Appendix B

The Technology of Superconductivity

Electric currents travel through superconductors with no resistance, hence no losses (provided the current is steady—alternating currents meet resistance even in superconductors). When current flows in an ordinary conductor, say a copper wire, some power is lost. In a light bulb or an electric stove, resistance creates light and heat, but in other cases the energy is simply wasted. With no resistance, magnets wound with superconductors can create very high fields without heating up and dissipating energy. Motors and generators with superconducting windings could be smaller, lighter, and more efficient than those built with copper. Very high magnetic fields might be used to fire projectiles, to float molten metal in a steel mill, to levitate trains.

Table B-1 lists some of the possible applications. During the 1960s, low-temperature superconductors (LTS)—specially developed metal alloys like niobium-titanium—came into use in specialized applications such as magnets for scientific research. Some current LTS applications—e.g., ultrasensitive magnetic field detectors—will not be superseded by high-temperature superconductivity (HTS) (because of higher thermal noise at higher temperatures). Other applications, possible but not practical with LTS, could become much more attractive with HTS.

As table B-1 indicates, superconductors not only banish electrical losses, and provide the basis for very sensitive detectors of magnetic fields and other radiation, but can also be used to produce the fastest possible electronic switching devices. In addition, superconductors exclude magnetic fields, which means they can be used as radiation shields. (The exclusion of external magnetic fields is termed the Meissner effect, after the physicist who discovered the phenomenon in 1933.)

Many of the applications listed in table B-1 have been goals for engineers and scientists since superconductivity was discovered early in the century. Along with powerful magnets for a variety of purposes, prototype generators, electrical transmission lines, and computer chips have all been made, operating in most cases at liquid helium temperatures (about 4° K, or 4 degrees above absolute zero, figure B-l). But the very low temperatures have been a barrier for many of the applications possible in principle.

High-temperature superconductors and liquid nitrogen cooling (77 °K, figure B-1) would bring relatively modest improvements in costs, system complexity, and practicality for most of these applications. Liquid nitrogen temperatures, after all, are only high compared with the near-absolute zero of liquid helium. Where system designs already incorporate LTS—e.g., magnetic resonance imaging (MRI, ch. 2)–it might not pay to change over simply to take advantage of HTS. In applications where unattended operation is desirable—e.g., military surveillance or geophysical exploration—the much reduced boil-off rate of liquid nitrogen would be a major advantage. HTS also holds obvious attractions for applications in space; beyond low-Earth orbit, passive cooling may suffice to maintain superconductivity in the new materials.

Nonetheless, it is quite possible that continued R&D will bring new applications of HTS that cannot yet be anticipated. superconductivity at room temperature, moreover, would be truly revolutionary. Compact and efficient small motors and actuators, for example, could find uses ranging from household products and automobiles to machine tool drives and power-packs for replacing aircraft hydraulic systems.

Superconductivity

Above its transition (or critical) temperature, a superconductor exhibits electrical resistance like any other material. Below the transition temperature, the material has zero resistance to direct current (DC): a steady electric current will circulate in a superconducting coil forever, so far as anyone knows. Variation in the flow of current does lead to electrical losses; thus a superconductor dissipates energy when turned on or off, or when carrying an ordinary alternating current (AC losses). However, these losses are much less than those in a good normal conductor (e. g., copper) at the same temperature.

[1] Much of the material in this appendix is drawn from ' 'Superconductive Materials and Devices, " Business Technology Research, Wellesley Hills, MA, September 1987; and "Technology of High Temperature Superconductivity," prepared for OTA by G.J. Smith 11 under contract No. J3-21OO, January 1988. Also see *Physics Today,* Special Issue: Superconductivity, March 1986; A.P. Malozemoff, W.J. Gallagher, and R.E. Schwall, "Applications of High-Temperature Superconductivity," *Chemistry of High-Temperature Superconductors,* ACS Symposium Series 351, D.L. Nelson, M.S. Whittingham, and T.F. George (eds.) (Washington, DC: American Chemical Society, 1987), p. 280; "Research Briefing on High-Temperature Superconductivity," Committee on Science, Engineering, and Public Policy, National Academy of Sciences, Washington, DC, 1987.

Table B-1 .—Representative Applications of Superconductivity

Large-scale passive:

Shields, waveguides

Superconductors screen or reflect electromagnetic radiation; possible applications range from coating of microwave cavity walls to protection from the electromagnetic pulses of nuclear explosions.

Bearings

Repulsive forces created by exclusion of magnetic flux make non-contact bearings possible.

High-current, high-field:

Magnets

Medical imaging

LTS magnets widely used in commercial systems.

Scientific equipment

LTS magnets used in fusion experiments and particle accelerators.

Magnetic separation

Possible uses include separating steel scrap, purifying ore streams, desulfurizing coal, and cleaning up stack gases, At least one LTS magnet is in current use for purifying Kaolin clay.

Magnetic levitation

Levitated trains have been extensively studied, with prototypes in Japan and Germany.

Launchers, coil/rail guns

Electromagnetic launching systems can accelerate objects to much higher velocities than gas expansion; possible applications range from small guns for military purposes to aircraft catapults and rapidly repeatable Earth satellite launching.

Other

Powerful magnets could eventually find a very wide range of uses. Examples: compact synchrotrons for lithographic processing of integrated circuits; growth of the crystals for integrated circuits (a strong magnetic field yields more nearly perfect wafers of silicon and other semiconductor materials); MHD (magnetohydrodynamic) systems for energy conversion. MHD thrusters might also be used in place of propellers to drive ships and torpedos.

