

RECENT ADVANCES IN FABRICATION OF HIGH-T<sub>c</sub> SUPERCONDUCTORS  
FOR ELECTRIC POWER APPLICATIONS\*

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# RECENT ADVANCES IN FABRICATION OF HIGH- $T_c$ SUPERCONDUCTORS FOR ELECTRIC POWER APPLICATIONS

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## 1. Introduction

The U.S. Department of Energy (DOE) supports an applied superconductivity program entitled "Superconductivity Program for Electric Power Systems." Activities within this program contribute to development of the high-temperature superconductor (HTS) technology needed for industry to proceed with the commercial development of electric power applications such as motors, generators, transformers, transmission cables, and current limiters. Research is conducted in three categories: wire development, systems technology development, and Superconductivity Partnership Initiative (SPI). Wire development activities are devoted to improving the critical current density ( $J_c$ ) of short-length HTS wires, whereas systems technology development focuses on fabrication of long-length wires, coils, and on magnets. The SPI activities are aimed at development of prototype products.

A  $J_c$  of  $5 \times 10^4$  A/cm<sup>2</sup> at 77 K has been obtained in short-length ( $\approx 4$  cm) powder-in-tube (PIT)-processed Bi-2223 tapes. The  $J_c$  value increased to  $\approx 2 \times 10^5$  A/cm<sup>2</sup> at 77 K in short-length samples when an Ag wire was

introduced into the Ag tube while preparing the billet. Enhancements in  $J_c$  were made through increased packing density of the precursor powder, improved mechanical deformation, and adjustments to cooling rate. Ag-clad Bi-2223 tapes of lengths  $>1$  km with  $J_c \approx 15$  kA/cm<sup>2</sup> are being manufactured routinely. Due to the poor flux pinning characteristics of Bi-2223, this material has been limited to applications that operate at 35 K in a magnetic field of  $\approx 1$  T. However, because Y-123 performs better than Bi-2223 in a magnetic field, efforts are currently underway to further its development. A  $J_c \approx 10^6$  A/cm<sup>2</sup> at 77 K has been reported for short-length Y-123 films on a polycrystalline metallic substrate with buffer layers. A 2.4 kV/2.2 kA current limiter, a 286 hp motor, and a 50-m-long cable have already been demonstrated under the SPI activities. A current overview and recent progress in HTS tape and application development will be presented in this paper.

## **2. Applications Development**

Development of HTS technology will make possible the design and production of smaller, lighter, and more efficient electric power devices such as motors, generators, transformers, cables, and fault current limiters. As shown in Fig. 1, over the 1986-96 decade several potential applications have been envisioned for HTSs [1].

To expedite the commercialization HTS technology, DOE has formed multidisciplinary teams comprising national laboratories, industry, utilities, and universities. The national laboratories and universities play a key role in developing the fundamental technology necessary for HTS applications,

while industry and utilities are responsible for development, cost-benefit analysis, and commercialization of various products. The SPI project, which began in 1994, is a flagship program in the nation's effort to commercialize HTS technologies. The SPI program consists of a vertically integrated team of utilities, system manufacturers, HTS component manufacturers, and national laboratories. Phase I of the SPI consisted of four industry-led teams focusing on four HTS products.

The first team was led by Lockheed-Martin Corporation and included American Superconductor Corp. (ASC, which has since withdrawn), Los Alamos National Laboratory (LANL), and Southern California Edison (SCE). The team is developing superconductor fault current limiters, which have an estimated global market of \$20 billion. A sudden surge in power can render equipment or a system ineffective. Traditional approaches of using circuit breakers with higher fault current ratings 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. The Lockheed-Martin-led team had successfully demonstrated a 2.4 kV, 2.2-kA HTS fault current limiter in 1995. This experimental prototype is being scaled up in the Phase II (1996-98) SPI project to a precommercial unit rated at 15-kV and 20-kA, and Intermagnetics General Corp. (IGC) has joined the team for the Phase II activity [2].

