Chapter 1

Executive Summary

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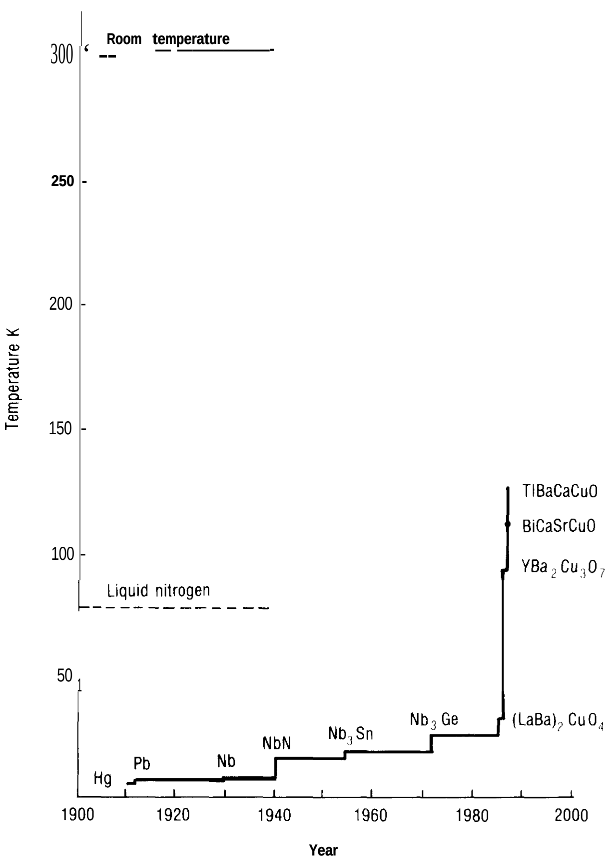
Executive Summary

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 I-I-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.)

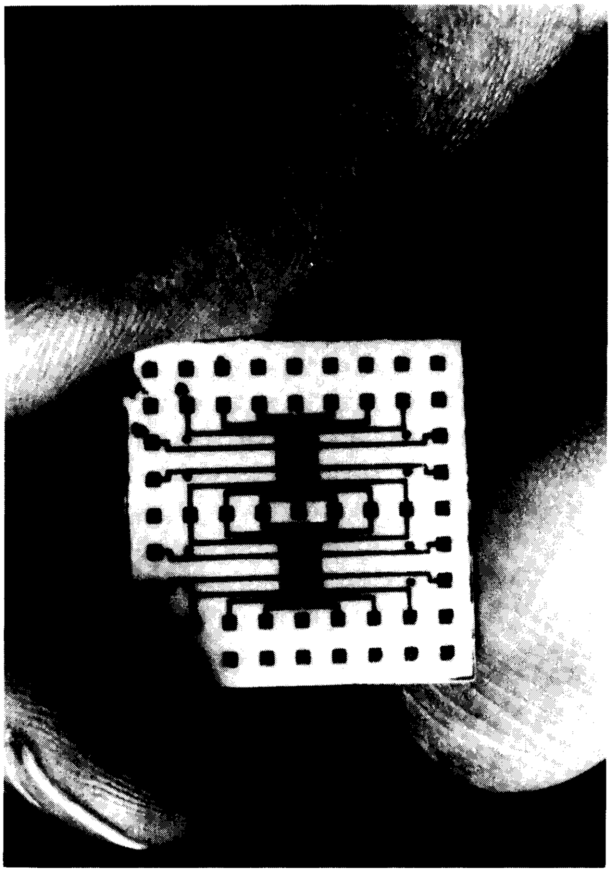


Photo credit: IBM Research

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

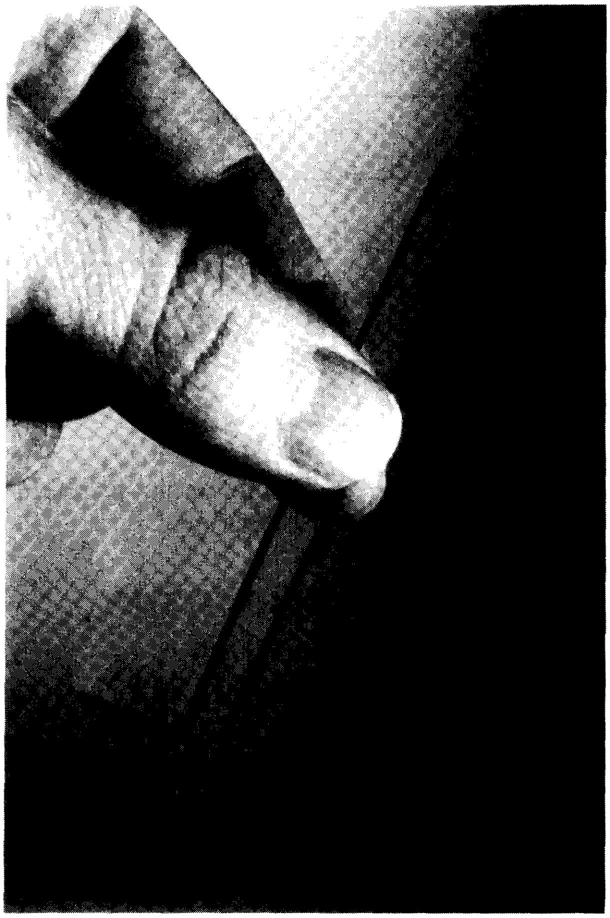


Photo credit: ICI Advanced Materials

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.

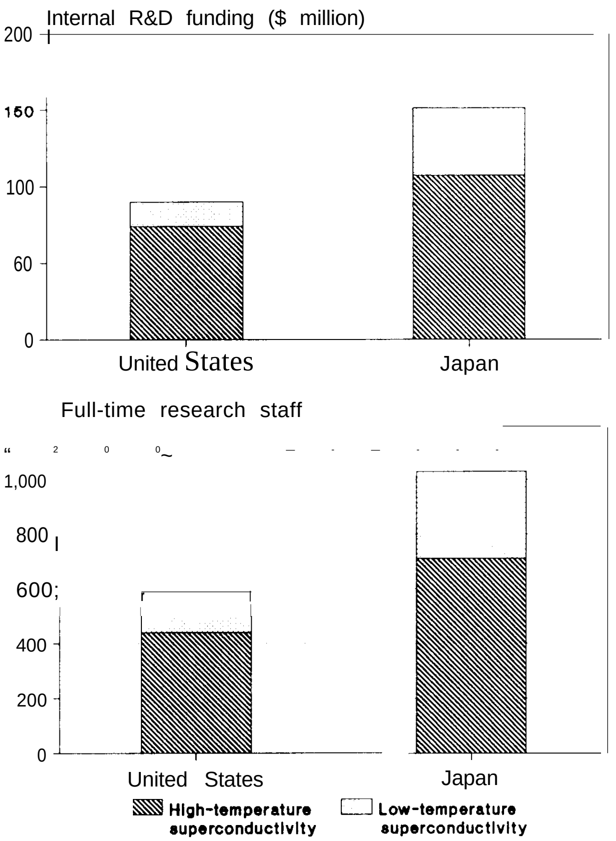
Although the European Community has been slow to organize cooperative research programs in HTS, the 12 member states represent an immense economic and intellectual potential, with more than a million scientists and engineers. In the past, effective collaboration has been hindered by dispersion of resources, 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.