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Report of the National Commission on Superconductivity

August 7, 1990



**Report prepared in accordance with provisions of the Omnibus Trade
and Competitiveness Act of 1988 (PL 100-418, Section 5143)**

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National Commission on Superconductivity
725 17th Street N.W., Room 5026
Washington, DC 20506
(202) 395-7200

August 7, 1990

The President
The White House
Washington, D.C. 20500

Dear Mr. President:

The final report of the National Commission on Superconductivity is enclosed pursuant to Public Law 100-418. The Commission came to a clear consensus on several major policy issues for U.S. research and development and commercialization in superconductivity:

- Strengthening of mechanisms that encourage enhanced industrial participation in superconductivity R&D through the leverage of federal investments in agency and university laboratories. This leverage reduces U.S. disadvantages of high interest rates, unfavorable tax policy, antiquated antitrust laws and other factors to compete effectively internationally for the great market potential that we foresee.
- Improvement of the business environment to encourage investment in long-range R&D leading to advanced, high-volume manufactured products.
- Identification of two ambitious goals to provide impetus and focus for U.S. superconductor technology:
 - an ultra high-speed computer operating at a million times the speed of today's state-of-the-art machines,
 - a prototype high temperature superconductor wire and magnet project.

The existence of these goals will provide targets and focus for the generic directions of superconductivity products, specifically advanced electronics and energy-related equipment with important fallout in other areas such as medical imaging. The Defense Advanced Research Projects Agency (DARPA) is suggested as the lead agency for the high-performance computing goal because of multiple defense-related requirements. The great importance of wires and magnets to energy efficiency makes the Department of Energy the natural lead agency for the second goal.

- Stable, strongly funded support of the university base, particularly for individual investigators. Breakthroughs will be required for large-scale use of superconductivity and it has been demonstrated repeatedly that these are most likely to originate from individual or small groups of researchers at universities, federal laboratories or industrial laboratories. University research provides the talent for tomorrow's technology. Positive actions are needed to reinforce support for the individual academic researcher.
- Establishment of a standing oversight group that will generate sound information on quality of the various superconductivity programs and establish support criteria and priorities.

These investments will pay abundant dividends.

Superconductivity is unique in its visibility and public appeal, as well as the basis for a wide range of promising applications that are important to the nation's future. Long term, well directed government support is essential to successful exploitation of the advanced products that will flow from the science of today.

The Commission was composed of dedicated individuals who though otherwise fully employed, gave freely of their time and energies. The presence of government employees as members of the Commission was extremely valuable and we hope that the resulting document will be more comprehensible and useful as a consequence of their efforts. The entire Commission worked hard, in a most harmonious manner, and as Chairman, I am indebted to them all for their vigor, intelligence, expertise and courtesy. We were fortunate to have the support of Dr. Bromley and his staff, the Office of Science and Technology Policy, and the National Critical Materials Council.

Sincerely yours,



D. W. McCall, Chairman
National Commission
on Superconductivity

Enc.
As above

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Prologue

The National Commission on Superconductivity was created through legislation (Public Law 100-418, The Omnibus Trade and Competitiveness Act of 1988) to "review all major policy issues regarding United States applications of recent research advances in superconductors in order to assist the Congress in devising a national strategy, including research and development priorities, the development of which will assure the United States leadership in the development and application of superconducting technologies." This legislation was a clear response to the explosion of interest in superconductors that began with the discovery of oxide materials that retain their superconductivity to much higher temperatures than had been previously achieved. Over the 3 years of this new era, important advances have come in rapid succession, and the measures of progress have broadened beyond critical temperature to include critical current capacity, critical magnetic field, processing, and other factors. Rapid progress continues in response to a worldwide emphasis on superconductivity science and technology. This activity is authentically global, with large numbers of publications from the European Community, Japan, and the United States, as expected, and surprisingly large outputs also from the Soviet Union and Eastern Europe, China, India, and other countries.

Superconductivity is a phenomenon of almost mystical character. The name itself, implying above or beyond conductivity, suggests properties that are at least unexpected, if not wholly improbable. Even today, scientists tend to think of superconductivity as a phenomenon in a class by itself, and intelligent nonscientists are susceptible to the charm of the field. Public awareness and enthusiasm has been sustained over the 3 years of the "high-temperature superconductivity era," and political leaders have encouraged vigorous, well-funded programs.

What are these remarkable properties? There are two broad areas of application. The first is the

improvement in magnets made possible through the zero direct current (dc) resistance property of superconducting materials. The strength of the magnetic field of permanent magnets is limited by the saturation of iron or other magnetic metals. Electromagnets based on normal high conductivity metals can achieve higher magnetic fields, but the resistance of the coils generates heat that must be removed by cooling water. A very high field magnet, say 10 tesla (T), requires removal of heat equal to the power needed by a small city. A magnet based on a superconducting coil can do the same job while creating no heat at all. Magnets are useful in medical imaging, scientific research, and similar pursuits. They also can be used to store energy and to help level the load of generating facilities. More important, all motors and generators are based on magnets, and superconducting magnets offer higher efficiency and much smaller machines. Superconducting technology's potential in the area of motors and power generation equipment is huge. In addition, electric power can be transmitted from generator to user more efficiently through superconducting wires and cables. Thus, the fabrication of wire to build magnet coils is a key enabling technology.

The second broad area of application is in the electronics field. Superconducting junctions are enormously sensitive to magnetic fields and are unique sensors capable of detecting blood flow and neuron signals in the brain or identifying military targets, to cite extreme examples. In addition, these "Josephson" junctions can exist in electronically identifiable states, possibly forming the basis of a new kind of electronics to process data orders of magnitude faster than the semiconductor circuits that create the miracles of today. The long-term potential of this new electronics in terms of the kinds of information processing that become accessible, such as weather prediction or rapid code breaking, is very great.

High-temperature oxide superconducting materials are in an early stage of their development

and the current emphasis is on enabling technologies. Progress has been rapid, and it is expected to continue. During 1989 and 1990, researchers from around the world reported important new results in the following areas:

- demonstration of ultrahigh magnetic field performance
- low-temperature growth of epitaxial films
- fabrication of non-hysteretic tunnel junctions that operate at 77K
- production of superior passive microwave cavities and devices
- flux pinning, to maintain currents in high magnetic fields
- steady progress in wire making
- single crystal growth and melt texturing to improve bulk samples
- increased understanding derived from crystal chemistry, electron doping, and quantitative measurements of normal and superconducting state properties

Discussions of the field of superconductivity usually focus on low-temperature and high-temperature materials. The low-temperature materials fall into two classes, ductile alloys such as niobium-titanium (Nb-Ti), which can be formed into strong wires and cables, and brittle intermetallic compounds such as niobium tin (Nb₃Sn), where

progress towards useful conductors has been less impressive, despite several decades of development. The high-temperature superconductors are oxide materials which are even more brittle than the intermetallic compounds, but the superior temperature performance is attracting intensive efforts to fabricate these materials into useful conductors. There will be low-temperature applications for oxide superconductors (for example, in the generation of ultrahigh magnetic fields), and the low-temperature/high-temperature distinction may become less useful as time goes on.

Many reports on superconductivity have been published over the last 3 years, including general studies as well as more narrowly defined reports directed at specific areas of application, such as electric power or military uses. The earlier studies were largely carried out by experts in the field of superconductivity, technically trained representatives of Federal agencies or customer industries, or both. The Commission has a uniquely broad mixture of technical specialists, government agency representatives, and individuals drawn from the management ranks of industry and the Federal laboratories. A number of Commission members have been key participants in earlier studies, and the Commission heard testimony from many experts in related areas. Thus, the Commission is well positioned to assess the contemporary wisdom of the field that is ably stated in earlier reports and to interpret the patterns in the context of broader policy issues. We are indebted to the authors of the earlier reports (see Appendix I) and trust that the present report will confirm the wisdom of their conclusions.

Executive Summary

Recent scientific and technical progress in oxide superconductors bring the revolutionary promises for commercialization of these materials closer to reality. However, the road to widespread applications remains long and arduous. The United States must make a sustained, concerted effort to compete effectively for potential markets and to realize the enormous opportunities offered by the discovery of the materials.

First and foremost is the need to develop an industrial technology base and a manufacturing capability for superconductor technology and products. The investment and participation of U.S. industry in superconductivity research and development is insufficient, especially compared to the situation in Japan, where industrial R&D is twice as large, making the Japanese better able to take advantage of innovative research and to develop products for the marketplace. To a large extent, a disadvantageous business environment in the United States, rooted in high interest rates, unfavorable tax policy, antiquated antitrust laws, and other factors, discourages U.S. industry from investing in high-risk technologies such as superconductivity.

Until structural repairs are made to improve the business environment, the resulting disadvantage can be offset by leveraging industry's investment with Federal R&D funds to build a level playing field for U.S. industry. The Commission supports the efforts of the Defense Advanced Research Projects Agency (DARPA) to develop superconductor technologies and insert these in U.S. industry because of the convincing advantage that superconductors provide for military requirements and the beneficial spinoff they will have on the commercial sector.

Better mechanisms must be developed to realize the potential of superconductors for commercial applications. The Department of Energy Superconductivity Pilot Center programs at three of its laboratories appear to be a very effective

mechanism to engage U.S. industry in cost-shared, collaborative R&D. Industry-led consortia (or alliances) are beginning to pool the resources of U.S. industry and leverage them with university and Federal laboratory research. These mechanisms should all be strengthened and others, such as the new Advanced Technology Program initiative of the Department of Commerce, should be encouraged.

To provide impetus and focus to the U.S. effort to commercialize superconductor technology, the Commission recommends setting two ambitious goals for these collaborative R&D programs: an ultra highspeed computer, and a prototype, high-temperature superconductor wire and magnet project.

The intrinsic advantage of high processing speed and low power dissipation of superconductors combined with continued advances in massively parallel computer architecture opens the possibility of reaching the petaflop computer regime—a millionfold improvement over today's technology.¹ There are several defense requirements for such computing speed—including real-time image and information processing, cryptography, and anti-submarine target identification—that should justify defense support for the long-term goal of petaflop computing. Novel applications in the commercial sector—such as improved global climate modeling, weather forecasting, and aerodynamic aircraft design—will follow. In addition, the advances required in thin-film synthesis and superconducting digital electronics necessary for petaflop computing will stimulate innovation in U.S. commercial electronics and computer industries.

A concerted national effort is required to develop high-temperature superconducting wire suitable for magnets, motors, generators, energy storage systems, and transmission lines. This will require a research and technology development effort beyond the scope of universities or individ-

ual companies. The enormous potential improvements of such devices in energy efficiency leads us to suggest a lead role for the Department of Energy laboratories in developing generic, but commercially useful, superconducting wire and prototype magnets. The Department will have to collaborate closely with universities to incorporate the latest scientific innovations and with industry to assure commercialization potential. Such an effort will also be very beneficial to defense applications where magnets, motors, generators, and electric propulsion could be improved significantly by superconductors.

Next to encouraging greater industry participation in superconductivity R&D, the Commission strongly recommends increased support for university research scientists and engineers. Although we are encouraged by recent technical progress, it is clear that continued innovation and scientific breakthroughs will be required to achieve the full potential of the new superconductors. It has been demonstrated repeatedly that these are most likely to originate from individual researchers or small groups of researchers at universities, Federal laboratories, or industrial laboratories. The history of superconductivity supports this contention. Support for university research is also important because it provides the talent for tomorrow's technologies.

The Commission recommends establishment of a standing oversight group that will generate sound information on progress in superconductivity. This group would report to the President's Science Advisor and the Office of Science and Technology Policy (OSTP) on the effectiveness of research being supported by the various agencies, on the effectiveness of mechanisms for coupling government R&D investments and U.S. industrial activity, on the establishment of research priorities, and on gaps in technical programs.

The Commission suggests the creation of an international committee to enhance planning and cooperation among the programs of the various nations. This group is not to be confused with the standing oversight group recommended above.

The Commission proposes that the National Science Foundation, with the cooperation of industry and other government agencies, should increase support for science education in the early grades and on through college. This is vitally important for maintaining the Nation's supply of scientists, engineers, and mathematicians. Superconductivity, with its public appeal, should be a useful subject for stimulation of student interest in these fields.

1. The speed of a computer is measured in terms of the number of floating point numerical operations (flops) it can carry out per second. Today, 10^9 operations per second, a gigaflop, is fast. A petaflop is 10^{15} operations per second. Massively parallel system architecture will be required to build a petaflop machine. The role of superconductivity would be to enhance the performance of individual processors.

Chapter I

Technical and Competitive Issues

It is generally accepted that recent discoveries in superconductivity will result in products with significant market value. A number of studies have shown that, for this to happen, a sustained effort will be required in an environment that combines industrial knowledge of markets and product development with both engineering experimentation and fundamental materials research. In a globally competitive environment, superconductivity is therefore a test case of the determination of our Nation to persevere and to cooperate in a well-defined technical area.

In this chapter, the scientific and technological developments that need to take place, the industries that might be affected, and the setting for these developments in the United States, Japan, and the Federal Republic of Germany are summarized, followed by the Commission's recommendations.

Scientific Perspective

Discovery

High-temperature superconductors were discovered by Bednorz and Mueller in 1986 at the IBM Research Laboratory in Zurich. These superconductors are layered compounds of copper oxide containing lanthanum and barium. Since that discovery, extraordinary progress has been made by scientists working at university, industrial, and government laboratories in many countries. Although the frenetic effort immediately following the discovery has abated, a large, steady activity continues. The largest and most coordinated efforts are in the United States, Japan, and Germany, but significant programs are also being pursued in other European countries and particularly in the U.S.S.R. The driving force for this activity comes not only from the intrinsic intellectual challenge of the phenomenon itself, but also more substantially from the large scale of its potential applications.

The discovery of the high-temperature superconductors has also revitalized interest in the search for new classes of superconducting materials, from organic metals to the more traditional alloys, that are now referred to as the low-temperature superconductors.

Recent Progress

Critical Temperature (T_c)

The highest reported superconducting transition temperature in the layered copper oxide compounds has quadrupled in the last 4 years, and currently the highest confirmed value is 125 Kelvin (K),¹ well above the boiling temperature of liquid nitrogen, which is 77K, or -196°C . This increase has been accomplished by greatly extending the family of superconducting copper oxides. This family consists of materials having superconducting layers containing one or more copper oxide sheets separated by "inactive" layers of variable oxygen content. Clarification of the crystal chemistry of these oxides has proven to be a fascinating chapter in the history of materials science.

Critical Current (J_c)

As important as critical temperature is critical current. A critical current density of over 5×10^6 amperes per square centimeter (A/cm^2) at 77K—a value, in principle, adequate for almost all conceivable applications—has been demonstrated. This value has been achieved in materials in thin films and demonstrates the magnitudes of currently attainable densities.

Critical Magnetic Field (H_c)

Several groups in Germany and in Japan have shown that critical current densities in the new oxide materials measured at 4.2K, the temperature of liquid helium, and at magnetic fields greater

than 25 tesla (T) exceed those of the best traditional materials. Plans are under way in both Japan and Germany to build magnets with these materials.

Devices

Rudimentary thin-film devices (superconducting quantum interference devices, or SQUID's) that use Josephson junctions to measure small magnetic fields or are passive components for microwave applications have been built and operated successfully. Significant progress has been made in producing tunnel junctions of these materials.

Although these accomplishments demonstrate that remarkable progress has been made in superconductivity in the last 4 years, much still needs to be done before widespread commercial applications of the high-temperature superconductors can be realized.

Low-Temperature Superconductors.

Progress in low-temperature superconductors is steady and primarily aimed at technological applications. For example, exploratory work on the use of superconductivity for digital applications continues in Japan and to a lesser extent in the United States. Researchers in the United States, Japan, and Germany are competing to improve wires for magnets used primarily in high-energy particle accelerators and medical applications of magnetic resonance imaging (MRI).

Areas of Research

Theory of High-temperature Superconductivity

The Bardeen, Cooper, and Schrieffer (BCS) theory of superconductivity provided a conceptual framework against which all experimental observations could be viewed. Although it has had remarkable success, the applicability of BCS to high-temperature superconductors is not universally accepted. It would be highly desirable to have a theoretical framework not only for its intrinsic intellectual interest but also to help find what limits critical current densities and upper critical fields, to show how equilibrium or nonequilibrium devices operate, and to guide the search for new

mechanisms for superconductivity or for new materials.

Grain Boundaries

In sharp contrast to low-temperature superconductors, grain boundaries in high-temperature superconductors limit current densities in polycrystalline materials. Systematic studies with bicrystals have shown that the critical current densities are a function of the misorientation of the two grains adjoining the boundary, but the origin of this behavior has not been established. Empirically, this means that wires must be made of aligned grains if high current densities are to be achieved. Japanese laboratories have recently been able to produce high-current-density wires primarily because they have been able to align grains within the wire.

From a practical standpoint, it is important to understand the origin of the grain boundary behavior and, based on this understanding or through empiricism, to minimize or eliminate the limitations it introduces. Eliminating these limitations would greatly expedite the fabrication of these materials in both films and wires. For films, it would relax the requirement of epitaxial growth, and for wires, it would remove the need to develop processes that align grains.

Processing

The ability to fabricate thin films and wires with the required properties represents a fundamental enabling technology that, once demonstrated, would help remove the skepticism of U.S. industry regarding the commercial opportunities these materials offer.

The electronics industry looks for the ability to prepare films with the desired properties on arbitrary substrates at the relatively low temperatures used in the fabrication of integrated circuitry on semiconductor chips. Controlled fabrication of tunnel junctions with long life and in narrow-line patterns is a prerequisite to active devices in highly integrated microchips.

Power applications all depend on the availability of long-length wires, tapes, or composite cables. The manufacture of multifilamentary superconductive wires with sufficient current-

carrying capacity, mechanical strength, and the ability to remain superconducting in high magnetic fields remains a formidable challenge, albeit one in which much progress has been made. This development needs to be integrated with overall conductor design that accounts for the necessary thermal, mechanical, and electrical stability required in the end-use applications. Although important contributions to the solution of this problem can be expected to come from individual investigators, the development of a manufacturing capability will require an interdisciplinary effort.

New Materials

In some applications, notably in electronics and instrumentation, it is desirable that a device's operating temperature be below room temperature, but for most other applications, the need for refrigeration is a constraint. Even in space applications, the highest transition-temperature materials (125K) are barely acceptable for ambient-temperature operation. Finding new materials—including new classes of materials—with still higher transition temperatures is therefore an important goal. The search for these materials is currently guided by crystal chemistry and by the intuition of the investigator rather than by an established theoretical framework.

Mechanical Properties

The high-temperature superconductors have an anisotropic crystal structure, which imparts to them a highly anisotropic thermal expansion; moreover, they are brittle ceramics. Consequently, the high- T_c materials tend to crack during processing and device fabrication and under tensile mechanical loads, making the fabrication of many high- T_c devices difficult. For example, these properties limit the radius of curvature with which wires can be bent in the winding of magnet coils. Work is needed to explore how to form these materials into desired shapes. Although this problem is difficult, experience with brittle low- T_c materials suggests that the problem will prove to be tractable, but that it requires sustained effort.

Refrigeration

Most high-temperature superconducting devices will require cooling well below their transition temperature for effective operation. Experi-

ence gained from low-temperature superconductivity applications suggests that the temperature of operation should be no more than approximately two-thirds of the T_c to ensure stable performance of devices. For bulk applications, such as motors or magnets, gas compression-expansion techniques or bath cooling will be adequate to support applications in the near term, and longer term development will not be constrained by lack of adequate refrigeration. A neon refrigerator operating at approximately 30K is an attractive option, particularly where we wish to combine ease of refrigeration with superior properties of high-temperature superconductivity. However, refrigeration may be a powerful enabling technology for micro-electronic devices, such as computer microprocessors, that are characterized by very small size, light weight, ruggedness, varied operating environments, and relatively low cost.

The goal for microelectronics is to develop microscale refrigerators. Ideally, such refrigerators would have the same operating life as the microelectronics themselves, so the refrigerators could be incorporated directly into the devices. In light of the size of the market for high-speed digital products, these novel technologies could provide the single greatest competitive advantage in the whole realm of superconductivity.

Industrial Perspective

Historical

Superconductivity remained an academic scientific phenomenon until the late 1950's, when two important scientific discoveries led the way to the technological application of low-temperature superconductors. The first of these was the discovery of type II superconductors and the realization of materials that can support supercurrent densities of 10^6 A/cm² at magnetic fields greater than 10 T (see Appendix VI). These advances in materials science opened up the possibility of a wide range of applications of superconductors to electric power equipment, high-energy accelerators such as the Tevatron and the Superconducting Super Collider (SSC), MRI for medicine, fusion devices, and levitation systems for transportation.

Around 1960, a second major discovery was the realization of electron tunneling through thin

insulating barriers between separate superconducting regions. This was followed shortly thereafter by the theoretical prediction and experimental realization of electron-pair tunneling, or Josephson tunneling, through thin barriers. These advances soon led to the realization that the zero-voltage critical current of a Josephson-tunnel junction could be used as a bi-stable electronic element of interest for digital electronics and computer applications. The coupling of such elements in a SQUID provides the possibility of detecting small changes of magnetic field on a much smaller scale than previously available. For example, changes as small as 10^{-11} gauss are readily measurable. For comparison, the Earth's magnetic field is approximately 0.5 gauss.

In the 30 years since 1960, considerable progress has been made in developing the technology of low-temperature superconductors for applications, specifically in the development of superconductor magnets, accelerators, and medical imaging. However, superconductors have not been widely applied in the electric power industry. There are many factors involved, but one of the most important is the inconvenience of the liquid-helium refrigeration technology needed to operate low-temperature superconductors.

Low-temperature superconductors have been used to build Josephson circuits and SQUID's. Various prototype superconducting computer chips were developed in the past decade by IBM in the United States and by ETL in Japan. The application of SQUID's to medicine, geophysical exploration, and military sensors was also widely explored. Nevertheless, the general impact upon the communications and electronics industries of low-temperature superconductors has been minuscule compared with the enormous industrial growth realized from silicon microcircuits.

The 1987 discovery of high-temperature superconductors with critical temperatures currently around 125K opened up the possibility of operating at temperatures above the constraint set by helium or hydrogen refrigeration. An operating point of 77K, the boiling point of liquid nitrogen, is a much more attractive goal than one of 4K, the boiling point of liquid helium. Because nitrogen is a component of Earth's atmosphere, it is relatively inexpensive and its refrigerator technology is

simple and well developed. Operation near 30K with neon refrigeration is also attractive.

Industry Sectors

The potential application of superconductors to specific industry groups will now be summarized, including present development work in low-temperature-superconductor systems. Substitution of high-temperature superconductors could occur in most cases as these materials develop.