Other static applications

Electric power transmission

Prototypes of LTS underground lines have demonstrated feasibility, but such installations are not cost-effective (compared with overhead high-tension lines) at present.

Energy storage

Solenoids wound with superconducting cable could store electrical energy indefinitely as a circulating current; i n addition to utility applications (e. g., load leveli rig), superconducting storage could find uses in military systems (e.g., pulsed power for large lasers). Cheap and reliable superconducting energy storage would eventually find many other applications.

Rotating machinery

Generators

A number of LTS prototypes have been built to investigate possible electric utility applications.

Motors, motor-generator sets

Used in conjunction with a superconducting generator, a superconducting motor could be an efficient alternative to mechanical power transmission for applications such as ship and submarine drives, railway locomotives, and perhaps even for helicopters. Sufficiently low costs would open up many industrial applications.

Electronics:

Passive

Superconducting wiring (interconnects) for computers, on-chip or between chip, could help increase processing speed.

Sensors

SQUIDS (superconducting quantum interference devices) made from Josephson junctions (JJs) are the most sensitive detectors of electromagnetic signals known; applications range from detecting neural impulses in the human brain to geophysical exploration, detection of submarines in the deep ocean from airplanes or, potentially, from space, and nondestructive inspection.

Digital devices

JJs can also be used for digital switches, opening up such applications as computer logic and memory; competitive three-terminal devices with substantial gain may eventually be developed; combined semiconductor-superconductor devices or systems also hold many attractions.

Other devices

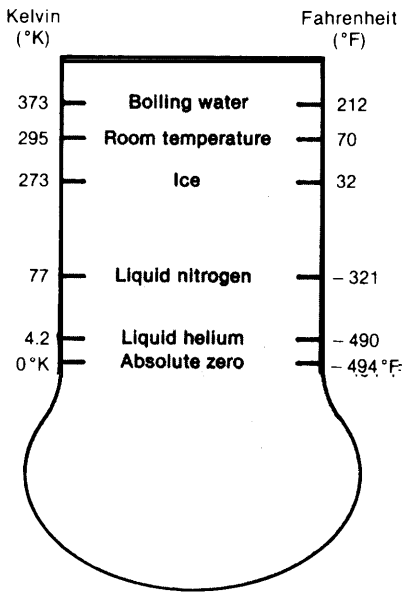
Analog/digital converters, voltage standards, many types of signal processors, and microwave mixers can all be designed, in principle, with superconductors; some of these applications (e. g., voltage standards) have been reduced to practice with LTS JJs.

NOTE This list is based on known properties of known materials. It is not exhaustive, even for existing, well. understood low-temperature superconductors

SOURCE Off Ice of Technology Assessment, 1988

Until 1986, the highest known transition temperature was 23° K (in niobium-germanium). Then two IBM scientists in Zurich discovered a new class of materials that showed superconductivity at 35-40 °K (see box C, ch. 2). Shortly thereafter, the compositions now termed the 1-2-3 superconductors were found, with transition temperatures in the vicinity of 95° K. The first of the 1-2-3 materials announced contained yttrium, barium, and copper oxide. More recently, copper-oxide ceramics containing bismuth or thallium have been found. These have superconducting critical temperatures in **the** range, respectively, of 110° K and 125° K. In April 1988, the first HTS compositions containing no copper were announced, with transition temperatures up to 30° K.

Figure B-1.—Temperature Scales



SOURCE: Office of Technology Assessment, 1988.

A major advantage of the new materials, of course, is the potential for simpler, less expensive cooling, For technical reasons, superconductors must be operated well below their transition temperatures— as a rule of thumb, at half to three-quarters the transition value. In fact, then, liquid nitrogen temperatures will be marginal for the 1-2-3 compositions (although the practical advantages of operating in the range of 40 °K rather than 4° K can be great), If the more recently discovered ceramics, with critical temperatures of 110° K and up prove to have otherwise useful properties, liquid nitrogen cooling will almost certainly prove adequate.

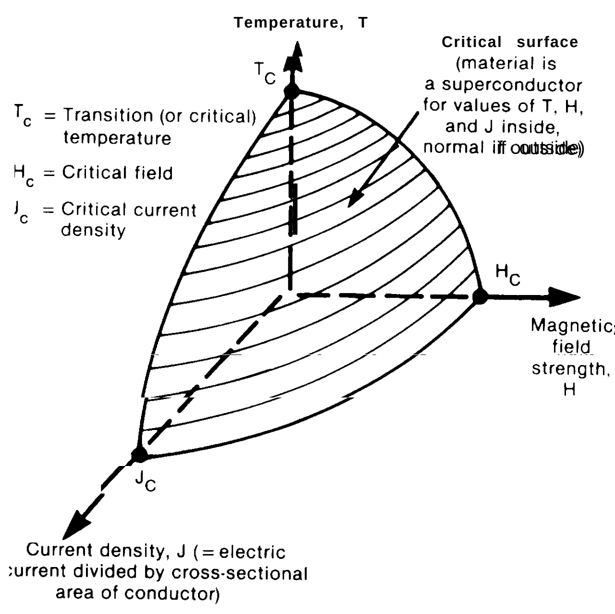
All the HTS compositions so far discovered are ceramics, rather than metals. They are new materials, poorly understood. All ceramics are brittle; they require processing and fabrication methods very different from metals and alloys.

