groups—Kronheimer and Mrowka and Clifford Taubes (Harvard), Zoltan Szabo (Princeton) and Morgan—proved related results using the Seiberg–Witten techniques, and the Thom conjecture quickly followed.

In addition to such "expected" results, there have been some unexpected ones. An example relating to symplectic manifolds was proven by Taubes. Symplectic manifolds are more general than Kahler manifolds; physicists know them from classical mechanics with finite degrees of freedom: The phase space of position and momentum variables is a manifold with a symplectic structure. A wide open question in Donaldson theory was whether the invariants of symplectic manifolds were very similar to those of Kahler manifolds. "It was an obvious question to ask," Morgan said, "but no one had any insight or any results to speak of outside the Kahler class. Taubes, using the Seiberg–Witten results, established what you wanted to prove quite easily: Symplectic manifolds look a lot like Kahler manifolds."

The old Donaldson theory opened up new vistas for topologists, "but it looked like the road to getting there was so difficult it would take forever," Morgan said. "The new results give us much more hope that we will in fact be able to establish everything we could ever reasonably expect to know."

▸GRAHAM P. COLLINS

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Applications of High-Temperature Superconductors Approach the Marketplace

Eight years after transition temperatures first exceeded that of liquid nitrogen, high-T_c superconductors are being used in magnetometer sensors, prototype filters for cellular-phone base stations and magnetic resonance applications. Further progress in thin-film technology and electronics could lead to applications for high-T_c materials such as nondestructive testing, medical and geophysical sensors, communications, and multichip modules.

When high-temperature superconductivity reached temperatures above that of liquid nitrogen eight years ago, thousands of researchers jumped in, lots of funding followed, and the most enthusiastic people talked of magnetically levitated trains, computers and motors all soon to be operating above 77 K. When reality set in a couple of years later, the field settled into a large, active one, but with only the simplest of products being proposed for the following few years. (See the June 1991 special issue of PHYSICS TODAY on high-temperature superconductivity.)

Now, after many years of hard work, outstanding progress is being reported in thin film technology and electronics applications using the high-temperature superconductors. Some products are already being sold and others appear imminent. Last month newly developed high-T_c filters were displayed at the Cellular Telecommunications Conference in New Orleans, and other exciting new results were discussed at a meeting in Kobe, Japan, in December (before the devastating earthquake struck), and at the 1994 Applied Superconductivity Conference in Boston in October. (Excellent progress has also been made in high-temperature superconducting wire for magnets and power transmission, but will not be covered in this story.)

The first high-T_c products to be sold in quantity are sensors for magnetometers. Work is well along on sensors for nmr spectrometry, and prototypes are being built for use in cellular-phone base stations and in military systems. At the Kobe meeting John Rowell, chief technical officer of Conductus in Sunnyvale, California, quoted a projection of industry experts that the market for high-T_c electronics and medical applications could reach \$75–\$100 billion per year by the year 2020.

One major advantage of high-T_c devices is that when the coolant is liquid nitrogen instead of liquid helium, the refrigerator and packaging is a lot less cumbersome, the coolant boils away ten times more slowly, and it's a lot cheaper. (Liquid helium costs about \$5 per liter, whereas liquid nitrogen costs about \$0.30 per liter.)

Support

In FY 1994 the US government was spending an estimated \$148 million per year for high-temperature superconductivity R&D (including large-scale applications). The largest chunk, \$70.2 million, was from the Defense Department, followed by \$49.8 million from the Department of Energy and \$23.4 million from NSF. The biggest DOD spender is the Advanced Research Projects Agency, which was spending an estimated \$46.0 million.

Since 1987 the ARPA program on high-temperature superconductivity has spent \$220 million on developing several promising applications: rf and microwave passive components and subsystems for radar, electronic warfare, wireless communications and medical instrumentation; a conductor for power applications; and high-T_c interconnects for multichip modules. ARPA is also supporting development of a variety of low-cost reliable cryocoolers that will "enable" those applications.

