Superconductivity: Is the Party Over?

Recent findings about high-temperature superconductors have revealed a possibly insurmountable obstacle to many of the hoped-for applications

THE ONCE HIGH HOPES for high-temperature superconductivity are nearly gone. Over the past 6 months, researchers have discovered a problem with high-temperature superconductors that will make commercial development of even the most promising applications much harder, if not impossible. "Impossible is a dangerous word to use," Robert Dynes of AT&T Bell Labs told *Science*, "but this certainly is giving us pause."

The obstacle arises from a rather technical feature of superconductors called a magnetic flux lattice. The unexpected weakness of this lattice means that high-temperature superconductors may not be able to carry enough current or hold a high enough magnetic field to perform many of the tasks once envisioned for them—no super-efficient power transmission, for example, and no low-cost levitated trains. Further, the problems with the lattice seem to have put the Holy Grail of useful room-temperature superconductivity forever out of reach, barring the discovery of an entirely new type of superconductor.

Two years ago, when the excitement first surged about high-temperature superconductors, the only property of interest seemed to be the materials' critical temperatures—the temperatures at which they lose all resistance to an electric current. When Maw-Kuen Wu of the University of Alabama in Huntsville and Paul Chu at the University of Houston announced the discovery of a material with a critical temperature of 93 K, attention focused on the fact that the material could be cooled with liquid nitrogen (boiling point of 77 K) instead of the more expensive and more difficult to work with liquid helium. Suddenly, dreams of commercial superconductivity seemed within reach.

It was not until some months later that the euphoria finally died down enough for people to start asking what other properties besides a high critical temperature would be necessary if these materials were ever to be of any practical use. Perhaps the most important of these criteria is the critical current density—the maximum amount of current the superconductor can carry before it loses its superconductivity. An intractable weakness of high-temperature superconductors has been their low current-carrying capacity when they are fashioned into wires for such applications as magnets and electrical transmission.

David Bishop: *The flux lattice melts at temperatures below the critical temperature.*

For more than a year, researchers have struggled to increase the critical current densities of high-temperature superconductors. The greatest success has come in thin films, where critical current densities have reached several million amperes per square centimeter, enough for most electronics applications. The best bulk materials, by contrast, can carry less than one-hundredth as much current. Now, scientists working at IBM, Bell Labs, and several other laboratories have discovered a serious complication to the search for superconductors with large critical currents.

That complication arises from the behavior of the flux lattice, a structure unique to superconductors. Certain types of superconductors, called Type I, do not allow any magnetic field to penetrate them when they are in a superconducting state—in other words, they "expel" magnetic fields. Unfortunately, the superconductivity in Type I materials is destroyed by very small magnetic fields, which makes them unusable for most applications.

Type II superconductors, on the other hand, do allow a magnetic field to penetrate their interior, which lets them remain superconducting in the presence of very high magnetic fields. Most of the useful low-temperature superconductors, and all of the high-temperature superconductors, are Type II.

When a magnetic field penetrates a Type II superconductor, something strange happens. It does not spread over the entire superconductor but rather is concentrated into individual flux lines, each containing one quantum of the magnetic flux. These lines make up what researchers call a flux lattice.

The existence of the flux lattice has been recognized for some time. In the early 1960s, physicists realized that when a current passes through a superconductor that contains magnetic flux, the current creates a force that pushes against the flux lines. If the flux lines move under the influence of this force, it means that some of the energy of the current has been used inside the conductor. In other words, the movement of the flux lines creates a resistance inside the superconductor, which is undesirable because one of the most valuable properties of a superconductor is that it can pass electrical current without resistance.

In low-temperature superconductors, this resistance is negligible because of the so-called pinning of the flux lattice. Tiny defects in the material create obstacles that the flux lines cannot move over, and because the lattice in these materials is rigid, all of the flux lines are held in place. "It is the equivalent of holding a carpet in place by nailing it in just a few places," says David Bishop of Bell Labs.

When the flux lattice is pinned this way, the flux lines will not be moved by the force from a current. There is, however, a small amount of "flux creep" as the thermal motions in the material cause a few flux lines to hop over the pinning centers, but the resistance created by this is too small to measure.

The picture is quite different for the new high-temperature superconductors. Because of the internal structure of these materials, it takes much less energy for a flux line to get over a barrier. Further, because the superconductors are operated at higher temperatures, there is more thermal energy pushing the flux lines. The result, say Alex Malozemoff and Yosef Yeshurun of IBM, is "giant flux creep." This effect creates a measurable resistance in the material when the superconductor is placed in a magnetic field.

Bishop of Bell Labs speaks of the "melting" of the flux lattice: At a certain temperature, the flux lines become free to move around. Then, even if the material is in a superconducting state, the movement of the flux lines creates resistance in the material, and it is no longer a perfect conductor. "The number you should be excited about is not the critical temperature, but the melting temperature," he says.

For low-temperature superconductors, the lattice melting temperature is well above the critical temperature, so melting of the flux lattice does not affect the superconductivity. For this reason, the melting phenomenon was never noted in the earlier superconductors.

It's a different story, however, for the new high-temperature materials. In the yttrium-barium-copper-oxygen material discovered by Wu and Chu, which has a critical temperature of 93 K, the lattice melts around 75 K, Bishop says. The bismuth- and thallium-based superconductors, which were discovered a year later and which have higher critical temperatures, have lattice melting temperatures around 30 K, he says.