Computers and Communications Industry

The inexorable trend towards miniaturization of electronic components continues in the computer and telecommunication industries. High-temperature superconductors offer a unique opportunity to combine semiconductors and superconductors at temperatures where both operate optimally. Such hybrid systems offer the potential of extending miniaturization further than a straightforward extension of today's silicon technology could. Such enhancements are desirable in our goal of increasing the speed of computers. Since this is an important goal, we suggest that considerably more emphasis be placed on programs exploring novel devices. For example, if a three-terminal superconductor device were developed, it would increase significantly the probability of using superconducting devices as active elements in commercial computer circuits. All superconductor microcircuit work is being done with low- T_c films, but as the ability to prepare high-precision high- T_c films improves, high- T_c superconducting microcircuits will emerge. The United States and Japan are running neck and neck in this area, ahead of the rest of the world. Some of the early products in high- T_c superconductors are likely to be SQUID's (discrete devices) and microwave components, which are passive.

Energy Industry

For 30 years, efforts in the United States have been made to develop superconducting power-system components such as generators, transmission lines, transformers, motors, and energy storage magnets with low- T_c materials. Despite considerable technical success with prototypes of generators and lines, the technology is currently moribund in the United States, except for an inter-

esting project on superconducting magnetic-energy storage. This latter work is supported by the Strategic Defense Initiative (SDI) and the Electric Power Research Institute (EPRI) as a possible energy source for beam weapons and electric-power load leveling.

Low- T_c superconducting generators are currently under development by SUPER GM in Japan, by Siemens in West Germany, by Alstom in France, and in the U.S.S.R. Unless the United States participates in this area, this market will be lost to foreign competition. Despite the fact that the growing pace of development in the less developed countries and Eastern Europe will expand the worldwide market for generators and motors and also create market opportunities for energy-storage systems, there is no large-scale program for motors and generators in the United States now. Because of structural disincentives for long-range investment or risky investment (see Chapter II), U.S. industry does not choose to compete for these potentially large markets. In view of the nature of the problem of magnet fabrication with high- T_c wire highlighted above, the Department of Energy laboratories would appear to provide an opportunity for a collaborative government-industry effort to develop the essential enabling technology in this field.

Low- T_c magnets have been widely tested in advanced energy-conversion devices such as tokamaks (fusion) and magnetohydrodynamic (MHD) systems, where they serve as an enabling technology.

Aerospace Industry

The aerospace industry has a strong interest in both the electronic and the energy applications of superconductors because both areas are important for military and space technology. The present emphasis is on thin-film processing and characterization for applications in the detector and sensor area. In the longer term, the interests also include power generation equipment, motors, magnetic shielding, energy storage devices, particle accelerators, and rail gun launchers. Present oxide superconductors are marginally able to operate in space without refrigeration.

Transportation Industry

The magnetically levitated train is a topic of widespread public interest, and the Commission discussed the issue at some length. Safe, high-speed ground transportation is a recognized national need of great benefit to U.S. society. Three general types of systems are under consideration:

- Advanced (rolling) railway technology
- Electromagnetic (that is, not superconducting) levitated trains (EMS-MAGLEV)
- Electrodynamic (superconducting) levitated trains (EDS-MAGLEV)

The choice among these systems will be largely one of performance including cost, speed, convenience, safety, and other aspects. It is possible that rolling technology might apply in certain areas while MAGLEV would apply in others. While EDS-MAGLEV is currently the only MAGLEV that uses superconducting magnets, advances in high-temperature superconductivity could also benefit the EMS-MAGLEV technology. The field of superconductivity would also benefit through advances in wire technology, magnet design, linear motor design, and the development of shielding technology. The National MAGLEV Initiative, which is transportation-oriented, will very likely stimulate activity in the U.S. industrial sector. Thus, assuming that MAGLEV is sound from a transportation perspective, its implementation would provide an important stimulus to the development of superconductivity as a basis for commercial applications. The Japanese National Railway has achieved speeds of more than 300 miles per hour (mph) in a 32-passenger vehicle levitated by a superconducting magnet. However, there is strong competition in this area from other types of systems. For example, SNCF in France has operated a steel-wheeled train, the *Train à Grande Vitesse* (train of great speed, or TGV), at speeds up to 320 mph and MBB in West Germany has achieved speeds of 256 mph with an EMS-MAGLEV system using conventional electromagnets.

Superconducting motors and generators have the potential to reduce the size and weight of all electric-drive ship-propulsion systems, as has been demonstrated by the U.S. Navy. There is also the possibility of using high-field superconducting magnets as an aid to an MHD ship drive in salt water. The Japanese have a 100-foot-long vessel scheduled for completion and testing in 1991.

Materials

The yearly demand for low-temperature-superconducting wire has remained at less than \$100 million worldwide. In the United States, this market has fallen into the hands of small entrepreneurial businesses because of lack of interest from big companies. However, in Japan and Europe the big electric companies have subsidiaries that are active in offering low- T_c product lines, usually more advanced than U.S. material because the parent company provides ample R&D funds. Copper wire companies, such as Sumitomo and Furukawa in Japan and Otokumpu in Europe, are extremely active in developing both low- and high- T_c wires. The world's chemical companies have recently realized the potential for high- T_c materials and some, such as Du Pont, Hoechst, and ICI, have committed significant R&D funds.

Medical Industry

A revolutionary approach to producing images of organs in the bodies of living creatures by noninvasive means is the use of nuclear magnetic resonance (NMR) combined with computer-based analysis. Magnetic resonance imaging, or MRI, requires a large-volume uniform magnetic field, usually provided by a large superconducting (low- T_c) magnet. Dynamic MRI is now under development to observe the motion of organs, such as the heart and its fluids.

MRI has already revolutionized internal diagnostic procedures in the developed countries. It is anticipated that in the future it will be augmented by magnetic resonance spectroscopy (MRS), in which it will also be possible to analyze organs for biological function. These developments will require large and uniform magnetic fields. The high-temperature superconductors, which may be able to produce magnetic fields substantially larger than the low-temperature superconductors, are

candidates when operated at liquid-helium or liquid-neon temperatures.

Another application of superconductivity to medicine is the use of SQUID's to detect magnetic signals from the brain, heart, and muscles and to analyze the location of specific signals to better understand the body's electrical systems. The high-temperature superconductors can, in principle, give higher resolution simply because the detector can be closer to the source of the signal in the human body. This advantage arises from the simpler design of the cryogenic equipment for 77K operation.

Instrumentation Industry

More and more useful instruments are being created to exploit the various phenomena that take place in high magnetic fields produced by low- T_c coils. For example, the analysis of small energy differences between the various protons bound into complex biological molecules is made possible by NMR performed in highly uniform high-magnetic fields provided by low- T_c magnets. Two other commercial applications using superconductivity are magnetometers and high-speed sampling oscilloscopes.

Other developments, such as compact light sources that produce monochromatic x-ray radiation suitable for x-ray lithography, would benefit the electronics industry but may also find applications in medicine. These machines, with selective radiation wavelengths, would produce enhanced-contrast images while minimizing radiation doses to the patient. Higher magnetic fields from superconductor magnets allow the apparatus to be made more compact.

Country Perspective

Much has been written about the comparison between the activities in the United States and Japan in the field of high- T_c -superconductivity R&D. Japan is clearly the principal actor among the Asian nations, though India and China have active research groups. We give below a brief summary of the work being carried out in several European countries, followed by a more indepth comparison of the United States, Japan, and Germany.

In Europe, Germany is the principal competitor, although France, England, the Netherlands, and Italy contribute strongly to the overall European effort. Oxford Instruments of England, for example, supplies low- T_c high-field magnets for MRI scanners. Moreover, the European Economic Community (EEC) fosters collaborative R&D programs that involve university, industrial, and national laboratory teams for three or more countries. The immediate response to the advent of the high- T_c superconductors was the establishment of national research centers and an EEC thrust. In this report we highlight the German activities, as these appear to be most strongly coordinated with industry for the exploitation of applications.

Eastern Europe, particularly the U.S.S.R., has a distinguished history of superconductivity research; they have made a number of fundamental contributions to theory, in particular to our understanding of high-field superconductors. After 1960, high-field multifilamentary conductors of niobium-zirconium and Nb-Ti were developed and used in low- T_c magnets for accelerators, bubble chambers, hot-gas MHD systems, and experimental fusion systems of the tokamak type. Various advanced electrical machines—including dc homopolar and ac synchronous generators—have been developed in the 2- to 20-megawatt (MW) range; a 300-MW generator for use in the Soviet electric power grid is under construction. The Soviets are also experienced in refrigeration technology, and they have extensive experience with high-technology ceramic materials. They have allocated substantial funds to research on high- T_c materials, and various laboratories have reproduced and confirmed most of the experimental results reported from the United States and Japan. However, there is little evidence that linkages between science and industry have been developed in this area. Russian industry is not yet in a position to compete commercially in a free world market.

Before summarizing the respective—indeed competitive—efforts in the United States, Japan, and Germany, attention is called to the fact that international cooperation is excellent on the fundamental theory of high- T_c superconductors and on how to address the materials problems that underlie the principal enabling technologies. In view of the long-term nature of the challenge of high- T_c superconductors, this cooperation is to be

applauded. The U.S. provision of data bases and updates open to all is a contribution to this cooperation that deserves special mention.

United States

The Federal Government is the largest source of high- T_c research and development funds, supplying \$130 million in fiscal year 1990, followed by industry, with \$66 million, and special State programs, with approximately \$15 million.² Most of the work, 49 percent, is performed by industry, while Federal laboratories perform 26 percent and universities perform 25 percent. Federal funds are authorized annually, and the commitments by industry typically range from 1 to 3 years.

As reported by industry, 28 percent of its effort is in basic research for fundamental understanding, 47 percent is in applied research on the process and device scale, and 26 percent is in the development of larger scale components and systems aimed at applications. Thin films for electronics applications are the sole aim of 53 percent of the companies; bulk superconductors, such as wires, are the focus of 22 percent; and 25 percent work in both areas.

Department of Defense support constitutes 47 percent of all Federal funding, or 29 percent of all U.S. efforts. This fact indicates a strong, but not overwhelming, emphasis on defense applications.

It is estimated that there are 1,000 full-time researchers in high-temperature superconductivity in the United States. Three companies report having more than 20 researchers. Of these three companies, two are in computers and communications and the third is a materials supplier.

Integration of industry, university, and Federal laboratory research results for applications development is a challenge being addressed by several major efforts.

Japan

Japan's total effort in high- T_c superconductivity is equivalent to \$165 million per year. Industry supports \$86 million and the government most of the remainder. Industry performs 57 percent of Japan's high- T_c R&D, with the remainder primarily in national laboratories and in some universi-

ties. Funding commitments are generally long-term. The Ministry of Education supports several three-year university programs. The Ministry of International Trade and Industry (MITI) supports two 10-year high- T_c programs, including materials and process work at the International Superconductivity Technology Center (ISTEC) and the national laboratories, and a bridging forum between this program and industry.

Industry reports that 37 percent of its efforts are in basic research, 42 percent in applied research, and 20 percent in development. Forty-one percent of the companies are pursuing thin films exclusively, 7 percent bulk, and 51 percent both areas.

Approximately 1,200 full-time researchers work in high- T_c superconductivity. Nine companies have more than 20 researchers each. The companies represent diverse industries.

ISTEC is a major initiative by MITI, but it is viewed as focusing on enabling and new-materials research rather than specific applications development.

The success of Japan's superconductivity effort has been demonstrated by the early development of prototype wires, coils, and microprocessors. Mitsubishi has produced 2-centimeter lengths of YBCO ($\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$) wires that can carry currents of 730,000 A/cm² at 77K. Sumitomo expects to market high- T_c magnet coils by 1991, based on BSCCO ($\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$) tape, currently capable of producing a 140-gauss magnetic field at 77K in a 1-T magnetic field. Furukawa has demonstrated 210,000 A/cm² in a BSCCO tape at 4.2K and 30 T. Results of this genre pave the way for substitution of high- T_c for low- T_c materials in high-magnetic-field applications.

In the digital-circuit arena, Fujitsu has demonstrated an eight-bit low- T_c microprocessor based on Josephson junctions. It operates 10 times faster than gallium arsenide (GaAs) circuits with only 0.2 percent as much power dissipation.

These are only some examples of Japan's prowess and long-term commitment to winning the race for advanced superconductor markets. The reports listed in Appendix I provide much

more material than can be recounted here. In this area, the United States is competing with a Japanese program that is a source of national pride to the Japanese people and is focused on those markets that are most challenging in the long term. Perhaps the Japanese recognize that the structural disincentives to U.S. industry put it at a disadvantage in long-term economic competition.

The primary vehicle for integrating research results into practical applications is within each individual company. The government support is focused on ten large companies; continuing efforts in low- T_c superconductivity development and applications provide a productive template for rapid commercial applications of high- T_c superconductivity. The Commission believes that Japanese industrial activity is ahead of industrial work elsewhere.

Federal Republic of Germany

The Federal Republic of Germany has a long history of excellent fundamental research and vigorous development in superconductivity and its applications. This continues to be the case with the new high- T_c superconductors. Germany has the largest overall program in Europe for their development; present government support is about \$50 million per year, with at least 50 percent more from industry. The German program is also one of the best coordinated in the world, rivaling that of the Japanese. It must be noted that research dollar values are highly leveraged because the salaries of all university professionals and many industry and laboratory professionals are paid through other means.

The German Ministry for Research and Technology (BMFT) supplies about half the government funding for superconductivity research. This program supports four major thrusts in universities, industry, and government laboratories: development of superconducting magnets, cryogenics, development of practical conductors, and new applications for superconductors. Another quarter of the government support is through the DFG, the German equivalent to the U.S. National Science Foundation (NSF); this support goes exclusively to universities for fundamental research. The final fourth is direct funding to the two major government laboratories—the Kernforschungszentrum, Karlsruhe (KFK), and the Kernforschungs-

anlage, Julich (KFA)—and to the several Max Planck Institutes for the entire spectrum of very fundamental to applied research.

Accurate levels of industrial support are difficult to obtain, but estimates range from half to more than all the amount the government supplies. The major industries supporting high- T_c research are Hoechst, a major chemical company; Siemens/Vacuumschmelze, a diverse large-equipment manufacturer (and its superconductor subsidiary); Daimler-Benz/AEG/Dornier, another large conglomerate; and Bosch, a major electronics company. Siemens has historically produced most of Europe's superconducting magnets and has been very strong in development. Vacuumschmelze is one of the best and largest superconducting-wire manufacturers in the world and has already produced relatively long lengths (100 meters) of a composite silver-clad YBCO wire. Hoechst, Daimler, and Bosch have been aggressive in producing high- T_c films, microwave components, devices, and wires. Many small companies are involved in the development of possible products through joint funding with universities. A key feature of the industrial activity is continued involvement with conventional superconductor applications, including several international large-scale projects such as fusion or accelerator cavities and magnets.

In addition to the several Max Planck Institutes, there are about 15 universities active in high- T_c research; some of these have been long-time leaders in fundamental superconductivity research. Their support is frequently contingent upon industrial involvement, and personnel exchanges are common and intensive. Funding commitments are long, up to 7 years, which enhances the ability to draw bright, young researchers to the field.

Two major government laboratories, KFK and KFA, take on advanced technology development in conjunction with industry. KFA formed a new electronics institute for semi-superconducting hybrid devices.

Overall, Germany has a long-term commitment, is well-balanced between low- and high- T_c R&D, and includes university-government laboratory-industry consortia or collaborations that are

well positioned to develop and exploit any breakthrough achievements in the enabling technologies.

Summary

Almost all the research related to applications can be divided into two broad categories. The first of these is directly important to the computer, communication, aerospace, and instrumentation industries. We shall broadly define this category as superconducting electronic devices and components. The second is of direct concern to the energy industry but also influences the medical and transportation industries, and this we shall call superconducting wire products. Programs in the United States, Japan, and Germany can be compared using this categorization.

Superconducting Electronic Devices and Components

Research in this area is largely, but not completely, evolutionary. That is, the research will continue to produce improvements and innovations through a systematic and sustained effort. We understand well enough our goals and what is needed to improve materials and processes to the point where successful devices and components can be built. No fundamental limitations in materials have been identified. These can be for analog or for digital applications.

However, there is also the potential in this category for either unanticipated applications or for a revolutionary new device. Invention and discovery cannot be planned, but a climate conducive to their occurrences can be. It will require an emphasis on device physics and a concomitant search for novel devices and applications.

The United States and Japan lead the world in the superconducting components and device area. The Japanese commitment to the evolutionary approach is firm and broad. There is a strong cross flow among various institutions to rapidly assimilate new results that may lead to products. The United States has only recently embarked on encouraging sustained cross flow among university, government, and industrial laboratories. These efforts should be encouraged and monitored to

ensure industry participation (see Chapter III for further discussion).

There appears to be no systematic approach to encouraging revolutionary devices or new applications in the United States, Japan, or Germany. Here, perhaps, may be a unique opportunity for the United States to establish a leadership program.

Superconducting Wires

Germany and Japan have produced many of the first prototype wires of the high-temperature superconductors. Although there is a program in the United States, it lacks the coordinated focus that appears to be present in Germany and Japan. Success in this area will be directly related to strengths in materials science and the pull to use the wire for some significant application. In Japan there is a commitment to make magnets from high-temperature superconducting wires. Such a commitment is lacking in the United States.

Recommendations

Recent scientific and technical progress in oxide superconductors bring the revolutionary promise for commercialization of these materials closer to reality. There is an ongoing need to maintain a strong, sustained program in the field of superconductivity. In high-temperature superconductivity this spans the range from fundamental issues connected with the mechanism of superconductivity through a search for new materials to prototype devices and components. The Federal Government in the United States must continue to play a pivotal role through funding mechanisms to promote cooperation among universities, industry, and Federal laboratories. It must also provide significant encouragement for researchers to work on novel devices, new appli-

cations, and refrigeration techniques. For research on wires, coordination needs to be improved and a goal set for the use of wires. Such an approach would provide the United States with an enabling technical base from which industry could compete. Hence, we recommend the following:

- The Federal Government must continue to foster a broad base of research on superconducting materials as part of a larger effort on materials science.
- A national coordinated effort to develop and to use wire made with high-temperature superconducting materials should be established to enable commercialization of motors, generators, and other products. Department of Energy laboratories are well positioned to lead this effort with strong input from universities and industry.
- There is significant potential for making discoveries that lead to new electronic devices with great impact on society, particularly in the high-temperature superconductor area. This type of effort needs to be encouraged through increased attention and funding. The Defense Advanced Research Projects Agency (DARPA) is sensitive to important defense needs and would be the logical lead agency to stimulate industry activity.
- Compact refrigeration techniques could greatly affect semiconductor and superconductor devices. Research in this area needs to be strengthened.
- The recommendations made in the "Wise Men" report (see Appendix I, item 8) that urge collaboration among industry, university, and government laboratories must be sustained until we can properly assess their impact.

1. Kelvin is a temperature scale for which 0K corresponds to -459 degrees Fahrenheit and room temperature is approximately 300K. Note also that the units are Kelvin and not degrees Kelvin.

2. The breakdown of funding given in this section is taken from the 1990 Office of Technology Assessment Report *High Temperature-Superconductivity in Perspective*. Note that this breakdown covers only high- T_c expenditures, while the tables in Chapter III cover both high- and low- T_c activity.

Chapter II

Legislative Issues

Legal and Regulatory Barriers

Superconductivity is an extraordinarily promising technology. However, there is a general perception that the level of industrial investment in superconductivity research and development in the United States is too low, especially in view of the international competition in this area. To overcome the technical barriers necessary to bring applied superconductivity to the marketplace rapidly enough for the United States to be competitive, barriers to increased industry investment in superconductivity research and development (R&D) will have to be surmounted.

Superconductivity has three attributes that are relevant in assessing government policies that are barriers to increased industry investment in R&D. First, the technology probably will be very expensive to develop. Second, investments in the technology are extremely risky. That is, even if large sums are invested, there is no guarantee that all the technical barriers to practical high-temperature superconductivity will be overcome. Third, even if the technology does eventually prove practical, it could be many years before a firm recovers its investment in R&D and starts to make a profit. These three attributes make investment in superconductivity R&D more sensitive than many other kinds of R&D investment to government tax, antitrust, and patent policies.

Tax Policy Barriers

Several features of the U.S. tax code tend to reduce saving and investment and to increase the cost of capital—a disincentive to industry investment in R&D. This, in turn, limits the level of effort focused on the development of new technology because it reduces the rewards for basic and applied research. Removal of these tax policy barriers is essential to encouraging increased industry investment in research on superconductivity.

The Commission received testimony from outside experts who made specific suggestions for revision of the U.S. tax code to help reduce the high cost of capital. However, it is beyond the scope of this report to reiterate those recommendations inasmuch as most of them have been reviewed extensively elsewhere.

Nevertheless, the cost of capital is such an overwhelmingly important barrier to increased industry R&D investment, including superconductivity R&D, that it must be re-emphasized. Among the issues that would have to be addressed to reduce the cost of capital are the need to eliminate the basic tax bias against saving and investment, the need to remove the double taxation of corporate income paid as dividends, and the need to reduce the capital gains tax.

In addition, several suggestions that apply specifically to R&D investments were presented to the Commission. Some of those that have direct implications for superconductivity research investment could be adopted without general tax reform. Primarily, they involve restructuring the Research and Experimentation (R&E) Tax Credit.

Beginning in 1990, current law provides for a credit generally equal to 20 percent of a taxpayer's qualified incremental research expenditures in excess of a fixed amount. Startup companies can also qualify for the credit. This is a significant improvement over prior law, in which the base was a 3-year moving average. Under the previous law, the effective advantage of the R&E Tax Credit was much less than 20 percent; some estimate only a 3-percent incentive, too small to have much effect on industrial investment. Authorization for the credit will expire at the end of 1990 unless it is extended by law.

Another structural defect is that large increases in R&D spending are not encouraged because no credit is available on expenses that exceed 50 percent of current qualified expenses.

In addition, expenses for research carried on outside the United States are not eligible for the tax credit. Nor is the tax credit available after commercial production is begun, which ignores the fact that global competition requires accelerated implementation, with research, development, and initial production frequently taking place in a continuum of activity.

Another factor limiting the tax impact of the R&E Tax Credit is the effect of apportionment of domestic research and development expenses to foreign source income as required under current tax rules. And finally, the continual threat of repeal of the R&E Tax Credit, which has always carried an expiration date, reduces the impact of the tax credit as an incentive. Research and development is by its nature long-term, and to be an effective incentive, the R&E Tax Credit and the allocation rules for foreign source income should be made permanent, as the Administration has proposed.

Adoption of any or all of these suggestions would tend to encourage R&D investment, especially in long-range, high-risk R&D, which characterizes superconductivity research.

