SUPERCONDUCTORS
An Emerging Power Technology[†]

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Superconductors offer effectively zero resistance to the flow of electricity and thus have the potential to significantly reduce Joule energy losses in the distribution and utilization of electric power, as well as the size and weight of power generators and motors. Although superconductivity was first discovered in 1911, temperatures near absolute zero were required for their operation, and so large-scale application of superconductivity was limited until the discovery in 1986 of a new class of oxide superconductors that operate at much higher (although still cryogenic) temperatures. Recent, remarkable progress has been made in the fabrication of practical conductors using the new oxide superconductors. Some of the properties of superconductors (both low- and high-temperature types) and the progress that has been made in overcoming the impediments to their commercialization are reviewed. Also discussed are on-going demonstration projects for transmission lines, motors, generators, syn–chronous condensers, and transformers that are currently being constructed by teams of industry and government researchers to implement and test this new technology in commercial settings.

1. INTRODUCTION

Superconductors are materials that offer zero resistance to dc current flow if cooled to low enough temperatures and operated in low enough magnetic fields. What makes them practical is their ability to carry very large current densities, $\geq 10^5$ A/cm^2, with little or no power dissipation. As such, they are potentially useful in a wide range of power applications, including generators, motors, and power transmission lines.

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Their ability to carry high current densities offers the prospect of increasing current levels by 5 to 7 times in existing utility corridors without raising the voltage. In urban settings this can be done by threading them through existing underground conduits without digging up streets or acquiring expensive property. The prospect is tantalizing. Superconducting power cables also offer a very environmentally friendly avenue for increasing power, without higher voltages, without hazardous oil, and without electromagnetic interference. In sensitive environmental cases, they offer an acceptable solution to increased energy capacity. Superconductors also provide a way to fabricate motors and generators that are smaller, lighter, and more energy efficient.

Here we consider superconductor performance limits and the tremendous advances that have occurred recently in their ability to operate at higher temperatures and magnetic fields. We also look at the potential for producing practical conductors and cables, and we briefly review the specific applications currently under development.

2. SUPERCONDUCTIVITY—WHAT ARE ITS LIMITS?

For practical applications, superconducting materials must have a critical current density $>10^5$ *A/cm*^{2} *under the conditions of temperature, magnetic field, and strain that they will see in service.* Otherwise they do not offer sufficient advantage over ordinary copper wire. (More specifically, the engineering requirement is that the *overall* composite wire, including other components, must have current densities $>3\times10^4$ A/cm^2 for rotating machinery designs and $>1\times10^4$ A/cm^2 for transmission lines).

Unfortunately, this requirement precluded the use of superconductors in practical devices for nearly half a century following their discovery in 1911.[1] These early superconductors operated only at very low temperatures (just a few degrees above absolute zero), and, to make matters worse, researchers soon learned that magnetic fields of only hundredths of a tesla destroyed their superconductivity. (The fields could arise either from self-fields generated in transmission lines or fields generated by winding them into magnet coils; either way, they were useless in practical applications.)

2.1. Discovery of Type-II Superconductivity

Then, in 1961, the superconducting compound Nb_3Sn was discovered to have a critical field over 20 T,[2] and suddenly the path was open for the production of high-field magnets. Paradoxically, these high-field superconductors were impure,

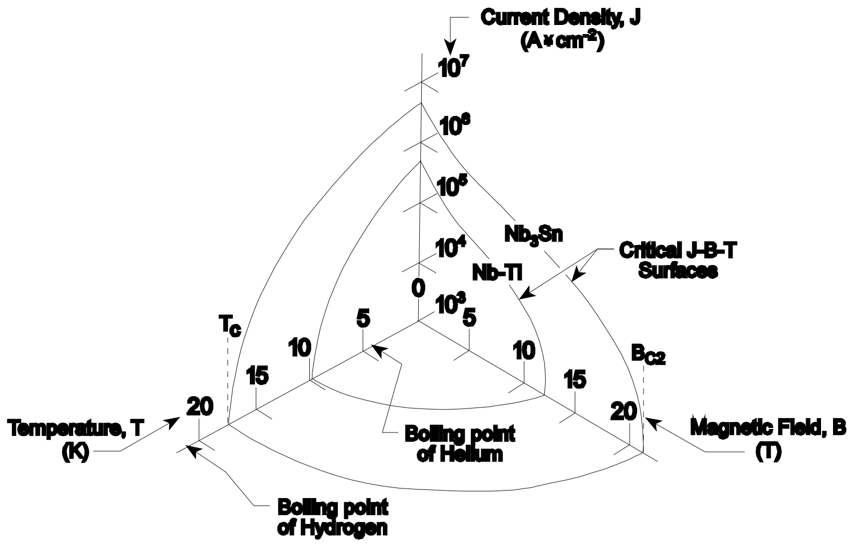

Figure 1. Critical-current density J_c of two commercial low-temperature superconductors as a function of magnetic field *B* and temperature *T*. In the region between the origin and the critical *J–B–T* surface, the material is superconducting; above the surface the superconductor reverts to the normal resistive state.

