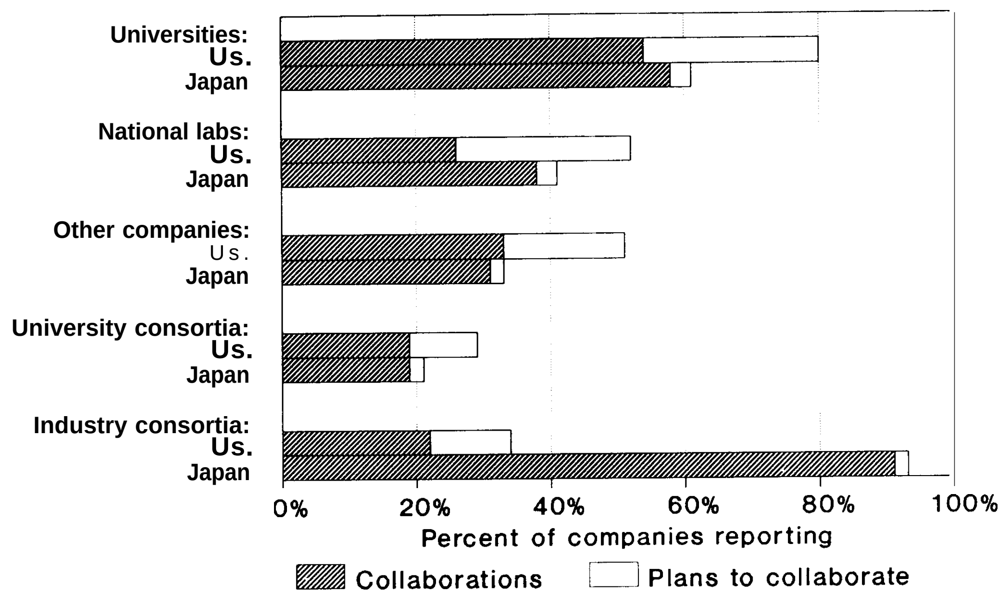
SOURCE: Office of Technology Assessment, 1990.

support for HTS, the other 7 companies received 87 percent of all government funding--on average $953,000 per company. These companies were also investing an average of $3.6 million of their own funds.

Among these big spenders, the Japanese companies were more likely to have broader superconductivity programs—both in terms of types of materials being developed, and the scope of research. For instance, although in both countries a majority of these companies employ research staff who have had experience working in LTS, 11 of 20 Japanese companies actually have ongoing LTS programs of over $100,000 per year, compared with just 4 of 14 in the United States. As discussed in chapter 2, continuing experience with LTS could have valuable carryover to the commercialization of HTS.

While HTS thin films are the most popular research area in both countries, 16 of the 20 Japanese companies also had R&D programs on bulk materials, compared with just 6 of 14 in the United States. This overlap could be important because the cross-fertilization of these two types of research within the same firm could speed the commercialization of both. The greater breadth of the Japanese superconductivity programs reflects the greater horizontal

Figure 6-9--Comparison of Industry Collaborations in HTS R&D in the United States and Japan



As of late 1988, industry collaboration behavior in HTS research was similar in the two countries, except that most Japanese companies surveyed were members of the industrial consortium ISTEC.

SOURCE: Office of Technology Assessment, 1990.

integration of the Japanese firms compared with Us. firms.

Midrange HTS Programs

In 1988,58 U.S. companies spent $100,000 to $1 million on HTS R&D (averaging $245,000-less than the equivalent of two full-time researchers). This compared with 29 companies in this range spending an average of $434,000 in Japan. These companies are maintaining a nucleus of HTS expertise that presumably could be quickly expanded if promising commercial applications are identified. In the United States, the midrange companies accounted for 21 percent of the total HTS R&D, and received 29 percent of Federal funds. In Japan, they accounted for 15 percent of the R&D total, and received 13 percent of government funding.

Small HTS Programs

One hundred and fifteen U.S. companies performing HTS R&D-over half of the sample-have small efforts; i.e., spent less than $100,000 on HTS in 1988 (an average of $23,000 each). These companies can be considered “watchers”; i.e., long-term competitiveness in HTS cannot be maintained at such small expenditure levels. The 115 U.S. small efforts together account for only 4 percent of the total internal company funds, but receive about 29 percent of all Federal funds.[21]

Owing to the different sampling method used in Japan, many small efforts were not captured in the Japanese sample.[22] The 10 small Japanese programs captured spend an average of $40,000 each and none receives government funds. These 10 companies account for less than 1 percent of captured internal funds invested in HTS by Japanese firms.

INDUSTRY ATTITUDES

Companies were asked to project the year in which they expected to bring their first HTS-related product to market, and to specify a category for that

[21] Seventeen companies in the sample spend no internal funds for HTS—they are dependent on other sources for all of their R&D dollars. Twelve of these companies received a total of $830,000 from the Federal Government in 1988.

[22] In a separate survey, Nikkei Superconductor identified some 56 Japanese companies with efforts less than $80,000. See S. Tajima, ''HTS R&D Results in 1988 and Prospects for Applications,'' a paper presented at the New Superconducting Materials Forum's 7th Symposium on Superconductivity, Tokyo, Japan, Dec. 8, 1988.

Table 6-1-U.S. Industry HTS Programs, 1988 (grouped by the amount of company's own funds)

	Major efforts ($1 M or more)	Midrange ($1OOK-$1M)	Small[a] (<$1OOK)	Total, all companies
Number of companies	14	58	115	187
Number of R&D staff	446	299	256	1,001[b]
(>50% time)	203	104	54	361
R&D totals	$54.6 M	$18.4 M	$6.8 M	$79.8 M
Own $	$49.6 M	$14.2 M	$2.7 M	$66.3 M
Federal $	$5.0 M	$3.4 M	$3.5 M	$11.9 M
Other $	$0.0 M	$0.8 M	$0.6 M	$1.4 M

[a]A total of 17 companies have no internal funds for HTS and are dependent on other sources for all of their HTS R&D dollars. Twelve of these companies received a total of $830,000 from the Federal Government.
[b]An additional 9 companies did not report funds, but reported a total of 59 individual researchers, of which 32 spent 50 percent or more of their time on HTS research.
[c]Other sources of funds include State and local governments, other U.S. companies, etc.

SOURCE: Office of Technology Assessment, 1990.

Table 6-2--Japaneae Industry HTS Programs, 1988 (grouped by the amount of company's own funds)

	Major efforts ($1 M or more)[a]	Midrange ($1OOK-$1M)	Small (<$1OOK)	Total, all companies
Number of companies	20	29	10	59
Number of R&D staff	558	235	42	835[b]
(>50% time)	419	130	6	555
R&D totals	$80.5 M	$13.6 M	$0.4 M	$94.6 M
Own $	$72.7 M	$12.6 M	$0.4 M	$85.7 M
Federal $	$6.7 M	$ 1.0 M	$0.0 M	$7.7 M
Other $[c]	$ 1.1 M	$0.0 M	$0.0 M	$ 1.2 M

[a]Converted from yen values; yen conversion used was 128.2 for 1988.
[b]An additional 7 companies did not report funds, but reported a total of 24 individual researchers, of which 10 spent 50 percent or more of their time on HTS research.
[c]Other sources of funds include local governments, other companies, etc.

SOURCE: Office of Technology Assessment, 1990.

product.[23] The results show that the anticipated relative timing of the products is similar in both countries: e.g., powders, wires, fabrication equipment, and small-scale electronics-related products were expected before large-scale applications such as high-field magnets or electric power equipment. But in Japan, these products were anticipated an average of 8 years later than in the United States.[24] The average first year-to-market in the United States is 1992; in Japan, 2000.

There are several possible interpretations of this result. At first glance, it would appear that U.S. companies are more optimistic about early introduction of HTS products. Actually, though, this may simply reflect the short-term pressures on U.S. managers to produce a product within 3 to 5 years. The willingness of Japanese companies to spend so much on R&D even though commercial products may be at least 10 years away suggests a strong commitment to HTS technology. The continuing commitment of Japanese companies to commercial LTS technology—largely abandoned by U.S. companies —reinforces this conclusion, and raises the troubling question of whether U.S. firms are prepared to compete vigorously in HTS over the long term.

Some Company Comments

In addition to the surveys in the United States and Japan, OTA conducted a number of interviews with industry representatives in the United States on attitudes toward HTS development, Federal Government R&D policy, multisector collaborations, and a

23Only 78 percent of U.S. respondents and 69 percent of Japanese respondents specified a date for their first expected product incorporating HTS materials.

24This generalization held across the board for each product category.

number of related issues.[25] Many survey respondents in both countries also volunteered opinions on subjects covered in the survey questionnaire. Several of these comments and interviews raise doubts about the level of commitment on the part of U.S. companies to long-term R&D programs.

