Magnesium diboride can't match the properties of high-temperature superconductors. But it is far easier to work with, which may prove even more valuable in the end

MgB_2 Trades Performance for A Shot at the Real World

To the ancient Greeks, he was known as Hermes, the messenger god. Updated to rule over modern scientific disciplines, this fleet-footed deity and renowned trickster would undoubtedly govern superconductivity. The phenomenon owes its existence to agile electrons that sprint through superconductors unencumbered, without the resistance that plagues electrons in standard wires. But researchers in the field sometimes feel like the butt of an ongoing cruel joke: Every tantalizing new superconductor invariably turns up a serious flaw.

Perhaps Hermes has gone soft, or he's developed a little sympathy for mortals. Last year, a team of Japanese researchers discovered a new superconductor called magnesium diboride (MgB_2) that so far seems to be holding its luster. After just a year of working with this powdery black compound, researchers are already pushing MgB_2 headlong toward applications. They've forged it into long wires, a feat some high-temperature superconductors (HTS) have yet to match. Two new companies are now working to commercialize the results. "The area of hot activity has shifted from basic research to applied," says Paul Canfield, a physicist at Iowa State University in Ames. "This is a healthy transition and incredibly rapid."

Practical advantage. Unlike some rival materials, crystalline superconductor MgB_2 is readily made into wire.

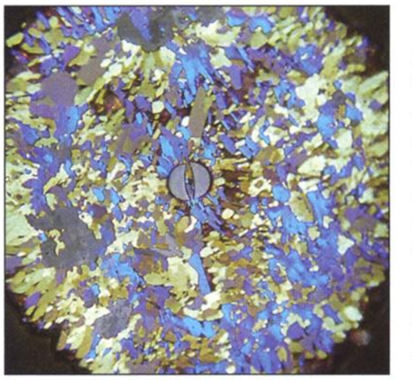
But as heady as this progress seems today, MgB_2 still faces numerous hurdles before anyone makes any money from it as a superconductor. And because commercializing superconductors is never as easy as it seems, Hermes may still have the last laugh.

He certainly had the first. Many theorists believed for years that conventional metallic alloy superconductors would never superconduct above 20 kelvin. Around that temperature, researchers thought, the added heat would create vibrations in the material's crystalline lattice that would break up pairs of electrons that surf through the material together, the signature of superconductivity. But MgB_2 turns out to be extremely efficient at linking electrons in pairs and superconducts all the way up to 39 K. That's well below the 138 K of the record HTS material, a copper oxide–based compound. But it's potentially still useful for widespread applications, such as making transformers used by the electric power industry. And unlike the copper oxides, MgB_2 is simple to make, cheap, and relatively easy to turn into wires.

Fifteen years after the discovery of the copper oxides, companies are only now nearing the commercialization of the first generation of HTS wires, generators, and motors. But even now, some experts question whether these products will survive the marketplace. First-generation HTS wires are made by taking ceramic grains composed of bismuth, strontium, calcium, copper, and oxygen (BSCCO) and cladding them in an expensive silver sheath. That coating drives up the cost dramatically. Using one standard measure that's based on the price of transmitting current over a meter, first-generation HTS wire checks in at an exorbitant $200 for a kiloampere per meter (kA/m). Experts expect large-scale manufacturing to drive the cost down to $50 a kA/m.

The upside for HTS wire is that it works at 77 K. That allows for the use of cheap liquid nitrogen to cool the material to its operating temperature, saving companies a bundle of money. By contrast, low-temperature superconductors, such as niobium-titanium (NbTi), must be cooled to 4 K, which demands expensive liquid helium. However, that alloy costs only $1 kA/m to produce, and the price is expected to drop even further.

MgB_2 splits the difference on both counts. Although the superconductor operates at temperatures up to 39 K, it would likely be chilled to between 20 and 30 K, because superconductors tend to work better below their peak temperatures. But even 20 K is good news for many applications, because it allows the use of a cryocooler, a type of no-hassle refrigerator that can be plugged into the wall. "There's a big difference [in cooling costs] between 4 K and 20 K," says Mike Tomsic, president of Hyper Tech Research, a Columbus, Ohio–based company attempting to commercialize MgB_2.



Moreover, magnesium and boron, MgB_2's starting materials, are dirt cheap. And instead of requiring a silver cladding, MgB_2 works just fine with a sheath of cheap metal, such as iron. At a meeting of the Materials Research Society in December 2001, superconductivity expert Paul Grant of the Electric Power Research Institute in San Francisco estimated that MgB_2 wire will eventually match NbTi's cost of $1 kA/m, making it cheaper than copper wire. After factoring in all the costs—not just the wire but also the cooling equipment and electrical losses—Grant found that an MgB_2 transformer would soundly defeat not only an HTS version but also a standard copper wire system today (see figure, p. 787).