Superconducting Properties and Behavior

In 1911, Heike Kamerlingh-Onnes, a Dutch physicist, made the astounding discovery that mercury lost all electrical resistance at 4° K. Earlier, Kamerlingh-Onnes and his research group at the University of Leiden had developed cryogenic refrigeration equipment capable of reaching these very low temperatures, In 1913, Kamerlingh-Onnes found that lead became superconducting at 7.20 K. At this point, the Leiden group built a superconducting magnet with lead windings, only to find the lead reverting back to its normal state when the magnetic field reached a few hundred gauss—a severe limitation on practical use, given that a common kitchen magnet creates a field of about 1,000 gauss. (The average magnetic field of the Earth is one-half gauss; the windings in electric motors create fields of about 10,000 gauss,)

Critical Properties.—Later it was learned that maintaining the superconducting state requires that both the magnetic field and the electrical current density, as well as the temperature, remain below critical values that depend on the material. Figure B-2 shows this schematically, while table B-2 gives the critical values of temperature and field for a number of superconducting materials, Practical applications, in general, require that both the transition temperature and the critical current density be high; in some cases, relatively high magnetic fields are necessary as well.

Figure B-2. —Dependence of the Superconducting State on Temperature, Magnetic Field, and Current Density



SOURCE: Off Ice of Technology Assessment, 1988

Table B-2.—Critical Values for Superconducting Materials

	Temperature (degrees Kelvin)	Magnetic field (gauss)	Current density [a] (amps per square centimeter)
Aluminum	1.2	105	
Mercury	4.2	410	
Lead	7.2	800	
Niobium	9.2	0.4×10^4 [b]	
Niobium (75%) - titanium (25%)	10	14×10^4 [b]	$\sim 10^5$ [c]
Niobium - tin	18	23×10^4 [b]	$\sim 10^7$ [c]
1-2-3 ceramic ($YBa_2Cu_3O_{6.9}$)	93	$100 + \times 10^4$ [b]	10^3 to $>10^6$ [d]

[a]At zero magnetic field
[b]Upper critical field (Type II superconductor
[c]At 4.2 K
[d]At 77 K The highest values are reached with oriented single-crystal films

SOURCE Offrceof Technology Assessment 1988

By the late 1930s, scientists had distinguished Type I and Type II superconductors. Type I materials, in which the phenomenon had first been studied, shift abruptly to their normal state above the critical magnetic field. Type II superconductors exhibit a mixed state between two values of magnetic field, the lower and upper critical fields. The new HTS materials show Type II behavior, with extremely high critical fields (table B-2)–indeed, so high in the 1-2-3 compositions that simply measuring them has proven very difficult.

As Kamerlingh-Onnes found with his lead-wound magnet, Type I superconductors have critical fields too low to make useful magnets. While Type II materials have much higher critical fields, the new HTS materials have proved to have disappointingly low values of the third critical parameter—the current density (table B-2).

Raising allowable current densities in the 1-2-3 ceramics from the values found initially in polycrystalline samples (consisting of many grains, randomly oriented)—below 10^3 amps per square centimeter—quickly became a major research target. For most applications, improvements of 100 times or more—to the range of 10^5 or 10^6 amps per square centimeter—will be needed, This is important not only for high-power applications; electronic devices carry small currents, but current densities are high because cross-sectional areas are microscopic.

Not a fundamental limitation, the low current densities are materials processing problems (critical current density depends on the microstructure of the material, hence on its processing). Many years of R&D were needed to raise the critical values for Type II superconductors like niobium-titanium to the values shown in table B-2, Similar effort lies ahead for the new HTS materials; so far, progress has been most rapid in thin films,

From the 1930s to the 1980s.—The 1930s and 1940s saw a good deal of progress in the cooling and refrigeration systems needed to reach very low temperatures, spurred in part by wartime needs for liquid oxygen.[2] After the end of the Second World War, the newly formed Office of Naval Research established a major research program in low-temperature physics. One consequence—rapid improvements in the technology for producing liquid helium—made experimental research in superconductivity much easier.

Federal support during the 1960s included development of very powerful superconducting magnets, principally for conducting experiments in high-energy physics and nuclear fusion, as well as exploratory studies of possible electronic applications of superconductivity. The first of the current generation of conductors, niobium-tin, was developed during the early 1960s. A brittle intermetallic, very difficult to work with, niobium-tin found little use. Within a few years, almost all LTS magnets were being wound with niobium-titanium—more ductile, though with a lower critical field.

With steady progress in processing techniques, niobium-titanium conductors could be fabricated as braided cables each containing thousands of very fine filaments. Small filaments—less than the diameter of a human hair—reduce the AC losses stemming from variations in current, and have other highly desirable properties for magnet applications. These filaments are embedded in a copper matrix, capable of carrying the full current in the event of an accidental loss of superconductivity. The conductors must be flexible enough for winding, and

[2]"Government's Role in Computers and Superconductors, " prepared for OTA by K. Flamm under contract No H36470, March 1988, pp 43ff.

mechanically strong because the magnetic field creates very high forces. Many years of R&D have led to steady improvements in LTS magnets.

The discovery of the Josephson effect in the early 1960s opened up a new class of possible applications in electronics. Josephson junctions (JJs), made with a thin insulating layer (a matter of a few atomic diameters) separating two superconductors, can act as very fast electronic switches—comfortably exceeding the fastest semiconductor devices. Because they dissipate so little power—about 1,000 times less than semiconductors—JJ electronics can be more tightly packed, which also contributes to speed.