The views of several respondents were summed up by one researcher who cited a need to "show results within 3 to 5 years-although 'corporate' may claim that they are more patient than that. The average year-to-market for a U.S. company's first HTS-based product—1992—may simply be a reflection of this time horizon: it falls 4 to 5 years after the start of industrial HTS R&D programs. One LTS systems supplier states that his company "cannot afford to spend 5 years and $10 million without some assurance of a nearer term pay back." Another industry representative looks for as short a payback as we can get. " Said one respondent about the erosion of U.S. technological leadership in LTS electronics: "we're not just uncompetitive; we're not competing at all. "

One often-cited source of competitive strength for the United States is the small company. Thought to be more innovative and enthusiastic, small companies sometimes lack the capital and broad resource base of larger companies. U.S. small businesses captured in the survey predict an average year-to-market for their first HTS products about 3 years earlier than larger firms (1990, compared with 1993). This may be a reflection of the small company's enthusiasm and capacity for innovation. Alternatively, it may indicate greater market pressures (particularly from its initial investors) to produce quick results.[26] If progress in improving the properties of HTS materials continues to be incremental, sources of private capital for these small companies could dry up, leaving them in a poor position to compete with larger, better-financed Japanese companies.

U.S. companies are using small-scale products—e.g., powders or simple SQUIDS based on thin films-as a safe way of gaining experience with HTS. Small devices and materials are relatively low value-added products, but they are less risky. These companies plan to approach more challenging but higher-value-added products--e.g., computers—at a later point. Ultimately, though, the profits to be made in superconducting systems may be 10 times higher than the profits in the materials business alone. As one LTS materials supplier noted: "the LTS materials business is $10-30 million per year, compared with the total superconductivity products business of around $300 million per year. "

The discovery of HTS has caused are-evaluation of the feasibility of various LTS applications, precipitating a number of new paper studies on maglev transportation, electric power applications, etc. One HTS researcher cited a "much higher level of enthusiasm for LTS as a result of the HTS activity—and a higher level of comfort in working at low temperatures. ' And the amount of LTS R&D performed by U.S. industry did increase by 71 percent from 1987 to 1988. But only 15 percent of this increase came out of internal funds; 82 percent came from Federal sources such as the Department of Energy's Superconducting Super Collider and DoD's Superconducting Magnetic Energy Storage programs.

Despite the spotlight on superconductivity, industry funding for LTS R&D remains low compared to that for HTS R&D (see figure 6-l). On the other hand, HTS has not caused companies to be more pessimistic about the prospects for LTS, either. Industry interviewees feel that "LTS applications are real" and "realistically will never be replaced" by HTS technologies. OTA reached a similar conclusion in its evaluation of superconductivity applications in chapter 3.

[25]Technology Management Associates, ''Industrial Viewpoints on High-Temperature Superconductivity,'' contractor report prepared for the Office of Technology Assessment, Oct. 28, 1988.

[26]It may also indicate a certain naivete. Typically, companies with long experience grappling with the challenges of bringing LTS materials to market projected a later first year-to-market for HTS, compared with small HTS startup companies without this experience.

APPENDIX 6-A: A BREAKDOWN OF LTS RESEARCH IN THE UNITED STATES AND JAPAN

Table 6-3-U.S. Industry LTS Programs, 1988 (grouped by the amount of company's own funds)

	Major efforts ($1 M or more)	Midrange ($100K-$1 M)	Small[a] (<$1OOK)	Total, all companies
Number of companies	4	17	34	55
Number of R&D staff	63	114	67	244[b]
(>50% time)	23	75	17	115
R&D $ totals	$10.1 M	$21.3 M	$4.6 M	$36.0 M
Own $	$8.0 M	$6.2 M	**$0.5** M	$14.7 M
Federal $	$ 1.8 M	$14.3 M	$3.9 M	$20.0 M
Other $[c]	$0.3 M	$0.8 M	$0.2 M	$ 1.3 M

[a]A total of 11 companies have no internal funds for HTS and are dependent on other sources for all of their HTS R&D dollars. These 11 companies receive $3.5 M from the Federal Government.

[b]An additional 11 companies did not report funds, but reported a total of 40 individual researchers, of which 21 spent 50 percent or more of their time on LTS research.

[c]Other sources of funds include State and local governments, other U.S. companies, etc.

SOURCE: Office of Technology Assessment, 1990.

Table 6-4--Japanese Industry LTS Programs, 1988 (grouped by the amount of company's own funds)

	Major efforts ($1 M or more)[a]	Midrange ($1OOK-$1M)	Small (<$1OOK)	Total, all companies
Number of companies	12	7	9	28
Number of R&D staff	272	51	28	351[b]
(>50% time)	190	32	14	236
R&D $ totals	$33.4 M	$4.9 M	$0.3 M	$38.6 M
Own $	$29.9 M	$4.7 M	$0.3 M	$34.9 M
Federal $, ...	$3.3 M	$0.0 M	$0.0 M	$3.3 M
Other $[c]	0.2 M	$0.2 M	$0.0 M	$0.4 M

[a]Converted from yen values; yen conversion used was 128.2 for 1988.

[b]An additional 6 companies did not report funds, but reported a total of 54 individual researchers, of which 21 spent 50 percent or more of their time on LTS research.

[c]Other sources of funds include State and local governments, other companies, etc.

SOURCE: Office of Technology Assessment, 1990.

APPENDIX 6-B: OTA R&D SURVEY

United States Congress
Office of Technology Assessment

SURVEY OF SUPERCONDUCTIVITY
RESEARCH, DEVELOPMENT AND APPLICATION IN INDUSTRY

Congress has asked for an assessment of the commercial prospects of the new high temperature superconductors. We at OTA are convinced of the importance of an industrial perspective commercializatlon issues. The fallowing questionnaire was designed to capture the views of both U.S. and Japanese Industry on this Interesting new technology. Please help us to inform the Congress of the state of industrial superconductor research, and of potential problem areas in the commercialization of these materials, by participating in this survey.

The results of the American and Japanese surveys will be presented in an upcoming OTA assessment on high temperature superconductivity scheduled for release in mid-1989. You will receive complimentary copies of this assessment as soon as it is available for release. We hope that you will use this survey as an opportunity to express your views to the Congress and we thank you in advance for participating.

ALL INFORMATION PROVIDED FOR THIS SURVEY WILL REMAIN CONFIDENTIAL AND WILL NOT BE DISCLOSED TO THE PUBLIC EXCEPT IN AN AGGREGATED FORM THAT DOES NOT PERMIT IDENTIFICATION OF THE RESPONDENT OR THE RESPONDENT'S ORGANIZATION. The Office of . Technology Assessment is exempt from compliance with Freedom of Information Act requests. OTA Is not seeking proprietary data from any participants. Respondent information will be shared with the National Science Foundation, with the understanding that NSF will abide by the stated conditions of confidentiality. Richard E. Morrison [NSF (202) 634425] may contact you regarding NSF's participation In this survey.

If you have any questlons about this survey, contact Laurie Gavrin at (202) 228-6283 or Jane Alexander at (202) 228-6274. Please return the completed survey to:

Superconductivity Assessment
Office of Technology Assessment
Energy and Materials Program
U.S. Congress
Washington, D.C. 20510-8025

Company Name and Address:

Name of Respondent and Title:

Telephone:
( ) ____________________ Ext. __________

Reporting year (check ONE only - if possible, please use calendar year)

___ **Calendar year OR**

___ **Fiscal year beginning ____________________, ending ____________________**
Month day **Month day**

September 30, 1988

If you feel that this questionnaire does not apply to your company (e.g., your company does not conduct any business or R&D activity related to superconductivity and is not contemplating any), please indicate this below and mail the questionnaire back to OTA Fed free to answer any questions which do apply to your company. Your participation will still remain confidential.

_____ My organization is not conducting or planning to conduct any business or R&D activity in superconductivity or superconductivity-related products

OTA would still be interested in knowing why your organization is interested in superconductivity, however limited this interest may be, and would appreciate your description below of the reasons behind your interest.

INTRODUCTION

This survey covers both traditional, low temperature superconductivity (LTS) R&D as well as the newer high temperature superconductivity (HTS) R&D activities. Except as otherwise noted, data for HTS R&D and for LTS R&D are to be reported separately.

if you fed that you cannot complete this questionnaire, please forward it to the person within your company who would be better able to complete it.

if the answer to a given question is zero, indicate by writing "zero" or "0"; do not use a dash and do not leave blank. if you don't wish to answer the question for any reason, please indicate that you have seen the question by marking the question in some obvious fashion, such as putting a slash mark across it. Do not leave any question unmarked.

Please read the "Definitions" page found at the back of this survey, and refer to it if you are unsure about a question.

For questions on value of sales and number of employees, please report only the data for your company and its dependent divisions; do not include your parent company, or any independent divisions or subsidiaries. if your company has foreign-based operations, please report availabie or estimated data for U.S.-based operations only.

Personnel data should be reported as of January of your reporting year.

