Will MgB_2 Work?

In January, Japanese researchers announced the discovery of superconductivity near 40 K in magnesium diboride (MgB_2), a material that has been around since the 1950s (*Nature* 2001, *410*, 64). The discovery proves the maxim: if you run across a new metal, or an old one, cool it down. You might get a pleasant surprise.

Superconductivity in MgB_2 engendered a special evening session at the March American Physical Society (APS) meeting in Seattle—dubbed Woodstock West by veterans of the 1987 APS session in New York on high-T_c superconductivity. Most indications now suggest that MgB_2 is the ultimate strong-phonon-coupled superconductor. In such a system, the charge carriers (holes or electrons) are paired together by lattice vibrations (phonons), as explained by the Bardeen-Cooper-Schrieffer (BCS) theory proposed in 1956. This pairing is in contrast to the high-T_c (up to 164 K) copper oxide compounds in which many believe excitations of copper d electrons mediate the pairing of charge carriers in a manner not yet understood.

Several talks in Seattle supported the BCS theory as the explanation for MgB_2's superconductivity. The Ames Laboratory–Iowa State University collaboration reported a classic isotope shift of the superconducting transition temperature upward by 1 K on replacement of all boron by the lighter isotope ^{10}B. In the BCS theory, the lattice vibrations, which pair the charge carriers, depend on the mass of the constituent atoms.

The Ames group and the University of Wisconsin–Princeton University collaboration independently reported that MgB_2 appears scalable to inexpensive wire manufacture (Figure 1). Paul Canfield detailed the Ames work on a method for thermally diffusing Mg into commercially available boron fibers. The resulting "wires" yielded encouragingly high critical current densities. David Larbalestier of the University of Wisconsin–Madison revealed that—unlike the superconducting copper oxide perovskites—there was a remarkable absence of "weak-link" behavior in the applied magnetic field. That is, the connectivity between MgB_2 grains is good enough to allow the robust flow of superconductivity in substantial applied magnetic fields.

Initially, work by David Caplin and his co-workers at Imperial College in London indicated that flux creep—the unimpeded motion of vortices in a type II superconductor that results in power dissipation and loss—was quite large in pristine MgB_2, even substantially below its transition temperature. However, they reported new data in Seattle, which indicated that flux creep essentially stabilizes by 25 K when irradiated with "atomic particles." The Imperial College group has since revealed that it used proton bombardment of up to 2 MeV in kinetic energy.

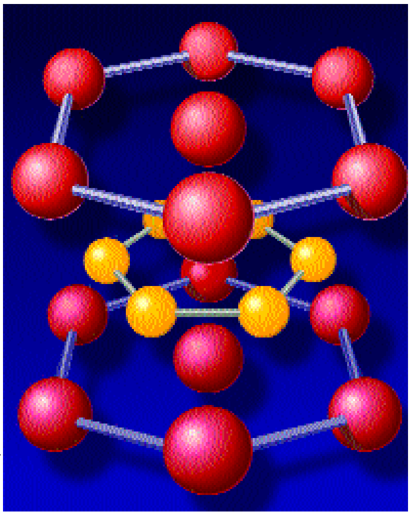
Ian Warpole

Figure 1. Will the crystal structure of magnesium (red) diboride (yellow) lend itself to the production of superconducting electric cables?

It has been known for some time that bombardment of ^{11}B by protons results in a "light fission" reaction yielding three energetic alpha particles. I would suggest that the particles' kinetic energy "rips up" the MgB_2 crystal lattice and produces pinning centers—lattice defects that help stabilize the dissipative flow of vortices.

The boiling point of liquid nitrogen, 77 K, is not a necessary operating temperature for many power applications, electric cables excepted (maybe). The reason: at the high magnetic fields that the noncable applications encounter, neither current Generation I bismuth–strontium–calcium–copper oxide/silver oxide-powder-in-tube superconductors nor projected Generation II superconductors coated with yttrium–barium–copper oxide can conduct much current at 77 K.

