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The U.S. Department of Energy supports an applied superconductivity program entitled "Superconductivity Program for Electric Power Systems." Activities under this program are designed to help develop the high-temperature superconductor (HTS) technology that is needed for industry to proceed with the commercial development of electric power applications. Research is conducted in three categories: wire development, systems technology development, and Superconductivity Partnership Initiative (SPI). Wire development acitivities are devoted to improving the critical current density (J_c) of short-length HTS wire, whereas activities in systems technology development focus on fabrication of long-length wires, coils, and magnets. Finally, SPI activities focus on the development of prototypes that consist of a generator coil, a fault current limiter, a transmission cable, and a motor. A current overview and recent progress in the development of HTSs are outlined in this paper.

Introduction

Since the advent of superconductivity in 1911, considerable effort has been expended to raise the critical temperature (T_c) below which this phenomenon occurs. A significant breakthrough was achieved in 1986 with the discovery of the so-called "copper oxide" compounds, or high-temperature superconductors (HTSs), such as lanthanum-barium-copper-oxygen (LBCO) and lanthanum-strontium-copper-oxygen (LSCO) [1-2]. Immediately following this discovery, three additional HTS compounds, namely, yttrium-barium-copper oxide (YBCO), thallium-barium-calcium-copper oxide (TBCCO), and bismuth-strontium-calcium-copper oxide (BSCCO) were synthesized [3-5]. All of these compounds have T_c values that are well above the boiling point of liquid nitrogen (77 K). Cheap and readily available liquid nitrogen could now be used to replace the costly and difficult-to-obtain liquid helium as the refrigerant.

Potentially, HTSs can be used in motors, generators, transmission cables, fault current limiters, and in the medical and electronics industry. Because of the technical and economic incentives that these uses offer, the ensuing pace of the development of HTS materials has been fairly rapid [6]. Several prototype devices have been tested under real operating conditions and plans are underway to scale them up. The results are very encouraging inasmuch as they foster the hopes of the entire scientific community for phenomenon of superconductivity. This paper addresses current issues of the HTS industry and briefly summarizes the progress that has been made.

Research and Development of High-Temperature Superconductors in the U.S.

High-temperature superconductor technology is considered essential for American competitiveness in the next millenium. Because they can be used to build smaller and more efficient devices, design more efficient energy transportation and storage systems, and, more importantly, because the technology is environmentally friendly, the benefits of HTSs are remarkable. The global superconductivity market is projected to be $45 billion by 2010 [7]. There is no doubt that the development of HTSs will have a significant impact on both the industry and the end user. Therefore, the U.S. Department of Energy (DOE) and Department of Defense (DOD) have been actively sponsoring research and development activities on these materials. In FY 1994, the U.S. government spent an estimated $148 million for HTS research and development. The largest contribution, $70.2 million, was contributed by DOD, followed by $49.8 million from DOE, and $23.4 million from the National Science Foundation (NSF). The objective of the various programs is to develop the technology required for the commercial development of various HTS-related applications. By offering superconducting products, U.S. industry will not only regain a major share of the global market but it will also have a more efficient and flexible energy system [8,9].

To achieve this objective, DOE has established alliances, through its Superconductive Partnership Initiative (SPI) program with national laboratories, universities, and private industries. The SPI, a flagship program in the nation's effort to commercialize HTS technologies, is funded to $12 million over 2 years, with $9 million coming from DOE and $3 million from cost sharing provided by the industry. While the involved industries will be responsible for the initial demonstration and commercialization of the technology, research at universities and government laboratories is targeted for long-term technical support and improvement. Currently, four industry teams, focusing on four specific HTS products, are participating in Phase I of the SPI program [10].

The first team is led by Martin Marietta Corp. (General Dynamics) and includes American Superconductor Corp. (ASC), Los Alamos National Laboratory (LANL), and Southern California Edison (SCE). The team is working on a $4.2 million project to develop superconducting fault current limiters, which have an estimated global market of $20 billion.

The second team, which is led by General Electric Company (GE), includes the Electric Power Research Institute (EPRI), Intermagnetics General Corp. (IGC), New York State Energy Authority, New York State Institute for Superconductivity, Niagara Mohawk Power, and Argonne, Los Alamos, and Oak Ridge National Laboratories (ANL, LANL, ORNL). The team has formed a $4.2 million partnership to develop superconducting generators that are projected to lower the cost of electricity and serve a worldwide market estimated at $30 billion.