When reporting total sales, if your company performs contract research or other services, report sales of research and other services as well as components, systems, and other commodities.

Please report R&D which is performed in-house separately from R&D which is contracted out to a university, Federal laboratory, industry association or consortium, or another company.

All requested financial data should be provided in thousands of dollars. An expenditure of $25,643 should be rounded to the nearest thousand dollars and be reported as $26K if exact data are not available, reasonable estimates are welcome. To the extent possible, ail data should be reported by calendar year.

A. DESCRIPTION OF COMPANY

1. Provide a description of your organization and its main business areas by checking any and all of the fallowing categories that apply.

____Aircraft/aerospace
____Ceramics/glass
____chemical
____Computers/data processing
____Contract research
____Cyogenics
____Defense
____Electrical/power systems
____Electronics
____Energy
____Fabrication equipment
____Industrial manufacturing
____Industry association
____Land/sea transportation
____Magnets
____Medical
____Metals
____Petroleum
____Public utility
____Research consortium
____Scientific instruments
____Semiconductors
____Sensors
____Superconductor materials
____Telecommunications
____Wire/tape mfg.

Other (describe)____

2. is your organization a recent start-up (within the past five years)?

____Yes ____No

3. What percent of total company sales are to:
(Check one for each row)

	0-25%	25-50%	50-75%	75-100%
military markets?	_____	_____	_____	_____
other Federal Government markets?	_____	_____	_____	_____

4a. is your company an independent division or subsidiary of another company

____Yes ____No ____Not applicable

if no, goon to question 5.

4b. What is your parent company____

4c. U.S. respondents: is your parent company at least 50 percent foreign-owned?

____Yes ____No ____Not applicable

5a. Is your' company a parent of any independent divisions or subsidiaries which are involved in superconductor R&D or sales?

____Yes ____No ____Not applicable

comments? ____________________

5b. If yes, list the U.S.-based independent divisions or subsidiaries, their locations, and potential contacts within these companies:

B. COMPANY SIZE

6. What was the value of total sales for your company in 1987? (For purposes of this survey, use the conversion rate $1 = 133 yen.)

____No sales

____Less than $1 million

____$1-10 million

____Not available

____$10-100 million

____$100 million to $1 billion

____Greater than $1 billion

____Not applicable

7. How many people are employed within your organization?

____10 or less ____11 to 50 ____51 to 500 ____501 to 10,000 ____Over 10,000

C. COMPANY HISTORY IN SUPERCONDUCTIVITY

8. Has your company performed low temperature superconductor (LTS) R&D and/or produced LTS-related products?

____Yes ____No ____Not applicable

Comments? ____________________

9. Approximately when did your organization first become involved in superconductivity (LTS and/or HTS) R&D activities?

Year ____________ Month, if known ____________

D. SUPERCONDUCTIVITY R&D EXPENDITURES BY SOURCE OF FUNDS

10. Please indicate below your company's expenditures on both high and low temperature superconductivity R&D for 1987 and 1988. Allocate expenditures by the source of the funds. [As in other questions about R&D expenditures, include only expenditures for R&D activities performed by your organization.] Report expenditures in thousands of dollars, e.g. $26K instead of $25,643.

	1987 HTS	1987 LTS	1988 HTS	1988 LTS
a) TOTAL SUPERCONDUCTIVITY R&D EXPENDITURES	$____	$____	$____	$____
b) Company's own funds	$____	$____	$____	$____
c) Other industry	$____	$____	$____	$____
d) Federal Government	$____	$____	$____	$____
e) State & Local governments	$____	$____	$____	$____
f) Foreign	$____	$____	$____	$____
[Foreign industry]	[____]	[____]	[____]	[____]
[Foreign government]	[____]	[____]	[____]	[____]
g) All other sources	$____	$____	$____	$____

E. SUPERCONDUCTIVITY EXPENDITURES BY TYPE OF R&D ACTIVITY

In this section we would like to obtain a rough breakdown of industrial R&D expenditures by type of R&D activity, and to become familiar with what areas of research industries are most interested in. (See the end of this survey for a definition of R&D activities.)

11. Allocate your total superconductivity (HTS and/or LTS) R&D expenditures (from question 10a above) for 1987 and 1988 (estimated) across the three major types of R&D activity listed below. If your expenditures cover multiple or overlapping activities, you may allocate proportionally among activities or allocate them entirely to a primary expenditure activity, but please make sure that the total here adds up to the total indicated above in question 10a.

Within each of the three major R&D activity areas, indicate with checkmarks any and all of the following HTS and LTS R&D performed in-house at your organization.

	1987	1988 (estimated)	
BASIC RESEARCH	$______	$______	___Not applicable

Basic research is defined to include the following:

	(Check as applicable) HTS	LTS
Theory/Experimental characterization of superconductivity	___	___
Characterization of presently known materials, including property analysis, and composition/structure characterization	___	___
Searching for new types of materials (metallic, ceramic, or organic) and/or materials with more desirable properties	___	___
Other basic research not covered above	___	___

	1987	1988 (estimated)	
APPLIED RESEARCH:	$__________	$__________	____Not applicable

Applied research is defined to include the following: (Check as applicable)

	HTS	LTS
Cryogenic systems research	____	____
Processing research for tape or wire development	____	____
Thin film processing research	____	____
Josephson junctions/Prototype devices	____	____
Powder/raw material processing	____	____

Processing research in any of the following technologies:
developing high quality raw materials, thin film formation, wire, tape, fiber, encapsulation, or bulk superconductors (magnets) for the purpose of:

	HTS	LTS
Improving superconducting/mechanical properties	____	____
Finding economical processes	____	____
Compatibility with semiconductor processing	____	____
Processing research for other technical reasons	____	____
Applied research (not specified)	____	____

	1987	1988 (estimated)	
DEVELOPMENT WORK	$__________	$__________	____Not applicable

Development work is defined to include the following: (Check as applicable)

	HTS	LTS
Component development or modification (e.g., magnet, Josephson junction circuits, SQUID) . . . . Briefly describe this component____________________________	____	____
System development or modification (e.g., a cryogenic system, a motor, an MRI system) . . . . Briefly describe this system________________________________	____	____
Systems design	____	____
Development work (not specified)	____	____

12. PRELIMINARY WORK - As in question 11, please indicate with checkmarks any and all of the following activities which your firm has conducted or is conducting. (Check as applicable)

	HTS	LTS
Technology monitoring	____	____
Feasibility and/or Market studies	____	____

Describe any types of HTS-related research which your organization performs in-house, but which is not covered by the above listings in questions 11 and 12.

F. FEDERAL GOVERNMENT FUNDING

In this section we would like to get a picture of the need for Federal funding of industrial superconductivity (HTS and/or LTS) research.

13a. Did you apply for money from Federal government sources for HTS R&D conducted during 1988?

___Yes ___No

13b. If you did apply, were any of your applications approved?

___Yes ___No ___Not applicable

13c. (For U.S.-based respondents only) From which Federal agencies have you obtained financial assistance for 1988? (Check all that apply.)

___Air Force (including AFOSR)

___Navy (including ONR)

___Army (including ARO)

___Defense Advanced Research Projects Agency (DARPA)

___Strategic Defense Initiative Office

___Other U.S. Department of Defense agencies

___Other National security agencies

___NASA

___National Institute of Standards and Technology (formerly NBS)

___National Science Foundation

___U.S. Department of Energy

___U.S. Department of Transportation

___Other (specify)___________________

G. R&D WORKFORCE

From this section we would like to know the size of the industrial superconductivity (HTS and/or LTS) R&D workforce and the ease or difficulty of finding trained superconductivity researchers.

14a. How many scientists and engineers were employed by your organization and engaged in all types of R&D activities (not just superconductivity) as of: January 1987?______________________

January 1988?______________________

14b. How many of these were employed in superconductivity (HTS and/or LTS) R&D as of January 1987 January 1988, and October 1988? (Report in the first column all individuals spending at least part-time on superconductivity, and in the second column those spending greater than 50% of their time.)

	Part-time	Greater than 50%
number of HTS researchers (Jan. 1987)	_______	_______
number of LTS researchers (Jan. 1987)	_______	_______
number of HTS researchers (Jan. 1988)	_______	_______
number of LTS researchers (Jan. 1988)	_______	_______
number of HTS researchers (Oct. 1988)	_______	_______
number of LTS researchers (Oct. 1988)	_______	_______

14c. Has the upsurge in superconductivity R&D activities required or induced you to hire new science and engineering personnel to pursue this work?

____Yes ____No

14d. Have you encountered significant difficulties in hiring appropriately trained science and engineering personnel to conduct superconductivity (HTS and/or LTS) activities?

____Yes ____No

14e. To what extent have you been able to reassign personnel already employed by your organization to fulfill your superconductivity (HTS and/or LTS) R&D personnel needs? (Check the percentage of your superconductivity R&D workforce that was assembled through reassignment rather than through new hires.)