Theory

Theoretical work had likewise moved ahead, culminating in 1957 in the Bardeen-Cooper-Schrieffer (BCS) model, for which a Nobel Prize was later awarded. The BCS theory explains superconductivity in terms of interactions between electrons (which carry current) and phonons (atomic vibrations). Under normal conditions, the electrons collide with atoms, leading to electrical resistance and energy loss. In the superconducting state, electrons move in coordinated fashion without any collisions.

While the BCS model explains superconductivity in the old materials, so far HTS has baffled the theorists. Until 1986, most of those working in the field had agreed that BCS superconductivity at temperatures above about 30 $^{\circ}$K was impossible. Given the recent experimental results, the theoretical community has been scrambling to extend the BCS model or find some new explanation.

Although the Josephson effect was first predicted theoretically, and later confirmed by experiment, theory gave little or no guidance in the search for LTS materials with higher transition temperatures. Thus the situation is really no worse for HTS. Looking for materials with higher transition temperatures remains largely a matter of trial-and-error, guided by intuition—laboratory research that is time-consuming and expensive.

Processing and Fabrication

Tailoring HTS materials for applications either in electronics or where high currents and/or fields are needed (e.g., electric power) will entail design and processing at size scales from the atomic level on up. Engineers and scientists engaged in applications developments, as well as materials processing, will have to concern themselves with electronic structure (energy gaps), crystal structure (the arrangement of atoms in the material), microstructure (grain boundaries), and the fabrication of films, filaments, tapes, and cables.

The HTS ceramics are not only brittle, and chemically reactive, but highly anisotropic—meaning that properties vary with direction within a grain of the material. The 1-2-3 ceramics, for instance, show differences of as much as 30:1 in critical current density depending on grain orientation. Some of the current density limitations can be traced to anisotropy, but grain boundaries seem to be the primary culprit.

Some of the processing and fabrication techniques familiar from work with electronic and structural ceramics hold promise for the new superconductors. Bulk samples of HTS material can be made by hot pressing, extrusion, and tape casting, among other methods. The anisotropy in the 1-2-3 materials has led many research groups to seek processes for aligning the grains—e.g., extruding a slurry of single crystals in a high magnetic field to create a tape. Semiconductor fabrication techniques, likewise, can in some cases be adapted for making thin films.

Past work on niobium-tin, a brittle intermetallic compound, may also hold lessons for HTS materials, which, like other ceramics, cannot deform plastically. Because they break easily and without warning–like glass, being very sensitive to small imperfections (hence the scribed lines used to “cut” glass)—practical applications may require specialized in-situ processing, as well as careful design to minimize strain. Magnets wound with niobium-tin are made starting with strands of niobium in a copper-tin alloy matrix–flexible and ductile. Heat treatment after the wires have been drawn and wound into coils causes the tin to combine with the niobium, forming the superconducting compound, with its vastly different properties. Some R&D groups have pursued similar processes for ceramic superconductors.

Progress has been faster with thin films, which can be created via a wide range of well-known techniques—e.g., sputtering, and evaporation by molecular or electron beams, Finding good substrates on which to deposit the HTS layer has been the primary problem. The HTS compounds react chemically with many otherwise desirable substrate materials, including those used for integrated circuits (silicon, sapphire). Strontium titanate gives high current densities compared to other choices, but is expensive and has otherwise undesirable properties. Silicon would be ideal as a step toward combining semiconductor and superconducting electronics. While the temperatures so far required for creating the proper HTS composition have posed difficulties, many research groups have been working on the problems, with encouraging results.

Applications

Much of the excitement over HTS has been stirred by speculation concerning such possible applications as low-loss electric power transmission or magnetically levitated trains. In some of these cases, commercialization will depend more on system costs and progress in competing technologies than on the specifics of HTS. Both transmission lines and levitated trains have been demonstrated with LTS materials. Superconducting transmission lines, which must be run underground because of the cooling requirements, may eventually prove cost-effective relative to conventional underground transmission; thus far, however, these applications have not moved out of the test stage, Maglev trains could be built by the end of the century in Japan and West Germany. Competing technologies sometimes present a moving target for superconductivity: after more than 10 years of R&D aimed at a Josephson computer, IBM concluded that competing semiconductor technologies were improving rapidly enough that its approach to JJ computer elements would probably not bear fruit.

More than likely, then, 5 to 10 years of R&D lie ahead before many applications of HTS emerge. Those that come earlier are likely to be highly specialized—perhaps in military systems, perhaps targeted on very demanding civilian needs (for example, Hypres' very high-speed data sampler, which incorporates LTS electronics]. The ongoing R&D will involve:

1. Basic research, both theoretical and experimental, aimed at explaining HTS, at finding new materials and exploring their properties, and at understanding structure-property relationships.
2. Applied research, focused particularly on development of processing methods and optimization of material properties through manipulation of processing variables, A great deal of R&D will be needed before routine production of tapes and multifilamentary conductors could begin, with substantial improvements in critical currents an early step. Josephson junctions for electronics will also be difficult to reduce to practice.
3. Applications engineering (for HTS)—e.g., development of prototype chips containing many JJs–including extensive testing under realistic operating conditions (environmental exposure, thermal cycling, mechanical vibrations, electrical surges, loss of temperature control), Joining techniques for conductors will be needed; so will repair methods.
4. Process engineering—manufacturing methods for routine (rather than laboratory) production. Problems here will include yields and reliability in superconducting circuits, and methods for producing long continuous lengths of superconducting cable. Inspection, testing, and quality control procedures will need a good deal of attention.
5. Systems engineering—design, development, and demonstration of applications in which superconducting components are integrated into such end products as computers, electrical generators, and coil or rail guns. For instance, without further progress in transition temperatures, HTS interconnects in computers will require cooling to liquid nitrogen temperatures. Fortunately, these temperatures also offer performance advantages for semiconductor chips.