unlike the early pure elements that had been studied. The scattering of electrons in these materials caused by impurities resulted in a new type of superconductivity, called Type-II superconductivity, wherein magnetic fields could penetrate the material as small, localized *magnetic vortices* that did not destroy superconductivity in the bulk of the material. (A good introduction to Type-II superconductivity is given in the book by Rose-Innes and Rhoderick.[3])

Figure 1 shows the key parameter, the critical-current density J_c (vertical axis) as a function of magnetic field *B* and temperature *T*. The data from each conductor form a *critical surface*: below the surface, the material is superconducting; above the surface, the superconductor reverts to the normal (resistive) state.

Since, to be practical for large-scale applications, a superconductor typically should have a J_c greater than about 10^5 A/cm^2, we see from Fig. 1 that Nb_3Sn can be used in liquid helium (which boils at 4.2 K) in magnetic fields up to about 14 T to 16 T. Nb_3Sn is a brittle superconducting compound, however, and several decades of experience were needed to learn how to handle this delicate material. In the meantime, Type-II superconductivity was discovered in the *ductile* alloy Nb–Ti. As shown in Fig. 1, this material can be used in liquid helium at magnetic fields up to about 7 T to 8 T. Although more limited in magnetic field than Nb_3Sn, Nb–Ti is much easier to handle and so has been the workhorse superconducting material until the present time, principally for magnetic-resonance-imaging (MRI) systems.

2.2. Discovery of High-T_c Superconductors

The problem still remained that superconductors operated at only very low temperatures. Then in 1986, superconductivity was discovered in a very unlikely class of materials—ceramics.[4] With these materials emerged the possibility of applications at higher temperatures utilizing liquid-nitrogen cooling, which boils at 77 K. They could also operate at magnetic fields much higher than those possible with low-T_c superconductors.

However, just after their discovery, we discovered that the critical-current density of high-T_c superconductors (HTS) was limited to very low values by weak links at grain boundaries.[5] The weak links were a result of the charge carrier density being much less in high-T_c than in low-T_c superconductors as well as from the loss of coherence between the superconducting pairs of electrons as they cross very small crystalline imperfections at grain boundaries. In one of the most promising high-T_c superconductors, $YBa_2Cu_3O_7$ (YBCO), grain boundaries

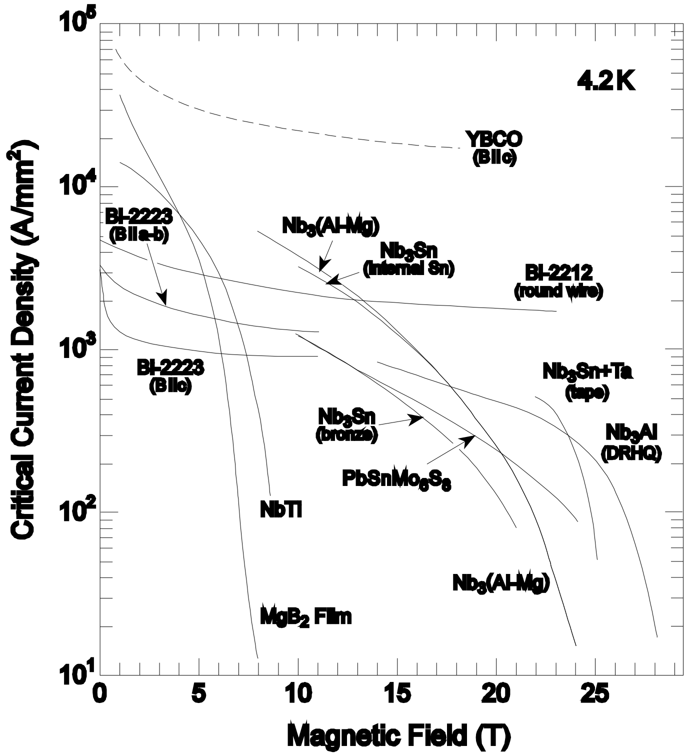

Figure 2. Critical current density as a function of magnetic field for a number of high-field superconductors at *liquid-helium* temperature (from a compilation by Lee[8]). Data are referenced to the superconducting-material area alone, as opposed to the entire cross section of the wire, which contains structural and stabilizer materials needed for the practical use of superconductors.