Less than 25% ____25 to 50% ____51 to 7596 ____76 to 100%

Comments?____________________

H. COOPERATIVE ARRANGEMENTS

This section is intended to give us a picture of the extent of cooperative arrangements between industry, universities, and the national labs at this point in time. Japanese respondents should report information only for cooperative efforts with institutions located in Japan. U.S. respondents should report information only for cooperative efforts with institutions located in the United States.

15a. Does your organization currently participate in any cooperative arrangements for HTS R&D with:

(Check one for each row)	Yes	No	No, but plan to
National labs?	____	____	____
Universities?	____	____	____
University-based consortia?	____	____	____
Other individual companies?	____	____	____
Industry consortia/associations?	____	____	____

____not applicable

15b. Please indicate below your company's expenditures on any collaborative superconductor R&D activities in 1987 and 1988. Report expenditures only for research performed outside your organization. List in the first column below only expenditures on researchers that are not working with you through their affiliation with other firms, universities, industry consortia, or university-based consortia.

1987

	Indiv. Researchers	Nat'l Labs	Other Industry*	University
HTS	$_______	$_______	$_______	$_______
LTS	$_______	$_______	$_______	$_______
Total	$_______	$_______	$_______	$_______

1988

	Indiv. Researchers	Nat'l Labs	Other Industry*	University
HTS	$_______	$_______	$_______	$_______
LTS	$_______	$_______	$_______	$_______
Total	$_______	$_______	$_______	$_______

* - Includes other individual firms, industry consortia, and industry associations.

I. COMMERCIALIZATION ATTITUDES

The aim of this section is to discover the attitudes of industry representatives about the commercialization and timing of superconductor-based products, and is not intended as a future prediction measure.

16a. Indicate below roughly in what year you first expect to reach market with a final product or process that is a result of your HTS R&D activity.

Year_______________

16b. What are the natures of these products/processes? (Check as many as apply.)

_____Computers/data processing
_____Cryogenic systems
_____Electrical machinery
_____Electronics/avionics
_____Fabrication equipment
_____Ground or sea transportation
_____Industrial processes
_____Magnets
_____Medical applications
_____Power applications
_____Scientific instruments
_____Space applications
_____Superconductor powders
_____Tape/Wire
_____Military
_____Unspecified commercial

17. List the companies world-wide that you think will be on the forefront in developing superconductor-related products in each of the following areas. (Mark no opinion where you are unfamiliar with the area.)

Area	Companies (up to five, in any order)	No opinion
Computers/data processing	____________________	____
Cryogenic systems	____________________	____
Electrical machinery	____________________	____
Electronics/avionics	____________________	____
Fabrication equipment	____________________	____
Industrial manufacturing	____________________	____
Magnets	____________________	____
Medical applications	____________________	____
Power applications	____________________	____
Scientific instruments	____________________	____
Superconductor powders	____________________	____
Tape/wire	____________________	____

Comments? ______________________________

J. PRODUCTION AND SALES OF SUPERCONDUCTING COMPONENTS AND SYSTEMS

18. Estimate roughly your 1987 gross sales of products incorporating one or more superconducting components. (Rounded to the nearest thousand dollars).

$____________________

19. Estimate roughly the total number of jobs, in 1987, involved in the production of superconducting components or systems by your company.

____

K. TIME TO COMPLETE SURVEY

20. Please estimate how long it took you to fill out this form.

_____Less than 1 hour

_____1 to 2 hours

_____2 to 4 hours

_____4 to 8 hours

_____More than 8 hours

THANK YOU FOR TAKING THE TIME TO COMPLETE THIS SURVEY.

Please use the following space to comment on any aspect of superconductivity research, development and commercialization that was not sufficiently covered by this survey.

DEFINITIONS

Research and development(R&D) - Research and development includes basic and applied research in the sciences and in engineering, and design and development of prototype products and processes. For the purposes of this questionnaire, research and development includes activities carried on by persons trained, either formally or by experience in the physical sciences including related engineering, and the biological sciences including medicine but excluding psychology, if the purpose of such activity is to do one or more of the fallowing things:

1) Pursue a planned search for new knowledge, whether or not the search has reference to a specific application;

2) Apply existing knowledge to problems involved in the creation of a new product or process, including work required to evaluate possible uses; or

3) Apply existing knowledge to problems involved in the improvement of a present product or process.

R&D Scientists and engineers are defined as all persons engaged in scientific or engineering work at a level that requires a knowledge of physical or life sciences, engineering, or mathematics, equivalent at least to that acquired through completion of a four-year college program with a major In these fields, regardless of whether such persons hold a degree In the field. Exclude technicians and other supporting staff unless successful performance of their job responsibilities requires having the qualifications above.

Superconductivity - A physical state of a material in which the material presents zero resistance to an electrical current and simultaneously excludes magnetic fields (the Meissner effect).

HTS - high temperature superconductors These include: LaSrCuO materials; YBaCuO or other 1-2-3 materials; BISrCaCuO materials; TlBaCaCuO materials; BaKBiO materials; and other new materials with transition temperatures above 30K

LTS - low temperature superconductors These include: NbTi materials; NbN materials; NbSn materials; and other known LTS materials.

Industry associations - Consortia are defined as any research organizations comprised of industrial members, performing precompetitive research. (e.g., MCC, ISTEC)

Comments? Section - Use this part of each question to explain anything you wish about your answer or to provide your answer in a format not compatible with the question as asked.

Chapter 7

Policy Issues and Options

CONTENTS

Chapter 7
Policy Issues and Options

INTRODUCTION

The discovery of HTS has come at a time of increasing doubts about the capability of the United States to compete in global high-technology markets. The list of markets in which U.S. industry has slipped badly is growing: e.g., consumer electronics. memory chips, automobiles, and machine tools. Moreover, the U.S. private sector is investing less than its main competitors in a number of emerging technologies such as x-ray lithography, high--definition television (HDTV), and—as shown in the previous chapter—in superconductivity research. There is a serious question whether U.S. industry, as it is currently financed and managed, can compete in markets for these technologies in the next century.

While there is a reluctance within the Administration and Congress to talk openly about "industrial policy,' there is a growing recognition on both sides that changes in the technological relationships between the Federal Government and the private sector may be necessary to firm up flagging U.S. competitiveness. This new attitude is reinforced by the recognition that foreign competitors have targeted the most promising emerging commercial technologies with coordinated, government/industry efforts. In Japan, the progress achieved by close cooperation between the government and industry is legendary, and the newly industrialized countries on the Pacific Rim (South Korea, Taiwan. Hong Kong, and Singapore) are following closely behind. In Western Europe, cooperation among governments and major corporations has long been the hallmark of science and technology programs, and the prospect of a unified European market after 1992 suggests that U.S. firms can anticipate tougher competition from these large European companies in the future, in both European and U.S. markets.

Unfortunately, the growing interest in new Federal policies to promote commercial technology development comes at a time of growing pressures to reduce the Federal budget deficit. After all, high-temperature superconductivity (HTS) is only one of many emerging technologies---optoelectron - ics, ceramics, and HDTV, to name a few—that could become commercially important in the future. When added to such big-ticket Federal R&D commitments as the NASA space station, the Superconducting Super Collider, mapping the human genome, and the Strategic Defense Initiative, it is apparent that difficult budgetary choices will have to be made.

In 1987, shortly after the discovery of HTS, optimism was rampant and room-temperature superconductivity seemed just around the corner. The United States was seen to be engaged in a heated race to commercialize HTS products before its competitors. By 1989, as the scope of the remaining challenges became clearer, a more realistic view had taken hold. HTS became a test case, not of the United States' ability to commercialize a new technology rapidly, but of its ability to look beyond the immediate future and sustain a consistent R&D effort over the long term.

It is now apparent that the real race will begin after practical HTS conductors are developed, and will involve the incorporation of these conductors into larger, integrated systems. The race will not be a sprint, won by a technical breakthrough; rather, it will be a marathon, won by painstaking attention to design, low-cost manufacturing, and high quality—the same factors that determine competitiveness in any other industry. Thus, the so-called "superconductivity race" should be seen in the broader context of the competitive prowess of the entire U.S. manufacturing sector.

This chapter ranks a series of policy issues raised by HTS in three categories: first, those considered by OTA to be of minor importance; then, several issues that bear watching in the future; and finally, those that OTA considers to be of critical importance. Where appropriate, specific options for addressing these issues are discussed. The importance of stable funding for superconductivity is stressed, if the potential of this technology is to be realized. Finally, the chapter concludes by placing HTS in a broader policy context of U.S. competitiveness, noting that while the Federal Government's R&D policies are important. its fiscal policies are even more important

MINOR ISSUES

As the realization sank in that HTS is a long-term technology, several issues that were earlier thought to be urgent now appear to be of minor importance

Adequate supplies of raw materials, chemical precursors, and powders for HTS are not a problem now, nor are they likely to be in the foreseeable future.