Antitrust Policy Barriers

The same three attributes of high-temperature superconductivity that entered into the analysis of tax policy barriers to increased industrial investment in R&D also are relevant in assessing the impact of antitrust laws. Because development of high-temperature superconductivity will require large speculative investments and may take many years to pay off, relatively few firms will likely be willing to undertake such investments on their own. The Commission received testimony indicating that fewer than a dozen U.S. corporations have significant programs in superconductivity R&D.

However, by pooling their efforts and sharing risk, firms can greatly reduce the risk borne by each individual firm investing in high-temperature superconductivity R&D. Moreover, combining knowledge, skills, expertise, and technology can greatly increase the likelihood that the R&D efforts will be successful. Cooperation also makes possible a larger scale of operation than any one

firm acting alone might be capable of, thereby making available economies of scale and scope and eliminating unnecessary duplication of effort.

For all these reasons, superconductivity is a natural candidate for the formation of joint R&D ventures. Many firms that could not even consider investing in superconductivity on their own might be willing to participate in a joint venture with other firms—provided that such ventures will not expose them to liability under the antitrust laws.

The antitrust laws originated in the last century, when foreign competition was not a significant factor. Now, however, many U.S. companies must compete in worldwide markets against foreign companies whose operations are largely beyond U.S. antitrust regulation. One attempt to modernize U.S. antitrust laws relevant to commercialization of technology is the National Cooperative Research Act of 1984 (NCRA). The NCRA currently provides limited protection from State and Federal antitrust laws for coordinated R&D activities, which could include joint ventures formed for the purpose of engaging in precompetitive research and development related to superconductivity. However, the provisions of the NCRA as currently structured limit its usefulness.

Most important, production and marketing are not covered by the NCRA. This feature limits the impact of the NCRA as a stimulus to coordinated research and development. The nature of competition in international high-technology markets is such that bringing a product to market quickly is essential. Modern technology transfer, however, is not based on a stepwise transition from innovation to development to commercialization. Rather, transfer often involves an interactive process, with simultaneous investment in research, development, production, and marketing. These steps are integrally linked and frequently can be conducted more efficiently through cooperative efforts. Such activities, however, are not currently protected under the provisions of the NCRA. Antitrust laws in the United States are still a major concern for industrial firms wishing to engage in cooperative programs to commercialize superconductivity.

An extension of the NCRA to production or to production and marketing would encourage industry investment in cooperative superconduct-

tivity research and development as well as commercialization. Action on the several bills currently pending in Congress that would extend the NCRA to cover production or production and marketing would greatly assist U.S. competitiveness in developing and commercializing products based on superconductivity. It should be noted that legislation supported by the Administration, transmitted to Congress by the Departments of Justice and Commerce, would extend the NCRA to cover production but would exclude marketing.

There are, of course, serious concerns about the possible abuse of extended provisions of the NCRA, but anticompetitive behavior would still be illegal and significant penalties for such behavior would remain in place. However, the resulting stimulus to industry investment in superconductivity research, development, and commercialization would be an important outcome.¹

Intellectual Property Law Barriers

Several steps have been taken to revise the American patent system in ways that affect the field of applied superconductivity. One change has been directed specifically at the science and technology of superconductors. In July 1987, the President announced the High Temperature Superconductivity Initiative with the stated objectives of improving cooperation among government, industry, and universities in research and enabling U.S. firms to move quickly in turning scientific advances into new or improved products and processes. The President called for stronger intellectual-property protection and requested the Patent Office to accelerate the review of applications dealing with superconductivity.

In reviewing the impact of current intellectual property laws on U.S. industrial investment in innovation and commercialization of technology, external experts presented several suggestions for improvement of the domestic patent situation. These changes would provide U.S. inventors with greater protection and would allow them to compete in the international marketplace.

Among the issues discussed was harmonizing the U.S. patent system, which differs in several

respects from those of our international competitors. There are ongoing negotiations on the possibility of bringing the U.S. system into harmony with those in effect in Japan and Europe. The most significant difference is that in the United States the system is based on the "first to invent" concept, whereas elsewhere the system is based on the "first to file" concept.

Other issues include extending exemptions from the Freedom of Information Act, increasing the public availability of foreign patent applications, modifying the Doctrine of Patent Misuse and antitrust restrictions to permit patent holders to maximize their return by licensing, encouraging Japan to change its system substantially to eliminate flood patenting, and strengthening the ability of the Patent Office and the courts to protect intellectual property rights by full implementation of the High Temperature Superconductivity Initiative.

Summary of Legal and Regulatory Barriers

The preceding tax, antitrust, and intellectual property issues are discussed more fully in Appendix VIII, along with more specific recommendations that were presented to the Commission by outside experts.

Reducing the cost of capital, extending certain exemptions from the antitrust laws, and full implementation of the High Temperature Superconductivity Initiative to strengthen intellectual property rights under the patent laws will be crucially important in preventing the relative decline of the United States in key technologies such as superconductivity. But other significant steps must also be taken, including investing in science and technology education to provide the skilled work force needed in modern society, enforcing trade policies designed to open markets abroad, and providing strong support for those Federal agencies that conduct or fund research in superconductivity. Taken together, these steps will help the United States to remain competitive with Japan and the European Community and in time will certainly encourage the successful commercialization of innovative technologies such as high-temperature superconductivity.

Technology Transfer and the Federal Laboratories

A substantial part of the research on superconductivity carried out in the United States takes place at the Federal laboratories, primarily under funding from the Departments of Defense, Commerce, and Energy. This work has tended to be basic, at a precompetitive stage, and not well enough developed to make the transition to commercialization.

Recognizing that remaining competitive in fields such as superconductivity requires integration of activities in all sectors of research and development, Congress has enacted legislation that emphasizes the importance of technology transfer from Federal laboratories to industry and has substantially improved the ability of the laboratories to carry out this mission. The legislation includes the Stevenson-Wydler Technology Innovation Act (1980, Public Law 96-480), the Bayh-Dole Act (1980, Public Law 96-517), as amended (1984, Public Law 98-620), the Federal Technology Transfer Act (1986, Public Law 99-502) and the National Competitiveness Technology Transfer Act (1989, Public Law 101-189).

In general, these legislative acts collectively mandate expenditure of funds for technology transfer activities, create a presumption of ownership in inventions to government contractors that are small businesses or not-for-profit organizations, delegate to the directors of laboratories the authority to enter into cooperative R&D agreements with private organizations and to provide exclusive licenses on mutually developed technologies, and provide to an inventor who is a government employee an award of at least 15 percent of any royalties received by the agency from the invention.

By Executive Order 12591 (1987), President Reagan instructed the agencies to delegate the authority for implementation of the Federal Technology Transfer Act to laboratory directors. In addition, he required the agencies, to the extent permitted by law, to grant title to all contracts to inventions made in whole or in part with Federal funds in exchange for royalty-free use by or on behalf of the Government. Subsequent increases in the number of cooperative agreements signed, the number of patents issued and licensed, and the

amount of royalties received by the laboratories under licensing agreements with industrial organizations have been reviewed recently in a Department of Commerce report, "The Federal Technology Transfer Act of 1986: The First Two Years."

In 1988, the Department of Energy specifically addressed technology transfer with regard to superconductivity when it created the Superconductivity Pilot Centers at the Argonne, Los Alamos, and Oak Ridge National Laboratories. These Centers are designed to offer expedited procedures for concluding collaborative agreements, greater protection of intellectual property, and easier access to patents and exclusive licenses for collaborative R&D. With the leverage provided by the strong basic-research programs and the major user facilities in the laboratories, the Pilot Center program was considered to be an effective model for economically integrating laboratory and industrial activities in collaborative development.

The Pilot Centers have provided an innovative incentive by granting industrial organizations contracting with national laboratories the authority to withhold for a period of up to 2 years data specifically developed under cooperative R&D agreements. Industry has responded well, with approximately 30 agreements signed to date, and there are now more proposals involving industry than there are funds to support them. While the nature of the agreements vary, the most common mode is a straightforward cooperative agreement with joint funding on a roughly 50-50 basis. The three Pilot Centers have recently formed an Industrial Oversight Committee to ensure that the programs are guided by input from industry.

In 1989, an amendment to the Technology Innovation Act expanded once more the flexibility given to Federal laboratories. Under the provisions of this act:

- The procedures for forming agreements have been further decentralized. The Director of a Federal laboratory (both contractor-operated and Government-operated) has the authority to execute cooperative agreements with a sponsor, including assigning or licensing laboratory employee inventions to the sponsor. (This requires the express approval of the funding agency.)

- Investigators have been provided further incentives. Royalties to the laboratory from a cooperative agreement may be used by the laboratory to pay the inventors and for scientific R&D consistent with the laboratory mission.
- The approval process has been accelerated. A joint work agreement by a laboratory must be approved or disapproved by the Federal funding agency within 90 days after submission. A cooperative agreement under the joint work statement must be approved or disapproved within 30 days after submission.
- Protection of data has been expanded. Public dissemination of commercially valuable data generated under a cooperative agreement may be withheld for a period of up to 5 years. These data are expressly exempted from a Freedom of Information Act request.

At this point, considerable legislation is in place to allow the laboratories to pursue technology transfer more effectively than was possible in the past. It will be important to monitor such activities to ensure that the current legislation is adequate. A major task at present is to learn how to effectively implement what is now available. This will require dealing with both legal and institutional issues. For example, strong cultural differences exist between the Federal laboratories and industrial organizations that may cause difficulties in some areas—such as the conflict between freedom of publication and proprietary rights. Agreements such as those developed by the Pilot Centers have been effective in putting together disparate infrastructures. Concerns about potential conflicts of interest involving compensation of investigators working simultaneously under a collaborative agreement and on related work within the base programs are expected to be resolved.

1. A recent report by the Office of Technology Assessment, *High-Temperature Superconductivity in Perspective*, states that "antitrust restrictions are not a serious inhibitor to U.S. competitiveness in HTS technology." (8, 118) Our analysis of the impact of antitrust policy leads us to believe that the OTA report was referring only to pre-competitive R&D and did not take into account the continuum of research, development, production, and marketing that is required for effective commercialization in a worldwide competitive environment.

Chapter III

Enhancement of Superconductivity Research and Development

Introduction

There has been a strong response throughout the scientific and engineering communities to the discovery of high-temperature superconductivity by Bednorz and Mueller. Individual scientists at universities and Federal laboratories and in industry have undertaken new lines of research designed to understand the new superconductors and to measure their physical properties. New ways of dealing with the interdisciplinary nature of the subject and the transfer of potential technology from research laboratories to manufacturing plants have already been set up. University-based superconductivity centers; consortia among industry, universities, and Federal laboratories; alliances of venture capital companies with larger industrial laboratories; Pilot Centers at national laboratories with industrial partners; and numerous State-supported efforts are already functional. Federal support for these programs comes mainly from the National Science Foundation, the Department of Energy, and the Department of Defense. The new Advanced Technology Program supported by the Department of Commerce (DOC) and a Defense Advanced Research Projects Agency venture initiative offer further opportunities for superconductivity technology.

It is the opinion of this Commission that these new approaches to coordinate and improve research and development efforts are experimental in themselves, and close attention needs to be paid to ascertain how well they realize their potential. It is important to monitor the progress being made from laboratory science to commercial product in order to eliminate bottlenecks and to speed the process by ensuring that adequate support goes to the most effective organizations. Judging from all past experience, it will take more than a decade of sustained effort before the new superconductors enter the marketplace in a significant way. It is

essential that the planning be made and the development be undertaken with the recognition that a sustained effort is required. The lessons learned from the past 30 years of experience following the basic scientific discoveries of conventional superconductors are useful in planning for the future. It is the object of this chapter to discuss how the "push" from bench-top discoveries can be coordinated with the "pull" of the marketplace.

Flow From Research to Market

The steps which must be traversed following the bench-top discovery by Bednorz and Mueller and subsequent discoveries and inventions related to the synthesis, properties, and theoretical understanding of improved superconductors are shown schematically in Table III-1. Both large-scale power technologies and small-scale electronic technologies are considered together. It is quite likely that one or the other may proceed more rapidly because the obstacles to be overcome in processing long lengths of superconducting wire for winding solenoids are unrelated to those for making reliable and reproducible tunnel junctions. It is clear that at a comparable stage in the development of conventional superconductors, the new superconductors would be in the 1965 era and have not yet taken step 2, the development of the enabling technology. It is necessary to produce the superconductors in usable forms, shapes, and combinations before devices can be produced.

Discoveries and Inventions

From past experience, it is expected that most of the discoveries and inventions of ways to make better superconductors will be forthcoming from individuals and small groups with independent programs. These programs are where breakthroughs in new materials and the fundamental

Table III-1
Flow From Discovery to Market

Step	Objective	Activity	Considerations	Examples
1	Discovery, invention	Undirected research	Support of individual investigators	Synthesis, theory, properties, processing
2	Enabling technology	Directed generic research	Interdisciplinary research programs	Flexible wires, Josephson devices
3	Manufacture, commercialization	Production of items for market	Demand, cost, reliability, competition	Motors, generators, computers

understanding of materials are likely to emerge. While discoveries cannot be planned, the climate in which they flower can be improved. This can best be realized by continuation of the successful methods our country has used in the past, namely supporting strong individual and small-group research efforts that are rated by peer review and are locally directed by the principal investigators (PI's). The scientific and technological challenges and opportunities deriving from the discovery of high-temperature superconductivity have stimulated widespread activity in the past 3 years. There has been a large increase in the number of workers entering the field in different disciplines, including physics, chemistry, material science and engineering, chemical engineering, electrical engineering, and mechanical engineering. Even though the available funding has increased, it has not come close to keeping up with the increased demand. As a result, many highly qualified PI's at universities are currently being seriously underfunded or not funded at all. The situation has recently become so serious that we can no longer take it for granted that this country will be first in the basic sciences that relate directly to competitiveness in superconductor-based technologies. Europe is becoming increasingly strong in this area, and the Japanese are now making a national commitment to an increased level of basic research in the PI mode. They well appreciate that technological breakthroughs normally depend on advances in basic science carried out essentially in the mode of Bednorz and Mueller.

The need to give priority funding to PI's has been emphasized by nearly every committee that has assessed research funding in recent years. Even those reports directed at major facilities

recommend protection of PI grants. The Commission found vigorous support for enhanced PI funding in testimony and in previous reports (Appendix I) on superconductivity. There is a Commission consensus for increased PI funding for superconductivity research. No one questioned the need and the benefits to the Nation. In fact, grant size has decreased in recent years and the cost of doing research with modern instrumentation has risen rapidly. NSF Director Bloch acknowledged the problem when he spoke to the Commission.

Why have PI funds lost ground when all parties recognize their importance and advocate increases? The NSF is the major provider, and the overall NSF budget has risen significantly. Clearly, competition for funds has been intense. The number of proposals for research funding received in the Division of Materials Research of the NSF more than doubled during the 1980's—from 650 in 1980 to 1,328 in 1989—but the number of awards decreased from 347 to 309. The individual research scientist can be neglected as agencies seek funds to finance new and large-ticket projects that are proposed and encouraged by well-focused special interest groups with political backing. Dr. D. Allan Bromley recently spoke to this issue: "One of the reasons for this problem at NSF is that the agency has taken on additional responsibilities in recent years. For example, its portfolio now includes greatly expanded science and mathematics education programs, supercomputing centers and computer networking. Despite the promise of a larger budget each year, overall funding at NSF has not kept pace."¹ The Commission calls for more attention to the strength of PI grants on the part of NSF. Similar comments

apply to other agencies, as well, such as DOE's Basic Energy Sciences program. The Commission concludes that PI funding can be greatly improved by infusion of funding at levels that are modest in the context of total expenditures. Success in this stage requires collaboration between the research community and industry's development effort to ensure that research directions mesh with product development.

Enabling Technology

Step 2 from Table III-1, the development of enabling technology, involves the directed research that leads to the generic understanding and technology needed for production of devices and systems for the marketplace. For example, to manufacture magnets, motors, and other large components, it is necessary to wind coils of wire or tape. To do this, large lengths of flexible superconducting wire and cable, with improved superconducting properties—such as high T_c , H_c , and J_c —are needed. "Improved" is defined for the purpose of this chapter as meaning distinctly better figures of merit than those available using classical superconductors, which will introduce technologies or make possible significantly more efficient devices than are currently available. Here the "enabling technology" would be the processing of superconductors and normal metals into long lengths of flexible superconducting wire and cable; it does not yet exist for high- T_c superconductors.

For the small-scale electronic Josephson devices, an example of enabling technology is the fabrication of reproducible superconductor-insulating-superconductor (SIS) tunnel junctions or weak superconductor-normal metal-superconductor (SNS) links. When properly made, such devices make possible circuits and computers that are orders of magnitude faster than those currently available. Generic research involves learning how to grow films with controlled microstructure, orientation, interfaces, and barriers. It is being actively pursued on an international level. The processing is common to both the military and commercial sectors. Therefore, coordination among mission-oriented funding agencies of the Federal Government, numerous State agencies, industrial laboratories, and the NSF is helpful all around. There is a need to bridge the gap from

enabling technology development to the end-use product. For example, DOE should play a similar role to that played by DARPA in facilitating the manufacture of high- T_c power devices.

Manufacture and Commercialization

Large commitments of people and money are required to proceed both with the development of prototype devices and, eventually, the manufacturing of complete systems for the marketplace. Moving from research to development and then to commercialization prematurely can be a very expensive, even a fatal, error. There should be timely feedback from the marketplace to guide the generic research and prototype development. There can even be national and international consensus and coordination on the selection of technical targets.

Pull From the Market

The evolution of conventional superconducting technology is worth recalling. The impetus for developing the large-scale technology came from the high-energy physics community. Immediately after the discovery of high- J_c superconductivity in 1961, it was realized that superconductors offered the *only* possibility for meeting the need to scale up to higher energy accelerators. As a result, throughout the 1960's, 1970's, and 1980's, there has been sustained government support to provide the "pull" to get through step 2. As yet, there has been no comparable "pull" for high- T_c superconductors. Although there are many sectors that can benefit mightily once the enabling technology is available, there is no currently identified need for which high- T_c technology offers the *only* technical solution. Compelling reasons may emerge when the improved superconductors are more fully appreciated. As an example, recent results obtained in Germany and Japan show that short lengths of wire carry useful currents in the highest test field available, 26 T. Such results show that magnets for NMR experiments in the 25- to 50-T range are possible. These magnets could revolutionize molecular biology by the imaging and mapping of large molecules. They might also lead to compact x-ray sources and other technologically valuable devices. The need to support high- T_c technology for 10 or more

years into the future becomes evident when its integrated effect is considered. A strong superconductor technology can do much to help the United States maintain technological leadership in the next century.

While both commercial and military markets for improved superconductors share the need to build roughly the same generic technologies, ultimately different requirements of performance, cost, and reliability will cause the paths to diverge. In Chapters I and IV we discuss the needs of and opportunities for U.S. industry to develop commercial markets and the needs of the military market that have been identified. New modes of support funding and new interorganizational structures already in place are designed so that perceived requirements can be brought to bear early in the development stage.

Support Funding

Government Funding

The Commission has been frustrated in its efforts to catalog R&D funding for superconductivity. U.S. Government agency expenditures are relatively easy to obtain, but interpretation of the data is tricky when large expenditures move on or off the budget, as with the magnet coils for the Superconducting Super Collider (SSC). Expenditures of foreign governments are even more difficult to assess owing to inconsistent reporting practices, such as the exclusion of salaries, which is a major factor. Industry funding is very difficult to estimate, as corporations do not publish subject-area breakdowns of their R&D expenditures. Industry also spends significant amounts of government agency funds, which tends to mingle and confuse the two categories. State funding is often overlooked but is significant and growing. Again, the numbers are not easy to obtain and are confusing in format. These uncertainties encourage caution in drawing conclusions from published funding levels. Consequently, the Commission has chosen to focus on general aspects of the funding pattern that are less sensitive to details of the numbers. Even so, funding analysis is best approached with skepticism.

Budgets appear to be changing only slowly in the 1989-90 time frame. A very rough estimate of

international spending for 1990 is given in Table III-2. For a more detailed breakdown see Appendix IX.

The United States and Japan (when estimated salaries are included) are spending at comparable rates, while Europe is somewhat lower. The total funding for R&D, about \$800 million, is very large when compared with the total sales of superconductor-based products, about \$400 million. Anecdotal evidence of Soviet Union and Eastern European activity indicates that the number of people involved is comparable with that of the United States, Japan, or Europe. Numbers of research papers published support this conclusion and indicate considerable activity in other countries as well. Thus, there is a worldwide expectation that superconductivity has an extremely promising economic future.

Table III-3 gives an indication of where U.S. Government agency money is spent. In-house means Federal laboratory expenditure of DOE, DOD, and DOC. It should be kept in mind that university funding covers groups, centers, and user facilities in addition to grants to individuals. The data indicate that mission-oriented laboratories spend about half the money, while universities and industries share the rest.

A very crude distinction between basic and applied work is given in Table III-4.

Again, the numbers are easily confused. For example, DOE funding for superconductivity in connection with high-energy and nuclear physics, SSC magnets, and magnetic fusion energy research, which totals \$81.8 million in 1990, has

Table III-2
Estimated High- and Low-T_c Funding by
Source, 1990
(million dollars)

Source	Government	Industry	Total
United States	230 *	70	300
Japan	100	200	300
Europe	140	60	200

*Does not include an estimated \$15 million of State-supported projects.

Table III-3
1990 Federal Funding for Superconductivity
(million dollars)

Agency	In-House	Universities	Industry*
Department of Defense	20	16	36
Department of Energy**	86	8	22
National Science Foundation	—	29	—
National Aeronautics and Space Administration	2	5	1
Department of Commerce (National Institute of Standards and Technology)	3	—	—
Total	111	58	59

*Industry puts an estimated additional \$70 million of its own funding into superconductivity.

**A substantial fraction of the DOE funds listed are directed to the fusion energy program and the SSC.

been reported as basic research in some tabulations. From the point of view of superconductivity, however, these are applied programs leading to the use of superconducting magnets. Thus, it is concluded that Federal agency funding for basic research is only about 30 percent of the total. A large fraction of the basic research effort is devoted to high- T_c superconductors, whereas almost all of the applied work is concerned with low- T_c superconductors.

State funding levels are less well-known but are considerable. Some tens of millions of dollars are probably spent each year on superconductivity,

and the numbers tend to include building construction as well as operating budgets. Some State superconductivity initiatives are funded by Federal agencies, which tends to lead to double counting. These funds can also flow through to industry, further compounding the difficulty of accounting.