The third SPI team is led by Reliance Electric Co., and includes ASC, Centerior Energy, EPRI, and Sandia National Laboratories. This team is working on a $3.4 million project to develop superconducting motors. Large industrial motors consume nearly 30% of the electricity generated in the U.S., so the development of a more efficient motor would provide a competitive advantage in the $300-million-per-year market [10].

The fourth team comprises Pirelli Cables North America, ASC, EPRI, and LANL. The goal of the team is to develop HTS power cable systems and introduce them to the electric power market by the year 2000. Two types of HTS cables are to be developed: the first type, retrofit cables, as the name suggests, will be drawn into existing conduits. Copper cables that are worn out or exhibit lower power capacity will be extracted and replaced by the retrofit cables. The second type, coaxial cables, will be used primarily for underground installations [11].

The biggest DOD sponsor is the Advanced Research Projects Agency (ARPA), which is spending an estimated $46 million to develop various microelectronic devices. The ARPA also supports the Consortium for Superconducting Electronics, which was formed in 1989 to conduct research and development in the same area. Participants in the consortium include IBM, AT&T, Conductus, Concurrent Technologies Inc., Lincoln Laboratories, and Massachusetts Institute of Technology. The consortium is actively involved in two applications: cellular base stations for wireless communications, and medical instruments that use superconducting quantum interference device (SQUID) magnetometers and gradiometers. Microelectronics-related applications are outlined in detail in a review article by Lubkin et al. [12]. The objective of the various programs is to accelerate the introduction of HTS technology into the commercial marketplace.

Characteristics of High-Temperature Superconductors

Most of the applications that have been envisaged for HTSs are still in their developmental stages and, so far, only a few products have been introduced into the marketplace. The reason for such a low output stems from the complexities of the HTS system [13]. Although major HTS compounds exhibit T_c values well above the boiling point of liquid nitrogen, they have both advantages and disadvantages. While TBCCO and mercury-barium-calcium-copper oxide (HBCCO) are still in the developmental stages, most applications currently use either BSCCO or YBCO. Toxicity of both thallium and mercury has posed a major stumbling block to the development of TBCCO and HBCCO. Several superconducting phases have been identified in the BSCCO homologous series, the most popular versions being $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (Bi-2212) with a T_c of ≈80 K, and $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) with a T_c of ≈110 K [13]. Because the homogeneity range of the Bi-2212 phase is well known, this phase can be prepared easily over a large composition range. In contrast, little information is available about the homogeneity range of the Bi-2223 phase, which has the highest T_c in the BSCCO homologous series. Two major issues seem to complicate the development of the Bi-2223 phase; it is stable in only a very narrow temperature range and the kinetics of its formation are so slow that it is almost impossible to obtain the phase-pure material [13]. Because of this, precise control over the processing parameters is required so the desired properties can be realized.

Current transport in HTSs is controlled by intra- and intergranular critical current density (J_c). High intragranular J_c values have been achieved in HTSs. Because current flow occurs by a percolative process, intergranular J_c is the main factor that controls the overall current transport property of a polycrystalline superconductor. A grain with high intragranular J_c will not be of much use if it is poorly coupled to the adjacent grain. Poor coupling or "weak link" is more severe in YBCO than in the other HTS families. In YBCO, weak links occur because of the formation of high-angle grain boundaries. These boundaries tend to act as barriers to the flow of supercurrent. According to Dimos et al., the principal way to avoid such weak links is to texture or align the grains so that their boundaries are at a low angle [14]. Salama et al., on the other hand, have recently shown that, in melt-processed polycrystalline YBCO samples, substantial current can be transported across grain boundaries with misorientations up to 30° [15]. Briefly, J_c characteristics of HTS are closely related to the distribution of grain boundary misorientations.