ARPA also supports the Consortium for Superconducting Electronics, formed in 1989 to do precompetitive R&D on high-temperature superconductors on a cost-shared basis with several industrial firms. The consortium members are Lincoln Labs, MIT, AT&T, IBM, Conductus and CTI-Cryogenics of Mansfield, Massachusetts. The consortium is now pursuing two system applications—cellular base stations for wireless communications and medical instruments using superconducting quantum interference device (SQUID) magnetometers and gradiometers.

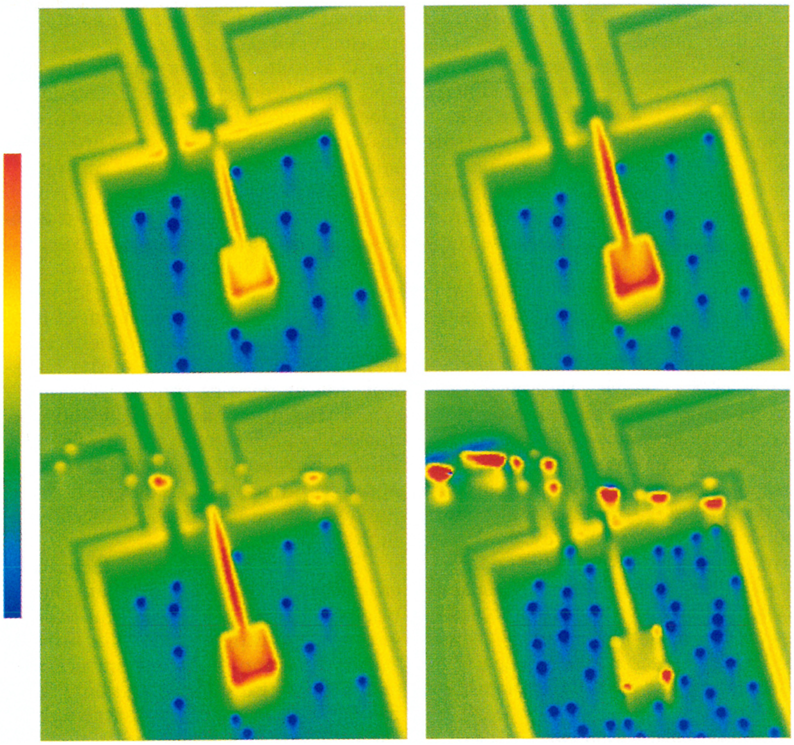
The High-Temperature Superconductivity Space Experiment program, which was started in 1989 by the Naval Research Lab, has played a crucial role in getting high-T_c workers to produce microwave applications. For HTSSE-I, 20 different organizations designed, fabricated and packaged high-T_c devices and components, but unfortunately HTSSE-I didn't reach orbit. Now HTSSE-II, which has arrays of high-T_c filters, receivers and signal processing subsystems, has been shipped to NRL to be prepared for a satellite launch next year.

In Japan, the government is spending $174.5 million per year on all superconductivity R&D, both high and low temperature.

Fabricating thin films

The workhorse material for high-T_c applications is $YBa_2Cu_3O_7$, familiarly known as YBCO. To fabricate thin films of YBCO, one must control the production of grain boundaries, which act as weak links, reducing the supercurrent. A number of groups use the bicrystal technique developed by Praveen Chaudhari, Chang Tsuei and their collaborators at IBM's Thomas J. Watson Research Center, in Yorktown Heights, New York, in 1988. You take a substrate of $SrTiO_3$, cut out a 24° notch, polish the edges, press and fuse the edges together; you then use laser deposition or sputtering at 800 °C in oxygen at low pressure to grow YBCO on the substrate. You wind up with a grain boundary junction at the notch. "Most of the time YBCO wants to be something else," Rowell says. A group at the Forschungszentrum Julich in Germany is very successfully using another approach—the step-edge junction, in which one cuts a step in a $SrTiO_3$ substrate before depositing the YBCO film. A grain boundary junction is formed in the film where it crosses the step.

