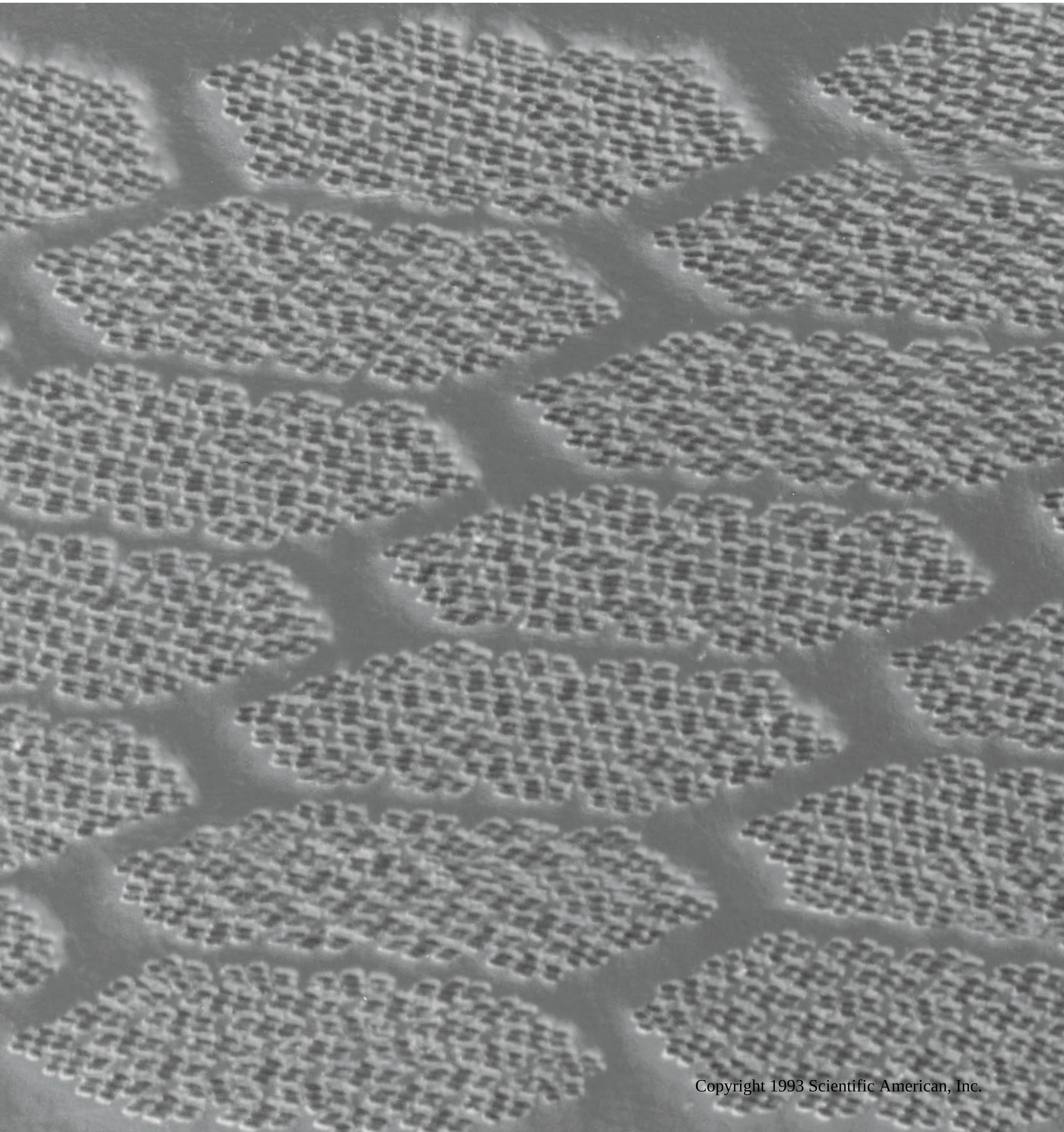
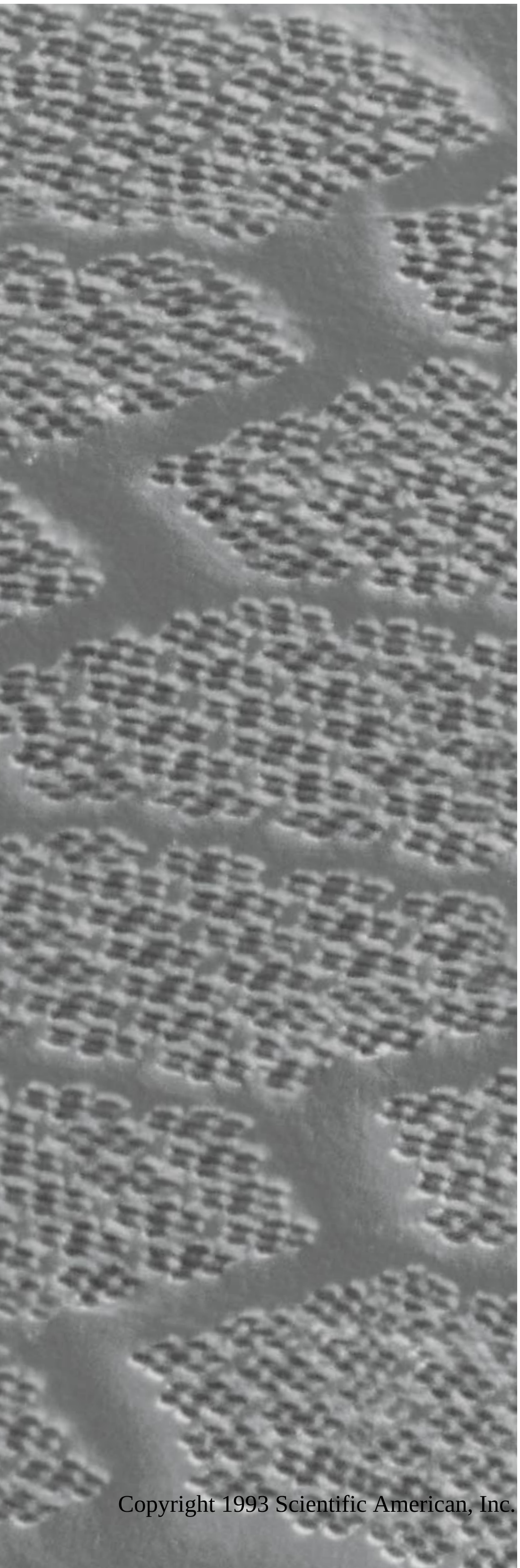
Current Events

by Philip Yam, *staff writer*



Now that the blizzard of hype has stopped, workers are gradually realizing the promise of high-temperature superconductors



Over a smoky bath of liquid nitrogen hovers a disk-shaped magnet. Wei-Kan Chu, the deputy director for research at the Texas Center for Superconductivity at the University of Houston (TCSUH), suggests knocking the floating magnet about. Such demonstrations have become a customary part of a visitor's tour at many laboratories that harbor work in superconductivity, but they are, like a rainbow, still impressive. As expected, the suspended disk resists all attempts to force it up, down or sideways. It can, however, be set spinning, slowed only by friction with the air. The system is about the closest thing to a perfect ball bearing or flywheel.