At present, the United States is heavily dependent on imports for yttrium, bismuth, and thallium, key ingredients in three of the most promising HTS materials.[1] These metals are byproducts of the production of primary metals, e.g., lead. Since HTS is still at the research stage, the incremental demand due to HTS materials is relatively small. Moreover, as discussed in chapter 3, the most probable near-term HTS applications are likely to be in electronic devices, which will require only very small quantities of material. Present supplies appear sufficient to support even significant growth in large-scale applications.[2]

HTS does not appear to raise unmanageable health and safety problems, though this deserves further study.

There appear to be two principal health and safety issues associated with HTS: the toxicity of the materials themselves (and of their chemical precursors), and the potential health effects of human exposure to the high magnetic fields produced by superconducting magnets.

The main toxicity problem with HTS materials appears to be the risk of poisoning by inhalation, ingestion, or skin contact with heavy metals such as barium, yttrium, bismuth, and thallium.[3] For instance, thallium-a key ingredient in the HTS material having the highest known transition temperature—is dangerous not only because it is extremely poisonous,[4] but also because it readily evaporates when heated to process temperatures, and can be easily inhaled. Present techniques are adequate to minimize exposure to these heavy metals on a research scale, but further studies are needed to ensure that laboratory processes are scaled up safely to production quantities. The potential hazards of disposing of these materials also deserve further study.

Several large-scale applications of superconductors, e.g., magnetic energy storage, maglev vehicles, and MRI, produce high static magnetic fields, and raise the issue of the potential health effects of public exposure to these fields. In the past 20 years, there have been numerous studies investigating the biological effects of both static and time-varying magnetic fields. While the health effects of exposure to power frequency (60 hertz) fields remain controversial,[5] there is no evidence for adverse effects in healthy individuals exposed to static fields up to **2** tesla (20,000 gauss).[6] Nevertheless, because relatively small magnetic fields can interfere with heart pacemakers and a variety of paramagnetic body implants, public exposure must be limited to around 10 gauss. The shielding and/or exclusion zone required to reduce the field to this level can add significantly to the cost of the application.

Antitrust restrictions are not a serious inhibitor to U.S. competitiveness in HTS technology.

The first item of President Reagan's 1 l-point Superconductivity Initiative (see ch. 4) proposed exempting certain joint production ventures in the private sector from antitrust litigation under the Clayton Act (15 U.S.C. 18). This was intended to facilitate the formation of joint ventures to commercialize products featuring HTS, thus permitting U.S. firms to share the risks and expenses. Similar relaxations of antitrust restrictions have been suggested as a means of encouraging the formation of consortia to commercialize several other technologies, including semiconductor memory chips (DRAMs) and HDTV. Proposed legislation to relax the antitrust laws is under consideration at the Justice Department.

The National Cooperative Research Act of 1984 (Public Law 98-462) cleared the way for companies to form joint ventures or consortia to conduct R&D,

[1]Charles A. Sorrell, U.S. Bureau of Mines, "The New Superconductors—An Overview," *Minerals and Materials*, June-July 1988, p. 7.

[2]S. Beggs et al., "Long-Run Supplies of Raw Materials for Commercialized High-Temperature Superconductors," Argonne National Laboratories, ANL Project 85923, Mar. 23, 1989.

[3]S.D. Arnold and G.M. Halley, "Health and Safety Guide for Inorganic Compounds and Metals Used in the Fabrication of Superconductive Compounds," Los Alamos National Laboratory, to be published, 1990.

[4]Thallium oxide was used as a household rodenticide prior to 1986, when it was banned in the United States because of its toxicity to humans.

[5]For a recent review, see U.S. Congress, Office of Technology Assessment, *Biological Effects of Power Frequency Electric and Magnetic Fields—Background Paper*, OTA-BP-E-53 (Washington, DC: U.S. Government Printing Office, May 1989).

[6]T.S. Tenforde, "Biological Responses to Static and Time-Varying Magnetic Fields," *Electromagnetic Interaction With Biological Systems*, J.C. Lin (ed.) (New York, NY: Plenum Press, 1989), p. 83.

as distinct from commercial production. As discussed in chapter 4, several HTS R&D consortia of this type are either being planned or are already in operation. OTA found no evidence from its industry interviews that fear of antitrust litigation is holding back U.S. progress in HTS. In fact, most companies feel that HTS is not yet mature enough for commercial joint production ventures to be considered seriously.[7] Therefore, changes in the antitrust laws are more likely to be driven by the needs of more mature technologies, such as HDTV, rather than HTS.

Fears that the prolific HTS patenting by Japanese companies could block U.S. companies from participating in major superconductivity markets appear to be exaggerated.

In one year, Japanese companies filed some 5,000 patents on various aspects of FITS in Japan. Sumitomo Electric Co. alone is said to have filed over 1,000. The U.S. Patent Office reports that 1,200 patents relating to superconductivity have been filed in the United States since 1985, about 40 percent by foreign companies.[8]

Some observers have become alarmed by these developments, worried that the Japanese could "lock up" the technology with patents, and force U.S. companies into an inferior position. OTA's analysis suggests that these concerns are exaggerated:

- U.S. firms have also taken an aggressive approach to patents in HTS. In fact, five separate U.S. laboratories (University of Alabama, University of Houston, AT&T, Naval Research Laboratory, and IBM) have applied for patents on the original YBaCuO materials. Resolution of this patent conflict could take years; meanwhile the technology moves on.
- Although it is conceivable that there will be one "best" patentable material, it is at least as likely that a range of compositions and structures will be available to the designer of HTS products. The recent discoveries of much broader classes of oxide compositions and structures supports this view.

These considerations suggest that, although HTS patents may have value in the context of specific narrow markets, the possibility of global Japanese dominance of the technology based on a few key patents seems remote. In the long run, the real significance of HTS patents may be as trading property in cross-licensing negotiations between competitors. On the whole, patent attorneys interviewed by OTA did not think that HTS raises any patent issues that are substantively different from those encountered in other fields, such as electronics, polymers, or pharmaceuticals.

ISSUES THAT BEAR WATCHING

There are several aspects of the U.S. HTS effort that may not be a problem now, but are potential areas of concern for the future.

Federal laboratories may be receiving a disproportionately large share of the HTS budget.

In fiscal year 1988, 45 percent of Federal HTS funding went to support work in Federal laboratories of the Department of Defense (DoD), Department of Energy (DOE), National Aeronautics and Space Administration (NASA), and Department of Commerce (DOC). These laboratories conduct a broad range of research, from very basic to prototype development, in support of their agency missions. Some of this research uses the unique facilities available only in the Federal laboratories, and some is simply not being done anywhere else.

But questions remain about whether Federal laboratories should have such a large share of the HTS budget-especially given the scarcity of resources for university research (see below). To assess the quality and relevance of HTS programs in Federal laboratories, Congress may wish to establish a single, independent advisory committee with strong industry representation to evaluate the quality of HTS research at Federal laboratories (including military laboratories).

Historically, Federal laboratories have not considered it part of their mission to transfer technologies of commercial interest to U.S. industry. With the advent of HTS, traditional attitudes and cultures in both Federal laboratories and U.S. companies have begun to change. Programs such as DOE's Superconductivity Pilot Centers represent good faith efforts to address the needs of industry, and they

[7] Kay Rhyne Adams, "The DARPA Manufacturing Initiative in High-Temperature Superconductivity," *Superconductor Industry,* vol. 2, No. 2, summer 1989, p. 12.

[8] *Superconductor Week,* vol. 3, No. 37, Sept. 25, 1989, p. 1.

have attracted a large number of industry collaborators. Such experiments are valuable and if successful, could be extended to other Federal laboratory programs.[9]

One area of research where a Federal laboratory makes a unique contribution is the National Institute of Standards and Technology's (NIST) work on standards for making measurements that are reproducible and accurate. Standard techniques for measuring key HTS materials properties such as critical current density in the presence of magnetic fields are crucial for timely progress in developing the materials. The need for standard measurement techniques was explicitly recognized in President Reagan's 1 l-point Superconductivity Initiative. Nevertheless, the NIST effort in standard HTS measurement techniques in 1989 was only about $200,000 per year. 1°

NIST is already recognized as the world leader in LTS standards development. By increasing NIST's annual budget by about $300,000 (the equivalent of fill support for two or three additional staff), the United States could also become a world leader in standards for HTS. As HTS matures and begins to be used in applications, a strong U.S. position in HTS measurement standards will not only facilitate trade by U.S. firms, but will help ensure that the United States has a strong voice in the formation of international standards.

At present, defense and civilian requirements for HTS technology are similar, but this could change as the technology mutures.

