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High-temperature superconductivity research moving steadily ahead

by Mark Wilsey

In fall of 1986 a team of researchers at an IBM laboratory in Zurich announced that they had achieved superconductivity in a ceramic material at the record high temperature of 30 K setting off a flurry of research. The following months witnessed the development of a number of related high-temperature superconductors (HTSCs), which are materials that transmit electricity with no resistance, no energy loss, and do so at a temperature higher than a few degrees above absolute zero, 0 K, or $-273°C$.

By February 1987, Paul Chu at the University of Houston was able to report the development of a superconductor with a T_c, the temperature at which it becomes superconductive, of 95 K. The breakthrough held the potential to revolutionize electronics, transportation, and power systems, because at these higher temperatures, practical use of superconductivity became far more feasible, if for no other reason than because more inexpensive coolants, such as liquid nitrogen, at 77 K, could now be used in superconducting systems, instead of liquid hydrogen at 4 K, which is 50 times more expensive.

From 1986 to 1988 the critical temperature, T_c, of high-temperature superconducting materials rose by 100 degrees, but has not risen past about 125 K since then. Moreover, HTSC materials have proved difficult to work with: Their brittle nature was not amenable to forming wires, for instance, unless one applies a great deal of ingenuity.

Granted that the breakneck speed of earlier developments has slowed; nonetheless, progress has been sure and steady, in a way that David Larbalestier, director of the University of Wisconsin Applied Superconductivity Center, compared to perseverance in baseball: Whereas the discovery of a new high-temperature superconducting may be a home run, he told this author, the game as a whole is won by base hits. In short, there is every reason to be confident that the promise of high-temperature superconductivity may soon be realized.

Japan develops scientific expertise

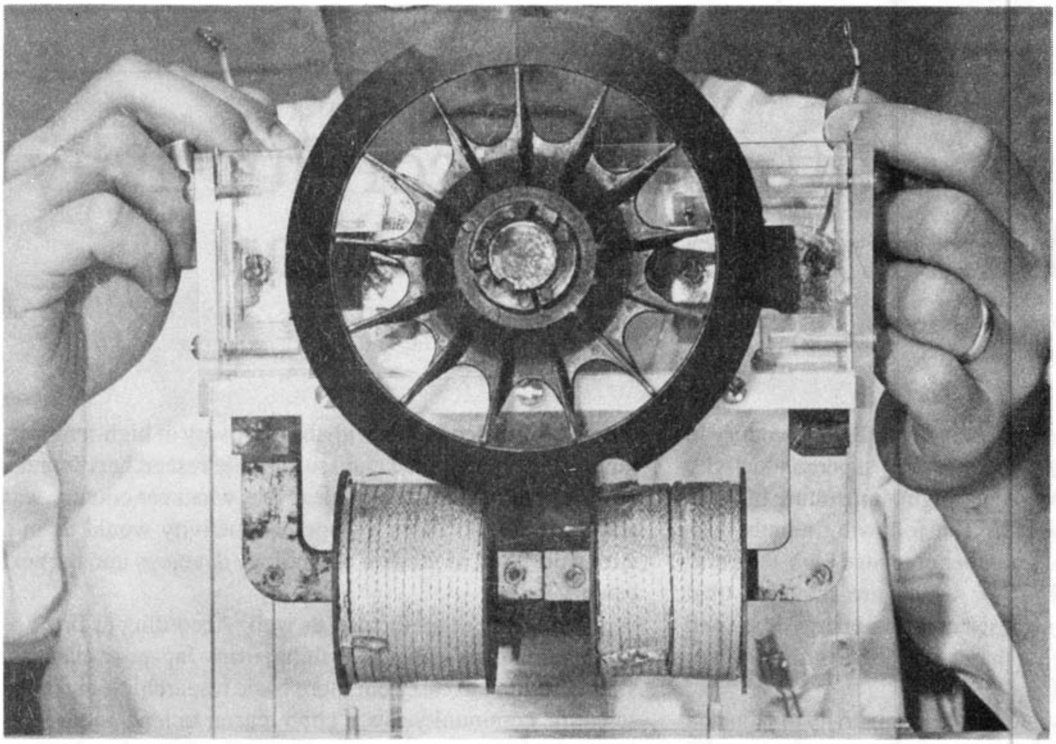
In 1986, when high-temperature superconductivity broke into the news, Japan found itself in a good position to research these materials, because, during the 1970s and 1980s, it had built a strong foundation of expertise in advanced ceramics. Ceramic research had been on the wane, and hundreds found their jobs threatened, but with the discovery of high-temperature superconductors, Japanese ceramic researchers found a new field to turn to. It was clear that whatever country was able to make advances in superconductivity would be in a strong position, as the new technology develops into the next century.