The second SPI team, selected to develop superconducting generators to lower the cost of electricity and serve a worldwide market estimated at \$30

billion, was led by General Electric Company (GE), which included the Electric Power Research Institute (EPRI), IGC, New York State Energy Authority, New York State Institute for Superconductivity, Niagara Mohawk Power, and Argonne, Los Alamos, and Oak Ridge National Laboratory (ANL, LANL, ORNL). This team focused on the conceptual design and assessment of a 100-MVA generator and the development of an HTS race track coil suitable for use in a full-scale generator. Ag-sheathed multifilamentary Bi-2223 superconductor tapes for the race track coil was manufactured by IGC. The coil, assembled with  $\approx 3.5$  km of Bi-2223 tape, achieved 34A at 25 K, which corresponds to  $\approx 40,000$  ampere turns and is considered adequate for an HTS generator.

The third SPI team was led by Reliance Electric Co. and included ASC, Centerior Energy, EPRI, and Sandia National Laboratory. This team is working on a 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 [3]. This team successfully tested in February 1996 a four-pole, 1800-rpm synchronous motor with HTS windings operated at 27 K. This HTS motor had an output of  $\approx 28$  hp. The HTS coils, manufactured from Bi-2223 tape by ASC, achieved currents of 100 A. The combined peak field attained by the four coils during the testing was nearly 1 T [4]. In August 1997, the DOE extended the RELiance-led motor program into a Phase II SPI effort, to develop a precommercial prototype of a 5000 hp HTS motor.

The fourth team's goal is to develop two types of HTS power cable systems. Pirelli cables North America, ASC, EPRI, and LANL are at work on retrofit cables and coaxial cables. The retrofit cables, as the name suggests, will be drawn into existing conduits where they will replace copper cables that are worn out or exhibit reduced power capacity. The second type, coaxial cables, will be used primarily for underground installations [5]. A 50-m-long flexible conductor assembly was manufactured by Pirelli with Bi-2223 tapes supplied by ASC and was tested at 3300 A DC.

Besides the four SPI projects, industry-led teams have also started projects on transformers and flywheels, as well as one new transmission cable design. Waukesha Electric Systems has teamed with IGC, Rochester Gas and Electric Corp., Rensselaer Polytechnic Institute, and ORNL to develop a HTS transformer. This team has conducted a series of reference designs concentrating on a 30-MVA, 138-kV/13.8 kV HTS transformer. This rating is representative of a medium-power transformer class foreseen as comprising about 50% of all U.S. power transformer sales in the next two decades [6]. One major advantage of the HTS transformer is the elimination of fire-hazardous oil used in conventional transformers. In the HTS transformer, the only substance present in large volume is nonflammable and environmentally benign liquid nitrogen. The Waukesha-led team has focused on the design of a low-loss conductor and winding configuration and has come up with a proprietary design for its HTS transformer. At present, this team is working on the demonstration of a 1-MVA cryocooled, 13.8 kV/6.9-kV single-phase transformer that uses a relatively low cost surface coated Bi-2212 conductor.

Commonwealth Research Corp., a subsidiary of Commonwealth Edison, has joined ANL in developing flywheels with HTS bearings for energy storage applications. Other groups active in the flywheel project in the U.S. include the University of Houston and Boeing Co., Southwire Co., the largest U.S. cable manufacturer, has teamed with ORNL, ANL, and IGC to develop a new transmission cable design. The Southwire-led team plans to build a 33-m-long, cryogenic-dielectric, three-phase, 12.4 kV, 1250-A system by 1999. This team has already fabricated and tested several 1-m-long conductors carrying up to 2 kA at 77 K.