Transformers are just the beginning. "I think it's good enough right now for motors and generators in the 20-to-30-K range," Grant says. Predictions that the annual market for HTS-based wire and machinery will approach $2 billion by 2025 suggest that there's plenty of room for sales of MgB_2.

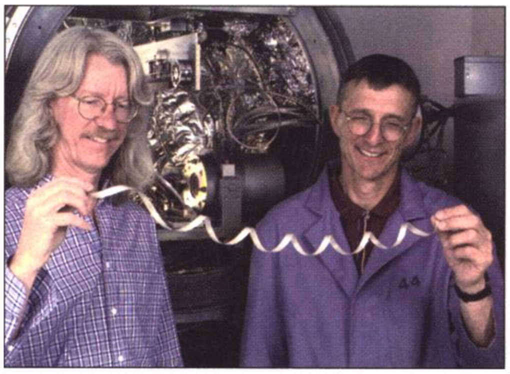
MgB_2 is well on its way to fulfilling this potential. For starters, groups in the United States and Italy recently reported making

CREDITS: (LEFT TO RIGHT) HYPER TECH RESEARCH INC.; D. K. FINNEMORE/IOWA STATE UNIVERSITY

YBCO Confronts Life in the Slow Lane

While MgB_2 researchers are already gearing up efforts to make kilometers of wire, researchers working with the top-of-the-line high-temperature superconductor (HTS) are struggling for every meter. "We aren't making the progress we had hoped for in 1995," says Paul Grant, a superconductivity expert at the Electric Power Research Institute in San Francisco, California. Adds physicist Steve Foltyn of Los Alamos National Laboratory in New Mexico, "There is some sense of impatience."

In 1995, Los Alamos researchers reported that a brittle ceramic superconductor composed of yttrium, barium, copper, and oxygen (YBCO) deposited atop a thin metal tape could carry a phenomenal 1 million amperes of electrical current per square centimeter of cross section (A/cm^2) (*Science*, 5 May 1995, p. 644). What's more, it worked at a balmy 77 kelvin and in strong magnetic fields, conditions that no other superconductor, including MgB_2, has even approached. Dreams of widespread use of superconductors seemed within reach.



Power coil. Los Alamos physicists Steve Foltyn and Paul Arendt show off a meter-long strip of YBCO tape.

The trouble was that the early YBCO tapes were only about 4 centimeters long, not the kilometers needed for applications. Six years later, the Los Alamos team and most others still can't make tapes longer than a meter. Last year researchers at Fujikura, a leading superconductivity research company outside Tokyo, Japan, reported an 11-meter tape. "That's impressive," says Balu Balachandran, a physicist at Argonne National Laboratory in Illinois. But he and others acknowledge that even these tapes aren't close to being ready for practical uses. "You can't make a motor, transmission line, or transformer out of a few meters of tape," Foltyn says.

The problem lies in the physics of YBCO. Pairs of electrons surfing through the superconductors breeze along its crystalline lattice, but YBCO crystals break up into tiny grains when the material is deposited on metal tapes. And electrons have trouble hopping between neighboring grains unless the adjacent crystalline axes share nearly perfect alignment. Any effort to scale up the technology must preserve this alignment between grains throughout the wire. "It's like trying to make a mile-long single crystal," Grant says.

That's not the only problem. To make real world wires, engineers also have to lay down a conventional conductor atop the YBCO to carry the current should part of the superconductor stop working; otherwise, all the electricity would turn to heat and instantly vaporize the wire. Yet when researchers add conductors alongside YBCO, the superconductor mysteriously loses some of its ability to carry current.

Researchers also face the challenge of making thicker wires. So far the best YBCO tapes contain only a 0.3-micrometer-thick layer of YBCO. Even though they are great conductors, such skimpy threads of superconducting material don't carry much overall current. Yet it's been much harder than expected to bulk up YBCO. "When you make the superconductor thicker, the critical current declines," says Los Alamos physicist Dave Christen. "That's one of the bottlenecks right now."