Many of these activities can go forward in parallel. In some cases it makes sense to proceed sequentially. For instance, applied research aimed at increasing current density can and should proceed in conjunction with process R&D, because processing affects microstructure, and microstructure affects current density. But work on production scale-up must wait until the effects of processing variables can be reasonably well understood. On the other hand, research intended to discover whether a particular processing technique—e.g., laser annealing—compromises some properties will be needed early.

High-Current, High-Field Applications

Magnets.—Most past applications of superconductivity have involved the design and construction of powerful magnets wound with LTS materials and cooled with liquid helium. Such magnets have been used in scientific experiments (e. g., the Tevatron, ch. 2), and in MRI. Learning to design and build magnets helps with more demanding applications, such as rotating machinery.

Almost all the power consumed by a superconducting magnet goes to operate the cooling system. For a big magnet wound with copper, resistive losses far outweigh the refrigeration costs for an equally powerful LTS magnet. Indeed, large copper-wound magnets need their own cooling systems just to carry off the heat generated through resistance. The cost comparison below, for a bubble chamber magnet at Argonne National Laboratory—a typical early scientific application—shows that a conventional magnet would cost five times more to operate:[3]

Annual operating costs (thousands of dollars)

	Superconducting magnet (actual)	Conventional magnet (estimated)
Electrical power.	$17.5	$550
Cooling	81.3	4
Maintenance	5.2	?
	$104	$554 +

Superconducting magnets have other advantages compared with conventional magnets. Stability is easier to achieve, for instance. In a conventional magnet, the field strength varies as the windings heat up and expand. The stability characteristics of LTS magnets give them advantages both in scientific apparatus and in MRI.

With LTS magnet technology well in hand, HTS designs will have to perform at least as well (in terms of characteristics such as stability) before their simpler cooling systems and lower operating costs will make them competitive. Fabricating the conductors will be difficult, Stable operation and protection against overheating in the event of refrigeration failures require multifilamentary cables, just as for LTS, with filament diameters of a few microns.[4] Given the brittleness of the new ceramics, methods for producing filaments and for fabricating cables are not yet in sight.

Once HTS wire and cable become available, applications-specific requirements will come to the fore. MRI, for example, while requiring highly stable fields for good image quality, does not otherwise make heavy demands on the magnet system. Still, joining methods that eliminate resistive imperfections will be needed for image quality comparable with that already achieved using LTS.

MRI systems are expensive, and savings from simpler cooling will not make that much difference for commercial competition. Magnetic separation is another story. Here, for instance, cheap but powerful magnets could be used to sort scrap metal for recycling, in refining ores, purifying chemicals, removing sulfur from pulverized coal, and cleaning up waste water, In all these applications, cost, reliability, and ease of use (including maintenance) by a largely blue-collar labor force become significant design considerations. Design considerations for maglev trains likewise include cost, reliability and longevity, and safety. But the political and economic questions loom even larger than for, say, desulfurizing coal, In the United States, investments in fixed-rail transportation would have to clear obstacles ranging from opposition by airlines to high costs for rights-of-way. In Japan, where the needs and constraints differ, R&D on HTS-based maglev is much more likely to go forward.

Electric Power and Utility Applications.—Magnets have no moving parts. Technical complexities grow in electrical machinery, and in the entire range of electric utility applications. Transformers, for example, would demand more attention to AC losses than magnets, while superconducting transmission lines will almost certainly have to go underground, so long as refrigeration is required. Underground lines are costly, although already in use in many urban areas. Still, the over-riding design requirement is reliability, Utilities are quite willing to trade off higher operating costs against lower probability of failures and down-time, A disabling failure, after all, can lead, not only to a blackout, but to an ongoing need to purchase power from other suppliers until repairs have been completed.

In general, HTS-based generators will need conductors similar to those for magnets. Dynamic forces, however, will add to static forces, while cooling also becomes more difficult. Large conventional generators already have efficiencies greater than 98 percent. Superconducting field windings can increase this to more than 99 percent, In a large machine, an improvement of 0.5 percent to 1 percent in efficiency can be significant—reducing the losses by half—while superconducting generators have the additional advantage (for utility applications) of increasing network stability (they are less sensitive to shifts in electrical load).

Worldwide, at least two dozen LTS generator R&D projects have been undertaken since the middle 1960s, but none has gone beyond construction and testing of a prototype. Utilities will have to be convinced that such machines offer reliable service over periods of many years before investing; HTS will not affect the economics much compared to LTS, and, lacking even the experience base of

[3] P. J. Reardon, "High Energy Physics and Applied Superconductivity, " *IEEE Transactions on Magnetics*, vol. MAG-13, 1977, p. 705, This magnet, for Argonne's 12-foot bubble chamber, draws 1800 amperes, producing a field of 1.8 X 10^3 gauss. The cost figures assume 140 operating days per year.

