Recent Advances in Long Length Bi-2223 HTS Multifilamentary Composite Wire Development

M.J. Minot, D. Buczek, J.J. Gannon, P.K. Miles, and D.R. Parker
American Superconductor Corporation, Two Technology Drive, Westborough, MA 01581

P. Metra
Pirelli Cavi SpA, Divisione Italia, Milano, Italy

Abstract — **Developing applications for HTS technology are now enabled by a new generation of superconducting wires that bring together the required electrical and mechanical properties in long lengths that are durable when exposed to practical application environments. Advances in the development and scale-up of long-length Bi-2223 HTS composite wire are reviewed. Powder-in-tube processing was used to produce multifilamentary tapes in continuous lengths up to 1 kilometer. Electrical performance and uniformity results are reported for the wire in 300 meter and 1 kilometer lengths. Mechanical and environmental durability performance results are reported for multifilament wire tapes being developed for react-and-wind cable application as well as for wind-and-react coil and magnet applications. The use of these wires in practical demonstration applications is also reported.**

I. INTRODUCTION

The availability of long lengths of high temperature superconducting tape with robust performance is now making it possible to demonstrate practical applications for this rapidly evolving technology. Active development of practical applications is underway in the United States and elsewhere, including motors and generators, current limiters, power cables and transformers. These applications are enabled by a new generation of superconducting wires that bring together the required electrical and mechanical properties in long lengths that are durable when exposed to practical application environments. This represents a significant advancement over earlier stages of HTS wire development, where promising wire properties were demonstrated in short length experimental samples, but never achieved together in the same wire, and readily available for practical demonstrations.

II. EXPERIMENTAL METHODS & RESULTS

A. *OPIT Process*

Multifilamentary wires were produced using the OPIT (oxide-powder-in-tube) Process, as reported previously [1],[2]. Starting with reagent grade (3N) reactants, oxide powders having a stoichiometry of $Bi_{1.8}Pb_{0.3}Sr_{1.9}Ca_{2.0}Cu_{3.1}$ were produced by pyrolysis of nitrate solutions. Powders were packed and sealed into cylindrical silver billets that were then deformed into long monofilamentary, hexagonal shaped wire lengths. Conventional deformation technology, including wire drawing, was used.

B. *Multifilamentary Wire Architecture*

Wire architecture, including dimensions, fill factor, filament count as well as the distance of filaments from the neutral axis, can have a direct impact on the electrical, mechanical and durability performance of the wire. These variables can be varied independently and are selected depending on the end use of the wire to optimize performance. The hexagonal-shaped monofilamentary wire was cut, bundled in a close-packed array, packed into silver tubing and re-drawn to produce 19, 61, 85, 313 or 1,615 filament wire. Figure 1 is a metallographic cross section of 19, 61 and 85 filament tapes, showing filament structure and architecture.

Alternate roll / sinter cycles were then used to produce finished tape having dimensions that depend on the final requirements: 2.5mm X 0.2mm X 1,000 meters long for 19 filament tape, 4.0 mm X 0.23 mm for 61 filament tape, or 2.5 mm X 0.25 mm for 85 filament tape. Wires were heat treated in long continuous lengths between 800 and 830 C in 7.5% oxygen.

C. *Critical Current measurement techniques for long lengths.*

Following final heat treatment, all wires were characterized electrically at 77K. Kilometer long wire lengths were measured by the four probe technique, and J_c reported using both the 1 μV/cm and a 10^{-11} ohm-cm criteria. Measurements were done over the entire length of the wire, with intermediate voltage taps used to determine performance uniformity over length. The wire was spaced