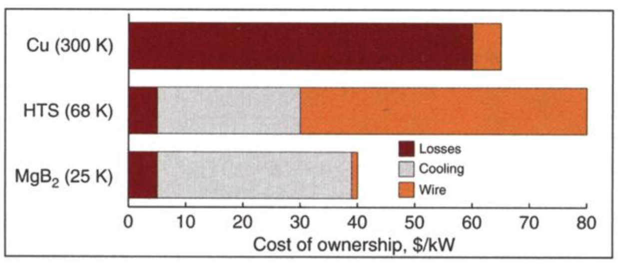
As if such technical troubles weren't enough, the window for some applications of these second-generation HTS wires may be closing. Transformers and other components of the electric utility grid are aging so rapidly, Grant says, that companies may not be able to wait for researchers to perfect YBCO wires. And because many such components last for decades, "if we can't get the job done fast enough we may miss some opportunities," Christen says.

Of course, that may be good news for MgB_2's proponents. YBCO's loss could be their gain. **–R.F.S.**

MgB_2 wires as much as 60 meters long using techniques very similar to that used to make BSCCO wires. By contrast, after 6 years of work on the second-generation HTS wire technology—made from a mix of yttrium, barium, copper, and oxygen—researchers have only managed to make wires about 11 meters long (see sidebar).

Researchers can thank basic physics for this rapid progress, says Giovanni Grasso, a MgB_2 and BSCCO wiremaker at the National Institute for the Physics of Matter in Genoa, Italy. Grasso points out that electron pairs travel through different superconductors at different distances from one another, an association known as their coherence length. In MgB_2, electrons have a coherence length of 5 nanometers. That's large, particularly compared to the unit cell of an MgB_2 crystal, which measures just 0.3 nanometer across. The result is that in MgB_2, electron pairs stretch over 10 unit cells in the material. If there is a defect in the material or a jagged boundary between two grains, the electron pairs are effectively so big that, like an SUV encountering a pebble, they simply don't notice it.

High-temperature superconductors, by contrast, suffer from the opposite problem. In BSCCO, for example, the unit cell is over 10 times larger than the coherence length, says Grasso. For electrons to pass unencumbered through a BSCCO wire, successive grains must be tightly packed with their crystalline axes closely aligned to prevent electron pairs from getting stuck at every pothole they encounter. "This is very difficult to achieve," Grasso says.



Cheap shot. Transformers made with MgB_2 wire should cost less than those based on copper or high-temperature superconductors.

The challenge for MgB_2 wiremakers is to improve its ability to carry current. Many groups are working overtime to find answers. Last May, for example, a team at Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, reported that iron-coated MgB_2 wires can carry 35,000 amps per square centimeter of wire (A/cm^2), a value still well below the 80,000 to 100,000 A/cm^2 needed for many applications. In July, five groups reported even higher current-carrying values for the material, up to 200,000 A/cm^2 at 25 K in a magnetic field of 1 tesla. The finding suggests that MgB_2 wires might soon meet real-world demands.

Another challenge is that MgB_2's current-carrying capacity appears to wither if the magnetic fields get much stronger. But early results hold out hope that tinkering with the material will allow researchers to maintain carrying capacity. In the 31 May 2001 issue

CREDITS: (TOP TO BOTTOM) P. ARENDT; SOURCE: P. M. GRANT of *Nature*, two groups reported that they had added defects to their MgB_2 wires to help trap magnetic eddies called vortices that can course through the material and sap its ability to carry current. So far, eliminating vortices altogether has proven impossible. But researchers know that if they can pin them down and keep them from moving, the wire will still superconduct. To do so, one team, led by physicist Chang-Beom Eom of the University of Wisconsin, Madison, substituted oxygen for some of the boron; the other team, led by David Caplin of University College London bombarded its film with protons.

Iowa's Canfield and others predict more results in the coming months but not necessarily more announcements. "This is where you get to all the patentable stuff," says Philip Sargent, president of Diboride Conductors, a U.K.-based start-up intent on commercializing MgB_2. Sargent insists he's heard of unpublished work describing improvements. But he declines to specify just what those are.

Whether these rumored improvements will be enough to vault MgB_2 over its commercial hurdles is anyone's guess. But not everyone is convinced that the newest superconductor will make it, particularly folks at established HTS companies, such as American Superconductor Corp. (ASC), that are making HTS wire. "It's enough to monitor [their progress] extremely closely," says ASC's chief technical officer Alex Malozemoff. But so far he hasn't seen anything to make him want his company to switch gears. "An army of researchers has pounced on the material and doped it with everything under the sun. But so far the [superconducting temperature] has only gone down," he says.

Perhaps that's because Hermes is just up to his old tricks. Whether MgB_2 makes it to market may depend on how many more impediments the capricious deity throws in the path of superconductivity researchers.