Du Pont has been a leader in making all kinds of high-T_c thin films, including thallium barium calcium copper oxide (with a T_c ranging from 90 to 120 K) and thallium lead strontium calcium copper oxide (with a T_c of 125 K. When the Department of Commerce started its Advanced Technology Program in 1990, Du Pont won the first superconductivity award.



FLUX TRAPPING in a high-T_c, edge-junction, "washer"- style SQUID. In these scanning SQUID microscope images of the normal component of the magnetic field above the SQUID, the false-color table spans a range of 0.3 gauss from large fields in one direction (red) to large fields in the opposite direction (blue). The large bluish-green square is a solid washer of superconductor 200 microns on a side surrounding a square hole of bare insulating substrate, which leads up to the junctions (too small to be visible) in the top center edge of the washer. Dark blue circles are flux vortices strongly pinned in the superconducting washer. The four images were taken after cycling the SQUID in increasing magnetic field: at 4.2 K to 2 mG, 0.6 G and 2.2 G in the top left, top right and bottom left panels, respectively, and at 77 K to 2.4 G in the bottom right panel. At successively higher fields, more and more flux traps in two horizontal scratches one-third of the way from the top of the image. At high enough fields, flux vortices also trap in the inside corners of the square hole. According to John Kirtley of IBM's Thomas J. Watson Research Center, who supplied the images, "These images tell us how to avoid flux trapping, which causes hysteresis in the output of these SQUIDs—avoid defects in the films, and don't design SQUIDs with sharp inside corners."

SQUIDS

SQUIDs are ideal for making sensitive magnetic field measurements, and their high-T_c versions show promise for geophysics, magnetocardiology and nondestructive testing. John Clarke of the University of California, Berkeley, says that the high-T_c SQUIDs reported by a number of groups at the Boston conference in October have sufficiently low noise levels that they will soon replace their low-T_c counterparts in some applications. He feels the SQUIDs are already sensitive enough for studying the heart and on the verge of being sensitive enough for brain studies. Rowell told us that Conductus is selling commercial SQUIDs comparable to the best ones reported by researchers at the Boston conference—an extraordinary feat, given that commercial products typically lag by an order of magnitude behind the performance of those being built by researchers.

When researchers first began making high-T_c thin films, there was so much low-frequency $1/f$ noise that "we thought this is never going to work," Clarke reminisces, but seven years later, the spectral density has been reduced by eight orders of magnitude. Conductus's iMAG sensor system has a noise specification of less than 300 femtotesla per square root of Hz at 1 Hz, although the noise in many of the Conductus sensors is lower than this.

Since 1986, when George Bednorz and Alex Müller at IBM's Zurich Research Lab discovered materials that were superconductors at 30 K, IBM has had an active research program, but not a large-scale development effort in exploiting high T_c. Last October IBM and Quantum Magnetics of San Diego, California, announced a joint development and licensing agreement allowing Quantum Magnetics to commercialize superconducting technology developed by IBM for magnetic sensing applications. Quantum Magnetics was spun off in 1988 from

Quantum Design, which sells low-T_c SQUID instruments.

For many years IBM Federal Systems, in Manassas, Virginia, and IBM Research in Yorktown Heights have been working with the Naval Coastal Systems Lab, in Panama City, Florida, on magnetic sensing. Now that Loral has purchased the Federal Systems Division, IBM is a partner with Loral on the Navy effort. In the past the detectors sought submarines; now they seek unexploded ordnance or mines, especially those laid by third world countries, said Mark Ketchen, senior manager of superconductivity at IBM Research. Most such "targets" have very strong magnetic signatures. To detect them you need to configure a high-T_c gradiometer that will work while moving in the Earth's field; in addition the system has to have an electronic readout that even works in a thunderstorm. Then that system must be integrated with a synthetic aperture sonar and lidar system to eliminate false positives. IBM and its partners have shown that the SQUID sensor works for low T_c; now they're trying to do the same with high T_c.