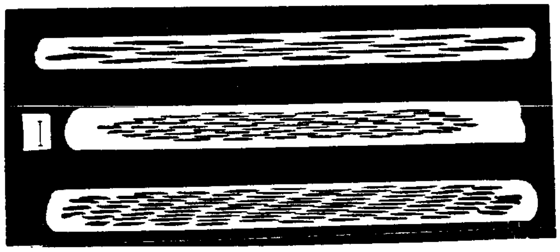


Fig. 1. - filament architecture of a) 19 filament, b) 61 filament and 85 filament wire tapes. (Scale marker = 200 μm)

sufficiently far apart on a dielectric mandrel to prevent shorts between turns and to reduce the impact of self field effects on the measurement. Kilometer lengths, although processed as a continuous length, must be cut in sections for this measurement. The wire length, wrapped on the dielectric mandrel was then immersed in liquid nitrogen for the measurement. Championship results, shown in Table I, are expressed in terms of critical current (Ic), engineering current density (Je=Ic/wire cross-section area) and critical current density (Jc=Ic/core cross-section area). Wire dimensions and core cross-sectional areas are determined by metallography combined with image analysis, as reported elsewhere [2].

A number of factors affect the electrical performance of the finished wire, including details of wire processing, internal defects as well as wire handling during processing. Performance uniformity over length is shown in fig. 2, using both the 10^{-11} ohm-cm criteria and the 1 µV/cm criteria. Performance reductions at the 0.40 kilometer and 0.78 kilometer locations correspond to locations where the wire was cut for measurement, and possibly damaged. The selection of a measurement criteria depends on the requirements of the application. The 10^{-11} ohm-cm criteria is particularly sensitive to wire defects as seen by the larger off-set in electrical performance observed at 0.63 and 0.90 kilometers, compared to the 1 µV/cm criteria. In addition to a direct impact of initial electrical performance, wire defects can be expected to affect the stability of the wire performance, over time.

D. Accelerated Durability Testing

Thermal cycling and environmental exposure are known to have an impact on the electrical performance of HTS wires [3],[4]. Three tests, applied one after another to the same sample, were used to evaluate the performance of bare wires, when exposed to accelerated environmental conditions:

a) Cycled exposure between ambient temperature and liquid nitrogen @77K ,
b) Exposure to elevated temperatures, in dry air, over time,
c) Humidity exposure testing.

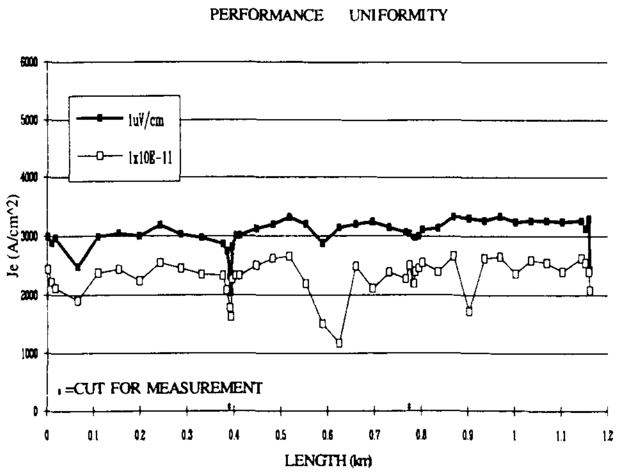


Fig. 2. Performance uniformity along length is shown for a 1.1 kilometer wire length using both the 1 µv/cm and 10^{-11} Ω-cm resistive criteria.

Testing begins with the measurement of the initial critical current. Tapes were then evaluated in terms of the degradation of critical current following the series of exposures. Thermal cycle and humidity testing provide a measure of sheath integrity as well as Ic stability. Wires which have proven to be stable to liquid nitrogen cycle testing (a) were tested further in terms of the degradation of critical current following the series of exposures, for the effects of elevated temperature over time (b) and humidity (c). Tears and other breaks in the sheath lead to moisture penetration and Ic degradation. Wire ends were sealed to prevent end-effect-related degradation. An example of the test flow and corresponding results for 61 filament tape is shown in Table II.

