Superconductor Race Shifts to a New Arena

Materials research and a fair bit of ingenuity have made possible a new—albeit limited—range of applications

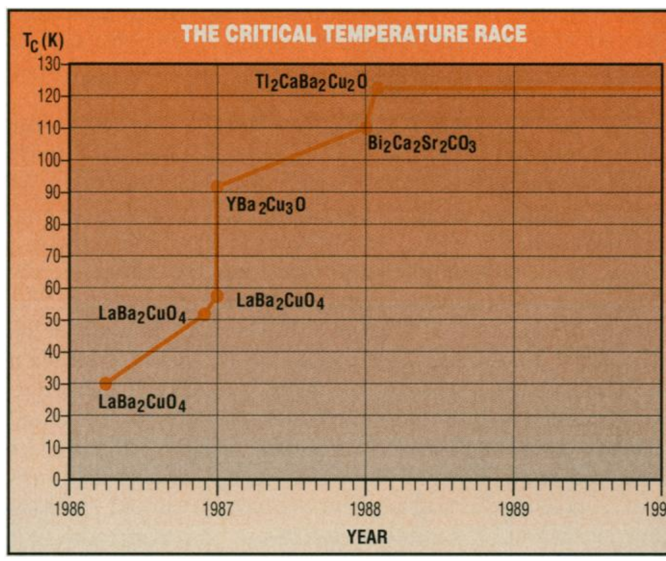
WHEN IBM RESEARCHERS GEORG BEDNORZ and Alex Müller announced in 1986 that they had discovered a material that lost its resistance to electricity at 30 K, visionaries soon began prophesying a new world of high-tech marvels based on high-temperature superconductors (HTSs). But reality quickly intruded. After 2 years of spectacular advances, critical temperatures (T_c)—the point at which a superconductor's critical current density drops to zero—hit a brick wall (see chart). With one exception—an unconfirmed report from Hitachi researchers who last month described a vanadium oxide compound with a critical temperature of 130 K—T_c has been flat at about 125 K for nearly 3 years. The race to find compounds with ever-higher critical could be all but over. "In 6 or 8 months, we went from 23 K to 100 K," says Alex Ignatiev, director of the Texas Center for Superconductivity at the University of Houston. "It was hoped and expected that we'd go another 100 K in another 6 to 8 months. It just hasn't happened...There are no simple or obvious modes for going another 50 K."

But as that race has stalled, another has been revving up: the competition to engineer useful materials out of the brittle and balky ceramic compounds that make up the family of high-temperature superconductors discovered so far. The original materials were limited in the electric current they could carry before losing their superconductivity, and they were far too fragile to form into wire or withstand the stresses of high magnetic fields—but these problems are gradually yielding to intense research efforts. Although only a few enthusiasts talk of levitating trains or launching spacecraft with HTS magnets these days, high-temperature superconductors may soon find a niche in applications ranging from temperature sensing to communications.

Most of the research is focusing on $YBa_2Cu_3O_x$, also known as Y123 or YBCO, which has emerged as the workhorse of applied superconductivity research. Although not a record-holder—its T_c is 90 K—Y123 is probably the best understood HTS compound.

The earliest high-temperature superconductors could carry currents little stronger than 100 amperes per square centimeter—and even that paltry current vanished if the material was subjected to a magnetic field of just 0.1 tesla. Enter "melt-textured" processing. Researchers at several laboratories—notably Argonne National Laboratory and the University of Houston—have partially melted HTS compounds and then cooled them to form a solid without current-obstructing grain boundaries. The result: they have pushed current density to 10^5 amperes per square centimeter, according to University of Houston researcher Kamel Salama. And that's good enough for magnet applications. What's more, the same materials are capable of sustaining superconductivity (although at lower currents) in the presence of a field as strong as 30 tesla—an important prerequisite for the development of most energy or transportation applications.

