High-temperature superconductors are a scientific breakthrough, but technical and economic obstacles to useful applications remain.

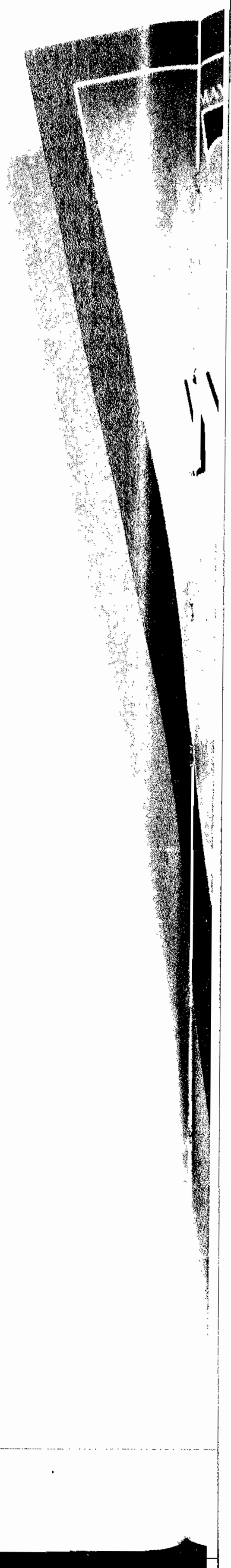
Superconductors: The Long Road Ahead

BY SIMON FONER AND TERRY P. ORLANDO

FEW developments have captured the imagination of scientists, politicians, and the public more quickly or thoroughly than the recent discovery of a new class of "high temperature" superconductors.

In January 1986, Karl Alex Müller and Johannes Georg Bednorz, scientists at the IBM Zurich Research Laboratory, discovered a ceramic material able to "superconduct"—carry an electric current without resistance—at about −238° Celsius, significantly higher than any previously known substance. Since then, researchers have pushed the threshold of superconductivity in ceramic materials even higher; some are even predicting superconductivity at room temperature. And last October, Müller and Bednorz won the Nobel Prize for their efforts, one of the most rapid recognitions of a major scientific breakthrough by the Nobel committee since the establishment of the prize for physics 86 years ago.

As scientists explore the characteristics of high-temperature superconductors, government officials are championing superconductivity as a crucial arena of international economic competition. In 1987 the Department of Energy doubled its funding of superconductivity research from $20 million to $40 million. The Department of Defense has developed a three-year $150 million research-funding plan. "The breakthroughs in superconductivity bring us to the threshold of a new age," President Reagan told a special federal conference on the commercial applications of superconductivity last July. "It's our task to herald in that new age with a rush."



Recent developments in superconductivity have inspired predictions of a technological revolution. But many proposed applications are far from commercial viability, and some are simply absurd. For example, storing enough energy to power the automobile shown on this magazine cover would require an impossibly large superconducting magnet. One weighing 100 pounds could generate about 130 horsepower—but only for a single second.

IBM researchers Karl Alex Müller (below) and Georg Bednorz received the Nobel Prize in Physics for their 1986 discovery of high-temperature ceramic superconductors. Their copper oxide, mixed with barium and lanthanum, was capable of superconducting at 35 Kelvin (the Kelvin scale measures the number of degrees Celsius above absolute zero).

PHOTO: WALTER P. CALAHAN

Meanwhile, magazines, newspapers, and television have celebrated the promise of superconductivity to transform our physical world with everything from high-speed levitating trains to pollution-free electric cars, from wasteless power lines to hyper-fast computers powered by exotic new circuits. "The lightbulb, the transistor—now the superconductor revolution," runs one typical headline.

The discovery of high-temperature superconductivity is indeed exciting and important. And yet the more than 75-year history of superconductivity research suggests that we take some of the claims made for the new materials with a dose of caution—especially where discussions of applications are concerned.

After all, superconductivity is not a new phenomenon. It was first discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911. It wasn't until the 1960s and 1970s that the first practical superconducting technologies were developed. And despite the growing use of conventional low-temperature superconductors in a variety of highly specialized applications, translating scientific breakthroughs into widely available technological options remains a difficult challenge, usually requiring years and sometimes decades of development.

This will almost certainly be the case for high-temperature superconductivity. There are still major technical barriers to the use of superconducting ceramics. In fact, they pose thorny materials-science challenges not experienced with existing metal-alloy superconductors. And even if practical high-temperature ceramic superconductors can be perfected, they will often represent only an incremental, as opposed to revolutionary, benefit over conventional superconductors or other competing technologies.

Most current or potential applications of superconductors can be divided into two broad categories. The first involves the use of superconducting material in large-scale technological systems, either as wire for the transmission of electricity or in magnets. Examples of the latter include magnetically levitated trains, high-energy accelerators, energy-storage systems, and nuclear magnetic resonance (NMR) imaging machines. Widespread use of these superconductor technologies will have far more to do with questions of public policy and economics than with the nature of the new materials.

The second category of applications involves the use of superconducting material as "thin-films" in small-scale electronic devices similar to semiconductor chips. Here, the new ceramic superconductors should have a more immediate impact, but it will still not be as radical as it first appears.

So while the science of superconductivity has taken a dramatic leap forward, in the absence of a further breakthrough—for example, superconductors that can operate at room temperature—the transformation of our physical world by superconducting technologies will happen considerably more slowly.