are misaligned by more than about four degrees form weak links.[6,7] This need for

that are misaligned by more than about four degrees form weak links.[6,7] This need for highly aligned grains constitutes the main challenge of fabricating practical high-J_c HTS conductors. (In contrast, low-T_c superconductors do not lose superconducting coherence across grain boundaries and, in fact, the grain boundaries play the important beneficial role of immobilizing the magnetic vortices.)

Figures 2 and 3 show the current record holders for high critical-current density in both high-T_c and low-T_c superconductors: Fig. 2 at the boiling temperature of liquid helium (4.2 K) and Fig. 3 at the boiling point of liquid nitrogen (77 K). Notice that as the temperature is raised from 4.2 K to 77 K, all but YBCO and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223) are eliminated from the plot. So these are the two materials currently being used to develop superconducting transmission lines that operate at liquid-nitrogen temperature.

Our work at NIST has focused on yet another limitation to the performance of high-T_c superconductors—their mechanical tolerances. At first it was feared

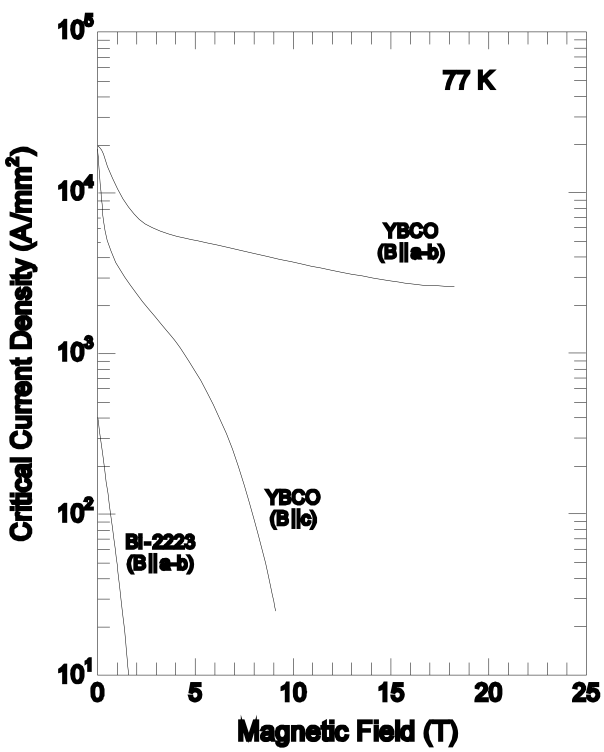

Figure 3. Critical-current density as a function of magnetic field for high-T_c superconductors at *liquid-nitrogen* temperature (from a compilation by Lee[8]). The critical-current density J_c is referenced to the superconductor area alone.

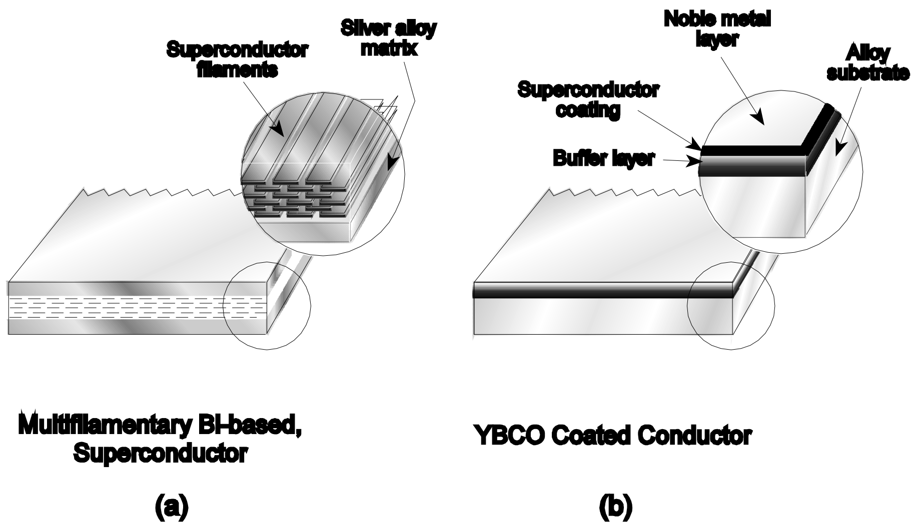

Figure 4. Cross-sectional view of practical high-T_c superconducting composites: (a) multi-filamentary $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) silver-alloy-sheathed high-T_c superconductor tape; (b) coated thick-film $YBa_2Cu_3O_7$ (YBCO) superconductor tape (from American Superconductor).

