Chapter 3

Applications of Superconductivity

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INTRODUCTION

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

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

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

APPLICATIONS

High-Energy Physics

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

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

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

Superconducting Super Collider (SSC)

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

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

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

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

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

Photo credit: Fermi National Accelerator Laboratory

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

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

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

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

Electric Power

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

Fusion Magnets

Magnetic fusion requires confinement of a heated plasma in a magnetic field long enough to get it to ignite—about 1 second.[10] Superconducting magnets are considered essential for the continuous, high-field operation that would be necessary for a commercial fusion reactor.

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

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

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

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

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

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

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

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

Superconducting Generators

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

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

Most studies indicate that LTS generators are only competitive with conventional generators at very high power ratings (500 to 1,000 MW). But with low load growth in the 1980s and continuing uncertainties about demand in the 1990s, there appears to be little enthusiasm among U.S. firms to put up their own cash for R&D on such large machines. *8 In principle, use of HTS could make smaller machines more competitive, but estimates differ on how much. The refrigeration system would be much simpler, and this would lead to greater reliability and maintainability. But the application involves a high-field, high-current, wire-wound magnet, spinning at high speed, under large centrifugal stresses. HTS wires would have to carry current densities on the order of 100,000 Amps/cm^2 in a 5 tesla magnetic

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

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

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

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

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

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

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

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

Table 3-1-Applications in the Electric Power Sector

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

SOURCE: Office of Technology Assessment, 1990.

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

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

Superconducting Magnetic Energy Storage (SMES)

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

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

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

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

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

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

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

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

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

Power Transmission Lines

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

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

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

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

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

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

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

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

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

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

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

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

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

Current Limiters, Switches, and Fuses

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

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

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

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

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

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

[32] *EPRI, op. cit.,* footnote 14. 1988, p. 18.

[33] Ibid., p.18.

[34] Ibid., p. 18.

