Present Status and Future Perspective of High-Temperature Superconductors

Ken-ichi SATO

In 1986, high temperature superconductors (HTS) were discovered, and in 1987 a yttrium-based HTS material (YBaCuO) was discovered followed by a bismuth-based (BiSrCaCuO) HTS material in 1988. Among them, the BiSrCaCuO HTS material was discovered in Japan, and we can improve a critical current property by adopting plastic deformation process with a feature of mass production. Althogh this material has shortcomings of brittleness due to a nature of oxide, a multi-filamentary structure could overcome this shortcomings. Furthermore, usually it is hard to obtain 100% density of oxide by conventional sintering technique resulting in 85% density of oxide. By developing a controlled over pressure technique, so called "CT-OP™", it became feasible to obtain 100% density of oxide leading to higher critical current due to improvement of crystal connectivity and better mechanical properties due to eliminating porosities in the oxide. This newly developed technique could make it possible to supply execellent BiSrCaCuO wires (DI-BSCCO®) commercially with high performance and long length features. This paper will describe our history of wire development and together with application prototypes and future directions.

1. Introduction

In 1911, the year of the establishment of the Sumitomo Electric Wire & Cables Works (first founded as the Sumitomo Copper Rolling Works in 1897), H. Kamerlingh-Onnes in the Netherlands discovered "superconductivity" by measuring the resistance of mercury at liquid helium temperature (4.2 *K*), which rapidly went below the lower limit of detection of his measuring system. After the discovery of superconductivity of mercury, a variety of metals, alloys and compounds were revealed to show superconductivity. A. Müller and J. Bednorz [(1)] in Switzerland discovered high-temperature superconductivity in the compound LaBaCuO at 35 *K*, which was far above the temperature predicted by the BCS theory. S. Tanaka and K. Kitazawa [(2)] confirmed that LaBaCuO has superconducting properties, i.e. zero resistance and diamagnetism. High-temperature superconductivity (HTS) is a basic and innovative technology that is involved in one of the three greatest technological discoveries of the 20th century, namely nuclear power, electronics and superconductivity.

After the discovery of the cuprate compound LaBaCuO in 1986, YBaCuO [(3)] whose critical temperature is 90 *K*, BiSrCaCuO [(4), (5)] whose critical temperature is 110 *K* and TlBaCaCuO [(6)] whose critical temperature is 125 *K* were discovered, enabling the use of liquid nitrogen (77.3 *K*) as coolant. It was enthusiastically expected that high-temperature superconductivity has a great influemce on the fields of energy and electronics from the technological, economical and resources-related perspectives and because of the possibility of liquid nitrogen cooling.

Among various cuprate compounds with a composition of BiSrCaCuO, $Bi_2Sr_2Ca_2Cu_3O_{10-x}$ has a high critical temperature of 110 *K* (-163°C), which is close to the boiling temperature of liquid natural gas (LNG), and can be cooled with liquid nitrogen, meaning that there is no need to use expensive liquid helium used for metallic superconductors such as NbTi and Nb_3Sn. Moreover, BiSrCaCuO does not contain expensive rare-earth elements and toxic elements. Cuprate compounds belonging to the BiSrCaCuO family had attracted a great deal of public attention and there had been global competition to develop BiSrCaCuO wires.

Despite above world-wide efforts after 1988, for a long time it remained an open question how a wire with high critical current (*Ic*), long length and ductile shape can be obtained using this brittle oxide material. Because relation between microstructure and superconducting properties was unclear, it had been unable to establish clear development principle.

This paper describes the results of a fundamental research regarding electromagnetic properties and relation between microstructure and superconducting properties. This research was aimed at obtaining a clear development principle and achieving high levels of critical current, strain tolerance, tensile strength and operation performance under a wide range of conditions that are important in actual applications. Typical applied products of superconductivity include transmission cables and magnets.

Table 1 shows the history of the development of BiSrCaCuO superconducting wires and applied products. Both developments were concurrently pursued to understand the merits and demerits of products that use high-temperature superconductors.

Table 1. Development history of BiSrCaCuO wires and applied products

	1988-1989	1990-1994	1995-1999	2000-2004	2005-2006	2007
Material	·Discovery of BSCCO					
Wire	·High-Jc & long-length wire ·Multi-filamentary wire		·Ag-alloy sheath ·1,000-m-long wire	·CT-OP (Controlled Over-Pressure)	·Critical current = 200 A ·Tough type	·Critical current = 218 A ·Slim type ·AC type
Current lead & Busbar		·500 A lead ·2,000 A lead ·1,000 A/5 m busbar ·10,000 A busbar	·600 A lead for MAGLEV ·2,000 A lead for SMES and SR ·10,000 A lead for fusion magnet ·20,000 A busbar			
Cable		·2,000 A cable conductor ·"3-in-One" 66 kV /7 m cable	·50 m/2,00 A cable conductor ·"3-in-One" 66 kV /30 m cable	·66 kV/100 m/114 MVA cable	·22.9 kV/100 m /1250 A cable for KEPRI ·34.5 kV/350 m /800 A cable for on-grid connected Albany HTS cable system	·66 kV/200 MVA project started
Magnet		·2T/40mm	·4 T/50 mm/RT bore ·7 T/50 mm/RT bore	·Magnet for Si crystal growth		·8.1 T/200 mm/ RT bore
Transformer			·800 kVA	·1 MVA	·3.5 MVA	
Motor					·12.5 kW ship motor	·365 kW ship motor

2. Development of BiSrCaCuO superconducting wires

2-1 Metal-sheathing and rolling process

Table 2 describes the three different processes (solid-phase, liquid-phase and gaseous-phase) for making a high-temperature superconductor into a wire shape. Systematic research was pursued on the metal-sheathing and rolling process, which is a solid-phase process, for the purpose of establishing a principle for developing BiSrCaCuO wires having higher critical currents through research on microstructures, especially regarding relations between critical currents and non-superconducting compounds and between critical currents and grain boundary microstructures.

The metal–sheathing and rolling process is advantageous that (1) long and thin wires can be mass-produced by using metal deformation techniques such as drawing and rolling, and (2) metal sheath can work as a stabilizer when superconductivity is partially destroyed. On the contrary, at the beginning of the wire development stage, the critical current density (*Jc*) of BiSrCaCuO wires fabricated by this process was extremely low and was 1,000 A/cm^2 at 77.3 *K*, which was three orders lower compared with *Jc* of thin film superconductors. Moreover, the magnetic field dependence of *Jc* was 1/100 at several hundreds gausses, which means that these wires cannot be practically applied.

For example, it has been revealed that wires made from YBaCuO, which was discovered one year earlier than BiSrCaCuO, can have its *Jc* improved to 3,330 A/cm^2 by use of the rolling technique from 230 A/cm^2 that was achieved by the drawing technique [7]. It is believed that this is due to the improved density of YBaCuO (from 5.3-5.4 g/cm^3 to 5.7-5.9 g/cm^3) and the shape uniformity of superconductors. However, there was no clear principle of quantitative analysis on homogeneity of superconducting phases, superconductor alignment and grain boundaries. In regard to the

Table 2. HTS wire manufacturing processes

Phase	Principle	Technology	
Solid	Metal-sheathing	Extrusion	
		Drawing	Silver-sheathing
		Rolling	
	Organic binder	Doctor blade	
		Extrusion	
		Spinning	
	Diffusion		
Liquid	Melting	Solidification	
		Directional solidification	
		Rapid solidification	
		Spray	
	Solution	Sol-gel	
		Metal organic deposition (MOD)	
Gas	Physical vapor deposition (PVD)	Sputtering	
		Evaporation	
		Molecular beam epitaxy (MBE)	
		Pulsed laser deposition (PLD)	
	Chemical vapor deposition (CVD)		

anisotropy of *Jc*, it was already known that in the aligned single-crystalline YBaCuO thin films on SrTiO3 single crystal substrates, *Jc* in the direction of a-b plane was $1.8\text{x}10^6$ A/cm^2 while *Jc* in the direction of c-axis was 10^4 A/cm^2, which was two orders lower than that in the direction of *a-b* plane. However, it was still unclear which direction improves *Jc* of polycrystalline superconductors such as wires.