Although the demonstration hasn't changed, the atmosphere in the world of high-temperature superconductivity has. Gone is the sound of hype, the White House pronouncements, the high-level conferences from which "foreign" researchers were pointedly excluded. Discussion in the field no longer swirls around national competitiveness, magnetically levitated trains (the putative offspring of the floating magnet) and super supercomputers. Today workers focus on incremental advances and modest applications—a strategy that may actually bring the millennial visions of the hypesters to reality faster than any crash program would have.

Discovered in the late 1980s, these ceramic compounds—yttrium-barium–copper oxide (YBCO for short, and pronounced "yibco") and its relatives, containing bismuth or thallium combined with copper oxide—promised to expand greatly the market for devices that exploit superconductivity. When cooled below a critical temperature, a superconductor not only transmits electricity without resistance but also wards off intruding magnetic fields. Conventional superconductors, made of metals and alloys, must be cooled to a brittle four degrees above absolute zero with liquid helium. They have seen limited applications because of the cost (about $4 a liter) and rapid boil-off of the liquid helium. The critical temperature of the ceramic superconductors exceeds 90 kelvins. A material could be cooled to a point below that temperature with liquid nitrogen, which boils at 77 kelvins. Liquid nitrogen costs as little as 10 cents a liter, making it cheaper than Kool-Aid. Equally important, liquid nitrogen lasts 60 times longer than liquid helium given the same heat load.

HIGH-WIRE ACT: a lateral cross section of a high-temperature superconducting wire is magnified 300 times. Made by American Superconductor, the wire consists of superconducting filaments, each four microns thick, packed into hexagonal patterns. This approach makes what would otherwise be a brittle wire bendable and able to resist cracks.

The products available now are such specialized devices and components as magnetic field sensors for educational purposes, current leads in magnetic resonance imaging (MRI) systems and even a dipstick that measures levels of liquid nitrogen. Although hardly the kinds of applications that fire the imagination or revolutionize a society, these and other devices represent tangible victories in making the new superconductors a commercial success. "Progress to date has far exceeded realistic expectations," says Thomas R. Schneider of the Electric Power Research Institute (EPRI), the utility-funded organization headquartered in Palo Alto, Calif.

Schneider chooses his words deliberately, emphasizing "realistic." As he uses the term, realistic means prototypes, demonstrations, contracts and long-term goals. By that measure, progress has indeed been gratifying—and ahead of schedule, according to many workers. Investigators have demonstrated and are ready to produce components for microwave communications and military tracking. Wires are getting longer and are able to carry more current. Devices have been built from them that prove the technical feasibility of power applications. "I didn't expect to see anything real this century," remarks physicist John Clarke of the University of California at Berkeley. "The field has progressed much more quickly than I would have guessed." Adds Alan Lauder, director of Du Pont's superconductivity research: "I am perhaps more optimistic than I ever have been that this technology will develop into beneficial systems."

Against the Grain

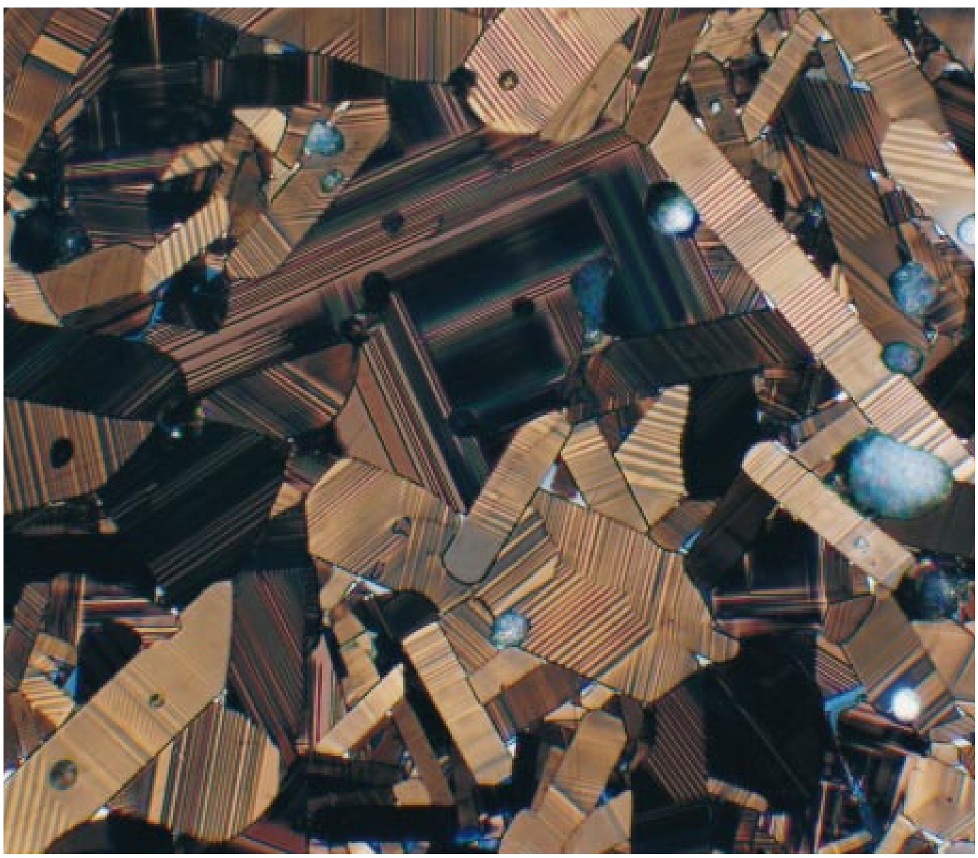
What makes the recent progress such a source of optimism is that the materials are inherently intractable. After all, they are ceramics. How does one fashion wires or circuits from a substance with the fragility of chalk? Just as challenging, the material can suffer from "weak links." High-temperature superconductors consist of grains. Electricity has no problem flowing within a grain, but sometimes it does have trouble getting from one grain to the next because the grains are not always properly coupled to one another. Large gaps can separate them, and any misalignment—even by a mere five degrees—inhibits the resistanceless flow. Weak links can limit by two orders of magnitude the amount of current carried.

