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SUPERCONDUCTIVITY: AN OVERVIEW

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SUMMARY

Recent discoveries of materials that are superconducting, i.e., capable of conducting electricity with no resistance, at temperatures much higher than previously known, raises the possibility of greater application of superconductivity with substantial economic benefits over the next several decades. If the materials can be made to carry electric current levels needed for most applications and can be fabricated easily into usable shapes (e.g., wires and tapes), superconducting electromagnets, power generators, power transmission cables, and electronic devices could operate at less cost and with much less engineering complexity than with existing technology. Successful development probably will require a three-pronged research and development effort emphasizing: (1) basic research toward achieving superconductors which can operate at temperatures sufficiently high that external cooling is not required for most applications (a so-called room temperature superconductor); (2) development of the new high-temperature superconducting materials into shapes and forms that are routinely manufactured and which, in turn, can be easily fabricated into various devices; and (3) greater operating experience with superconducting systems and applications using existing and evolving technology. The initial policy questions focus on the proper role for the Federal Government in research, in materials, and in technology and applications development needed to successfully apply these new materials. A more detailed report on superconductivity will be completed by CRS in the near future.

ISSUE DEFINITION

The discovery of materials that are superconducting at much higher temperatures than previously known has opened up the possibility of widespread applications with significant economic benefits. Many technical problems remain, however, and much research and development is needed to move the new materials to a commercial stage. In addition, there is concern that other industrial nations may move ahead of the United States in reaping the potential economic benefits of these new materials.

BACKGROUND AND ANALYSIS

Recent discoveries of materials that are superconducting, i.e., capable of conducting electricity with no resistance, at temperatures much higher than previously achieved, raises the possibility of greater application of superconductivity with substantial economic benefits over the next several decades. If the materials can be made to carry electric current levels needed for most applications and can be fabricated easily into usable shapes (e.g., wires and tapes), superconducting electromagnets, power generators, power transmission cables, and electronic devices could operate at less cost and with much less engineering complexity than with existing technology. Many observers have expressed concern, however, that other countries, particularly Japan, will take the lead in developing these technologies and exploiting their potential, leaving the United States at an economic disadvantage if it does not soon take effective action.

Scientific Background

Superconductivity was discovered in 1911 when the Dutch physicist, Kammerlingh Onnes, found that mercury lost all electrical resistance when cooled by immersion in liquid helium to 4.2 Kelvin (K) (equal to -452 F). [Gaballe, T.H., and J.K. Hulm, Superconductors in Electric-Power Technology, Scientific American, Nov. 1980, p. 141.] A temperature at which the material becomes superconducting is called its transition temperature. The absence of resistance means that no electric power is needed to maintain an electric current, and there are no energy losses as exist in conventional electrical devices. Kammerlingh Onnes was not able to exploit this discovery, however, because of other characteristics which caused the superconductivity to disappear when a small magnetic field was created. Discoveries in the 1930s uncovered materials that had higher transition temperatures and remained superconducting under more stringent conditions, but practical devices still eluded researchers. In the 1950s, a theory was developed that explained superconductivity, although the theory was not able to predict materials that would have higher transition temperatures. In the 1960s metallic superconducting materials were discovered, which could operate under conditions required for most applications (electromagnets, electronics, electric motors, etc.). Transition temperatures of these new materials were still low, about 18 K to 23 K (-427 F to -418 F), which meant that liquid helium was still required as the coolant. [Gaballe, T.H., and J.K. Hulm, Superconductors in Electric-Power Technology, Scientific American, Nov. 1980, p. 144.] These metallic superconductors, however, stimulated considerable worldwide activity in applications research that was continuing when the recent discoveries of high temperature superconductors were made.