Industrial Programs

A comparison of industry funding for superconductivity R&D (Table III-2) indicates that Japanese industry is much more committed than either Europe or the United States. Japanese industry appears to be spending three times as much

Table III-4
1990 Federal Funding for Superconductivity
(million dollars)

Agency	Basic	Applied
Department of Defense	12	60
Department of Energy*	21	95
National Science Foundation	29	—
National Aeronautics and Space Administration	5	3
Department of Commerce (National Institute of Standards and Technology)	1	2
Total	68	160

*A substantial fraction of the DOE funds listed are directed to the fusion energy program and the SSC.

as industry in either Europe or the United States. Further, there is reason to believe that the U.S. industrial numbers are inflated. This lack of U.S. industrial interest leads the Commission to conclude that Japanese firms will have a major advantage in terms of commercialization.

The electric utility industry sponsors research through the Electric Power Research Institute (EPRI). EPRI's current programs support approximately \$3.5 million of work in low- and high-temperature superconductivity at universities, private industry, and the national laboratories. EPRI is collaborating with both the Federal agencies and private firms with the primary objective of developing the generic technology needed to develop superconductors for large-current applications in electric utilities and for performance and efficiency improvements in the use of electricity by their customers. The Commission believes that the U.S. effort in energy-related superconducting technology is exceedingly weak, much weaker than in the electronic area. A strong industrial initiative in motors and generators must be stimulated. The Department of Energy is the clear choice as the lead agency to initiate a program to build a small-bore magnet operating at fields greater than 2 T and temperatures greater than 25K. A strong high- T_c -wire program is an essential precursor to magnet development. A joint DOE-industry effort is indicated.

A strength of the American system is provided by venture capital, which has been the source of a number of startup companies. Companies are started with venture capital when an initially modest need of the market with potential appears to be realizable with technology that exists or almost exists and there seems to be a likelihood of moving rapidly into the marketplace. In the small interactive environment, steps 2 and 3 from Table III-1 are narrowed and undertaken rapidly. Venture capital is supplemented by established industrial partners, government small-business grants, and cooperative programs with universities and Federal laboratories. It is interesting to note that one of the startup companies, Superconductor Technologies, Inc., has more than 30 scientists and engineers on its staff, making it one of the largest efforts in the United States.

Institutional Responses

The area of superconductivity provides an excellent arena for studying and improving interactions among the various elements of the U.S. technical community. The United States possesses a university-based research system that is number one in the world. The United States has in place a large and vigorous Federal laboratory structure that has the expertise, facilities, and scale needed for large, important technical developments. On the industrial side, U.S. high-technology laboratories have been leaders in high- T_c research. Collaboration and coordination of all of these research efforts are badly needed to eliminate redundancy and reduce commercialization intervals. New mechanisms to accomplish this have been put in place recently. This is a good time to encourage these and other mechanisms and to establish procedures for monitoring their progress and evolution.

Universities

Experimentalists and theorists jumped into the study of copper oxide superconductors following the initial discovery. All known synthesis approaches were quickly evaluated, and every characterization tool was directed at this fascinating class of materials. Condensed-matter theorists applied known models and derived new ones to explain behavior. The initial challenges were well met by the existing organizations. However, there are some deficiencies that should be remedied for the long haul, and already some solutions have been put into place. New organizational structures mentioned below have been formed to overcome specific problems; there is an obvious need to evaluate their performance and cost effectiveness.

It has already been noted that the university research community has been under financial stress for some time. For example, the average grant size funded by the NSF Division of Materials Research has, in real dollars, decreased by 8 percent during the past 5 years while the cost of doing research has gone up. A well-recognized lack of modern laboratory space and equipment and a lack of startup funds for PI's now exists. The universities have responded by seeking addi-

tional funding from industry, private donors, foundations, and mission-oriented agencies with limited success. The ability of the university community to continue generating new discoveries and insights in superconductivity and to continue educating the number of scientists and engineers to meet the Nation's needs for superconductivity is in jeopardy. The needs are not only confined to superconductivity; to some extent, the transfer of resources into superconductivity programs has been at the expense of other equally important programs in materials science, and funding for these programs needs to be restored.

Traditional university research along departmental lines is not conducive to the interdisciplinary research that is clearly needed. The Materials Research Laboratories were set up more than 25 years ago by DARPA and continue today under NSF sponsorship to facilitate interdisciplinary research. Those at Stanford, Illinois, Northwestern, MIT, Chicago, and Harvard are actively engaged in superconductivity research. Smaller Materials Research Groups at Minnesota and Wisconsin are similarly involved. A large Center for Superconductivity, which embraces interinstitutional research projects using resources existing in different organizations, has been established at the University of Illinois with the active participation of Northwestern University, the University of Chicago, the Argonne National Laboratory, and industrial partners. A smaller Air Force-supported Center for Superconducting Materials Research and Electronics has been established at Stanford with industrial participation from Conductus, Hewlett-Packard, TRW, Varian, and Xerox.

National Laboratories

The national laboratories operated by the Department of Energy have a wealth of expertise, established facilities, and connections that are being applied in basic research, enabling technology development and mission applications. As a matter of national policy, these laboratories have a mandate to cooperate with universities and industry, large and small. Direct experience in sophisticated scaleup has been obtained through programs to provide superconducting magnets for high-energy physics machines. DOE has established an innovative program: the Superconductivity Pilot Centers at the Argonne, Los Alamos, and Oak Ridge National Laboratories. Funds are provided

for an industry-driven cooperation that will enhance the transfer of national laboratory technology to industry for rapid commercialization. This program will advance the Nation's science and technology base in the laboratories and drive generic, enabling technology development in the directions of greatest interest to industry. The Commission heard many comments, all positive, on the Pilot Centers. It appears that they are well conceived and off to a fast start. More than 30 formal collaborations have been initiated. One arrangement, involving Los Alamos National Laboratory, du Pont, and Hewlett-Packard in a 3-year, \$11 million project for the development of electronic applications, could well be presented as a consortium.

Industry

There may only be five corporations in the United States with programs having more than 15 scientists devoted to superconductivity. These are AT&T, Du Pont, IBM, TRW, and Superconductor Technologies, Inc. The first three and smaller efforts at Bellcore and elsewhere have been among the most productive research organizations since the opening of the high- T_c era. Corporations with research programs having between 10 and 15 scientists include Bellcore, GE, GM, Rockwell, and Westinghouse. These corporate programs emphasize basic research on electronic applications. The situation today insofar as high- T_c superconductors are concerned is to be contrasted with what existed in the comparable stage of the development of low- T_c superconductors. Westinghouse, GE, RCA, Bell Laboratories, North American, and other companies were very active in developing the generic technology. The present-day technology that is capable of constructing the SSC magnets, MAGLEV trains, superconducting magnetic energy storage (SMES) coils, and other large-scale projects from Nb-Ti (low- T_c) wire is in large measure attributed to development in those industrial laboratories that later flowed into smaller, more specialized companies, the Federal laboratories, and Japanese and European institutions. In contrast, the response of many companies today is to support the research efforts of a few scientists for the prime purpose of keeping the company aware of new developments.

The primary reason for the different industrial response to the opportunities in high- T_c supercon-

ductivity relates to the different legal and regulatory environment in which industry currently operates, as discussed in Chapter II. The cost of capital in the United States 25 years ago, for instance, was not twice the Japanese cost of capital. Because it is not likely that the legislative barriers will be removed in the near future, programs must be developed in which Federal support is used in ways that result in increased industrial investment in long-range research, development, and production of materials and devices involving superconductivity. These programs would allow industry to overcome the disincentives of tax, antitrust, and patent policies. They represent, in large part, the out-of-pocket cost of failure to make the structural corrections necessary to allow U.S. industry to compete internationally on a level playing field.

Consortia

The "Wise Men" report on superconductivity recommended the formation of four to six Superconductivity Consortia involving direct participation by universities, industry, and government. These consortia were intended to do basic research and precompetitive R&D over a range of industries, including aerospace, electronics, and energy. Two prominent consortia have now been established along the lines proposed. MIT, MIT Lincoln Laboratories, IBM, and AT&T have formed the Consortium for Superconducting Electronics, and other organizations may join in time. The goal is to develop the enabling technology for thin-film electronics. Planning, sample preparation, device fabrication, and evaluation of results are being carried out in a collaborative mode. Researchers of the four member organizations are working in their home laboratories. No Consortium buildings are planned, but a high-technology facility is in the planning stage. The University of Houston has formed a second major consortium, the Texas Center for Superconductivity at the University of Houston (TCSUH), with participation of the Microelectronics and Computer Technology Corporation (MCC). Funding is provided by the State of Texas, DARPA, and du Pont. MCC has over a dozen corporate members and is engaged in other electronics development work. TCSUH has programs on both bulk- and thin-film-superconductor applications.

Improvement and Coordination of Superconducting Data Bases

In a fast-moving field such as superconductivity, access of U.S. research and development personnel in industry, academia, and government laboratories to the most up-to-date, accurate data is essential to rapid commercialization. Data can take many forms, ranging from the most basic measurements of the electronic and physical properties of the superconductors to citations of technical publications and standards. In 1987, President Reagan designated the Ames Laboratory at Iowa State University as a Center for Basic Scientific Information and established a Bibliographic Computer Data Base on Superconductivity in the DOE Office of Scientific and Technology Information (OSTI) at Oak Ridge, Tennessee. The Center at Ames publishes a newsletter (High T_c Update) that contains news concerning interesting reported results, abstracts of the latest papers, bibliographic information, and meeting notices. OSTI provides subscribers with on-line information regarding abstracts and actual papers.

Data bases are also required that contain property measurements. A prime example is the need for accurate phase diagrams that describe to the materials processor the temperature and compositional requirements to prepare optimum materials. These diagrams also act as guidelines to the compositions from which pure single crystals can be obtained.

There is also a need for evaluated data bases on other key properties of the high-temperature superconducting materials. For instance, a repository on critical current measurements, including a description of test techniques and materials processing information, would be extremely valuable. Evaluated data on fundamental properties of the materials, such as vapor pressures, thermal expansion, and thermal conductivity, would be equally valuable.

Recommendations

- The recently implemented mechanisms for involving industry by leveraging Federal funds should be encouraged to evolve. These

mechanisms include university centers, superconductivity-specific consortia, the Superconductivity Pilot Centers at the DOE laboratories, and the Advanced Technology Program of DOC.

- A high-level external advisory group with membership from appropriate industrial and scientific sectors should be established. This group would advise the President's Science Advisor and the Office of Science and Technology Policy (OSTP) on the effectiveness of research being supported by the various agencies and on the cost effectiveness of new organizational structures that have been formed to advance superconductivity development and technology, to encourage the coordination of existing programs, and to facilitate the establishment of research priorities.
- A long-term commitment for support for superconductor research and development should be made a national policy. A specific 5-year program with OSTP review annually should be planned and updated on a yearly basis. It should be recognized that a sustained effort well into the next century will be needed to ensure that the promise of new superconducting technologies is realized with the entry of new products into the market.
- Funding for university-based PI's should be increased substantially and made commensurate with the increased number of PI's that have become active in superconductivity and related condensed-matter science research in

the past 3 years and with the increased cost of carrying out research. Funding for individual research efforts should be given the highest priority.

- A program to build a small-bore superconducting magnet operating at fields greater than 2 T and temperatures greater than 25K should be initiated under joint DOE and industry direction. The development of commercial-quality high- T_c wire should be the first step of such a joint program.
- International cooperation on research and specific applications should be actively pursued. The creation of an International Committee on Superconductivity is suggested to enhance planning for coordination and cooperation between the national programs over the long term and to enhance the effective exchange of research that is already taking place. The collection and dissemination of research data, discussed in the appendix, should be supported.
- NSF directly, and with the cooperation of industry and other government agencies, should support scientific education using superconductivity as a vehicle in the early grades and on through college, as the Science and Technology Center at the University of Illinois is doing. The battle for gaining the new scientists needed is already lost by grade 8. Improved science instruction should be implemented in each State.

1. *Physics Today*, (July 1990): 50.

Chapter IV

National Security

This chapter evaluates the projected development of superconductor technology for military applications. An early insertion of high-temperature superconducting microwave and radio frequency (RF) components is likely in the current course of Department of Defense programs, leading to the production of hybrid communications and electronic-warfare systems. Other sensor and processing systems will follow. Two projects are recommended that are outside the scope of existing programs, but of crucial importance to the future requirements of national security with important implications in industry and commerce: the construction of a petaflop (10^{15}) speed superconducting supercomputer, within a time span of 10 to 15 years, and the development of a maximally efficient superconducting propulsive electric motor; a primary issue here is the development of a manufacturable high- T_c superconductor wire of the requisite electric and mechanical capabilities.

Military Applications

Superconductor technology, both for the older low-temperature materials and the new high-temperature materials, has very wide utility in both military and civilian products. A recent Defense Science Board¹ report on military applications for this technology detailed a number of electronics and high-power applications:

Electronics

- Infrared sensors
- Analog-to-digital converters
- Microwave and millimeter-wave systems
- Analog-signal processors
- Magnetic-field sensors
- Digital data processors

High Power

- Magnets
- Energy transmission

- Electrical machinery
- MHD propulsion
- Electromagnetic launchers
- Energy storage

As stated in that report, this technology will support a number of important military systems, such as ballistic missile submarines; ballistic missile defense; guidance and electronics for aviation and tactical missiles; and anti-submarine warfare (ASW).

The division between electronics and high-power applications also is a division between thin-film and bulk superconductor-materials technology. A distinction also must be made between the low-temperature superconductors and the more recent high-temperature superconductors. The high- T_c material, which is more suitable to the requirements of military technology, requires development to achieve levels of current density and critical magnetic field to meet applications criteria.

From the vantage point of the Nation's overall defense posture, the implications of superconductivity range from tactical to strategic. Superconducting components can address needs that cannot be met otherwise—for example, efficient detection of long-wavelength infrared radiation, construction of very small antennas and antenna arrays, detection of small changes in magnetic field, and minimum bandwidth communication in space. Superconducting components will permit significant improvement to existing systems' speed, accuracy, capacity, or fieldworthiness. They may extend or enable capabilities in sensing from space and in military command, communication, and control systems. Strategically, much faster computation and information transfer may enable major new systems or protocols for developing defense systems, such as more practical applications of artificial intelligence and automated software development. Superconducting power systems will extend design flexibility and available performance to

levels significantly beyond present systems, making possible, for example, submarines that are faster, more maneuverable, and harder to detect.

Electronics Applications

Military and space systems place the greatest demands on electronic devices, components, and systems. In this performance-driven field, ultra-high speed, low noise, and low power can be realized simultaneously in superconductors. Superconductive electronics can have a major impact on sensor, signal processing, and data processing systems. This impact in electronics is based on several unique attributes that make possible:

- Ultra-low loss/dispersion transmission lines and filters
- High-speed, low-noise, and low-power Josephson junction active devices
- SQUID's for magnetic and electromagnetic sensing
- Monolithic integrated circuits for both analog (microwave and millimeter-wave) and digital components

Although IBM attempted to develop a superconducting computer a decade ago, the project ended because of problems in using lead-based low- T_c tunnel junctions for the circuits. Since then, the technology has become more robust, as embodied in the marketing of a superconducting sampling oscilloscope by Hypres, Inc. The delay-power product is orders of magnitude lower for Josephson junctions than for competitive semiconductor technology. Even with the expectation of further improvement in semiconductor reduction and integration, the basic problems are heat generation and complexity of processing. Smaller circuit dimensions will be possible for superconductors because of much smaller power dissipation. Superconducting interconnects will allow greater packing density and even 3-dimensional circuits (because of simpler processing).

The Federal High Performance Computer Program² plan has set requirements for the development of high-performance computing to meet national challenges. Among these challenges are

accurate modeling of turbulent flow, climate modeling, and vehicle dynamics, which are important military needs as well. Teraflop (10^{12}) processing speed is considered necessary in this regime, with some concomitant increase in memory size to perhaps 10 gigawords. Semiconductor technology can achieve this goal by the mid-1990's, but waste heat dissipation becomes significant. Superconductor technology, together with parallel multiprocessor configurations, may be the means to solving these problems.

Beyond the teraflop processing level, there are military mission-critical information processing requirements for ASW, image analysis, cryptanalysis, and distributed surveillance—defined as an assemblage of low-cost sensor platforms for observation and communication, configured into a redundant network.³ Threshold computational requirements for such capabilities are about 10^{13} floating point operations per second (flops), and mature systems would require capabilities orders of magnitude higher. It has been estimated that ASW will require 10^{16} flops to protect the U.S. coastline by the turn of the century.

Superconducting technology will have to surmount several obstacles before it can be applied to an advanced computer, notably the large-scale integration of Josephson junction circuits and the development of a superconducting transistor with power gain. A succession of hybrid technologies with semiconductor circuitry seems a likely route, probably with the introduction of superconducting interconnects (on the back plane).⁴ The combination of high processing speed and low power dissipation of superconducting electronics, together with parallel multiprocessor architecture, is the most likely path to the next revolution in digital computation for future military requirements. *A worthwhile goal for a superconducting supercomputer would be a petaflop (10^{15}) capability, with similar enhancements to memory size.* Such a goal would have collateral commercial benefits in the future design of airplanes, drugs, chemicals, and the simulation of phenomena such as the weather.

Infrared Sensors

There are several ways that the application of superconductivity could affect infrared (IR) sensor technology. The performance of mercury-cadmi-

um-telluride (HgCdTe) detectors could be improved by substituting high- T_c superconducting elements, whose operational bandwidth would extend much further into the long-wavelength infrared, to 100 microns. A bolometric mode of detection has been demonstrated, in which the detector is simply biased in temperature at the high- T_c transition temperature. More speculative detection modes consist of direct breaking of Cooper pairs by the incident photons, leading to an increased quasiparticle tunneling current at a Josephson junction; indirect modes also may be possible.

The signal processing and data extraction components following the IR detection elements could be built from superconducting elements. A key issue is to employ analog-to-digital (A/D) converters that can operate at the detector temperature, allowing integration at the chip level. The extremely low power dissipation of superconductor processors offers significant advantages in lowering the heat load that must be handled by cryocoolers. Conventional semiconductor processors dissipate 10 to 100 times as much power. This advantage is particularly significant when very large IR arrays are used, and in fact such arrays may be feasible only with superconducting A/D converters.

Microwave and Millimeter-Wave Systems

One property of high- T_c materials that has immediate application is the reduction of surface resistance at microwave frequencies, better even than the conventional low- T_c materials. Transmission lines at these frequencies have substantially reduced loss; other components, such as microstrip resonators and filters with greatly improved Q and insertion loss, are being fabricated from high- T_c materials. Such components can provide many of the ingredients for an efficient and very compact, wideband, communications system. When combined with a superconducting multiplex feed system to a phased array antenna, this will have a major effect on satellite communications over multiple channels. In time, as better cryocoolers are developed, it is expected that such capability will transfer to aircraft and missiles.

As in the case of IR sensor technology, the transition to superconducting components will

entail an integration of the detector and processing/data extraction functions at the chip level, to form a monolithic microwave integrated circuit. All of the above discrete components can be fashioned on a chip, along with the A/D converters and amplifiers, and the combination should function optimally at about 80K for the high- T_c case. It is now possible to design a high- T_c radar receiver on a chip, excluding the antenna and active electronics.

The Strategic Defense Initiative Office (SDIO) is developing high- T_c superconductive coatings for the interior walls of accelerator cavities, to increase their operational efficiency and to reduce the requirements for heat removal. Satisfactory electrical performance has been achieved on small samples using a fabrication process that appears to be amenable to scaleup.

Magnetic Field Sensors

Superconducting Quantum Interference Devices (SQUID's), which function as magnetometers and gradiometers, already have been developed from low- T_c materials and are available commercially. These devices, which currently operate at liquid helium temperatures, are under evaluation by the Navy for ASW applications and mine detection. SQUID's have 100 to 1,000 times greater sensitivity than conventional magnetic sensors. A high- T_c form of SQUID would have slightly less sensitivity than a low- T_c device, but much greater ease of operation. The difficulty in producing a high- T_c SQUID, common to much of high-temperature superconducting electronics, is in the reliable fabrication of a sharp superconductor-insulator junction.

Analog-to-Digital Converters

Although low- T_c A/D converters have been built, a significant problem remains in fabricating a high- T_c A/D converter, namely the consistent fabrication of a superconductor-insulator junction. The basic reason is that such a junction must be very narrow, of the order of a few tens of angstroms, and the materials are inherently granular. A great deal of progress has been made in solving this fundamental problem in high- T_c electronics, though a reasonable production mode is at least 5 years away.

Superconducting A/D converters offer great advantages in speed and power efficiency over comparable semiconductor devices. In making the extrapolation to circuitry with even greater component density, it is clear that the reduced power dissipation, and consequent reduced cooling requirement, of the superconducting A/D converter will lead to its clear preference. This will make it possible to deploy multichannel A/D converters for analysis of multi-gigahertz (GHz) spectral signals.

There is a small U.S. effort to integrate a U.S.-developed low- T_c A/D converter into a full superconducting analog signal acquisition and processing system.

Analog Signal Processors

Perhaps the earliest applications of the new high- T_c materials will be in passive low-loss RF transmission circuitry for analog signal processing and for high-speed logic interconnection networks. This property derives not from the perfect dc conductivity of a superconductor, but from the low resistance skin resistivity at high frequencies—as cited for the microwave application.

Analog signal processors based on tapped delay lines can provide wideband signal processing for wideband radar and communications systems. Superconductor devices have the capability to perform waveform chirp, convolution, correlation, spectral analysis, and matched filtering with bandwidths as high as 20 GHz. Use of the new high- T_c materials will allow integration with semiconductor devices to expand functional performance. The reduced cooling requirement will open deployment opportunities in many wideband-radar and intercept systems.

Digital Data Processors

A/D converters based on low- T_c technology have been built both in the United States and in Japan. Fujitsu has reported an eight-bit microprocessor based on Josephson technology that is 10 times faster and consumes 1/500 the power of a gallium arsenide version of the microprocessor. The potential benefits of low- T_c digital processing is very great. Rapid progress is being made by a number of Japanese groups in solving the fabrica-

tion issues. Systems-level demonstrations of low- T_c digital processing are achievable in the next few years. Digital processing based on high- T_c is currently impossible.

As circuit density continues to increase with conventional technology, the biggest problem is heat removal. The very low power requirements of Josephson junction technology is partially offset by the power required to maintain the low temperature. However, the very low power required by even a large system permits the system to be built in a very small volume. The greater device speed combined with the shorter transit time will provide greater computational capability in low T_c for equivalent total power dissipation, including cooling. For defense requirements, it would be important to develop onboard signal processors for space applications.