that the brittle superconducting component in these conductors would be susceptible to breakage at very small strain levels where the substrates of these composites yield, about 0.2 %. Very recently we discovered that nature has been kind to us and, in fact, YBCO performs well at strains far above the yield strain of the substrates.[9] This opens the door for potentially replacing the lower current density Bi-2223 materials, currently being used in high-T_c demonstration projects, with YBCO conductors, which can operate at much higher current densities (see Fig. 3).

Figure 4 shows cross-sectional views of practical Bi-2223 and YBCO conductors. More information about the fabrication of practical high-T_c superconductors can be found in the *Handbook of Superconducting Materials*.[10]

3. SUPERCONDUCTING POWER DEMONSTRATION PROJECTS

Annual production of energy by electrical utilities is about 3×10^{12} kWh in the United States. Energy losses associated with power transformation, transmission, and distribution amount to about 7 %. These losses would be cut approximately in half with the full implementation of superconducting technology, including transformers, power-quality devices, fault-current limiters, and underground transmission cables.

3.1. High-T_c Superconductor Power Cables

As of the year 2000, there were about 8000 km of high-voltage (> 69 kV) underground cable in the United States, generally in urban areas. Power utility companies could increase the current-carrying capacity of these underground cables by 5 to 7 times by retrofitting copper cables with superconducting cables through existing underground utility conduits. Thus, HTS power cables will most likely find their first application in these regions of highly priced real estate. HTS power cables would also increase system efficiency.

Table 1. High-T_c Superconducting Power Cable Demonstration Projects

Location / Partners	Type of Cable	Specification	Comments
Completed cable projects			
Carrollton, Georgia Southwire Cable Co.	3-Coaxial (separate cryostats) Cold dielectric Above ground	30 m long 1250 A 12.4 kV	First HTS cable demonstration project >26 000 h of fault-free operation
Copenhagen NKT	3-Separate cables	30 m long 2000 A 30 kV	First HTS cable to supply 50 000 customers
Tokyo Sumitomo Electric Tokyo Electric Power Cent.Res.Inst.of El.Power	3-Core cable (in one cryostat)	100 m long 1000 A class 66 kV	First test of three-core cable in one cryostat
Cable projects under construction in the United States			
Columbus, Ohio Southwire Cable Co. American Electric Power American Superconductor	Triaxial cable (in one cryostat) Cold dielectric Underground Includes splice and multiple 90^o bends	300 m long 3000 A 13.2 kV	First three-phase coaxial cable Scheduled to be energized mid-2005
Albany, New York SuperPower Niagara Mohawk Power Sumitomo Electric BOC	3-Coaxial cables (in one cryostat) YBCO section 30 m long Underground Underground joint	350 m long 800 A 34.5 kV	Installation between two major urban substations Scheduled to be energized mid-2006
Long Island, New York American Superconductor Long Island Power Auth. Nexans Air Liquide	3-Coaxial cables (in separate cryostats)	600 m long 2400 A 138 kV	First transmission-level (138 kV) HTS cable Scheduled to be energized end 2005

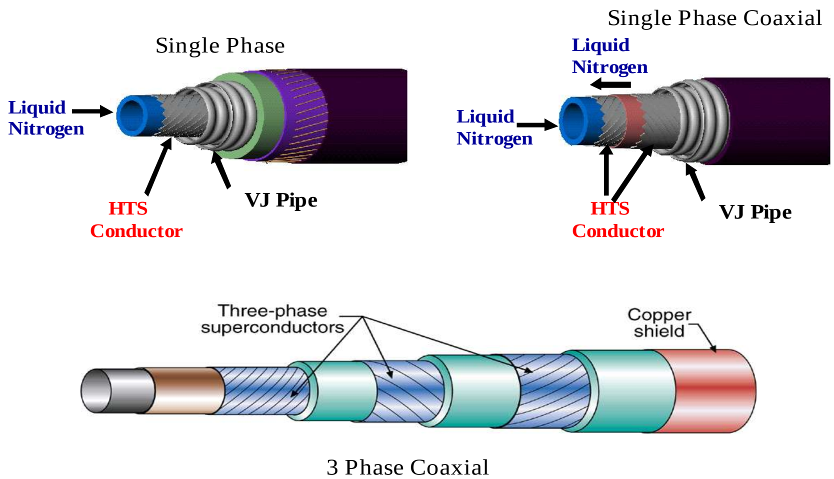

Figure 5. Three types of HTS power cables being developed and tested: single phase, single-phase coaxial, and 3-phase coaxial (or triaxial). All are cooled by flowing liquid nitrogen and thermally insulated with vacuum-jacketed (VJ) pipe (from Southwire).

