Potential Electric Power Applications for Magnesium Diboride

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ABSTRACT

The newly discovered superconductor, MgB_2, has significant potential for a number of electric power applications, even though its critical temperature, T_C, is "only" 39 K. In recent months, there has been rapid improvement in its critical state parameters, J_C and H*, properties crucial to deployment in power devices, which now rival NbTi at 4.2 K, and equal or surpass many of the high temperature superconducting copper oxide perovskites in the 20 – 25 K range. Moreover, substantial progress has been achieved in realizing wire embodiments that appear economically scalable to commercial production. In this paper, we will review several opportunities to exploit these developments for transformer and electric cable applications, and hint at the possibility of a novel and visionary power delivery system centered on an MgB_2-based dc cable cooled by gaseous or liquid hydrogen supplying both electrical and chemical energy to the end user.

INTRODUCTION

"Advances in superconductivity begin with the empirical search for new materials." Thus commenced the historic 1986 paper by Bednorz and Mueller announcing the discovery of "high temperature superconductivity" in the family of layered copper oxide perovskites [1]. However, it is occasionally fruitful to closely examine low temperature transport data measured on old ones. This is just what happened during January, 2001, in Japan when a group at Aoyama-Gakuin University, while investigating the properties of an titanium-magnesium-boron ternary compound in search of magnetic or superconducting behavior noticed trace superconductivity at 39 K in an impurity phase subsequently shown to be MgB_2 [2]. In fact, there was even an indication of possible superconductivity in MgB_2 that went unrecognized in 1957 in published low temperature specific heat measurements [3]. It is difficult to imagine how differently many applications to both power and electronics would have evolved had MgB_2 superconductivity begun development in the 1950s.

Within several months following its discovery, a widely accepted theoretical consensus arose that MgB_2 was probably the penultimate strong coupled electron-phonon superconductor whose intrinsic properties behave as predicted by extensions of the Bardeen-Cooper-Schrieffer formalism advanced in the 1960s and 70s [4]. At the same time attention began to focus on the applications potential within MgB_2 in spite of its relatively low transition temperature of "only" 39 K. One of the earliest indications of promise was the apparent absence of "weak links" between micro-crystals or grains of the material, the Achilles' Heel of the HTS copper oxides which limit their critical current and magnetic field performance, key parameters for power applications [5]. However, early measurements also indicated a low value of the irreversibility field relative to the upper critical field resulting from thermally activated flux flow and creep, quite possibly due to the high level of microcrystalline perfection in MgB_2. These concerns were soon allayed as significant improvements in both J_C and H* were observed as extrinsic vortex pinning centers were introduced via radiation [6], impurities [7], and thin film fabrication [8, 9].

But perhaps most astounding of all were the almost immediate prospects for realizing practical lengths of MgB_2 wire. A group at Iowa State and Ames reported at the 2001 APS March meeting the successful infusion of Mg into commercially available boron fibers used in the production of sports equipment such as skis and tennis racquets [10], an approach in principle scalable to kilometers. Short lengths of such "wires" yielded critical currents of the order 10^5 A/cm^2 in a 1 T field at 25 K. This announcement was quickly followed by the disclosure that MgB_2 wires, cladded by iron or nickel, could be produced using a variety of standard "powder-in-tube" techniques, similar to those employed for low temperature superconductor monofilaments, and whose initial performance appear quite promising [11, 12]. Table I below contains a summary of representative values from several groups worldwide, some yet to be published.

Table I. Representative values and origin of MgB_2 wire critical current density in A/cm^2 under 1 T applied field at 4.2 K and 25 K, as reported in the MgB_2 special session at the 2001 Cryogenic Engineering Conference (CEC) and International Cryogenic Materials Conference (ICMC), July 16-20, 2001, Madison, WI.

Institution	4.2 K	25 K
UniGe[a]	250,000	100,000
OSU Collaboration[b]		59,000
Karlsruhe[c]	100,000	37,000
INFM – Genova[d]	100,000	50,000
Ames[e]	500,000	~200,000

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As of the submission date of this paper, two companies have been formed with the intention to manufacture MgB_2 wire; Hyper Tech Research, Inc. [13], in Troy, OH, and Diboride Conductors, Ltd. [14], in Cambridge, UK. The former has been able to produce a 60 meter monofilament of monel-clad MgB_2 by the continuous-tube-forming and filling (CTFF) technique. Its end-to-end performance is presently under evaluation.

POWER APPLICATIONS OF SUPERCONDUCTIVITY

To be able to utilize the "perfect conductor" nature of superconductivity for practical application has been the dream of physicists and engineers since its discovery in 1911. However, this dream was delayed until the 1960's maturation of "type II" superconductors capable of sustaining substantial electric current in high magnetic fields. These developments resulting in the commercialization of magnetic resonance medical imaging (MRI), the most ubiquitous application of superconductivity visible to the public at large today. The advent of high temperature superconductivity has expanded the possible range of application to electric industry power devices, and a rapidly growing program of prototype development and demonstration projects is currently underway worldwide [15].

In order to understand the window of opportunity available to MgB_2, consider the various operation ranges believed necessary for the power devices identified in Table II [16].