There were other factors, as well. According to Jiro Yoshida, research scientist at Toshiba, many Japanese scientists simply wanted to carry out more basic research. Some in the scientific community saw a good reason to lend encouragement, since it was no longer sufficient for Japan to subsist by applying others' results: Japan needed to create its own ideas if it was to make progess.

Japan saw high-temperature superconductivity as an area in which it could prove itself equal to the West in basic research. In 1987, the Japanese government spending for superconductivity research exceeded that of the United States. However, a 1990 report from the U.S. Office of Technology Assessment noted that, although the U.S. government was spending $130 million, compared to Tokyo's $70 million, the difference was nearly made up for by Japanese industry investments of $107 million, as against $73 million invested by U.S. companies.

In 1988 Japan's Ministry for International Trade and Industry (MITI) launched a 10-year project to study superconductivity, establishing a consortium with private companies, called the International Superconductivity Technology Center (ISTEC), which runs the state-of-the-art Superconducting Research Laboratory (SRL). In 1992 alone, project members will receive almost $24 million. Among the firms teamed with MITI are Fujitsu, Hitachi, Mitsubishi Electrical, Toshiba, NEC, Oki Electric Industry, Sanyo Electric, and Sumitomo Electric Industries. SRL has now grown into the world's largest collaborative effort in high-temperature superconductivity research with dozens of Japanese companies and several foreign companies. In November 1992, DuPont joined ISTEC, becoming the first U.S. company to come on board as a full member.

One leading goal in high-temperature superconductivity research has been the ability to fabricate useful shapes from these fragile materials—particularly long, flexible wires; an-



Superconducting motor developed by American Superconductor and Reliance Electric. The motor powers a fan and generates 25 watts. The superconducting field coils are at the bottom.

other goal is to alter the materials' structure in order to improve their properties in high magnetic fields. Like the efforts in other countries, Japan's progress has been incremental, yet steady. Two years ago Sumitomo Electric could, at best, produce a few meters of wire using a bismuth-based superconductor it had developed. (In fact, it was Japan that pioneered this class of HTSCs based on the element bismuth.) Now Kenichi Sato and his colleagues at Sumitomo are making good-quality wires 100 meters long, and in the next two years they expect to be making lengths of high-temperature superconducting wire up to a kilometer in length. Such lengths are needed to begin to make practical devices. Sato uses a technique which sheaths the superconducting compound in a silver tube and is then rolled flat. The silver protects the superconductor from contact with the environment, since the compounds are not very stable chemically, and the silver also adds flexibility.

Another goal is to be able to send high currents though HTSCs, while keeping them superconductive. The problem arises because an electric current will generate a magnetic field, or flux; the higher the current is, the stronger the magnetic field will be. These magnetic field lines tend to shift around, producing what is called "flux creep," which dissipates energy and ends the resistance-free flow of electricity in a superconductor, at a point which is called the critical field. The magnetic flux becomes more sluggish, at temperatures near absolute zero, the temperature at which low-temperature superconductors operate. However, for high-temperature superconductors, techniques must be developed to deal with flux creep, in order for HTSC materials to be used for motors, generators, or electromagnets on a practical scale.

Researchers are looking into ways of enhancing what is known as flux pinning, in which magnetic field lines are locked into place and are prevented from shifting by pinning sites. These pinning sites are structural defects or impurities in the crystal lattice of the high-temperature superconductor. A new fabrication technique is being developed at SRL, called melt-powder melt-growth (MPMG), which introduces impurities into an yttrium-barium-copper-oxide (YBCO) superconductor to trap magnetic flux. In the melt-powder melt-growth technique the YBCO compound, initially a powder, is melted. Then a YBCO crystal is dipped into the molten mixture and slowly extracted, forming a filament of YBCO crystal. The MPMG technique has increased the material's current carrying capacity sevenfold, to over 100,000 amps per square centimeter at a temperature of 77 K.