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

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

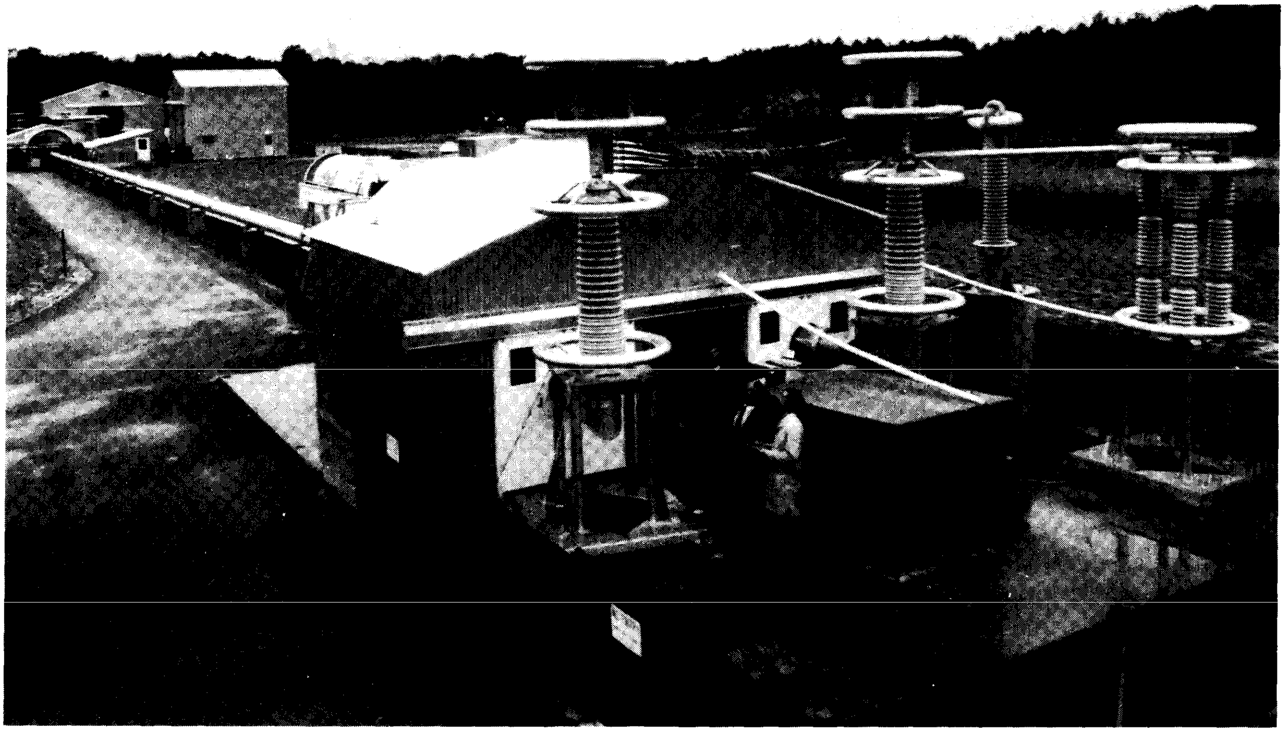

Photo credit: Brookhaven National Laboratory

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

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

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

Transportation

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

Maglev Systems

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

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

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

Table 3-2—Applications in the Transportation Sector

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

SOURCE: Office of Technology Assessment, 1990.

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

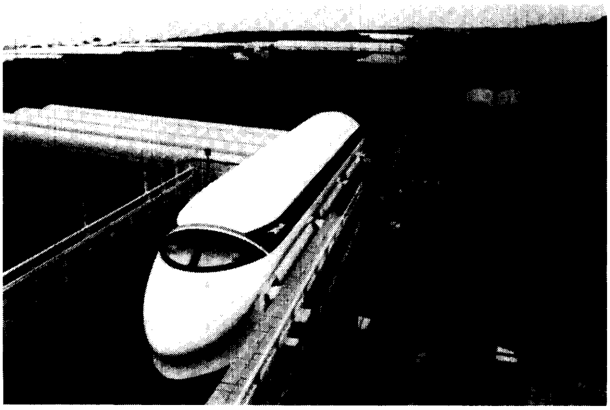

Photo credit: Japan External Trade Organization

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

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

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

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

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

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

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

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

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

Notable disadvantages of maglev center around development and construction costs. Development costs for the West German Transrapid system have exceeded $1 billion, $800 million of which has been subsidized by the West German government.[42] Development costs of the Japanese system have also exceeded $1 billion, and construction costs for the new 27-mile Japanese system are expected to be around $56 million per mile (not counting tunneling costs).[43] Development of a U.S. system is estimated to cost $780 million[44] plus $15 million per mile for construction.[45]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Automobiles

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

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

Ship Propulsion

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

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

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

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

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

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

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[52] 1bid.

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

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

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

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

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

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

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

Industrial Applications

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

Sensors

Industrial sensor applications of superconductors have been discussed by several authors[60] and include applications both inside and outside the factory: for example, inspection of raw materials, monitoring of manufacturing functions such as the positioning of the work piece and tool, nondestructive inspection in finished parts, detection of corrosion in bridges, or exploration for mineral and oil deposits, etc.

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

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

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

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

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

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

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

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

Table 3-3-Applications in the Industrial Sector

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

SOURCE: Office of Technology Assessment, 1990.

well-positioned to participate in the early markets for HTS SQUIDs.[c2]

Magnetic Separation

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

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

Superconducting magnetic separation systems have recently been demonstrated commercially in several countries for separation of discoloring impurities from white kaolin clay, a material widely used in the paper industry (see box 3-A). Superconducting magnets could also be used for removal of environmentally harmful materials from municipal solid waste and wastewater streams, removal of sulfur from coal, and pretreatment of water to reduce carbonate scale formation in pipes and fixtures.[c3]

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

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

Materials Processing

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Compact Accelerators

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

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

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

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

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[64] Ibid. p.70.

[65] Ibid.

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

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

[68] Ibid.

Table 3-4-Applications in the Medical Sector

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

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

SOURCE: Office of Technology Assessment, 1990.