The Fragile State of Superconductivity

The excitement about recent discoveries is only natural, because superconductivity provides a means to eliminate one of the most fundamental technological limits of the electrical age—resistance. When the electrons in a current pass through a conductor such as copper wire, they bump against imperfections in the crystal structure of the material and scatter. The

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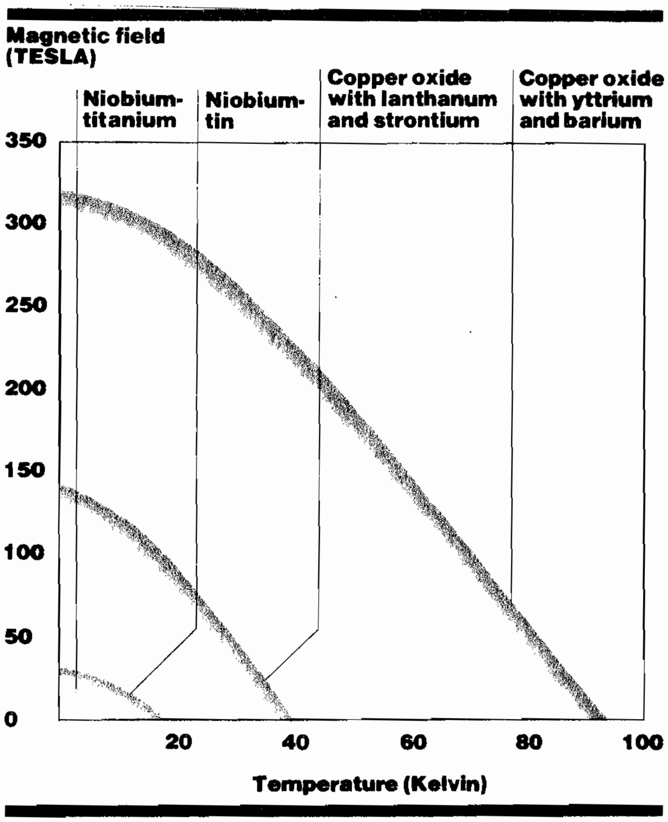
This graph shows the temperature and magnetic field at which four different superconductors revert to the non-superconducting state. For example, at absolute zero, niobium-titanium stops superconducting at about 14 tesla (approx. 280,000 times the earth's magnetic field). At zero tesla, it becomes non-superconducting at about 9 K. The two copper-oxide ceramics are a significant improvement over the conventional superconductors niobium-titanium and niobium-tin. But technical limitations may block some applications.



result is resistance, a loss of energy through heat. The problem of resistance affects everything from how large a magnetic field you can have in a motor or transformer to how small you can make a computer before its components become so hot that they melt.

Superconductivity is a special state of solids—one in which an electrical current can pass through without any resistance or loss of energy. A current flowing in a loop of superconducting wire would continue forever, much as an electron circles an atom forever.

However, achieving superconductivity is a fragile process. It depends on three interrelated factors—the temperature of the conducting material, the strength of the magnetic field generated by the current, and the current density. Each of these three is crucial to the practical application of superconductors. Changes in any one can return a superconducting material to its normal state.

Nearly all the attention about recent discoveries has emphasized the first factor, temperature. Superconductivity depends on extreme cold, usually in the neighborhood of absolute zero, or −273.2° Celsius. As the temperature increases, the amount of superconducting electrons decreases until a given material ceases to superconduct. The point at which this happens is known as the "critical temperature."

Before Müller and Bednorz's discovery, the highest critical temperature on record was only −250° Celsius, or 23 Kelvin (the Kelvin scale measures the number of degrees Celsius above absolute zero). Using a superconductor with such a low critical temperature requires cooling it with expensive liquid helium to near 4.2 K.

Müller and Bednorz's ceramic (a copper oxide mixed with two rare-earth elements, barium and lanthanum) showed evidence of superconductivity at 35 K, the first increase in critical temperature in nearly fifteen years. A mere one year later, research teams headed by Paul C. W. Chu at the University of Houston and Maw-Kuen Wu at the University of Alabama discovered that a different copper oxide, this time mixed with barium and yttrium, would superconduct at up to 94 K, allowing it to be cooled with relatively cheap liquid nitrogen (77 K) instead of with the far more expensive liquid helium. Today, the highest critical temperature on record is in the neighborhood of 100 K.

The second factor that affects the ability of a material to superconduct is the presence of a magnetic field. The stronger the field at a given temperature, the fewer superconducting electrons. For every temperature, there is an "upper critical field" at which the material returns to its normal non-superconducting state. From a practical point of view, this is extremely important because one of the basic uses of superconductors is in magnets. A current is run through superconducting wire wound into a "solenoid," or coil. Because the current can pass without resistance, you can create far more powerful magnets with superconductors than with conventional materials.

The third and final factor affecting the ability of a material to superconduct is current density, the amount of electrical current it can carry through a given area. In general, the "critical current density" of a superconducting material—the point at which too much current causes it to return to a non-superconducting state—decreases as either the temperature or the magnetic field increases. This is important for many applications because the greater the current density of a particular superconductor, the smaller the magnet necessary to produce a given field. And small magnets mean cheap and efficient magnets. Fortunately, unlike critical temperature and critical field, which are basic properties of the materials used, the critical current density of a par-

CHART: TOM BRIGGS DESIGN AND GARDINER MORSE

Ceramic superconductors are more difficult to fabricate than their conventional counterparts, which is a major obstacle to their use in magnets.

ticular superconductor can be improved by techniques used in processing.

Technical Limitations of the New Materials

How do high-temperature superconductors stack up against these three critical factors? So far, the new materials have many technical limitations that prevent their immediate use in commercial technologies.

