Final Report for

Cooperative Agreement No. DE-FC36-02GO11103, A000

Cost Effective, Open Geometry HTS MRI System

amended to

BSCCO 2212 Wire for High Field Magnets

Background

The original goal of this Phase II Superconductivity Partnership Initiative project was to build and operate a prototype Magnetic Resonance Imaging (MRI) system using HTS coils wound from continuously processed dip-coated BSCCO 2212 tape conductor. MRI is the largest existing commercial application of superconductors. In 1999 – 2000 a business opportunity was perceived for competitively priced, superconducting MRI systems having an open architecture to allow patient comfort and easy access by medical personnel. At that time, open architecture MRI was the fastest growing segment of the market. Most open geometry systems of the time were not superconducting, because of the complex cryogenic systems needed for liquid helium cooling of low temperature superconducting (LTS) magnets, while still allowing open access to the high field region. However, superconducting systems offer distinct advantages in terms of field quality and field strength, and therefore obtainable image quality. Although the feasibility of making conduction cooled HTS MRI coils from multifilamentary BSCCO-2223 conductors had already been shown at that time, the price of the 2223 tape was (and remains) too high. However, BSCCO-2212 can be melt processed and thus can be made as an inexpensive slurry coated conductor, without the need for labor intensive powder-in-tube deformation processing.

Cost estimates showed that dip-coated 2212 tape would have labor and materials costs that are between 10 and 25% of those for multifilamentary 2223 tape. In addition, capital costs are significantly lower. Thus there were compelling reasons to explore the possibility of using dip-coated tape. The melt processing of 2212, which is not feasible with 2223, is what makes the lower cost, coated conductor format a possibility; however, the technical methods for continuously melt processing long lengths needed to be established. One of this program's original aims was to verify that uniform properties, including current density, physical dimensions, and mechanical strength, could be achieved in long lengths of this tape.

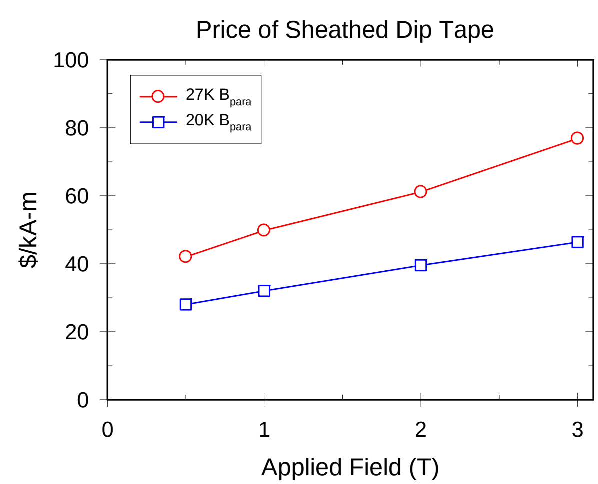
Using dip-coated tape, the plan was for MRI magnet coils to be wound to fit an established commercial open geometry, 0.2 Tesla permanent magnet system. New electronics and imaging software for a prototype higher field superconducting system would have added significantly to the cost. However, the use of the 0.2 T platform would allow the technical feasibility and the cost issues for HTS systems to be fully established. Also it would establish the energy efficiency and savings of HTS open MRI compared with resistive and permanent magnet systems. The commercial goal was an open geometry HTS MRI running at 0.5 T and 20 K.

It was expected that success with this prototype system would lead to lower costs and increased performance for open geometry MRI. This progress was expected to result in a greatly expanded market for the low cost end of MRI applications. This could have very significant and positive contributions to human life and welfare, as well as very significant economic benefits for the nation. Especially compared with resistive magnet systems, power consumption of HTS MRI would be drastically reduced: dissipation in an HTS magnet is ~ 1 watt compared with 15 kWatts for a resistive magnet.

The SPI team assembled to achieve this goal was led by Oxford Instruments, Superconducting Technology (OST), who developed the methods of producing commercial dip coated tape. Superconductive Components Inc. (SCI), a leading US supplier of HTS powders, supported the conductor optimization through powder optimization, scaling, and cost reduction. Oxford Magnet Technology (OMT), a joint venture between Oxford Instruments and Siemens and the world's leading supplier of MRI magnet systems, was involved to design and build the HTS MRI magnet and cryogenics. Siemens Magnetic Resonance Division, a leading developer and supplier of complete MRI imaging systems, was expected to integrate the final system and perform imaging trials. In addition, Los Alamos National Lab was a partner to support conductor and coil development. The National Renewable Energy Lab was a partner to support precursor powder development.