Table II. Critical state parameter requirements for several electric power applications. Data abstracted from Table I of Reference 16.

Application	T (K)	Field (T)	J_C (A/cm^2)
Fault-current controller	20 - 77	0.1 - 3	$10^4 – 10^5$
Large motor	20 - 77	4 - 5	10^5
Generator	20 - 50	4 - 5	10^5
SMES	20 - 77	5 - 10	10^5
Power cable	65 - 77	< 0.2	$10^4 – 10^5$
Transformer[a]	25 - 77	0.5 - 2	$8×10^4$

[a]Values adjusted from Ref. 16 to reflect range addressed in DOE Superconductivity Partnership Initiative transformer projects.

A comparison of Table II to Table I reveals MgB_2 performance is already at levels where serious consideration can be given to its use in electric power devices. It is expected that this performance will only improve with time given that it has been barely a year since the discovery the compound was indeed superconducting at all.

It is important to keep in mind that each of the applications addressed in Table II individually comprise significant engineering undertakings and a wide variety of specification and performance tradeoffs can be entertained, and thus individual entries have wide associated margins. In addition, two of the applications considered in Table II – cables and transformers – can involve serious line frequency ac losses, as opposed to fault-current controllers, motor and generator rotors and SMES. However, even these are susceptible to some induced ac loss due to pickup, and, in the case of SMES, charging and discharging. The only power application relatively free from transient loss would be a supply/load balanced dc transmission line.

COST/PERFORMANCE OF SUPERCONDUCTING WIRE

A summary of the cost performance (C/P), measured in units of USD ($) per kiloampere-meter product ($/kA×m) for several LTS and HTS wire technologies [17], compared to some preliminary analyses for MgB_2 [18, 19], is given in Table III. Although we identify capital plant as the primary cost driver for MgB_2, we expect this investment to be considerably less than for YBCO coated conductor, since most of the manufacturing methods under consideration for the former are variants of already existing wire drawing, swaging and filling technologies used for LTS, HTS BSCCO and other metals.

Table III. Comparison of the Cost/Performance (C/P) of several LTS and HTS wire technologies, and their principal cost driver, derived from References 17 – 19.

Wire	C/P ($/kA×m)	Cost Driver
NbTi (4.2 K, 2 T)	0.90	Materials (Nb)
Nb_3Sn (4.2 K, 10 T)	10	Materials (Nb)
BSCCO (25 K, 1 T)	20	Materials (Ag)
YBCO (25 K, 1 T)[a]	4	Capital Plant
MgB_2 (25 K, 1 T)[b]	1	Capital Plant

[a]Ref. 17.
[b]Refs. 18, 19.

As pointed out in Ref. 17, the true engineering C/P of superconducting wire, especially HTS, has many independent variables. Among these are anisotropy (and thus angle of an external magnetic field), strain, and various de-ratings related to practical operating current as a fraction of critical current under conditions of a conventionally accepted voltage drop. For simplicity, the values taken to compute the entries in Table III for BSCCO and YBCO were the current densities measured at a field of 1 μV/cm.

EXAMPLE APPLICATION: TRANSFORMERS

Over the past several years, the U. S. Department of Energy, through its industrial Superconductivity Partnership Initiative program, has conducted two prototype superconducting transformer studies, one with ABB and another with Waukesha Electric Systems (WES) [15]. Both have focused on employing BSCCO HTS wire, ABB at or near 77 K and WES at a lower temperature yet to be determined, with a shift to YBCO coated conductor when readily available long lengths have been commercialized.

In or about the year 2000, ABB evaluated the projected cost/performance for BSCCO wire and as a result made the decision to pause their effort until a less expensive wire, perhaps YBCO coated conductor, became available [20]. In order to make the wire cost component visible with respect to other aspects of transformer operation, principally cyrogenics, ABB projected the capitalized cost of ownership due to losses onto the same basis as wire cost, using an on-load loss evaluation of 1 $/W, an "experience number" typical of current transformer industry practice. To estimate refrigeration costs for a given loss load, ABB assumed a unit expense of $5 per watt "nameplate" electric input requirement. We note this figure is rather aggressive compared to a recent DOE estimate of $25/W [21].

Table IV summarizes the cost of ownership for several HTS wire scenarios plus MgB_2. The columns for copper and BSCCO (77 K, 0 T) follow directly from the original ABB analysis and reflect an ownership cost differential of 15 $/kA×m in favor of the conventional copper wire technology.

Table IV. Cost of ownership normalized to kA×m units of wire specification for several scenarios of HTS operating points in temperature and magnetic field relevant to transformer application. The analysis follows the general methodology of Reference 20.

