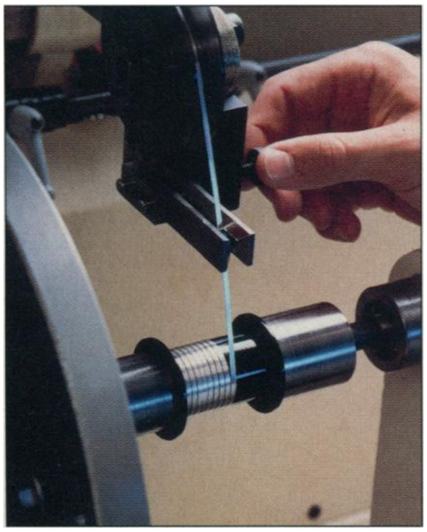
New Superconductors: A Slow Dawn

Step-by-step improvements in the craft of making these balky materials into wires and films have readied them for a commercial debut

What's extraordinary about the pilot plant on the ground floor of a humble, two-story industrial building in Watertown, Massachusetts, is just how ordinary it seems. In many ways the facility looks just like any other plant that makes electrical wires. But there are hints nearby of something unusual. In a darkened room just off the factory floor, microscopists slice and examine the wires, while upstairs, amidst sweating tanks of liquid nitrogen and measuring equipment, engineers test whether the products have what it takes to perform in the real world.

The wires being made here every day, you see, aren't the kind that might connect your telephone to the wall. The company is the American Superconductor Corp. (ACS), and hidden within the pretty silver jackets of the wires and tapes are superconducting threads made from a gritty, brittle ceramic called BSCCO (for its atomic constituents, bismuth, strontium, calcium, copper, and oxygen). BSCCO is a descendant of a family of high-temperature superconducting (HTS) ceramics that in 1986 parachuted from nowhere directly onto science's center stage, then made an offstage exit as the materials failed to live up quickly to the high hopes that had been offered for them.



AMERICAN SUPERCONDUCTOR

Now in production. A high-temperature superconducting magnet winding.

Now, however, ASC has brought them back onto center stage in a nearly commercial form. The company now routinely transforms the rock-like substances into 100-meter-long wires and thinner, ribbon-like tapes, then sells them to companies like Pirelli Cable Corp., which aims to use them in HTS cables for underground power transmission, and Reliance Electric Co., which is developing prototype HTS motors. And ASC isn't alone: A handful of other companies in the United States and abroad have started making and selling the materials—mostly to other companies hoping to turn the wares into pathbreaking technologies. "A lot of people still think of HTS materials as an exploratory research area," says Alex Malozemoff, ASC's vice president of research and development. "We have moved things to this next stage"—development and manufacturing.

Each of the new HTS materials being exploited by these small companies offers a combination of strengths and weaknesses (see box on page 308). In all likelihood none of them will overcome at a single stroke all the daunting processing and engineering problems researchers face in making HTS materials practical. ASC and its competitors, such as Intermagnetics General Corp. (IGC) in Guilderland, New York, Sumitomo Electric Industry in Japan, and Vacuumschmelze GmbH. in Germany, don't expect that. Instead, these high-tech entrepreneurs practice an approach that Kevin Ott, director of the Council on Superconductivity for American Competitiveness (CSAC) calls "raging incrementalism."

And as that kind of incrementalism improves the materials, prospects for technologies based on HTS materials have brightened —at least according to the optimists. Says Thomas Schneider of the Office of Exploratory and Applied Research at the industry-funded Electric Power Research Institute (EPRI) in Palo Alto, California: "If today's rate of progress continues, the common assumption that we will have to wait until the next century for applications of high-temperature superconductors will not prove to be correct." Among the HTS-based prototypes that Schneider says researchers already have demonstrated are underground power transmission lines for cities and more compact and efficient motors. Microelectronic circuits based on thin films of HTS, which have always been more tractable than wires, may be even nearer at hand (see box on opposite page).

Not everybody sees things in hues as rosy as Schneider does. But even less optimistic types like Simon Foner, associate director of the Francis Bitter National Magnet Laboratory at the Massachusetts Institute of Technology (MIT), don't dispute the assertion that HTS materials are approaching feasibility. Whether they also turn out to be profitable, says Foner, depends on whether markets emerge that can support the materials' high manufacturing costs—and the costs of employing them at temperatures that, proponents are realizing, may never be quite as high as the name high-temperature superconductor implies.

Promise deferred

In defending their side of the argument, the pessimists point to the fact that, when it comes to superconductivity, hopes have been deferred before. In the 1960s, when the first (low-temperature) superconductors were formulated, proponents dreamily envisioned superconducting wires and cables, which could save the many millions of dollars wasted as the resistance of standard conductors turns electricity into heat, and compact magnets powerful enough to levitate trains.