It was essential to explore the direction in which *Jc* improves by clarifying the relation between microstructures and critical current properties from the aspects of the materials and the processing techniques. The basic procedure of the metal-sheathing and rolling technique is as follows: After the oxide or carbonate powders of Bi, Pb, Sr, Ca and Cu were weighed, mixed, calcined and pulverized, they are packed into a silver tube, drawn into a round wire, and finally rolled into a tape-shaped wire. The tape-shaped wire is then sintered to become a superconducting wire. Because silver does not oxidize at high temperatures and does not react with superconducting materials, silver sheaths can be used as stabilizers. The notable feature of this BiSrCaCuO wire fabrication technique is that repeating the rolling and sintering processes [9] made it possible to improve *Jc* from 5,000 A/cm^2 to 54,000 A/cm^2 at 77.3 *K*, thus achieving critical current performance 5 to 50 times higher than that obtained by the conventional technique [(10)-(12)].

2-2 Development of high-pressure sintering technique (CT-OP: Controlled Over-Pressure)

Figure 1 shows the manufacturing process of BiSrCaCuO wires. Crystals need to be aligned to overcome the two-dimensionality of HTS materials. For this purpose, the author and his team at Sumitomo Electric developed the double-rolling/ double-sintering process. The author and his team also developed a new process named the CT-OP process in which the wire is sintered at the controlled pressure, temperature and precisely controlled oxygen content [(13)-(15)]. By using the CT-OP process, the following improvements were achieved: (1) Crystal connectivity is improved and critical current (Ic) is enhanced to between 150 and 218 A, 1.5 to 2 times higher than that obtained by the conventional technique, (2) mechanical properties are improved to 1.5 to 2 times higher than that obtained by the conventional technique, (3) production yield is enhanced to a level high enough for an industrial product, and (4) wire unit length exceeds 1,800 m. **Figure 2** shows the improvements in *Ic* measured over wire lengths.

This newly developed CT-OP technique is very different from the conventional technique and requires oxygen content to be controlled at high precision. Therefore, a large amount of time was spent in developing this technique. The CT-OP furnace was installed in 2004 after five years of R&D efforts, and has been in operation successfully since then. The BiSrCaCuO wires manufactured by the CT-OP process have superconductors having a 100% density, and also exhibit greatly improved characteristics. These wires are named DI-BSCCO, which stands for "dynamically innovative BSCCO".

2-3 Improvement of microstructure

It was very difficult to obtain homogeneous superconducting phases in BiSrCaCuO at the early stage of

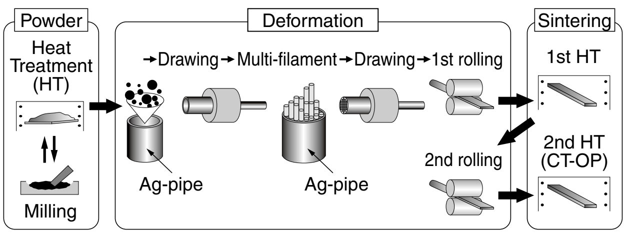


Fig. 1. BiSrCaCuO superconducting wire manufacturing process and CT-OP sintering process

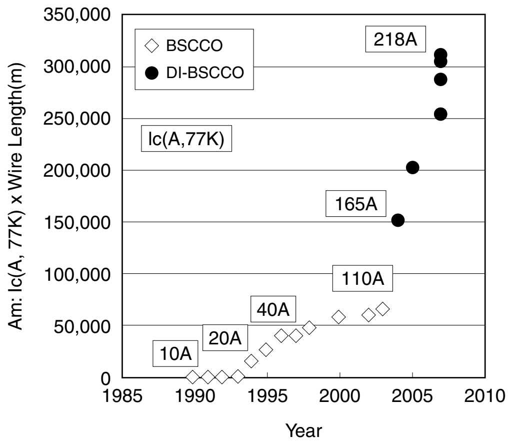


Fig. 2. Improvement in performance of BiSrCaCuO superconducting wires

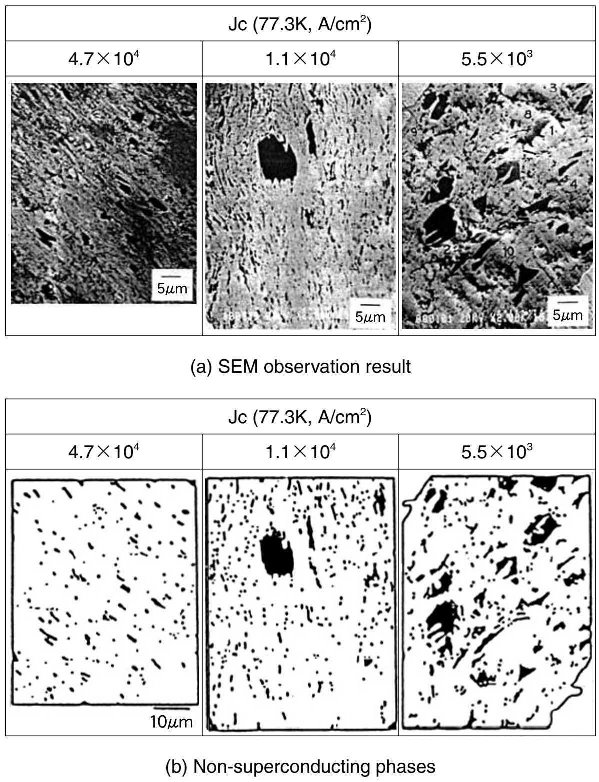


Fig. 3. Microstructures of BiSrCaCuO wires

development. This was because BiSrCaCuO exhibits three superconducting phases (2223 phase, 2212 phase and 2201 phase), and contains 10 or more of non-superconducting compounds. **Figure 3** shows SEM photographs of the cross-sections of three BiSrCaCuO wires with different *Jc* and hand-drawn illustrations of non-superconducting phases. **Table 3** shows the percentage of non-superconducting phases in the cross-sectional area of each wire [(16)]. The percentage of non-superconducting phases decreased from 30% to 8% as *Jc* increased from *Jc* (77.3 *K*) = 5,500 A/cm^2 to *Jc* (77.3 *K*) = 47,000 A/cm^2, showing a quantitative relation between microstructure and *Jc*. Obtaining more homogeneous 2223 phase still remains to be an important research theme studied among many researchers [(17)-(24)].

Table 3. Relation between Jc and non-superconducting phases

Jc (77.3K)	Percentage of area of non-superconducting phases
5,500A/cm^2	30%
11,000A/cm^2	20%
47,000A/cm^2	8%

2-4 Current transport properties and grain boundaries

It was observed in systematic studies of the electromagnetic characteristics of wires having *Jc* ranging from 1,000 A/cm^2 to 54,000 A/cm^2 that improving weak links at grain boundaries could lead to the improvement of *Jc* and its dependence to magnetic field. It was also observed that the transport current flowing in the *c*-axis direction through platelet crystal grain boundaries greatly affects the magnetic field dependence of *Jc*, which means that crystal connectivity and microstructure of grain boundaries have a great effect on determining transport current properties. **Figure 4** shows an example of such effect.

Figure 5 shows TEM photographs [(25)] of the wires with different *Jc*: (a) *Jc* (77.3 *K*) = 5,000 A/cm^2 and (b) *Jc* (77.3 *K*) = 45,000 A/cm^2. Wire (a) has non-superconducting phases at grain boundaries, while wire (b) has no such phases and grains bond together along the c-plane. It is anticipated that the non-superconducting phases that exist at grain boundaries worked as the weak links, as can be explained by a grain boundary model shown in **Fig. 6** [(26)].