High-T_c SQUIDs also can be used for nondestructive testing, for example, to detect and quantify hidden cracks and corrosion in aging commercial and military aircraft, or to test nuclear-reactor pressure vessels. The Air Force Office of Scientific Research supports development of SQUID gradiometers to detect magnetic anomalies produced by eddy currents in the fields just above the surface of aircraft. Harold Weinstock, who manages the program, explains that SQUIDs are good down to 1 Hz, unlike conventional eddy-current techniques, which don't work below 200 Hz.

The Superconducting Sensor Lab in Chiba, Japan, is operating a 16-SQUID system for medical magnetic studies using high-T_c SQUIDs in a magnetically shielded room. In Julich, Alex Braginski and his collaborators have operated two- and four-SQUID gradiometers in an unshielded environment. Both groups have obtained magnetocardiograms with their devices.

Cellular telephone filters

Because every large geographic region has two cellular-phone providers, with interleaving frequency allocations, a filter must ensure that signals from one provider don't leak into the other's band. Existing cellular systems operate in the 800–900-MHz frequency range. At last month's Cellular Telecommunications Conference in New Orleans, four companies showed high-T_c filters to replace the conventional copper filters used in cellular-phone base stations: Illinois Superconductor Corp of Evanston, Illinois; Superconductor Technologies Inc of Santa Barbara, California; Conductus; and Superconductor Core Technologies of Golden, Colorado. According to Weinstock, high-T_c filters are sharper and less lossy than copper, even when the copper runs at 77 K.

Illinois Superconductor uses a technique developed at ICI near Liverpool, UK, in which a thick (about 10 microns) film of high-T_c material is applied to a substrate or preform of arbitrary shape, for example, a helix or rod. Although the quality of the material isn't as good as that of the epitaxial thin films used by STI and Conductus, according to James Hodge of Illinois Superconductor, the Illinois approach allows one to design a resonant structure with an intrinsically high-Q geometry.

Robert Hammond, chief technical officer of STI, says the company is producing YBCO and thallium barium calcium copper oxide thin films (about 1 micron) with low surface resistance for use in base stations. Initially STI used 1-cm^2 substrates, but the company has now used 2- and 3-inch-diameter substrates, with films deposited on both sides. "You need to grow the second side without destroying the first side, and to keep it clean," says Hammond.

To pattern the film into a structure with capacitors and inductors, STI uses process technology similar to that used for silicon and company-developed design software. Instead of the micron-size components in silicon technology, however, the high-T_c components are tens to hundreds of microns. Capacitors can be formed, Hammond says, with interdigital fingers of high-T_c material or parallel plates of high-T_c material between the top and bottom of the substrate. Inductors can be formed with spirals of high-T_c material or other structures.

The complete filter package for a cellular base station, Hammond says, will consist of a cryogenic refrigerator, a vacuum dewar around it for good insulation, and temperature-controlling electronics that are good to less than 1 K. The filters will be operated between 70 and 80 K. STI has been developing its own cryogenic refrigerator, because, Hammond says, existing commercial refrigerators are too unreliable and too expensive. STI has delivered a prototype filter system to a large company that makes base stations, Hammond told us. The complete filter unit is 10 times smaller in volume than conventional filters for cellular base stations. Hammond believes cellular-phone receiver filters are the first major market opportunity for high-temperature superconductivity—greater than $100 million per year in potential sales.