Apart from phase purity and grain alignment, an even more daunting challenge is to overcome the effects of an external magnetic field. In many envisioned bulk applications, such as motors, generators, transformers, and transmission cables, the presence of a magnetic field is an integral part of the systems operations [16]. An external magnetic field that is sufficiently strong can penetrate the superconductor in discrete bundles of flux lines or vortices. As long as the flux lines remain stationary, the HTS can withstand the external magnetic field without losing its superconducting properties. However, when an electric current is applied, the flux lines move or "creep" because of Lorentz force. Flux creep also occurs when the operating temperature increases in the presence of a magnetic field. Motion of flux lines blocks current flow and thereby causes dissipation of energy [8,13,17,18]. Effort is currently focused on circumventing the problem of flux motion by adopting various metallurgical techniques, for example, precipitating secondary phases, introducing fine-scale microstructural defects such as twins and inclusions, irradiating the material to form columnar defects, etc. These microstructural inhomogeneities are expected to pin the flux lines to their respective positions. By doing so, one can limit their disruptive tendency [8,13,17-21]. Modifications that are based on smart material design approaches have produced remarkable results.

YBCO samples have now been produced that carry 1 x 10^6 A/cm^2 at 77 K, dropping to only 4 x 10^5 A/cm^2 when a magnetic field of 9 T is applied. Both values are much better than the initial results, when YBCO could carry only 10 A/cm^2 and lost all conductivity in a field of only 0.01 T [21]. Although the intrinsic flux pinning of YBCO has improved, its intergranular current transport characteristics are poor because of weak links. On the other hand, despite its inadequate flux pinning, BSCCO has been preferred for various bulk applications. The irony is that the material with poor flux pinning characteristics is the one that is being most highly developed for various applications [8,18-22].

Status of High-Temperature Superconductor Applications

Widespread use of superconducting technology will depend on the performance of the HTSs and the economics involved in their operation. While bulk applications, such as transmission cables, motors, generators, transformers, and magnets, require that the superconducting material be either in the form of a wire or tape, microelectronic applications involve the use of superconducting material as thin films. This section briefly summarizes the progress made by the industry in developing HTSs for various applications.

Development of HTS Wires

For successful applications in high-field magnets, transmission cables, motors, transformers, etc., it is very critical that the HTS be fabricated into long-length conductors that exhibit high J_c values and mechanical reliability. However, to process HTSs, which are brittle oxide ceramics, into a more reliable and robust form is an extremely challenging and formidable task.

Because conventional techniques, such as sinter forging, hot pressing, tape casting, and jelly roll, could not be used, the powder-in-tube (PIT) technique was developed. The groups at Vacuumschmelze and Sumitomo Electric Industry (SEI) were the first to apply the powder-in-tube (PIT) technique to HTSs [13, 23-25]. In this technique, various ingredients for the precursor powder are mixed and treated so they react with each other. The resultant powder is then packed into a high-purity silver or silver alloy tube. Silver is used because it diffuses oxygen at high temperatures and thereby allows sensitive control of oxygen partial pressure during the reaction of the superconductor

[26]. The tube is then swaged and drawn through a series of dies to form a single-sheath wire ≈2 mm in diameter. The wires that are obtained are then rolled to form a tape with a final thickness of ≈0.1 mm. Multifilament conductors are fabricated by restacking monofilament wires in a larger silver tube and then subjecting it to a similar deformation sequence. The final step involves thermomechanical treatment that consists of a series of heat treatments and mechanical deformation steps [13]. During this stage, the precursor powder reacts to form the desired superconducting phases.

Tapes made by the PIT technique have a desirable geometry in which a brittle superconductor oxide is surrounded by a metallic sheath that protects the superconductor core from chemical, thermal, and mechanical abrasion. The main advantage of the PIT technique is that the metallurgical techniques employed in the fabrication of the tapes are all well established and can therefore be readily scaled up for mass production of long-length conductors. Also, texturing and grain alignment, which dictate the superconducting properties of the tapes, can be achieved very easily during the final thermomechanical treatment steps [13,23,24]. However, a complete understanding of the various parameters, such as the powder characteristics, sintering temperature, mechanical processing conditions, heat treatment time, cooling rate, etc., is essential so the desired properties can be realized. By carefully controlling these parameters, several research groups have reported J_c values of 5.4×10^4 A/cm^2 and 6.9×10^4 A/cm^2 for short-length BSCCO tapes that were subjected to a combination of uniaxial pressing and heat treatment [27,28].