As pointed out in chapter 4, Federal funding for HTS R&D is dominated by DoD (about 45 percent in fiscal year 1989) and DoD provides most of the Federal I-ITS R&D funds going out to U.S. industry. This has raised concerns that DoD involvement might skew the U.S. agenda for HTS development toward high-cost, specialty materials designed for one-of-a-kind military weapons systems, while foreign competitors develop low-cost, easily manufactured HTS materials well-suited for profitable commercial applications. A second concern is that heavy military involvement might lead to the lowering of a cloak of secrecy over Federal HTS R&D efforts, preventing timely access of U.S. firms to research results that could lead to commercial applications.

At the present stage of HTS technology development, OTA finds that military and civilian agency objectives for HTS are the same. The great majority of DoD-funded HTS R&D (with the possible exception of some Strategic Defense Initiative work) remains at a very basic or generic level, and the results are useful for both military and civilian purposes. Without the DoD HTS programs, the HTS R&D funding pie would undoubtedly be much smaller, and many programs of potential value to the commercial sector would not be going forward at all. For example, the Defense Advanced Research Projects Agency (DARPA) HTS initiative provides an emphasis on HTS processing technologies that is unique among government efforts. Also, without 95 percent funding from the Strategic Defense Initiative Organization, the Superconducting Magnetic Energy Storage project would never have started; only 5 percent of the program's support comes from the electric utilities.

As HTS matures and begins to be incorporated into specialized weapons systems, DoD and commercial interests could well diverge. The special demands made on materials for military and space applications, e.g., high radiation hardness or ultrahigh frequency operation (as well as a lower priority placed on cost, manufacturability, or long-term stability), are likely to cause this divergence. One area of special concern is superconducting electronics, widely predicted to be one of the earliest and largest commercial application areas of HTS. With the exception of a small program at NIST, DoD is the only Federal agency that considers development of superconducting electronics to be part of its mission, If DoD funding concentrates on solving problems of primarily military interest as the technology matures, U.S. commercial competitiveness in HTS could suffer,

Thus far, Federal agencies have not restricted access to I-ITS research results for national security reasons. However, HTS was one of 22 technologies recently identified as critical to future military missions.[11] This designation could lead to greater

[9]Funding for the Pilot Centers, which stood at $6 million in fiscal years 1989 and 1990, is slated to increase to $15 million in the Administration's fiscal year 1991 budget request.

[10]NIST's budget for HTS stayed constant in fiscal year 1990 but is slated for a 70 percent increase in the Administration's fiscal year 1991 budget request.

[11]U.S. Department of Defense, "Critical Technologies Plan," a report to the Committee on Armed Services, U. S. Congress, Mar. 15, 1989.

funding, but as HTS is used more widely in weapons systems, pressures will probably increase to control access to information about the superconducting components and to prevent their export to unfriendly nations. In the past, such restrictions have proven to be a nuisance for companies interested in commercialization of advanced materials, electronics, and computer technology originally developed for military applications,[12] and this situation needs to be watched closely.

Congress could move to forestall these concerns by requiring DoD or other relevant agencies to inform Congress in advance of intentions to place HTS on the Militarily Critical Technologies List, Commodity Control List, Munitions List, etc.[13] In addition, it could establish an independent advisory committee of government and industry researchers to conduct periodic review of progress in dual-use military projects and report on the extent to which military and commercial objectives may differ.

If progress in HTS technology continues to be incremental, small HTS startup companies could face a critical shortage of capital.

In recent years, the manufacture of commercial products having LTS superconducting components has shifted from large companies to medium and small companies. While several large companies maintain substantial LTS R&D efforts (often supported in large part by government contracts), most have backed away from commercial markets, finding them insufficiently profitable in the near term. The only large U.S. company presently producing a commercial LTS product is General Electric Co., with its MRI system.

OTA's survey (see ch. 6) identified a dozen venture capital-financed startup companies in HTS. These companies are conducting innovative research, and two are spending more than $1 million per year on HTS R&D. During 1987-1988, first round venture capital funding for seven of these firms was quite plentiful, averaging more than $3 million per startup.[14] However, a second round infusion will be needed soon to keep these companies going.

If markets for HTS products develop as slowly as those for LTS have done over the past 30 years, we may see large firms backing out, and the venture capital sources could dry up, leaving the field to a number of undercapitalized small companies largely supported by government/military R&D grants and contracts. It is unlikely that these small companies could carry the standard of U.S. competitiveness against their better-financed and more diversified foreign competitors. In fact, most small HTS start-ups report that they have received buyout offers from large foreign companies. If U.S. sources of capital begin to dry up, such offers will become more and more difficult to resist.

The importance of active U.S. participation in international superconductivity meetings and programs is growing, while Federal funding to support these activities is stagnant or declining.

At present, the United States does not have a qualitative lead over its competitors in superconductivity R&D, and indeed, it lags in several areas of LTS technology (e.g., large-scale integration of Josephson Junctions for LTS electronics, and rotating LTS machinery). The pace of HTS research abroad is rapid, and U.S. scientists—both in Federal laboratories and universities-have an urgent need to know about the most recent developments.

The opportunities for tapping into foreign research and for conducting international collaborative research are growing, and occur on several levels: formal government-to-government programs; long-term fellowships for U.S. scientists conducting joint research in foreign laboratories, and short-term visits and attendance at international meetings. Examples include the U.S.-Japan Agreement on Cooperation in Science and Technology (specific projects still under negotiation), and the postdoctoral research fellowship slots in Japan that were recently made available to U.S. scientists and funded by the Japanese Government through NSF.[15]

[12] National Academy of Sciences, "Balancing the National Interest: U.S. National Security Export Controls and Global Economic Competition" (Washington, DC: National Academy Press, 1987).

[13] See U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design: New Structural Materials Technology,* OTA-E-351 (Washington, DC: U.S. Government Printing Office, June 1988), p. 272.

[14] A.M. Rosa and C. Suchors, "The Venture Capital Viewpoint," *Superconductor Industry*, vol. 2, No. 1, Spring, 1989, p. 11.

[15] In 1988, the Japanese Government provided NSF with $5 million to pay the expenses for 100 U.S. postdoctoral fellows to conduct long-term research projects in Japanese laboratories. In the past, this program has been undersubscribed, but the number of applicants continues to grow. With about one-third of the funds left, NSF program managers are concerned that they may succeed in filling these slots just when the money runs out.

There is a growing recognition among U.S. scientists of the importance of taking advantage of these opportunities. But although it is hard to quantify, there is considerable anecdotal evidence that Federal agency funding for these activities is not keeping pace with the demand. Key superconductivity experts in Federal laboratories and universities interviewed by OTA report that funding for travel to international meetings is becoming more difficult to get, and the time required for approval of such travel is as long as 3 to 6 months.[16]

Important international exchange programs could also be caught in the budget squeeze. For instance, several new joint superconductivity projects are under negotiation in the U.S.-Japan Agreement mentioned above,[17] but U.S. agencies are expected to fund the costs of their participation out of other budgets.[18] In contrast, Japan has been much more generous in supporting the participation of its scientists in international collaborations.

Many observers have expressed concern that the United States gives away more technical information than it gets from abroad. By failing to support strongly U.S. representation in international technology agreements, the Federal Government may be ensuring such an unequal exchange.

The importance of U.S. participation in international superconductivity programs is emphasized in the National Action Plan for Superconductivity, recently released by OSTP.[19] Congress could require that OSTP prepare an evaluation of the adequacy of Federal funding for these international activities as part of its mandated annual progress report on the Plan, and appropriate additional funds if these are deemed necessary.

KEY ISSUES

OTA considers the following issues to be especially important in determining the future U.S. competitive position in HTS:

U.S. companies are investing less than their main competitors in both low- and high-temperature superconductivity R&D.

The OTA survey results (see ch. 6) illustrate the problem: Japanese firms are investing at least 50 percent more than U.S. firms in HTS R&D, even though they don't expect a payback on their investment until the year 2000. In contrast, U.S. firms typically projected a payback by 1992.

HTS presents a difficult problem for U.S. industry. The materials themselves are evolving rapidly. No one knows when practical conductors will be developed. There is general agreement that the most important applications have not yet been thought of. Profitable markets are not yet in sight. There is no guarantee that any one company will be able to appropriate the full benefits of its R&D investment. In short, HTS is a high-risk, long-term gamble. In the absence of major research successes in the next few years, it seems likely that U.S. firms will have difficulty continuing even their present levels of HTS R&D expenditures.

It is tempting to focus on how changes in Federal R&D policy can help companies to adopt a longer term perspective--e. g., establishing federally funded industry consortia. But while such Federal programs might be helpful, they are almost certainly not decisive, because they do not change the financial and economic climate in which U.S. companies make long-term investment decisions.