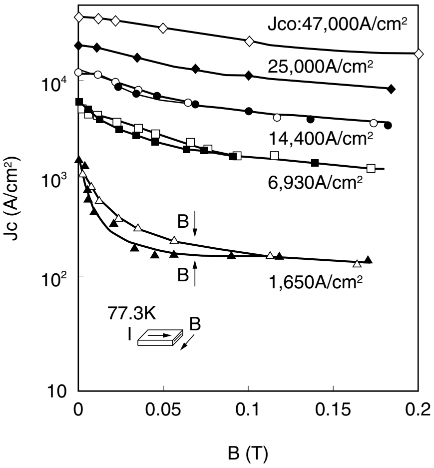
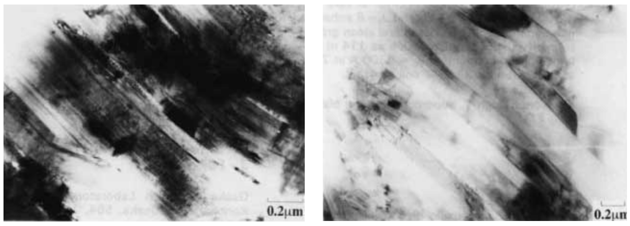


Fig. 4. Magnetic field dependence of Jc



(a) Jc = 5,000 A/cm^2 (b) Jc = 45,000 A/cm^2

Fig. 5. TEM observation results

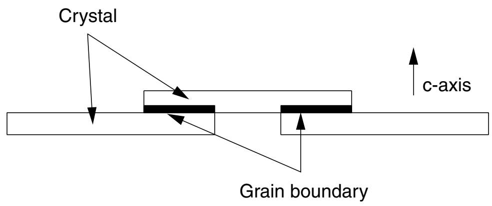


Fig. 6. Grain boundary model

3. Properties necessary for actual applications

3-1 Flexibility

In actual applications such as power cables, motors and magnets, superconducting wires need to be flexible in order to withstand the wire winding process and tolerate stress and strain during use.

Metallic superconducting wires should have a multi-filamentary structure for the purpose of obtaining electromagnetic stability, but HTS wires do not need to be formed into a multi-filamentary structure to obtain stability. This is because HTS wires exhibit good heat capacity characteristics at higher operating temperatures, and thus can operate more stably against thermal disturbance from the outside and inside of the wire (i.e. wire movement).

Strain characteristics of wires with different filament numbers (36, 762 and 1296 filaments) were investigated. Bending strain was applied at room temperature and *Ic* was measured at 77.3 *K* in the bended condition to evaluate the change in *Ic* before and after bending. Bending strain was applied as is shown in Equation (1).

Bending strain (%) = t/2R x 100 ··········(1)

t: Thickness of BiSrCaCuO wire (mm)
R: Bending radius (mm)

Figure 7 shows the result that the more the number of filaments, the less the degradation of *Jc* caused by strain [27]. Because the 1296-filament wire could withstand a strain of upto 0.7% without reducing *Jc*, it was revealed that this multi-filamentary structure makes wires flexible even if the HTS material is brittle. This is considered to be due to the fact that when BiSrCaCuO is dispersed in a silver matrix, BiSrCaCuO is not easily cracked even when a certain amount of bending strain is applied to the wire.

When the wire is cooled down to 77.3 *K* after being sintered at 830°C to 850°C, the BiSrCaCuO portion is compressed due to the difference in thermal expansion coefficient between BiSrCaCuO and silver (BiSrCaCuO: $13x10^{-6}$/°C, silver: $22x10^{-6}$/°C). When bending strain is applied to the wire, the wire can withstand against bending strain until residual compressed stress [28] is offset by bending tensile stress. When applied tensile stress increases beyond residual compressed stress, cracks are formed in BiSrCaCuO and results into the degradation of Ic. The more the number of filaments, the less the cracked area. Because bending stress applied to a wire is smaller at the center of the wire than at the surface, a larger number of filaments results into less cracked filaments. Thus, the tolerance against bending strain can be improved by increasing the number of filaments.

During the manufacturing process, a BiSrCaCuO wire is bent many times and then finally reeled on a spool. In power cable applications, for example, the wire is wound around a former to form a conductor, wrapped with an electrical insulation layer, and then inserted into a thermally-insulated pipe to become a power cable. The cable is wound on a drum and shipped to a cable laying site. At the laying site, the cable is drawn off from the drum and pulled into a conduit. Therefore, because bending is applied many times in actual applications, bending evaluation must be conducted on not only a single bending but on repeated bendings.

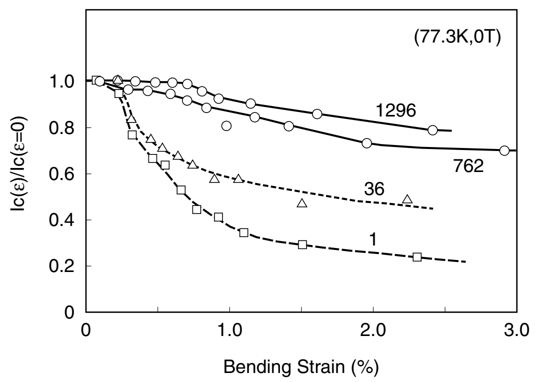


Fig. 7. Bending characteristics of multi-filamentary wires

Figure 8 shows the repeated bending characteristics of the 61-filament wire [27], [29]. A bending cycle consists of bending, straightening, reverse bending, and straightening. After 150 cycles (600 times bending) with a 0.18% bending strain, the wire exhibits *Ic* retaining

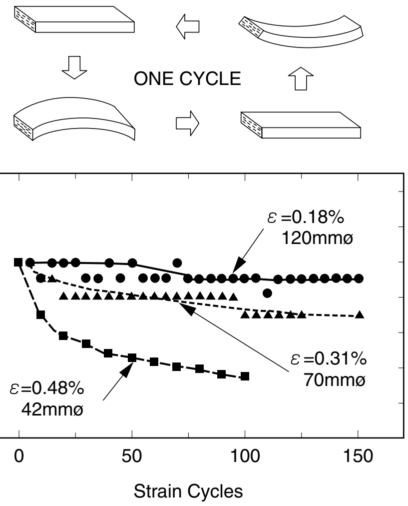


Fig. 8. Repeated bending characteristics of 61-filament wire

90% of its initial value and thus shows excellent anti-bending characteristics.

Although more filaments results into better bending properties, it also means more complex manufacturing process and smaller Ic. Therefore, the number of filaments was optimized [30].

3-2 Critical current density evaluation at wide temperature and magnetic field ranges

BiSrCaCuO wires are aimed for many applications at wide ranges of magnetic field and temperature (at 77.3 *K*, 20 *K* and 4.2 *K*) [31], [32]. They have higher *Jc* than metallic superconductors at 20 *K* and 4.2 *K* at 20 *tesla* (= 200,000 *gauss*) [33]-[35]. The result of the evaluation of *Jc* at wide ranges of temperature and magnetic field is summarized in **Fig. 9**.