The high critical temperatures of ceramic superconductors have led many observers to predict the replacement of expensive liquid helium with cheaper liquid nitrogen as a coolant in practical superconducting technologies. However, superconductor performance deteriorates rapidly as one approaches a material's critical temperature so that, for most purposes, a given superconductor operates best at below half its critical temperature. Before a material could be efficiently operated in liquid nitrogen, it would have to have a critical temperature in the neighborhood of 150 K—considerably above any to date.

Many technical obstacles also remain to using the new ceramic materials in practical superconducting magnets. Most superconducting magnets in use today are made of the alloy of the metals niobium and titanium. It is ductile (so it is easy to form into the spiral shape necessary for a magnet), and when cooled to the temperature of liquid helium it can generate a field up to 9 tesla—nearly five times that of an iron magnet (1 tesla is equal to about 20,000 times the earth's magnetic field). Another commercially produced superconductor, a compound of niobium and tin, can generate even greater fields, up to 15 or 16 tesla. This material is brittle and therefore more liable to fracture under the strains of the forces generated by a strong magnetic field. However, scientists have developed ways to process niobium-tin so that it can be used in high-field magnets.

Because the new ceramic superconductors have high critical temperatures, one might expect that they have higher upper critical fields, and this is in fact the case. At the Francis Bitter National Magnet Laboratory, we have estimated that the upper critical field of the high-temperature superconductors is in the range of 250 to 350 tesla at absolute zero.

The first problem with the new materials is that they are considerably more difficult to fabricate than their conventional counterparts. Like other ceramics, they are brittle and break easily. They are also extremely sensitive to oxygen, water, and carbon dioxide, which suggests they may be highly susceptible to environmental degradation. So far, no one knows whether they can be reliably processed into the long lengths of wire necessary for winding into the complex configurations of a magnet or whether they can be adequately supported to withstand the forces of high magnetic fields.

The new materials are also "anisotropic"—their ability to conduct current depends strongly on the direction of the current with respect to individual crystals. To use the superconducting ceramics in a magnet may depend on precisely aligning their crystals and require unconventional processing techniques.

Finally, unlike conventional metal-alloy superconductors, the ceramics seem to have a broad "phase boundary." With conventional superconductors, there is a complete lack of resistance until the material gets very close to its upper critical field. Then there is a sharp increase in resistance and the material ceases to superconduct. With the ceramics, resistance begins far below the upper critical field and increases gradually until the material becomes non-superconducting. At liquid-nitrogen temperatures, the new materials show signs of resistance at less than 10 tesla, approximately a tenth of the upper critical field that one would expect. If this broad phase boundary turns out to be inherent in the physics of the new materials, it could represent a major barrier to their use in high fields at high temperatures.

Perhaps the most serious shortcoming of the new ceramic superconductors is that their critical current density has so far been low. The most current density that bulk wires have been made to carry at liquid-nitrogen temperatures is only about 1,000 amperes per square centimeter at 1 tesla. But superconductors used in motors, generators, magnets, power lines, and electronic components must be able to carry as much as 100,000 amperes per square centimeter.

Again, no one knows for sure why the critical current density of the new materials is so low. In the samples tested so far, it appears that the ceramics consist of individual superconducting crystals with non-superconducting areas in between. The superconducting current is not continuous; rather, it "jumps" from crystal to crystal by a process known as "intergranular conduction." This and the ceramics' anisotropic character could be the source of the current-density problem.

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"Nuclear magnetic resonance imaging" is the one large-scale superconductor application now commercially available. It uses the magnetic properties of the protons of hydrogen atoms to generate detailed images of the body's soft tissues.

