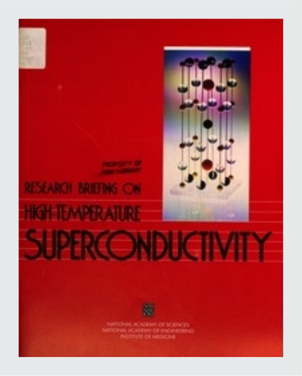

Research Briefings 1987: Report of the Research Briefing Panel on High-Temperature Superconductivity

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AUTHORS

Research Briefing Panel on High-Temperature Superconductivity; Committee on Science, Engineering, and Public Policy; National Academy of Sciences

Research Briefings 1987

Report of the Research Briefing Panel on High-Temperature Superconductivity

for the Office of Science and Technology Policy,
the National Science Foundation,
and Selected Federal Departments and Agencies

Committee on Science, Engineering,
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National Academy of Sciences
National Academy of Engineering
Institute of Medicine

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Dedication

This report is dedicated to the memory of Bernd T. Matthias, who laid the foundation of the modern materials physics of ferroelectricity and superconductivity, and revealed to us the great beauty and diversity of materials properties achievable through crystal chemistry and the creative use of the Periodic Table.

Research Briefing Panel on High-Temperature Superconductivity

John K. Hulm (*Chairman*), Director, Corporate Research and R&D Planning, Westinghouse R&D Center, Pittsburgh, Pa.
Neil W. Ashcroft, Department of Physics, Cornell University
Roger W. Boom, Professor and Director, Applied Superconductivity Center, Nuclear Engineering and Metallurgical Engineering, College of Engineering, University of Wisconsin, Madison
H. Kent Bowen, Ford Professor of Engineering, Massachusetts Institute of Technololgy
Robert J. Cava, Technical Staff, AT&T Bell Laboratories, Murray Hill, N.J.
Paul C.W. Chu, Department of Physics, University of Houston, Tex.
John Clarke, Professor of Physics, University of California, Berkeley, and Principal Investigator, Lawrence Berkeley Laboratory
Marvin Cohen, Professor of Physics, University of California, Berkeley
James S. Edmonds, Senior Project Manager, EPRI, Palo Alto
Douglas K. Finnemore, Associate Director, Science and Technology Division, Ames Laboratory, Department of Energy
Eric B. Forsyth, Chairman, Accelerator Development Department, Brookhaven National Laboratory
Theodore H. Geballe, Professor of Applied Physics, Stanford University
David C. Larbalestier, Associate Director, Applied Superconductivity Center, Department of Metallurgical Engineering, University of Wisconsin, Madison
Charles Laverick, Private Consultant, Patchogue, N.Y.
Alexis P. Malozemoff, Division Coordinator for High-Temperature Superconductivity, T.J. Watson Research Center, IBM Corporation
James H. Parker, Private Consultant, Penn Hills, Pa.
David Pines, Professor, Loomis Laboratory of Physics, University of Illinois, Urbana

Carl H. Rosner, President, Intermagnetics General Corporation, Guilderland, N.Y.
John Rowell, Assistant Vice President, Solid State Science and Technology Research Laboratory, Bell Communications Research, Red Bank, N.J.
Arthur Sleight, Central Research and Development Department, Experimental Station, E.I. duPont de Nemours & Company
James L. Smith, Senior Scientific Advisor, Center for Materials Science, Los Alamos National Laboratory
Masaki Suenaga, Senior Metallurgist, Department of Applied Sciences, Brookhaven National Laboratory
Maury Tigner, Newman Laboratory, Cornell University
Michael Tinkham, Physics Department, Harvard University
John Williams, Head, Magnet Technology Division, National Magnet Laboratory, Massachusetts Institute of Technology

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Topics cited below are followed by the names of units that provided staff support for their development. A collected volume is published each year as *Research Briefings 1987, Research Briefings 1986*, etc., by the National Academy Press, Washington, D.C.

1987

1. Order, Chaos, and Patterns: Aspects of Nonlinearity (*Commission on Physical Sciences, Mathematics, and Resources*)
2. Biological Control in Managed Ecosystems (*Commission on Life Sciences*)
3. Chemical Processing of Materials and Devices for Information Storage and Handling (*Commission on Physical Sciences, Mathematics, and Resources*)
4. High-Temperature Superconductivity (*Committee on Science, Engineering, and Public Policy*)

Policy Topic

5. Research and Research Funding: Impact, Trends, and Policies (*Committee on Science, Engineering, and Public Policy*)

1986

1. Science of Interfaces and Thin Films (*Commission on Physical Sciences, Mathematics, and Resources*)
2. Decision Making and Problem Solving (*Commission on Behavioral and Social Sciences and Education*)
3. Protein Structure and Biological Function (*Institute of Medicine*)
4. Prevention and Treatment of Viral Diseases (*Institute of Medicine*)

1985

1. Remote Sensing of the Earth (*Commission on Physical Sciences, Mathematics, and Resources*)
2. Pain and Pain Management (*Institute of Medicine*)
3. Biotechnology in Agriculture (*Board on Agriculture*)
4. Weather Prediction Technologies (*Commission on Physical Sciences, Mathematics, and Resources*)
5. Ceramics and Ceramic Composites (*Commission on Engineering and Technical Systems*)
6. Scientific Frontiers and the Superconducting Super Collider (*Commission on Physical Sciences, Mathematics, and Resources*)
7. Computer Vision and Pattern Recognition (*Commission on Physical Sciences, Mathematics, and Resources*)

1984

1. Computer Architecture (*Commission on Engineering and Technical Systems*)
2. Information Technology in Precollege Education (*National Academy of Sciences*)
3. Chemical and Process Engineering for Biotechnology (*Commission on Physical Sciences, Mathematics, and Resources*)
4. High-Performance Polymer Composites (*Commission on Physical Sciences, Mathematics, and Resources*)
5. Biology of Oncogenes (*Institute of Medicine*)
6. Interactions Between Blood and Blood Vessels (Including the Biology of Atherosclerosis) (*Institute of Medicine*)
7. Biology of Parasitism (*Institute of Medicine*)
8. Solar-Terrestrial Plasma Physics (*Commission on Physical Sciences, Mathematics, and Resources*)
9. Selected Opportunities in Physics (*Commission on Physical Sciences, Mathematics, and Resources*)

1983

1. Selected Opportunities in Chemistry (*Commission on Physical Sciences, Mathematics, and Resources*)
2. Cognitive Science and Artificial Intelligence (*Commission on Behavioral and Social Sciences and Education*)
3. Immunology (*Institute of Medicine*)
4. Solid Earth Sciences (*Commission on Physical Sciences, Mathematics, and Resources*)
5. Computers in Design and Manufacturing (*Commission on Engineering and Technical Systems*)

1982

1. Mathematics (*Commission on Physical Sciences, Mathematics, and Resources*)
2. Atmospheric Sciences (*Commission on Physical Sciences, Mathematics, and Resources*)
3. Astronomy and Astrophysics (*Commission on Physical Sciences, Mathematics, and Resources*)
4. Agricultural Research (*Board on Agriculture*)
5. Neuroscience (*Institute of Medicine*)
6. Materials Science (*Commission on Engineering and Technical Systems*)
7. Human Health Effects of Hazardous Chemical Exposures (*Commission on Life Sciences*)

Preface

This report on high-temperature superconductivity is one of five research briefings organized in 1987 by the Committee on Science, Engineering, and Public Policy (COSEPUP). It brings to 37 the number of such reports presented on a broad range of topics since the first volume in 1982. (A complete list of topics begins on page vii.) The briefings are developed at the request of the President's Science Advisor, who also serves as Director of the Office of Science and Technology Policy (OSTP), and the Director of the National Science Foundation (NSF).