However, power cables require a liquid cryogen for heat removal because of the long distance (1–2 km) they span without direct refrigeration support, the low magnetic fields involved, and especially their inherent power losses under ac operation.

Superconductors are only "perfect conductors" at dc; under ac operation, there are hysteretic losses similar to those in the iron cores of transformers. Thus, the situation could be radically different for dc transmission cables. It is hard to pick an "average operating point," but for an early evaluation of MgB_2's promise for power usage, I chose a temperature of 25 K and a magnetic flux density of 1 T. This combination is close to the operating range targeted for Generation I high-T_c tape for transformers and rotating machinery.

The figure of merit for superconducting wire, the cost/performance (C/P), is in units of currency per kiloampere of critical current per meter, or \$/kA·m, stated at a particular operating temperature, typically 2/3 of its transition temperature and operating magnetic field. For comparison, the C/P of niobium–titanium (NbTi) is roughly \$1/kA·m at 4.2 K and 2 T, and that of niobium–tin (Nb_3Sn) is about \$10/kA·m at 4.2 K and 10 T. The present C/P of Generation I high-T_c tape is \$200/kA·m at 77 K at 0.005 T, and is expected to drop to \$50/kA·m as production capacity and sales increase. By scaling this last number to 25 K and 1 T for comparison with MgB_2, we obtain a C/P of \$20/kA·m. Thus, the engineering economics involved in designing a particular superconducting power device is a trade-off between the wire C/P at a desired operating point and the cost of cryogenics.

For MgB_2, materials costs are relatively easy to estimate using metal commodity-

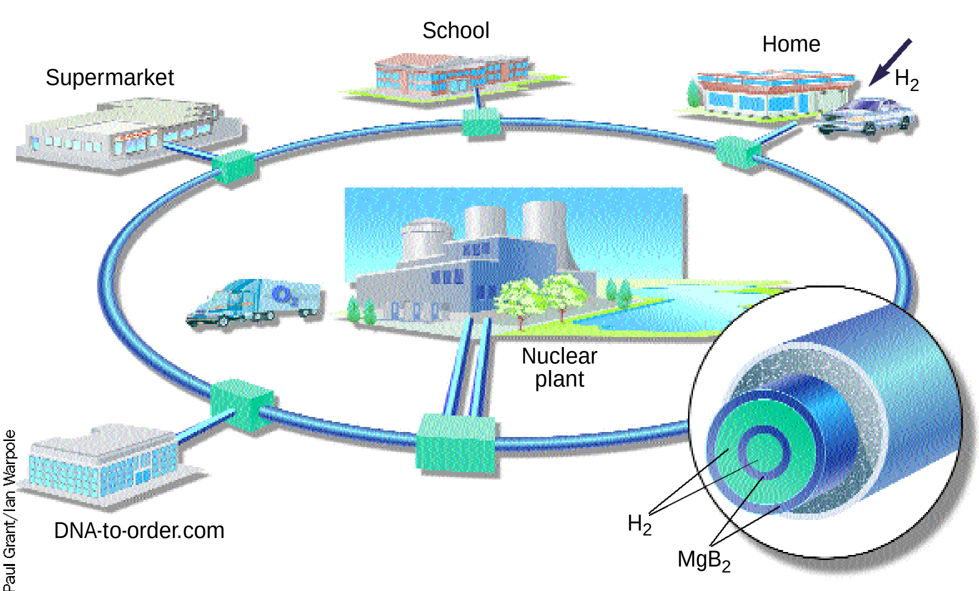

Figure 2. An emissions-free, light industrial/residential community of the future uses nuclear power, with hydrogen and dc electric energy supplied via a cryo/superconducting delivery system.

exchange data for magnesium and borax, the ore for metallic boron. It is more difficult to gauge nonmaterials production costs. MgB_2 is an intermetallic, and although it is brittle, a recent paper (*Nature* 2001, *411*, 53) suggests that it may be amenable to swaging, drawing, and postprocessing methods much like those used for NbTi and Nb_3Sn, the workhorse low-T_c wires used in magnetic resonance imaging (MRI) magnets and research applications.