In Japan, Tokyo Electric Power Co. (TEPCO) is working with Sumitomo Electric Industries (SEI) and Furukawa on developing a 66-kV, 1000-MVA HTS cold-dielectric cable system with the ultimate goal of deploying it around Tokyo to meet the city's growing needs. The TEPCO team has tested a 50-m-long conductor carrying 2 kA AC [7]. In Europe, Siemens plans to develop a 100-m-long prototype cable by 1999. Siemens and Hydro Quebec are collaborating to develop fault current limiters based on two different concepts (screened core and resistive type). Asea Brown Boveri (ABB) is developing an inductive fault current limiter and a transformer. ABB connected the world's first operating HTS transformer to the Geneva (Switzerland) Power Supply network in March 1997. This three-phase transformer has a rating of 630 KVA and converts power from 18.7 kV into 420 V, using Bi-2223 windings cooled in liquid nitrogen. This unit is now undergoing long-term performance monitoring under actual power grid conditions. ABB is planning two commercial 10-MVA transformers in 2001. ABB has also reported endurance and performance test results for a 1-MVA

HTS fault current limiter, installed in November 1996 at the Kraftwerk am Loentsch hydroelectric power plant in Switzerland. This fault current limiter uses bulk Bi-2212 rings and displayed smooth current limitation without high overvoltages when tested with a prospective short-circuit fault current of 60 KVA. Endurance tests indicated no major problems after six months of operation and, according to ABB, refilling of the nitrogen tank was the only significant maintenance required during the testing period. ABB is beginning to focus its efforts on developing a 10-MVA unit with closed-cycle cooling.

### **3. HTS Wire Development**

Most prototype products currently use either bismuth-strontium-calcium-copper oxide (BSCCO) or yttrium-barium-copper oxide (YBCO) superconductors. 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 the current flows 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. Therefore, phase purity, grain alignment, and grain connectivity are very important in the fabrication of HTSs. For successful applications, HTSs must be fabricated into long-length conductors that exhibit high- $J_c$  values and mechanical reliability. However, the processing of HTSs (which are brittle oxide ceramics) into more reliable and robust forms is an extremely challenging and formidable task. The groups at Vacuumschmelze and SEI

were the first to develop the powder-in-tube (PIT) technique for the fabrication of HTSs [8,9]. In this approach, various ingredients for the precursor powder are mixed and treated so they react with each other. The resultant powder is then packed into a silver or silver alloy tube that is then swaged and drawn through a series of dies to form a silver-sheathed wire  $\approx 2$  mm in diameter. These wires are then rolled to form a tape with a final thickness of  $\approx 0.1$  mm. Multifilament conductors are fabricated by restacking monofilament wires in a larger silver tube and then using a similar deformation sequence. The final step involves thermomechanical treatment that consists of a series of heat treatments and mechanical deformation steps [10-13]. 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. Companies such as IGC, ASC, and SEI have been successful in making kilometer-long high-quality mono- and multifilament conductors. Recently, ASC reported a self-field  $J_c$  of  $\approx 7 \times 10^4$  A/cm<sup>2</sup> in short-length rolled multifilamentary tapes [14]. A  $J_c$  of  $1.5 \times 10^4$  A/cm<sup>2</sup> has also been achieved in a 1.26 km-long multifilament conductor fabricated by IGC [15].

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 near the silver sheath. Existence of such a layer has been confirmed by microslice experiments, high-resolution electron microscopy, and magneto-optical imaging [16-18]. The high-current superconducting layers are generally  $\approx 2.3 \mu\text{m}$  thick and have been shown to support a transport current with a  $J_c$  value  $> 10^5 \text{ A/cm}^2$  at 77 K [16,19]. Transport  $J_c$  values of tapes with identical superconductor cross-sectional areas, but differing Ag/Bi-2223 interfacial lengths, confirm the importance of the interfacial region [20]: the critical current was shown to be proportional to the Ag/Bi-2223 interface perimeter length (IPL), expressed as a linear function. These results imply that  $< 10\%$  of the Bi-2223 superconductor transports the vast majority of supercurrent in Ag-clad Bi-2223 tapes. Thus,  $J_c$  values can be increased by microstructural design through optimization of the IPL.