This briefing was prepared at the specific request of Erich Bloch, Director of the NSF, after the 1987 briefing activity was under way, in response to the exciting new developments in superconductivity in ceramic oxide materials announced earlier this year. The panel's specific charge was to examine not only the scientific opportunities in high-temperature superconductivity but also the barriers to commercial exploitation.

Research briefing topics generally are selected by the OSTP and NSF directors in the late fall in response to suggestions put forward by COSEPUP. COSEPUP's suggestions are selected from a much larger list offered by the commissions and boards of the National Research Council (NRC); members of the NAS, NAE, and IOM Councils; members of COSEPUP; as well as officials of the NSF and OSTP. Individual briefings are designed either (1) to assess the status of a field and identify high-leverage research opportunities and barriers to progress in the field (including, where appropriate, progress in commercial exploitation), or (2) to identify and illuminate critical aspects of a policy issue related to the health of U.S. science and technology. The briefings are then prepared by panels of experts, usually in the spring, with the day-to-day assistance of NRC staff. This schedule allows time for COSEPUP review in late spring and presentation of the briefings, in both oral and written form, to federal officials early in the upcoming fiscal year's budget preparation cycle. The briefing reports, both in individual form and as an annual collection, are then published by the National Academy Press.

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*COSEPUP is a joint committee of the National Academy of Sciences (NAS), the National Academy of Engineering (NAE), and the Institute of Medicine (IOM).

Report of the Research Briefing Panel on High-Temperature Superconductivity

EXECUTIVE SUMMARY

The recent discovery of superconductivity at temperatures up to 95 K is one of the more important scientific events of the past decade. The sheer surprise of this discovery, as well as its potential scientific and commercial importance, largely underlie the degree of excitement in the field. Because our previous understanding of superconductivity has been so fundamentally challenged, a door has been opened to the possibility of superconductivity at temperatures at or above room temperature. Such a development would represent a truly significant breakthrough, with implications for widespread application in modern society.

While the base of experimental knowledge on the new superconductors is growing rapidly, there is as yet no generally accepted theoretical explanation of their behavior. Applications presently being considered are largely extrapolations of technology already under investigation for lower-temperature superconductors. To create a larger scope of applications, inventions that use the new materials will be required. The fabrication and processing challenges presented by the new materials suggest that the period of precommercial exploration for other applications will probably extend for a decade or more.

Near-term prospects for applications of high-temperature superconducting materials include magnetic shielding, the voltage standard, superconducting quantum interference devices, infrared sensors, microwave devices, and analog signal processing. Longer-term prospects include large-scale applications such as microwave cavities; power transmission lines; and superconducting magnets in generators, energy storage devices, particle accelerators, rotating machinery, medical imaging systems, levitated vehicles, and magnetic separators. In electronics, long-term prospects include computer applications with semiconducting-superconducting hybrids, Josephson devices, or novel transistor-like superconducting devices.

The United States has a good competitive position in the science of this field, and U.S. researchers have contributed significantly to the worldwide expansion of scientific knowledge of the new materials. International competition is intense. Several other leading industrialized countries have mounted substantial scientific and technological efforts, especially Japan, a number of Western European nations, and the USSR.

The short-term problems and long-term potential of high-temperature superconductivity may both be easily underestimated. Given this potential and the current limited understanding of the new superconducting materials and their properties, it is essential that government, academic institutions, and industry take a long-term, multidisciplinary view. Since science and technology in this field are strongly intertwined, progress must occur simultaneously in basic science, manufacturing/processing science, and engineering applications. It is also important to maintain an open and cooperative international posture.

The panel has identified eight major scientific and technological objectives for a national program to exploit high-temperature superconductivity. They are:

1. to improve understanding of the essential properties of current high-temperature superconducting materials (especially T_c, H_{c2}, J_c, and alternating current losses) through the acquisition of additional experimental data;
2. to develop an understanding of the basic mechanisms responsible for superconductivity in the new materials;
3. to search for additional materials exhibiting superconductivity at higher temperatures by the synthesis of new compositions, structures, and phases;
4. to prepare thin films of controllable and reproducible quality from present high-temperature superconducting materials and to establish preferred techniques for growing films suitable for electronic device fabrication;
5. to develop bulk conductors from current high-temperature superconducting materials, with special emphasis on enhanced electric current-carrying capacity;
6. to advance the understanding of the chemistry, chemical engineering, and ceramic properties of the new materials, focusing on synthesis, processing, stability, and methods for large-scale production;
7. to fabricate a range of prototype circuits and electronic devices based on superconducting microcircuits or hybrid superconductor/semiconductor circuits, as suitable thin film technologies become available; and
8. to fabricate a range of prototype high-field magnets, alternating and direct current power devices, rotating machines, transmission circuits, and energy storage devices, as suitable bulk conductors are developed.

The panel recommends that the following actions be taken to carry out the objectives listed above:

- The U.S. government should proceed with its plans to provide funding for high-temperature superconductivity research and development on the order of $100 million for fiscal year 1988. This funding level represents a good beginning in addressing the challenges and opportunities offered by the new materials.
- Sufficient new money must be provided both to the science and the technology of high-temperature superconductivity so that other important and promising areas of research and development are not held back.
- A mechanism should be established to monitor the potential demand for increased scientific and technical manpower if the promise of high-temperature superconductivity is fully realized, and to make appropriate recommendations on the funding of U.S. graduate and postgraduate research programs.
- An interagency mechanism should be established to help coordinate planning for superconductivity programs among the various federal agencies.
- Given the anticipated rate of advance in high-temperature superconducting science and technology, the federal government should review progress in the field after 12 months as a guide to future resource allocation.

- Through its agencies, the U.S. government must enhance the probability that U.S. industry gains a competitive advantage in this new field. This could be accomplished by the close association of industry with the Engineering Research or Science and Technology Center programs of the National Science Foundation, by cost-sharing between government and industry on proof-of-concept projects, and by other joint efforts.

- An important mechanism for enhancing U.S. industry's position is improved technology transfer from the national laboratories to the private sector. Although a variety of means are already in place to encourage such transfer, the panel is concerned about the effectiveness of past efforts and urges both government and industry to pursue linkages more aggressively.