Figure 10 shows the characteristics of a present 200-*A*-class BiSrCaCuO wire under various ranges of temper-

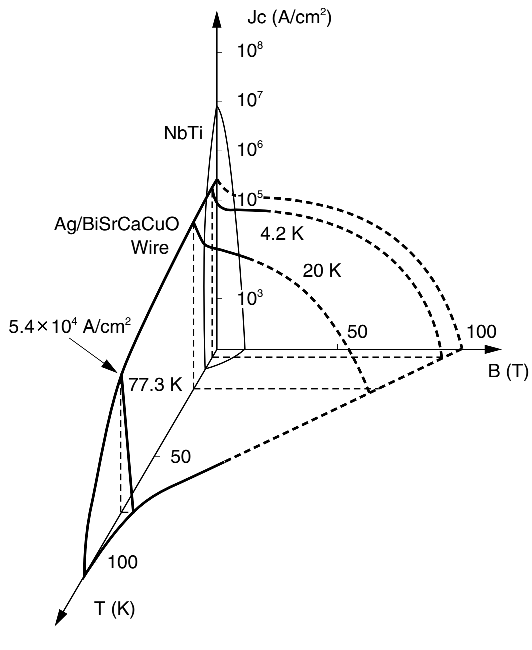
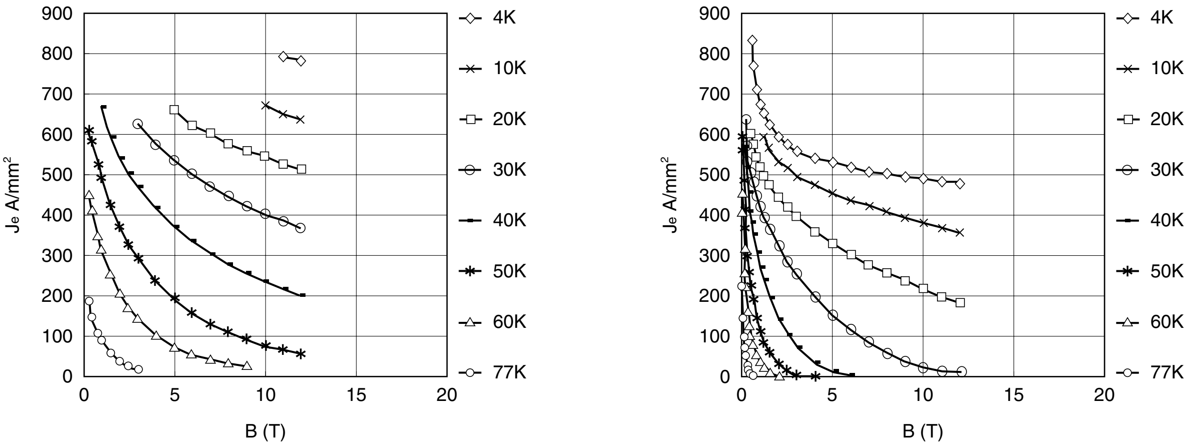


Fig. 9. Superconducting critical surface of BiSrCaCuO wire



(a) Magnetic field parallel to wire surface

(b) Magnetic field perpendicular to wire surface

Fig. 10. Engineering current density (Je) vs magnetic field (B) of 200 A-class BiSrCaCuO wire (measured by H. Kitaguchi et al. at NIMS)

ature and magnetic field measured by Dr. H. Kitaguchi of the National Institute for Materials Science. This figure shows a variety of application possibilities at wide temperature and magnetic field ranges.

4. Application of BiSrCaCuO superconducting wires

As described in the previous section, it is revealed that BiSrCaCuO superconducting wires could be flexible and have higher *Jc* at 20 *K* or below compared with metallic superconductors. It is expected that the wires can be used in building electric power cables, transformers and motors that operate at 77.3 *K*, high-field magnets for maglev trains, MRI and other applications that are cooled with 20 *K* refrigerators, and super-high field (23.5 *tesla* or higher) magnets that operate at 4.2 *K* for 1 *GHz* or higher NMR systems [(36)-(38)]. **Table 4** shows the applications and advantages of BiSrCaCuO superconducting wires.

For use in transformers, motors and magnets, the

Table 4. Applications and advantages of BiSrCaCuO wires

Applications	Features	Low loss	Compactness	Light weight	Torque	High B	Precision	Quietness	Maintainability	Stability	Economy	Remarks
MRI	High magnetic field	○				○			○	◎	○	Usable at anywhere
NMR	Super-high magnetic field	○				◎					○	Technically indispensable (>1 GHz)
Power cable (AC/DC)	High power capacity, compactness, low loss	◎	○							○	◎	Many novel applications
Transformer	High-speed train		○	◎								Light weight
	Electric power utility	◎	○								○	Compactness
FCL	Fault current suppression	○								○	○	Applicable to existing grids
SMES	Magnetic energy storage	○				◎						Stabilization of grids
MAGLEV	Next-generation high-speed train		○	◎					◎	◎	◎	Overall economic efficiency/Reliability
Ship motor	Compact, light weight, low loss	◎	◎	◎	◎			◎	○	◎	◎	400 kW (IHI)
Aircraft	Light weight	○	○	◎				○			◎	US Air Force
Molten metal	Convection suppression	○				◎				○		Silicon single crystal
Robot	Precision, light weight		○	○	◎		○					Compact motor
Machine tool	Gearlessness, precision, high torque			○	○		◎		◎			High precision production
Magnetic separation	Purification	○				◎				○	○	Wastewater purification
Automotive	High torque, low loss	◎	◎	◎	◎						◎	Fuel cell
Wind generator	Structure simplification		○	◎	○			○			○	Light weight

wires can be wound into coils at room temperature and no heat treatment is needed at high temperatures (up to 850˚C). Thus, very thin organic electric insulators can be used to achieve more compact sizes, and highly thermally conductive metals such as copper or aluminum can be used for making magnets. In high field magnet applications at 20 *K*, a cooling technique called conduction cooling can be used. Conduction cooling does not use liquid coolants and instead uses 20 *K* refrigerators, which means that magnets can be operated by simply switching on the refrigerators and electricity needed is one-fifth that needed by 4.2 *K* refrigerators. Furthermore, conduction cooling at 20 *K* have another merits of anti-thermal disturbance and anti-quenching characteristics, because the heat capacity of a material at 20 *K* is 100 times higher than that at 4.2 *K*. When cooled by liquid helium as in the case of metallic superconductors, BiSrCaCuO superconducting wires may be able to generate a super-high magnetic field of 23.5 tesla or higher, which is technically impossible with metallic superconductors.

Regarding power cable applications, it is possible to fabricate compact, large current conductors by spirally winding the wires over a former, thus achieving large capacity, compactness and low energy loss.

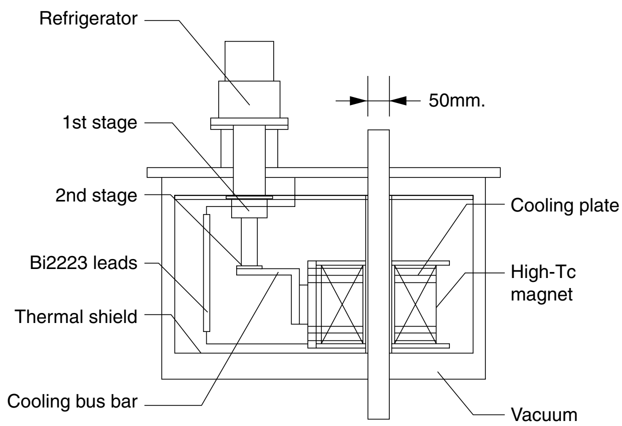
4-1 Refrigerator-cooled magnets (without liquid coolants)

The author and his team are the first in the world to study and propose a new concept of coil cooling technique, which is conduction cooling by directly connecting a cooling head of a 20 *K* refrigerator to coils [39].

A 20 *K* two-stage Gifford-McMahon (GM) refrigerator, which has been used in many cases, was used for cooling the coils by thermal conduction. The first stage of the 20 *K* refrigerator is capable of cooling the radiation shield and thermal anchor for current leads to 80 *K*, and the second stage cools the BiSrCaCuO coils to 20 *K*.

Figure 11 shows a stack of BiSrCaCuO double-pancake coils, each made by winding BiSrCaCuO superconducting wires, that was developed for making magnets that generate 4 T or 7 T at 20 *K* [40]. **Figure 12** shows the outer appearance and internal structure of these magnets. Pancake coils were jointed together by using the usual soldering technique, and then put into a vacuum

(a) Outer appearance



(b) Structure

Fig. 12. 7-T BiSrCaCuO magnet

Fig. 11. Outer appearance of double pancake coils of 7-T BiSrCaCuO magnet

vessel (below 10^{-5} *torr*) with a radiation shield and a super-insulation provided for thermal insulation.