Because uniaxial pressing is not amenable to the fabrication of long-length conductors, a more practical approach, such as rolling, has been adopted [13,23,24]. Companies such as IGC and ASC, in close collaboration with various universities and national laboratories, have been successful in making kilometer lengths of high-quality mono- and multifilament conductors. Figure 1 illustrates the current transport properties achieved in long-length HTSs that have been manufactured by two leading U.S. companies [7]. In collaboration with ANL, IGC reported a J_c of 1.8×10^4 A/cm^2 at 77 K and zero applied field for a 125-m-long monofilament conductor. Similarly, a consistent J_c of 1.2×10^4 A/cm^2 has also been achieved in a 1.26-km-long multifilament conductor fabricated by IGC [29]. The results indicate the substantial progress that has been made in the development of long-length conductors. However, comparison of their current transport properties with those of short-length tapes indicates that there is much room for improvement.

At present, efforts are underway to develop power transmission cables from these long-length conductors. The main advantage of these cables is that, for a given cross-sectional area, the superconducting cable can carry more current, without much

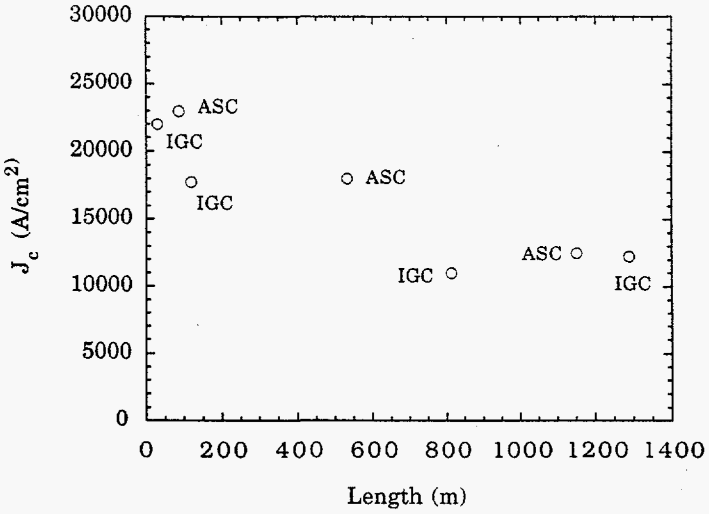

Fig. 1. Current transport properties of long-length HTSs manufactured by two leading U.S. companies.

transmission loss, than a conventional copper or aluminum conductor. Also, it can replace the ubiquitous high-tension towers and power lines that are a constant electrical and biological hazard [26,30].

Several cable and wire manufacturing companies around the world have teamed up to develop prototype power transmission cables. A consortium consisting of the world's second largest cable manufacturer, Pirelli Cables North America, ASC, EPRI, and DOE is developing a three-phase conductor enclosed in an 8-in. steel tube. Pirelli Cable recently reported a 50-m-long prototype conductor that carries 1800 A of DC. In Japan, the Tokyo Electric Power Company (TEPCO) is collaborating with SEI and Furukawa Electric Company to develop a coaxial power cable with a transmission capacity of 0.5-1.0 GW. Recently, TEPCO and SEI conducted a 7-h transmission test with an AC of 1 kA rms on a 7-m prototype cable [8,26].

Apart from the economics of the wire development projects, a few technical issues must still be addressed. When carrying an AC or in the presence of a changing magnetic field, HTSs exhibit energy losses. These losses generate heat, which, in turn, could lead to degradation of the current-carrying properties of the tapes. The level of such losses will have a critical impact on the commercial potential and engineering feasibility of an application. By twisting the tapes and by employing an alloy sheath material, the industry plans to mitigate the AC loss characteristics of the conductors [31].

Because BSCCO exhibits poor flux pinning characteristics, applications of this superconductor have been limited to those areas where operations are conducted at 35 K and in a magnetic field of 1 T. Inasmuch as YBCO behaves better than BSCCO in the presence of a magnetic field, effort is currently underway to use it for conductor development. In 1991, Iijima and his collaborators [32] at Fujikura Limited, Tokyo successfully developed a thick film of YBCO. The film was deposited by laser ablation on a nickel alloy substrate with a buffer layer of yttria-stablized-zirconia. The group achieved a critical current density of 1.13 x 10^6 A/cm^2 at 77 K and zero field in short-length samples and J_c of 2.1 x 10^5 A/cm^2 in a 70-m-long tape. The research group at LANL [33] reported a YBCO film, ≈1-2 μm thick, that was deposited by a similar technique. This was the first time the thickness of the film had exceeded 0.5 μm. The group reported very little loss in J_c when a field of 19 T was applied parallel to the tape surface. In a field of 5 T, applied normal to the plane of the tape, J_c was 1 x 10^5 A/cm^2 at 77 K. These results are encouraging, because they promise to extend the range of HTS applications, especially in the presence of high magnetic fields and temperatures [33].