An even more daunting challenge came from external magnetic fields. In many envisioned bulk applications, such as motors, transformers and levitation devices, the presence of a magnetic field is an integral part of the technology or, at least, an unavoidable byproduct of the system's operation. Whatever its provenance, a sufficiently strong external field can penetrate the superconductor in the form of discrete bundles of flux lines, or vortices. If the superconductor is cold enough, the vortices remain locked in place, forming a latticelike pattern. Current flows around them without much difficulty. But at warmer temperatures, the magnetic flux bundles begin to "creep." At sufficiently high temperatures, the vortex lattice "melts": the vortices move around in the material, blocking the flow of electricity [see "Resistance in High-Temperature Superconductors," by David J. Bishop, Peter L. Gammel and David A. Huse; SCIENTIFIC AMERICAN, February]. More distressingly, the melting transition for all the copper oxides lies below the temperature of liquid nitrogen.

The combination of weak links and vortex motion can severely hamper the flow of current in the new superconductors. Unless a way could be found to overcome the problems, there was little reason to replace existing low-temperature superconductors, which do not suffer from those difficulties. Such conventional superconductors, mostly niobium alloys, can carry more than 100 times the current ordinary copper can: 100,000 amperes per square centimeter in a high magnetic field of several teslas. (For comparison, the earth's magnetic field is only about 0.1 millitesla, and the field generated by MRI devices is less than two teslas.) Fundamental issues such as vortex motion are relevant to those seeking applications, says David J. Bishop of AT&T Bell Laboratories, one of the investigators who discovered the vortex phenomenon. "It makes what they are trying to do harder." It did—and does—indeed. By 1989, less than three years after their discovery, the high-temperature superconductors did not seem so super after all. Media reports suggested that the large-scale applications might remain a fantasy, and pessimism pervaded the field.

Filming the Ceramics

Like guerrillas confronting a superior force, some workers in the field decided to go around rather than through



DISORDERED GRAIN STRUCTURE of the superconductor YBCO causes the weak link problem. The poor alignment, as well as any impurities that might exist at grain boundaries, strongly hampers the flow of electric current moving from one grain to another.

the opposition. They knew that the problems of weak links and flux creep would severely challenge "bulk" applications—that is, in uses as wires for motors, coils and transmission lines. They also knew that the problems were much less daunting in so-called thin-film uses—specifically, in the area of electronics.

Instead of drawing flexible wires out of brittle material, electronics developers attempted to lay down micron-thin surfaces and etch circuit patterns on them. Weak links are not a serious issue, because the grains can line up with the substrate on which the film must be grown (the substrate acts as mechanical support and affects the direction of grain development). Furthermore, the entire sample is small, so relatively few grain boundaries exist that could impair current flow. Flux creep is not a problem, because electronic components are rarely used in an environment suffused by strong magnetic fields. Thin films of YBCO can conduct five million amperes of current per square centimeter at 77 kelvins.

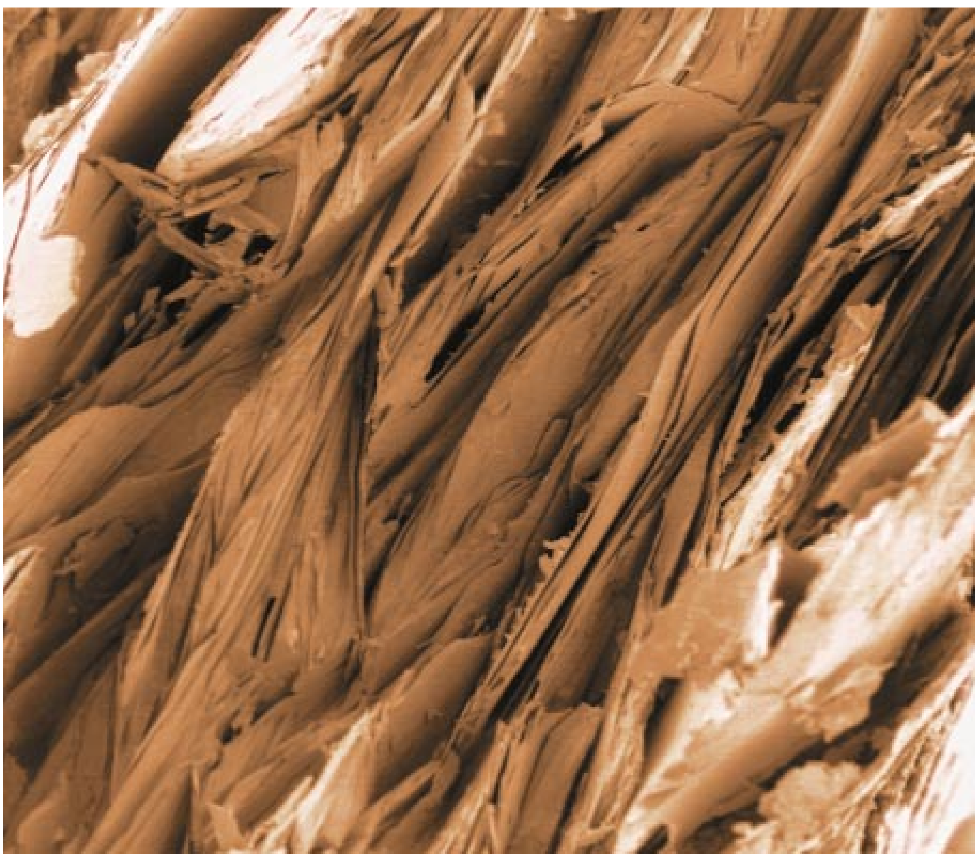
Because they suffer less from weak links and magnetic flux, thin films were predicted to reach the market early as components in electronic devices. They would, experts said, be useful in cellular communications systems and in biomedical sensors. In such applications, they would be much smaller and would handle more information than existing elements could.