Several superconducting power-cable projects have been completed, and three more are under construction in the United States. One of the completed projects was the first to supply electricity to 50 000 customers; another project has logged more than 26 000 h of fault-free operation (20 000 h unattended) while powering three manufacturing plants. A summary of details is given in Table 1.

Figure 5 shows three types of HTS power cables that are in use or planned for installation. To facilitate fabrication and maintenance of the vacuum jacket that thermally insulates these superconducting cables, all projects currently under construction in the United States employ dielectric materials operating at cryogenic temperatures inside the jacket.

Several new projects are planned throughout the world. The ones in the United States include the first three-phase triaxial cable, the first installation between two major urban substations, and the first transmission-level (138 kV) HTS cable.

3.2. High-*Tc* Superconductor Motors, Generators, and Transformers

3.2.1. Motors

Electric motors consume over 60 % of the total industrial demand for power.

Superconducting motors would be less than half the weight and size of conventional motors. For example, a 25 MW superconducting motor would weigh between 45 Mg and 63 Mg (compared with 122 Mg for a conventional motor), and its size would be between 2 m and 3 m in diameter (compared with a diameter of 4.5 m for a conventional motor). Substantial ac synchronous motors have been demonstrated by Siemens (400 kW), Rockwell (750 kW) and American Superconductor (3.7 MW). Of particularly high impact are motors for ship propulsion, where size and weight are a premium. A 5 MW high torque, low-rpm motor has been demonstrated by American Superconductor and Alstom, and a 36.5 MW motor is under development.

3.2.2. Generators

Superconducting generators offer even greater reductions in weight and size. For example, a 26 MW generator would weigh between 9 Mg and 18 Mg (compared with 54 Mg for a conventional generator), and its size would be between 0.8 m and 1.8 m in diameter (compared with a diameter of 3 m for a conventional generator). Superconducting generators also offer the benefit of a 0.35 % to 0.55 % efficiency gain. A 1.5 MVA demonstration machine is currently being built by General Electric and a 100 MVA HTS demonstration generator is scheduled for 2005.

3.2.3. Transformers

Superconductors also offer the potential for constructing smaller, environmentally friendly transformers. A conventional 30 MVA transformer weighs about 44 Mg and contains about 23 kL of oil. The HTS transformers would weigh from 22 Mg to 15 Mg and contain no oil. The HTS transformers also offer inherent overload protection without loss of equipment life, a smaller “footprint,” elimination of expensive and environmentally risky oils, and potential for indoor siting without unnecessary hazard. A 5/10 MVA superconducting transformer is being build by Waukesha Electric Systems and SuperPower.

3.2.4. Other Power Projects

Other superconducting demonstration projects currently being built with HTS wire include fault-current limiters (General Atomic, with Southern California Edison Power), energy-storage flywheels with superconducting bearings (Boeing), superconducting magnetic energy storage (SMES) devices for uninterruptible power systems (Japanese Super-ACE program), magnetic separation for ore refinement and chemical processing (DuPont), and smaller, more accessible magnetic resonance imaging (MRI) systems. However, the application nearest to commercialization is the dynamic synchronous condenser, a rotating machine without prime mover that can inject inductive and capacitive out-of-phase power for reactive compensation and grid stabilization. The HTS design is compact, producing many times the VARs of a conventional machine with high efficiency and subcycle response times. An 8 MVAR unit by American Superconductor is under beta-test in the Tennessee-Valley-Authority power grid.

3.3. Future Applications

From 1970 to 2000, superconductivity slowly entered the market place in applications where performance could not be matched by existing products (research magnets, MRI, and high-energy physics accelerator magnets). Refrigeration requirements were a major impediment. From 2004 to 2010, HTS applications will enter niche markets where cost is not as important as size, weight, effectiveness, and ancillary benefits. This will be a period where cryogenic engineering and system reliability will improve significantly, along with ever lower cost wire, setting the stage for applications in large markets where cost as well as size, weight, efficiency, and performance are important.

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