Such promise, however, has been realized only on small scales or in experimental settings, because the first generation of practical superconductors live up to their name only at temperatures colder than the surface of Pluto. In practice, that means they need to be cooled with liquid helium, which at 4 degrees above absolute zero is expensive to maintain. The only major commercial application that has been able to support those costs so far is magnetic resonance imaging (MRI) for medical diagnosis. Many of the 4000 or so MRI machines in use generate the powerful magnetic fields needed for imaging by relying on magnetic coils of niobium titanium alloy, a low-temperature superconductor.

No wonder the science and technology community was excited in 1987 when researchers at the University of Alabama and the University of Houston unveiled a ceramic that becomes superconducting at the relatively tropical temperature of 92K. The new material promised all the advantages of conventional superconductors—at a temperature reachable in a bath of dollar-a-gallon liquid nitrogen.

From the beginning, though, cautious observers warned that getting the brittle, rock-like HTS substances to behave as though they were ductile metallic wires—the form best suited for many of the envisioned larger scale applications—is a transformation of matter meriting the talents of a Merlin. The first efforts yielded only a few brittle inches. And unlike conventional, metallic superconductors, these ceramic ones are made up of tiny grains that suffer from a so-called weak link problem: Current can't always travel efficiently between grains. As a result, the first HTS wires carried a mere trickle of current—far too little for underground power lines or train-hefting magnets. And magnetic fields themselves conjure up another depressing problem. If the field is strong enough, it breaks into so-called flux lines that penetrate the material. When current flows through the ceramic, it can push the lines around in a phenomenon called flux creep, giving rise to electrical resistance.

By 1989, the problems appeared so daunting, particularly for bulk preparations like wires, that some researchers suspected these beguiling HTS materials would forever stay off the big-time stage. The highwater mark of the pessimism may have come in May of that year, when *Science* ran a news story titled "Superconductivity: Is the Party Over?"

Against that background of frustration, it's startling to see how quickly the field has moved in the past year—so quickly, in fact, that a handful of small and large companies have succeeded in making long lengths of HTS wires and tapes that carry enough current to put at least some dreamed-of applications within technical, if not yet commercially practical, reach. "Twelve months ago, we had the potential of making long wires out of high-temperature superconductors," says David C. Larbalestier, head of the Applied Superconductivity Center at the University of Wisconsin. "Now, the real capability of making long wire has been put in place."

Wired again

At the World Congress of Superconductivity in Munich last September, Sumitomo—often cited as the outfit to beat—reported spinning out 114-meter wires of bismuth-based HTS that, at 77K, can carry 11,300 Amps of current for every square centimeter of wire thickness. ASC makes more flexible cables of comparable lengths that carry about 12,000 Amps per square centimeter under similar conditions, says Gregory Yurek, the president of the company. Ditto for IGC, says Carl Rosner, its president.

Although none of these wires retains its high current capacity at liquid nitrogen temperatures in the presence of moderate magnetic fields, they do approach a long-standing benchmark, points out Roger Poeppel of Argonne National Laboratory. As a performance standard for new conductors in the power industry, he says, "we always have picked 10,000 Amps per square centimeter in a magnetic field of 2 tesla." That's well beyond the current carrying capacity of copper, even when copper cables are refrigerated to carry away heat generated by resistance.

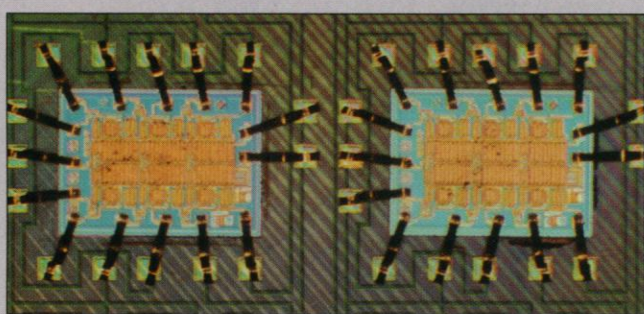
Behind that milestone lies a step-by step victory over the weak link problem. Soon after the development of high-temperature superconductors, researchers realized that they couldn't simply draw the ceramic materials into wires, as is done with conventional metallic conductors. If the material didn't simply crumble, it would end up riddled with weak links. Instead, they began looking for ways to synthesize the materials in the shapes of the finished objects—wires and coils. The most promising strategy now—the so-called powder-in-tube approach—was first shown to work for an HTS material in 1989 by researchers at Vacuumschmelze when they applied it to a bismuth-based superconductor.