Motors

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

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

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

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

Medical Applications

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

Magnetic Resonance Imaging

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

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

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

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

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

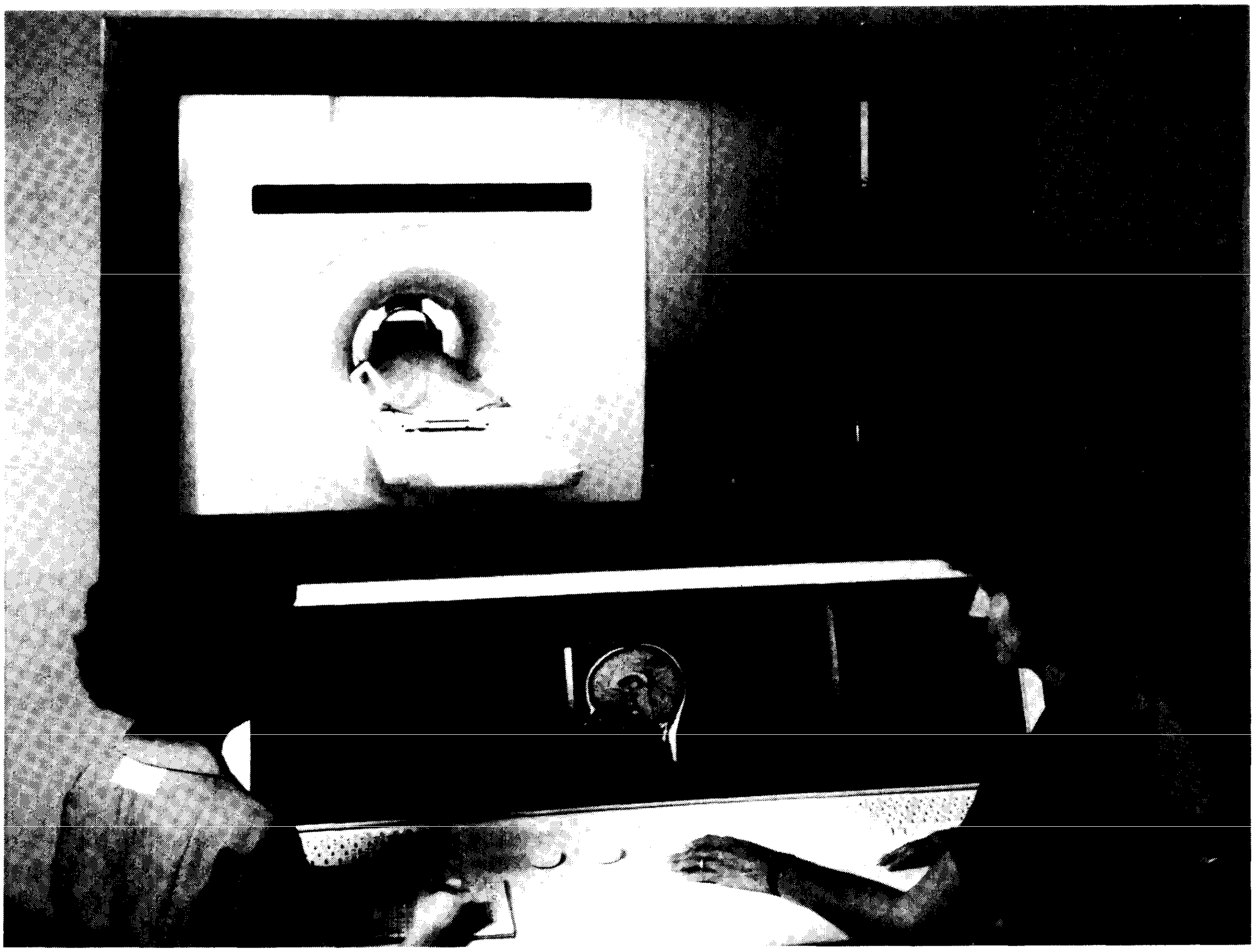

Photo credit: General Electric Medical Systems

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

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

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

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

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

Box 3-B--Magnetic Resonance Imaging

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

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

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

Why Was MRI Successful?

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

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

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

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

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

[3] Ibid., p. 49.

[4] 1bid., p. 154.

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

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Box 3-B—Magitetic Resonance Imaging--Continued

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

Lessons for HTS

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

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

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

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

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

Biomagnetic Applications

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

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

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

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

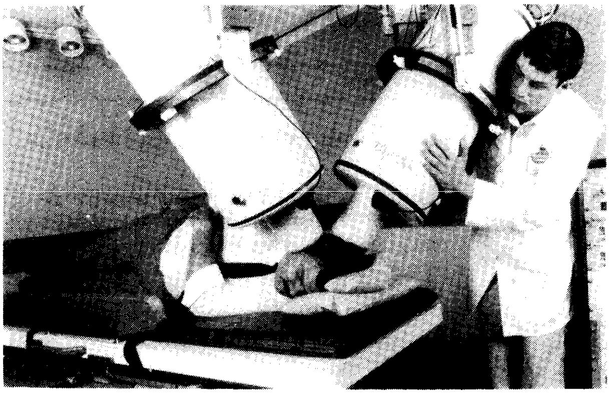

Photo credit: Biomagnetic Technologies, Inc.