SUCCESS IN THIN FILMS enables John M. Rowell of Conductus to offer for purchase one of the few products made from the new superconductors: Mr. SQUID, a $1,995 magnetic field sensor.

Such experts were not the first to use a cloudy crystal ball. The manufacture of large thin films of good quality proved to be the prime barrier to electronic applications. "We were surprised to find out how difficult these materials are to work with," says John M. Rowell, the chief technical officer of Conductus, a Sunnyvale, Calif., start-up specializing in thin-film applications. "There was no knowledge base for the oxide materials." The superconducting properties depend heavily on crystal structure. During processing, insulating phases of the material often appear. Substrate choice was also a challenge. During the manufacture, "the substrate might get chewed up or go into the superconductor," says James H. Long of Superconductor Technologies Incorporated (STI) in Santa Barbara, Calif. Largely through trial and error, film makers have mastered their craft. They can create market-worthy films that are as much as a few inches in diameter.

The superconductor of choice for most film applications is YBCO. A YBCO film carries more current than do members of the bismuth family. The relatively small number of elements in YBCO makes the material simpler to produce than thallium-based films. Organizations producing thin films have settled primarily on two ways to deposit the superconductor: laser ablation and sputtering. In laser ablation, a pulsed excimer laser vaporizes bits of the superconductor, which then crystallize on the substrate. In sputtering, the superconductor is evaporated by a plasma onto a substrate.

Companies such as STI and Du Pont have recently delivered filters, resonators and delay lines that operate at microwave and radio frequencies. Although not the kind of devices to appear in the Sharper Image catalogue, such components are common elements in military instruments and communications systems. Devices made with superconducting materials provide better signal strength and allow more efficient signal processing while avoiding such drawbacks as large size and high electrical loss. For example, STI made a delay line used by the military to deconstruct for analysis signals from a target. The component measures less than four inches square, a major reduction from the 70 feet of stainless steel coaxial cable typically needed to provide similar performance, according to STI.



PLATELIKE GRAINS of the superconductor BSCCO overcome the problem of weak links. In a process called powder-in-tube, a combination of deformation and thermal processing aligns the grains, laying them flat on top of one another. Electricity proceeds unimpeded from one grain to the next.

Several companies have also created interconnects, resistanceless bridges linking one component to another. Interconnects could be useful in multichip modules. These dense packages of several computer chips constitute an alternative to ever finer patterns etched on silicon wafers.

For entrepreneurs seeking large-scale commercialization, the telecommunications industry is the obvious target. "The cellular market is enormous," says Ora E. Smith, president of Illinois Superconductor, which makes the dipstick for liquid nitrogen. Industry experts say cellular base stations already constitute a $5-billion-a-year business. One way to tap into this market is through filters, which base stations use to remove the extraneous radio-frequency noise that peppers the cellular environment. Filters made from superconducting materials would maintain the integrity of calls better than conventional filters do and would help each cell handle more channels. AT&T Bell Labs, Illinois Superconductor and other companies are working on such cellular filters. "We're hoping to have the filter on the market in 1994," Smith says.

Electronic Calamari

Demand for acute magnetic-sensing devices also constitutes an opportunity. A high-temperature superconductor can be configured as a SQUID (a superconducting quantum interference device). A SQUID is a loop of superconductor etched in silicon. The loop contains one or two links that are only weakly superconducting. The flow of electrons that tunnel through the link, called a Josephson junction, is extremely sensitive to magnetic fields. The change in the flow shows up as a measurable change in voltage across the junction. Making such devices embodies fabrication challenges that only now are just being met.

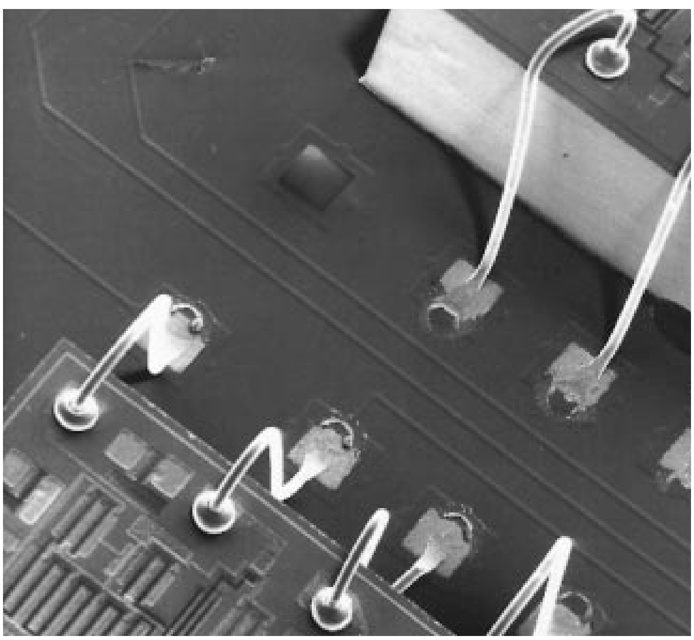
Conductus already markets a magnetometer called Mr. SQUID, designed primarily as an educational tool. Improved versions should enable engineers, at low cost, to discover defects without damaging or coming into contact with a mechanical structure. That is because defects in metallic structures produce magnetic "signatures" that SQUIDs can detect. Energy companies might also find SQUIDs useful. Because rock conducts electricity weakly and oil is an insulator, geologists could rely on the devices to prospect for petroleum. But the biggest prize for small companies is the clinical market. "The Holy Grail of the SQUID business is biomagnetic measurement," Clarke points out. SQUIDs made with copper oxides should soon be sensitive enough to detect electromagnetic signals from the heart and brain, thus providing a noninvasive diagnostic tool.