As another example, a magnetic separator for purifying Kaolin clay (table B-1) consuming 270 kilowatts (kW) if built with a conventional magnet, plus another 30 kW for cooling the magnet, could today be replaced with an LTS magnet that needed no more than 60 kW, all for refrigerating the windings,

[4] *Report of the Basic Energy Sciences Advisory Committee Panel on High-Tc Superconducting Magnet Applications in Particle Physics*, DOE/ER-0358 (Washington, DC: Department of Energy, December 1987), pp. 9-12.

LTS systems, the new materials have an added hurdle to overcome. Energy storage rings—with no moving parts, and tolerable failure modes—will almost certainly come first.

Other Electrical Machinery.–For non-utility applications, characteristics other than efficiency and reliability come to the fore: superconducting machines promise to be smaller and lighter than conventional motors and generators by half and more, These are the attractions for ship propulsion, where a superconducting generator driving a superconducting motor could eliminate the gearing and shafting between turbine (or other prime mover) and propeller. With much more freedom in packaging, nuclear submarines could carry more weapons (or be smaller), So could surface ships. Submarines might also prove quieter, perhaps even faster. Moreover, with the motor/generator set(s) providing speed control (and reversing), efficiency during part load operation would rise (the turbine can run at its optimum speed).

As table B-1 indicated, other, more cost-sensitive, applications for motor/generator sets might also open up at some point. And of course, given high enough operating temperatures, the many large electric motors used throughout industry (ranging from pump, fan, and blower drives to machine tools and rolling mills) would be candidates for replacement.

Electronics

From the beginning, Josephson junctions have been the basis for many superconducting electronic devices, SQUIDs—superconducting quantum interference devices, simple circuits incorporating JJs–have extremely high sensitivity levels, which have led to a considerable range of practical uses for LTS SQUIDS. The Josephson effect can also be exploited for computer logic and memory; although a number of practical problems stand in the way, JJs could in principle replace semiconductor chips in powerful digital processors (box J, ch. 3).

Sensors.–SQUIDs can detect the very faint signals produced by the human heart (10^{-6} gauss) and brain (10^{-9} gauss). These simple circuits can also measure a wide variety of other electromagnetic signals (anything with an associated magnetic signature from DC up to microwave frequencies). SQUIDS are about **1,000** times more sensitive than the next best magnetic field detectors, They can sense the disturbances in the Earth's magnetic field caused by a submarine deep in the ocean, or the field distributions caused by geologic formations holding oil or mineral deposits, Requiring, in simplest form, only one or two JJs (rather than the large numbers required in computer applications), LTS SQUIDs—typically fabricated from niobium—are now made routinely.

To minimize thermal noise, SQUIDS should be operated at the lowest possible temperature, and in any case at less than half to two-thirds of the superconducting transition temperature, At liquid nitrogen temperatures, for instance, sensitivity will be 20 times poorer than at liquid helium temperature, Even so, an HTS SQUID would still be a more sensitive magnetic field detector than any of the alternatives except an LTS SQUID, If they can be built successfully, HTS SQUIDS will quickly find a considerable range of applications (though none of these are likely to be high-production-volume applications).

Computers and Other Digital Systems.—JJ-based electronic devices promise switching speeds **10** times faster than the very best compound semiconductors. Because the energy losses are several orders of magnitude smaller, JJ-based integrated circuits could be packed much more densely, However, the practical problems of making JJ-based chips far exceed those of SQUIDS.

Even if the practical problems were solved, Josephson computers might not be commercialized. The competing technologies extend well beyond silicon and gallium arsenide chips: a good deal of R&D has been going into alternative computer architectures such as massively parallel processors. Much of this work seeks increases in processing power without major advances in components. Still, faster chips will always promise faster machines, But, in a further contrast with SQUIDs—which are the most sensitive magnetic field detectors known—the theoretical limits of JJ-based logic devices fall well short of what might eventually be possible, for example, using optical switching. Thus the window of opportunity for JJ-based computing may never open. (It may never open for optical computing, either.) On the other hand, advances in device design—and, in particular, a practical three-terminal device that would erase the primary drawback of JJ chips, low gain–could open a broad new frontier.[5] It is simply too early to say,

R&D in the United States and Japan on LTS-based JJ computing illustrates some of the problems that designers of HTS logic and memory would face. IBM was able to build logic chips with 5,000 junctions reliably, but had trouble with cache memory.

[5]S. G, Davis, "The Superconductive Computer In Your Future, " *Datamation*, Aug. 15, *1987,* p 74.

(Fast logic does no good without fast cache memory for support.) IBM's prototype memory chips, with over 20,000 JJs, proved susceptible to errors caused by slight variations in control current—a good example of the kind of problem that a 3-terminal device would help solve. More recently, Japanese companies have built several kinds of LTS chips incorporating niobium JJs. Fujitsu's 4-bit microprocessor, 25 times faster than a similar silicon chip, and 10 times faster than a gallium-arsenide microprocessor, consumes only 0.5 percent as much power as either. NEC has produced a 1,000 bit dynamic memory, containing 10,000 JJs; access time is a factor of 200 better than for silicon.

The first applications of HTS in computers may be interconnects–electrical pathways joining otherwise conventional chips. Signal dispersion and other problems associated with transmitting electrical pulses within the processor limit performance; practical means for incorporating HTS interconnects should find ready application in large and powerful machines.