E. Mechanical Strain Properties

Single and reverse bend tests [5] were used to evaluate the mechanical strain tolerance of multifilamentary wires. Percent strain was calculated by dividing the thickness of the wire tape by the diameter of bend X 100. The results plotted in fig. 3 demonstrate the enhanced bend strain performance achieved by increasing the filament count and reducing the filament cross section. The bend strain performance observed is consistent with behavior modeled elsewhere [6]. The 61 filament case with greater sheath thickness shows improved strain tolerance as summarized in Table III.

Table II
Typical durability test results

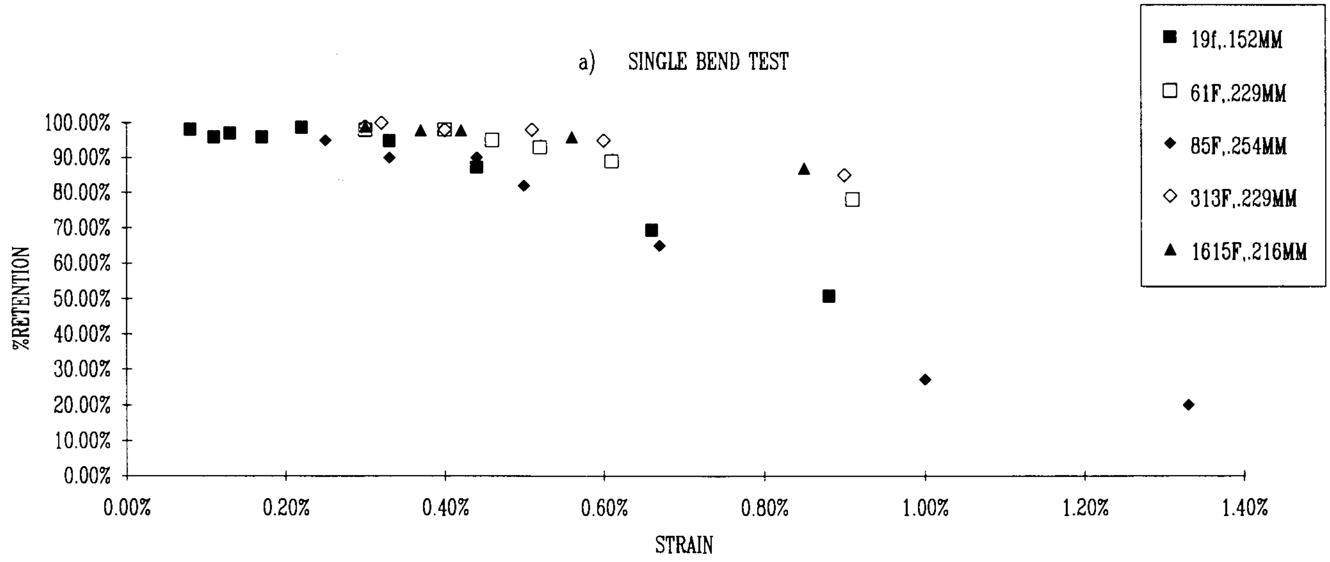
Test	**% Initial Ic** **1 µv/cm**	**% Initial Ic** **10^{-11} Ω-cm**
Thermal Cycle 300K ⇔ 77K 10 cycles	99.7	97.1
Temperature Stability 130 ^{c} - 3 days, dry air	↓	↓
Humidity 95% @ $70^{o\ c}$ for 7 days	97.8	97.0

Table III
61 filament wire bend strain tolerance

	Surface Strain	**Critical Current % Retention**
Single Bend Test	0.60%	90%
	0.46%	95%
Reverse Bend Test	0.50%	90%
	0.40%	95%

Table I
Championship electrical results

Length meters	Filament Count	Ic amps 1 μV/cm,	Ic amps 10^{-11} Ω cm	Je amps/cm^2 1 μV/cm,	Je amps/cm^2 $10^{-11}\Omega$ cm	Jc amps/cm^2 1 μV/cm,	Jc amps/cm^2 $10^{-11}\Omega$ cm
1,160	19	15.5	10.8	3,048	2,126	12,700	8,860
480	85	24.2	14.4	3,936	2,244	16,400	9,770
25	61	41.0	32.8	4,090	3,272	19,500	15,600
73	19	24.6	19.9	6,160	4,984	22,000	17,800