Both Conductus and STI have worked over five years developing the thin film technology both companies use. Conductus has stuck to YBCO exclusively and is now working with 3- and 4-inch diameter wafers coated on both sides. Rowell hopes that eventually cellular base stations will use high-T_c filters for transmitting as well as receiving. "In the end a good fraction of the base station could be superconducting. Until recently superconducting filters couldn't handle the power required by base-station transmitters, between 10 and 100 watts. With less power consumption, you can cut back on the amplifiers you need." That could allow base stations to be further apart, although in a city that issue is irrelevant. In the future, customers could be separated by codes instead of frequencies, and the superconducting consortium is looking at a variety of future systems.

At the Boston conference in October the consortium demonstrated (at the Conductus trade-show booth) two working prototype wireless filters for cellular base stations. One was a five-pole transmitter filter that handled a record power level of over 20 watts at 2 GHz. The second was a receiver filter, with nine poles in the 890-MHz cellular band.

Bertram Batlogg of AT&T Labs, one of the consortium directors, remarks that the cellular-phone market is expanding 30% each year. AT&T is already making 4-inch lanthanum aluminum oxide substrates, so that filters with even more functionality (that is, better bandpass characteristics) can be fabricated on a single substrate. "Cooling, packaging, substrates and reliability are all issues," says Batlogg. So are the cost of the filters, cryosystems and space. "No one has committed to a superconducting communications link. Recent progress in filter functionality and systems integration, however, has stimulated serious interest in the engineering community, and prototype evaluations are in progress." Batlogg notes that the consortium members are cooperating closely, with samples passing back and forth from Lincoln Labs, Conductus, IBM and Bell Labs, for example. But, Batlogg says, "It's much more challenging to introduce a new technology than physicists would have thought five years ago. Just making a good thin film and a single good device doesn't bring a single customer knocking on your door."

CTI-Cryogenics has recently delivered to Conductus a repackaged Gifford–McMahon refrigerator developed to operate with the Conductus high-T_c filter on a standard relay rack. Rowell does not believe that the reliability of cryorefrigerators will be an immediate problem for cellular technology. He notes that in silicon production lines most vacuum systems are already maintained by a cryopump, which typically needs servicing only once a year. But as cellular equipment becomes smaller, the cost, size and reliability of the coolers will certainly be issues.

STI has been developing an array of microwave filters that each can be switched in and out of a circuit (using optical fibers) to reject unwanted signals. STI has produced for the Air Force a 32-filter bank made from 2-inch wafers, and STI is now building a 100-filter array. "This technology," says Hammond, "makes possible the first application of high-temperature superconductivity that can't be done by other means." Martin Nisenoff of the Naval Research Lab explains that switchable filters with such a narrow frequency range can't be made with conventional techniques if you want them to fit in an aircraft.

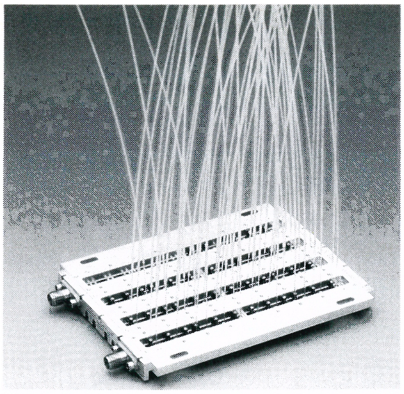
Westinghouse researchers, funded by ARPA and NRL, have fabricated a four-channel bank of microwave filters and a 22-nanosec delay-line module. These devices will be tested in experimental systems this year. Westinghouse has made a stabilized local oscillator from high-T_c material, funded by ARPA; it will have important applications to military and commercial radar systems and frequency synthesizers. One interesting possibility for the advanced radar is early detection of wind shear.

In the recently initiated multiagency Technology Reinvestment Program, Du Pont received an award, in partnership with COM-DEV of Cambridge, near Toronto, Canada, to develop high-power high-temperature superconducting components for satellites. Alan Lauder and Robert Dorothy of Du Pont say their group has built a variety of oscillators, one with thallium barium cuprate, operating at 80 or 90 K, and a unique high-Q oscillator using thallium lead barium cuprate that operates at 107.5 K and 27.5 GHz. "But with high T_c there's no existing market," Lauder says.