Recently, several research groups have reported that most of the current in the BSCCO tape flows exclusively in a thin layer of highly aligned Bi-2223 grains that are present near the silver sheath. Existence of such a layer has been confirmed by microslice experiments, high-resolution electron microscopy, and magneto-optical imaging [34-36]. A high degree of texturing and high current transport properties have been observed in BSCCO tapes that consisted of two and four coaxial layers of Bi-2223 and silver [37]. In addition, Schwartz et al. have observed improved strain tolerance characteristics in Bi-2212 tapes fabricated by the silver wire-in-tube (WIT) technique [38]. Based on these results and the ever increasing demand for conductors with high current transport properties, we tried to fabricate superconducting tapes by the WIT method. Figure 2 is an optical photomicrograph of the WIT wire we obtained. The precursor powder in this case was synthesized by the freeze-drying technique. The powder was calcined at 800°C for 2 h in a 7% oxygen atmosphere. Short samples were cut and thermomechanically processed at various temperatures between 790 and 810°C in a 7% oxygen atmosphere. Development of the WIT technique was a joint effort between the University of Pittsburgh and ANL. Figure 3 shows the variation of J_c as a function of heat treatment time at 800°C in a 7% oxygen atmosphere. The best result of $J_c > 2.0$ x 10^5 A/cm^2 (I_c was 22 A) was obtained after 200 h and three intermediate uniaxial pressing. The results imply that the central region of the superconductor core does not contribute much to the overall current-carrying capabilities of the PIT tapes [34].

Poor mechanical properties have seriously hampered the commercial applications of HTSs. During fabrication and service, conductors are subjected to axial and bending stresses. The temperature gradient and magnetic field generated during operation can

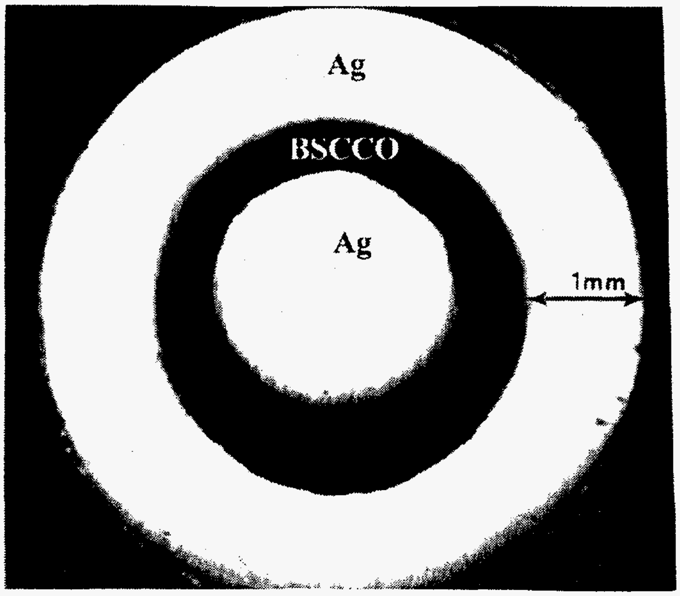

Fig. 2. Optical photomicrograph showing cross section of the silver wire-in-tube before rolling.

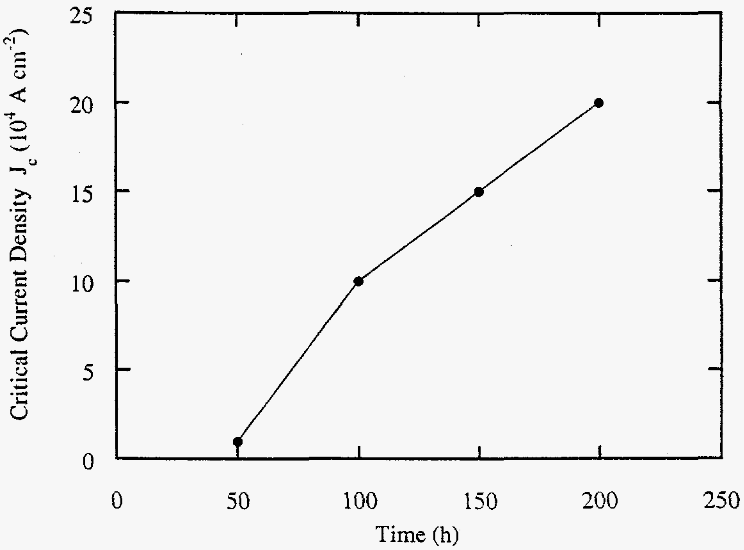

Fig. 3. Progression of J_c with time at 800°C in a 7% O_2 atmosphere; each step is accompanied by uniaxial pressing.