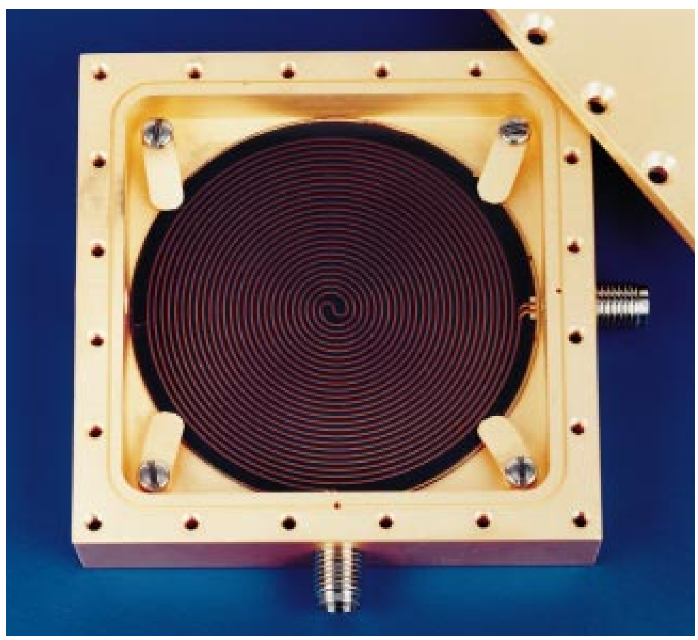
The new superconductors may also improve MRI systems or make them less expensive. Configured as a "pickup coil," a ceramic superconductor could improve the signal-to-noise ratio of many instruments without resorting to costlier large magnets.

What about superconducting computers? There has been some progress, but digital electronics products are not likely to emerge until past the turn of the century. Researchers have designed electronic switches from Josephson junctions, which consume only a few microwatts to turn on and off in a few trillionths of a second. The junctions not only consume one thousandth the power of semiconductor devices but are also 10 times faster. Workers have also demonstrated so-called flux flow transistors as alternatives to Josephson junctions. The principle turns a major shortcoming of the materials—the movement of magnetic vortices—into a benefit. The motion of flux lines generates voltages that can be modulated by a gate to perform logic functions.

A third kind of switch derives from a basic element in modern electronics: the field-effect transistor. In such transistors, an external electric field changes the number of charge carriers in a semiconductor. Only a few workers, however, have demonstrated superconducting field-effect transistors (suFETs). They include Xiaoxing Xi of the National Institute of Standards and Technology and his colleagues at the University of Maryland.

Whereas microwave and SQUIDs are the nearest in terms of substantive markets, "it will be 10 years before you see digital implementation," Du Pont's Lauder predicts. Manufacturing high-quality multilayer films and patterning them reproducibly and cheaply has proved difficult. "While the digital demonstrations are encouraging, there are some issues about circuit architecture that need to be clarified," says Richard W. Ralston, the principal director of the Consortium for Superconducting Electronics (CSE). Founded in 1990 during the height of the concern about American competitiveness, the consortium pairs two traditional rivals, IBM and





AT&T, with the Massachusetts Institute of Technology, the M.I.T. Lincoln Laboratory and several small companies and other academic institutions to speed commercialization of the new materials.

Stringing It Along

Success with thin films has put several markets for the copper oxide superconductors within reach. For their part, workers who attempt to master bulk materials have at least begun to enjoy some technical success. One measure of progress is in the production of wires—making them longer, more flexible and better able to resist the incursion of flux lines.

Amid the unremitting hum of machinery, punctuated by shrieking loudspeaker pagings, technicians are busy checking long lengths of wire. In its new facility, American Superconductor Corporation in Westborough, Mass., has been gradually coaxing the ceramic superconductor into wire. The joke, believed to have originated in the thin-film community, is that the move to this much bigger facility was necessary because the wire did not bend. But a tour of the pilot manufacturing line quickly dispels that bit of cynicism.

Since its founding in April 1987, American Superconductor has been competing vigorously with Sumitomo Electric Industries in Japan and Intermagnetics General in Guilderland, N.Y., to produce flexible, longer and better superconducting wire. The Massachusetts company has pulled ahead: it can regularly spin out 300 meters of ductile wire that can carry more than 10,000 amperes per square centimeter in zero applied field at 77 kelvins. The company plans to break the kilometer mark in April 1994. Such an advance would qualify the copper oxide wires for consideration as transmission lines. Transmission lines must sustain power densities of at least 20,000 amperes per square centimeter at kilometer lengths.

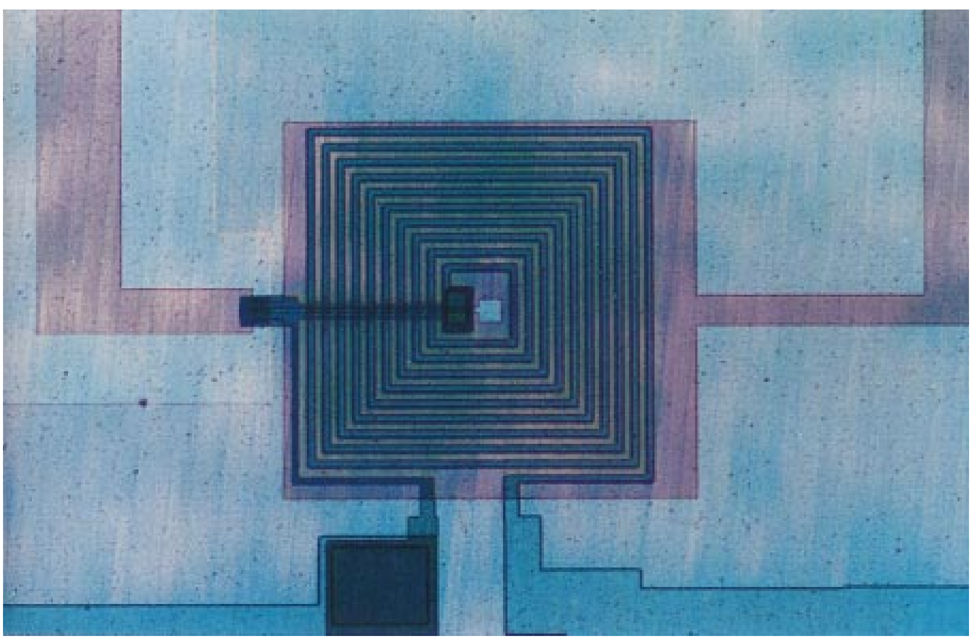
FOR SALE? Richard W. Ralston, principal director of the Consortium for Superconducting Electronics, holds a prototype filter for satellite communications and a disk of YBCO film ready to be patterned into a circuit.