In a typical powder-in-tube process, materials engineers fill a hole bored in a cylindrical silver billet with a powdered precursor of a ceramic HTS. Next, the workers pull the silver/HTS composite through a die that reduces its diameter, and then flatten it through rollers if they are making a tape. The silver, a malleable metal, deforms easily, and the powdered HTS deforms with it. The mechanical pressing and rolling overcomes the weak link problem in some HTS materials by aligning the crystalline grains in the powder. As a result, when the billet is in final form and is heated in a furnace, the grains sinter, or fuse, into a continuous superconductive path.

Although that technique isn't new, ex-

HTS Film-Makers Look for a Happy Ending

In the recent burst of improvements in high-temperature superconducting (HTS) materials, much attention has focused on wires (see main story). After all, wires and tapes are vehicles for large-scale uses such as power transmission and electromagnets. But, by one criterion, thin HTS films—candidates for speedier electronics, higher capacity communications, and ultrasensitive detectors—are further ahead. They were the first to make it to market in a commercial product: Mr. SQUID, a detector of weak magnetic fields introduced last year by Conductus Inc. of Sunnyvale, California. And other products are waiting in the wings.



Chip-to-chip chat. Conventional silicon chips are linked with networks of HTS film in a prototype superfast module.

Thin films started with some advantages over their bulk-material cousins. For one thing, microelectronic components made from thin films are not apt to be bathed in the magnetic fields that readily kill superconductivity in many HTS materials. In addition, the weak link problem that limits the amount of current bulk materials can carry is more easily overcome in thin films. The reason is that their crystal grains can be aligned by growing them on templates of other crystalline materials, creating a continuous path for current.

Even so, researchers couldn't always grow thin films of consistent quality at the large sizes needed for mass-producing electronic devices. But Conductus president John Rowell says that during the past year or two, by honing their processes, finding optimum temperatures and pressures, and reducing contaminants, workers at Conductus, DuPont, and other companies have been able to pattern substrates with HTS films up to 10 centimeters wide, a key to mass production.

The result is that thin films of HTS "are ready now," at least for military use, says Alan Lauder, program manager for superconductivity at DuPont, which has invested tens of millions of dollars in HTS R&D since 1987. This year the company plans to start making several thousand HTS thin film devices annually, for uses such as delay lines in radar units and high-frequency microwave resonators. And last month, Illinois Superconductor in Evanston received an Advanced Technology Program award of almost $2 million from the Department of Commerce to develop HTS-film microwave circuitry, which the company hopes to market for cellular telephone base stations. If that kind of progress keeps up, HTS films may win a technology Oscar.

–I.A.

periments with it in the past year have led to better and better products. In essence, Dean Peterson, head of the Superconductivity Technology Center at Los Alamos National Laboratory, notes in the November/December 1992 *Materials & Processing Report*, superconductivity workers, like novice potters, are getting to know their medium. As the keys to last year's progress, Peterson points to improvements in the quality of superconducting powders as well as empirical lessons about wire deformation and sintering conditions.

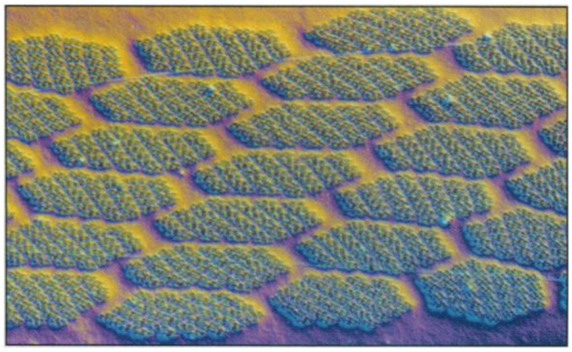
Now developers are looking for shortcuts to usable wires. Last fall, for example, Malozemoff of ASC announced a variation on the powder-in-tube theme that may yield equally good results without requiring so much finesse. The difference is that the billet is filled not with a ceramic powder but with metallic precursors. As a result, the wire blanks can be deformed more dramatically and therefore may be better for high-volume manufacturing and for making flexible multifilament wires, Malozemoff says. Once the precursor has been spun into wire, of course, it still has to be oxidized into the ceramic product. That can be done by heating the wire in a chamber containing oxygen, which diffuses in through the silver and reacts with the metal powder to form the HTS material.