Moreover, at liquid nitrogen temperatures, superconductors and semiconductors could operate compatibly in hybrid designs. Ordinary semiconductors cannot be used at liquid helium temperatures; even if they could be made to operate in otherwise satisfactory fashion, semiconductors would dissipate too much heat, overwhelming the cooling system. Given that hybrid LTS-semiconductor systems are not feasible, past work on Josephson computing has involved either all-superconducting chips, or unique designs with controlled temperature gradients. The Hypres data sampler, for example, uses an integrated circuit cooled to liquid helium temperature on one end only—that end holding about 100 LTS JJs.

Three-terminal devices could be a big step forward in superconducting electronics, making possible logic designs at the chip level much like those now used with semiconductors. It could well be, however, that major advances in HTS electronics would come only with devices that departed in a major way from currently known electronic devices, The first requirement, in any case, is mastery of thin-film fabrication technology.

Military Systems

As table B-1 indicated, possible defense applications of superconductivity range from shielding against nuclear blasts to high-speed computers and motor-generators for ships. Conceptually, there may be little difference between military and commercial applications. But in practice, differences will be pervasive at levels all the way from devices and components (e.g., radiation hardening) to the system configuration itself (cost-performance tradeoffs much different than for commercial markets). Computing requirements for smart weapons—for example, real-time signal processing—tend to be quite different from those important in the civilian economy. Thus, as development proceeds, military uses of superconductivity will diverge in many respects from civilian applications.

Some of the military applications could be compelling. Submarine detection with SQUID-based sensors, for instance, offers at least a factor of 10 improvement over current methods. Conventional electric generators for shipboard or vehicle use, or for producing electric power under battlefield conditions, produce about 2 horsepower per pound; prototype LTS generators have already reached 25 horsepower per pound. Superconducting coil or rail guns promise increases in projectile velocities of 5 to 10 times.

The U.S. Department of Defense (DoD) has funded superconductivity R&D since the early 1950s, contributing to the development of large, high-field magnets, electrical machinery, LTS sensors, and superconducting computers. DoD (and the Department of Energy) also supported much of the materials processing R&D that proved necessary to achieve high current densities in LTS wire and cable. Since 1983, the R&D objectives of DoD programs in LTS have been redirected, and the programs have grown, as a result of the Strategic Defense Initiative (SDI).

For SDI, HTS shielding, waveguides, and sensors (for use in space) hold obvious attractions, while LTS work also continues; early in 1988, Bechtel and Ebasco began an SDI-funded design competition on LTS magnetic energy storage for powering ground-based free-electron lasers. SDI has also targeted very high-frequency communication systems, where LTS could offer substantial improvements in performance and extended frequency range. Here, the 1-2-3 ceramics seem to offer theoretically promising electronic characteristics (i. e., larger energy gaps). They would also avoid the many practical problems that liquid helium cooling poses in a military environment.

DoD has also renewed its attention to two of the prospective high-field, high-power applications—ship propulsion, and coil/rail guns, Military funding of R&D on LTS machinery began in the middle 1960s, with a 300()-horsepower prototype completed several years ago. Magnetohydrodynamic (MHD) thrusters offer a wholly different alternative, doing away with propellers, as well as shafts and gearing. In 1978, the Defense Advanced Research Projects Agency began funding R&D on electromagnetic launchers, or coil/rail guns. The initial goal, apparently, was a cannon for the Navy. With the advent of SDI, much of the DoD work has been redirected toward higher velocity systems, capable of launching a projectile into space. Like the commercial applications, the requirements, whether for machines or for coil/rail guns, start with good conductors.

Developing the Superconductivity Technology Base

Table B-3 gives a sampling of expert opinion on timing for a number of the applications discussed above, Without too much oversimplification, the R&D needed for supporting these and other applications can be pictured as in figure B-3.

Leaving aside military applications, particularly those in which the superconductor serves as a passive shielding medium, sensors and other relatively straightforward electronics applications will probably come first. As noted earlier, without new and much more tractable families of HTS materials, learning to make practical wire and cable will be a long and tedious process. As a result, the high-current, high-field applications will be slower in reaching the marketplace than thin- and thick-film electronics.

The R&D tasks outlined in figure B-3 will take a wide range of skills. Materials synthesis and characterization demands well-equipped laboratories and sophisticated experimental techniques—e.g., X-ray and neutron diffraction, electron microscopy, molecular beam epitaxy. Making thin and thick films of the 1-2-3 materials with adequate current-carrying capacity will probably mean oriented grain structures—a good deal more difficult in production than in the laboratory. Fabricating useful Josephson junctions will mean controlling the deposition of very thin layers. The processing techniques are likely to be more demanding than related semiconductor processing technologies.

Still, there is much that can be learned from related technologies, not only in microelectronics, but in ceramics. Applications of both structural and electronic ceramics demand very pure starting materials, careful control of processing (and thereby structure), and sensitive nondestructive inspection techniques, Some of this experience base will translate to HTS, especially to fabrication processes for filaments and wires.

As figure B-3 suggests, cryogenics technologies will be needed for most applications of HTS (in the absence of room-temperature superconductivity], Space is the exception, Even if much higher transition temperatures emerge, good performance may still require cooling—e.g., to minimize electrical noise, or increase current-carrying capacity, Although much of the speculation concerning HTS has assumed liquid nitrogen cooling, closed-cycle refrigeration systems can reach temperatures as low as 100 K, and would probably be the technology of choice in many systems.