It was revealed that a combination of BiSrCaCuO superconducting wires and 20 *K* refrigerator could provide high field magnets that can be operated easily. It was also revealed that it is necessary to evaluate the relation between generated heat and conduction cooling capability in order to secure stable operation, with considerations given to the relation of transport current and generated voltage based upon the magnetic field dependence of Jc.

Figure 13 shows the evaluation result for the 4-*T* magnet [40]. The calculated and measured values of generated heat are shown in the figure. Cooling capability was calculated using a linear relation that the thermal conductivity between the second stage and coils is 1.5 K/W. Heat generated at 4-*T* operations was predicted to be over cooling capability at any given temperature and causes unstable operation, which was also experimentally observed. At 3.5-*T* operations, generated heat was below cooling capability at a wide temperature range, resulting into the stable operation of the magnet.

Figure 14 shows the evaluation result for the 7-*T* magnet [40]. Stable magnet operation is anticipated because generated heat is well below cooling capability at a wide temperature range. Stable operation was also

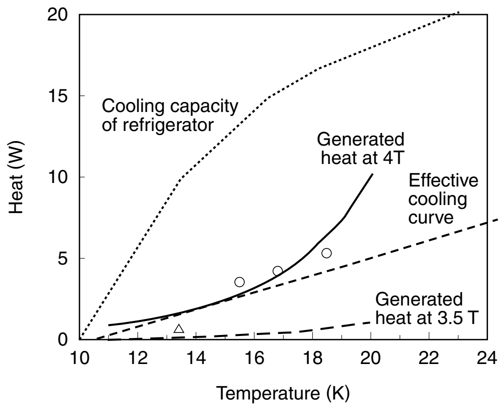


Fig. 13. Stability of 4-T BiSrCaCuO magnet
(○: Generated heat at 4 T, △: Generated heat at 3.5 T)

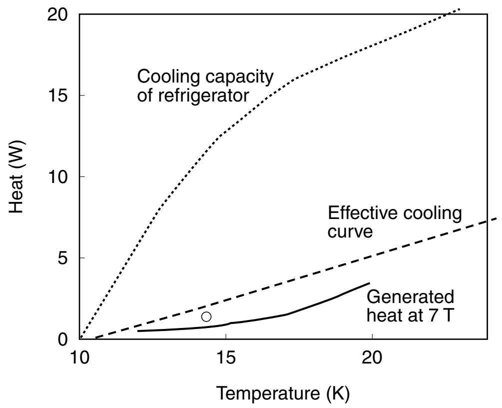


Fig. 14. Stability of 7-T magnet (○: Generated heat at 7 T)

observed experimentally and it was thus confirmed that magnets can be designed using this technique.

The 7-*T* magnet was installed at the Saitama Research Branch of the Japan Science and Technology Corporation (now the Japan Science and Technology Agency), and used for studying the influences of magnetic fields on chemical reactions (40), (41), including the method for fast-ramping magnetic fields (42). The 2-*T* and 4-*T* magnets were applied for researching magnetic separation technologies, such as kaolin clay purification (43) and wire drawing lubricant purification (44).

Table 5. Parameters of 8.1-T magnet

Room temperature bore diameter (mm)		200
Coil	Inner Diameter (mm)	232
	Outer Diameter (mm)	414
	Height (mm)	422
Conductor	Wire Width (mm)	4.2
	Wire Thickness (mm)	0.22
	No. of Bundles	2
No. of Double Pancake Coils		44
Total No. of Turns		15,840
Total Weight (kg)		320
Magnetic Field Coefficient (mT/A)		37.6
Inductance (H)		37.7

After these studies were made, a new magnet having a large room temperature bore was developed. **Table 5** and **Fig. 15** show the parameters and outer appearance of this magnet. This magnet can generate 8.1 T within a 200-mm room temperature bore (45), and is cooled using a 20 *K* refrigerator. Also, this magnet is operated at 20 *K*, which is a much higher temperature than 4.2 *K*, can tolerate thermal disturbances from the outside and inside of the magnet during temperature ramping and de-ramping.

Fig. 15. Outer appearance of 8.1-T magnet

4-2 Power cables

Before going into the current development status of HTS cables for underground cable applications, it would be informative to look back at the history of overhead transmission lines that had been developed to meet similar needs. In 1970s, there had been a serious need to increase the electricity transmission capacity in Japan, especially in the suburbs, and a new type of overhead transmission conductor called aluminum conductor invar reinforced (ACIR) (46), (47) that has twice the transmission capacity of the conventional type aluminum conductor steel reinforced (ACSR) while having the same size and same weight was developed. It had become possible to double the transmission capacity by simply replacing conductors with ACIR and using existing transmission line towers. The structure of ACIR consists of two different kinds of wires: One is the high-strength, low-expansion Fe-Ni alloy wires containing 40% Ni for replacing conventional steel reinforcement wires in the center of the cable, and the other is the highly heat-resistant aluminum alloy conductor wires that have Al_3Zr finely-dispersed in an aluminum matrix. The price of ACIR is about three times that of conventional ACSR, but it is excellent from the view point of total economic efficiency because existing infrastructures (i.e. tansmission line towers) can be used. The use of ACIR conductors started in the 1980s when they were first used by the utility companies in Japan. They are being used in South Korea, East Asia and the Middle and Near East, and also in China for the past few years. Recently, ACIR is gaining much attention in the USA. The total used length of ACIR strung since 1981 is reaching 10,000 km. Because ACIR's operating temperature is higher than that of conventional conductors, ACIR is called "high-temperature conductor".

It is prospected that the demand for new installation and transmission capacity increase of underground power cables grows as electricity consumption per area increases due to the spread of information technology devices and the population concentration in cities with population of over one million. In big cities like Tokyo and New York, it has become technically and economically impossible to lay new cables or construct new substations due to congested underground spaces and high construction cost for tunnels, conduits and substations. Contrary to conventional power cables of the same size, high-temperature superconducting (HTS) cables have 5 to 10 times higher capacity, and 50% lower loss. Conventional cables can be replaced with HTS cables while using existing infrastructures such as underground tunnels and conduits.

(1) Cable conductor flexibility

After a wire configuration having high flexibility was made known, a study was made on the development of power cable conductors having this configuration. Power cables need to withstand repeated bending during manufacturing, shipping and laying, as well as repeated thermal cycling between room temperature and liquid nitrogen temperature. Therefore, conductor flexibility and thermal cycling properties were first verified. Because demand for AC power cables is high, evaluation of AC loss and investigation of loss reduction method were also conducted.

The bending tolerance of long-length conductors was investigated on the spirally-wound conductors made of multi-filament BiSrCaCuO superconducting wires [48]. When spirally wound on a former, the wire itself showed no degradation up to 0.4% bending strain. The thermal cycling of a conductor between room temperature and liquid nitrogen temperature gave no change to Ic. **Figure 16** shows the structure of a spirally-wound conductor. The change of *Ic* in a 3-layer conductor 1.4 m in length was evaluated by bending the conductor to a radius of 0.75 m. **Figure 17** shows the evaluation result [48]. The *Ic* value did not change under this very severe bending condition.

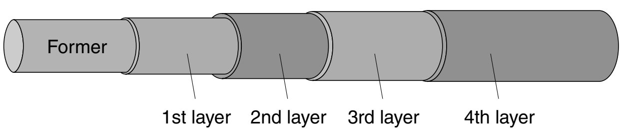


Fig. 16. Multi-layer conductor

An 8-layer conductor 5 m in length and with an electricity carrying capacity of 3,000 *A* (77.3 *K*) was fabricated and *Ic* was investigated with bending to a radius of 1.3 m and in a straight state [48]. There were no changes in the I-V characteristics in both cases, and it was confirmed that no change in *Ic* was observed even in a bent state.