Nuclear magnetic resonance coils

Magnetic resonance systems can be improved by replacing the copper rf detection coil with a high-T_c coil when the sample size is small or the magnetic field is low.

Conductus has signed an agreement with Varian to develop a high-T_c receiver coil to replace the copper coil in existing Varian nmr spectrometers. The coil is a thin film of YBCO patterned as a spiral on a substrate. This high-T_c coil offers a great increase in signal-to-noise ratio for chemists and biochemists.



SWITCHED RF FILTER bank produced by Superconductor Technologies Inc for the Air Force has 32 filters in series, uses optical switching of the high-T_c elements to reject unwanted signals, and has three optical fibers per filter.

Both Conductus and STI have developed low-noise receivers to replace the copper antenna in low-field magnetic resonance imaging devices. In most standard mri devices, which have relatively high fields, the noise from the body limits the resolution. If one works in low field or uses a small mri device to examine elbows, knees, fingers and so on, the noise is limited by the sensor itself. This fact makes possible smaller mri devices that can be much cheaper than full-size versions. STI has replaced the copper antenna with a high-T_c antenna and placed it close to the body. Tests have been made with Toshiba and Hitachi mri devices, at 0.06 T and 0.3 T, respectively. At 0.3 T, the signal-to-noise ratio improved by 50% in imaging a knee. The image of an eye was improved by a factor of ten in the 0.06-T device. STI has received premarket authorization from the Food and Drug Administration and is now trying to set up marketing agreements with manufacturers of mri devices. The antennas are made of TBCO 1 micron thick and 1–3 inches in diameter.

A group at Duke University Medical Center is using a "magnetic resonance microscope," an mri machine with very high magnetic fields, up to 9.4 T, for imaging small-scale biological objects. The Duke group and Conductus, with funds from the National Institutes of Health and SBIR, have developed a YBCO probe that gives a greatly improved signal-to-noise ratio for high fields. With such an improvement one can image smaller volumes or reduce imaging time, according to Duke's Robert Black.

In conjunction with Intermagnetics General, Du Pont just received a $5.8 million award from the Advanced Technology Program to develop high-T_c sensing systems for incorporation into mri devices, according to Carl Rosner of Intermagnetics General.

Analog and digital electronics

When will high-T_c materials be used for high-speed communications or computers? A key requirement for these technologies is the ability to fabricate multilayer thin films to interconnect individual devices. Although it's certainly more difficult to fabricate multilayer thin films than single-layer thin films, a number of groups have successfully made such structures out of YBCO. "The most critical issue is that Josephson junctions form at steps; so you have to avoid making steps in SQUID magnetometers, digital circuits and multichip modules," says Rowell.

Many years ago, long before high-temperature superconductivity was discovered, IBM, Bell Labs and some Japanese firms had R&D efforts to build a Josephson junction computer. IBM canceled its project because silicon technology was continuing to advance at such a rapid rate. A number of labs, however, have continued some efforts toward Josephson junction computers. In a recent interview IBM's Ketchen said that although IBM is not pursuing high-T_c computing at present, through the superconductivity consortium the company is working on some low-T_c digital devices, such as an analog-to-digital converter. Stuart Wolf, head of material physics at NRL, says there's still a great amount of R&D effort needed to make reproducible, reliable Josephson junction devices, especially as you increase the number of junctions beyond the pair needed for a SQUID.

Ketchen says that much of the emphasis in computers these days is on low power and lots of function rather than high speed, although there will always be some demand for the fastest possible circuitry. ARPA had a significant program in developing interconnects to operate at 77 K. A CMOS processor operating at that temperature could be interconnected with high-T_c multichip modules, speeding the system up by a factor of two.

▸GLORIA B. LUBKIN ■