In 1986, scientists at IBM discovered a ceramic compound that had a transition temperature of 30 K. [Superconductivity Seen Above the Boiling Point of Nitrogen, Physics Today, Apr. 1987, p. 17.] Although this material still required liquid helium to achieve a superconducting state, the discovery was a major increase in the transition temperature. More importantly, this finding quickly opened the door to discoveries of compounds with higher transition temperatures. In January 1987, a compound that was superconducting at 94 K (-364 F) was produced. [Superconductivity Seen Above the Boiling Point of Nitrogen, Physics Today, Apr. 1987, p. 19.] This discovery was significant because this temperature could be reached by liquid nitrogen, which is much cheaper and easier to handle than liquid helium. Therefore, if this material could be developed into a useful form, such as a wire or tape, the complexity and cost of cooling requirements for applications of superconductivity would be greatly reduced. Since then, there have been announcements of ceramic materials showing indications of superconductivity as high as 300 K (about 81 F). These latter observations have not been reproducible and appear in only part of the sample material. The highest temperature so far where all aspects have been seen is 225 K (about -54 F), although these results, too, are not firm. (Superconductor Breakthrough Reported Near, Washington Post, May 23, 1987, p. A1.]

There is a growing feeling among scientists that the observations above 200 K (about -100F) may be more a result of the measuring process than actual evidence of superconductivity. [Chemical and Engineering News, Sept. 7, 1987, p. 6.] Such feelings have grown stronger as months of effort have failed to confirm the numerous sightings above 200 K while the discoveries at 94 K were confirmed in several labs soon after the first announcement. Many of these researchers, however, remain optimistic that higher temperature superconductors will be found, although the search may take a long time. In this connection, researchers have been able to isolate those portions of some samples that do become superconducting at these high temperatures. This step may allow researchers to determine whether the observations above 200 K are real and, if so, what are the special properties that allow superconductivity. In addition, this isolation may permit construction of bulk materials that will remain superconducting at these high temperatures. The importance of findings nearing 300 K is the possibility of superconductivity without any external coolant, a so-called room temperature superconductor. Such a development would result in a reduction in cost and engineering complexity for any application that would be considerably greater than that which could be achieved by going from liquid helium to liquid nitrogen. It is this prospect that is most appealing for the new high-temperature superconductors.

Despite the excitement and promise of these recent discoveries, there are difficult problems that must be overcome before these new superconductors become a commercial technology. Foremost is that they must be able to carry large electrical currents without losing their superconductivity. To date, current densities (current per unit area of cross section) have been much lower than needed for nearly all practical applications, although IBM has achieved high current densities for certain ceramics in the shape of thin films. [IBM Superconductor Leaps Current Hurdle, Science, June 5, 1987, p. 1189.] Second, ceramics are hard, brittle materials not easily formed into shapes, such as wires and thin films needed for applications. It will be necessary to determine how to process these materials into such shapes in a relatively straightforward manner if widespread use of these materials is to take place. It is not yet certain that this goal can be reached, although advances are being made in a number of labs. In addition, inexpensive manufacturing technologies will have to be developed so that the desired shapes and applications can be made on a large scale.

Applications

The potential applications of superconductivity are vast. Since the mid-1960s engineers and scientists in the United States, Europe, and Japan have made use of metallic (low-temperature) superconductors in applications ranging from large electromagnets and electric power generators to very small microelectronic circuits.

The most successful application probably has been superconducting electromagnets, which take advantage of the very large current that can be carried by superconductors with virtually no power requirements. Superconducting electromagnets are used in many scientific labs in devices such as controlled fusion experiments and large particle accelerators. The high-energy physics accelerator at Fermilab has been using superconducting electromagnets since 1983 and the proposed superconducting supercollider would use nearly 10,000 such magnets. [Implications of the new high-temperature superconducting materials for the SSC are discussed in CRS Issue Brief 87096.] In addition, over 600 are in commercial use in magnetic resonance imaging medical diagnostic devices. Also, very large superconducting electromagnets are proposed for electric energy storage and tests have been run on such a device by the Electric Power Research Institute on the Bonneville electric power system. [Larbalestier, D., et al., High-Field Superconductivity, Physics Today, Mar. 1986, p. 32.] A limitation on superconducting electromagnets is the strength of the materials forming the structure of the electromagnet and the conductors themselves. The intense magnetic fields that can be generated by superconducting electromagnets create enormous forces. The ability to maintain the magnet's structure and to prevent movement of the conductors in the face of these forces ultimately limits the size of the magnetic field.