The upshot is that the bismuth and thallium materials are not likely to be useful at liquid nitrogen temperatures (77 K) in applications that demand a magnetic field, unless some way is found to prevent the motion of the flux lines. Many of the projected applications do in fact involve magnetic fields. Thus, the yttrium compounds, with their lower critical temperatures but higher lattice melting temperatures, become the material of choice for many uses. But even the yttrium compounds are looking much more difficult to develop for commercial applications.

Take, for example, the use of superconducting magnets in magnetic resonance imaging, the application that accounts for about half of all current sales of low-temperature superconductors. Thomas Worthington of IBM notes that these magnets need to maintain very stable fields for up to an hour, which puts stringent requirements on the conductivity of the coil that generates the field. Since any resistance in the coil will cause the current to drop off and the magnetic field to deteriorate, Worthington says, the flux lattice motion in the high-temperature superconductors may well prevent these materials from being useful for magnetic resonance imaging.

Ever since the discovery of high-temperature superconductors, people have hoped that materials could be found that work not just at liquid nitrogen temperatures but possibly at room temperature, where no refrigeration would be needed. But preliminary results from the study of flux lattice motion seem to put useful room-temperature superconductivity forever out of reach.

Because of the way all of the currently known high-temperature superconductors are structured, increasing the critical temperature seems to inevitably weaken the flux

Flux lattice motion captured live. *Electron micrographs of yttrium-based (left) and bismuth-based (right) superconductors at 15 K in a field of 20 gauss, with a 1-second exposure. The white dots are magnetic particles that are attracted to the ends of flux lines. The flux lines in the material on the left are fixed, but those in the material on the right move around considerably, indicating that the flux lattice has melted.*

AT&T Bell Labs

Giants Haven't Given Up on Superconductivity

Although hopes are fading for quick development of high-temperature superconductors, commercial giants with major research efforts still remain in the game. The expectation now, however, is that years of research lie between the discovery and successful commercialization of the highly touted materials.

Reports about smaller companies, however, are mixed. A number of them "have now decided to sit on the sidelines for a few years," observes Edward Mead, Du Pont's business manager for superconductivity. Mead adds that this pulling back is not necessarily bad but is rather an indication of a more sober approach. "People should not have jumped as hard as they did."

Nevertheless, tiny firms such as American Superconductor Corporation of Boston have decided to press ahead. Indeed, Charles C. Francisco, president of Hypres, Inc., an Elmsford, New York, electronics company, says "there still is a great deal of promise."

Meanwhile, at Du Pont "there has been some reevaluation of how much money we should be spending on superconductivity," says Mead, who adds that the company remains optimistic the field will eventually pay off. "We have not pulled back from the program." Other companies with big superconductivity research budgets tell the same story. At Bell Communications Research, the size of the superconductivity effort has remained the same, but the research emphasis has shifted in the past year, says John Rowell, assistant vice president of solid state science and technology research. Some researchers have set aside work on characterizing the properties of bulk superconductors to pursue studies on thin film superconductors, where the lattice problems generally don't come into play. Thin film superconductors "are where people see the first applications being made," explains Rowell.

Nor have the challenges posed by superconductors thwarted International Business Machine's interest in the area, says Paul M. Horn, director of physical sciences at the company's Thomas J. Watson Research Center. IBM's research effort, he says, "remains as intense as it was 2 years ago." Experimental and theoretical efforts continue to focus on understanding the underlying mechanism and synthesizing new materials.

At AT&T Bell Labs, the superconductivity budget is about the same now as it was in 1988, says Robert Dynes, director of chemical physics research. Some scientists who "dabbled" in superconductivity have gone back to their original interests, but "the serious ones are still here." ■ R.P. AND M.C.

lattice. Researchers speculate that even if a room-temperature superconductor is discovered, it will be unable to carry any current without resistance.

There is one hope for the high-temperature superconductors. If some way can be found to pin the flux lattice so that it does not move easily, it may still prove possible to run large amounts of current through them with negligible resistance. Several researchers believe they have found hints of a way to do this.

Matthew Fisher, a theorist at IBM, suggests that if there are enough pinning defects in the material, the superconductors may arrange themselves into a "vortex glass state" in which the flux lines (also called vortices) do not move. "The flux doesn't creep in this state, at least not at a rate proportional to the current," he says, which results in a material that is a perfect conductor, just as if it were in a zero magnetic field. Experiments by Worthington and Roger Koch, also at IBM, give some evidence for the existence of such a state, he says.

At Bell Communications Research, Steve Gregory and Charles Rogers have done very sensitive "vibrating reed" experiments, in which a thin film of superconductor is mechanically vibrated in a magnetic field and observed as the oscillations die out. These experiments, they say, strongly imply that the superconducting films were in a vortex glass state. They interpret the state as arising from an entanglement of the flux lattice lines. If the lines are flexible enough, they may twist around each other like a tangled pile of spaghetti. This tangling may then allow the entire flux lattice to be pinned with many fewer defects than would be necessary if the lines were free of each other.

If the vortex glass state is real, then developing useful superconductors may become a job of learning how to introduce the right number and type of defects into the superconducting materials. Right now, no one understands exactly what types of defects cause pinning, so that opens up a whole new line of research. Another line will be to find the right balance of defects, since too many defects damage the superconductivity of a material, but too few may allow the flux lattice to move around too much.

Even if the flux lattice problems can be overcome—by means that researchers cannot yet predict—at the very least they create one more obstacle to application. If it were not clear before, it certainly is now that molding high-temperature superconductors into commercially useful forms will be a long, slow process. "I would never want to go on record as saying it can't be done," Bishop says. "But it certainly will make the job harder." ■ ROBERT POOL