INTRODUCTION

Perhaps the most remarkable feature of the discovery of high-temperature superconductivity is the fact that it was so unexpected. The sheer surprise of this discovery, as well as its potential scientific and commercial importance, largely underlie the degree of excitement and fervor of the field. Superconductivity in the past has always been a challenging fundamental and technological problem, for which understanding and application have come slowly. Because our previous understanding of superconductivity has been so fundamentally challenged, there is hope that the progress that has been achieved so dramatically in the past 18 months can be continued.

High-temperature superconductivity offers an important opportunity for our nation's scientific and technological community. The opportunity merits a substantial thrust in fundamental research; at the same time, enough is already known to encourage commercial development efforts with the newly discovered materials.

BACKGROUND

Superconductivity was discovered by a Dutch scientist, Kamerlingh Onnes, in 1911. He found that the electrical resistance of frozen mercury (Hg) disappeared suddenly at 4.2 degrees Kelvin (K) (−269 degrees Celsius [C]), a temperature accessible only through immersion in liquid helium. In 1913 Onnes also found that weak magnetic fields (of a few hundred gauss) destroyed the effect, with the metal reverting to its normally resistive state. Subsequently, other metals such as tin (Sn) and lead (Pb) were found to be superconductors at similarly low temperatures. People soon began to invent applications for superconductors—for example, to reduce losses in electric power systems. However, in the 1920s it was found that superconductivity disappeared in these metals when rather low electric currents were passed through them. As a result, power applications were abandoned.*

Significant progress in understanding the physical basis of superconductivity came in the 1950s. In the theory of Bardeen, Cooper, and Schrieffer, interaction between electrons and "phonons" (vibrational modes in the lattice of atoms making up the material) leads to a pairing of electrons. At low temperatures, these so-called Cooper pairs condense into an electrical superfluid, with energy levels a discrete amount *below* those of normal electron states (known as the superconducting energy gap). In the same period, new materials were discovered that displayed superconductivity at temperatures as high as 20 K, almost 5 times higher than the temperature of superconductivity in mercury.

These scientific discoveries had two important consequences. First, in a direct experiment to verify the energy gap, Giaever at the General Electric Research Laboratories observed electron tunneling between superconductors—that is, electrons passing from one superconductor to another through a thin insulating barrier. The observation of normal electron tunneling led Josephson in England to speculate that Cooper pairs could also tunnel through a barrier, a prediction that was soon verified by Rowell and Anderson at Bell Laboratories. These discoveries laid the foundation for a whole new superconducting electronics technology.

Second, Kunzler and coworkers at Bell Laboratories established that a group of superconducting compounds and alloys (the Type-2 superconductors) could carry extremely high electric currents (up to a million amperes per cm^2 of conductor cross-section) and remain superconducting in intense magnetic fields (up to 30 tesla [T] or 300,000

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*Electric utility equipment typically carries thousands of amperes and has associated magnetic fields of up to 20,000 gauss or 2 tesla.

gauss). These materials, offering the prospect of very high magnetic fields and current-carrying capacity at a much lower cost than before, revived interest in superconducting magnets and electric power components.

In the years between 1960 and 1986, several hundred materials were found to be superconducting at sufficiently low temperatures. However, the highest critical temperature (i.e., the temperature below which a material becomes superconducting, T_c) achieved in this period was 23 K, which still required either liquid helium or liquid hydrogen cooling.

The workhorse of the high-field magnet technology has been niobium-titanium (NbTi), a ductile alloy that can be made into wires. A second material of great promise, niobium-tin (Nb_3Sn), can support even larger electric currents and remain superconducting in higher magnetic fields, but it has found much less use because of its brittle nature. Other materials have found more limited uses—for example, pure niobium in radiofrequency cavities and niobium nitride (NbN) in electronics.

RECENT DISCOVERIES

Recently, new materials have been discovered that have substantially higher T_cs. In January 1986 Bednorz and Müller, working at the IBM Laboratory in Zurich and searching for superconductivity in previously unexplored materials, determined that a lanthanum-barium-copper ceramic oxide became superconducting at temperatures over 30 K.

Spurred on by this unexpected discovery, laboratories in the United States and elsewhere have since found materials with even higher T_cs. The highest stable value to date that has been independently confirmed, 95 K (−178 C), was first achieved by Chu and colleagues at the University of Houston working with Wu and coworkers at the University of Alabama. At this temperature, liquid nitrogen (which boils at 77 K at atmospheric pressure and is much cheaper than liquid helium) can be used for cooling.

A large number of the so-called high-temperature superconductors are now known to exist, all of them variations of two basic types (the so-called 40 K and the 95 K [or 1-2-3] materials). Those with T_c greater than 77 K are based on only one structure, with copper (Cu) and oxygen (O) a constant feature. The new materials present an enormous scientific opportunity and open new vistas for potential applications. Because our understanding of superconductivity has been challenged in so fundamental a fashion, with the present theoretical understanding of superconductivity being insufficient to explain the properties of the new materials, there is hope that what has been achieved in such a short time can be extended. The excitement surrounding the field has caught the imagination of policymakers, the media, and the public at large. Research students are also attracted by this excitement, often being drawn from other areas of science by the prospect of careers in the field; but it is important to note that they are drawn from a manpower pool that can only be expanded slowly.*

There have been several preliminary reports of superconductivity at still higher temperatures, but at present there is no consensus as to their validity. It is likely that room-temperature superconductivity would make possible a much broader range of applications. A more immediate concern is whether the present high-temperature superconductors can be used to improve present electronic or power applications; on this question, researchers worldwide are cautiously optimistic.

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*Some of the manpower issues are discussed in *Physics Through the 1990s: An Overview*, Washington, D.C.: National Academy Press, 1986.

CURRENT KNOWLEDGE OF THE NEW HIGH-TEMPERATURE SUPERCONDUCTORS

The new high-temperature superconductors are mixed metal oxides that display the mechanical and physical properties of ceramics. A key to the behavior of the new materials appears to be the presence of planes containing copper and oxygen atoms chemically bonded to each other. The special nature of the copper-oxygen chemical bonding gives rise to materials that conduct electricity well in some directions, in contrast to the majority of ceramics, which are electrically insulating.

The first class of high-T_c oxides discovered was based on the chemical alteration of the insulating ternary compound La_2CuO_4 by replacement of a small fraction of the element lanthanum (La) with one of the alkaline earths barium (Ba), strontium (Sr), or calcium (Ca). The substitution led to compounds with critical temperatures of up to 40 K. In these materials, an intimate relation between superconductivity and magnetic order is presently under intensive study and has inspired one of the many classes of theories that attempt to explain high-temperature superconductivity.

In a second class of compounds, based on $YBa_2Cu_3O_x$ (where Y is yttrium, a rare earth), the metallic atoms occur in fixed proportions. These are the so-called 1-2-3 compounds, which are highly sensitive to oxygen content, changing from semiconducting, at $YBa_2Cu_3O_{6.5}$, to superconducting near 95 K at $YBa_2Cu_3O_7$, without losing their crystalline integrity. The high sensitivity of their properties to oxygen content is due to the apparent ease with which oxygen can move in and out of the molecular lattice.