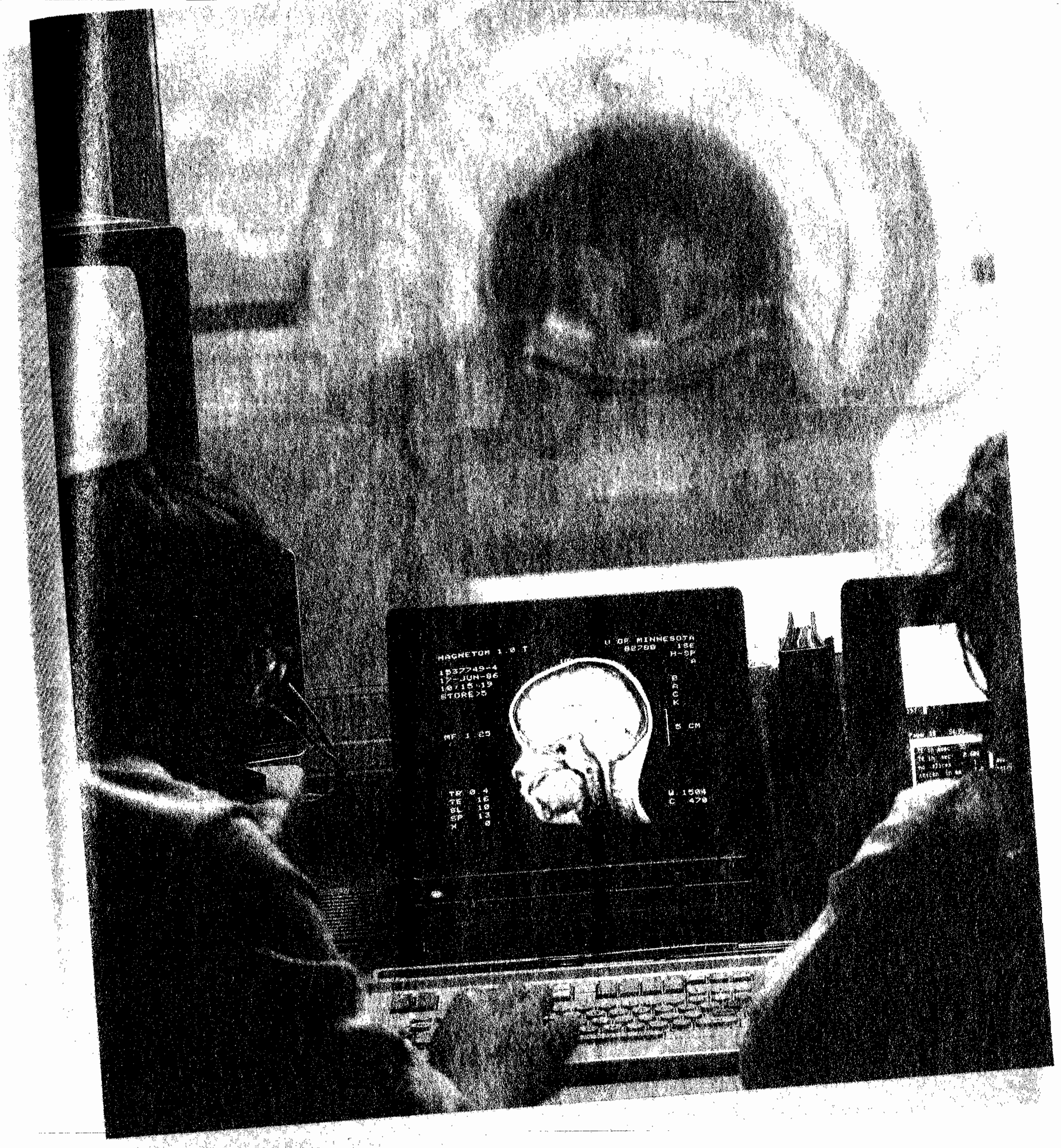

PHOTO: A.C. SHAMBROOM TECHNICAL CONSULT: E.C. KRYPER, M.D.

The University of Houston's Paul Chu holds the first ceramic capable of superconducting above the temperature of liquid nitrogen. The sample showed signs of superconductivity at up to 94 K.

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Large-Scale Superconducting Applications

Most large-scale applications involve the use of superconductors in capital-intensive technical systems, such as railroads, power generation and transmission, and particle accelerators. Because of their scale and expense, they would almost without exception have to be undertaken by government or by controlled monopolies such as utilities, and would depend on public-policy decisions for funding. Most are technically feasible with conventional superconductors, but the superconducting component of the system is a relatively small part of the total cost. Therefore, the potential savings from using high-temperature superconductors would also be small.

A case in point is one of the classic examples used to suggest the technological potential of superconductors—magnetically levitated (MAGLEV) trains. No article in the popular press about superconductivity fails to refer to super-fast trains floating from city to city on a cushion of magnetic field provided by superconducting magnets.

MAGLEV technology has been studied extensively during the past decade, and prototypes using conventional superconductors made from niobium-titanium and cooled by liquid helium have been built and tested in Japan and West Germany. At about 20 miles per hour, the superconducting magnets on the train induce enough current in a conducting trackway to produce a repulsive force that levitates the train. In unmanned tests, the Japanese MAGLEV prototype has reached 320 miles per hour.

Economic feasibility is another matter. The major expense in any superconducting rail system would not be the magnets but track development—including purchasing the right-of-way, preparing the roadbed, building bridges, and laying track. Stringent limits on track curvature and gradient increase the costs of high-speed trains. (*See "High-Speed Rail," April 1986, page 32.*) For example, between 1975 and 1982, capital costs for the Japanese bullet train that runs between Tokyo, Osaka, and Hakata were between $30 million and $40 million per mile. And because track geometry must be so precise, maintenance is expensive. It is likely that capital and operating costs for a MAGLEV train would be in the same range as those for the bullet train.

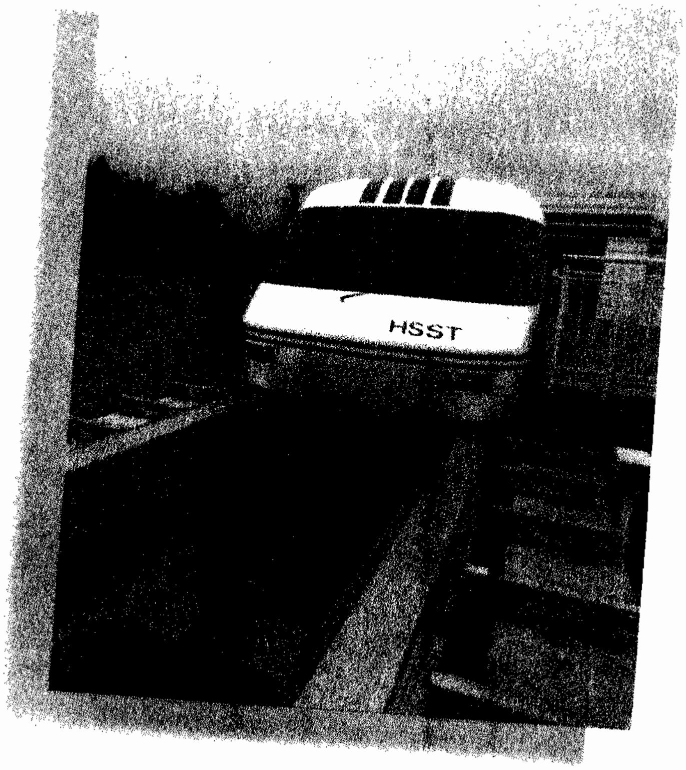
Such massive investments would require a major public commitment to high-speed public transportation. Moreover, even if federal or state governments were to decide to create a rapid-train system in the United States or in a single region, there are alternatives to MAGLEV technology. For instance, the French TGV (*Train à Grande Vitesse*) is a proven technology using conventional steel rails and wheels instead of magnets. It travels at speeds up to 180 miles per hour—slower than the Japanese MAGLEV prototype, true, but the technology is less risky. And should an American version of the train ever be built, chances are it would move passengers through the Northeast Corridor fast enough to compete with other modes of transportation.