This past year American Superconductor fashioned its wires into coils for Reliance Electric in Cleveland, Ohio, which built a two-horsepower motor—strong enough to power the cooling fan in a desktop computer. Even more recently, it constructed a sonar device for the U.S. Navy. "Essentially, it's a big woofer," explains Gregory J. Yurek, the president of American Superconductor. The device is meant to give coverage in a frequency range previously inaccessible to conventional sonar.

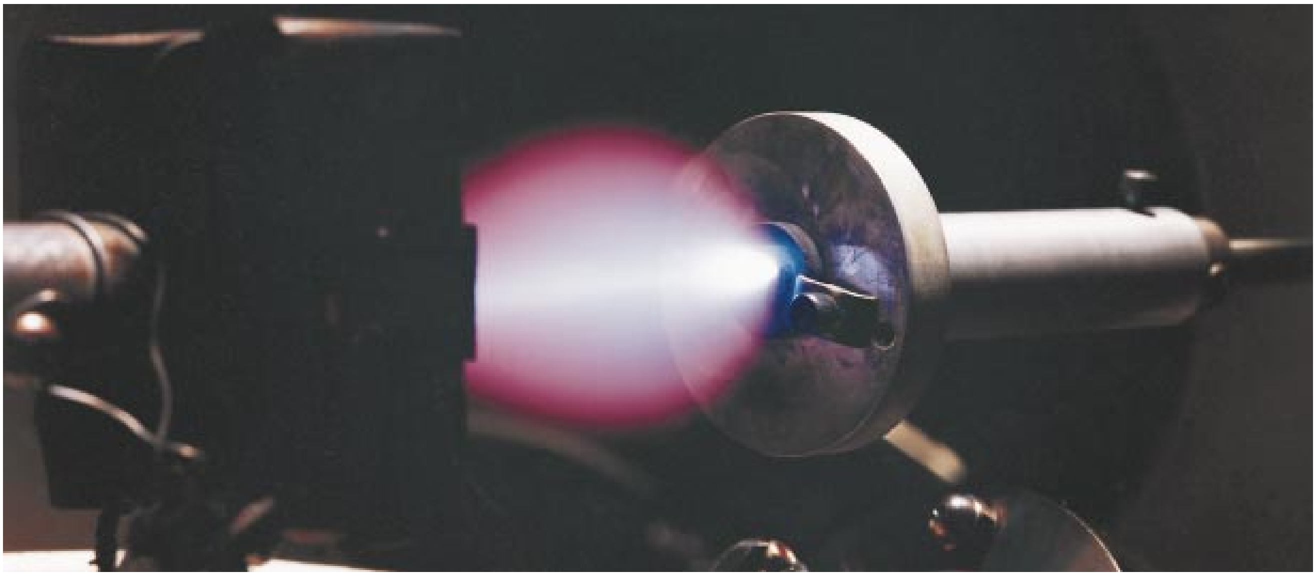
The long lengths of flexible wires, the coils and the big woofer stand as remarkable accomplishments in light of weak links and magnetic vortices. "Fortunately, the scientists and engineers did not give up on the materials," Yurek observes. The problem of weak links was solved by the discovery of a bismuth-strontium-calcium-copper oxide, or BSCCO ("bisco"), compound. "The breakthrough came with the bismuth material, which allows us to align the grains so that current flows from one grain to the next," says Roger B. Poeppel of Argonne National Laboratory.

Like other companies and laboratories, American Superconductor creates BSCCO wire using the powder-in-the-tube method, a technique first developed in 1989 by Vacuumschmelze in Germany. A silver tube is packed with a precursor powder. The tube is deformed—through extrusion, rolling or pressing—into a wire (or a tape if the cross section is rectangular). Then the tube is heated to transform the precursor powder into BSCCO. The resulting wire is protected by the silver sheath, which also serves as an alternative pathway for current in the event that the superconductivity is lost. The wires, too, are bendable, because they actually consist of thousands of even finer wires. Alexis P. Malozemoff, the company's chief technical officer, explains: "Without the multifilamentary structure, these wires would be brittle structures and would present a real problem in their handling, durability and their ability to perform over time."

To pack the filaments in, American Superconductor makes one wire, bundles it with other wires, then bakes the assemblage. Because composites are inherently stronger than a single pure



ELECTRONIC DEVICES made with copper oxides include 20-micron-wide interconnects (*the four etched lines that lie diagonally across the image*), which run between gold-wire bonds connected to silicon chips (*left*); a delay line, used in microwave electronic systems to slow signals down a few nanoseconds (*center*); and a SQUID magnetometer (*right*), an integrated circuit that consists of a stack of superconducting and insulating layers. The SQUID itself is the light purple layer; the multiple turns on the SQUID help to amplify the magnetic field to be detected.



LASER ABLATION lays down thin films of superconductor. The luminous plume appears when an ultraviolet laser pulse (*not visible*) strikes a sample of the superconductor mounted on a target holder (*device at right, where plume emerges*). The pulse vaporizes some of the sample, which collects on a heated substrate (*in housing at left of plume*).

material, the cable resists strain and cracking, even after many cycles of cooling and warming.

Although such multifilamentary BSCCO wires have surmounted the difficulties of weak links and flexibility, the motion of magnetic vortices continues to cause trouble. The BSCCO formulation used in wires, which becomes superconducting at 110 kelvins, has to be cooled to about 25 kelvins to keep the magnetic vortices fixed. In applications requiring exposure to high magnetic fields, BSCCO wires must be chilled with high-performance refrigerators called cryocoolers, which are more expensive than liquid nitrogen.

Because BSCCO pins magnetic vortices so poorly, researchers have been exploring ways to create wires out of thallium-barium-calcium–copper oxide, or TBCCO ("tibco"). TBCCO materials are superior in this respect. In TBCCO, flux can be frozen at temperatures near those at which nitrogen becomes liquid, Poeppel says. Furthermore, the transition temperatures of TBCCO formulations are among the highest of the copper oxides. Two varieties become superconducting above 120 kelvins.

But unlike BSCCO, whose grains are platelike and hence can lie flat, TBCCO consists of grains that are roughly spherical. This geometry does not lend itself to the manufacturing techniques that produce wires of BSCCO. An attempt to enclose a powder of TBCCO in a tube would resemble wrapping aluminum foil around rocks, explains John A. DeLuca of the General Electric Research and Development Center in Schenectady, N.Y. "The little rocks would come right through the silver tubing."

Instead many researchers are borrowing a method from thin-film workers: they deposit TBCCO onto a substrate. Although not yet commercially practical, this approach produces materials that successfully pin magnetic flux and maintain a high current density.