There is no fundamental reason to believe that a superconducting equivalent of the transistor is not feasible. If such a device can be developed that has power gain with very high performance, it would revolutionize the use of superconducting technology in computing systems. High- T_c materials show great potential because they may be much more compatible with semiconductor materials than the older superconductors, thus enabling hybrid approaches (superconductors with semiconductors).

High-Power Applications

The second major area where superconductivity can have significant military impact is that of high-power applications. These applications exploit the high magnetic fields that can be generated by high-current-density superconductor materials. Since dc currents persist indefinitely in the superconducting state, magnetic fields can store large amounts of energy for extended periods of time. They can also provide compact, high-magnetic-field sources for rotating electrical machinery such as motors and generators, and they offer the promise of more flexible compact electric-drive systems that provide military platforms with significantly improved speed and maneuverability and less likelihood of detection. Electromagnetic launchers can accelerate projectiles to exceptionally high velocities. Superconducting magnets for

accelerators can improve high-power sources for millimeter wave and optical beams via free electron lasers.

Superconducting magnetic energy storage (SMES) is militarily useful as an energy source for high-power lasers. Such lasers might require 1,000 MW in an interval of minutes. SDIO currently is supporting the development of a 20 megawatt-hour (MWh)/400 MW peak-power engineering test model of a SMES, constructed of low- T_c materials (Nb-Ti). DOE is studying the industrial economics of SMES units. High- T_c superconducting materials are currently undergoing rapid improvement in current-carrying capacity. Their higher operating temperature promises significant advantages in refrigeration reliability.

A primary issue in the application of high- T_c materials to magnets, motors, and generators is the requirement for high-current wire with high-field operating capability and the mechanical integrity of Nb-Ti wire for low- T_c applications. This derives from the so-called weak-link problem in bulk superconductors, in which the supercurrent is inhibited by intergranular barriers throughout the material. Present current densities in meter lengths of manufactured wire are of the order of a few hundred amperes per square centimeter, two orders of magnitude below useful values. Great effort is being expended to understand the nature of this problem, and to "texture" the material by alignment of the individual grains. Some recent results on 5-centimeter length samples have shown the success of this effort, in which thousands of amperes per square centimeter are obtained even at high magnetic fields (see Appendix VI).

Magnets

The highest magnetic fields that can be achieved by conventional permanent magnets or electromagnets are about 2 T; superconducting electromagnets can produce magnetic fields of 20 T using low- T_c materials. High- T_c materials can carry useful currents at 26 T at 4.2K. Although the greatest military and commercial potential lies in energy storage and power conversion devices, as cited above, present applications lie almost entirely in MRI devices using low- T_c materials.

High- T_c materials appear to offer advantages for magnets and their use in SMES, as well as insertion into motors and generators. A near-term goal would be the demonstration of a high- T_c magnet producing a minimum of 2 T, above 25K, with a bore greater than 1 inch and reasonable working volume.

Electrical Machinery

The largest payoff in high-power applications could come from the exploitation of superconductor materials in rotating electrical machinery. Substantial weight and volume savings can be realized by eliminating magnetic materials and customary field windings. Currently, an experimental 3-MW low- T_c dc motor has been built for ship propulsion at the David Taylor Research Center in Annapolis and tested at sea. This motor was 22 percent smaller than the equivalent conventional air-cooled ac motor.

Although superconducting motors and generators can provide somewhat higher efficiency than their conventional counterparts, their principal advantage is reduced size and weight, important on naval ships and especially submarines. Moreover, the flexibility afforded in avoiding the drive shaft is an important feature. High- T_c flux shields also can be built to diminish the electromagnetic signature of motors, and thereby diminish the vessels' vulnerability to detection.

Although the David Taylor Research Center has pioneered the development of superconductivity electric ship propulsion, the requirement for liquid helium has prevented its acceptance by the Navy. *The development of a high- T_c superconducting motor for naval propulsion would lead to the insertion of this technology and provide an excellent focus for the production of suitable high- T_c bulk materials.* Such a project would be a stimulus to applying superconducting technology to nonstatic components, such as magnets and transmission lines. Several agencies, including DOD, DOE, DOT, and NASA, could contribute to the development. The lead agency to establish a nationally focused program to develop practical superconductors for magnets, motors, and generators should be the Department of Energy. Given their success in the Pilot Center concept, the DOE national laboratories should lead a national project to develop wires and tapes with specific require-

ments for current, field, and temperature. It is important that there be a strong industrial component to this program.

The use of magnetohydrodynamic (MHD) drive also is being considered in submarines.⁵ Thrust is developed when an electrical current flows through water that is simultaneously flowing through a magnetic field. Superconducting magnets are the only practical option for producing the high magnetic fields needed, with a very large bore. The advantages of such a motive source is the elimination of vibrations caused by the motor and generator. However, there may be signatures associated with the MHD drive that mitigate this benefit. The Japanese plan to test this mode of propulsion in a 100-foot research vessel in 1991.

Electromagnetic Launchers

The electromagnetic launcher is of interest because it is capable of propelling a large mass to a very high velocity. Unlike chemical propulsion systems, the achievable terminal velocity is not limited by the speed of exploding gas, but rather by the speed of a traveling electromagnetic pulse. A projectile could be accelerated to act as an effective kinetic energy weapon. Such applications include: launching close-in ship defense projectiles against cruise missiles, or as a hypersonic anti-armor weapon which, because its velocity could exceed the sound velocity in protective armor, would be an assured penetrator.

Superconducting materials will increase the feasibility of electromagnetic launchers as military weapon systems for many of the reasons previously stated—lower weight, smaller volume, and higher efficiency. Superconductor materials would be used in the prime power generator, in the energy storage system, and in the high-speed switch, which could employ superconducting thin films. There are new concepts in electromagnetic launchers, such as entirely eliminating the rails on which the projectile slides, which could be made feasible only by high-current-density superconductor materials.

Relationship of Military and Commercial Development

In addition to the great potential for military applications, defense support for superconductivity R&D will also benefit commercial applications. In the past, demanding defense applications set the pace for the commercial electronics and computer industries. Today, fierce international competition in the commercial sector drives much of that technology. That is, we see spinoffs from commercial to military technology, not only spinoffs. In fact, since today much of the forefront of semiconductor technology is in Japan, we depend on the Japanese significantly for critical military components. The availability of commercially superior technology to other nations or arms merchants runs counter to the U.S. national security position, which continues to depend on technological superiority.

In superconductivity, defense-supported technology development once again has the opportunity to set the pace for applications. This investment can be justified strictly on the basis of military requirements. However, it can also have significant benefit for potential commercial applications. Unlike the electronics or computer fields, there is no large industry for superconductors. Technology development is in its infancy. Much must be done to develop generic technologies such as thin films and wire making. New ideas and innovations in synthesis, processing, refrigeration, device design, and other areas will be required to realize the great potential in defense and commercial applications alike.

Defense support should be structured to simultaneously develop a lasting competitive edge for U.S. industry. We have noted above that the U.S. business climate has private industry looking for leverage from Federal investment in R&D. Defense applications provide such leverage for research, development, technology insertion, and manufacturing.

Department of Defense support for university research in superconductivity should be increased

to promote innovation and scientific breakthroughs that will be necessary for achieving the full potential of these materials for defense applications. It has been demonstrated repeatedly that these are most likely to originate from individuals or small groups of researchers. Universities have been instrumental in the spectacular advances in high-temperature superconductors to date. In addition, defense-sponsored university research will also have a positive effect on commercial applications.

The promising defense applications discussed above argue strongly for a broad-based DOD program that sets aggressive goals, such as passive microwave circuitry, petaflop computing, and electric ship propulsion. Specific applications will allow early participation by U.S. industry in development and manufacturing. DARPA has been particularly effective in inserting new technology into U.S. industry and developing a manufacturing

base. For example, DARPA funded half of the key innovations in the field of high-performance computing.⁶ We believe that it can play a similar role in the application of superconductors. Radio frequency and microwave high- T_c superconductor analog circuitry are likely to mature quickly and could be inserted into communications and surveillance systems. These systems also provide a proper base to build upon for more difficult achievements in superconductivity, such as antennas, A/D converters, signal processors, and memory units. By phasing these technology insertions properly, a powerful thrust can be created to promote advantage in defense-critical applications and in commercial spinoffs. The SDIO and Navy programs are also aimed at specific applications—superconducting magnetic energy storage and electric ship propulsion, respectively. We strongly encourage the continuation of these programs with widespread participation by industry, universities, and Federal laboratories.

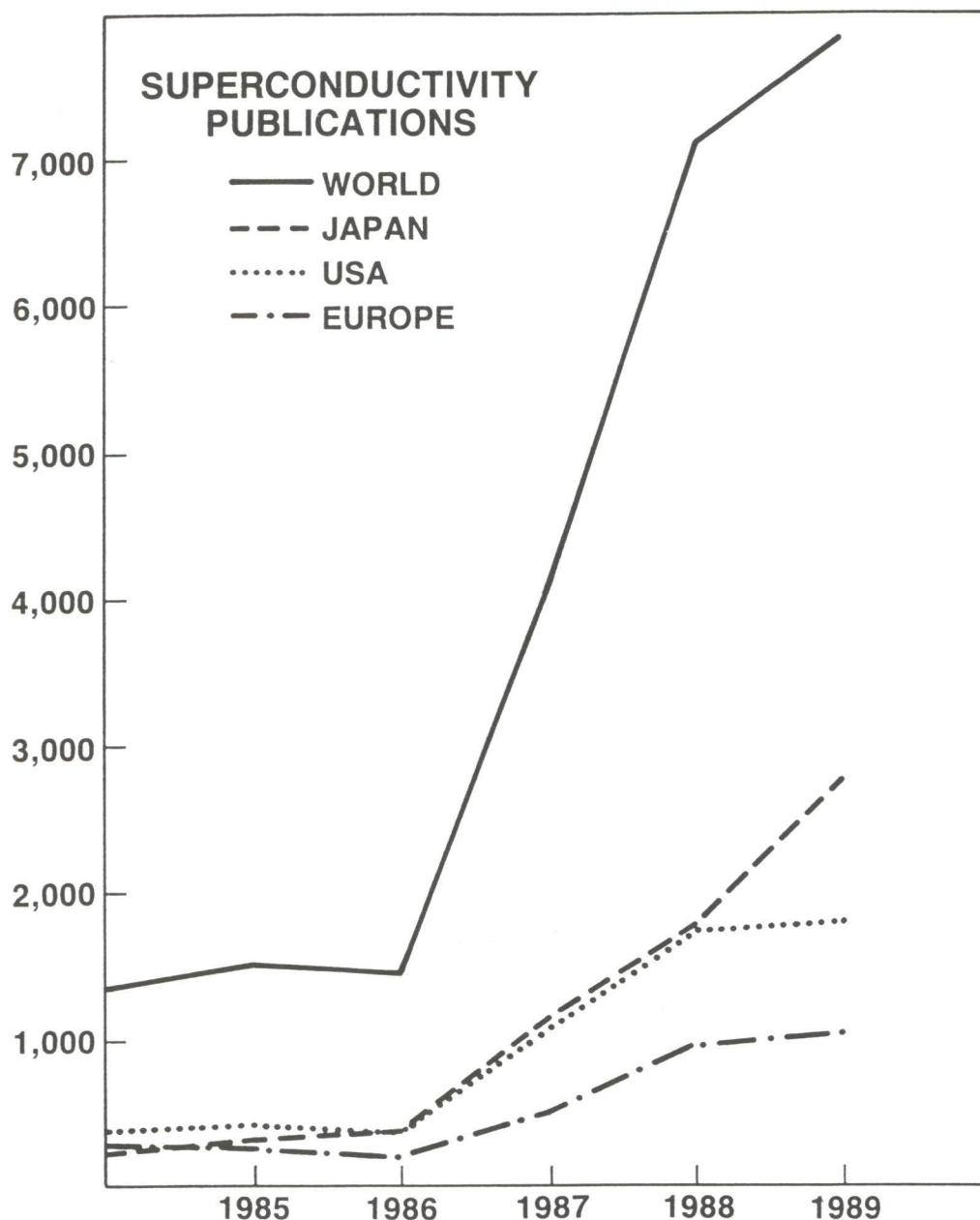
1. *Report of the Defense Science Board Task Force on Military System Applications of Superconductors* (October 1988).
2. Executive Office of the President, Office of Science and Technology Policy, (8 September 1989).
3. Unpublished remarks of Dr. G.A. Keyworth II, Hudson Institute.
4. *High Temperature Superconductivity in Perspective*, U.S. Congress, Office of Technology Assessment (April 1990).
5. This technology was portrayed fictionally in the novel *The Hunt for the Red October*.
6. *Made in America: Regaining the Productive Edge*, The Massachusetts Institute of Technology Commission on Industrial Productivity, (Cambridge: Massachusetts Institute of Technology Press, 1989), 115.

Appendix I

Published Reports on Superconductivity

The 15 reports listed below on advances in superconductivity have appeared over the last 3 years, that is, since the discovery of the copper oxide, high-temperature superconductors, and they indicate intense interest in the field. Inclusion in this list is somewhat arbitrary, as a recent survey found 38 published proceedings of conferences

(for the years 1988, 1989, and 1990), and the Commission has not had access to all of these. Over the same period, 70 books have been published with titles recognizing superconductivity. The technical literature has surged from about 1,300 papers in 1986 to 7,800 papers in 1989 (see the figure below).



SOURCE: CAS/E. MEAD (duPONT)

- Research Briefing on High-Temperature Superconductivity*, National Academy of Sciences, Committee on Science, Engineering, and Public Policy, Washington, DC (1987).
- Proceedings of the 1988 Conference on Electrical Applications of Superconductivity*, Electric Power Research Institute, Palo Alto, California (March 1988).
- Proceedings of the Electric Power Research Institute Workshop on High-Temperature Superconductivity*, Electric Power Research Institute, Palo Alto, California (April 1988).
- New Research Opportunities in Superconductivity, A Workshop Report*, sponsored by the National Science Foundation and ONR, Copper Mountain, Colorado (April 1988).
- New Research Programs in Superconductivity*, Federal Coordinating Committee on Science, Engineering, and Technology (May 1988).
- Commercializing High-Temperature Superconductivity*, Office of Technology Assessment (June 1988).
- Military Systems and Applications of Superconductors*, Defense Science Board (October 1988).
- High-Temperature Superconductivity: Perseverance and Cooperation on the Road to Commercialization*, Committee to Advise the President on High-Temperature Superconductivity (January 1989). ["Wise Men" Report]
- Federal Research Programs in Superconductivity*, Federal Coordinating Committee on Science, Engineering, and Technology (March 1989).
- High-Temperature Superconductivity in Japan*, Japanese Technology Evaluation Center, Loyola College, Baltimore, Maryland (November 1989).
- The National Action Plan on Superconductivity Research and Development*, Office of Science and Technology Policy (December 1989).
- Critical Technologies Plan*, Department of Defense (March 1990).
- Emerging Technologies*, Technical Administration, Department of Commerce (spring 1990).
- Superconductivity Research and Development Activities in U.S. Industry: 1989 and 1988*, R.E. Morrison, National Science Foundation (March 1990).
- High-Temperature Superconductivity in Perspective*, U.S. Congress, Office of Technology Assessment (April 1990).

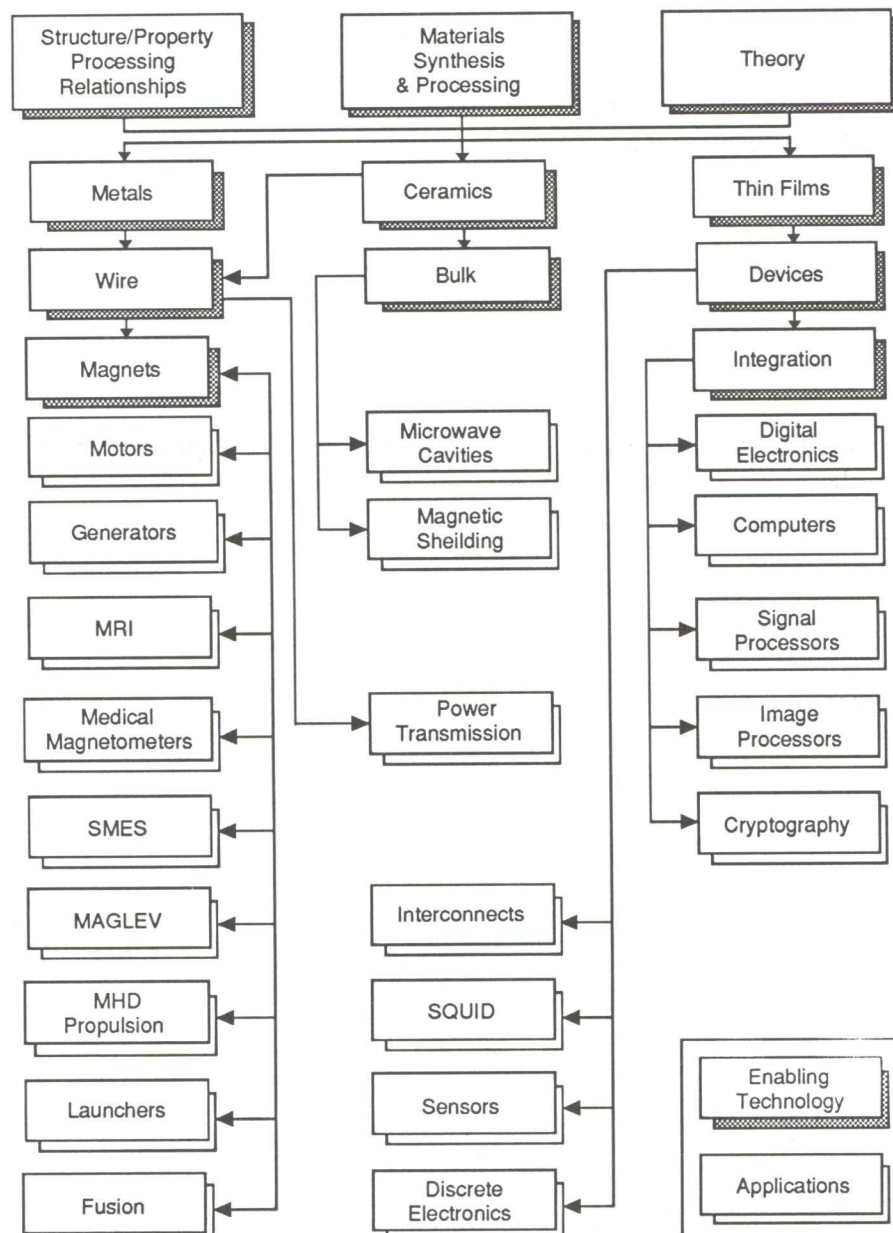
Appendix II

Relationships among Superconductivity Technologies and Applications

The figure below presents the sequential relationships among the various enabling technologies and applications. It is clear that ceramic wire making and copper oxide device fabrication are major milestones in the evolution of superconductivity technology. Bulk ceramic components can be made today. It is possible that 5 years will

be required to produce commercial high- T_c wire and electronic (discrete) devices. Magnets, motors, generators, and integrated electronics will require a decade or more for commercialization. It is important to note that once the enabling technologies are in hand, applications development can proceed in parallel.

Superconductivity Road Map



Appendix III

Proposal for an International Committee on Superconductivity

Creation of an International Committee on Superconductivity is proposed. All nations that are active in the field of superconductivity would be invited to join. Working membership would consist of two scientists or engineers from each member nation. The purpose would be to ensure the effective exchange of information on research results and progress and to promote open discussions of plans and emphasis. Each nation would present informal 1-year and 5-year plans. The group would serve to identify gaps in effort, reduce undesirable redundancy, and give opportunity for mutual assistance in the programs.

The International Committee would be, of course, cognizant of the international meetings on superconductivity and might, when the occasion arose, sponsor such meetings. In the near future, the meetings would continue to be primarily on research subjects, but meetings on industrial applications and possibly on programs could be increasingly included.

The representatives of the United States on the International Committee would need ample assistance from individuals who are experts on

superconductivity, particularly as related to the development in one country or in several countries. Such assistance would be given voluntarily (with expenses paid) on a part-time or full-time basis. In all cases, individuals should be thoroughly versed in superconductivity, and specifically qualified to follow developments in one country, such as Japan. Such an individual or individuals should go on fact-finding visits. They should be thoroughly conversant with the language and, as far as possible, with the important individuals working on superconductivity in that country. Several European experts, several Japanese experts, and at least one Russian expert would be associated with this committee.

These individuals would officially report to the United States representatives on the International Committee and could, on individual invitations, participate in the meetings of the International Committee when needed. They might, of course, have meetings with the American representatives of the Committee and appropriate groups might arrange meetings with each other. They might also advise other U.S. organizations.

Appendix IV

Proposal for Superconductivity Research in High Schools

There have been many reports of high school students reproducing some results of superconductivity. In view of the high desirability of involving our high schools in technical subjects, experimentation on superconductivity for high school juniors and seniors should be encouraged and supported.

To do this in a practical manner, at least one teacher in the high school should show reasonable familiarity with the subject. Relatively inexpensive equipment, including liquid nitrogen, would be made available.

The behavior of the new superconducting materials is dependent on the way in which they

have been prepared and handled. It is also dependent on the presence of a number of impurities. This is a situation where the broadest experimentation might prove to be useful. Students and student groups should, therefore, be encouraged to publish the results of their experimentation. A special paper might be started and circulated among the high schools that participate or intend to participate in the experiments.

A sum as little as \$10,000 might suffice to get one such program started, and with the participation of a few hundred high schools, the cost would still be limited to a few million dollars.

Appendix V

Research Needs for Refrigeration for Superconductivity Microelectronics

New technologies for refrigeration at the microchip level could provide the single greatest competitive advantage in the whole realm of superconducting microelectronics. They would correct the misperception that the utility of superconductors depends on the temperatures at which they function. Moreover, until refrigeration technology appropriate to the microelectronics environment is developed, it is unlikely that any superconductors, low-temperature or high-temperature, will become significant factors in the microelectronics industry.

For these reasons, the following set of goals is targeted:

- Develop manufacturable devices to provide up to 1 Watt of cooling power in the temperature range of 10 to 100K.
- Focus on simplicity in systems, preferably solid-state refrigerators with no moving parts.
- Integrate research on refrigeration with research on superconductive microelectronic devices and systems, because the goal is to integrate the refrigeration with the electronics.

A small research team would probably be able to develop a proof-of-concept for a solid-state refrigerator in 2 to 3 years, and it would take another 3 to 4 years to develop a manufacturable prototype. Such an effort might cost \$50 million. Within the range of 10 to 100K, there are several

possible approaches to providing closed-cycle refrigeration with no moving mechanical parts. The most obvious is to miniaturize the traditional means of refrigeration (gas compression and expansion), but this method carries serious drawbacks. It still requires a means of compressing gas, and though it is possible that some nonmechanical method could be devised (such as absorption/desorption from an appropriate material), the microelectronics package would carry the added demand of sealing in the gas indefinitely. There would also be a substantial chance over time that the micro-machined gas tubing would clog, especially if there were any contaminants in the gas that might freeze out.