Superconducting electric power generators also have been built at Westinghouse and MIT, although not yet on the scale required by an electric utility. [Kirtley, J.L., Jr., Supercool Generation, IEEE Spectrum, Apr. 1983, p. 28.] In addition to a slight increase in overall efficiency -- from about 98.5% for conventional machines to about 99.5% for superconducting machines, a superconducting generator would be much smaller for a given power rating than a conventional generator. This size reduction results from the much higher magnetic fields that can be generated by superconducting electromagnets compared to a comparably sized conventional magnet. The superconducting generator's rotating electromagnet (coil) can be made much smaller and the iron that is normally needed to concentrate the magnetic field in a conventional generator can be eliminated in the superconducting version. Considerable engineering complexity is introduced, however, by the necessity of providing liquid helium cooling to the rotating coil in the generator. In addition to electric power applications, since 1970 the Navy has been building and designing superconducting motors and generators for ship propulsion. Successful test runs have been made of a 400 horsepower motor. [Superczynski, M.J., David W. Taylor Naval Ship Research and Development Center, private communication.]

Another large scale application is electric power transmission. Successful development of a prototype superconducting electric power transmission cable has taken place at Brookhaven National Lab. [Forsyth, E.B., The Brookhaven Superconducting Power Transmission System, The Physics Teacher, May 1983, p. 285.] Such cables have very large power handling capacities although only a small gain in energy efficiency because of the energy requirements of the liquid helium refrigeration system. Superconducting cables would be buried underground, which would add to the relative cost of these systems compared to conventional, overhead cables. In addition, superconducting power cables need to deal with the difficult technical problems of making transitions between the superconducting portion of the system and the conventional conducting portion at the terminus of the power cable, and in being able to handle electrical disturbances that could cause superconductivity to disappear.

Small scale applications are also possible. In 1962, a superconducting device called the Josephson junction was discovered, which raised the possibility of very high speed computers with virtually no power use. [Hayakawa, H., Josephson Computer Technology, Physics Today, Mar. 1986, p. 46.] These junctions could be switched on and off to provide the same kind of electronic control as a transistor has in a conventional computer circuit. In addition, the junctions could carry out this switching several times faster than a conventional circuit. There are very difficult fabrication problems with using these junctions, however, which are compounded by the need for liquid helium cooling. In addition, constraints forced by the particular circuit designs required to make use of these junctions as elements of a computer combined with advances in conventional transistor technology have nearly halted work in the U.S. on Josephson junction computers, although work continues in Japan. [IBM Drops Superconducting Computer Project, Science, Nov. 4, 1983, p. 492.] Despite these problems, the Josephson junction has found application in electronic instrumentation designed to measure extremely low electric and magnetic signals such as magnetic pulses from the brain and low-level infrared radiation.

In the defense area, several possible applications have received attention over the past several years. In addition to their use for ship propulsion, superconducting generators have been designed for compact electric power supply such as may be needed aboard aircraft. Compact energy storage electromagnets to drive directed energy weapons and rail guns also would be possible. These electromagnets would release their energy in very short time periods, yielding enormous power levels. Superconducting microwave systems that allow very large microwave power levels are being developed to drive free electron lasers, which are the major candidate for directed energy weapons. [Aviation Week & Space Technology, Aug. 18, 1986, p. 40.] Such superconducting microwave systems also could be used in electronic warfare. Another example is low-level infrared detectors as sensing devices to locate enemy weapons. Such applications produce extreme selectivity in discriminating between various heat sources.