The flux pinning phenomenon can also be used to achieve levitation. Magnetic levitation using traditional superconductors depends on the Meisser effect, which is the tendency of a superconductor to expel magnetic fields, creating a repulsive force. In high-temperature superconductors, the magnetic field that is not expelled is pinned near the surface of the superconductor. The flux pinning acts as either a repulsive or attractive force as needed to maintain a relative position between the superconductor and the magnetic source. Using the example of magnetically levitated trains, this effect would not only levitate the train above the track, but would

The superconductivity revolution

Material or compound*		Critical temperature (T_c)
Ti	titanium	0.4 K
Al	aluminum	1.2 K
Hg	mercury	4.0 K
Pb	lead	7.2 K
NdCeCuO	niobium-cerium-copper-oxide	23 K
LaSrCuO	lanthanum-strontium-copper-oxide	40 K
YBaCuO	yttrium-barium-copper-oxide	93 K
BiPbSrCaCuO	bismuth-lead-strontium-calcium-copper-oxide	110 K
TlBaCaCuO	thallium-barium-calcium-copper-oxide	125 K

*Refers to components of the material, not a specific composition

At the turn of the century, it was discovered that some materials, when supercooled to temperatures near absolute zero—that is, 0 Kelvin, (−273°C or −461°F)—begin to conduct electricity without any detectable resistance. And many of these superconducting materials cannot even begin to conduct electricity at ordinary temperatures.

It took scientists 62 years to raise the temperature at which superconductivity takes place from 4 K to 23.3 K. This progress was achieved through exploring pure metals or alloys like niobium-tin. In 1987, there was a breakthrough, when superconductivity was achieved at 77 K using the new metal-oxide ceramic materials.

also lock the two in their positions relative to each other. Depending on the strength of this field, gravity (or the lack of gravity) would become less of a factor. For example, Toshiba is experimenting with high-temperature superconductors for a maglev conveyor system. Such a system, under gravity, would be able to climb walls and run across the ceiling; similarly, the pinning would allow it to function quite well in space.

SRL has put this flux pinning effect to use in developing a superconducting magnetic bearing. The bearing can support a 2.4 kilogram rotor spinning at 30,000 revolutions per second free of friction. Such a device could be used in gyroscopes.

HTSC Josephson junctions

In August 1991, researchers at Toshiba's Kawashi R&D Center developed the world's first Josephson junction exclusively using high-temperature superconductors. Previously, Josephson junctions had been made with conventional low-temperature superconductors, such as niobium and lead. Jiro Yoshida, chief research scientist at Toshiba's Advanced Research Laboratory, notes that the door is open to a whole new field of superconductive electronics.

A Josephson junction is made up of two supercondutors separated by a thin layer of a nonconductor. In this case the Toshiba Josephson junction, only 850 nanometers thick, consists of a sandwich of two layers of YBCO superconductor with a middle layer of praseodymium-barium-copper-oxide 100 nanometers thick. It was made using an advanced thin-flim fabrication process known as multi-target sputtering. Under superconducting conditions electron pairs will "tunnel" through the insulating layer from one superconductor to the other. If the current is kept below a certain critical current for the system, J_c, there is no voltage drop across the junction. With this effect, a Josephson junction can act like an electronic switch, or a basic computer component.

The future development of a Josephson computer is part of Japan's national supercomputer project. A superconducting computer would have a dramatic increase switching speeds over today's information systems. The advantages are that, at zero resistance, there is both little power loss, and also there is no heat generation. Simply put, one could pack as much circuitry on to a chip as our technology will allow without worrying about heat effect. A future superconducting supercomputer could be no bigger than today's laptop computers.

Josephson junctions using high-temperature superconductors could also be used to improve the high-sensitivity magnetic field sensors used in medical diagnostic systems. Called SQUIDs, for "superconducting quantum interference devices," they respond to changes that a magnetic field causes in its electrical properties.