One such approach is emerging from a collaboration between DeLuca's group and workers at Oak Ridge National Laboratory. A solution containing barium, calcium, copper and oxygen is sprayed on an inert substrate known as yttria-stabilized zirconia. The sample is then heated in a thallium-rich vapor to form a film three to four microns thick. This "thick film" approach produces colonies of aligned grains. In zero field at 77 kelvins, the films carried up to 104,000 amperes per square centimeter. The film has supported a current density of more than 10,000 amperes per square centimeter in a magnetic field of two teslas.

Laser ablation is also being studied as a method to deposit TBCCO. Richard E. Russo and his colleagues at Lawrence Berkeley Laboratory have managed to create the highest critical current density in bulk thallium samples to date: 600,000 amperes per square centimeter at 77 kelvins.

Fixing Fickle Fluxes

But to get the most out of the superconductors, researchers may ultimately have to be able to introduce magnetic flux pins deliberately, just as they do for the low-temperature materials. Flux pins are defects in a solid that have a particular size and shape. Magnetic vortices tend to settle on those defects, just as marbles will lodge in depressions on a surface. The best pins are those that match the size of the so-called coherence length of the substance. The coherence length refers to the separation between superconducting electrons. In a high-temperature superconductor the coherence length is extremely short, typically one to three nanometers—roughly 30 times the diameter of a hydrogen atom. In low-temperature superconductors, the coherence length is much longer, about five to 30 nanometers.

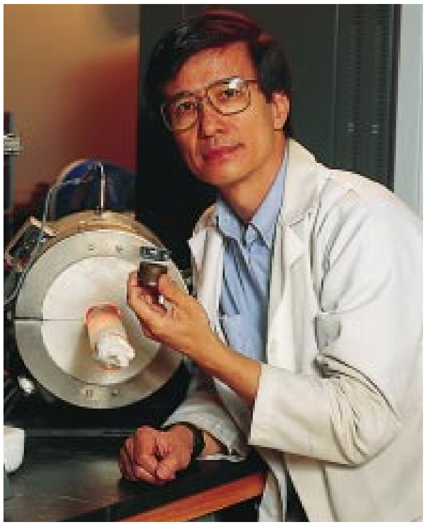
Investigations pursue several different approaches. The most common is particle irradiation: bombarding the sample with energetic ions, neutrons or electrons. Such shotgun techniques create pinning sites by slightly displacing the atoms in the material. Irradiation with heavy ions can also produce columnar defects that act as sleeves to hold the vortices.

The technique has a severe limitation. To use it, one must have a particle accelerator. "We are getting an understanding of what is required, and the national labs are working with industry to come up with practical methods," explains Robert A. Hawsey, director of the superconducting technology program at Oak Ridge National Laboratory. It may be possible to introduce defects or create crystalline faults during processing. Researchers are also examining how to pin flux without introducing defects. The scheme, called intrinsic pinning, would try to sandwich vortices between the copper oxide layers.

Can the progress in applying the bulk materials be expected to continue? "There's a convincing array of data that makes us believe we are not facing sleeping lions," Malozemoff says. Among the earliest devices would be superconducting magnetic energy storage (SMES) systems. To store energy, the SMES coils are charged with circulating direct current. Because there is no resistance in the wire, the current could theoretically circulate forever. A utility could tap the energy when needed—say, during a power outage or during peak demand time. More important, it could dampen power oscillations, which can damage generating equipment. Bechtel in San Francisco is working with conventional superconductors to construct a 20-megawatt prototype the size of a football field. The high-temperature materials would vastly decrease the size of such a unit.

Several collaborative efforts that include organizations such as TCSUH, General Dynamics and American Superconductor plan to demonstrate components called fault-current limiters within the next two years. Such devices shunt power surges to prevent damage to lines and substations. Surge protection is at present accomplished by means of fuses and circuit breakers, notes Dean E. Peterson, the director of the Superconductivity Technology Center of Los Alamos National Laboratory, "and you have to send a repairman." Southern California Edison estimates it could defer upgrades and use cheaper fuses, saving up to $7.5 million a year on its power grid. Estimates for the entire U.S. are about $100 million a year.

Superconducting ceramics could improve the efficiency of power transmission itself, perhaps by the year 2000. A superconducting transmission line could carry three to five times more electricity than can a copper line. Existing underground lines use copper wire immersed in an oil that helps to cool the wire and saturates the insulation to provide the proper conducting environment. "Replacing the oil with liquid nitrogen is a no-brainer," Yurek says. Prototype transmission cable made by American Superconductor has carried 1,100 amperes over its length, about half of what EPRI thinks is necessary for commercial use. As Yurek sees it, "There's no technological barrier to getting this done."



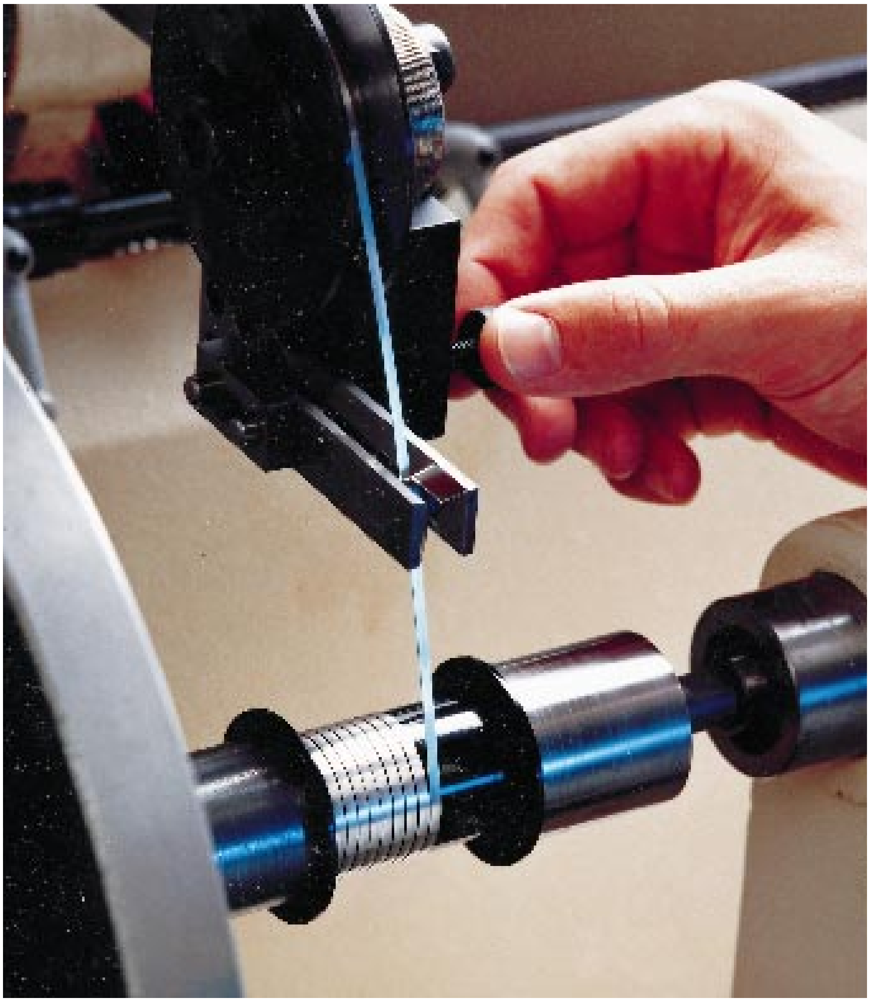
GREAT EXPECTATIONS: Paul C. W. Chu of the University of Houston floats a chunk of YBCO above an ordinary magnet. Chu recently reported that a mercury-based copper oxide under pressure superconducts above 150 kelvins.