Much of the R&D needed for commercialization of HTS will have to go on more-or-less simultaneously. For simplicity, one-way arrows join the boxes in figure B-3: a more realistic picture would be full of feedback loops representing the flows of knowledge accompanying development of a complex new technology (ch. 2), As conductor fabrication technology evolves, the design constraints for magnets and machines will take shape. System level studies of digital processors will feed back to the device level.

Developing the technology base in HTS means multidisciplinary research, and productive interactions among universities, national laboratories, and industry. Developing a technology base quickly, so that U.S. industry can keep up with Japanese industry, will mean taking risks, and managing overlapping R&D projects. The examples of industries ranging from automobiles to microelectronics (ch. 2) demonstrate that competing in HTS will require an R&D system that effectively supports parallel development on many different but inter-related problems.

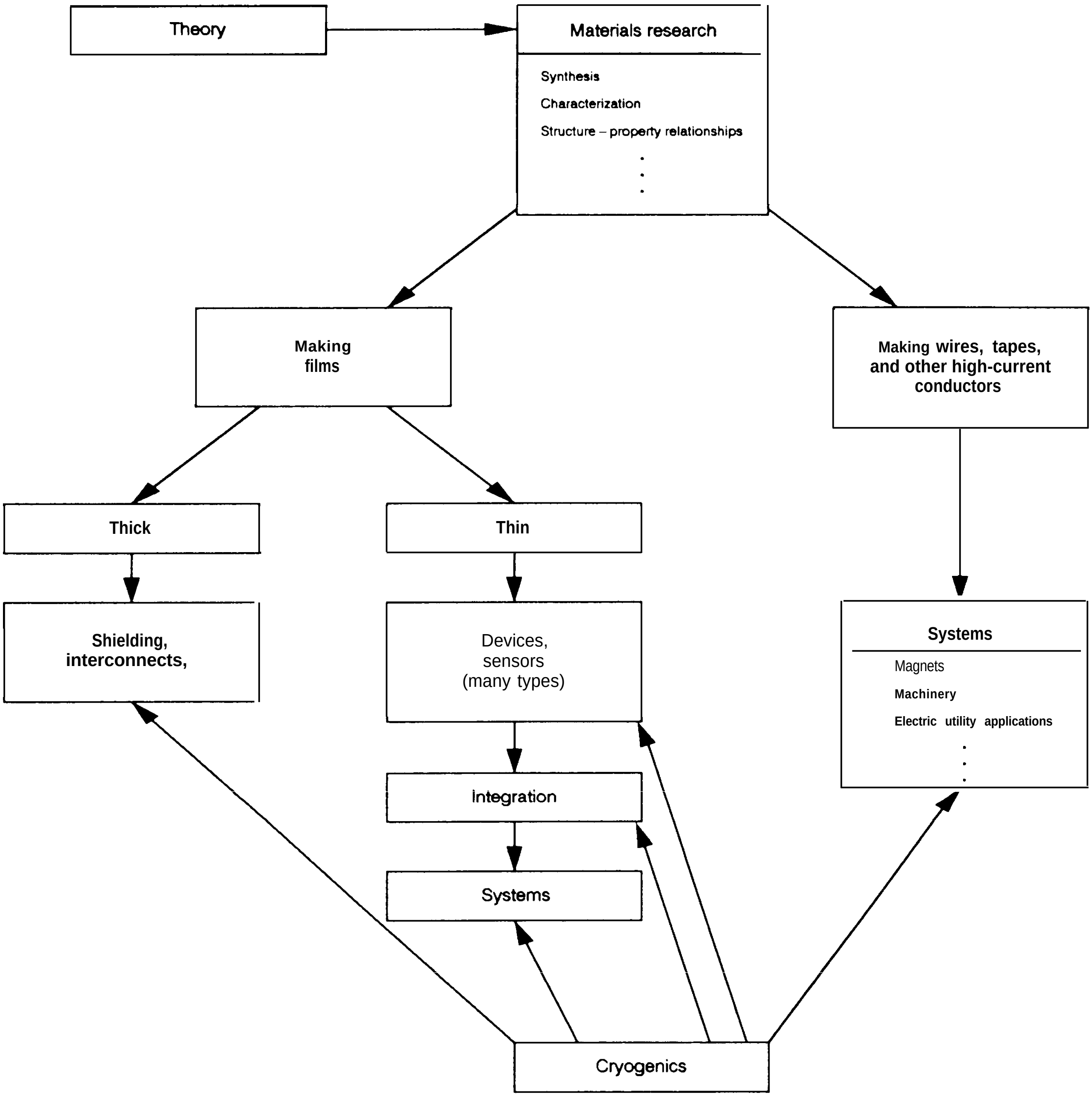
Table B-3.—Estimated Development Times for Prospective HTS Applications

Application	Time[a]
SQUIDS	Less than 5 years
Sensors	5 years
Computer interconnects	Less than 5 years
Superconducting computer	Long-term
Multifilamentary composite cable	5 to 10 years
Magnet system	over 10 years
Magnetic energy storage	Long-term
Transmission lines	Long-term
Electrical generators	Long-term

[a] until small-scale commercial Production

SOURCE "Technology of High Temperature Superconductivity, " prepared for OTA by G J Smith II under contract No J3-21OO, January 1988, p. V.97, based on interviews

Figure B-3. – HTS R&D



SOURCE: Office of Technology Assessment, 1988