The original MRI demonstration project was ended in July 2004 by mutual consent of Oxford Instruments and Siemens. Between the project start and that date, two significant shifts took place. First, Siemens Medical purchased Oxford Magnet Technology, the magnet partner in the project. Second, a substantial shift in the MRI marketplace occurred, with rapid growth for systems at higher fields (1.5 T and above) and a consequent decline in the low field market (<1.0 T). While the project aim appeared technically attainable at that time, the conclusion was reached that the system economics do not warrant additional investment.

The primary factor in this decision was the significant shift between 2000 and 2004 in the MRI market to higher field strengths. The original demonstration was planned at 0.2 T, but was targeted at a commercial system with a 0.5 T imaging field (peak field on conductor ~1 T). By July 2004, Siemens' position was that a new product introduction needed a minimum 1.5 T imaging field, which requires a peak field of ~3 T in the magnet winding. In addition to the shift in required field, Siemens changed the target operating temperature from 20 K to 27 K in order to reduce the cost of the cryogenic system. The graph at right shows the dramatic change in projected conductor cost in changing from 20 K, 1 T to 27 K, 3 T. Estimated conductor cost changed from 25-30 $/kA-m to 75-80 $/kA/m. Projections showed these prices might drop by 50% when volume production was reached. Our initial target was 10 $/kA-m, and the results of this study suggested 12-15 $/kAm was attainable at 0.5 T and 20 K, but the projected 35-40 $/kA-m for the revised commercial target was not viable. Although the project demonstrated relatively low cost 2212 conductor, a business assessment concluded that the likely return on investment did not warrant further development.



In discussions with Paul Bakke, SPI Project Officer and Jim Daley, DOE HTS Program Manager, it was agreed that there was value in redirecting the remaining obligated funds toward development of multifilamentary 2212 wires aimed at both higher field and higher temperature magnet applications. A formal request for a change of scope was submitted in August 2004 along with a revised budget and Statement of Work. Our original powder partner, SCI, was invited to join us in this work but declined. The work that took place between September, 2004 and the project end in early 2006 was focused on 2212 multifilamentary wire.

This report summarizes the technical achievements both in an HTS MRI system using 2212 dip coated tape, and in 2212 multifilamentary wire for high field magnets.

Technical Results: HTS MRI System

Precursor Powder Development

During the course of this project Superconductive Components Inc. successfully scaled up their powder production capability to 10 kg size lots. Powder from this production line was delivered to OST and qualified by multiple conductor fabrication runs.

An automated precipitation line was designed, built and installed during this project. An upgraded filtration system was installed and qualified. A calcination system capable of 10 kg lots was dedicated to the 2212 powder and optimized for the 2212 precursor. Two 10 kg lots were processed and qualified by OST's dip coating line. By July 2004 the complete system was qualified and ready for production.

A second main activity by SCI was the implementation of low cost raw materials. This development activity was accomplished a step at a time, with 1 kg powder lots being qualified by OST as each change was made. It was demonstrated that substituting lower cost nitrate solution materials into the SCI production process did not result in lower performance in qualification tapes processed by OST. The conclusion was that a total cost reduction potential of 60 - 70% was enabled using the alternate raw materials. This estimate was based on large lot size (total production >1000 kg per year).

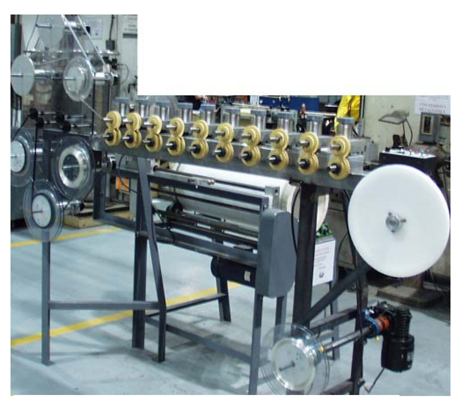
Coating Line

Dip Coated Tape Development

A prototype dip coated conductor processing facility was designed, built and qualified at OST by July 2004. There are three primary components to this processing facility: coating line, sheathing line, and melt heat treatment furnace.

The dip coating line includes in-line ultrasonic cleaning, a slurry reservoir with integral continuous agitation, an instrumented slurry coating tank which automatically refills from the reservoir to keep a constant active coating area, a capacitive coating thickness monitor which feeds back to the line speed motor and enables precision control of the coating thickness, multizone controlled temperature drying chamber, and a digital data acquisition system which monitors all key parameters for the coating process.