Item	Units	Cu	BSCCO	BSCCO	YBCO CC	MgB_2
Operating Temperature	K	300	77	77	68	25
Operating Field	T	2	0	2	2	2
Electrical Losses[a]	W/kA×m	60	0.25	0.25	0.25	0.125
"Effective" Carnot Factor[b]	W_t/W_e	1	20	20	23.6	76
Cryo-Unit Electrical Load	W/kA×m	0	5	5	5.9	9.5
Total Cost of Losses @ 1$/W	$/kA×m	60	5	5	5.9	9.5
Cryo-Unit Cost @ 5$/W Rating	$/kA×m	0	25	25	29.5	47.5
Wire Cost (T, H)[c]	$/kA×m	5	50	150	50	2
Total Cost of Ownership	**$/kA×m**	**65**	**80**	**180**	**85**	**59**

[a]Electrical losses for copper wire are ohmic in nature, whilst for superconductors are dominated by ac losses both "type II hysteretic" and eddy current inductive coupling to metallic addenda.

[b]Ref. 20 assumes a total "penalty" of 20 of watts-thermal to watts-electrical for BSCCO at 77 K accounting for both Carnot and other incidental losses.

[c]The cost/performance values for each wire technology have been adjusted for field and temperature set points. For example, C/P for BSCCO at 77 K, self field, nominally 50 $/kA×m, increases by a factor of 3 in a field of 3 T. Presently, there exists no accepted value for the eventual C/P of YBCO coated conductor in the absence of a preferred commercial scale-up path. Given this situation, we assume a C/P at 77 K, self field, of 25 $/kA×m, half the BSCCO target, which doubles at 2 T as suggested by J_C vs. field data from many sources.

The three right hand columns of Table IV extend the ABB analysis to BSCCO (77 K, 2 T), YBCO (68 K, 2 T) and MgB_2 (25 K, 2 T), respectively. On the basis of the requirements projected in Table I for transformers, especially if iron-free designs are to be considered, we have used 2 T as a more realistic field operating point. This move de-rates the wire C/P to the values shown for the HTS cases [17]. For MgB_2, we double the 1 T C/P based on typical field dependent measurements of J_C in the literature [4-9].

For the "effective Carnot efficiency," ABB chose a factor of 20 watts-electric to watts-thermal at 77 K, a number consistent with the DOE study [21]. On scaling this quantity to 68 K and 25 K, we employed simply the "ideal" Carnot factor,

$$\eta = T_{cold} / (T_{sink} - T_{cold}), \qquad (1)$$

where T_{cold} is the operating temperature (e.g., 25 K) and T_{sink} is the thermal sink, typically 300 K. Scaling the ABB 77 K factor of 20 to 25 K results in an effective Carnot of 76, also consistent with the DOE report value for this operating temperature [21].

In their analysis, ABB chose for the HTS case an "electrical loss" of 0.25 W/kA×m, a value we will assume constitutes primarily ac losses due both to type II hysteresis and eddy currents induced in the wire addenda (for Cu, of course, these losses are primarily ohmic in nature). There is good reason to believe, and evidence is emerging, that for MgB_2 monostrands clad in Fe or a steel alloy, the interstrand magnetic shielding thus obtained in a multifilamentary wire, may result in a reduction in ac loss by a factor of four over present HTS tape configurations [22, 23]. Moreover, powder-in-tube manufacturing presumably makes MgB_2 amenable to the kind of "Rutherford cable" designs common to LTS utilizing fine filaments and short twist pitch, further reducing ac losses vis-à-vis HTS tape. Taking these considerations into account, plus the lack of weak link behavior between MgB_2 grains, we make the conservative anticipation that MgB_2 may display at most half the ac losses at 25 K that HTS possess near 77 K, or 0.125 W/kA×m. Under these assumptions, MgB_2 becomes more attractive in total cost of ownership for transformers than copper or the HTS scenarios presented in Table IV.

DISCUSSION AND CONCLUSION

We see that MgB_2, despite its "low" T_C relative to the family of layered copper oxide perovskites, does indeed have a window of opportunity for electric power equipment application due to its potential low cost wire embodiment. This window would expand should YBCO coated conductor prove uneconomic to manufacture in long lengths, and as improvements to J_C in BSCCO begin to level out. As our transformer exercise has shown, for MgB_2 cost of ownership for ac intensive applications is dominated by refrigeration costs and ac losses, not the dc C/P of the wire, unlike HTS where wire costs prevail. Much more needs to be understood about the nature and magnitude of ac losses in various MgB_2 wire geometries and packaging, but the outlook is promising.

The anticipated low cost of MgB_2 should encourage the investigation and development of a refrigeration technology for operation at 25 K that "beats" the heretofore empirical linear dependence of cost on practical Carnot efficiency, especially regarding cryocoolers for spatially constrained applications such as fault-current controllers, transformers and rotating machinery.

With respect to electric power cables, the arrival of MgB_2 offers some interesting new possibilities. Cables, especially the ac variety, require distributed refrigeration to remove both heat in-leak and ac losses. That is why a liquid cryogen such as nitrogen or helium is an essential requirement and component of past and present superconducting cables. Now, it has not gone unnoticed that the performance of MgB_2 for cable application is quite satisfactory at liquid hydrogen temperatures, opening the door for a symbiosis of hydrogen and superconductivity to create a new energy economy [24].

The discovery of superconductivity in magnesium diboride early in 2001 displays all the attributes of the classic "disruptive event," forcing us not only to rethink some of our current approaches to power applications of superconductivity, but at the same time enabling others not possible or practical beforehand.

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