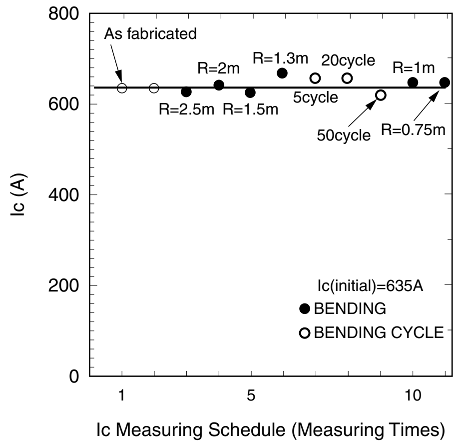


Fig. 17. Repeated bending properties of spirally-wound conductor

(2) AC current transport properties [48]-[50]

Conductors with different number of spirally-wound layers (1 layer, 2 layers, 4 layers and 6 layers) were fabricated and then evaluated by applying an AC current load. **Figure 18** shows the evaluation results. The 1-layer conductor had an AC loss proportional to I^3, and the 2-, 4-, and 6-layer conductors had AC losses proportional to I^2. These apparent differences revealed that the AC loss of a 1-layer conductor is dominated by hysteresis loss, while that of a conductor with two or more layers is dominated by eddy current loss or coupling loss.

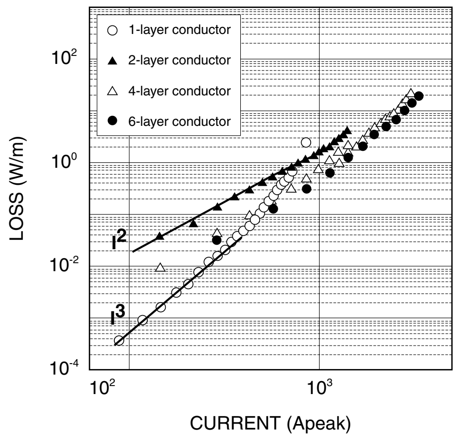


Fig. 18. AC loss of multi-layer conductors
(○: 1-layer, ▲: 2-layer, △: 4-layer, ●: 6-layer)

When coupling loss is the dominant loss, the current transporting across layers can be decoupled by adding electrical insulations between the layers. A 4-layer conductor with electrical insulations between layers was fabricated and then evaluated. **Figure 19** shows the result of the AC loss measurement. The AC loss of this conductor was proportional to I^3 and was 0.4 W/m at 1,000 A_{peak}, which was nearly a half that of a 4-layer conductor without electrical insulation between its layers (0.8 W/m) shown in **Fig. 18**.

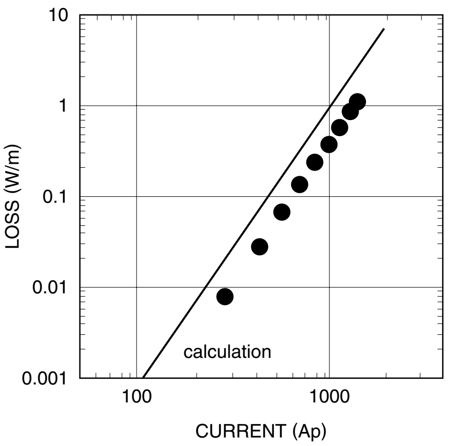


Fig. 19. AC loss of conductor with electrical insulation (Straight line: calculated value)

These results were theoretically studied. According to Norris' critical state model, the self-field AC loss (W) in an elliptical shape conductor is expressed in Equation (2).

$$W=\mu_0 f Ic^2 F(z)/\pi \quad \cdots\cdots\cdots(2)$$

$$F(z)=z-z^2/2+(1-z)ln(1-z) \quad \cdots\cdots\cdots(3)$$

$$z=Iop/Ic \quad \cdots\cdots\cdots(4)$$

f: frequency, *Ic*: critical current, *Iop*: operating peak current

If critical state changes from inner layer to outer layer, the AC loss of a multi-layer conductor will be described using the above equation. Because the conductor with electrical insulation between its layers is a cylindrical conductor, its AC loss can be described by modifying the above equation for elliptical shape conductor.

$$W=\mu_0 f Im^2 F(z')/\pi \quad \cdots\cdots\cdots(5)$$

$$F(z')=z'-z'^2/2+(1-z')ln(1-z') \quad \cdots\cdots\cdots(6)$$

$$z'=Iop/Im \quad \cdots\cdots\cdots(7)$$

$$Im=Ro^2 Ic/(Ro^2-Ri^2) \quad \cdots\cdots\cdots(8)$$

Ro: outer diameter of conductor, *Ri*: inner diameter of conductor
Im: critical current of superconductor with diameter of Ro
Iop: operating current

In a case where *Iop* is sufficiently smaller than *Im*, Equation (5) becomes Equation (9), and it is revealed that AC loss is proportional to I^3.

$$W \fallingdotseq \mu_0 f Iop^3/6\pi Im \quad \cdots\cdots\cdots(9)$$

It was experimentally observed that AC loss was proportional to I^3, as shown in **Fig. 19**.

(3) Prototype power cables [51], [52]

After it was verified that long-length, large-current conductors can be made and that AC loss can be decreased by inter-layer insulation, the fabrication of the prototype of long-length and large-current power cable was investigated. An actual cable conductor needs to be machine wound, and therefore strain in the machine stranding process must be also taken into account.

Total strain including wire stranding strain is expressed by Equation (10). It was decided based on this equation that the total strain in the wire must be below 0.3%. It was revealed that when 0.2% strain is added, the stress applied must be below 15 MPa.

$$\varepsilon=t/(D'+t) \quad \cdots\cdots\cdots(10)$$

$$D'=\sqrt{P^2+(\pi D)^2}/\pi \quad \cdots\cdots\cdots(11)$$

ε: wire strain, *t*: wire thickness, *D*: former diameter, *P*: spiral winding pitch
D': equivalent bending diameter of spiral wound wire

A 50-m-long multi-layer conductor was fabricated by machine stranding and with tensile stress controlled during stranding. The conductor demonstrated to have *Ic* of 2,900 A under a 10^{-12} Ωm criterion and 2,200 A under a 10^{-13} Ωm criterion, showing that these values are well fitted to design values.

Fabrication of a 7-m-long cable prototype was investigated. **Figure 20** shows the outer appearance of a prototype consisting of three phases housed in one cryostat, which is named the "3-in-One" type. The main parameters of the cable are 66 kV, 114 MVA and 1 kArms. This cable was subjected to 5 heat cycles between room temperature and liquid nitrogen temperature, and showed no change in electrical performance after passing the current for 110 hours. The AC loss at 1 kArms was 3.3 W/m/phase by electrical measurement and 3.5 W/m/phase by calorimetric measurement, and these values were in good agreement with the performance of conductors.

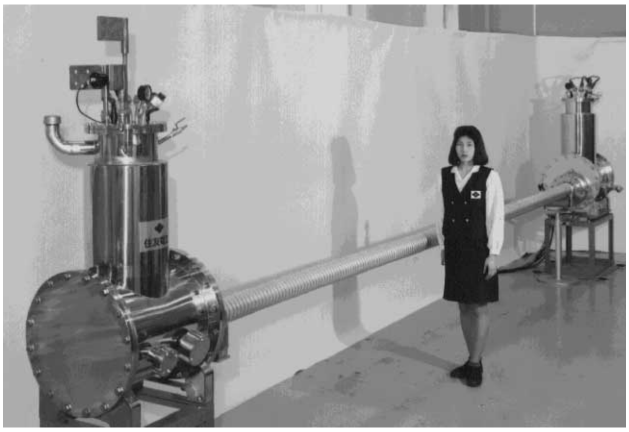


Fig. 20. 7-m-long "3-in-One" HTS cable prototype

(4) Long term verification test

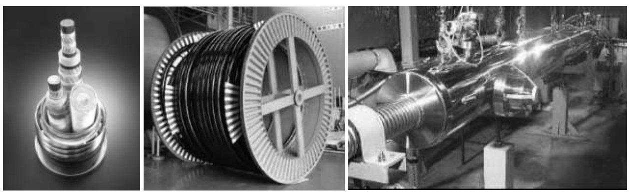
After the above mentioned evaluation results were successfully obtained, many HTS cable projects were launched around the world to bring HTS cables up to a practical level. **Table 6** shows the major projects. In 2002, Tokyo Electric Power Company and Sumitomo Electric, together with the Central Research Institute of Electric