Melt-textured processing, however, turns out to have its problems. The first is that it produces only a very small sample of Y123—typically a rectangular chunk with an area of 2 square centimeters. Though Salama says such chunks can be "glued" together to perform as a single magnet, producing each chunk is excruciatingly slow. The process currently in use in Houston can take 40 to 50 hours to produce a single sample.



Hitting the wall. *Critical temperature rose 100 K in less than 2 years but has been stuck around 125 K since early 1988.*

A strikingly different approach to processing has been taken by researchers at Argonne, where a team led by J. P. Singh has been trying to improve the mechanical properties of Y123. Singh says that, in general, firing the Y123 ceramic at a lower temperature reduces the grain size of the ceramic, which in turn improves its strength and flexibility—without sacrificing current density. That's a surprise because smaller grains ordinarily present more grain boundaries to a current, which must hurdle these potential "weak links." Though he has yet to verify it, Singh has come up with a tentative explanation: since larger grains are under greater stress than smaller grains, they contain more "microcracks" that are also potential weak links.

But Singh is not counting solely on low-temperature firing to improve Y123's mechanical properties. He and Salama are both working on what they call "microcomposites," in which they add silver to Y123 during processing. Already, they have boosted the material's malleability by a factor of 2 and its strength by about 30%. Singh reports no loss of current density, but Salama says his microcomposite material carries a critical current of only 25,000 amperes per square centimeter.

Salama has also tried a "macrocomposite" approach in which he embeds long fibers—probably carbon, although he won't confirm that—in Y123. That improves the malleability by a factor of 3 and puts it in the range of very hard steels—and just as strong. But there's a downside: the macrocomposite conducts no more than a few thousand amperes per square centimeter, Salama says.

Nevertheless, Singh, for one, is optimistic. "In my opinion, these compounds are good enough for commercial applications," he says. If he's right—and he is hardly disinterested—the likeliest candidates for immediate commercialization are sensitive temperature sensors known as bolometers and magnetically levitated bearings, which may one day be useful in harsh environments where mechanical bearings have a tendency to seize up.

Some types of superconducting electronics may also be early candidates for commercalization, thanks to recent work in generating thin films of HTS material on an insulating substrate. The major mechanical obstacle—obtaining a smooth and uniform film—has largely been solved by the use of laser ablation, says Roger Koch, a physicist at IBM. This technique involves vaporizing or "ablating" a single-crystal sample of Y123 with a laser and condensing the material on a substrate. This allows smooth, orderly crystal growth.

Researchers are already excited about forming circuits and devices out of HTS thin films. The most advanced work is being done in SQUIDs (*Science*, 24 August, p. 862), but several other applications look promising. Foremost among these are high-resolution antennae, which can be tuned far more precisely than non-superconducting receivers.

Laser ablation also lets researchers entertain the idea of forming transistor-like devices out of HTS material. Sandia National Laboratory researcher Chris Tigges has developed a "flux flow transistor," a device based on a thallium HTS compound that uses magnetic flux to modulate a current. Tigges says his transistor switches at speeds of up to 36 gigahertz—as fast as the quickest gallium arsenide devices. "When a new thin-film technology can have the same response as a conventional process that's been worked on for half a century—that's exciting," he says. But Tigges adds a note of caution: "I haven't the foggiest idea when you might make [an ultrahigh speed] computer," he says.

MIT physicist Marc Kastner has been exploring another transistor-like device, the superconducting field-effect transistor (FET), which would mimic the action of existing silicon or gallium arsenide transistors. Ordinary FETs modulate current flow through a narrow channel with an electric field. Kastner's idea is to do the same thing with a strip of Y123 that he has driven into an insulating state by heating the oxygen out of the crystal. He believes it should be possible to drive enough electrons into the denuded Y123 with an electric field to observe superconductivity. For now, he's able only to manipulate the density of electrons within the film in the absence of superconductivity—but he remains optimistic. "It took 20 years to make the FET work, although it was the first design they came up with," he says. "It's a matter of finding the right chemistry."