This is not to suggest that Federal R&D funding and Federal markets for superconductivity are not important; after all, Federal programs (especially those of DOE) kept LTS technologies alive during the 1960s and 1970s. Without this support, U.S. companies would not have been able to participate in today's growing commercial markets for superconducting magnets and other applications. But it is unrealistic to expect that changes in Federal R&D policies will by themselves solve U.S. competitiveness problems. Instead, Federal fiscal policies—

[16]During the 1960s and 1970s, researchers could apply to the National Science Foundation for individual foreign travel grants that were made from a centralized fund totaling some $500,000 per year. In 1978, this central fund was eliminated and the money was distributed among the various NSF research divisions and programs, with the result that foreign travel funds became more difficult to obtain.

[17]At this writing, joint projects under consideration include: a high-field superconducting magnet facility; development of measurement standards and a database on HTS materials properties; digital superconducting electronic devices; and maglev transportation.

[18]The U.S.-Japan Workshop on High-Field Superconductors, the Versailles Agreement on Advanced Materials and Standards, and the International Electrotechnical Commission are all becoming active in promoting international standards for superconductors. There is no additional funding for U.S. participation in these activities either.

[19]"The National Action Plan on Superconductivity Research and Development," Executive Office of the President, Office of Science and Technology Policy, December 1989, p. 13.

especially those that affect the cost of capital available to U.S. industry-are more important. *The availability of patient capital is the single most important policy objective for encouraging industry to invest in long-term technologies such as HTS* (see further discussion below).

University research on HTS merits a higher priority than it presently receives.

In fiscal year 1988, about 30 percent of Federal HTS resources went to support research in universities; about half of this came from NSF. Over the past 3 years, individual researchers at U.S. universities have contributed significantly to the development and characterization of new HTS materials, including the original discovery of the YBaCuO materials at the Universities of Houston and Alabama and the discovery of the thallium-based materials at the University of Arkansas. Yet there is a growing consensus that universities are not receiving a level of funding adequate to support the quality of research of which they are capable.[20 21 22] NSF continues to report that it is forced to turn down HTS research proposals of extremely high quality due to lack of funds. This situation is especially serious for young investigators entering the field, but even proven contributors have experienced difficulty getting funding.

As indicated in chapter 2, major questions remain about the mechanism of HTS and the relationships among the theory, structure, and properties of these materials. Because of the basic nature of this research and the long time-scales involved, much of it is best carried out in universities. Universities are an important component of U.S. industrial competitiveness; not only are they a favorite partner of companies for consulting and collaborative R&D, they also provide a pool of trained graduate students who will be hired by these companies.

Option: Increase NSF's budget by $5 million for individual investigator research grants in HTS.

While NSF's spending for superconductivity did increase from $20.4 million to $26.2 million from fiscal years 1988 to 1989, virtually the entire increase went to support the new superconductivity Science and Technology Center shared between the University of Illinois at Urbana, Northwestern University, and Argonne National Laboratory. Funding for individual university researchers stayed essentially constant. The high quality of proposals and the strong contributions in the past suggest that additional moneys invested in individual materials research grants would be likely to yield high returns.[23]

A balance between NSF funding for individual researchers and multidisciplinary centers is desirable for HTS. Individual researchers are better at investigating the physics of HTS and looking for new materials, while the resources and facilities of larger centers are needed for characterization and processing studies.

Option: Increase funding to upgrade university equipment for synthesis and processing of HTS by $10 million per year.

The need for greater investment in materials synthesis and processing at universities has been highlighted in a recent report.[24] The purpose of this initiative would be to build up the technological infrastructure of the Nation's universities in synthesis and characterization. U.S. capabilities in such areas as the synthesis of new HTS materials and preparation of large single crystals lag those of Japan.[25] To achieve optimum performance, advanced materials such as HTS must be synthesized using methods capable of control at the atomic level. This involves expensive processes, such as multi-

[20]Committee to Advise the President on High-Temperature Superconductivity, "High-Temperature Superconductivity: Perseverance and Cooperation on the Road to Commercialization," December 1988.

[21]U.S. Congress, Office of Technology Assessment, *Commercializing High-Temperature Superconductivity*, OTA-ITE-388 (Washington, DC: U.S. Government Printing Office, June 1988), p. 11.

[22]Although at this writing the National Commission on Superconductivity had not made any official recommendations, its chairman reported a concern among Commission members about the level of support for individual investigators at universities. See David W. McCall, Chairman, National Commission on Superconductivity, testimony before the Subcommittee on Transportation, Aviation, and Materials, House Committee on Science, Space, and Technology, Feb. 21, 1990.

[23]In early 1989, NSF's Division of Materials Research announced a new $1 million program to provide $40,000 per year for 3 years to young professors entering the HTS field. However, this amount is barely enough to pay the stipend, tuition, and overhead of one graduate student at a major university, let alone the costs of supplies and equipment.

[24]National Research Council, *Materials Science and Engineering for the 1990s* (Washington, DC: National Academy Press, 1989).

[25]Japan Technology Evaluation Center, "High-Temperature Superconductivity in Japan," a report for the National Science Foundation, NTIS #PB 90-123126, November 1989.

gun sputtering, molecular beam epitaxy, and excimer laser deposition. Few U.S. universities have these capabilities, and as a result few students receive training in the state-of-the-art synthetic methods that are likely to be crucial in a wide variety of advanced materials in the future.

A second area where university infrastructure is weak is in characterization of materials. University researchers need access to a variety of expensive equipment for characterization of materials, e.g., neutron sources, photon sources, electron microscopes, high-field magnets, and magnetometers. Much of this equipment is available only in a few research institutes and Federal laboratories.[26]

The idea of enhancing university capabilities in HTS is by no means a new one. The new NSF Superconductivity Science and Technology Center in Illinois is intended exactly for this purpose, but has received only baseline levels of funding. While this is a step in the right direction, it does not adequately address the needs of the many research universities across the country. A rough estimate of the scale of the program required is $10 million per year over the next several years, providing equipment funding for some 25 research groups across the Nation at a level of $400,000 each per year.

If HTS becomes a practical success, this initiative will have created a vital source of research capability and a pool of highly trained students. But even if HTS remains largely a research phenomenon, this capability is likely to pay dividends in numerous other areas of materials science, since such equipment is also needed for research on semiconductor manufacturing, optical coatings, etc. Thus, from a national point of view, the investment would have very high utility and low risk.

Option: Provide funding—perhaps through DARPA—for a limited number of university-based consortia in HTS.

The principal recommendation of the so-called "Wise Men's Report" on superconductivity is to establish four to six HTS R&D consortia, each involving a research university with participation by government labs and industry.[27,28] Properly organized and managed, such consortia could help to lengthen the time horizons of industry R&D and to improve the coordination of the U.S. HTS effort. But it is important to be realistic about what these consortia can be expected to accomplish. They are more likely to accelerate generic technology development and to create a pool of trained graduate students than to aid companies directly with commercialization of HTS products.[29]

Japan's International Superconductivity Technology Center (ISTEC)-a single consortium of all of the major Japanese companies involved in HTS—is viewed by some as a key factor that will put Japanese companies ahead in the race to commercialize HTS. But as explained in chapter 5, ISTEC's research agenda is focused primarily on materials development, not product development. For the latter, Japanese companies are relying on extensive in-house R&D programs (see ch. 6). Similarly, research consortia in the United States are no substitute for vigorous, independent R&D programs within the companies themselves.

There is also the danger that too many consortia could dilute the U.S. effort. U.S. companies involved in superconductivity R&D already have numerous consortia to choose from, including several in the private sector, at universities, and at Federal laboratories. (Some of the more prominent consortia are listed in table 4-10.) Most are seeking Federal funding (usually from DARPA), often proposing to do similar kinds of research. Ultimately, market forces and limitations of the Federal budget will sort out which consortia will survive and which will not. But the lever of Federal funding can be used to help consolidate resources into a limited number of strong consortia having clearly complementary objectives.

[26]The facilities for materials characterization at NIST are available at no charge for collaborative research projects with university scientists, as well as industrial and other government scientists.

[27]Committee to Advise the President on High-Temperature Superconductivity, op. cit., footnote 20.

[28]In May 1989, plans for a consortium based on the Wise Men's model were announced by IBM, AT&T, MIT, and Lincoln Laboratories, and $4 million to $6 million in seed funding was requested from DARPA. The announced goal of this consortium is to pursue prototype electronics applications of HTS.

[29]Previous experience with university-based consortia on the NSF Engineering Research Centers model suggests that the industrial participants are more interested in gaining access to new ideas and in hiring the graduate students than they are in the actual research performed. On the other hand, many companies view one-on-one research collaborations with universities as a far more productive vehicle for accelerating commercialization of technology. See U.S. Congress, Office of Technology Assessment, op. cit., footnote 13, p. 251.

Coordination of the Federal superconductivity R&D effort can be made more effective at the national level.