More promising as a concept are refrigerators that are entirely solid-state and contain no working fluid at all. One type would take advantage of the cooling possible during the transition from highly ordered to disordered atomic structures—as can happen in molecules when a strong field is suddenly removed. A rapidly cycled field could continuously remove heat without moving parts or gases. Approaches include magnetic and electric fields, as well as materials that produce cooling effects when they undergo phase changes.

Another technology worth exploring is the “thermo-acoustic-driven pulse tube” cryocooler. This method uses sound to set up standing waves in a tube that create a temperature gradient. The motion of gas particles in the tube provides the heat-transfer mechanism.

Appendix VI

Superconducting Wire

Conventional Low-temperature Superconducting Wire

Practical superconducting wire is usually a multifilamentary composite with substantial amounts of high-conductivity normal metal such as copper. Such a form allows adequate electrical, thermal, and mechanical properties (ac loss, stability, and strength) for practical applications.

A typical strand of low-temperature superconducting wire is 1 to 2 millimeters in diameter, contains thousands of continuous superconducting filaments, and is twisted about once every centimeter of length. The most common method of manufacturing the wire is hot extrusion of a large hand-assembled composite billet followed by conventional wire drawing with intermediate heat treatments. After drawing, the wire is given a final heat treatment to form a fine distribution of crystal defects within the superconductor to enhance the critical current. Fabrication is carried out so that the final diameter of the superconducting filaments is less than about 0.004 inch (100 m). Larger conductors are formed by cabling or braiding together many strands or by attaching strands to a solid block of metal. Stainless steel strips or wires are sometimes added for mechanical reinforcement.

Today the United States has a slight lead over Japan and Europe in the technology of fabricating high-performance Nb-Ti superconducting wire. Two points are important in this regard: the largest production capacity for Nb-Ti wire now resides in the United States, which supplies the MRI industry, and the majority of the technical innovation for improved wire performance that has occurred in the last 5 years has taken place in the United States, driven by the SSC project. Because Nb-Ti is ductile, strong, and the focus of a highly developed technology, it is the present-day workhorse of the applied superconductivity field. Although we are ahead by perhaps 6 months, the Japanese and Germans are very near and have an excellent record of rapidly adapting U.S. innovations, such as improved processing techniques for higher J_c and finer filaments, to practical technology and products. To illustrate our lead consider

these facts: one U.S. manufacturer of wire for Fermilab magnets recently processed four billets to wire with resulting critical current densities of 313,100 to 321,400 A/cm² at 4.2K and 5 T. The best wire from Japan so far has a current density of 309,700 A/cm². Production of SSC wire with J_c greater than 300,000 A/cm² is now considered routine in the United States, while in Japan the norm is 280,000 to 310,000 A/cm². Japanese and European Nb-Ti wire is considered generally to be comparable to, but not better than, U.S.-made wire.

The United States is slightly behind our Japanese and European competitors in the development of improved higher performance low-temperature superconducting materials such as Nb₃Sn, niobium nitride (NbN), and the Chevrel phases. These materials are of interest because they all exhibit higher critical temperatures and higher upper critical fields (H_{c2}). The potential is for magnets with stronger fields.

Nb₃Sn technology is well developed, and commercial magnets containing composite Nb₃Sn conductors are available today from many U.S., Japanese, and European vendors. Nb₃Sn is attractive because it has higher T_c , H_{c2} , and J_c values than Nb-Ti (see Table VI-1). The chief disadvantage of the material is brittleness. The United States halted most research on Nb₃Sn in the late 1980's when funding was cut severely. The fusion program has been responsible for keeping some research on Nb₃Sn going, although continued funding reductions are expected. It is possible that in 12 to 18 months, U.S. Government-sponsored research on Nb₃Sn will have ended. This trend will cause our industry to fall further behind in low-temperature superconducting technology.

Japan and several European countries have maintained R&D activities and are consequently ahead, especially in the very high field (greater than 20 T) regime. Vacuumschmelze of West Germany is probably the overall leader in Nb₃Sn wire technology.

NbN conductor research is nonexistent today in the United States. A prime reason for this is

Table VI-1
Low- T_c Materials of Technical Interest Summary of Properties and Comments^a

Material	T _c (K)	H _{c2} at 4.2K (T)	J _c at 4.2K (A/cm ²) in a magnetic field ^b				Comments
			0 T	5 T	10 T	20 T	
Commercially Available							
Nb-Ti ^c	9.5	11	1 x 10 ⁶	3 x 10 ⁵	2 x 10 ⁴		
Nb ₃ Sn	18.3	26	6 x 10 ⁵	2 x 10 ⁵	1 x 10 ⁵	1 x 10 ⁴	
V ₃ Ga	15.4	21	—	—	4 x 10 ⁵	1 x 10 ⁵	Japan only
Under Development							
NbN	16	24	—	—	7 x 10 ⁵	1 x 10 ⁵	Film (short lengths)
Nb ₃ Al	18.9	30	—	5 x 10 ⁵	1 x 10 ⁵	6 x 10 ³	Short wires (Japan)
PbMo ₆ S ₍₈₎	13	47-51	—	—	5 x 10 ⁴	1 x 10 ⁴	Short wires

^a Principal sources: ICMC and ASC Conference Proceedings and NIST-Boulder data (private communication).

^b J_c refers to the superconductor layer only. Additional necessary elements of the conductor reduce J_c values in V₃Ga, NbN, and PbMo₆S₍₈₎ typically by 2 to 5 times.

^c T_c and H_{c2} are composition-dependent in the technical range. The nominal composition is Nb46.5Ti.

that there is no good source of basic science funds for work in low-temperature superconducting materials. People coming into the field see the emphasis being placed on high-temperature superconducting materials and perceive that, in today's very tough reviewing climate, proposals on low- T_c materials will not be funded.

The Japanese probably lead in thin-film NbN technology, while the Germans have recently come close to developing a viable wire manufacturing process. The longest good quality samples of NbN tape available are meters in length at best. Dietrich in Germany has prepared tens of meters of fiber bundles of NbN on carbon fibers with a copper stabilizer added later. NbN is technologically attractive because it is insensitive to radiation and its J_c does not degrade with elastic strain (J_c in Nb₃Sn has degraded by 15 percent at the elastic limit). The fusion community has been very interested. Present-day NbN containing 0.05 percent carbon can be fabricated in thin films with a noncopper current density of about 10 percent of that for Nb₃Sn.

There are reasonable programs in Europe and Japan on Chevrel-phase materials, whereas U.S. efforts are minimal. Again our programs have suffered because researchers here switched to investigations on the high- T_c materials. Chevrel-phase materials are attractive because of extremely high measured values of H_{c2} (greater than 50 T). The J_c at 20 T is comparable to that for Nb₃Sn. The problem with the material is its brittleness and resultant difficulty of fabrication for long length wire. Small prototype magnet coils of lead molybdenum sulfide (PbMo₆S₈) wire have been built by Seeber in Geneva.

To support superconductivity for the long term, it makes sense to encourage work on high-field low-temperature superconducting materials rather than concentrating exclusively on high-temperature superconductor research. New money for continued research on low- T_c materials will help us to better understand high-temperature superconductivity and specifically how to improve J_c and develop better manufacturing processes. Continued work on NbN and the Chevrel-phase

materials may be especially fruitful because the problems with improving J_c at high fields and the fabrication of long conductors are similar to those we face with the oxide superconductors. The technology of practical high- T_c conductors will benefit by investigations on low- T_c materials.

The development of Nb-Ti technology provides an interesting lesson. Nb-Ti became the favored superconductor in the period between 1965 and 1970. However, a true understanding of how best to process Nb-Ti for optimum current-carrying capacity was not achieved until about 1985. The cost savings from this understanding have reached tens of millions of dollars for MRI magnets and potentially \$200 million for the SSC.

A table of T_c , H_{c2} , and J_c values of the low- T_c materials of greatest technical interest is included as a reference for the current status of low- T_c wire technology.

High-temperature Superconducting Wire

There has been significant progress in improvements to J_c in wires made from oxide superconductors over the past 12 to 18 months. During this period, J_c has moved from about 50 A/cm² at 4.2K and 5 T and essentially zero A/cm² at 77K and 5 T to the 1,000 A/cm² attainable today at 4.2K and 5 T in silver-clad YBCO wire. Many researchers report a critical-current density of 10⁴ A/cm² at 4.2K and 5 T in Bi containing tape samples, while the Japanese claim values greater than 10⁵ A/cm² at 4.2K and 5 T. This extremely high J_c requires good crystallographic orientation within the polycrystalline oxide superconductor layer.

Some recent best claims for J_c at 4.2K and 5 T in short lengths (3 to 10 cm) of bismuth-based high- T_c superconductors in silver-clad wire are:

$\approx 2 \times 10^5$ A/cm ²	Japan
$1-2 \times 10^4$ A/cm ²	Europe
$1-2 \times 10^4$ A/cm ²	United States

The Japanese have just reported¹ encouraging results at high fields in centimeter-length tape samples of Pb-doped 2223 material ($\text{Bi}_{1.8}\text{Pb}_{0.4}\text{Sr}_2\text{Ca}_{2.2}\text{Cu}_3\text{O}_8$). See Table VI-2. These results indicate that high- T_c magnets of engineering interest may be feasible.

For YBCO material in silver-clad wire, the current status at 4.2 K and 5 T is:

$3-4 \times 10^3$ A/cm ²	Japan
$1-2 \times 10^3$ A/cm ²	United States

Specific records for J_c in the oxide superconductors tend to be broken regularly and are often unsubstantiated. It is relatively easy to make 50 to 100 feet of high- T_c oxide wire, but magnets of several kilogauss have not yet been fabricated. This underscores the difficulty of manufacturing a long length of practical wire.

The wire fabrication methods that look most practical include the following:

- Oxide powder in a silver tube.
- Metallic alloy precursor method.
- Forming an oxide layer on a substrate tape.

Table VI-2
Critical Currents in BiPbSrCaCuO Tapes

Temperature (K)	J_c (A/cm ²) in a magnetic field			
	0 T	5 T	10 T	20 T
4.2	2.1×10^5	1.1×10^5	9.2×10^4	8.5×10^4
20	1.7×10^5	8.6×10^4	7.2×10^4	5.5×10^4
77	3×10^4	—	—	—

- Preparation of fibers by classic ceramic approaches.
- Melt texturing.

Each of these methods, of course, has its own set of advantages and disadvantages. It is clear, though, that practical wire must be available in long lengths, be mechanically strong, and have consistently good properties along the length.

Many of the high- J_c values reported are not reliable or well represented, for the following reasons:

- Many researchers have a short history in the wire-development area and are overly optimistic. We do not yet have measurement standards for J_c in the oxides, so one group's methods for determining J_c could differ from another's. The question arises: Over what length is the measurement taken? It has been suggested that the product $J_c L$, where L is the length over which the measurement is taken, is a means of reporting progress during the development stage of wire making.
- The value of J_c at 0 T may be quoted. This J_c is of only minor technical value.
- The J_c may not have been independently checked.

The Japanese probably lead in the development of high- T_c wire because they are very active "making things" and are committed to the long term. There are more groups in Japan that are making wire and are production oriented. Many sophisticated labs with a long history in the commercial low- T_c -superconductor field are involved in high- T_c -development activities. These labs have experience on their side and excellent experimentation facilities to assist with the understanding and characterization of high- T_c material property-structure-processing relationships. Japanese industry is spending large amounts of money on high- T_c superconductivity, which is bound to produce fruit.

An example of European initiative is Vakuumschmelze. They are supporting a 5-year program to study the bismuth-based materials. This

project is half government funded and half supported internally. The team is committed to a long-term program, involves a successful low- T_c company with experienced superconductor researchers, and is not overburdened with requirements for reporting and meetings.

How long will it take to make practical high- T_c superconductive wire? No one can answer this question with certainty. However, if there is stability with present programs, in 3 to 5 years we will probably have a good idea of where the technology will go. During this period we must make headway in several scientific and technological areas (some have said we will need breakthroughs). We need progress in our understanding of the following subjects:

- Simply how the physics and materials science of these oxide superconductors work. We need to know more about mechanisms, theory, and structure-property-processing relationships.
- How to control the weak-link problem.
- The 2D/3D/flux creep problem and the influence this has on determining the properties of yttrium compounds as compared to bismuth and thallium compounds.
- How to make mechanically tough conductors that are not plagued by weak-link problems.

And there exist the economic issues. Can a substitute for silver be found? One industry researcher estimates that long lengths of practical wire for applications not requiring high fields will be available in 2 to 3 years. Wire for use in fields above several T at 20K might not be available until after 1995.

Both Japan and Europe will do better in superconductivity than the United States unless we modify our strategy. Their approach is to develop strong groups, support them well, support them consistently, and support them for the long term. Our tendency is often to favor the home-run approach and place too small an emphasis on developing a true interdisciplinary understanding of the materials themselves.

1. "Critical Currents of Superconducting BiPbSrCaCuO Tapes in the Magnetic Flux Density Range 0–19.75T at 4.2, 15 and 20 K," K. Sato, T. Hikata, and Y. Iwasa, submitted to *Appl. Phys. Lett.* (23 August 1990).

Appendix VII

Low-temperature Superconducting Magnets

Superconducting Magnets

Conventional electromagnets have copper windings, operate at about $1,000 \text{ A/cm}^2$, and make extensive use of iron yokes to concentrate the field. These electromagnets are heavy, consume large amounts of power because of resistive losses, and are limited in field strength to about 20,000 gauss (2 T), the saturation field for iron. Higher fields and current densities are possible in conventional electromagnetism, but only at the cost of enormous power consumption.

Practical composite superconducting wire and tape is an enabling technology for efficient high-field magnets. The only power required by a superconducting magnet is that needed for refrigeration (to cool the magnet) and for a power supply to initiate current flow around the superconducting circuit. Low-temperature superconducting magnets are cheaper to buy and run than conventional high-field electromagnets, are more compact and lighter, and can produce higher fields. Field strengths in the range of 5 to 15 T are commonplace because of the high current densities attainable (about 10^6 A/cm^2 at 4.2K in zero field) in available low-temperature superconducting wire containing Nb-Ti or Nb₃Sn. The high performance of superconducting wire of composite niobium-titanium in copper, the workhorse of the applied superconductivity industry today, is the result of 30 years of persistent research and development activities supported primarily by government funding.

Many of the techniques used to construct superconducting magnets have been specially developed. The best method for a particular application will depend on the magnet's size, shape, field, conductor materials, operating current, and method of conductor stabilization. Conductor stabilization implies operation at the rated current without a catastrophic excursion to the resistive (normal) state. It is perhaps the single most important basis for design and includes heat transfer and stress effect considerations. The conductor within a superconducting magnet must be sufficiently cooled and be given adequate mechanical

support for the magnet to operate safely and reliably.

Zero-loss conductors capable of high current densities in strong magnetic fields enable the practical operation of superconducting magnets suitable for a host of electric power applications. Examples include magnets for magnetic resonance imaging, motors and generators, advanced transportation systems, energy storage, fusion power, materials processing and fabrication, and scientific research. Examples of key applications are discussed below to acquaint the reader with typical conductor specifications, device performance levels, critical supporting technologies, and obstacles to the application of high-temperature superconducting oxides.

Competition among Low-T_c Magnet Builders

Overview

Five to 10 years ago, most of the competition for building large superconducting magnets was in the United States. In recent years, however, more and more foreign companies have been bidding competitively on large-scale U.S. magnet projects. The SSC is an example, in which the Japanese might supply as many as 4,000 dipole magnets, half the total needed for the project. If too much magnet business is given to foreign companies, then we risk seriously damaging U.S. competitiveness in the wire and magnet area. We could probably recover if we were to fall 2 years behind, but it would be very difficult to recover if we were to get 5 years or more behind in this technology.

Any company that is doing more work than other companies in a specific area of magnet development and construction probably leads the field in that specific area. If the area is highly competitive and several companies are involved, then all may be within 6 months to a year behind the leader. This has been the tradition with low-temperature magnet technology because of several

factors: the dissemination of information to the community via open discussion among engineers, scientists, and project review teams; synergism between different magnet projects; and the rapid availability of technical information through the open literature.

Comments on the current status of low- T_c magnet technology in selected areas follows. This discussion is not meant to represent the field as a whole but to give specific examples of where we and our competitors stand today in certain areas:

Dipole Magnets (Niobium-Titanium)

We probably lead the Europeans and Japanese by 6 to 12 months because of SSC work. However, our capabilities for mass production are behind the Germans and Italians. Brown-Boveri and Ansaldo each built 240 dipole magnets 2 feet in diameter and 9 meters long for HERA at the rate of 4 magnets per week. The Japanese and Italians could probably catch us in 6 to 12 months. Brown-Boveri may decide to get out of the magnet business.

Quadrupole Magnets for Accelerators (Niobium-Titanium and Niobium Tin (Nb_3Sn))

The Europeans probably lead this technology. Alston of France, Noel and Elin of Austria, and Siemens of Germany are key players. Some of these magnets are in the 10-T range. The Japanese companies—Hitachi, Mitsubishi, and Furukawa—are not active now but could become major competitors in perhaps 6 to 12 months. Japan is not as open with information about its technology as are the United States and the Europeans.

Large Thin Solenoid Detector Magnets for High-Energy Physics (HEP)

Japan leads in this area in part probably because of government subsidies. U.S. Government contracting arrangements for these devices and most other large HEP magnets, such as the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer, usually are for guaranteed performance specifications and a fixed-price contract. Each magnet is a first-of-a-kind unit and may involve R&D to build. Many U.S. companies are not interested in bidding for

these devices because of the financial risk and lack of government assistance.

Superconductive Magnetic Energy Storage (SMES)

As discussed in the next two sections of this Appendix, companies in the United States such as General Dynamics and Westinghouse lead in large-scale military- and utility-scale units, whereas Japan leads in the small-scale area. Our lead is probably several years, whereas the Japanese lead in small-scale SMES is perhaps 12 to 18 months. The Europeans and Soviets are not strong competitors yet.

Magnets for National Security

Background

Magnets are the central component of most high-power applications of superconductivity. Examples include magnets for fusion energy, superconducting motors and generators, superconductive magnetic energy storage, electromagnetic thrust propulsion, MHD power generation, and magnetic separation of special materials. The major benefits from using superconducting magnets are very high field strength, specially uniform and time-stable field, low power consumption, and high reliability. Conventional copper-wound electromagnets with an iron core can produce fields up to about 2 T, while low-temperature superconducting magnets are readily available that produce fields greater than 14 T at 4.2K in small-diameter-bore (inches) solenoids. Superconducting magnets consume very little power except for refrigeration, while conventional electromagnets require both a large power supply and extensive water cooling.

Magnets made with high- T_c materials offer significant potential advantages over those made with low- T_c materials. Because high- T_c materials have higher critical temperatures and fields, magnets made with these materials have the potential of enormously high fields, less power consumption (due to smaller refrigeration requirements), and a smaller size, which is economically attractive. High-field high- T_c magnets cannot be built today chiefly because of two problems: It is difficult to achieve high critical-current densities at high fields in polycrystalline material, and long lengths of flexible wire are unavailable.

SMES

The Department of Defense is interested in superconductive magnetic energy storage (SMES) as a power supply candidate for high-powered ground-based lasers (GBL's). GBL's might require as much as 1,000 MW per laser, available on very short notice and for a period of some minutes. Studies have shown that stored energy is preferred over generation technologies such as diesel engines or gas turbines because of cost and quick startup time. To verify the projected cost and performance characteristics of SMES, SDIO, along with EPRI, initiated a program in November 1987, to design, build, and test a small SMES engineering test model (ETM). The stored energy and maximum power output of the ETM are 20 MWh and 400 MW respectively. During Phase I of the program (\$28 million), two different magnet designs were developed, and two different conductors as well as other magnet system components were tested. Phase II is planned for a 3-year period with experiments to begin in 1994 or 1995. The cost of Phase II is estimated to be \$125 million to \$150 million.

The United States has been active in SMES research since 1971. The rate of expenditure has been at an all-time high over the last 3 years because of the SDIO/EPRI ETM program and will accelerate if Phase II proceeds. We lead our international competitors in military and utility-scale (stored energy above about 10 MWh) SMES technology.

The Japanese have been active in SMES R&D since the mid-1970's, have followed U.S. developments closely, and are in a serious startup mode in this technology. They probably lead the technology for small-scale units (about 1 MWh), where they have concentrated their efforts in recent years. There is an active program in Japan at present (the privately funded Chubu Project) to develop storage units for eliminating the voltage and power transients at substations associated with electric rail and maglev vehicle transit. Japan is also active through a MITI-sponsored program in the conceptual design of an ETM-scale unit for utility applications.

The Soviets are very interested in SMES, and conceptual studies are underway. Germany is in a planning and proposal stage.

SMES for Power Load Leveling

Large-scale SMES has been suggested as a method for leveling the daily and weekly load demand from utility generating plants. Energy storage allows for reductions in the operation of less-efficient peak and intermediate generating facilities. SMES offers the utilities a new plan for operation and growth: cost-effective power generation with coal and nuclear baseload powerplants plus efficient large-scale energy storage. The potential benefits include a savings of 10 percent on total fuel costs and reduced air pollution due to cleaner combustion in the base units.

The SMES approach is an alternative to pumped hydro, compressed air, or battery methods, and offers the distinct advantage of superior net storage efficiency. The major loss during SMES is operating a refrigerator to maintain superconductivity in the coil. Another benefit of SMES is its ability to respond within tens of milliseconds to power demands. This capability allows the magnet to provide "spinning reserve" and improve network stability, which gives a substantial cost credit to this technology. SMES efficiency may be as high as 95 percent, whereas efficiencies for other forms of storage range from 65 to 80 percent at best.

The fraction of total U.S. electric utility generating capacity that could be in the form of energy storage is 5 to 15 percent. The 5 percent value might be a reasonable estimation and translates to 37,500 MW of the expected capacity available in the 1990's. At present, about 2 percent of our generating capacity is in the form of pumped hydro storage plants, but additional sites for these units are scarce.

SMES for the electric utility is a big-ticket item with economic use predicted for sizes above 1,000 MWh. Large plants are cheaper than small ones on the basis of cost per unit of stored energy and will cost roughly as much as new coal-fired generating plants of comparable size, \$1 billion to \$2 billion. The future market for SMES after the year 2010 is projected to be \$2 billion per year in the United States and \$6 billion per year worldwide.