The current state of HTS research is not cause for optimism if you're anticipating developments that a recent report by the National Commission on Superconductivity recommends as national goals—development of a high-speed supercomputer and a prototype HTS wire and magnet project. Neither is likely to come about soon. But if you're willing to live with incremental advances, the state of the art is progressing nicely, indeed. ■ DAVID P. HAMILTON

HTS Theory: Where's the Beef?

Four years after the dramatic announcement of the first high-temperature superconductors (HTSs), researchers are still trying to explain how these strange materials behave. Indeed, theorists are in a profound state of disarray, unable to agree on anything beyond basic assumptions that might explain superconductivity at temperatures above 35 K (about –396°F). And until a good explanation is available, it is impossible to predict whether changes in the composition of these new materials might push critical temperatures still higher.

Such a lack of consensus is hardly unusual, however. The workhorse theory of low-temperature superconductivity—the Bardeen-Cooper-Shrieffer (BCS) theory—wasn't developed until about 50 years after the phenomenon was discovered. And even then, the theory explained the phenomenon of superconductivity well, but it didn't offer much predictive power.

Despite its shortcomings, the BCS framework makes a convenient foundation on which HTS theorists have been trying to build their own work.The most useful contribution of BCS is its description of superconductivity as a process in which conducting electrons somehow become "pair-bonded" into packets that slide through the superconductor's atomic lattice at low temperatures without the resistance encountered by single electrons.

Most physicists now agree that such Cooper pairs lie at the heart of high-temperature superconductivity—and that agreement is a major advance. "You couldn't have gotten people to agree on that 2 years ago," says Oregon State physicist Arthur Sleight. The convincing evidence was provided by magnetic flux measurements that demonstrated that quantized units of flux—known as "fluxons"—are inversely proportional to twice the electronic charge in HTS compounds. Physicists consider this measurement a clear indication that electron pairs still have a place in the model.

Today's arguments are mostly over exactly how pair bonding takes place at high temperatures, when thermal lattice vibrations should be energetic enough to disrupt the delicate mechanisms that make superconductivity possible in BCS theory. Most theories postulate some kind of a "mediator" for pair bonding. In BCS theory, that role is played by quantized lattice vibrations known as phonons, but a set of experiments suggests that phonon mediation cannot explain pair bonding in the new high-temperature materials. These experiments, performed at a number of laboratories over the last few years, measured a property known as the "isotope effect." Put simply, if electron-phonon interaction is at work, a superconductor's critical temperature should change in a certain predictable manner when heavy isotopes of a lattice atom—say, oxygen in Y123—are substituted for light isotopes. Despite some initially contradictory results (*Science*, 14 October 1988, p. 242), there is now substantial consensus that these experiments detect only very small isotope effects—not enough to explain HTS.

So now most physicists have devoted themselves to finding other mediators—but some initially promising candidates have run into trouble, too. For instance, a theory first described by Robert Laughlin of Stanford depends on the action of anyons—two-dimensional pseudoparticles traveling in the very thin copper-oxide layers present in most HTS compounds. Anyons break a property known as "time-reversal symmetry" and can be detected by measuring the polarization of light reflected from a sample. Groups at Bell Labs and the University of Dortmund in Germany say they have seen broken symmetry. But other recent measurements by a Stanford team with extremely sensitive equipment failed to detect any sign of this phenomenon. "It's very hard to see how the Stanford experiment could have gone wrong," says Bert Halperin, a Harvard physicist and erstwhile anyon fan.

There may be even bigger headaches for theorists yet to come. Sleight, for instance, believes that HTS materials exhibit a peculiar disorder that defies one of solid-state physics' most cherished assumptions—periodic symmetry of the crystal lattice over "long" distances much greater than the width of a unit cell. Such symmetry greatly simplifies calculations of solid-state behavior, so if the assumption falls, the consequences for figuring out what is going on in HTS materials could be dramatic. "No one's put this into their model," says Sleight. Could it be time for a change? ■ D.P.H.