Despite extensive work on superconductivity applications, success to date has been limited by a number of factors. Foremost are the high operating costs and technical complexity of using liquid helium as the coolant, although operating experience has shown that, with sufficient care, liquid helium can be handled reliably. In addition, as discussed above, there are other technical problems which are related to characteristics of superconductivity other than its cooling requirements. For example, the necessity of protecting against electrical disturbances and the circuit requirements of Josephson junctions are two such problems. [Kirtley, J.L., Jr., Supercool Generation, IEEE Spectrum, April 1983, p. 28.] Nevertheless, the development of materials that can use cheaper coolants (or, ideally, none at all), would make applications of superconductivity much more attractive. While the capital costs of these devices might not be less than those using metallic superconductors -- indeed such costs may be higher depending on the cost of ceramic high temperature superconducting materials -- the operating costs would surely drop. Further, the devices would be more forgiving to problems with the entire cooling system if liquid nitrogen could be used. Of course, if no cooling were needed they may not be much more complicated to operate than conventional systems.

Research and Development Needs

If we hope to realize the promise of high-temperature superconducting materials, research and development is needed. These R&D efforts should focus on three areas.

First, the research should continue for higher temperature superconductors and for a better understanding of how these new materials work. These goals are the primary target of much of the current basic research on superconductors both in the United States and abroad. In particular, researchers are seeking to find out why some materials display near room-temperature superconductivity in only part of the sample and why such behavior often is not reproducible. Another goal of this phase is to determine the factors that control the amount of current that can be carried by the high-temperature ceramic superconductors. Until the current carrying capacity of these materials is increased by at least factors of 10 to 100, their applications will be severely limited.

Second, research and development is needed so that high-temperature superconducting materials can be easily formed into wires, tapes and thin films, all of which are needed for various applications. As ceramics, these materials are difficult to shape and fabricate. In addition, such wires, tapes, and films need to be easily fabricated into the particular application. For applications in electromagnets and generators, the materials need to be strong in order to accommodate the enormous forces that will be generated by the intense magnetic fields. Also, the materials must be chemically stable and relatively insensitive to corrosion resulting from contact with the environment. Without these latter characteristics, applications using these new materials would be hampered by the need to provide protective coverings.

In addition to the materials properties themselves, reliable low-cost processing and manufacturing techniques will need to be developed. Such techniques are important for producing wires, tapes, and films from the high-temperature materials as well as manufacturing the superconducting devices themselves. Obviously, superconductors which would need no external cooling would greatly ease the manufacturing.

Finally, additional research and development on applications that use existing technology (metallic superconductors) would help provide the knowledge needed for routine operation of superconducting systems. At the same time, R&D should proceed on new applications that may be made possible by the new high-temperature superconductors. Most of the research on applications begun in the 1960s has wound down in the past few years. Much valuable experience and knowledge about building and operating superconducting systems, however, has been obtained. These efforts should be continued even though the new high-temperature materials are not yet ready and this applications research and development activity will require liquid helium-cooled technology for some time to come. It is important to solve those problems with superconducting applications -- some of which are described above -- that are not associated with particular cooling requirements. Also, it will be important to gain further operating experience with large scale superconducting systems even with liquid helium technology. A switch to liquid nitrogen or the elimination of any need for cooling, while certainly easing operations, will not change much of the fundamental behavior of superconducting devices. Also, the operating experience gained in this manner should speed the introduction of superconducting devices into electric power systems, computer systems, weapons systems, and other systems where these devices are likely to find application.

Research and development on applications under development with metallic low-temperature superconductors, however, must be carefully structured to allow a rapid and smooth transition to high-temperature superconductors when and if the materials become available. In other words, as high temperature superconducting wires and tapes with sufficient current carrying capacity become available, a well designed applications program should be able to substitute them for existing technology without major disruption of the program. For this reason, the applications R&D should be well integrated with the materials development in order to help the latter the most productive path.