Table 6. HTS cable projects

Project	Members	Utility	Funding	Budget	Cable			Terminal	HTS wire		Period	Remarks
TEPCO	Sumitomo Electric (SEI)	TEPCO	Private	18M$	66kV-1000A-100m	CD	3-in-One	Fixed	Bi2223	SEI	2001-2002	
Copenhagen	NKT		Danish DOE		30kV-2000A-30m	WD	Single x 3		Bi2223	NST	2001-2003	
Southwire	Southwire		DOE		12.5kV-1250A-30m	CD	Single x 3		Bi2223	IGC	2000-	
Detroit	Pirelli	Detroit Edison	DOE		24kV-2400A-120m	WD	Single x 3		Bi2223	AMSC	2001.10-	Failed
Super-ACE	Super-GM (Furukawa, CEPRI)		METI/NEDO		77kV-1000A-500m	CD	Single x 1		Bi2223	-	2004-2005	No Heat Cycle
Yunnan	Innopower, InnoST, Shanghai Cable	Yunnan Electric Power	Chinese MOST, Beijing City, Yunnan Prov.	4.3M$	35kV-2000A-33.5m	WD	Single x 3		Bi2223	Inno ST	2004.4-	
DAPAS	LS Cable, KERI, KIMM	KEPCO	Korean MOST		22.9kV-1250A-30m	CD	3-in-One		Bi2223	AMSC	2004.5-12	
Lanzhou	IEE/CAS, Changtong Power Cable Company		China S&T	1.2M$	10.5kV-1500A-75m	WD	Single x 3		Bi2223	AMSC	2005-	
KEPRI	KEPRI, SEI, KERI, KBSI, etc.	KEPCO	KEPCO, Korea Gov.	2.3M$	22.9kV-1250A-100m	CD	3-in-One	Fixed	Bi2223	SEI	2006-	Alive
DAPAS	LS Cable		Korean MOST		22.9kV-1250A-100m	CD	3-in-One		Bi2223	AMSC	2007-	
Albany	SuperPower, SEI, BOC	National Grid	DOE、NYSER-DA	26M$	34.5kV-800A-350m	CD	3-in-One	Fixed	Bi2223 YBCO*	SEI (SP*)	2006-	On Grid
Ohio	Ultera, ORNL	American Electric Power	DOE	9M$	13.2kV-3000A-200m	CD	Triaxial		Bi2223	AMSC	2006-	On Grid
LIPA 1	AMSC, Nexans, AirLiquide	Long Island Power Authority	DOE	46.9M$	138kV-2400A-600m	CD	Single x 3		Bi2223	AMSC	2007	Under Constr.
On Grid	SEI	TEPCO	METI/NEDO	22.5M$	66kV-200MVA-~300m	CD	3-in-One	Fixed	Bi2223	SEI	2007-2011	Started
Hydra	AMSC, Southwire	Con-Edison	DHS	39.3M$	13.8kV	CD	Triaxial		YBCO	AMSC	2007-2011	Started
Entergy	Southwire, NKT	Entergy	DOE	26.6M$	13.8kV-60MVA-1,760m	CD	Triaxial		TBD	TBD	2007-2010	Planning
LIPA 2A	AMSC, Nexans, AirLiquide	LIPA	DOE	18M$	138kV-2.4kA	CD	Single x 3		YBCO	AMSC	2007-2013	Planning
Amsterdam	NKT, Plaxair	Nuon	TBD	TBD	50kV-250MVA-6,000m	CD	Triaxial		TBD	TBD	2008-2011	Planning

Power Industry, jointly started the world's first long-term (one year) verification test of the 3-in-One type HTS cable (66 kV, 1 kA, 100 m) [(53), (54)], which demonstrated stable cable operation for a long term over a year.

Figure 21 shows the world's first HTS cable installed in a live grid. This cable, made from DI-BSCCO and 350 m in length, and a cable joint in the vault constituted a cable system and was laid in a long underground con-



(a) Cable (b) Drum (c) Cable joint

Fig. 21. 350-m-long HTS cable for Albany Project

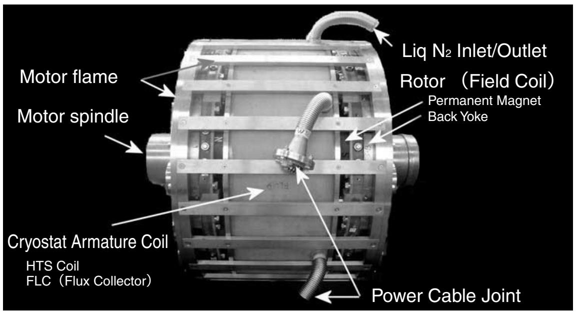
Fig. 22. Cable test site (Albany, NY)

duit in Albany, NY, USA. The system was connected to the real grid of National Grid on July 20, 2006 and was successfully operated for 9,000 hours supplying electricity to 70,000 homes [(55), (56)]. At present, the 30-m portion of the cable is replaced with YBaCuO cable, which is made from YBaCuO wires supplied from SuperPower, and the cooling process started on November 19, 2007. The world's-first connection of YBaCuO cable system to a live grid was done on January 9, 2008. **Figure 22** shows the test site.

4-3 Superconducting motor

Superconducting motors have features such as compact size, reduced weight and energy saving characteristics. There are many different types of superconducting motors, such as synchronous or inductive, radial or axial, and superconducting field or armature windings, and they can be constructed in various combinations. Among these types, the axial type is being developed by the Japanese frontier research group in which Sumitomo Electric participates. The participating organizations are (alphabetical order): Fuji Electric Systems Co., Ltd., Hitachi, Ltd., IHI Corporation, Nakashima Propeller Co., Ltd., Niigata Power Systems Co., Ltd., Sumitomo Electric Industries, Ltd., Taiyo Nippon Sanso Corporation and University of Fukui (Prof. Hidehiko Sugimoto). The group coordinated by IHI has recently succeeded in developing a prototype of 365-kW HTS motor cooled by liquid nitrogen. This motor uses DI-BSCCO armature windings [(57), (58)] with a novel flux collector. **Figure 23** shows the outer appearance and structure of this motor. In this motor the superconducting coils are fixed to offer many advantages, including the elimination of a rotary joint for supplying liquid coolant.

(a) Outer appearance



(b) Structure

Fig. 23. 365-kW BiSrCaCuO motor

5. Future perspective

HTS wires can be used at a wide temperature range between 20 *K* and 4.2 *K*, and around liquid nitrogen temperature (63K~77K) and have a wide application. In future HTS wires need to have better critical current properties, and they must move on from the development stage to the demonstration stage, implementing technical and economical viability tests.

In order to have larger critical current values, the following points need to be achieved: (1) More homogeneous superconducting phase and elimination of non-superconducting phases, (2) improved crystal alignment, (3) higher critical temperature (a critical temperature of Tc = 117.8 *K* is already confirmed [(59), (60)]), and (4) clarification of solid-state chemical reaction mechanism of superconducting phase formation.

The technology of HTS is applicable for achieving various objectives. To fulfill energy saving and sustainability objectives, the following development themes will be pursued: (1) Combination of natural energy sources (such as photovoltaic power and wind power) and HTS DC cables [(61)] for building a worldwide electricity network [(62)], and (2) HTS motor cooled by liquid hydrogen [(63)-(65)] for zero-emission vehicles.

6. Conclusion

It had been a long-held dream of the researchers of HTS superconductors to enhance the properties of HTS materials for use in industrial applications and start mass production of HTS products. Since the discovery of BiSrCaCuO superconductors in Japan in 1988, Sumitomo Electric has been working to develop BiSrCaCuO superconducting wires that have good electrical and mechanical characteristics.