cause additional stresses in the material. In large and/or high-field magnets, the electromagnetic hoop stresses developed as a consequence of Lorentz force could even reach the ultimate strength of the material. These stresses can cause microstructural damage in the conductors and thereby degrade current transport properties. Although silver is widely used as a sheath material, its mechanical properties are not adequate to withstand the stresses developed during fabrication and service. Therefore, several techniques, such as adding silver to the superconductor powder, using alloy sheath material as an alternative to silver, and fabricating multifilament conductors, have been developed to improve the strain tolerance characteristics of the conductors [13, 39-41].

In-situ axial and bending tests were conducted with custom-designed test fixtures. Such in-situ characterization circumvents the errors introduced by repeated handling and thermal cycling of the tapes during external tests. Axial tests at 77 K and 0.5 T applied field indicated that the multifilament conductor exhibits better strain tolerance than the monofilament conductor, retaining >90% of its initial I_c at a strain that is ≥1%. While the irreversible strain (e_{irr}) for the multifilament conductor was ≈1%, that for the monofilament conductor was ≈0.2%. Figure 4 shows preliminary results on bending characteristics of monofilament conductors and of a multilayer composite tape, with various superconductor fill factors. The plot shows that ε_{irr} for the monofilament conductor increases with a decrease in superconductor fill factor. Also, the multilayer tape (with a fill factor of 40%) exhibited higher strain tolerance than the monofilament conductors, retaining 90% of its initial I_c at a bend strain of 1%. Thus, the added silver layer not only increases the strain tolerance of the tape, but by increasing the silver/superconductor interfacial area it should also increase the current transport properties of the tapes [42].

Magnets, Transformers, and Motors

Long-length monofilament HTSs have been co-wound to form pancake-shaped coils. Figure 5 shows an example of a pancake coil that was developed by IGC. The coil, wound from three 10-m lengths of rolled BSCCO tape, contained 57 turns and exhibited an I_c of ≈22 A at 77 K and 280 A at 4.2 K. The coil generated a magnetic field of ≈4200 and 330 G at 4.2 and 77 K, respectively. IGC has also fabricated a superconducting test magnet by stacking such pancake-shaped coils and connecting them in series. A prototype test magnet, fabricated by stacking 20 pancake-shaped coils, with a total conductor length of 2400 m, generated a field of 3.2 T at 4.2 K and zero applied field. Figure 6 shows an HTS magnet, fabricated by IGC, that generated a field of 1 T at 4.2 K in a 20-T background field [43]. ASC has developed a test magnet that generates a field of 0.6 T at 77 K and 3.4 T at 4.2 K. Currently, SEI holds the record for the highest field generated by a superconducting magnet; their magnet generated a field of 4 T at

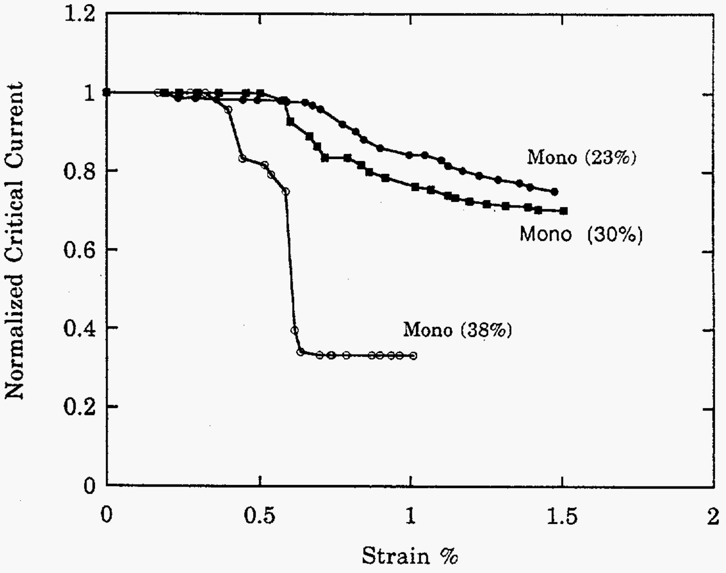

Fig. 4. Strain tolerance of silver-clad BSCCO monofilament tape with various fill factors.