The 40 K and 1-2-3 (or 95 K) materials have similar structures but differ significantly in other respects. In both compounds, the rare earth and alkaline earth atoms provide a structural framework within which the chains of copper and oxygen atoms may be hung.

Surprisingly, the substitution of other rare earths, even magnetic ones, for yttrium in the 95 K compounds results in very little change in superconducting properties. Various substitutions are under study, both to understand the present materials and to achieve higher critical temperatures in new ones.

STATUS OF THEORETICAL UNDERSTANDING

In the microscopic theory of Bardeen-Cooper-Schrieffer, the presence of a net attractive interaction between conduction electrons, which would normally repel each other because of their like electrical charges, is essential to the occurrence of superconductivity. In conventional superconductors this attraction originates in the dynamic motion of the crystal lattice, which leads to an attractive "electron-phonon-electron" interaction. But the recent appearance of superconductivity in a class of materials quite different from the conventional superconductors, and with extremely high transition temperatures as well, has led physicists to explore a very wide spectrum of possible new pairing mechanisms involving, for example, spin fluctuations, acoustic plasmons, and excitonic processes. The physical origin of the pairing "glue" remains an open and to some extent crucial question. There is a wide range of theoretical possibilities, and the ultimate explanation may involve a combination of mechanisms. Indeed, some theorists have discarded conventional Bardeen-Cooper-Schrieffer theory and have suggested that there may not even be the traditional close relationship between energy gaps and basic superconducting properties.

Given the wealth of puzzling experimental features in a variety of different materials, it may take a considerable effort, with a diverse theoretical program, to unravel fully the secrets of these compounds. In the meantime the fact that they obviously do exist can form the basis of immediate commercial exploitation. But the prospect of even more promising materials has led to a substantial theoretical effort aimed at elucidating the principles underlying the phenomenon. Typical of the questions currently under active consideration are the role played by oxygen, the nature and scope of dynamic mechanisms and the resulting electron pairing, whether this coupling is weak or strong, and whether the anisotropic nature of the materials is a truly important feature. The appearance of superconducting coherence lengths 1 or 2 orders of magnitude smaller than those previously encountered, the very low carrier concentrations, and the apparent importance of both copper and oxygen will probably require a considerable extension of our current understanding of superconductivity. The fact that the superconducting interaction mechanism in the new materials is likely to be very different from that in low-temperature superconductors certainly enhances the prospect that other high-temperature superconducting materials may be discovered.

PHYSICAL PROPERTIES IMPORTANT FOR TECHNOLOGY

The most important physical properties for applications are the superconducting critical temperature (T_c), the upper critical magnetic field (H_{c2}), and the maximum current-carrying capacity in the superconducting state (J_c). Also important are the mechanical, chemical, and electromagnetic properties: physical and thermal stability, resistance to radiation, and alternating-current loss characteristics. Each is discussed more fully below.

Critical Temperature, T_c

A rule of thumb for general applications is that materials must be operated at a temperature of ¾ T_c or below. At about ¾ T_c critical fields have reached roughly half their low-temperature limit, and critical current densities roughly a quarter of their limit. Thus, to operate at liquid nitrogen temperature (77 K), one would like T_c near 100 K, making the 95 K material just sufficient. To operate at room temperature (293 K) one requires a material with T_c greater than 400 K, well above the highest demonstrated value. Higher T_c materials would be superior across the board for applications, other properties being acceptable, and materials with T_cs above 400 K would have a truly revolutionary impact on technology. In this temperature domain one could consider mass market applications.

Upper Critical Magnetic Field, H_{c2}

$YBa_2Cu_3O_7$ samples generally exhibit extremely high upper critical fields. Preliminary measurements indicate that for single crystals H_{c2} is anisotropic, that is, dependent upon field direction relative to the *a*-, *b*-, or *c*-axes of the orthorhombic lattice. Values ranging from 30 T (*c*-axis) to 150 T (*a*- or *b*-axes) are reported at 4.2 K. The mechanical stresses associated with the confinement of such high magnetic fields in typical compact geometries are frequently beyond the yield or crushing strengths of known materials. Hence, improving these intrinsic H_{c2} values is less important than increasing T_c or J_c values. In fact, materials with higher T_cs should exhibit higher H_{c2} values if the performance of known materials is any guide. However, developing materials that can practically be fabricated into magnets and that retain useful J_cs at fields approaching H_{c2} even at 77 K is an important challenge.

Critical Current Density, J_c

For practical applications, J_c values in excess of 10^3 amperes per square millimeter (A/mm^2), are desirable both in bulk conductors for power applications and in thin film superconductors for microelectronics.

Bulk ceramic conductors of $YBa_2Cu_3O_7$ have achieved about 10^3 A/mm^2 at 4.2 K and 6 T. However, J_c falls off very steeply to levels around 10 A/mm^2 at 77 K and 6 T. There is no clear understanding of these reduced J_c levels at the present time, but achieving acceptable values for J_c in bulk high-temperature superconductors is of critical importance and must be a principal focus of research on fabrication processes.

Based on current experience, a reasonable target specification for a commercial magnet conductor would be J_c of 10^3 A/mm^2 at 77 K and 5 T, measured at an effective conductor resistivity of less than 10^{-14} ohm-m,* with strain tolerance of 0.5 percent, and availability at prices comparable to or less than those of conventional low-temperature superconductors.

Preliminary measurements on epitaxially grown single-crystal thin films indicate J_c values in excess of 10^4 A/mm^2 at 77 K and zero magnetic field. These values seem adequate for microelectronic applications.

Mechanical Properties

Present ceramic high-temperature superconducting materials can be strong, but they are always brittle. Hence, it may be that high-temperature superconductors wire will be wound into magnets prior to the final high-temperature oxidation step in its fabrication, after which it becomes very brittle. Other conductor fabrication techniques might be feasible, however—for example, those used for producing flexible tapes of Nb_3Sn. An elastic strain tolerance of 0.5 percent may be achieved in a multifilamentary conductor by a fine filament size and by induced compressive stresses.

Currently available ceramic technology allows the fabrication of the kinds of complicated pieces that may be needed for such applications as radiofrequency cavities. There are some indications that the new materials may be deformable above 800 C and can then be shaped. The development of a mechanical forming process, however, is constrained by the parallel need for the process to optimize J_cs, both by aligning anisotropic crystal grains and by increasing the strength of the intergranular electrical coupling.

Life testing will also be necessary to understand the performance of materials under realistic conditions such as temperature cycling and induced stresses due to transient fields. The adhesion of high-temperature superconductors to other materials is important in microelectronics, in which temperature cycling results in thermal expansion and contraction that cause stresses at the interface. More attention is needed to this problem.

Chemical Stability

The 1-2-3 compounds readily react with the ambient atmosphere at typical ambient temperatures. These problems seem to be less severe, however, as the purity and density of the materials are improved. Both water and carbon dioxide participate in the degradation through the formation of hydroxides and carbonates. Further study of the nature of this degradation is needed to develop handling procedures or protective coatings that will ensure against impairment of superconducting properties by atmospheric attack.