In the face of these major public-policy decisions—whether to build a high-speed rail system and whether to use MAGLEV technology for it—it is unlikely that the savings high-temperature superconductors might make possible will be the critical economic factor.

A similar example is one large-scale application where conventional superconductors are already in use. Magnets are central to high-energy ring accelerators. A magnetic field bends a beam of charged particles in a roughly circular path as they travel at

PHOTO: DAN FORD CONNOLLY/PICTURE GROUP

Japanese engineers have built this experimental levitating train, which uses superconducting magnets to reach speeds in excess of 300 miles per hour. However, constructing an actual rail system based on the new technology may not be economically feasible. The magnets themselves represent a relatively small part of total costs, but the expenses associated with track development could reach tens of millions of dollars—per mile.



nearly the speed of light around the circumference of the accelerator. The higher the field, the higher the energy level achievable over a given circumference—and the smaller the circumference necessary for a given level of energy.

Ring accelerators always used to employ iron-core magnets. In the early 1980s, however, Fermilab in Batavia, Ill., built a superconducting accelerator in the same tunnel as the iron-core Tevatron accelerator. This doubled the energy level while avoiding the construction costs of a new tunnel.

Recently, the high-energy physics community has proposed a Superconducting Super Collider (SSC). The plan calls for a high-energy accelerator approximately 53 miles in circumference and operating at a field of 6.6 tesla generated by some 10,000 superconducting magnets made of niobium-titanium and cooled to the temperature of liquid helium. The SSC is estimated to cost between $4.4 billion and $6 billion.

Why not use higher-field superconducting magnets—whether conventional or high-temperature—to create accelerators with smaller circumference and save on construction costs? Unfortunately, there are technical problems with this scenario. When a current is carried in a superconducting wire, the field interacts with the superconductor, producing powerful forces that can tear the magnet apart. Magnets must be engineered with structures that hold the wires in place. Moreover, because the force increases as the square of the field—for example, when the field doubles, the forces are four times as great—higher fields require much larger amounts of supporting structure. This adds to the cost. So does the fact that, as the field increases, current density decreases. The lower the current density, the more superconducting material necessary to generate the magnetic field. Thus, any superconducting magnet is the product of a compromise. The designers of the SSC have concluded that 6.6 tesla is optimum.

If high-temperature superconductors are perfected, it would be technically possible to save money on cooling. But as with the example of the MAGLEV train, the savings would be relatively minor. The estimated cost of the superconducting magnets and cooling for the SSC is approximately $250 million, only 5 percent of the total cost.

Finally, it could well be that liquid helium will be necessary in the SSC no matter what kind of superconductors are used. Liquid helium's intense cold helps to maintain the ultrahigh vacuum necessary to prevent speeding particles from colliding with air molecules or other impurities.

The one large-scale application not based on generating high magnetic fields—superconducting power transmission—also faces economic obstacles. In 1985, the United States consumed $175 billion worth of electricity, sustaining about $8.75 billion in transmission losses, or approximately 5 percent. Robert Jaffe of the Electric Power Research Institute in Palo Alto, Calif., has estimated that superconducting transmission lines might generate a saving of perhaps $5 billion per year. But the capital costs of installing such lines, Jaffe points out, might be hundreds of billions of dollars.

One problem of superconducting power cables is that because they would have to be refrigerated, they would almost inevitably go underground. The significance of this is that over long distances, overhead transmission wires are from 10 to 30 times cheaper to construct than underground cables.

Second, because the initial capital costs would be so high, the only way to make superconducting power transmission cost-effective would be by send-

PHOTO: CLAUDE CHARLIER

Superconducting ceramics have already been used in prototype electronic devices.

ing large quantities of electricity over a given line. This is technically possible, and the prospect has inspired numerous predictions of entire cities serviced with electricity from a single superconducting cable. But to depend on a single cable to provide the needs of a large metropolitan region is to risk massive disruption from breakdowns or power outages. At the least, it would require adding significant overcapacity—which would add to the cost of the entire system.

Superconducting magnets can also be used to store energy without any loss. Energy is held in the field generated by a magnet. Periodically, the magnet is discharged, feeding the energy back to the original source used to generate the field.

Superconductor energy storage might be feasible for utilities, but only on so large a scale as to be a substantial capital investment. To be cost-effective, an energy-storage magnet would have to be hundreds of meters in diameter—able to hold enough power to supply the electricity needs of New York City for one to two hours. The capital costs of such a system would be in the neighborhood of a billion dollars.

What about using the same technique to store smaller amounts of energy—for example, enough to power vehicles such as automobiles? Unfortunately, this idea has a fundamental flaw. To store enough energy for an automobile engine, you would still need an absurdly large magnet. A magnet weighing about 100 pounds could store enough energy to generate about 130 horsepower—but only for one second.

Nuclear magnetic resonance (NMR) imaging, which uses the magnetic properties of the protons of hydrogen atoms to generate detailed images of the human body's soft tissues, is the one large-scale superconducting application currently on the commercial market. (*See "NMR: The Best Thing Since X-Rays?" January 1988, page 58.*) This is one area where high-temperature superconducting magnets could make some difference.