Efforts to enhance  $J_c$  by increasing the Ag/Bi-2223 interfacial area continue. Fabrication of multifilamentary tapes achieves this goal, but, in general, the areal fraction of Ag increases for such tapes [21]. An alternative approach is to incorporate Ag wires into a Bi-2223 core. Initial work focused on use of a single Ag wire. The  $J_c$  value increased to  $\approx 2 \times 10^5 \text{ A/cm}^2$  at 77 K in short-length samples by this approach [19]. In addition to offering possibilities for improved transport  $J_c$ , significant enhancement of bend-strain tolerance with a wire-in-tube approach has been reported [22]. This duplex-core work has recently been extended to a two-step process in which many fine Ag wires are coated with Bi-2223 precursor powder and then loaded into an Ag tube. Conventional PIT working then produces a tape

with a very high Ag/Bi-2223 interfacial area [23]. To date, up to 600 Ag wires, coated with Bi-2223 precursor, have been loaded into a single Ag tube and processed into tapes. Despite the smaller cross-sectional area of the superconducting core, transport  $J_c$  values are now greater than those of corresponding monofilament tapes [23].

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  $<1$  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 collaborators [24] at Fujikura Ltd. 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-stabilized-zirconia (YSZ). The buffer layer was obtained by the ion-beam-assisted deposition (IBAD) technique. The group achieved a critical current density of  $1.13 \times 10^6$  A/cm<sup>2</sup> at 77 K and zero field in short-length samples, and a  $J_c$  of  $2.1 \times 10^5$  A/cm<sup>2</sup> in a 70-cm-long tape. SEI reported a  $J_c$  of  $3 \times 10^5$  A/cm<sup>2</sup> in a 10-cm-long YBCO film on a Hastelloy substrate with a YSZ buffer layer. The YSZ layer was produced on the substrate by an inclined substrate deposition technique. The research group at LANL, working on the IBAD technique, reported a YBCO film  $\approx 1.2$   $\mu$ m thick and  $\approx 2$ -cm-long with  $J_c \approx 1 \times 10^6$  A/cm<sup>2</sup> [25]. 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  $1 \times 10^5$  A/cm<sup>2</sup> at 77 K. ORNL has produced epitaxial YBCO films with  $J_c$  in the range of  $1-3 \times 10^6$  A/cm<sup>2</sup> at 77 K [26]. The YBCO film was obtained by using

laser ablation on rolling-assisted biaxially textured substrates. Oxide buffer layers were deposited on textured nickel substrates by three techniques: laser ablation, electron-beam evaporation, and sputtering. A team consisting of researchers from the University of Munich, University of Göttingen, and Siemens have deposited YBCO films using coevaporation technique on substrate as large as 20 x 20 cm. They reported a  $J_c$  of  $0.7-2 \times 10^6$  A/cm<sup>2</sup> on small regions of 20 x 20 cm film [27]. These results are encouraging because they promise to extend the range of HTS applications, especially in the presence of high magnetic fields and temperatures.

#### **4. Conclusions**

Significant progress has been made in the development of HTSs for various applications: some applications have already made significant strides in the marketplace, while others are still in the developmental stages. For successful electric power applications, it is very important that the HTS be fabricated into long-length conductors that exhibit desired superconducting and mechanical properties. Several parameters of the PIT technique must be carefully controlled to obtain the desired properties. Long lengths of Bi-2223 tapes with respectable superconducting properties have been fabricated by a carefully designed thermomechanical treatment process. A 1-MVA capacity fault current limiter, a 286-hp motor, and 630-kVA transformers, and a 50-m-long conductor, all using HTSs, have already been demonstrated. While the use of HTS devices in the electric utility area has clear advantages, impediments to successful commercialization remain. Issues such as AC losses, conductor cost, and reliable superconducting joints

must be addressed. The cost of HTS conductors are still quite high, and significant R&D effort must be focused on this issue. The general acceptance of HTS power equipment will ultimately be based on system performance, reliability and maintenance, efficiency, and installed cost relative to those of conventional technologies.