Policy Considerations

The promise of the recent discoveries coupled with the Nation's concern about future economic growth and foreign competition in developing new technologies and products have prompted calls for a concerted Federal effort to develop rapidly the new superconducting technology. In particular, the Japanese have formed a joint government-industry committee to direct research and will establish a center for testing and application of the new materials. [Two Different Cadences In the Superconductor Race. Washington Post, May 21, 1987, p. A1.] Their actions have raised the concern that the United States will see other countries dominate the commercial application of these high-temperature superconductors. One result of this concern has been the upsurge in funding of superconductivity research in recent months by both the U.S. Government and private sectors. Research on superconductivity has long been supported by the Federal Government, including the National Science Foundation, Department of Energy, Department of Defense, National Bureau of Standards, and NASA, although funding was declining prior to 1987. The major reasons for the decline were decreasing economic prospects for potential applications -- particularly in the electric power field -- and difficult technical problems. From a low of about 10 million dollars in 1986, Federal funding for superconductivity research has grown to about $32 to $50 million, all by reprogramming. A considerable increase is expected in the coming fiscal year.

In addition to greater research funding, other measures are being proposed to accelerate U.S. efforts to develop and exploit high temperature superconductors. These proposals emphasize coordination of research and development within the Federal Government. Some designate a lead agency. Another commonality is a strong focus on technology development; in other words, providing resources to develop the technology of high-temperature superconductors to a point close to commercial readiness.

In assessing these proposals, there are several points that might be considered. The first question is whether the Government needs to play an expanded role if the new high temperature superconductors are to find their way into commercial applications. The vigor with which companies such as IBM, AT&T, DuPont, and a host of smaller companies are pursuing the development of superconducting materials appears to support the contention that the private sector will not need additional help. Further, the larger companies may possess resources to carry through development of these materials, although this only may be true for electronic applications. Federal funding of research into the physics and engineering of the new materials will likely be a strong supplement to the industrial efforts.

Timely and effective technology development, however, may require a more concerted, planned effort with several approaches possible. If a lead agency is to be designated, consideration of the limits of its authority is important. For example, a lead agency may be charged solely with ensuring, to the extent possible, that all Federal R&D efforts complement those of the private sector, and that there is effective transfer of results of the federally sponsored programs. This approach may be especially useful for pursuing large-scale applications that are farther away in time and may not command the same level of private sector support as the electronic applications. If this path is followed, it would be important for the lead agency to be experienced in a wide range of potential application areas. Another approach would be to make extensive use of existing Federal facilities. Designating an existing national lab to carry out most or all of the Federal civilian R&D efforts in basic research and technology development, and to be responsible for cooperative research projects among industry, universities, and Government researchers, may be one way to deal with this issue. This approach may be particularly productive in assuring that research on materials development and processing is managed effectively, and that development and testing of large-scale applications requiring extensive resources and facilities is carried out. An alternative to a single major R&D center might be to have several cooperative materials and applications development projects carried out or managed by different Federal facilities. This could involve existing Materials Research Centers and Engineering Research Centers. In the case of a dispersed research effort, the question of how and to what level R&D activities among the various Federal sponsors should be coordinated still would need addressing. Finally, the potential for greater international collaboration should be considered. While an important goal of the several proposals is to ensure major U.S. participation in the development and marketing of high-temperature superconductors, there are and will continue to be substantial international efforts. The most efficient path to exploiting these new discoveries may be through strong international collaboration.

Initiatives have come forth from both the Congress and Administration to address these issues. At the Federal Conference on Commercial Applications of Superconductivity, held on July 28 and 29, 1987, President Reagan announced an 11-point Superconductivity Initiative. The Initiative establishes superconductivity research centers within the Department of Energy and the National Bureau of Standards, directs the Department of Defense to spend $150 million over the next 3 years on the development of superconductivity technologies for military systems, and creates a "Wise Men" Advisory Group on superconductivity, composed of representatives from industry and academia, who would advise the Administration on research and commercialization policies. The Administration plan also proposes modifications in laws pertaining to patents, antitrust, and intellectual property. Congressional initiatives are described below.