A typical NMR machine costs from $1 million to $2 million, and the superconducting magnet costs approximately $200,000 to $300,000. Another $100,000 goes toward insulating the magnet, and the liquid helium necessary to cool it accounts for about $30,000 of the roughly $100,000-plus annual operating cost.

Liquid-nitrogen coolant for high-temperature superconductors would cost considerably less—around $2,500 per year. Depending on the cost of the superconducting ceramics and other materials used, some savings might also be possible for the magnet and the insulation, but the ceramics are likely to be expensive because of the technical problems with fabricating magnets out of a brittle material.

Superconductor Electronics

Small-scale applications of superconductors are less visible but far more common than their large-scale counterparts. They define a field sometimes known as "superconductor electronics." At present all commercially available superconducting electronic products are based on a phenomenon of superconductivity known as "tunneling."

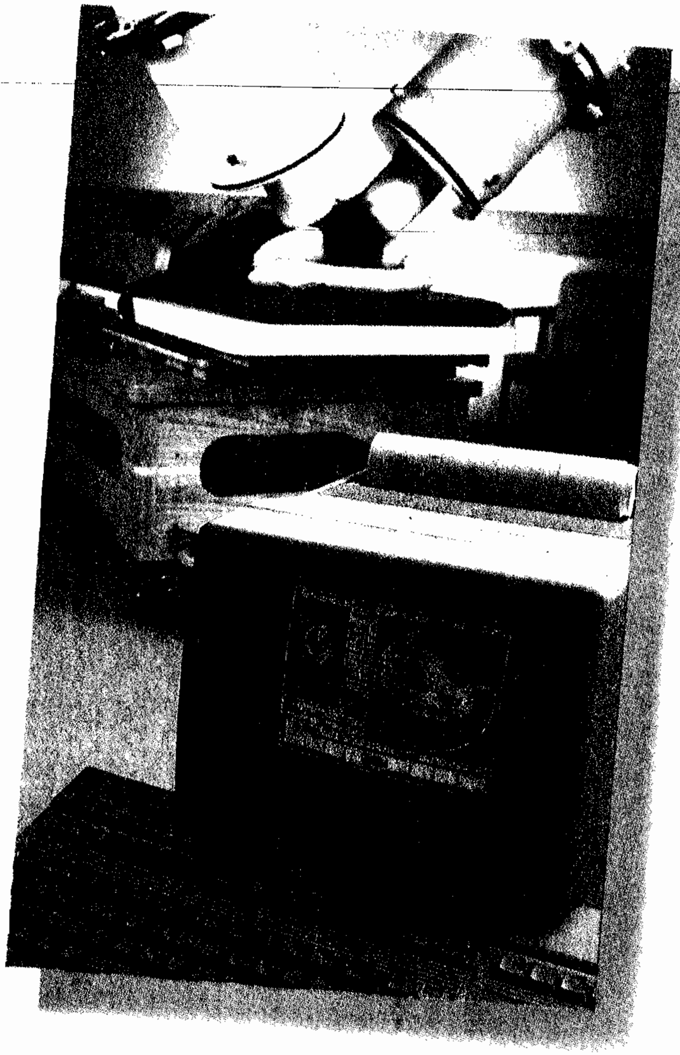
To understand tunneling, consider two superconductors separated by an insulating barrier such as silicon or an oxide. As British physicist Brian Josephson predicted in 1962, a superconducting current is able to tunnel through the insulating barrier and connect the two superconductors without any resistance. Josephson also showed that the amount of current able to tunnel across the barrier had a maximum value that could be controlled by a very small magnetic field. This made it possible to use what have come to be called "Josephson junctions" as extremely sensitive detectors of magnetic field.

Superconducting quantum interference devices, or SQUIDs, use the extreme sensitivity of Josephson tunneling to measure fields a thousand times smaller than is possible with any non-superconducting device. The SQUID doubles as a voltmeter, able to detect voltages as low as a billionth of a billionth of a volt and currents as small as 10 electrons per second passing through a wire.

One important application of SQUIDs is in biomedical research. (In fact, the sole domestic manufacturer of SQUID technology is Biomagnetic Technologies of San Diego, Calif., which serves the health field.) Employed in the process known as "magnetoencephalography," the magnetometer measures small magnetic fields produced by the firing of neurons in the brain. Magnetoencephalography has two advantages over its electrical counterpart, electroencephalography (EEG). It is completely noninvasive and can locate the sources of specific signals in the brain.

Geologists also use SQUID magnetometers to de-

This "superconducting quantum interference device" measures small magnetic fields produced in the brain. Such highly specialized electronic instruments are among the most common superconductor applications so far.



tect the magnetic properties of rock samples, and to locate geological faults or explore for oil, water, and mineral deposits. Another application derives from the phenomenon of "paleomagnetism," which allows researchers to date a portion of the earth's crust by determining the direction of its magnetic field. In addition, it may be possible to use SQUIDs for defense purposes—for example, to detect sudden changes in the earth's magnetic field caused by submarines.

In 1960, the American physicist Ivar Giaever discovered a different kind of tunneling. Whereas Josephson tunneling occurs without any resistance, allowing a current to flow across the insulating barrier at zero voltage, Giaever tunneling does not occur *until* a certain voltage is reached. The voltage causes some of the electrons in the material to return to a non-superconducting state, at which point they are able to pass through the barrier.

In a second class of commercial superconducting devices, specific voltages are applied to make the superconducting material switch rapidly (within a few picoseconds) from the Josephson to the Giaever tunneling current. This allows for analog-to-digital conversions at an ultra-fast rate, particularly important for operating advanced communications systems or for capturing analog signals to be processed and analyzed in a digital computer.