The sheathing line uses roll forming principles to continuously wrap a silver or silver alloy sheath around one or more layers of the dip coated tape. Six independent tension controlled payoff spools can accommodate up to five internal layers in addition to the sheathing layer. This line was developed after detailed comparisons between sheathed



Sheathing Line

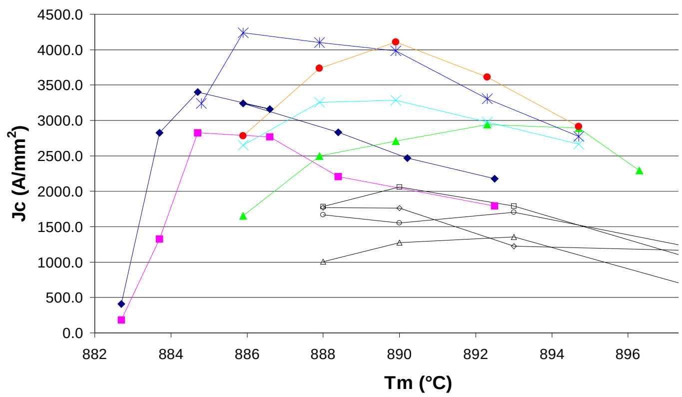
and bare tape, and based on observed degradation upon multiple windings with bare tape a decision was made to focus on the sheathed version. One hundred meter qualifying runs were made on this line.

In parallel experiments with sheathed and bare tape, comparisons were made using continuous heat treatment and batch heat treatment. (Only continuous heat treatment is suitable for the bare tape.) Using sheathed tape, there was consistently better performance from the batch heat treatment. A one cubic meter box furnace was dedicated to the batch heat treatment.

Heat Treat Furnace

A variety of conductor optimization exercises yielded steady improvements in tape performance . A wide range of precursor powder compositions were compared and a final selection made based on maximum J_c and the widest possible melt temperature window for high J_c. A range of substrate types was compared for both bare and sheathed conductor configurations.

A range of coating thicknesses were compared in order to determine the dependence of J_c, and especially J_E (the current density normalized to the entire conductor cross section) on the coating thickness. A peak was found in J_E for coating thicknesses in the range of 50 to 60 µm.



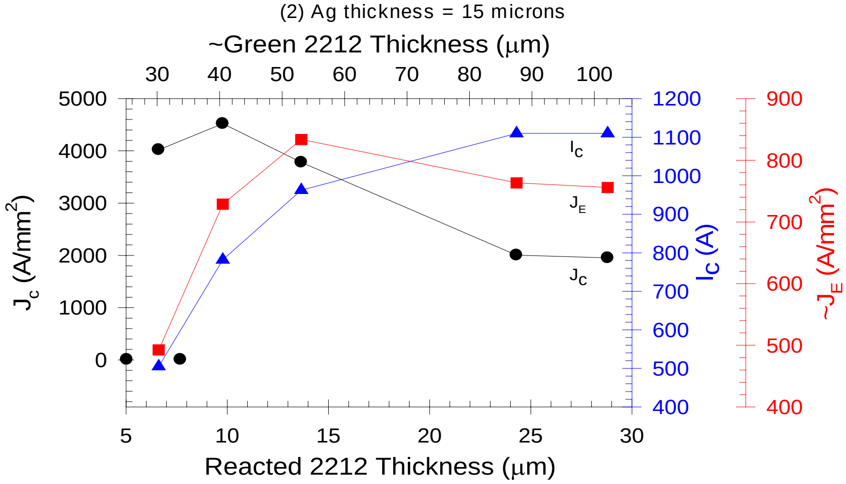
$J_c(T_m)$ in 10 Different Powder Compositions

J_c Dependence on Substrate Material

Substrate	Silver sheathed Avg. I_c (A)	Silver sheathed Avg J_c (A/mm²)	Bare Avg. I_c (A)	Bare Avg J_c (A/mm²)
Ag	986	4107		
AgMg	852	3170	440	1635
AgAu	534	2411		
AgAuMg	528	2485		
Ag/Ni/Ag (1)	765	2548	453	1511
Ag/Ni/Ag (2)			818	3410