I took the nonmaterials cost of NbTi at \$0.225/m as a ballpark figure for MgB_2 because the manufacturing techniques for MgB_2 will likely be similar. I also assumed a wire center-core cross-sectional area of 2 mm^2, all of which is superconducting. What is more problematic is the critical current density, because it is changing (upward) almost weekly. For now, I will use the number 100,000 A/cm^2, 25 K, 1 T, as reported in July by a University of Geneva team at a cryogenics meeting in Madison, Wisconsin.

The materials costs of Mg and B will not play as big a role as Nb in NbTi and Ag in other high-temperature superconductors. In arriving at a total C/P of \$0.45/kA·m, I have assumed an extraction cost of \$10/kg (\$0.01/g) to chemically reduce raw boron pentahydrate to metallic boron, and a similar amount to subsequently react Mg and B for wire processing. Admittedly, these numbers are wet-fingers-in-the-wind estimates and could wind up substantially in error, but let's say they represent a lower limit. As an upper limit, I estimate the purchase price of commercially prepared MgB_2, presently \$750/kg, to drop to \$300/kg with future volume demand. This yields a C/P for MgB_2 wire in the range of 0.16 to \$0.88/kA·m, 25 K, 1 T. When we compare this result with \$20/kA·m for Generation I tape, we see that MgB_2 wire would be competitive for power devices such as transformers and rotating machinery, in which high-T_c superconductors would need to be cooled to operate properly. Furthermore, MgB_2 wire could potentially replace NbTi in future MRI magnets.

But what about something "far out" that MgB_2 might enable? The boiling point of hydrogen at atmospheric pressure is 20.13 K. Thus, one might envision liquid hydrogen or cold hydrogen gas as a cryogen for an MgB_2-based dc cable system delivering both electrical and chemical energy to an end user—a hydrogen–superconductivity symbiosis to enable an emissions-free energy economy in the future.

This year, at a peer-review panel meeting of the U.S. Department of Energy's Superconducting Program for Electric Power, I presented a vision of a community powered by a system based on a symbiosis of nuclear, hydrogen, and superconducting technologies (Figure 2). I placed it in a remote part of Mexico, off the power grid, and called it Laguna Genome, a green-sited, biotech-industrial and residential development of 50,000 people.

The community derives its power from a 1,500-MW, pebble-bed-reactor, Generation 4 nuclear plant, one-third of whose output is used to manufacture liquid hydrogen through electrolysis of water. One could imagine an MgB_2 transmission cable loop cooled by liquid hydrogen with distribution taps to end users employing shorter high-T_c copper oxide cables using gaseous hydrogen in the 60 to 70 K range. The transition from transmission to distribution voltages, and liquid to gaseous hydrogen, would occur at substations, which would also store gaseous hydrogen at room temperature and high pressure to power substation-sited fuel cells for load peaking. Residential and industrial customers would have a choice of energy source, perhaps using electricity for its usual purposes and cold hydrogen for space conditioning (cooling and heating), cooking, and hot water, as well as in fuel-cell-powered personal and business vehicles. Additionally, hydrogen or electricity would power commuter transportation.

Several reporters present in Seattle asked how I would compare the MgB_2 discovery and the attendant commotion of 2001 with the 1987 APS session on high-T_c superconductivity. There were some similarities, including the overcrowded ballroom in Seattle and a few altercations in the foyer between latecomers and hotel security barring them from entry. There were 70 speakers, each allotted 2 minutes with 1 minute for questions (in 1987, we had 5 minutes plus another minute for questions). By the time my turn came to speak at 11:30 p.m., I jokingly remarked that I thought the field was now old enough to deserve a review talk.

Although "Woodstock West" was indeed exciting, the meeting in New York was the experience of a lifetime—until room-temperature superconductivity finally arrives.

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