Chemical stability is also limited because oxygen leaves the structure under vacuum, even at room temperature. Surface protection techniques need to be developed to allow satisfactory performance and lifetime of the materials under various conditions of storage and operation. These concerns are heightened in thin films, in which, for some applications, the chemical composition of

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*The sensitivity of many of the measurements reported on the new ceramics is poor, and "zero resistance" often means 10^{-10} to 10^{-7} ohm-m, 4 to 7 orders of magnitude greater than values required for practical application.

the outer atomic layers near the surface must be maintained through many processing steps, and in which diffusion into the substrate interface could degrade superconducting properties.

Radiation Effects

High-temperature superconductors appear to be somewhat more sensitive to radiation than conventional superconductors. High sensitivity to radiation damage could pose a difficult, although not insurmountable, problem for application to magnetic fusion machines. For electronic applications the substitution of either conventional or high-temperature superconducting devices for those employing semiconductors would result in an improvement of several orders of magnitude in resistance to radiation damage.

Alternating Current Losses

Conventional superconductors exhibit losses in alternating current applications, such as in 60 Hertz power transmission or in microwave devices. Although little is known about the alternating current characteristics of the new high-temperature superconductors, there is no reason to expect that the new materials will exhibit lower alternating current losses than other superconducting materials. Recent measurements on thin films in parallel applied fields show the presence of a large surface barrier for the entry of flux, which indicates that hysteresis losses would be small. More extensive measurements of such losses are required.

SYNTHESIS AND FABRICATION

Two steps are required to synthesize the 95 K superconducting materials. First, the basic structure must be formed at temperatures above 600–700 C. The tetragonal structure so formed is deficient in oxygen and does not possess superconducting properties. Accordingly, the second part of the synthesis involves annealing under oxygen at a temperature below 500 C. The arrangement of this additional oxygen in the lattice causes a conversion from tetragonal to orthorhombic symmetry that supports high-temperature superconductivity.

For the future development of high-temperature superconducting materials, we require a much better understanding of how synthesis conditions relate to the structure of the 1-2-3 compounds on the atomic and nanometer scales. We need to know, further, how this structure relates to superconducting properties and to other important properties such as chemical stability and mechanical strength.

The fabrication of many high-temperature superconducting ceramics involves grinding of prereacted starting materials, which can result in contamination from grinding media. At the present time there is no evidence that impurities introduced by grinding degrade superconducting properties; however, further work is required to optimize this process. Also, the rate of oxygen uptake during the oxygen anneal depends on the available surface area of the sample; for large particles or very dense ceramics, this critical oxygen uptake reaction can be slow. A recently announced fabrication technique, in which materials in bulk are made by melting the ingredients, may make the manufacture of wires and specially shaped pieces much easier and may eliminate the need to work with sintered materials.

In addition, processes are required for the commercial production of high-quality thin films on useful substrates. What is needed is to compare the various ways that have been used to produce thin films—electron beam, planar magnetron sputtering, pulsed laser evaporation, molecular chemical vapor deposition—and establish the strengths and weaknesses of each method. Epitaxial growth methods also need to be studied.

A further requirement is the achievement of reliable, low-resistance ohmic contacts to the new materials. A better understanding of phase equilibria, solid solutions, and intermetallic compounds is needed to find stable ohmic contacts that do not degrade superconducting behavior.

NEW SUPERCONDUCTING MATERIALS

Finally, we must not neglect the search for new compounds with intrinsically superior superconducting properties. Operation at 77 K leaves little margin when running a device that utilizes a superconductor with a T_c of 95 K. Cryogenic systems that operate below 77 K should be investigated, and the compatibility of high-temperature superconductors with refrigerants other than liquid nitrogen (e.g., liquid neon) should be tested. Further, and perhaps most importantly, the events of the past year have shown that surprises do occur, and it may be that superconductivity at or above room temperature may be detected at some future date in compounds not yet studied.

CURRENT FIELDS OF APPLICATION AND THE LIKELY IMPACT OF THE NEW MATERIALS

Virtually all of the applications currently envisioned for high-temperature superconductors are extrapolations of devices already operated at liquid helium temperatures. The most important applications, however, may well involve devices that have yet to be contemplated, much less invented.

As shown in Table 1, present and potential applications fall into several distinct classes. Present applications include high-field magnets, radiofrequency devices, and electronics. Superconductivity brings unique advantages to high-field applications because resistive conductors such as copper dissipate large amounts of energy as heat when carrying large currents. Superconductors are also useful in high-Q cavities because of their low alternating current losses at high frequencies compared to those in normal metals.

TABLE 1 Principal Applications of Superconductivity[a]

PRESENT APPLICATIONS

Magnets

- Commercial and industrial uses
  - —Medical diagnostics and research (magnetic-resonance imaging and spectroscopy)
  - —Radiofrequency devices (gyrotrons)
  - —Ore refining
  - —R&D magnets
  - —Magnetic shielding
- Physics machines (colliders, fusion machines, radiofrequency cavities)

Electronics

- Sensitive accurate instrumentation (superconducting quantum interference devices, infrared sensors)
- Electromagnetic shielding

POTENTIAL APPLICATIONS

(Proven superconducting technology, but no current market adoption)

- Power utility applications
  - —Energy production (magnetohydrodynamics, magnetic fusion)
  - —Large turbogenerators
  - —Energy storage
  - —Electrical power transmission
- Transportation
  - —High-speed trains (magnetic levitation)
  - —Ship drive systems
- Computers
  - —Semiconducting-superconducting hybrids
  - —Active superconducting elements

[a] There are many other potential applications, some of which are mentioned in the text.

Electronic applications for superconductors usually involve low electric currents (although high current densities) and low magnetic fields. The core element has been a unique bistable device, the Josephson junction. Superconductors may also eliminate resistive current losses in electronic lines and device interconnections. In addition, various kinds of superconducting sensors have been produced. All of these applications, including the assembly of superconducting electronic components into larger devices, will be reconsidered with the new compounds.

Potential applications of high-temperature superconductors divide into those relevant to currently available materials with critical temperatures near 95 K, and those relevant to possible future materials with higher critical temperatures. The most exciting possibilities, of course, arise with materials with critical temperatures above room temperature.

HIGH-FIELD AND LARGE-SCALE APPLICATIONS

Superconducting magnets using liquid helium technology have been successfully applied for a number of years in engineered systems and development projects in hospitals, mines, industrial plants, laboratories, and transportation systems. Most of these applications require multiple technologies, with superconductivity playing a critical role.

In medicine, superconductors have been a significant factor in the development of a new market. In high-energy physics, superconductors have led to machines of unprecedented and previously inconceivable energy. In electric power, potential applications in energy storage and power transmission equipment promise to extend the capacity and range of current technology. Superconducting magnets are essential components in experimental systems for magnetic fusion and magnetohydrodynamics (MHD). The extremely high power-to-weight ratio possible for superconducting machines makes them particularly attractive for space applications.

For magnet and power applications, the higher the critical temperature, the smaller will be the scale at which commercial viability will be achieved. As an example, the power level at which motors and generators become competitive will be much lower than with the present low-temperature superconductors, when compared to nonsuperconducting machines. A liquid nitrogen-cooled motor, for instance, operating at modest current and magnetic field, might well be smaller, more efficient, and more reliable for the same power output than many present-day motors.