For example, Hypres, Inc., of Elmsford, N.Y., has developed and marketed a workstation that can be used as a high-speed superconductor oscilloscope. It measures voltage changes at rates even faster than occur in gallium-arsenide electronic circuits (for which conventional oscilloscopes are simply too slow). The superconducting component of the oscilloscope consists of fewer than 100 tunnel junctions, comparable to the most primitive integrated-circuit technology. Nevertheless, it is the first commercial application of superconductors in a digital electronic system.

A third and last variant of commercial superconducting devices relies on another aspect of the Josephson effect. When a superconducting tunnel junction is irradiated with a known frequency of microwaves, a voltage develops across the junction. The voltage is proportional to the frequency of the waves, and because this frequency can be made extremely precise, a correspondingly precise voltage can be produced. In 1972 the National Bureau of Standards developed an array of superconducting tunneling junctions to serve as a national voltage standard. And in 1985 the bureau developed a chip consisting of some 2,000 Josephson junctions to produce voltages up to two volts with an accuracy of one part in 100 billion. The chip is now commercially available to designers and manufacturers of high-precision instruments and electronic components.

In certain respects, high-temperature superconductors ought to have a greater immediate impact on these electronic applications than on the large-scale technological systems described above. For example, in most electronic applications the superconducting material is deposited on a silicon chip (or some other material) in the form of a thin-film. Early indications suggest that the new ceramics can be successfully applied in this way. Also, researchers at IBM have achieved high current density in thin-film samples made from these materials. The company has used its ceramic thin-film in a prototype high-temperature SQUID.

However, even if the new materials can be used in electronic systems, their effect on the cost and functioning of present-day devices will be moderate. Consider the SQUID. The extreme sensitivity of su-

PHOTO: BIOMAGNETIC TECHNOLOGIES

Military satellites may some day carry superconducting electronic systems cooled by the low "room temperature" of outer space.

perconducting electronics to magnetic fields degrades as the temperature increases, because the higher the temperature, the greater the "noise" from moving electrons. For applications where a SQUID's ability to detect magnetic fields is already near the limit (magnetoencephalography is one example), it will be necessary to operate at liquid-helium temperatures—whatever the critical temperature of the particular superconductor used.

The superconductor oscilloscope would probably benefit somewhat from the new high-temperature superconducting materials, as operating at liquid-nitrogen temperatures would save on cooling costs. However, the improvement would be marginal, because the superconducting part of the electronics, albeit critical, is only a few percent of the overall cost of the system. And the National Bureau of Standards voltage standard is such a specialized application that any cost savings would have a neglible economic impact.

What about applications not yet commercially viable? One frequent suggestion is to replace all the interconnecting wire in semiconductor electronic devices with superconducting material, generating less heat and increasing circuit speed. However, two main difficulties stand in the way.

First, a superconductor has zero resistance only at direct current (DC), not at alternating current (AC). The back-and-forth movement of the alternating current leads to resistance. And AC is the current at which computers and other electronic devices run.

One way to decrease the resistance is to lower the temperature. The lower the temperature, the more electrons condense into the superconducting state. This means that a superconductor has to be operated at below half its critical temperature. Even those new high-temperature superconductors with critical temperatures in the neighborhood of 100 K must operate at below approximately 50 K to be practically useful.

And even if a superconductor could be found with a transition temperature of 150 K or more, so that it could safely operate at the temperature produced by liquid nitrogen (77 K), the technological benefit would most likely be small. At such low temperatures, copper is an effective connector in silicon devices. Indeed, a superconductor that could improve on copper wire at room temperature would have to have a transition temperature in the neighborhood of 600 K or about 327° Celsius!

Another much-discussed possibility is the use of Josephson junctions to build a much smaller—and therefore much faster—computer. A conventional semiconductor transistor uses a small voltage to act as the "on-off" switch necessary for the binary arithmetic of digital devices. The amount of heat this produces has traditionally been a crucial obstacle to miniaturizing computer components. When a Josephson junction switches to the non-superconducting state, the voltage that occurs is 100 times weaker than that produced by semiconductor transistors, so considerably less heat is generated.

Unfortunately, it is not simply a matter of replacing semiconductor transistors with superconducting Josephson junctions. Totally new concepts in circuit design and computer architecture are necessary before superconducting computers can be built. Josephson junctions are controlled by the application of a small magnetic field provided by a current, while most semiconductors are controlled by applying a voltage. Also, the ability of transistors to function as amplifiers has proved convenient in conventional computer designs—but Josephson junctions do not have this capacity. And once these design challenges are met, still other problems having to do with the reliable manufacture of Josephson junctions will need to be resolved. Whether they use conventional or high-temperature superconductors, superconducting computers are a long way from commercial application.