4.2 K [26]. They plan to use these magnets as inserts in analytical equipment, such as that used for nuclear magnetic resonance (NMR) imaging, where low-temperature superconducting magnets are currently employed.

Intermagnetics General Corporation has developed a 0.25-KVA HTS transformer that includes a racetrack-wound solenoid. The primary end of the transformer was made of ≈85 m of BSCCO tape, the secondary end was 31 m long. Turns in the primary and secondary windings were 140 and 40, respectively. Intermagnetics General Corporation and Waukesha Electric Systems, Wisconsin have teamed with Rochester Gas and Electric and ORNL to develop a single-phase transformer rated at 1 MVA and operating at 20-50 K. The world's first prototype transformer is scheduled to be installed in the power grid for Geneva, Switzerland. The transformer is designed to produce 630 kVA at 77 K. American Superconductor Corporation will be providing the superconducting wire for ASEA Brown Boveri, which is involved in the project. Although issues such as AC loss remain, extensive studies by Pacific Northwest National Laboratory on size, weight, and cost savings indicate that transformers made with HTSs are commercially viable [8,26].

Reliance Electric Company and ASC, in cooperation with DOE, recently demonstrated a 200-hp HTS motor, which represents an output power 60% greater than the original design output of 125 hp. The 200-hp motor was designed and built by Reliance and included HTS rotor coils supplied by ASC. The motor was operated at

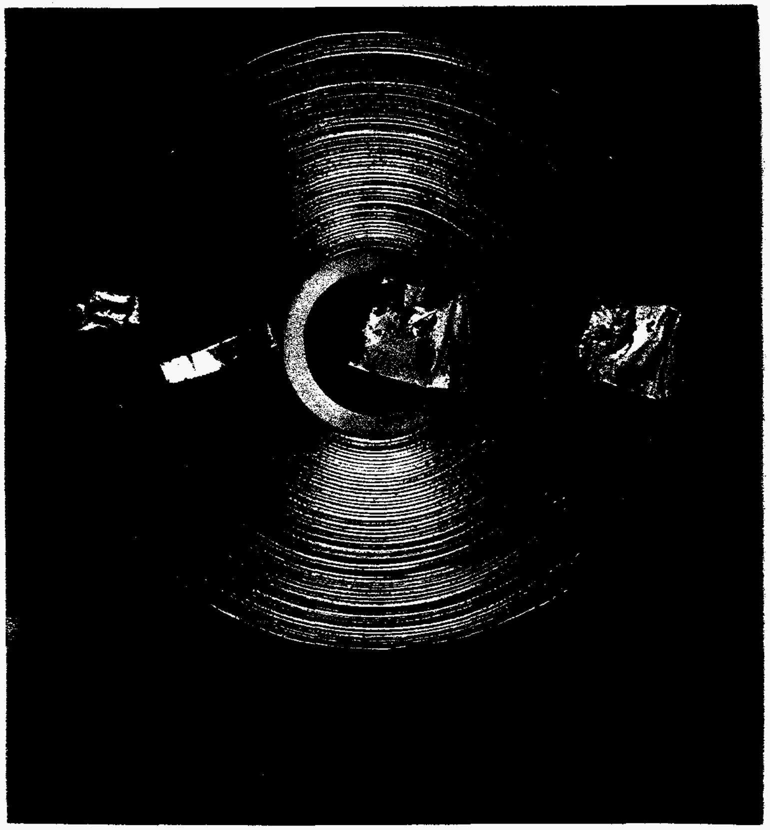

Fig. 5. Pancake coil co-wound with three 10-m lengths of rolled BSCCO conductors.

1800 rpm, with the rotating superconducting coils at 27 K [44]. The Naval Research Laboratory and the Naval Surface Warfare Center have also developed a motor that includes HTSs. The field magnet for the motor consisted of two racetrack coils each supplied by ASC and IGC. The output of the motor was 167 and 112 hp at 4.2 and 27 K, respectively [8]. DOE studies have established that ≈58% of the electrical energy generated in the U.S. is used by electric motors. Because of their current-carrying capacity, HTS motors will be smaller, lighter, and more efficient than currently available motors. As a result, economic benefits associated with superconducting motors are remarkable [45].