For most applications the switch from liquid helium to liquid nitrogen technology is not revolutionary but will lead to improvements. The continued need for refrigeration is a disadvantage and will reduce market penetration. Of course, the reconsideration of applications held to be impractical at liquid helium temperatures might lead to new products. A hollow conductor cooled with liquid nitrogen is easy to visualize in practical use, for instance. It may not be necessary to demand that the technical specifications of new materials compete with the best commercial superconducting materials of today: a conductor of modest specifications may have value in a wider context than conventional low-temperature superconductors. The new materials, in short, may not so much replace present-day superconductors as extend the applications of superconductivity to a larger circle of users.

Medical Applications

Magnetic-resonance imaging (MRI) and spectroscopy (MRS) constitute radically new techniques in medical diagnosis and treatment, and their full impact is yet to be realized. Much more widespread availability of MRI and MRS systems can be anticipated, with concomitant reductions in cost and enhancement of features. The use of high-temperature superconducting materials would likely bring further small reductions in the costs of manufacture and operation. The redesign of MRI and MRS systems with liquid nitrogen cooling would also make them more user-friendly and reliable by reducing cooling system complexity.

Superconducting Radiofrequency Cavities

If microwave alternating current loss characteristics are tolerable, the new superconductors may greatly improve the performance of superconducting radiofrequency cavities by allowing them to operate at higher fields. Indeed, the potential impacts embrace all of microwave power technology, especially in the promising millimeter-wave region. Accelerator technology might also be significantly advanced by the availability of liquid nitrogen-cooled superconducting cavities. The applicability of superconducting technology to recirculating linear accelerators, on the other hand, is an accepted fact. In addition to providing high-quality beams for nuclear physics research, these machines are natural candidates for continuous beam injectors used in free-electron lasers. As technology matures and industrial applications develop for high-power, high-efficiency tuneable lasers in biotechnology, fusion plasma heating, and other fields, superconducting radiofrequency devices will proliferate.

Transportation

Ambitious attempts to apply superconductivity to land and ocean transportation have been made over the years with some success in the United States, Europe, and Japan. In fact, a Japanese magnetic levitation rail system is available for interested buyers and is economically viable.

Superconducting ship propulsion systems were studied in England in the 1960s. The U.S. Navy successfully installed a prototype superconducting drive system on a small ship in 1980; the development of a 40,000-horsepower drive system continues. A second concept uses seawater as the working fluid in an MHD propulsion system; the drive scheme is known as an electromagnetic thruster (EMT). Ship models based on this propulsion principle were promoted in the United States in the 1960s and operated in Japan in the 1970s. Practical designs for a full-scale EMT ship have been proposed, and industrial collaboration is being sought.

Because the present worldwide systems of air, sea, and land transportation are well established and represent a substantial investment, society has not yet made use of the potential advantages that have been demonstrated in prototype transportation systems using low-temperature superconductors. In land-based systems the principal advantage is high speed. Ship-based systems are lighter, have better speed control, and permit the radical rearrangement of power drive systems within ship structures. The combination of room-temperature superconductors and the low specific volume of superconducting machines could revolutionize surface transportation.

ELECTRONIC APPLICATIONS

Some of the most promising applications of high-temperature superconductors are electronic systems involving thin film lines or Josephson elements. Applications in computers would have the largest commercial impact, but may take longer because of their complexity. Sensor and instrument applications are simpler and are likely to be commercialized within a few years. Simplest of all is the use of high-temperature superconductors for low-field electromagnetic shielding.

Computers and Logic Devices

Much work has already been carried out on computer subsystems based on liquid helium superconductors. Semiconductor technology is still advancing rapidly, however, and continues to dominate the computer field. The discovery of high-temperature superconductors may change this situation.

One possible role of superconductors in such systems is simply to interconnect the semiconducting devices with superconducting microcircuit transmission lines. This possibility is already interesting at 77 K, because certain semiconducting devices switch faster at this lower temperature. However, 77 K copper lines present significant competition because of their decreased resistivity compared to that at room temperature.

The most exciting opportunities would use room temperature superconductors, offering compatibility with the entire line of semiconductors, including the highest performance bipolar devices. In the most promising scenario, the use of room temperature superconductors could affect the full range of data processing systems, which form the largest high-technology industry in the world today.

Although the implications of high-temperature superconductors for semiconducting computer systems have yet to be assessed, the reduced losses compared to normal conductors offer many possible advantages. System performance (i.e., switching speed) can be increased by reducing the RC time constant associated with the interconnect line. Narrower lines can be used, saving space on the chip. The elimination of power losses and voltage drops permits miniaturization of power busses and potentially, therefore, of the entire system.

The high-temperature superconductors have also been proposed for computer applications using Josephson junctions. High-temperature superconductors may offer higher device switching speeds, higher bandwidth transmission, and the possibility of using semiconducting memory to supplement ultra-high-speed superconducting logic. The disadvantages of high-temperature superconductors are increased thermal noise and switching power losses at 77 K compared to earlier liquid-helium temperature designs.

A variety of superconducting transistor-like devices have been proposed, among them superconducting field-effect transistors (FETs), several nonequilibrium devices, and optically switched FETs. These devices are at early stages of development, even using the conventional low-temperature superconductors; but although there are still considerable materials and fabrication problems, the potential performance of some of these devices might be enhanced by higher switching speeds and output voltage changes stemming from the larger energy gaps of the high-temperature superconductors.

SENSORS AND OTHER APPLICATIONS

SQUIDs

Superconducting quantum interference devices (SQUIDs), operating at liquid helium temperatures as sensitive magnetic field detectors, are already of value in many disciplines including medical diagnostics, geophysical prospecting, undersea communications, and submarine detection. SQUIDs made with the new high-temperature materials have been operated at liquid nitrogen temperatures. Relatively inexpensive SQUID-based magnetometers operating at 77 K or higher would be deployed in large numbers if electrical noise can be held to acceptably low levels.

Radiation Detectors

Superconducting microwave and far-infrared radiation detectors (quasiparticle mixers, superconducting bolometers) already exist using conventional superconductors. In spite of a loss of sensitivity due to increased electrical noise at higher temperatures, the increased energy gap of high-temperature superconductors would offer sensitive detection in a largely inaccessible frequency range, and the simplified refrigeration allows increased ease of use. Other microwave applications include high-Q waveguides, phase shifters, and antenna arrays.

Analog Signal Processors

High-speed analog signal processors performing such functions as filtering, convolution, correlation, Fourier transformation, and analog-to-digital (A-to-D) conversion are important for many applications. Various high-speed A-to-D converters have been tested successfully at 4.2 K. If high-quality Josephson junctions can be fabricated from the new superconductors, these devices should perform comparably at 77 K. At this temperature, integration of the superconducting devices with some semiconducting devices (for example, complementary metal-oxide semiconductors) becomes feasible, and new hybrid systems may well result in the fastest A-to-D converters available.