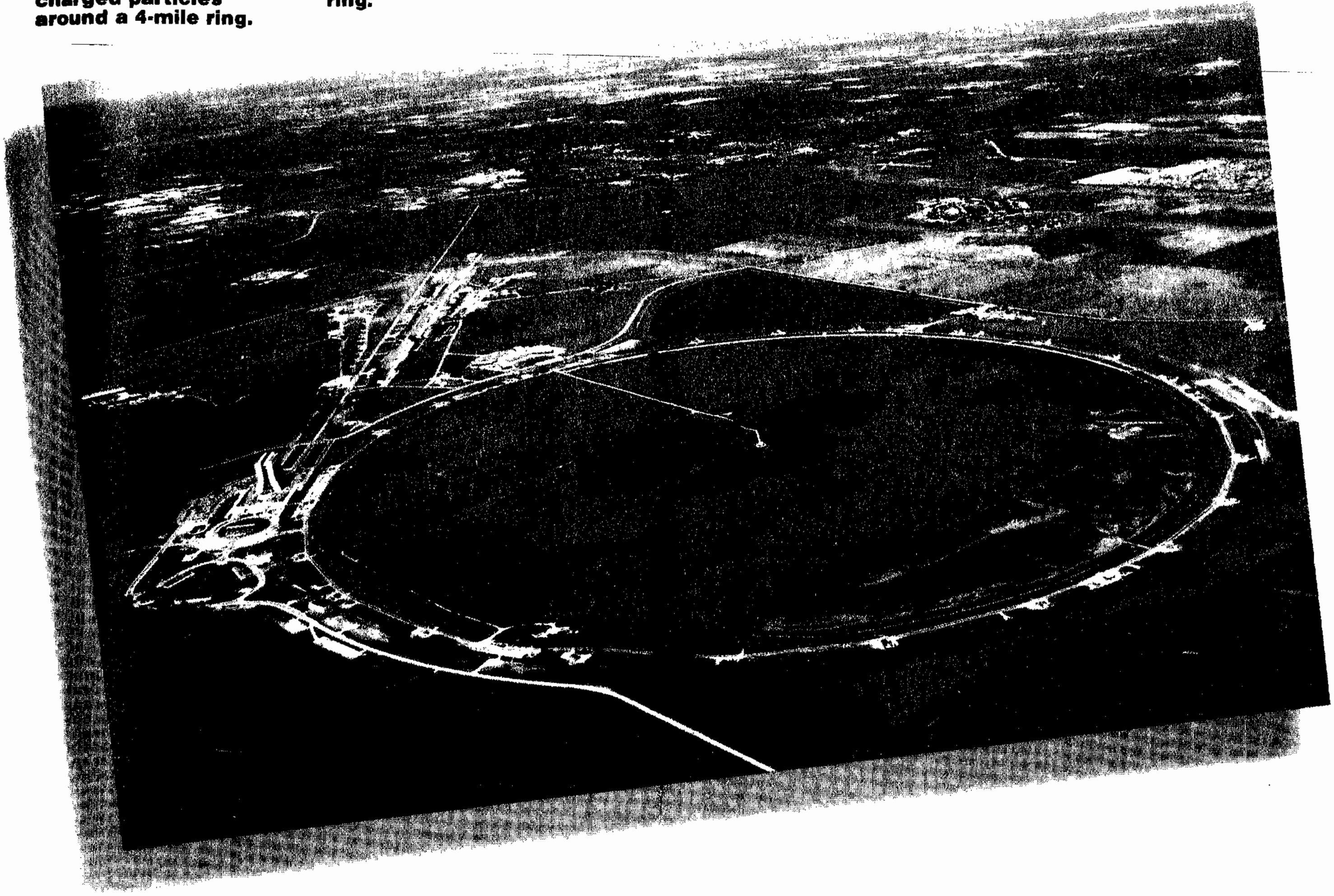
One highly specialized but important small-scale application where the new materials may make an immediate difference is space electronics, in particular special sensors and detectors used by the Department of Defense. Here, performance rather than cost is the key factor. Cooling a superconductor with liquid nitrogen would mean lighter payloads and, hence, less need for rocket fuel. Systems might also operate much longer with a given amount of coolant. Finally, with appropriate shielding from the sun, it might even be possible to run a high-temperature superconducting electronic system with no coolant whatsoever, leaving refrigeration to the cold "room temperature" of outer space.

The Challenges Ahead

Despite the many challenges on the road to practical superconducting technologies, the recent scientific breakthroughs in the field remain extremely important. They are the prelude to the continuing devel-

Fermilab's Tevatron high-energy accelerator in Batavia, Ill., uses conventional superconducting magnets to bend charged particles around a 4-mile ring.

Physicists have proposed a Superconducting Super Collider that would use 10,000 such magnets in a 53-mile ring.



opments that will make widespread superconductor applications possible.

Before the discovery of high-temperature superconductors, progress in superconductivity was measured by quite small increases in critical temperature, often of less than one degree. Today, there is no reason to believe that the dramatic leaps in critical temperature inaugurated by superconducting ceramics are over. Researchers may find new high-temperature superconducting materials with less severe technical limitations than the ceramics we know today. And if the day ever comes when a superconductor can be reliably manufactured to operate effectively at room temperature, then superconductors will be incorporated in a broad range of everyday household devices—motors, appliances, even children's toys—with a large consumer market.

High-temperature superconductors may also cause us to extensively revise our traditional theories about how superconductivity works. Should it turn out that superconductivity in ceramics involves new physical mechanisms, then these mechanisms could lead to applications never considered before.

The recent discoveries have already reinvigorated superconductivity research. What was once largely the domain of a relatively small group of scientists has become a genuinely multidisciplinary realm. Now physicists, materials scientists, chemists, metallurgists, ceramists, and solid-state electronics engineers are all focusing on superconductivity. The cross-fertilization of these disciplines should contribute to further discoveries of importance to the practical application of superconductors.

Finally, all the attention generated by recent discoveries has led to increased funding for superconductivity research. Venture-capital firms have identified superconductivity as a promising area for investment. And given the potential importance of superconductor technologies to national-security needs, the Defense Department may become a major catalyst of superconductor R&D, much as it did for the fledgling computer industry some 30 years ago.

All these indicators suggest that superconductivity has entered a dynamic new phase. But a great deal remains to be done. ☐

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