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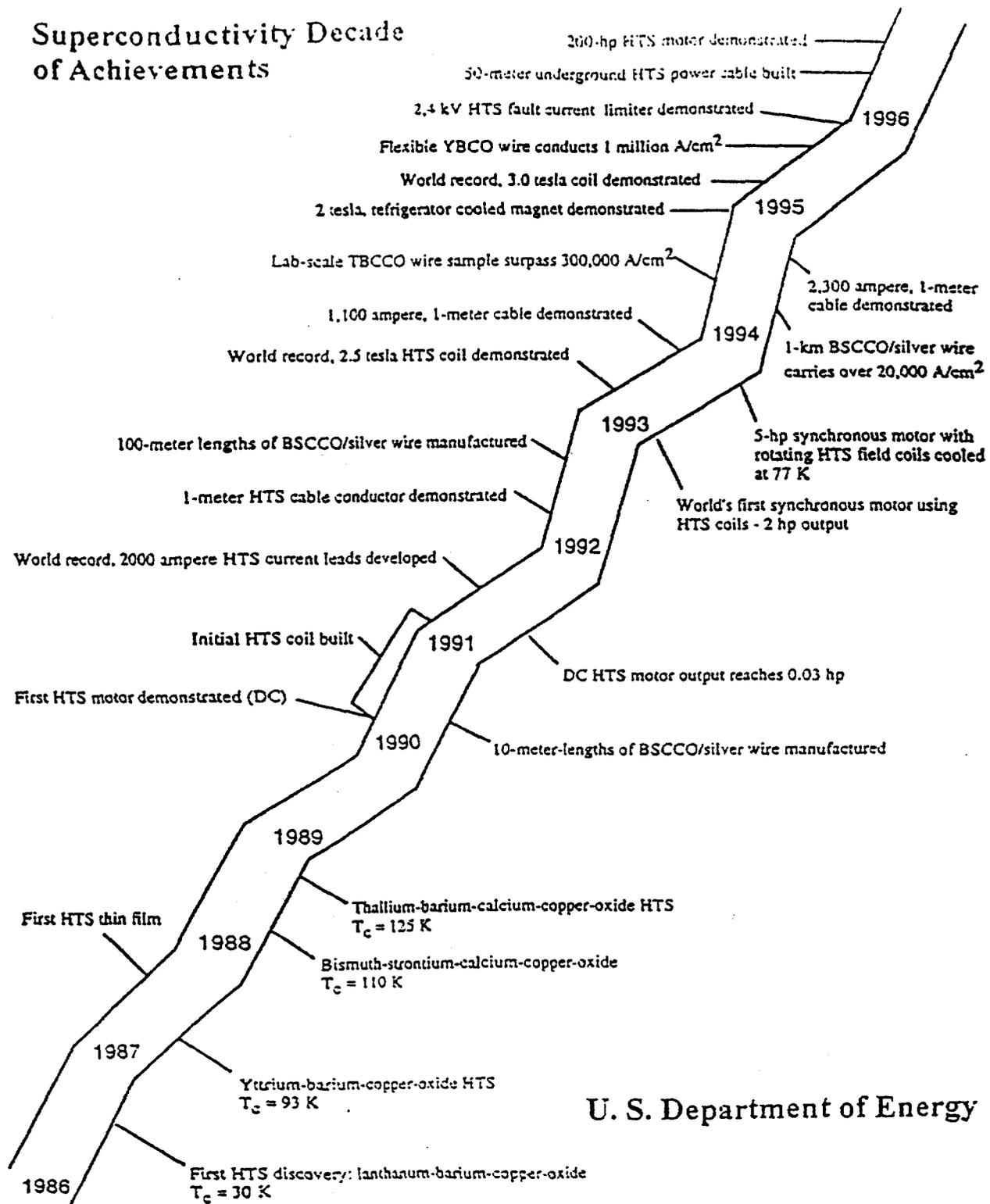
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# Superconductivity Decade of Achievements



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Figure 1. Progress made, 1986-1996, in developing several potential bulk and microelectronic applications (ref. #1).