Magnetic Shielding

Both superconducting wires and superconducting sheets have been used for many years to create regions free from all magnetic fields or to shape magnetic fields. The advent of high-temperature superconductors may extend the range of this application. Like niobium-tin, high-temperature superconductors may be plasma-sprayed, permitting their use on surfaces of complex shape.

Voltage Standard

Many countries now maintain a voltage standard in terms of the voltage generated across a low-temperature superconducting Josephson junction irradiated by microwaves at a precise frequency. This standard could be more cheaply maintained and more widely available with no significant loss of accuracy by operating at 77 K with the new materials.

THE PRESENT MARKET FOR SUPERCONDUCTORS AND LIKELY CHANGES ASSOCIATED WITH THE NEW MATERIALS

The world superconductor industry is small, but superconducting devices are usually components of larger systems whose gross annual sales volume is many times the value of the devices themselves. Annual device sales total about $400 million, of which medical imaging machines and electronics instruments each account for approximately $150 million. Magnet coils represent 10 to 20 percent of device costs in MRI systems, and annual sales of basic materials such as alloy rod and sheet are on the order of $10–$20 million.

It is difficult to estimate the potential economic impact of today's high-temperature superconductors because so little is known about them and much depends on improved understanding and technological development. Assuming that satisfactory conductors can be manufactured, there are considerable advantages to operation in liquid nitrogen. Refrigeration units are simpler and cost less to operate. Conductor stability generally improves as the temperature increases because of the higher heat capacity of materials; however, the protective effect of the shunting normal conductor is reduced slightly because of its increased resistivity. Structural materials are less brittle at higher temperatures; therefore, more conventional structures can be used. Cryogenic liquids and systems, however, will still be needed. In comparing superconductor technology with present room temperature devices, the need for cooling is a serious economic and technological disadvantage. There is a great difference between switching on a machine as needed and having to supply continuous refrigeration, or having to wait for refrigeration systems to reach operating temperatures.

Assuming that some utility and heavy

electric power applications can be competitively marketed using systems cooled by liquid nitrogen, the superconducting materials market may be substantially increased; the market for heavy electrical equipment, however, would be mainly a replacement one, because few new systems are being built.

For substantial business growth above that projected for low-temperature superconductors, new technology developments are needed. There is little doubt that the new materials offer technological advantages, for they promise high-magnetic-field devices and new types of electronic sensors and switches at lower refrigeration costs than before. The panel is unanimous in stating that advances are bound to result in new applications and new economic growth. If room temperature superconductors become available, we can confidently expect a truly revolutionary expansion of superconducting applications in electrotechnology.

THE GLOBAL PICTURE: SUPERCONDUCTIVITY CAPABILITIES IN OTHER COUNTRIES

On a global scale, today's world superconductor industry is small but mature and principally confined to the developed countries. Basic research capabilities are more widespread.

Although much of the early impetus for research and development came from the United States, technology transfer has not been unidirectional. National and international conferences on all aspects of low-temperature physics have become routine.

Over the past 25 years, in several countries a wide variety of applications of superconducting electrotechnology have been examined in prototype development programs. No replacements for conventional applications have reached the market, however. As a result the demand for superconducting materials has been relatively small and has lacked continuity, being largely oriented toward development. Nevertheless, in most countries, government programs have supported a fledgling industry.

In the United States, magnet development for high-energy physics machines has been carried out in the national laboratories. Fusion and MHD magnets have been built both in the national laboratories and in private industry. There is also a rapidly growing commercial market based mainly on new medical imaging systems. A small materials and wire industry serves magnet development efforts. Many U.S. firms have supported their own research and development efforts in superconductor technology, both for power and electronic applications. A few small, continuing ventures have succeeded in superconducting electronics; a large market for superconducting electronic devices or systems has not yet developed.

Corporations in Europe and Japan have also fostered and maintained an expertise in superconductivity. In those nations, foreign governments have to some degree protected their superconductor industries by ensuring that equipment for government laboratories is built by domestic private industry; foreign bids are not accepted, a policy that ensures national industrial expertise. By comparison, much of this work in the United States is carried out in the federal laboratories from which there is little transfer to industry. In addition, foreign superconductor firms are allowed to bid on equipment needed by the United States government.

The USSR also has aggressive, long-term programs in energy conservation (including superconducting power transmission and storage), fabrication of superconducting wires and tapes, electronics, collider construction, magnetic fusion, magnetohydrodynamics, and superconducting generators.

Over the years, the United States has provided world leadership in superconducting science and technology, and has generously shared its own technology with other nations. Current collaborative efforts include the International Large Coil Fusion Project at Oak Ridge National Laboratory and Japanese development of a very large detector magnet for the Fermilab collider interaction area. In the evaluation of conductors for the physics collider magnets (the Superconducting Super Collider and the heavy-ion collider), material has been purchased from Japanese and European firms. The United States, through Brookhaven National Laboratory, also provides test evaluations of cables and conductors for the Hadron Electron Ring Accelerator (HERA) collider under construction in Hamburg, West Germany. Two prototype magnets for the Relativistic Heavy-Ion Collider (RHIC) have been purchased from the Brown Boveri Corporation (West Germany) because this was the cheapest and quickest way to obtain them (Brown Boveri had the necessary tooling because of their work for HERA).

BASIC HIGH-TEMPERATURE SUPERCONDUCTING RESEARCH

Basic research in high-temperature superconductivity is being actively pursued in all of the developed nations mentioned above and in several developing nations. In most cases scientists have switched spontaneously from other scientific activities into high-temperature superconductivity research. To this point, however, little new money has gone into basic research efforts. Plans are being prepared for 1988, but at present no major new government resources have been committed. The prevailing attitude appears to be that of waiting to see how the science progresses.

In *Japan* the scientific and technical community has responded vigorously, but aside from reprogramming there has been modest immediate additional action by government agencies. The latter have, however, been quite active in formulating plans for the next fiscal year (which begins in April 1988). Private industrial corporations are said to be investing their own funds heavily in research on high-temperature superconductors, with the government intervening to establish industry consortia to pursue prototyping and other early development activities. Japan offers perhaps the strongest long-range competitive threat to the U.S. position.

In *Europe*, historical strengths in basic research and industrial development are being applied to the new superconductors. National and cross-national efforts are in the early organizational stages at best (again, with the exception of the reprogramming of research funds), and major project goals to drive technical problem solving are not yet in place. On the other hand, a variety of industrial corporations are involved in research, and precompetitive collaborations appear to be at advanced planning stages.

In the *USSR*, traditional scientific strengths in superconductivity theory and basic experimental approaches are being applied to the new materials. In addition, work is being carried out on the susceptibility of high-temperature superconducting materials to radiation damage.