Conclusions

If engineering requirements can be met, the promise of superconducting materials is quite large. The potential is particularly great if a superconductor is found that does not require external cooling. Despite the rapid advances seen thus far, fulfilling all of this promise will take several years. Along with continued painstaking search for higher temperature superconductors, development of materials and applications is still needed. Further, the large capital stock in place -- e.g., generators and power cables -- that could clearly benefit from the new superconducting materials will take considerable time to be replaced. The difficult problems that remain to be solved and the long-term economic potential of high-temperature superconductors, however, lend urgency to beginning efforts that will best allow this Nation to benefit from these exciting and promising discoveries.

LEGISLATION

H.R. 2069 (Ritter)

Superconductivity Competition Act of 1987. Creates a National Commission on Commercial and National Defense Applications of Superconductors to study methods of developing improved superconductors and ways to expand the commercial and strategic use of superconductors. Introduced Apr. 9, 1987; referred jointly to Committees on Science, Space, and Technology and on Armed Services.

H.R. 3024 (Ritter)

National Superconductor Manufacturing and Processing Technology Act of 1987. Establishes a National Superconductor Manufacturing and Processing Technology Initiative to be implemented by the Defense Advanced Research Projects Agency (DARPA), Department of Energy (DOE), National Science Foundation (NSF), and National Bureau of Standards (NBS). Identifies DARPA as the appropriate agency to implement the majority of this initiative. Establishes a Superconductivity Manufacturing and Processing Technology Coordinating Council to coordinate Federal superconductivity R&D. Creates a National Commission on Superconductivity (composed of members from Government, industry, and academia) to assist the Congress in devising a national strategy to assure U.S. leadership in the development and application of superconducting technologies. Designates the National Critical Materials Council as the coordinating body of the Commission. Authorizes $400 million for FY88 through FY92 for the purposes of this program. Introduced July 28, 1987; referred jointly to Committees on Science, Space, and Technology and on Armed Services.

H.R. 3217 (McCurdy)

National Superconductivity, Competitiveness, and National Security Act of 1987. Directs the National Critical Materials Council (NCMC) to establish a 5-year National Federal Program on Superconductivity Research and Development. Prior to establishment of the Program, the NCMC is instructed to appoint a National Advisory Commission on Superconductivity (composed of representatives from Government, industry and academia) which to review all major policy issues surrounding the development and application of superconductivity technologies. Directs the Department of Energy, Department of Commerce (including National Bureau of Standards), Department of Defense, and National Science Foundation to implement this program by establishing (1) an Office of Superconductivity within each of these agencies; (2) one or more Consortia for Enabling Superconductivity Technologies within DOE's National Laboratories; and (3) National Superconductivity Research Centers within NSF. Authorizes $150 million for FY89 through FY93 for the purposes of this program. Introduced Aug. 7, 1987; referred jointly to Committees on Science, Space, and Technology and on Armed Services.

S. 880 (Durenberger)

Superconductivity Competition Act of 1987. Creates a National Commission on Commercial and National Defense Applications of Superconductors to study methods of developing improved superconductors and ways to expand the commercial and strategic use of superconductors. Introduced Mar. 30, 1987; referred to Committee on Governmental Affairs.

S. 1480 (Domenici)

Department of Energy National Laboratory Cooperative Research Initiatives Act. Title I directs the Secretary of Energy to establish cooperative research centers in enabling technology for superconducting materials at the National Laboratories. Also directs the Secretary of Energy to form a Council for Research on Enabling Technologies, composed of representatives of Government, industry, and universities, to provide guidance in setting goals and strategies for research on critical enabling technologies in high-temperature superconductors. Introduced July 10, 1987; referred to Committee on Energy and Natural Resources. Subcommittee on Energy Research and Development held hearing Sept. 15, 1987.