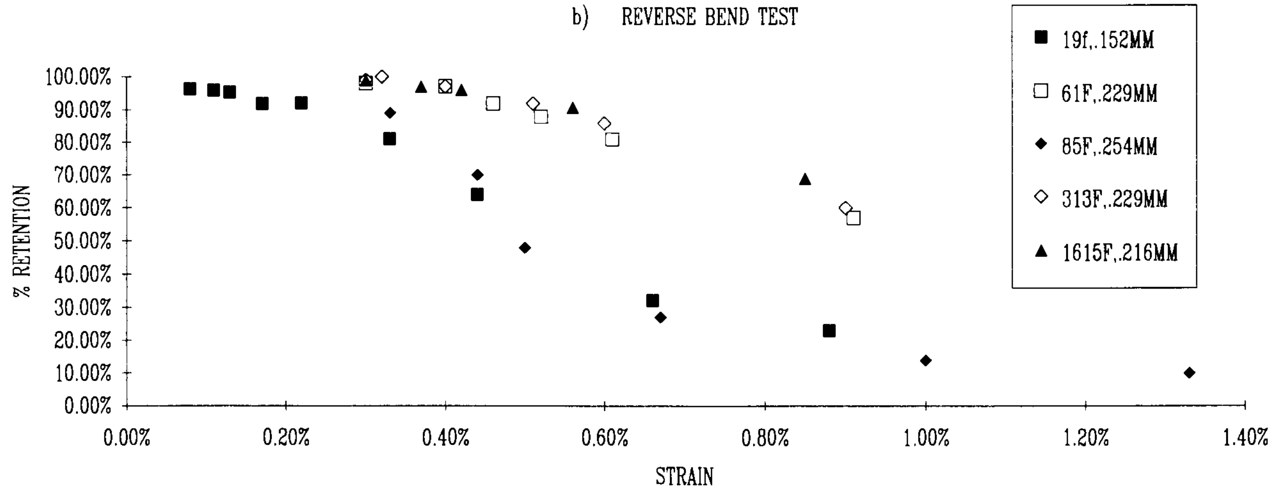


Fig. 3. - compares the strain tolerance of 19, 61, 85, 313 and 1615 filament tapes of different thickness using the a) single and b) reverse (double) bend test.

The optimal trade-off between mechanical strain and current carrying capability depends on the applications. React-and-wind assembly requires a tape with higher strain tolerance compared to applications that will be completed using a wind and react strategy. Furthermore, the architecture of the tape impacts manufacturability. As seen in fig. 3a, greater improvements (up to 0.75% strain, single bend, at 90% critical current retention) have been achieved with OPIT wires with 313 and 1615 filaments. These are of less significance for applications at this time, due to the reduced fill factor and lower critical current and related manufacturability issues of these tapes.

III. APPLICATIONS DEVELOPMENT

Long length HTS wire tapes are now available with performance characteristics that are enabling demonstrations of practical HTS applications. Although each application has unique requirements for wire, two broad categories with different performance and cost requirements can be differentiated: coil & magnet wire and power cable wire. Preliminary specifications for these wire types are summarized in Table IV.

Coil and magnet applications include rotating machinery and high-field magnets. Early applications of coils and magnets will likely be between 20-50 K, taking advantage of the improved high-field performance of HTS materials at these temperatures. The compact nature of these applications makes wind-and-react processing possible.

Underground HTS power cables will be operated at or above 77 K. Cable assembly will be done using react-and-wind wire that can tolerate the mechanical strains of cable assembly as well as the underground cable installation process. Early stage specialty demonstrations will proceed with wire available today. Widespread generalized application of HTS technology will follow, as wire is developed to meet more stringent performance and cost specifications.