Even proponents admit, however, that 100-meter lengths of wire, no matter how good, won't make it on—or under—Broadway. To give their wares a real future in cables and magnets, superconductor makers need to refine their craft further, until they can regularly spin out mile-long wires with unbroken superconductive pathways. And even then users will still have to confront another obstacle: the materials' sensitivity to magnetic fields. At the moment, none of the bismuth-based wires work well at the liquid nitrogen chill of 77K when they are exposed to anything like the fields generated in powerful electromagnets and motors. Only below about 30K, the temperature at which the magnetic flux lines "freeze" in place, can these wires carry high currents and still retain their superconductivity in a strong magnetic field.

That might seem to close the door on many of the most prized applications of HTS wires: compact, efficient industrial motors, for example, and powerful magnets for energy storage. But raging incrementalism offers a potential solution to the flux creep problem, too: In effect, give in to the need for lower temperatures. "There is nothing sacred about liquid nitrogen temperatures," Larbalestier says. Alan Wolsky, associate director of the energy systems division at Argonne National Laboratory, calculates that maintaining temperatures of 30K using, say, advanced cryocoolers (a 40-year-old refrigeration technology now being refined for HTS applications) might cost only five times or so as much as liquid nitrogen-based cooling. That's still a fraction of the cost of the liquid helium needed for low-temperature superconductors, he notes.

At the end of the rainbow

Since the new materials and cooling technologies rank as incremental improvements, however, they may herald incremental growth in markets rather than the HTS boom proponents hoped for. Foner of MIT warns that when managers of utilities and industries balance the intrinsic virtues of HTS-based technology against the large capital costs of changing to superconducting electrical systems, the advantage may not be compelling. Rosner, though optimistic that HTS materials will find major technology roles, doesn't see them carving out vast new commercial niches anytime soon. Instead, he thinks they will begin by "augmenting and expanding" the commercial market for low-temperature materials, which now centers on MRI and commands several hundred million dollars.



AMERICAN SUPERCONDUCTOR

Threads bared. Magnified 300 times, a slice of superconducting wire is laced with filaments of BSCCO.

How big that expanded niche might grow to be is anybody's guess. Last May at the International Superconductivity Industry Summit in Washington, D.C., Tsuneo Nakahara, vice chairman and deputy CEO of Sumitomo, projected that even assuming that the "high-temperature" materials will have to be chilled to 20 K, the market for HTS magnets, generators, Josephson junction devices (super-efficient digital components for computer chips), and other products could grow to $3.9 billion a year by 2000. By 2010, he projected, superconductors that work at liquid nitrogen temperatures ought to become available—and the market would then double. But Renée Ford, editor of *Materials & Processing Report*, demurs. Given the hundreds of millions of dollars already invested in research and development, she says, "HTS wire probably will not make money in our lifetime."

Even if HTS wires turn out to be less profitable than Yurek, Schneider, and others hope, perhaps bulk HTS materials will find some quite unexpected niches. Last year, for example, Illinois Superconductor Corp. began selling HTS dipsticks for electrically determining the level of cryogenic fluids like liquid nitrogen—something that could prove useful to those who, say, ship bull semen or store sensitive medical supplies. That may not be the bull market some visionaries once imagined. But just as MRI emerged out of the blue in the 1980s to make the 20-year-old low-temperature metallic superconductors profitable, there is hope eternal that a similar godsend might bring HTS ceramics back into the technology spotlight for good.

–Ivan Amato

Ceramic Superconductors, Warts and All

For the first few years after high-temperature ceramic superconductors burst on the scene in 1986, activity focused on the search for new materials that might have dramatically better properties—work at higher temperatures, resist magnetic fields better, or stand up better to being shaped into devices. No miracle material has turned up, but here are the three groups that have emerged as the most promising.

- Yttrium-Barium-Copper-Oxide (YBCO). In early 1987, a research wildfire broke out with the discovery of this compound ($YBa_2Cu_3O_7$), which remains superconductive at 92K, well above the liquid nitrogen temperature of 77K. Though YBCO suffers from the weak link problem, thin samples can carry the most current of any HTS material, and it remains a candidate for both bulk and thin-film applications.
- Bismuth-Strontium-Calcium-Copper-Oxide (BSCCO). In 1989, researchers in Germany found that this compound is less prone to the weak link problem than YBCO. Although it may end up requiring sub-liquid nitrogen temperatures for reliable operation, it has become a favorite material of wire makers.
- Thallium-based copper oxides. In 1988, the arrival of these compounds, one of which becomes superconducting at the record temperature of 127K, revived hopes that superconductivity at room temperature (300K) was still a real prospect. Although these materials stand up well to magnetic fields, the weak link problem so far has made them underdogs for bulk applications. For thin films that would work reliably at liquid nitrogen temperatures, however, they're a leading contender.

–I.A.