SMES devices will contain a number of unusual features but require no new enabling tech-

nologies to build. Current designs call for extremely large diameter (1,000 meters), short (19 meters tall), thin (1 meter) coils buried underground in shallow trenches and make use of soil and rock as mechanical support. The superconducting cable will carry a very large dc current—50,000 to 200,000 A—and be cooled by superfluid helium at 1.8K. A massive fiberglass-epoxy structure will support the conductor in a vacuum-insulated vessel and transmit large magnetic forces to the surrounding earth.

The superconductor for low-temperature SMES will likely be a composite of niobium-titanium in copper stabilized by high-purity aluminum. The estimated superconductor costs, which are a large fraction of the total plant capital cost, can be cut substantially (about 33 percent) by operating the magnet at 1.8K and grading the amount of conductor needed in different parts of the magnet to the local magnetic field strength. A typical conductor performance specification for SMES is operation at 1.8K in a 4-T field with a current density in the superconducting material of nearly 500,000 A/cm². Shown for comparison in Table VII-1 are the critical current density specifications for Fermilab and SSC conductors. For the

SMES application, the conductor may be designed to operate at about half the critical current value, so that the conductor can absorb large amounts of energy and increase its temperature appreciably without driving the superconductor into a resistive state.

A unique feature of SMES is that the mass of the magnet and cold support structure is very large relative to the available refrigeration. Cooling the magnet from ambient to its operating temperature is expected to take at least 1 month. Another unusual characteristic of the magnet is that when fully charged it has an extremely large value of stored energy per unit mass of conductor. If the magnet becomes resistive, it will warm up to above room temperature slowly as the stored energy is dissipated as heat in the coil. Because an accidental warmup (quench) would be expensive and time consuming, conductor designs are conservative and operating points allow a large margin of safety.

The substitution of high-T_c materials for Nb-Ti in utility-scale SMES will affect magnet system design and cost. The magnet design must be changed to accommodate the different electrical,

Table VII-1
Conductor Specifications

Type of Magnet	Conductor Materials	Current density (A/cm ²)	Temperature (K)	Magnetic Field (T)
Utility Scale SMES ^a	Nb-Ti filaments in copper and surrounded by pure aluminum	4-500,000	1.8	4-5
Fermilab Magnets	Nb-46.5 1.5Ti fine filaments in copper	180,000	4.2	5
SSC Magnets ^b	Nb-47 1Ti ultra-fine filaments in copper	275,000	4.2	5

^aPresent design thinking for one of the ETM designs.

^bCentral field is 6.6 T; peak field at conductor is 7 T. Actual conductor specification is different for inner coil and outer coil wire as indicated in the following table:

Conductor	I _c (A)	B (T)	T (K)	Approx. J _c (A/cm ²)	Wire Diameter (inches)	Strands in Rutherford Cable
Inner Coil	339	7.0	4.2	173,000	0.0318	30
Outer Coil	286	5.6	4.2	258,000	0.0255	36

thermal, and mechanical properties of brittle oxide superconductors. Costs could decrease slightly because of operation at 77K and simplifications to the dewar and refrigeration systems. These cost savings may be offset, however, by a more complicated conductor-support scheme. A significant impact on refrigeration costs is possible if oxide current leads are developed. If it is assumed that high- T_c material can be substituted directly for Nb-Ti at the same conductor cost and performance levels, then the decrease in plant cost is estimated to be 8 percent. This decrease, coupled with substantial decreases expected in operating expenses for a high- T_c -based system (refrigeration costs might be 10 times lower than those required by a liquid-helium system), could make smaller units economically competitive.

A logical next step for this technology is to build the proposed 10 to 20 MWh, Nb-Ti-based ETM. This device is needed to demonstrate basic design concepts, as well as efficient load following, ramping, regulation, small energy sales and purchases, pulsed outputs, and operational flexibilities. Construction procedures must be developed, the operational ranges and use must be determined, and extrapolations to economically competitive larger units must be verified. If a suitable high- T_c -based conductor were available, the magnet design could be altered and the newer conductor and magnet concept tested.

Motors and Generators

Motors consume over 60 percent of all electric power generated in the United States. Half of this consumption is in motors of 125 horsepower (hp) capacity or higher. Generators are highly efficient, typically greater than 95 percent.

Value of Superconductivity

About half the electrical losses in motors could be eliminated by using superconductors. Based on present projections, the most likely applications for superconductors are in the dc rotors of synchronous ac machines and in dc homopolar machines. Widespread adoption of this approach could increase average motor efficiency by 4 to 5 percent. Because generators are quite efficient, the improvement in using superconductors would be only about 0.5 percent.

Use of superconductors would provide several other advantages, partly by eliminating the need for an iron core:

- Reduced size—20-percent smaller diameter; 60-percent smaller length.
- Reduced weight—up to 60 percent.
- Potential cost reduction in large sizes.
- Smaller variation of efficiency with load.
- Potential for more forgiving design space by use of higher magnetic fields than are possible with an iron-core system (limited to about 2 T).

Development Requirements

- Conductors, presumably containing superconducting filaments, that can be fabricated and wound into desired configurations and can withstand the operational mechanical stresses and thermal cycling. The material properties of present high-temperature superconductors make this the most formidable challenge due to brittleness, current-carrying capacity, and the effects of magnetic fields on conductor performance.
- Mechanically simple cooling, to maintain the conductor at the desired temperature and to remove waste heat.
- System design to assure electromagnetic stability in startup and load-variation conditions.
- Minimum ac losses in the superconductor. If these can be made sufficiently low, then ac armatures might be fabricated from superconductors, with corresponding performance improvements.

Markets

The economics of motor and generator life-cycle costs dictate that superconducting devices will be used for the new and replacement market, the latter requiring about 20 years for optimal

impact. These analyses do not, however, measure the value and impact of sales to the developing nations. One key economic factor is the cost premium, if any, of superconducting over conventional devices. Although there have been analyses indicating that, above 300 MW, a high-temperature superconducting generator would be less expensive than a conventional one, significant motor market penetration is predicted even with a 50-percent cost penalty over a conventional motor.

Target Specifications

The target specification is a high-temperature superconducting magnet that could be installed on the rotor of a 1,000-hp motor. Its overall conductor current density would be 10,000 A/cm², capable of thermal and mechanical cycling typical of 20 years operation of a motor of this size. A 5 T magnetic field capability would demonstrate significant design improvement potential. It would operate at 30 to 60K with an attendant refrigeration subsystem. The configuration of the rotor magnet and all associated subsystems would be mechanically, electrically, and thermally compatible with operation in an actual motor. It would use fabrication and assembly technology such that a confident prediction of mass-production cost can be made and that the net projected cost premium for the motor be no greater than 50 percent above an equivalently rated conventional motor.

MRI

Magnetic resonance imaging for medical evaluation has produced the first large-scale commercial application of superconductivity. Over 2,000 magnets at an average price of about \$300,000 each have been manufactured in the United States, the United Kingdom, and Europe since the field began in 1980. The devices operate at relatively low fields (less than 2 T currently) and have been dependent on advances in basic superconductor materials or magnet technology. MRI has progressed in the areas of cryogen consumption, field homogeneity, transportability, shielding, reliability, and user interface.

MRI is possible without superconductivity; however, such nonsuperconducting systems cannot compete technically and economically with superconductive systems because of image quality and

power consumption considerations. Most high-resolution machines today operate at a magnetic field strength of around 1.5 T. The field must be very constant over a large central region of the magnet bore. Typical field decay rates and homogeneity specifications are 0.03 to 0.1 parts per million per hour and 3 parts per million throughout a 25-centimeter diameter spherical volume, respectively. Typical superconductor current densities are 10⁵ A/cm² at 4.2K. Cryogen consumption in passive units is typically 0.5 and 1.0 liter per hour for helium and nitrogen respectively. These consumption rates can be reduced significantly or eliminated by addition of refrigerators.

The FDA currently limits the maximum static magnetic field strength for human exposure to 2 T and below. The FDA also requires that access be controlled to all areas with static fields in excess of 5 gauss (0.0005 T). The reed switches in many pacemakers can be affected by fields above 10 gauss; CRT displays and magnetic recording media are sensitive to magnetic fields in the 10 to 100 gauss range. For reference, the Earth's field is about 0.5 gauss. In addition, ferromagnetic (iron) objects must be kept away from the energized MRI coil because of field and image distortion and safety concerns. A charged coil will attract any object normally attracted by a magnet. This attractive force can be very large and depends on field strength and object size.

Value of Superconductivity to MRI

- Strong magnetic fields and hence good image resolution capabilities.
- Smaller and lighter weight magnets, as compared to resistive versions, which allows mobile MRI to be practical.
- Low power consumption to operate the magnet.
- High reliability.

Potential for High-T_c Conductors

- Higher fields allowing better image resolution.
- Lower refrigeration costs.
- Smaller, lighter weight units.

- Cost may be comparable to low-temperature devices because the conductor cost is not a major cost item.

Obstacles to High- T_c Use

- Development of a strong and flexible wire or tape with appreciable current-carrying capacity in a strong magnetic field.

Market Issues

- Current market is 500 machines per year and growing. Typical costs: magnet—\$350 thousand, complete MRI system—\$2 million, siting and installation including shielding—about \$2 million.
- Higher field magnets may broaden the field of medical diagnostics tremendously because of

better image resolution and the ability to discriminate for higher atomic weight (P, Na) elements.

- The market is expected to drive this technology as it has done since the field began. It is noteworthy that private industry has paid for the vast majority of development progress in this field with the exception of the superconducting wire used. The high-performance wire is largely the product of a decade of DOE-sponsored research at universities and national laboratories.
- U.S. companies have shown that they can capture and maintain a strong world market position over an extended period in a highly competitive field.

Appendix VIII

Legal and Regulatory Barriers

Superconductivity is an extraordinarily promising technology. However, there is a general perception that the level of investment in superconductivity R&D in the United States is too low, especially in view of the international competition in this area. To overcome the technical barriers necessary to commercialize superconductivity rapidly enough to be competitive, barriers to increased industry investment in superconductivity R&D will also have to be surmounted.

Superconductivity has three attributes that are relevant in assessing government policies that are barriers to increased industry investment in R&D: First, the technology will probably be very expensive to develop, requiring the investment of large sums of money. Second, investment in the technology is extremely risky. That is, even if large sums are invested, there is no guarantee that all the technical barriers to practical high-temperature superconductivity will be overcome. Third, even if the technology does eventually prove practical, it could be many years before a firm recovers its investment in R&D and starts to make a profit. These three attributes make investment in high-temperature superconductivity R&D more sensitive to government tax, antitrust, and patent policies than many other kinds of R&D investment.

Tax Policy Barriers

Several features of the U.S. tax code tend to reduce saving and investment and increase the cost of capital. This, in turn, interferes with the development of new technology by reducing the rewards for basic and applied research. Removing these tax-policy barriers would be helpful in encouraging increased industry investment in research generally, and especially in high-temperature superconductivity.

One of the stated objectives of the Tax Reform Act of 1986 was a more neutral tax treatment of capital assets. The intention was to "level the playing field" by repealing special credits and allowances that favored one type of investment over another. A tax code was sought that would reduce distortion of economic decisions and that would permit investment to go where the greatest

real returns were to be found. Unfortunately, in leveling the tax treatment of various types of plant, equipment, and structures, the Tax Reform Act "leveled up," raising the overall cost of capital in the economy, particularly for assets with long lives.

Furthermore, the Tax Reform Act was not neutral between capital goods and consumption. The norm that was taken was the so-called broad-based income tax, with a built-in bias against saving and investment, rather than a truly neutral consumption-based approach. A tax structure was created with a higher cost of capital than in 1980, repealing the cuts in the cost of capital enacted in 1981.

It is often claimed that U.S. managers and investors are too shortsighted in the search for profits, and that this adversely affects R&D spending. Some propose tax changes to force U.S. managers and investors to take a longer view, such as penalizing debt finance or modifying capital gains rates to favor longer holding periods for stock. The problem with this approach is that it is backwards. U.S. savers and investors have not driven the cost of capital higher because they are myopic; if they have a short time horizon, it is because the cost of capital has been driven to higher levels by the tax code.

A fundamental disincentive to industrial investment in all long-range, high-risk R&D, including superconductivity, is the high cost of capital. In addition, the high cost of capital limits the availability of venture capital for small entrepreneurial companies. One way to reduce the cost of capital is a general revision of the U.S. tax code, an issue beyond the scope of this report. Nevertheless, the Commission obtained a better understanding of the problem as the result of written and oral testimony presented by external experts.

The Basic Tax Bias Against Saving and Investment

The income tax imposes a heavier burden on income that is saved and invested than on income that is used for consumption. Income is taxed

when earned. If used for consumption, there is little or no additional tax imposed. If the income is saved, the earnings of the saving are taxed again and again. This reduces the value of capital, and lowers productivity and real wages.

Saving transforms a lump of income into an earnings stream of equal present value. Consequently, the taxes paid on the earnings stream of a bond, for example, just equal in present value the tax paid on the income that went into the principal, hence a double tax.

For saving by individuals, eliminating this double tax requires one of two adjustments. Method 1: amounts saved should be deducted from taxable income, and the savings and earnings subject to tax on withdrawal, as with IRA's and 401(k) plans. Method 2: amounts saved should receive no deduction, but the earnings of the savings should be tax exempt, as with the "back-ended IRA" proposed last year by Senator Roth, the Bush Family Savings Account, and the Japanese tax-exempt savings account prior to Japan's recent tax reform. Ideally, all savings or earnings should be covered, not limited amounts.

In the case of individuals buying plant and equipment directly, as in partnerships and proprietorships, the investment should be expensed (deductible in the year purchased, as in method 1 above) rather than depreciated over time for tax purposes. The capital cost recovery provisions, which require that write-offs be stretched over time, reduce the present value of the write-off below the full cost of the investment, leaving a partial double tax in place. With expensing, the value of the taxes saved will just equal the value of the future tax stream on the profits, thereby eliminating the double tax on the capital.

The bias of the income tax against saving and in favor of consumption has led to increased use of consumption-based taxes around the world. Countries that use the Value Added Tax (VAT), for example, permit the expensing of capital investment in computing the value added which is subject to tax. This results in a "consumption-type" VAT, in which the tax base is consumption (GNP minus investment). They do this in preference to an "income-type" VAT based on depreciation, so as not to introduce a bias against saving in favor of consumption.

Additional Tax Burdens at the Corporate Level

The so-called "double" tax on dividends is merely one portion of additional layers of tax created by the taxation of corporate income, all of which are over and above the basic double taxation on saving and investment inherent in the income tax. These taxes are "triple" or worse.

One solution to the corporate tax problem is "integration," in which the income of the firm would be counted for tax purposes as income to the shareholders in the year earned. The income would be taxed at the shareholders' various tax rates.

Ending only the "double" tax on dividends leaves the corporate tax in place on retained earnings. Retained earnings raise the net worth or future earning power of the firm and raise the share prices. These earnings become "double-taxed" when the shareholder sells and records a capital gain on the share increase due to retained earnings.

Some have suggested that the tax code encourages leveraged buy-outs because of its bias against equity finance; that is, dividend payments are non-deductible and double-taxed, while interest on debt is tax deductible. Whether LBO's, mergers, and acquisitions adversely affect R&D is not clear, although anecdotal evidence certainly exists. But it must be clearly understood that the solution to the uneven tax treatment is not to end the tax deductibility of interest, which is treated properly in the tax code, but to end the double taxation of dividends. Any effort to "level the playing field" by raising it to new heights would further increase the cost of capital and reduce investment.

Reducing the Cost of Capital by Reducing the Capital Gains Tax

The capital gains tax is, in fact, an additional layer of tax whether related to corporate activity or not. The value of any property or business, including unincorporated businesses, will rise if earnings are expected to rise. The higher earnings, if they materialize, will be taxed. If the rise in the value of the property or the business is also taxed, there is a double tax imposed.

Some have suggested that it would be a service to the economy if the capital gains tax rate were reduced in a way that would encourage people to hold onto their shares of stock for longer periods, with the intent to encourage a longer time horizon in corporate management. The rate would be reduced more the longer the holding period of the stock. However, this is controversial. The corporate manager seeking to raise additional capital for research, expansion of capacity, or other uses, cares only that a new stock issue brings the highest possible price. It does not matter how long a particular shareholder holds a particular share before trading it for another. It matters that millions of people want to hold a large portion of their savings in the form of a stock portfolio, and that they put a high value on equity. For any given desired after-tax return on equity, share prices will be higher the lower the tax rates are and the easier it is to trade stock freely without unnecessary tax penalties. A reduction in the capital gains tax rates would reduce the cost of capital and thereby make investment projects with deferred payout streams financially more attractive.

The Research and Experimentation (R&E) Tax Credit

Beginning this year, current law provides for a credit generally equal to 20 percent of a taxpayer's qualified incremental research expenditures in excess of a fixed amount. Start-up companies can also qualify for the credit. This is a significant improvement over prior law, in which the base was a 3-year moving average. Under prior law, the R&E Tax Credit was not as effective as it could be in encouraging R&D, inasmuch as it has only a minor impact on the cost of R&D, a few percent at best. Authorization for the credit will expire at the end of 1990 unless it is extended by law.

Other structural defects are that large increases in R&D spending are not encouraged because no credit is available on expenses that exceed 50 percent of current qualified expenses. In addition, expenses for research carried on outside the United States are not allowed for credit purposes. Nor is the tax credit available after commercial production is begun, which ignores the fact that global competition requires accelerated commercialization, with research, development, and initial

production frequently taking place in a continuum of activity.

Another factor limiting the tax impact of the R&E Tax Credit is the effect of apportionment of domestic R&D expenses to foreign source income as required under current tax rules. The result, in effect, is the loss of a tax deduction for the amount so apportioned.

The final disincentive is the continuous threat of repeal of the R&E Tax Credit, which has always carried an expiration date despite its numerous extensions. Research and development is by its nature long term. Accordingly, in order to be an effective incentive, the R&E Tax Credit should be made permanent, as the Administration has proposed.

Adoption of any or all of these suggestions would tend to encourage R&D investment, especially in long-range, high-risk R&D which characterizes superconductivity research.

Antitrust Policy Barriers

The same three attributes of high-temperature superconductivity that entered into the analysis of tax policy barriers to increased industrial investment in R&D also are relevant in assessing the impact of antitrust laws. The technology will be expensive to develop, investments in the technology are extremely risky, and even if the technology does eventually prove practical, it could be many years before a firm recovers its investment in R&D and starts to make a profit.

As a result, relatively few firms are likely to be willing to undertake such investments on their own. However, by pooling their efforts and sharing risk, firms can greatly reduce the risk borne by each individual firm investing in high-temperature superconductivity R&D. Moreover, combining knowledge, skills, expertise, and technology can greatly increase the likelihood that the R&D efforts will be successful. Cooperation also makes possible a larger scale of operation than any one firm acting alone might be capable of, thereby making available economies of scale and scope and eliminating unnecessary duplication of effort.

For all these reasons, superconductivity is a natural candidate for the formation of joint R&D

ventures. Many firms that could not even consider investing in superconductivity on their own might be willing to participate in a joint venture with other firms. However, firms will not be willing to form such ventures if they believe that such cooperative efforts will expose them to liability under the antitrust laws.

National Cooperative Research Act of 1984 (NCRA).

The antitrust laws originated in the last century, when foreign competition was not a significant factor. Now, however, many U.S. companies must compete in worldwide markets against foreign companies whose operations are largely beyond U.S. antitrust regulation. One attempt to modernize U.S. antitrust laws relevant to commercialization of technology is the National Cooperative Research Act of 1984 (NCRA). The NCRA currently provides limited protection from State and Federal antitrust laws for coordinated R&D activities, which should include joint ventures formed for the purpose of engaging in pre-competitive R&D related to superconductivity.

Under the NCRA, if the cooperative activity of an R&D joint venture is challenged in court, the conduct of each participant is evaluated under a "rule of reason" standard rather than treated as illegal *per se*. Under a rule of reason standard, a court must take account of all relevant factors affecting competition, including the extent to which efficiencies achieved through cooperation produce pro-competitive effects large enough to offset any potential anti-competitive effects. Rule of reason treatment is more hospitable to cooperative R&D because a joint venture will avoid liability if it is found not to pose a threat to competition or if any threat to competition is outweighed by potential pro-competitive efficiencies.

In contrast, under a *per se* rule of antitrust liability, a joint venture could be enjoined, dissolved, or held liable for payment of treble damages—without any consideration of such factors as the venture's actual degree of market power, the ease with which other firms can enter the market, actual and potential foreign competition, or the venture's pro-competitive efficiencies.

In addition, under the NCRA, any R&D joint venture that files a written notification with the

Department of Justice and the Federal Trade Commission disclosing the venture's nature, objectives, and participants has its potential monetary liability limited to actual damages. Current antitrust laws impose treble damages in most instances not covered by the NCRA.

However, the provisions of the NCRA as it currently stands limit its usefulness.

Extension of the NCRA to Production and Marketing

Production and marketing are not covered by the NCRA. This feature limits the impact of the NCRA as a stimulus to coordinated R&D. The nature of competition in international high-technology markets is such that bringing a product to market quickly is essential. Modern technology transfer, however, is not based on a stepwise transition from innovation to development to commercialization. Rather, the process often involves an interactive process, with investment in research, development, production, and marketing taking place simultaneously. These steps are integrally linked and frequently can be conducted more efficiently through cooperative efforts. Such integrated cooperative efforts, however, are not currently protected under the provisions of the NCRA, which draw an artificial line between R&D on the one hand and production and marketing on the other.

An extension of the NCRA to production or production and marketing would encourage industry investment in superconductivity R&D, as well as commercialization. Action on the several bills currently pending in Congress that would extend the NCRA to cover production or production and marketing would greatly assist U.S. competitiveness in developing and commercializing products based on superconductivity. Some of the bills would extend the NCRA just to joint production and manufacturing. Others would extend it to joint marketing as well. It should be noted that legislation supported by the Administration, transmitted to Congress by the Departments of Justice and Commerce, would extend the NCRA to cover production but would exclude marketing.

There are, of course, serious concerns about the possible abuse of extended provisions of the NCRA, but anticompetitive behavior would still

be illegal, and significant penalties for such behavior would remain in place. However, the resulting stimulus to industry investment in superconductivity research, development, and commercialization would be an important outcome.¹

Advance Approval for Cooperative Efforts

Even under the best of circumstances, the analysis of the "rule of reason" is uncertain and unpredictable. At the very least, the "rule of reason" must be defined and clarified. Moreover, when a cooperative venture would involve production or marketing, even the prospect of single damages can be a substantial deterrent to cooperation. Therefore, so far as possible, consistent with legitimate antitrust concerns, steps should be taken to ensure that the prospect of single-damage judgments under the rule of reason standard not unduly deter firms from forming and participating in cooperative ventures for research, development, and commercialization. Ideally, cooperative arrangements involving less than some specified portion of the relevant market, perhaps 20 percent or 25 percent, should automatically be shielded from antitrust liability, and some method should be created whereby firms not eligible for this market-power-based safe harbor may secure advance approval for cooperative efforts.