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

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

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

Electronics and Communications

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

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

Digital Devices and Computers

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

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

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

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

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

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

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

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

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

SOURCE: Office of Technology Assessment, 1990.

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

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

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

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

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

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

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

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

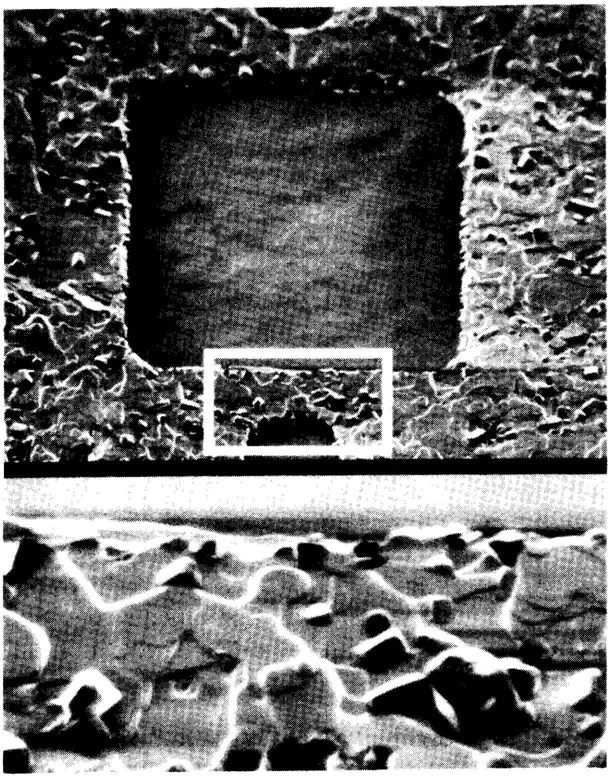

Photo credit: IBM Research

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

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

Analog Devices

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

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

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

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

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

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

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

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

Passive Devices

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

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

Communications

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

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

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

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

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

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

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

SOURCE: Office of Technology Assessment, 1990.

Defense and Space Applications

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

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

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

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

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

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

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

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

New Applications

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

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

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

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

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

LESSONS FROM LTS

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

- *The preferred materials for applications are those that are easiest to handle and manufacture, not necessarily the best superconductors or those with the highest T_c.* Although Nb$_3$Sn is a superior superconductor in terms of critical transition temperature, critical current density, and upper critical magnetic field, it is brittle and difficult to fabricate, and is consequently rarely used. Due to its ductility and workability, NbTi has become the workhorse material for LTS magnet applications, even though its cooling requirements are more stringent. This suggests that factors such as processability and brittleness may ultimately weigh as heavily as T_C or even J_C in determining the feasibility of using certain HTS materials.
- *Even after a practical superconducting material is developed, it may take many years to develop a practical conductor from that material and then to demonstrate its viability in a commercial protype.* Although relatively high performance was achieved with NbTi alloys within a year of their discovery, some 10 years elapsed before a sophisticated NbTi cable conductor was developed. A practical superconducting cable involves a tremendous amount of engineering, including drawing fine filaments of superconductor to reduce AC losses, stabilization with normal conductors for quench protection, channels for coolant flow, dielectric insulation, etc. Moreover, scaling up from small sections to long lengths in prototype applications requires significant additional time. These phases of development are basically serial, and cannot proceed in parallel. This suggests that even if the superconducting properties of bulk HTS materials can be brought up to the level of present LTS materials, it will still be many years before practical tapes or cables for large-scale HTS applications will be available.
- *Highly reliable, conservative designs are necessary, especially in the commercial sector.* While it is tempting for engineers to push a design to the state-of-the-art, reliability is crucial in establishing a new beachhead. Even after LTS has been successfully demonstrated in some commercial applications, it may be necessary to conduct extensive demonstrations of HTS (perhaps by insertion into the existing LTS design) to convince commercial customers of the reliability of HTS.

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

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

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

FACTORS THAT WILL DETERMINE THE PACE OF HTS COMMERCIALIZATION

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

Performance

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

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

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

cost

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

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

Reliability

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

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

Market Demand

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

FORECASTING THE COMMERCIALIZATION OF HTS

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

Near-Term: Defense/Space and Electronics/ Communications

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

Medium-Term: Medicine, Industry

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

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

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

CONCLUSIONS

Based on the discussion above, OTA draws several conclusions:

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

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