Yet another area under development in Japan is superconducting magnetic shielding. Hiroshi Ohta and his co-workers at the Institute of Physical and Chemical Research have designed a superconducting device, looking like a large bucket, that cuts off extraneous magnetic fields from the interior. The resulting magnetic "vacuum" would be enough to allow researchers to monitor the magnetic murmurings of the human brain. The joint development of this device and high-sensitive magnetic field sensor are examples of the commercial applications beginning to come out of Japan's effort in superconductor research.

Genya Chiba, vice president of the Research Development Corp. of Japan, has predicted that, within several years, high-temperature superconductors will begin to take over many of the functions that previously used low-temperature superconductors, while also gradually being deployed in new applications.

U.S. a principal player

There is no doubt that the U.S. is a principal player in the superconductivity field. There has been good, steady work here, Paul Chu of the University of Houston's Texas Center for Superconductivity told me. One company, American Superconductor, is producing 60 meters of bismuth-based superconducting wire which can carry 9,000 amps per square centimeter at 77 K. Argonne National Laboratory has develop a high-temperature superconductor magnetic bearing. Bellcore, TRW, and others are developing superconducting computer chips.

Overall, the state of U.S. superconductor research, said Wisconsin's David Larbalestier, is healthy.

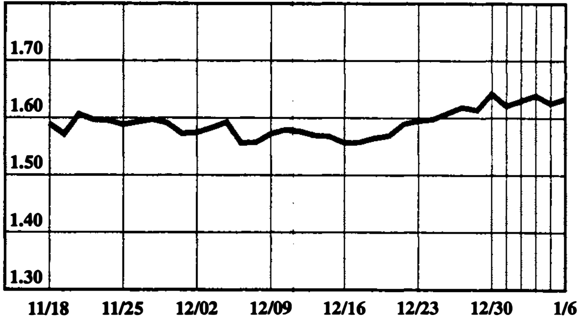
But looking ahead, it is not easy to predict when these devices will be ready for commercial use. Many of the electronic applications soon will be. Larbalestier pointed out that, considering that it took 15 or 20 years before silicon was fully appreciated as a semiconducting material, then in the six years we have been working with HTSCs we have come a long way. We have gained a lot of understanding of these materials, but our research also goes to define our ignorance of them. These are complicated materials, he pointed out, and the models we have are not very good, and they are not predictive.

Paul Chu outlined several areas that would help us to gain a better understanding of HTSCs. Better samples of the materials at higher purities would allow us to differentiate between intrinsic and extrinsic effects. Growing larger crystals would allow for the use of other analytic tools, such as neutron scattering, to examine their structure. Chu would like to see more work with other materials: At present, he said, there are some 75 compounds that are high-temperature superconductors, but they all fall into two or three groups. The elements that make them up are similar, with varying amounts of each. By bringing in other components to broaden the base of materials, one might gain some insight into the mechanisms at work in high-temperature superconductivity.

Currency Rates

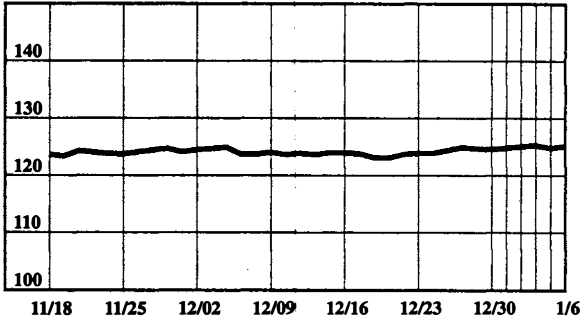
The dollar in deutschemarks

New York late afternoon fixing



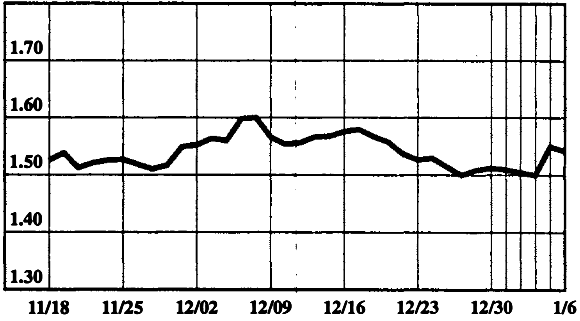
The dollar in yen

New York late afternoon fixing



The British pound in dollars

New York late afternoon fixing



The dollar in Swiss francs

New York late afternoon fixing