Perhaps. But even if there are no "sleeping lions," the technology does face some additional obstacles. One is the challenge of cooling the ceramic materials. To keep the current density in the superconductor high, most applications will rely on mechanical refrigeration rather than liquid nitrogen. Using cryocoolers, which can chill down to 20 kelvins, is more expensive than cooling with liquid nitrogen (but is cheaper than doing so with liquid helium). The units can also be cumbersome. "What is needed is a relatively compact refrigerator that the customer is not aware of," says Conductus's Rowell. Another snag is the maturity of rival methods. Superconducting digital electronics, for example, may never leave the laboratory. "Silicon is a darn nice technology," CSE director Ralston observes.

Beware of Hockey Sticks

Some people in the industry glow with optimism about the economic future of the technology. In a recently released report, the members of the International Superconductivity Industry Summit (ISIS) composed of industrial

ANOTHER DAY, ANOTHER DOLLAR: a technician from American Superconductor removes a BSCCO cable from a dewar of liquid nitrogen for testing. In most envisioned applications, cryocoolers rather than liquid nitrogen will be used.



FLEXIBILITY of high-temperature superconducting wire is now sufficiently high that the wire can be wound into coils to make magnets.

groups from the U.S., Japan and Europe, estimated that the current $1.5-billion market for superconductors (for MRI and scientific research) will grow to between $8 billion and $12 billion by 2000 and to between $150 billion and $200 billion by 2020.

But other managers are not so sure. "The jury is still out on the issue of profitability," observes Carl H. Rosner, the president of Intermagnetics General. The ISIS numbers include sales estimates for ancillary equipment, such as computers that would be needed to process information from superconducting sensors. "You have to beware of hockey stick projections," Bell Labs's Bishop warns.

Even if the ISIS numbers are overly upbeat, at least several niche markets should emerge. The CSE has done its own analysis, and although it will not divulge numbers, William J. Gallagher, the head of IBM's effort in the CSE, intimates that several niche markets that add up to the size of current MRI systems will spring up this decade.

Greater inroads may hinge on discoveries of superconductors that have higher critical temperatures. That would mean a less costly coolant (such as freon or dry ice) could be used, or at least a larger margin of safety could be obtained with respect to keeping the material superconducting, Paul C. W. Chu, TCSUH's director, points out. "There really is no theoretical or experimental basis for a limited critical temperature," Chu says. The new mercury-barium-calcium–copper oxide compounds discovered this past March offer such a hope. One variety superconducts at a record-high 133 kelvins, and Chu reported in September that under pressure the critical temperature reaches 153 kelvins—within the range of freon. The early word on the mercury-based superconductors is that they pin flux better than do the bismuth or thallium families. But like YBCO, the materials suffer severely from weak links.

Even as the technologists wrestle with the physical properties of the materials, their colleagues in the front office are struggling to keep investment dollars flowing. To raise more money, Conductus and STI have both gone public this year, joining American Superconductor. Illinois Superconductor plans to do so before the end of 1993.

Although the 1993 U.S. budget for research in superconductivity is $246 million, it does not always aid businesses. "That's a lot of money, but it's mostly spent within the structure of the national labs or on decidedly defense-oriented research," says Kevin D. Ott, the executive director of the Council on Superconductivity for American Competitiveness, the industry's trade group.

Despite technological challenges and sticky finances, history may be on the side of high-temperature superconductors. "It's incredibly early," observes EPRI's Schneider. "The transistor was invented in 1948 and used commonly in radios about 12 to 15 years later." The laser experienced a comparable lag between invention and widespread application. "As I see it, the train is leaving the station," Yurek says. His optimism seems to be shared by American Superconductor's stockholders: the stock price of the company has more than doubled since its initial public offering in December 1991—despite posting numbers in the red (Yurek expects the company to break even by December 1995). "The message we are trying to get across is that superconductors are a reality," STI's Long says. "We need to press the engineering community, in effect, saying, 'Hey, here's another tool. Consider it, look at it and don't reject it out of hand as a laboratory curiosity.' "

Alan Schriesheim, the director of Argonne Lab, perhaps best sums up the feeling in the applied community. Like a field general, or a coach during halftime, he exhorts his troops: "The prize in the long run goes to those who stay the course in what is a long campaign. We cannot guarantee success, but we guarantee failure by getting out."

FURTHER READING

THE PATH OF NO RESISTANCE: THE STORY OF THE REVOLUTION IN SUPERCONDUCTIVITY. Bruce Schechter. Touchstone, 1989.

HIGH-TEMPERATURE SUPERCONDUCTIVITY. Special issue of *Physics Today,* Vol. 44, No. 6; June 1991.

ENERGY APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTORS: A PROGRESS REPORT. Electric Power Research Institute, 1992.

SUPERCONDUCTIVITY: 5 YEARS' PROGRESS. Special issue of *Logos: Argonne National Laboratory,* Vol. 10, No. 1; Winter 1992.