Wire products now available have been engineered to bring together the mechanical properties, environmental durability and electrical performance needed to enable applications development concurrent with HTS wire development. Depending on the specific requirements, wire configurations and geometry's are modified to optimize mechanical properties, environmental durability, and critical current. Applications where mechanical performance and wire durability are not critical can take advantage of high fill factors and thus higher critical currents. Applications sensitive to mechanical performance and environmental durability may sacrifice fill factor and critical current. Examples of currently active or planned prototype demonstrations include[7]:

- **Motors** - A five horsepower synchronous motor cooled to 77K has been demonstrated. It was designed and built by Reliance Electric Company for the Electric Power Research Institute with HTS coils manufactured by American Superconductor Co. Motor development is now being scaled up to a 125 hp motor, cooled to 20 K funded by the DOE Superconductor Partnership Initiative program. Future plans are for 1,000 and 5,000 hp demonstration units.

- **Generators** - ASC and others have supplied coils for a 1 MW HTS generator being designed by the US Air Force. The Department of Energy is sponsoring the development of a 100 MVA HTS generator being developed for electric utilities.

- **Current Limiters** - A number of concepts are under development including some based on the use of bulk HTS materials. ASC and Martin Marietta are developing the use of HTS triggered shunt coils to prevent excessive over-current conditions.

- **Transformers** - Recent studies at the DOE Hanford Laboratory point to the feasibility of transformers utilizing HTS windings. Although challenges remain related to ac losses, size, weight, environmental and cost savings suggest this as a promising application.

- **Power Cables** - Plans are now underway for ASC and Pirelli Cable Corporation to build a 30-meter single phase cable for a testing and demonstration program sponsored by EPRI and the Department of Energy. This effort will be followed by the development and manufacture of a 100-meter, 3-phase prototype that will undergo long term testing prior to installation as a pilot link in the power grid.

HTS cables for new and retrofit installations of underground power systems offer a number of technical and economic advantages over conventional copper cables including decreased loss and increased transmission capacity within the same volume of pipe.

Power cables are likely to benefit from HTS wire development sooner than other commercial applications since most of the magnetic field and mechanical requirements can be met with wire performance presently available. A number of companies report progress with the development of short length prototype cable conductors [8],[9]. Multifilamentary HTS tapes were used to assemble multistrand cable conductor prototypes which are an integral element of the fully-integrated, three-phase HTS cable. These prototypes were fabricated for the purpose of evaluating critical current and ac loss performance [8]. The most recent conductor prototype demonstrated at ASC was a 1 meter long assembly which carried over 4,200 amps in self field at 77 K and 1 μV/cm[9]. This cable conductor prototype was fabricated by winding tapes helically around a cylindrical former, assembling the tapes into a multi-layer conductor. The winding pitch was

Table IV
Application Specific Wire Requirements

Coil & Magnet Wire	Power Cable Wire
React and Wind, or Wind and React	React and Wind
Operating Temperature 20 - 50 K, cryointegration	Operating Temperature *liquid nitrogen*
Critical current: 10^{-11}ohm-cm resistivity criteria. $J_c(B)$ for Magnet Design	Critical current: 1 μV/cm criteria. $J_c(0.02T) = 10^4$ amp/cm^2 (specialty application) $J_c(0.1T) = 10^5$ amp/cm^2 (generalized application)
Insulated Wire	Bare Wire
AC Loss: Application Specific	AC Loss: 10^{-3} W/m (specialty application) 10^{-4} W/m (generalized application)
Mechanical Properties: Support Lorentz Forces, Stress (Pressure)	Mechanical Properties: Bend Strain Tolerance during Cable fabrication and thermal cycle
Internal Architecture: Twisted Filaments for reduced ac loss	Internal Architecture: optimized for mechanical and durability factors
Sheath Selection: Alloyed for Strength, High Resistance, Quench Stability	Sheath Selection: Minimize Silver for Cost Savings, Minimize eddy losses
Wire Form Round preferred 3:1 --> 1:1 Aspect Ratio	Wire Form Tape preferred 3 - 5 mm Tape 20:1 Aspect Ratio
Tight Dimensional Tolerances Required = +- 0.0025 mm Width & Thickness	+- 0.1 mm (width)
Finished Coil must be compact, can not deform	Finished cable must be flexible

155 mm and the former diameter 3 cm. A total of 140 strands were used and the overall critical current retention of the react-and-wind-processed tape elements was near 70%.