Current Leads and Fault Current Limiters

Current leads are used to connect superconducting devices in a cryogenic environment to the outside. Because HTSs exhibit low thermal conductivity, they can minimize energy loss, reduce boiloff of the cryogen, and raise efficiency of various

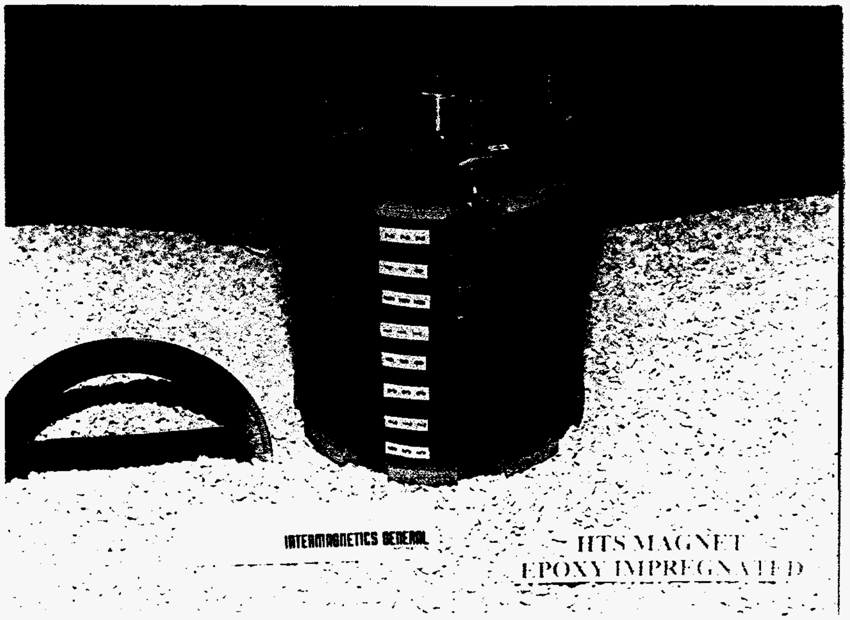

Fig. 6. HTS magnet, fabricated by IGC, that generated a field of 1 T at 4.2 K in a background field of 20 T.

superconducting devices. Sumitomo Electric Industries has been using an HTS current lead that carries 2000 A for its Nb_3Ti synchrotron radiation magnets [8]. Recently, ASC and ANL developed a 16,000-A-capacity HTS current lead for Babcock & Wilcox, who anticipate using the CryoSaver™ current lead, ASC's first commercial HTS product, for an energy storage device planned for Anchorage Municipal and Power in Anchorage, Alaska [46]. In fact, the CryoSaver™ current lead is the vanguard of a series of products that ASC plans to introduce in the near future.

A sudden surge in power can render equipment or a system ineffective. Traditional approaches of using circuit breakers with higher fault current ratings to curtail such power surges have proved to be expensive and inefficient. A fault current limiter that was developed with HTSs can reduce the current to a fraction of its peak value in <8 ms, thereby mitigating the effects of short circuits or power fluctuations [8,44]. Strategic location of the fault current limiter can result in effective cost savings in improved system operation. American Superconductor Corporation, in collaboration with Lockheed Martin Corporation, SCE, LANL, and DOE, successfully demonstrated a 2.4-kV, 2.2-kA HTS fault current limiter. This is the second commercial HTS product that ASC is marketing. Plans are underway to develop, with IGC, a 15-kV, 10.6-A HTS fault current limiter [47,48].

Conclusion

Significant progress has been made in the development of HTSs for various applications; some of them have already made significant strides in the marketplace, whereas others are still in the developmental stages. Several parameters involved in the PIT and WIT techniques must be carefully controlled to obtain the desired properties. By improving the superconductor/silver interface, we can improve not only the strain tolerance characteristics but also the current transport properties of the HTS tapes. Long-length mono- and multifilament conductors with consistently high current transport properties have been fabricated by a carefully designed thermomechanical treatment process. An HTS magnet and a prototype transformer have been fabricated from these long conductors. An HTS magnet that contains 2400 m of tape generated a field of 3.2 T at 4.2 K and zero applied field. In addition, considerable effort is being expended to improve the characteristics of HTSs for several other applications.

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