The author is pleased to report in this paper the present status of the development of BiSrCaCuO HTS wire and of state-of-the-art superconducting magnets, motors and power cables made using this wire.

Now, Sumitomo Electric's BiSrCaCuO HTS wire has successfully completed the verification stage and progressed to the demonstration stage to demonstrate its practicality for use in current leads and HTS magnets (magnetic separation, chemical reaction, silicon single-crystal pulling, maglev trains, transformers, ship propulsion motors, etc.). Power cables are especially promising among various applications and are already operating in a live grid. With the Kyoto Protocol agreed in 1997 and put into effect in 2005, world-wide efforts are being made to build a global society that produces less CO_2 emissions. The author sincerely hopes that HTS technology contributes to this objective with its capabilities to reduce size and weight and save energy.

References

(1) J. G. Bednorz and K. A. Müller: Z.Phys. B64(1986)189.
(2) S. Uchida, H. Takagi, K. Kitazawa and S. Tanaka: Jpn.J.Appl.Phys. 26(1987)L1.
(3) M. K. Wu et al.: Phys.Rev.Lett. 58(1987)908.
(4) H. Maeda, Y.Tanaka, M.Fukutomi and T.Asano: Jpn.J.Appl.Phys. 27(1988)L209.
(5) M. Takano et al.: Jpn.J.Appl.Phys. 27(1988)L1041.
(6) Z. Z. Sheng and A. M. Hermann: Nature 332(1988)138.
(7) M. Okada et al.: Jpn.J.Appl.Phys. 27(1988)L185.
(8) Y. Enomoto, T. Murakami, M. Suzuki and K. Moriwaki: Jpn.J.Appl.Phys. 26(1987)L1248.
(9) Japanese Patents:no. 2636049, no. 3149429, no. 3149441
(10) T. Hikata et al.: Jpn. J. Appl. Phys 28(1989)L1204.
(11) M. Ueyama, T. Hikata, T. Kato and K. Sato: Jpn. J. Appl. Phys. 30(1991)L1384.
(12) K. Sato: Application of high-temperature superconductivity edited by JST (Maruzen, 1990)174.
(13) T. Kato et al.: Physica C 412-414(2004)1066
(14) S. Kobayashi et al.: Physica C 426-431(2005)1132
(15) N. Ayai et al.: IEEE Trans. Applied Superconductivity 17(2007)3075
(16) K. Sato et al.: IEEE Trans MAG 27(1991)1231.
(17) K. Osamura, S. Nonaka and M. Matsui: Physica C 257(1996)79.
(18) M. Daumling, G. Triscone and R. Flukiger: Physica C 214(1993)403.
(19) A. Jeremie: Physica C 255(1995)53.
(20) H. K. Liu, Y. C. Guo and S. X. Dou: Supercond.Sci.Technol. 5(1992)591.
(21) Y. E. High et al.: Physica C 220(1994)81.
(22) G. Grasso, A. Jeremie and R. Flukiger: Supercond.Sci.Technol. 8(1995)827.
(23) J. A. Parrel, Y. Feng, S. E. Dorris and D. C. Larbarlestier: J.Mater.Res. 11(1996)555.
(24) K. Osamura: Superconducting materials (Yoneda Publishing, 2000)197.
(25) K. Sato et al.: Cryogenics 33(1993)243.
(26) K. Sato: Science of high temperature superconductivity edited by M. Tachiki and T. Fujita (Syokabo, 1999)428.
(27) H. Mukai et al.: Adv. SuperconductivityIII(ISS'90), Sendai(Springer, Tokyo, 1991)607.
(28) K. Osamura and K. Matsumoto: Ouyo Butsuri 73(2004)3.
(29) K. Sato: Processing and Properties of High Tc Superconductors edited by S. Jin (World Scientific Pub., Singapore, 1993)121.
(30) Japanese Patent: no.3350935
(31) J. Tenbrink and H. Krauth: Bismuth-based high-temperature superconductors edited by H. Maeda and K. Togano(Marcel Dekker, Inc., New York, 1996)369.
(32) Y. Iwasa and Y. M. Butt: Cryogenics 30(1990)37.
(33) K. Sato, T. Hikata and Y. Iwasa: Appl. Phys. Lett. 57(1990)1928.
(34) Y. Iwasa: Cryogenics 31(1991)174.
(35) K. Sato et al.: Appl. Phys. Lett. 61(1992)714.
(36) T. Hara and H. Ishii: Ouyo Butsuri 65(1996)401.
(37) K. Sato, K.Hayashi, K.Ohkura and K.Ohmatsu: Proc. of 15th Int. Conf. on Magnet Technology (Science Press, Beijing, 1998)24.
(38) K. Sato et al.: Proc. the Nineteenth International Cryogenic Engineering Conf. (ICEC19)(2003)225.
(39) K. Ohkura et al.: Adv. SuperconductivityVI(ISS'93), (Springer, Tokyo, 1994)735.
(40) T. Kato et al.: Proc. of 15th Int. Conf. on Magnet Technology (Science Press, Beijing, 1998)793.
(41) K. Sato et al.: Supercond. Sci. Technol. 13(2000)18.
(42) K. Sato et al.: Proc. of The First Symposium on New Magnetic Science (JST, 1998)175.
(43) J. Iannicelli et al.: IEEE Trans. Appl. Superconductivity 7(1997)1061.
(44) K. Fujino et al.: Proc. of The Second Symposium on New Magnetic Science (JST, 1998)358.
(45) K. Ohkura, T. Okazaki and K. Sato: SEI TECHNICAL REVIEW, No.171(2007)50.
(46) S. Sakabe, N. Mori, K. Sato, Y. Miyake and T. Tanaka: IEEE Trans. on Power Apparatus and Systems PAS-100(1981)1505.
(47) S. Sakabe et al.: Sumitomo Electric Technical review No.117(1980)38
(48) K. Sato et al.: Bismuth-based high-temperature superconductors edited by H. Maeda and K. Togano (Marcel Dekker, Inc., New York, 1996)477.
(49) J. Fujikami et al.: Adv. SuperconductivityVIII(ISS'95), (Springer, Tokyo, 1996)1319.
(50) K. Sato et al.: IEEE Trans. Appl. Superconductivity 7(1997)345.
(51) T. Shibata et al.: Pro. 16th CEC/ICMC, (Elsevier Science, Oxford, 1997)967.
(52) J. Fujikami et al.: Pro. 16th CEC/ICMC, (Elsevier Science, Oxford, 1997)975.
(53) S. Honjo et al.: IEEE Trans. Applied Superconductivity 13(2003)1952.
(54) T. Masuda, K. Kato, M. Hirose and K. Sato:IEEJ Trans. PE 126(2006)827.
(55) H. Yumura et al.: SEI TECHNICAL REVIEW, No.64(2007)27.
(56) T. Masuda et al.: IEEE Trans. Applied Superconductivity 17(2007)1648.
(57) K. Fujino et al.: SEI TECHNICAL REVIEW, No.171(2007)46.
(58) http://www.sei.co.jp/news/press/07/prs545_s.htm
(59) J. Shimoyama et al.: Jpn. J. Appl. Phys. 44 (2005) L1525.
(60) J. Shimoyama: FSST NEWS, No.114(2007)1.
(61) M. Hirose, T. Masuda, K. Sato and R. Hata: SEI TECHNICAL REVIEW, No.61(2006)29.
(62) K. Kitazawa: Journal of the Cryogenic Association of Japan 1(2007)2.
(63) G. Arnold and J. Wolf: TEION KOGAKU 40 (2005)221.
(64) K. Yamane and H. Naya: TEION KOGAKU 42(2007)334.
(65) K. Sato: TEION KOGAKU 42(2007)338.

Contributor

K. SATO

• Dr. Eng., Fellow, General Manager, Materials and Process Technology R&D Unit