The demonstration of a 4kA dc critical current cable conductor prototype is significant since the 50-60 Hz operating current threshold for commercial application is approximately 2 kA. The AC operating current of HTS cables will be largely determined by the losses. Previous measurements have indicated that the hysteresis loss dominates individual HTS tapes in self-field. When the tapes are wound in parallel to build a cable conductor the losses increase. Eddy losses due to increased current flow in the silver matrix appears to be the mechanism involved and, depending on the field configuration and level, might become a dominant factor. While further work is needed to investigate the performance of HTS cable conductors in three-phase configuration, the levels measured in cable conductor prototypes show promise and are well below the predicted acceptable value of 1 W/phase meter[10].

Kilometer lengths of high temperature superconducting tape have been shown to have electrical, mechanical and environmental durability performance suitable to demonstrate practical applications of HTS technology. As wire technology continues to improve, the pace of development of applications is also accelerating. This concurrent approach to application and wire development is establishing a demand for HTS wire tapes with improved critical current, alternative architecture such as round wire, twisted filaments for ac loss, hardened sheaths for improved mechanical properties, as well as low costs alternatives to silver sheathed wires.

ACKNOWLEDGMENT

The authors thank Craig Christopherson, Tom Santos, Joe Davis and Andy Curda and the ASC wire production team for their contributions to this paper. We would also like to acknowledge the financial support provided by Pirelli Cavi SpA for cable wire development.

REFERENCES

[1] K. Sandhage, G.N. Riley Jr. and W.L. Carter, J. Metals 43, 21 (1991)

[2] A.P. Malozemoff, W.L. Carter, J. Gannon, C.H. Joshi, P. Miles, M. Minot, D. Parker, G.N. Riley Jr., E. Thompson and G. Yurek, Progress in the development of bismuth-based high-temperature superconducting tapes, Cryogenics 32, ICMC Supplement, 478 (1992)

[3] L. Gherardi, P. Metra, G. Vellego, P.Radaelli, Critical current decay with ageing for polycrystalline YBCO wires and rings, Cryogenics, Vol. 30, (July, 1990).

[4] S. Ochiai, K. Hayashi and K. Osamura, Influence of thermal cycling on critical current of superconducting silver-sheathed high Tc oxide wires, Cryogenics, Vol 31, (Novermber 1991)

[5] L. Gherardi, P. Caracino, P. Metra and G. Vellego, Investigation into the strain tolerance of BSCCO composite tapes, Presented at *TMS Meeting, Pittsburg, (October 18-25, 1993)*

[6] A. Otto, C.Craven, D. Daley, E.R. Podburg, J. Schreiber, and L.J. Masur, Properties of High-Tc Wires Made by the Metallic Precursor Process, JOM, Vol. 45, No. 9, p. 48-52 (September, 1993)

[7] N. Schiff, E. Schempp, HTS Conductor Development for Power Applications, Superconductor Industry, Summer, (1994)

[8] J.J. Gannon Jr., P. Metra, G. Vellego, Performance Summary of Superconducting Bi-2223 Cable Conductor Prototypes, Invited Paper, International Workshop on Superconductivity, Kyoto, Japan, (June 6-9, 1994).

[9] J.J. Gannon Jr., M.J. Minot, D. Buczek, P. Metra, G. Vellego, Performance Summary of High-Temperature Superconducting Cable Conductor Prototypes, to be presented at the Applied Supercondivity Conference, Boston, MA, October 16-18, (1994)

[10] D. Von Dollen, P. Metra, and M. Rahman, Design concpet of a room-temperature HTS cable, Am. Power Conf. Chicago III (1993).