SUMMARY OF PANEL VIEWS AND RECOMMENDATIONS

STATUS OF SCIENCE AND TECHNOLOGY

- The discovery of materials that exhibit superconductivity at temperatures up to 95 K is a major scientific event, certainly one of the more important of the last decade. Meeting the complex challenge of understanding the phenomenon will improve fundamental knowledge of the electronic properties of solids.
- Although a large number of promising theories are being explored, there is as yet no generally accepted theoretical explanation of the high critical temperature behavior. Current theoretical understanding does not preclude T_cs above 95 K.
- The base of experimental knowledge on the new superconductors is growing rap-

idly. The intrinsic properties that can guide theory are still being determined. A number of investigators have reported superconducting-like transitions at temperatures above 95 K, in some cases even above room temperature; at present those effects have not been firmly established.

- The prospect exists for applying the new superconductors to both electrical and electronic technology. The nature of the new materials (quaternary ceramic oxides) suggests that a substantial materials engineering effort will be required to develop bulk conductors for power applications or thin films for electronic applications.
- The applications currently being considered are largely extrapolations of technology already under investigation for lower temperature superconductors. To create a larger scope of applications, inventions that use the new materials will be required. Given the materials engineering problems already mentioned, the period of precommercial exploration of the new superconductors for other applications will probably last for a decade or more. Although it is too early to make a sound engineering judgment about most of the possible high-temperature superconductivity applications, the potential impact could be enormous, especially if operation at room temperature can be achieved.
- Near-term prospects for high-temperature-superconductivity applications include magnetic shielding, the voltage standard, SQUIDs, infrared sensors, microwave devices, and analog signal processing. Longer-term prospects include large-scale applications such as microwave cavities; power transmission lines; and superconducting magnets in generators, energy storage devices, particle accelerators, rotating machinery, medical imaging systems, levitated vehicles, and magnetic separators. In electronics, long-term prospects include computer applications with semiconducting-superconducting hybrids, Josephson devices, or novel transistor-like superconducting devices. Several of these technologies will have military applications.
- The complexity of the materials technology and of many of these applications makes a long-term view of research and development essential for success in commercialization. The infectious enthusiasm in the press and elsewhere may have contributed to premature public expectations of revolutionary technology on a very short time scale. Overreaction in either direction could be detrimental to achieving the true long-term potential of high-temperature superconductivity.

THE UNITED STATES AND THE WORLD SITUATION

- Although the initial high-temperature superconductivity discovery was made in the Swiss research laboratory of IBM, the next advances occurred very soon afterward in the United States. These advances were the synthesis of 1-2-3 compounds with T_cs of up to 95 K. Before the constituents of the material were known, independent discoveries of the superconducting behavior of these compounds were also made in China and Japan a few days later.
- The United States has a good competitive position in the science of this field. It has also shown flexibility; scientists in universities and industrial and government laboratories have spontaneously switched into this field from their previous endeavors and have contributed significantly to the worldwide expansion of scientific knowledge on the new superconductors. Nevertheless, there is concern about the effectiveness of the nation's capabilities for translating this research strength into commercial products.
- The U.S. government has already reprogrammed close to $30 million of research funds for high-temperature superconductivity work in universities and industrial laboratories for fiscal year 1987. We estimate that at least an equivalent amount of private funds are being expended by U.S. corpora-

tions. Total annual funding levels will probably be in the range of $100–$200 million by 1988, although firm figures for industry are not available.

- These expenditures will expand the U.S. graduate and postgraduate population working in areas relevant to high-temperature superconductivity and will create pressures on the nation's scientific manpower pool.
- The rapid dissemination of scientific results has occurred mainly through word of mouth, preprints, and press releases, reflecting the close-knit global community of scientific endeavor. At present there are hardly any restrictions on the flow of information throughout the world.
- International competition in high-temperature superconductivity is intense. The leading industrialized countries, especially the United States, Japan, several Western European countries, and the USSR have mounted substantial scientific and technological efforts.
- Should successful technologies emerge from the discoveries in high-temperature superconductivity, the United States has many of the ingredients needed to develop and commercialize those technologies. Whether this will result in business success for U.S. corporations in the global market will depend not only on technological factors but also on company business strategies and a range of government policies. The panel is not qualified to address these latter issues comprehensively but has made some recommendations, listed below, that should assist commercialization.

FURTHER PROGRESS: THE NEXT STEPS

The short-term problems and long-term potential of high-temperature superconductivity may both be easily underestimated. Given this potential and today's limited understanding of the new superconducting materials and their properties, it is essential that government, academic institutions, and industry take a long-term, multidisciplinary view. Because science and technology in this field are strongly intertwined, progress must occur simultaneously in basic science, manufacturing processing science, and engineering applications. It is also important to maintain an open and cooperative international posture.

Scientific and Technological Objectives

The panel has identified eight major scientific and technological objectives for a national program to exploit high-temperature superconductivity. They are:

1. to improve understanding of the essential properties of current high-temperature superconducting materials (especially T_c, H_{c2}, J_c, and alternating current losses) through the acquisition of additional experimental data;
2. to develop an understanding of the basic mechanisms responsible for superconductivity in the new materials;
3. to search for additional materials exhibiting superconductivity at higher temperatures by the synthesis of new compositions, structures, and phases;
4. to prepare thin films of controllable and reproducible quality from present high-temperature superconducting materials and to establish preferred techniques for growing films suitable for electronic device fabrication;
5. to develop bulk conductors from current high-temperature superconducting materials, with special emphasis on enhanced electric current-carrying capacity;
6. to advance the understanding of the chemistry, chemical engineering, and ceramic properties of the new materials, focusing on synthesis, processing, stability, and methods for large-scale production;
7. to fabricate a range of prototype circuits and electronic devices based on superconducting microcircuits or hybrid supercon-

ductor/semiconductor circuits, as suitable thin film technologies become available; and

8. to fabricate a range of prototype high-field magnets, alternating and direct current power devices, rotating machines, transmission circuits, and energy storage devices, as suitable bulk conductors are developed.

PANEL RECOMMENDATIONS

The panel recommends that the following actions be taken to carry out the objectives listed above:

- The U.S. government should proceed with its plans to provide funding for high-temperature superconductivity research and development on the order of $100 million for fiscal year 1988. This funding level represents a good beginning in addressing the challenges and opportunities offered by the new materials.
- Sufficient new money must be provided both to the science and the technology of high-temperature superconductivity so that other important and promising areas of research and development are not held back.
- A mechanism should be established to monitor the potential demand for increased scientific and technical manpower if the promise of high-temperature superconductivity is fully realized, and to make appropriate recommendations on the funding of U.S. graduate and postgraduate research programs.
- An interagency mechanism should be established to help coordinate planning for superconductivity programs among the various federal agencies.
- Given the anticipated rate of advance in high-temperature superconducting science and technology, the federal government should review progress in the field after 12 months as a guide to future resource allocation.
- Through its agencies the U.S. government must enhance the probability that U.S. industry gains a competitive advantage in this new field. This could be accomplished by the close association of industry with the Engineering Research or Science and Technology Center programs of the National Science Foundation, by cost-sharing between government and industry on proof-of-concept projects, and by other joint efforts.
- An important mechanism for enhancing U.S. industry's position is improved technology transfer from the national laboratories to the private sector. Although a variety of means are already in place to encourage such transfer, the panel is concerned about the effectiveness of past efforts and urges both government and industry to pursue linkages more aggressively.