Summary of Possible NCRA Revisions

Specific structural and operational modifications of the NCRA that were suggested by testimony presented to the Commission are summarized:

- The NCRA should be amended to include joint commercialization efforts (production and, if possible, marketing) to encourage innovation and accelerate commercialization.
- A market-power-based safe harbor should be expressly adopted that would shield from antitrust liability cooperative innovation arrangements or strategic alliances that involve less than some specified portion, perhaps 20 or 25 percent, of the relevant market.
- An "openness safe harbor" should be made available, so that companies cooperating in product development, production, or market-

ing that make the results of their collaboration publicly available, by patenting or otherwise, will be shielded from per se antitrust liability and treble damages.

- Market definition should be tailored to the context of innovation and should focus initially on the market for knowhow; specific product markets become relevant only when commercialization is included within the scope of the cooperative arrangement.
- The rule of reason should be clarified to take specific account of the pace and stage of technological change and the need for operational and strategic coordination of innovation and commercialization.
- Antitrust law enforcement should not bias the selection of interfirm organizational forms; integration by contract should be treated no less favorably than full merger.
- A certification procedure should be created to permit the Department of Justice or the Federal Trade Commission, perhaps in consultation with each other or with the Department of Commerce, to "sign off" on a proposed arrangement as not violative of Federal or State antitrust laws.
- When a cooperative innovation arrangement has been certified, private antitrust suits challenging cooperative innovation arrangements under Federal or State antitrust laws should be limited to equitable relief; attorneys' fees should be awarded to the prevailing party.

Many of these changes could be made by the courts interpreting the rule of reason and the NCRA. However, Congressional action would be needed to create a certification procedure, eliminate treble damage actions, and make attorney fees symmetrical. A generic approach to amending the antitrust laws would be preferable to industry- or technology-specific approaches.

Intellectual Property Law Barriers

Several steps have been taken to revise the American patent system in ways that affect the field of applied superconductivity. One change

has been directed specifically at the science and technology of superconductors. In July of 1987, President Reagan announced the High Temperature Superconductivity Initiative with the stated objectives of improving cooperation among government, industry, and universities in research, enabling U.S. firms to move quickly in turning scientific advances into new or improved products and processes. The President called for stronger intellectual property protection and requested the Patent Office to accelerate review of applications dealing with superconductivity.

However, in reviewing the impact of current intellectual property laws on U.S. industrial investment in innovation and commercialization of technology and the implementation of the President's High Temperature Superconductivity Initiative, several changes for improvement of the domestic patent situation become apparent. Written and oral testimony presented to the Commission by external experts included many suggestions for changing the U.S. patent system or improving the administration of the process. The primary goal of the recommended changes is to improve the climate surrounding intellectual property issues so that U.S. inventors could receive greater international protection for their ideas and thereby remain competitive.

Harmonization of the U.S. Patent System

The U.S. patent system differs in several respects from those of our international competitors, and there are ongoing discussions on the possibility of bringing the U.S. system into harmony with those in effect in Japan and Europe. The most significant difference is that in the United States, the system is based on the "first to invent" concept, whereas elsewhere, the system is based on the "first to file" concept.

There are several strong arguments for and against the United States moving to a "first to file" system. Actually, many U.S. corporations already file application early under "first to file" guidelines to protect foreign markets, having recognized that by accelerating internal patent processing the advantages of both systems can be used with the only disadvantage being increased costs.

There are several disadvantages to adopting a "first to file" system. With an internationally recognized and accepted "first to file" system, all inventors would probably be given a 1-year grace period for filing after a public disclosure. This would put U.S. inventors at a cultural disadvantage because many, from universities especially, are used to publishing early and filing late. They would initially continue this practice and probably lose some patent rights to others. Most foreign inventors, on the other hand, were trained under their old "first to file" system and traditionally have had to file before any public disclosure. In addition, there would be a need for more patent examiners to handle the increased number of applications and follow-up continuation-in-part applications, which may increase overall patent costs.

From the university perspective, one of the major problems with adopting a "first to file" system is the requirement for absolute novelty. Under most foreign "first to file" systems, the inventor cannot obtain a patent if there has been any publication or public disclosure of the invention anywhere. Given that university researchers generally publish early and before filing for a patent, this "first to file" system could limit their ability to protect technology through the patent process.

A compromise position might be a "first to file" system including "absolute novelty" with a 1-year grace period limited to the actual inventor. Japan is already moving in this direction with a "first to file" system that includes a 6-month grace period limited to open disclosures and publications by the inventor.

Freedom of Information Act Exemptions

Government contract reporting requirements often obligate researchers to disclose patentable ideas early in the form of periodic reports and proposals. These may be viewed as open literature via the Freedom of Information Act. Researchers at universities are often unaware of the fact that monthly reports or proposals can jeopardize the granting of a patent when the 1-year grace period is exceeded.

President Reagan proposed that within certain time limits, Federal agencies may reject requests made under the Freedom of Information Act for scientific and technical information from Federal laboratories that could be "reasonably expected to cause harm to the economic competitiveness of the United States." This has not been enacted but would be desirable. It would be further advantageous if the legislation were extended to include the private industry and university sectors of the U.S. innovation community, especially in the field of high-temperature superconductivity.

Public Availability of Foreign Patent Applications

Pending U.S. patent applications are preserved in secrecy so that if the patent is not granted, the applicant or inventor can rely on trade secret rights. In most foreign countries, on the other hand, pending patents are either published or are made available for public inspection. This practice eliminates trade secret rights. To improve U.S. competitiveness, the patent law should be amended so that when a foreign patent application has been submitted and is available for public inspection in that foreign country, the counterpart U.S. application should be made available for public inspection to the United States.

Implementation of the recommendation would mean that, for the first time, U.S. industry would have access, in English, to all U.S. counterpart applications of those pending in Japan or Europe. This technology is already available to the foreigners in their native languages. This would increase the data base of conveniently accessible technology.

Patent and Know-How Licensing Issues

Exclusive exploitation of patents may not be the best way to access global markets or maximize the return on R&D. Licensing represents a viable alternative to exclusive exploitation. However, restrictions imposed by the antitrust laws and the Doctrine of Patent Misuse severely limit the opportunity for patent holders to maximize their return by this route. For example, royalties

cannot be obtained following the expiration of the licensed patents even though valuable trade secrets and other know-how may have been included in the license.

Prior to the intrusion of the antitrust laws and the Doctrine of Patent Misuse, it was possible for a patentee to obtain license restrictions and suitable compensation for the trade secrets and know-how even after expiration of the underlying patent. This provided the maximum return on the R&D investment. The inability to obtain similar compensation and restrictions today substantially reduces the benefits of licensing and can create direct competitors for the licensor after a relatively short time.

It is extremely likely that commercialization of high-temperature superconductors will entail substantial know-how and that licensing will not be very useful as a way of ensuring reasonable financial returns on the R&D investment. A substantial liberalization of the antitrust laws as applied to patent and know-how licensing should be adopted, and the Doctrine of Patent Misuse should be severely restricted or eliminated. At the very least, a misuse should not be found except pursuant to the rule of reason.

Patent Flooding

In Japan the low cost of filing patent applications and the minimal requirements for disclosure have resulted in what is called "patent flooding." Over 500,000 patent applications are currently filed in Japan per year compared to about 130,000 patent applications filed in the United States. The recent OTA report notes that in Japan, about 5,000 superconductivity applications were filed in a single year, while the total number of U.S. superconductivity patent applications filed by U.S. companies since 1985 is only about 500. The problem with flood patenting is that major advances made by an inventor in the United States are often overwhelmed by a flood of patents in Japan on bare ideas without any proof of principle. The United States should encourage Japan to change its system by substantially increasing its filing fees and its disclosure requirements for patent applications.

Full Implementation of the High Temperature Superconductivity Initiative

The Commission received suggestions for strengthening the ability of the Patent Office and the Judicial System that would better protect intellectual property rights related to commercialization of high-temperature superconductors. Many of these problem areas could be resolved by full implementation of the President's High Temperature Superconductivity Initiative.

Patent Office Staffing and Procedures

It is of tremendous importance to the Nation that all patents be processed promptly. Obviously, the commercialization cycle is accelerated when patent protection is assured. At the same time, others can learn from these patents and can commit to new products and plant facilities with the maximum practical knowledge of competing patents. This is in contrast to having to commit to a specific product design and new plant facilities in ignorance of still-pending applications from the competition.

As indicated above, some progress has been made on this issue in the area of superconductivity. The President's Initiative on Superconductivity directs the Patent and Trademark Office to, on the applicant's request, accord "special" status to all applications for inventions involving superconductive materials and their manufacture and use. This special "fast track" status ought to place the application in a stream which assures timely examination and processing. Specifically, the Patent Office should be staffed and should adopt procedures to assure that all superconductor-related applications are examined and patents are issued within 18 months of the filing date.

Judicial Procedures and Staffing

For the patent system to work efficiently, timely remedies must be provided in cases of conflict. Many patent infringement suits are not disposed of within 4 years of filing nor within 2 years after the close of evidence. The patent is a wasting asset if effective judicial remedies cannot

be obtained within a reasonable period of time. Infringement suits should be disposed of, finally, within an 18-month period.

The creation of the Court of Appeals for the Federal Circuit (CAFC) has provided consistency in patent decisions and increased public confidence in the U.S. patent system. As of June 1990, however, the court, which hears all appeals of patent cases, was understaffed with two vacancies; 12 judges are authorized. Suggestions presented to the Commission for the improvement of this court system include the following:

- Appoint more judges with extensive patent-law background. The workload of this court includes 30 percent to 50 percent of cases related to patents, with probably 60 percent to 80 percent of the working time taken up by patent cases. It makes sense to have at least half of the judges on the court with patent experience. As of June 1990, there were four judges with patent law background, but two are eligible to take senior status or retire.
- Appoint more judges with trial experience. Extensive trial experience is needed to evaluate cases adequately and to speed the review process.
- Appoint more judges or court support staff with a technical background because of the large number of cases with significant technical content. This one court may have a greater impact on controlling technology than any other court in the United States. It should reflect the highest standards.

In summary, by strengthening the protection provided for intellectual property rights under the patent laws and by strengthening the implementation of Patent Office and judicial processing of those laws, the risk associated with long range R&D investment can be reduced. Any action along those lines will increase the incentives for investment in R&D by industry, and, to the extent that such changes are specifically targeted toward commercialization of superconductivity, U.S. competitiveness in the field will be enhanced.

1. A recent report by the Office of Technology Assessment, *High-Temperature Superconductivity in Perspective*, states that "antitrust restrictions are not a serious inhibitor to U.S. competitiveness in HTS technology." (8, 118) Our analysis of the impact of antitrust policy leads us to believe that the OTA report was referring only to pre-competitive R&D, and did not take into account the continuum of research, development, production and marketing which is required for effective commercialization in a worldwide competitive environment.

Appendix IX

1990 Federal Funding Details for Superconductivity

Department of Energy Funding for High-temperature Superconductivity R&D (thousand dollars)

Source	FY 88	FY 89	FY 90	FY 91
Office of Energy Research				
Basic Energy Sciences	15,063	16,517	20,880	20,605
Fusion Energy	125	0	0	0
High Energy & Nuclear Physics	275	170	180	190
Defense Programs	5,800	6,661	6,651	6,651
Office of Conservation & Renewable Energy				
Energy Utilization Research	525	1,400	1,400	1,400
Energy Storage & Distribution	3,855	12,872	12,472	21,300
Office of Fossil Energy				
Advanced Research & Technical Development	294	75	0	0
Bonneville Power Administration				
Electric Energy R&D	50	20	20	20
Small Business Innovation Research Program	743	650	^a	^a
Total High-temperature R&D	26,730	38,365	41,603	50,166

^aSBIR estimates for FY 1990 and 1991 cannot be given because awards have not yet been made.

Department of Energy
Funding for Low-temperature Superconductivity R&D
(thousand dollars)

Source	FY 88	FY 89	FY 90	FY 91
Office of Energy Research				
Basic Energy Sciences	1,000	600	600	650
Fusion Energy	9,115	7,500	5,675	5,200
Superconducting Super Collider	11,200	29,000	43,800	49,300
High Energy & Nuclear Physics	6,000	23,958	24,170	22,890
Office of Fossil Energy				
Magnetohydrodynamics	275	188	99	0
Bonneville Power Administration				
Electric Energy R&D	37	80	150	300
Small Business Innovation Research Program	3,108	1,297	a	a
Total Low-temperature R&D	30,735	62,623	74,494	78,340

*SBIR estimates for FY 1990 and 1991 cannot be given because awards have not yet been made.

Additional Details for the Office of Basic Energy Sciences, Division of Materials Sciences
(thousand dollars)

Source	High T _c	Low T _c
University Grant Program	3,756 ^a	210
University-based programs operated in National Laboratory mode	3,771	390
Subtotal	7,527	600
Nonuniversity National Laboratories	13,353	0
Total	28,407	600

*Includes \$2,465 for congressionally mandated Midwest Superconductivity Consortium at Purdue University.

Department of Defense

(thousand dollars)

Unit	Objective	Amount
Army	Development of mission-related devices (estimate 50 percent university, 50 percent industry)	3,200
Navy	Mission-related and fundamental research (40 percent basic, 33 percent applied, 27 percent development) (17 percent universities, 27 percent industry, 56 percent Navy laboratories)	18,500
Air Force	Mission related and fundamental research	9,500
DARPA	To synthesize, process, and fabricate materials in engineering shapes and sizes for application to electronic, microwave, and power devices. Manufacturing issues of reproducibility, quality, and quantity for military products (100 percent applied research) (65 percent industry, 25 percent university, 10 percent other)	27,600
National Security Agency	Electronics, cross-bar switch (100 percent industry) (100 percent development)	3,000
Total		73,800

National Science Foundation, NASA, and the Department of Commerce

Agency	Objective	Amount (thousand dollars)
National Science Foundation	To increase the knowledge base of superconductivity and the behavior of superconducting materials and to enhance the infrastructure by training students in the field of superconductivity. Fundamental research on superconductivity is supported primarily at universities through three different funding modes: individual investigator grants, support of groups and centers, and support of national user facilities.^a	28,800
National Aeronautics and Space Administration	To investigate the potential of high-T _c superconductivity technology for the enhancement of NASA missions. (67 percent basic, 17 percent applied, 16 percent development) (29 percent in-house, 7 percent industry, 64 percent university)	8,000
Department of Commerce	To develop superconducting instrumentation, methods of measurement, national physical standards required to support industrial efforts; to develop practical superconductor products, and electronic devices. ^b	3,300

^aFunds for the National Science Foundation were distributed as follows: Individual investigator grants—\$11.9 million; Groups and centers—\$10.2 million; the National High Magnetic Field Laboratory—\$6.7 million.

^bThe Department of Commerce's Advanced Technology program has a 1990 funding level of \$10 million, some fraction of which may be for superconductivity.

Appendix X

Glossary of Technical Terms

ac	Alternating current: descriptive of a signal that varies periodically in amplitude as a function of time.
A/D converter	Analog-to-digital converter: an electronic device that translates an analog signal from a sensor, for example, to a set of corresponding discrete signals intelligible to a computer.
Bi-stable electronic element	An element capable of two distinct "switching" states through which a binary computer operates.
Bolometer	A sensitive detector operated in a transition region between superconducting and normal states capable of sensing certain forms of radiation.
Bulk superconductor materials	Superconducting material that is synthesized and processed so that it can be shaped or molded to form bearings, magnets, wires, or tapes by techniques such as chemical precipitation.
Cavity	An electromagnetic resonator useful for generating or amplifying very high frequency signals, as in a gyrotron.
Cooper pairs	The paired electrons that are believed responsible for the phenomenon of low-temperature superconductivity and may play a role in high-temperature superconductivity.
dc	Direct current: an electric current that maintains constant amplitude over time. Superconductivity involves zero resistance in a direct current.
Dielectric constant	A measure of the capacity of an insulating material to store electric energy.
Electron doping	The controlled addition of atoms in order to produce desired materials properties.
EM launcher	Electromagnetic launcher: a structure capable of accelerating large masses, such as projectiles or vehicles, to high velocities (see rail gun).
flops	Floating point operations per second: a measure of computer speed.
Flux creep	Movement in lines of magnetic flux induced by electric current or magnetic field that is sufficient to decrease the performance of superconductors.
Flux pinning	A superconducting phenomenon characterized by lines of magnetic flux being confined or localized in bulk material, which is potentially useful for enhancing current-carrying capacity.
Focal plane array	A dense set of detectors of, for example, infrared radiation, used in sensitive image detection and analysis.

Free electron laser	A wavelength-selectable source of laser light using an accelerated electron beam as its energy source. A technology under development for medical applications and for the Strategic Defense Initiative.
Giaever junction	A device similar to the Josephson junction but consisting of two superconductors with different energy gaps (incident radiation with energy exceeding this "gap" level eliminates superconductivity).
Gyrotron	A cavity vacuum tube device capable of generating extremely high power levels at millimeter wavelengths (MMW) and that requires magnetic fields of several T, necessitating cryogenic magnets.
H_c	Symbol for critical magnetic fields, measured in tesla, above which material is not superconducting.
High-temperature superconductivity	Generally referring to ceramic materials that exhibit superconducting properties above 77K, the boiling point of nitrogen.
hp	Horsepower: a measure of power equivalent to 746 watts.
Hysteretic	Nonreversible behavior indicating energy dissipation or a change in state for an electronic device, as in a binary switch.
IR	Infrared: a range of the electromagnetic spectrum between millimeter waves and visible light.
J_c	Symbol for critical current density, above which the material is no longer superconducting. A J_c from 1×10^5 to 1×10^6 A/cm ² is required by integrated circuit interconnections.
Josephson junction	A device consisting of an extremely thin insulating barrier sandwiched between two superconductors that is capable of extremely fast switching speeds.
K	Kelvin: a temperature scale for which 0K corresponds to -459 Fahrenheit and room temperature is approximately 300K.
Low-temperature superconductivity	Implying conventional metallic materials that exhibit superconductivity at temperatures near absolute zero (about 4 to 20K).
MAGLEV	Magnetically levitated (train): an evolving mode of transportation that uses high-field magnets to suspend and propel a vehicle to speeds greater than 300 miles per hour.
Magnetometer	A device that exploits Josephson junction technology and is capable of detecting extremely small magnetic fields, especially promising for anti-submarine warfare and basic scientific research.
Magnetoplasma-dynamics	An engine principle that uses a magnetic field to direct plasma through a nozzle, capable of high efficiency and low thrust, which is useful for interplanetary travel, for example.

Melt texturing	A method of producing bulk materials and wire that improves the conductive characteristics.
Metallic superconductors	Alloys and compounds of metals such as Nb ₃ Sn and Nb-Ti that become superconductors at around 4.2K (low-temperature superconductors).
MHD	Magnetohydrodynamics: the technology for converting the kinetic energy in a moving fluid, such as plasma, into electrical energy by applying a magnetic field. This process can be applied in reverse to use electric power to move fluids in, for example, ship propulsion.
Microwave	A range in the electromagnetic spectrum above 200 megahertz and through millimeter waves.
Mixer	An electronic device that combines two electromagnetic signals together and produces a signal that is the difference of the original inputs, an essential component in communications systems.
MMW	Millimeter wave: referring to a portion of the electromagnetic (frequency) spectrum between 30 and 300 gigahertz.
MRI	Magnetic resonance imaging: a medical diagnostic technique that measures weak radio frequency signals emitted by certain nuclei in soft body tissues responding to applied magnetic fields.
Oscillator	An electronic device that generates an ac signal, required by communications transmitters and directed energy weapons.
Oxide material	A compound of oxygen with one other more positive element or radical. In the context of superconductivity, these are compounds of oxygen and copper—the so-called ceramic or high-temperature superconductors discovered in 1986.
Particle accelerator	A device for accelerating particles, such as electrons, to high velocities.
Passive circuit elements	Electronic components that process and condition electromagnetic signals without amplifying those signals.
Quantum tunneling	A physical phenomenon whereby electrons can cross a thin insulating barrier, enabling a number of novel device applications.
Quench gun	An electromagnetic launcher where, in theory, the energy stored in a series of persistent-current superconducting magnets is transferred to the kinetic energy of a projectile with only modest transient field losses.
Radar	Radio detection and ranging: a technique for observing and tracking targets by processing a reflected electromagnetic signal.
Rail gun	A highly efficient electromagnetic structure capable of accelerating projectiles to high velocities by directly converting electromagnetic to kinetic energy.

RF	Radio frequency: referring to a portion of the electromagnetic (frequency) spectrum from essentially dc to infrared.
SIS	A superconductor-insulator-superconductor tunnel junction with hysteretic characteristics useful for digital and analog electronic devices.
SMES	Superconducting magnetic energy storage: a highly efficient technique for storing power that requires fields of perhaps 2 to 5 T. A typical system would consist of a large superconducting ring or coil that could maintain an electrical current indefinitely and be tapped when necessary.
SNS	A non-hysteretic superconductor-normal metal-superconductor tunnel junction, similar to the SIS junction.
SQUID	Superconducting quantum interference device: the most sensitive sensor known for measuring magnetic flux (less than 0.000001 T). Clinical, geological, astrophysical, and military applications are prevalent.
SSC	Superconducting Super Collider: when constructed, will be the world's largest accelerator for high-energy physics experiments.
Superconducting thin film	A superconducting layer, less than 10 micrometers in thickness, deposited on a substrate, useful for electronics applications.
T	Symbol for tesla, a unit of magnetic flux density. The most powerful magnets available produce (pulsed) fields of approximately 50 T but require excessive mass and cooling.
T_c	Symbol for critical temperature, above which the material is no longer superconducting. Present technology limits are approximately 125K.
Tevatron	A high-energy particle accelerator and collider located in Fermilab in Illinois; it uses 1,000 LTS magnets.
Three-terminal superconducting device	A superconducting device having input/output and a modulation terminal, which can amplify a signal like a transistor.
Type II superconductors	Superconductors that can be penetrated by magnetic fields up to a critical level and remain superconducting.
UHF	Ultra high frequency: referring to a portion of the electromagnetic (frequency) spectrum between approximately 470 and 890 megahertz.
X-ray lithography	A method for creating patterns for integrated circuits using radiation.
YBCO	Yttrium barium copper oxide: the first oxide material to show superconducting properties at near the boiling temperature of liquid nitrogen (77K). Also known as 1-2-3 for the comparative ratios of elements, although more recently other combinations have been used.