–ROBERT F. SERVICE

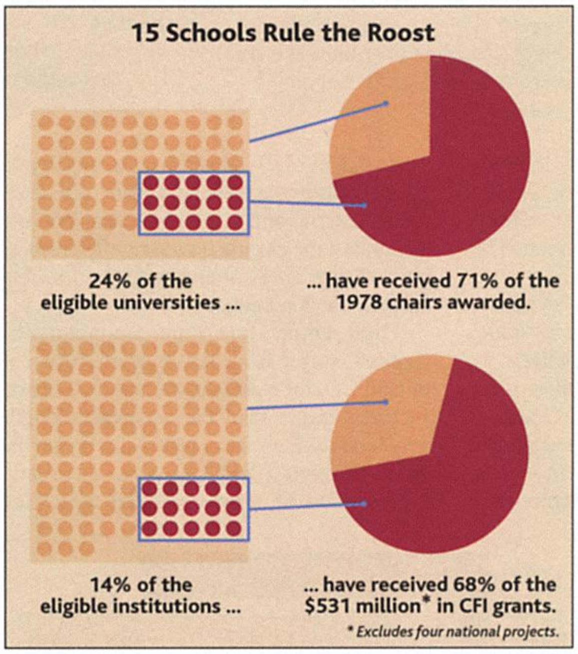
CANADA

New Money Widens Gap Among Universities

New programs are pumping more than a billion dollars into academic research. But a relative handful of universities are getting most of the money

OTTAWA, CANADA—When Robert Birgeneau decided 18 months ago to leave a deanship at the Massachusetts Institute of Technology (MIT) to become president of the University of Toronto (UT), the chance to move up the academic ladder was only part of the reason. Born and educated in Canada, Birgeneau also was attracted by the opportunity to compete for billions of dollars that the government is shoveling into targeted programs aimed at creating an MIT or two north of the 49th parallel. But although Birgeneau and other top academic administrators praise the new programs as a "crowning achievement" of the current Liberal government, some educators worry that the government is purchasing excellence for a few at the expense of the majority of institutions, faculty, and students. A forthcoming government policy paper on innovation promises to provide a forum for this debate.

Three new programs have changed the Canadian academic landscape. The \$600 million Canada Research Chairs program was created to stem an ostensible brain drain to the United States and Europe (*Science*, 22 October 1999, p. 651). The Canada Foundation for Innovation (CFI), with an initial endowment of \$520 million, is intended to renovate aging buildings, laboratories, and other university facilities (*Science*, 25 September 1998, p. 1933). And the newly restructured Canadian Institutes of Health Research (CIHR), whose budget has doubled in 3 years to \$353 million, hopes to spur biomedical advances that will strengthen the nation's economy and improve public health (*Science*, 21 December 2001, p. 2452). Funds for the chairs are awarded on a competitive basis using a formula that favors large institutions with a successful track record in attracting grants, whereas those with medical schools have a decided advantage in competing for CFI and CIHR awards.



Getting richer. The same 15 Canadian universities get the lion's share of infrastructure grants and chairs.

SOURCE: CANADA FOUNDATION FOR INNOVATION AND THE RESEARCH CHAIRS PROGRAM

"The combination of [these three programs] was a critical factor in my decision to return," says Birgeneau, who has inherited an institution bursting at the seams as a result of this new federal largesse. The university already has won \$53 million for some 120 CFI projects, including a state-of-the-art crystal growth facility. UT also will be able to anoint 270 faculty stars over 5 years, with generous funding for their labs (*Science*, 23 June 2000, p. 2112).

But not everybody is happy with the idea of the rich getting richer (see graphic). "The biggest 10 research universities are now getting close to two-thirds of all the money," says Jim Turk, executive director of the Canadian Association of University Teachers, with UT at the top. That imbalance shatters a cherished Canadian ideal of providing equal access to an excellent education regardless of the nature of the institution, says Turk. Whereas UT will get 270 new chairs, for example, nearby York University, a prominent liberal arts institution, will get a paltry 32.

The competitive funding pushes most universities even farther behind in their efforts to keep up with the rising costs of research, Turk says. A recent survey of growth rates among the 113 largest academic libraries in North America, for example, shows that Canadian universities occupy seven of the 11 bottom slots.

The chairs program has also created what Michael Stevenson, president of Simon Fraser University in Burnaby, British Columbia, calls "invidious distinction and irritation" within faculty ranks. And data suggest that it may not even achieve its desired end of deepening the academic research pool by attracting talent from outside Canada or from industry. Some 370 of 448 accepted chairs have been appointed from within institutions, and 29 involved hiring someone at another Canadian university. Fewer than 10% of