At present, U.S. superconductivity policy is essentially the sum of individual mission agency programs. Within each agency, coordination has been excellent (see ch. 4), and informal mechanisms for information exchange, e.g., the Office of Science and Technology Policy's (OSTP) Committee On Materials (COMAT) and its Subcommittee on Superconductivity, have done an excellent job in providing a snapshot of the various agency programs and budgets. But there is little in the way of a crosscutting overview of the U.S. effort that could provide a sense of coherence and direction. Such an overview is particularly important in times of fiscal austerity when difficult budgetary choices must be made-e. g., choosing which of the various HTS R&D consortia competing for Federal support should be funded.

It is this lack of a sense of direction that led Congress (in the National Superconductivity and Competitiveness Act of 1988, Public Law 100-697) to mandate that OSTP produce a 5-year National Action Plan for superconductivity, with the help of the National Commission on Superconductivity and the National Critical Materials Council (NCMC). The Act also requires that the implementation of the Plan be reviewed by OSTP in an annual report to Congress.

OSTP completed its work on the Action Plan in December 1989.[30] The Plan acknowledges the need for stronger leadership in coordinating the national superconductivity R&D effort, and proposes to initiate a crosscutting budgetary analysis of Federal HTS R&D spending in fiscal year 1991. But the Plan does not indicate how this analysis would be used to identify budgetary priorities, nor does it provide the 5-year perspective called for in Public Law 100-697.

Although several advisory committees on HTS have been appointed during the past 3 years—including the "Wise Men" advisory committee established by President Reagan, and the National Commission on Superconductivity established by Congress—these committees have been given only a temporary mandate, and cannot provide the long-term monitoring and analysis called for in the National Superconductivity and Competitiveness Act.

Option: Establish a standing advisory committee of experts on superconductivity to provide advice to Congress, the Science Adviser, and the President, and give it a mandate of at least 5 years.

There is no need for a "superconductivity czar. " But a standing advisory committee of experts could:

- identify overlaps and gaps in the Federal effort;
- help to catalyze a consensus among private sector groups on promising future directions;
- suggest rational guidelines for setting priorities where necessary, e.g., on limiting the number of consortia funded;
- evaluate the quality and relevance of HTS research in Federal laboratories, including military laboratories; and
- monitor follow-through on policy recommendations.

Ideally, such a committee would be small, with strong representation by industry-perhaps modeled on the Wise Men Advisory Committee. Its efforts would need to be supplemented by permanent staff, most appropriately at OSTP. In addition to providing assistance to the advisory committee the staff could:

- provide a central point of contact for menitoring industry concerns;
- provide a central source of information and referral regarding ongoing Federal HTS programs and activities of foreign competitors; and
- mediate disputes where the goals of different agencies conflict, e.g., disputes about restrictions on the dissemination of sensitive information.

Unfortunately, OSTP's present staff is small and poorly equipped to take on these additional responsibilities. One option for easing the burden on OSTP staff might be to give these responsibilities to the staff of the National Critical Materials Council and attach them permanently to OSTP.[31]

30"The National Action Plan on Superconductivity Research and Development," op. cit., footnote 19.

31This action may just formalize what is already taking place. Although NCMC had no active members during the period the Action Plan was being prepared, its staff contributed to writing the Plan and is temporarily housed at OSTP.

IMPORTANCE OF FUNDING STABILITY

There is one key point that relates to all of the issues discussed above, and it is one of the most important lessons derived from the history of LTS: *funding stability is essential for meaning/id progress.*

The Federal HTS budget grew from $45 million in fiscal year 1987 to an estimated $130 million in fiscal year 1990, with a budget request of $143 million for fiscal year 1991.[32] Are these funding levels sufficient? One early study called for annual HTS R&D budgets around $100 mi11ion;[33] this goal has been met and exceeded.

Today, the Federal HTS R&D budget is larger than that of any country in the world, approached only by that of Japan. In fiscal year 1989, the Federal Government spent about as much on HTS as it did on all other advanced ceramics R&D combined, and nearly twice the amount spent by U.S. companies. OTA finds that overall, the United States has an HTS R&D effort that is second to none. Present funding levels are sufficient to make progress, although perhaps $20 to $30 million more per year could be spent effectively (see options above). But if progress in HTS continues to be incremental, sustaining these funding levels in the face of mounting budgetary pressures may be difficult.

Except for the DARPA HTS program, there has been virtually no "new" money going into HTS. Instead, the money has been taken away from other research areas, notably advanced ceramics and LTS.[34] Given the pressures of the Federal budget deficit, it is appropriate that program managers in the various agencies should set priorities, and cut some projects to make funds available for areas of special promise. But while HTS continues to be a promising area, these other fields are also promising. As the initial euphoria over the discovery of HTS wears off and its political visibility is eclipsed by other more urgent priorities, pressures will build to shift funds away to other projects.

Whatever the funding levels, it is essential that they be dependable. Universities require stability in order to support graduate student thesis research. Companies require stability in order to plan their participation and give them the confidence to commit resources. Historically, Federal LTS R&D funding has followed an on-again, off-again course due to shifting political and economic winds. This has made it difficult to maintain a consistent set of technical goals and a stable pool of LTS engineering know-how.

The need for funding stability is by no means unique to HTS; it is a general requirement of efficient technology development. Mechanisms to improve stability, such as multiyear congressional appropriations, or moving to a 2-year budget cycle, have been proposed.[35] Options such as Federal funding for R&D consortia, participation in multiyear international programs, and focused, long-term projects (for examples in Japan, see ch. 5) represent alternatives that could enhance funding stability specifically for HTS.

SUPERCONDUCTIVITY IN A BROADER POLICY CONTEXT

OTA's finding that Japanese industry is investing about 70 percent more then U.S. industry in superconductivity R&D would not be so disturbing if it were not part of a larger pattern. But across a broad spectrum of emerging technologies—advanced ceramics, optoelectronics, robotics, etc., the story is the same. And Japan is not the only country where investment in these technologies is rising faster than it is in the United States. The common characteristic of all of these technologies is that they involve long-term, high-risk investments. Clearly, these kinds of long-term investments are becoming more and more difficult for U.S. managers to make.[36]

32Testimony of D. Allan Bromley, Director, Office of Science and Technology Policy, before the Subcommittee on Transportation, Aviation, and Materials of the House Committee on Science, Space, and Technology, Feb. 21, 1990.

33National Academy of Sciences, *Research Briefing on High-Temperature Superconductivity* (Washington, DC: National Academy Press, 1987).

34Overall LTS R&D budgets have been growing, but "R" has been cut while "D" has grown rapidly, because of DOE's Superconducting Super Collider program.

35Office of Technology Assessment, op. cit., footnote 21, p. 88.

36In the first half of the 1980s, industry R&D spending grew at an average annual rate of 8.2 percent; in the last half, real growth dropped to less than one-fifth that rate. National Science Foundation, Science Resources Studies Highlights, "Slow R&D Spending Growth Continues Into 1990s," draft report to be published, 1990.

The short-term mind-set of U.S. R&D managers is not the result of stupidity or ignorance about the importance of R&D to the company's future. Instead, the R&D investment decisions in both the United States and Japan are the product of rational choices made within the prevailing economic and financial environments of the two countries.[37] For decades, Japanese industry has benefited from higher rates of economic growth, lower effective capital costs, higher savings rates, and more stable financial markets than were the case in the United States. All of these factors made it easier for Japanese managers to make long-term investments.

Policy proposals aimed at lengthening the investment time horizons of U.S. industry have been the subject of a voluminous literature. Some have argued that direct tax incentives to companies, e.g., extending the R&D tax credit, or reducing taxes on capital gains realized on longer term investments (5 to 10 years), can help to stimulate long-term R&D. Others favor indirect policies that would reduce capital costs through Federal budget deficit reduction and encouragement of higher personal and corporate savings. Still others favor curbs on merger and acquisition activity to relieve pressures on managers to maximize short-term returns at the expense of long-term R&D investments and future earnings.

None of these policy prescriptions can be readily targeted on HTS, nor should they be. Although HTS remains a promising field, superconductivity at 77 K does not appear to stand clearly above other emerging technologies in its strategic or economic impact. HTS provides only the latest example of a technology that will require years of steady investment without a well-defined payoff if it is to achieve its potential.

Thus, the challenges associated with HTS research, development, and commercialization should be viewed as a microcosm of broader challenges to the U.S. manufacturing sector in an increasingly competitive world. It is tempting to rely on Federal R&D initiatives---e. g., new federally funded industry consortia, or creation of a new civilian technology agency—to regain a strong competitive position. But such initiatives, while they may be helpful, do not change the underlying economic and financial pressures on industry that dictate long-term investment decisions. The real solution-increasing the supply of patient capital to U.S. industry-will require politically tough fiscal policy choices that involve tradeoffs among military, economic, and social goals. If U.S. competitiveness continues to decline, it will not be because the United States lost the superconductivity race with Japan, but because policy makers failed to address the problems with long-term, private sector investment that HTS helped to bring into the spotlight.

[37] For a comparative analysis, see U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing*, OTA-ITE-443 (Washington, DC: U.S. Government Printing Office, February 1990), p. 93.