(1) Ag thickness = 10 microns

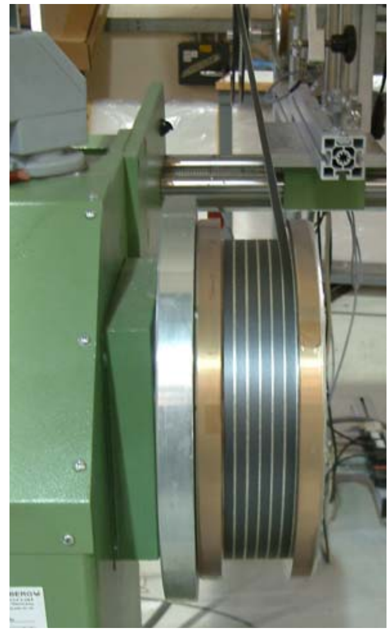
(2) Ag thickness = 15 microns



J_c, J_E dependence on 2212 thickness

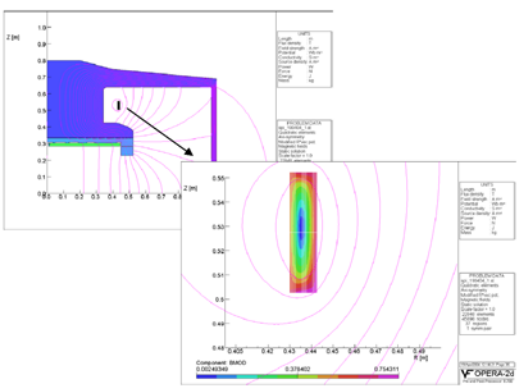
Magnet Development

Several 20 –50 meter lengths of conductor were delivered to OMT for winding trials. These conductors were handled using typical commercial magnet winding methods, wound onto formers, then wound back onto delivery spools and returned to OST where they were retested and compared with initial performance. Based on comparisons between bare and sheathed tape, a strong preference for sheathed tape was expressed. A significant activity in modeling of the proposed magnet was carried out at OMT prior to the change of ownership. Major design decisions had been made such as operating temperature, operating current, conductor and coil sizes and geometry. A comparison was made of performance and cost tradeoffs for designs with and without flux guides. A cryogenic design was studied and decisions made regarding the use of dual thermo-siphons (heat pipes) using nitrogen and neon.

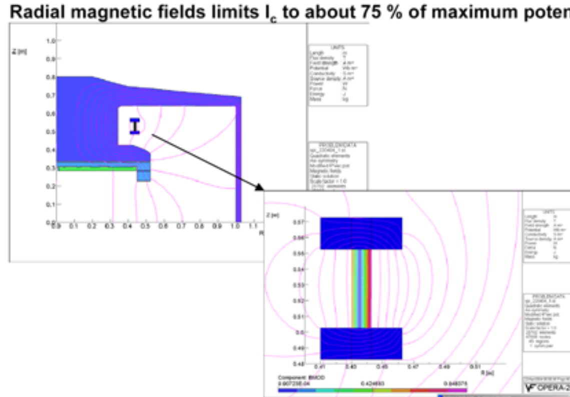


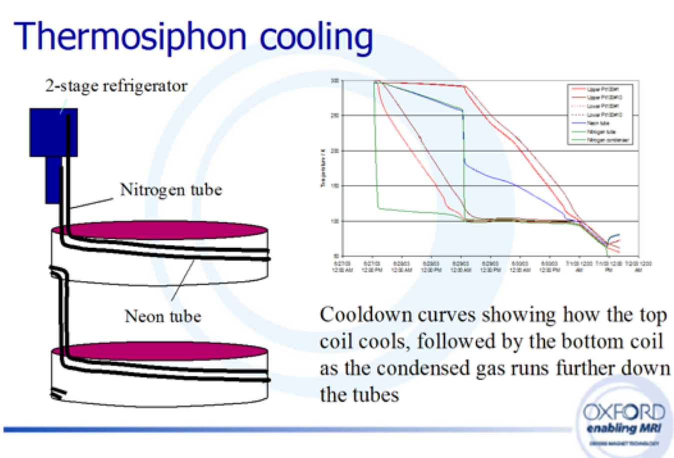
Winding trial at OMT with bare tape

No Flux guides :
Radial magnetic fields limits I_c to about 36 % of maximum potential



Flux guides :
Radial magnetic fields limits I_c to about 75 % of maximum potential





Technical Results: Multifilamentary Round Wire for Magnets

In our 8/27/04 Revision Proposal we stated our objectives for the wire effort as follows:

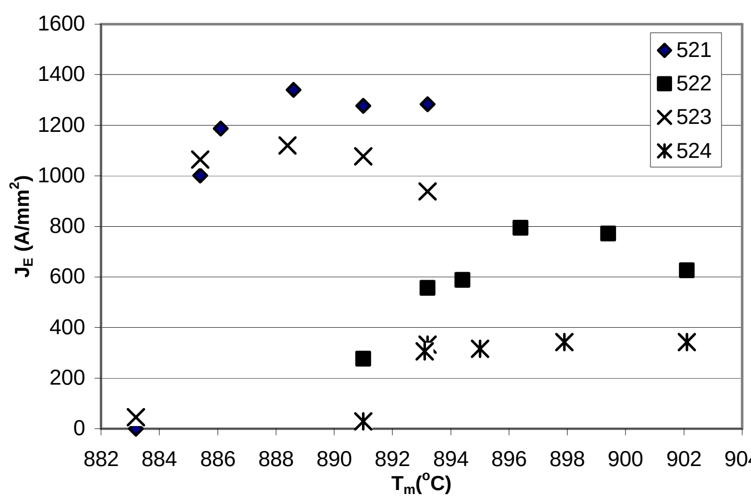
> The primary aim of this work is to increase Jc, J_E, and piecelengths in 2212 round wire that can be used for high field superconducting magnets. Practical performance will be evaluated in small coils tested in background fields that require mechanical strength. Specific objectives include:
>
> a) Achieve Jc > 6000 A/mm^2 at 4.2K, self field through use of best precursor composition and heat treatment.
> b) Achieve J_E > 1600 A/mm^2 at 4.2K, self field through use of best precursor composition and heat treatment, which should enable J_E > 500 A/mm^2 at 4.2K, 25T.
> c) Achieve Jc and J_E values in small coils containing at least 100 m of wire that are greater than 60% of short sample performance.

The SOW tasks planned to enable accomplishment of these objectives were:

1. Powder composition optimization
2. Billet ceramic fraction optimization
3. Heat treatment optimization
4. High field I_c/J_E characterization
5. Mechanical property improvement
6. Insulation development
7. Small coil development
8. Microstructure characterization
9. AC loss measurements

Powder composition

In collaboration with a new powder partner, Nexans Superconductors (NSC), OST fabricated billets from eight different precursor powder compositions. A statistically designed experimental matrix was used in order to study the interaction of powder composition with the major heat treatment parameters (discussed below). This experiment independently optimized the heat treatment for each of the compositions tried. The figure above shows engineering current density results for wires using four different precursor compositions. The result of these studies was the selection of a preferred powder composition for wire: $Bi_{2.17}Sr_{1.94}Ca_{0.89}Cu_2$. A more complete report of this study may be found in reference [1].



The dependence of J_E on the temperature T_m for 521-524 wires.

Billet ceramic fraction optimization

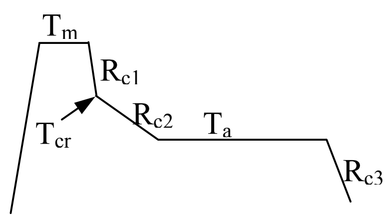
Efforts to increase J_E, the overall current density in the wire, should of course address the issue of how much superconductor can be put into the cross section. The higher the superconductor fill factor the higher the J_E (assuming constant J_c), however as the ceramic content increases so does the difficulty drawing the wire. A range of fill factors have been tried in this project and in related SBIR projects. The table below summarizes the experience to date. It is clear that superconductor fill factors of 29% and higher cause difficulties with drawing. Fill factors of 27% and lower have enabled successful drawing of long lengths.

For insert solenoid coils the fill factor can be pushed closed to 30% since the bending diameters are typically 40 mm or larger. However for Rutherford cables, which require a bend diameter comparable to the wire diameter, a lower fill factor certainly will lower the risk of cracking during the cabling process.

Sample ID	Fill Factor (%)	Piece Length	Comments on Drawability
927	33	Short	Many breaks, very difficult to draw
510B	30	Tens of meters	Many breaks, very difficult to draw
105	29.5	Ten of meters	Some breaks, difficult to draw
712	29	Hundreds of meters	A few breaks, otherwise drew okay
224	28	Hundreds of meters	Very few breaks, easy to draw
625	27.5	Hundreds of meters	Very few breaks, easy to draw
114	27	Hundreds of meters	No breaks, easy to draw
120	25	Hundreds of meters	No breaks, easy to draw
916	24	Hundreds of meters	No breaks, easy to draw
518	22	Hundreds of meters	No breaks, easy to draw

Heat treatment optimization

Bi-2212/Ag wires were heat treated in a flowing oxygen atmosphere using a partial melt-solidification process [2], with the general profile shown at right, where T_m and T_a are melting and annealing temperatures, R_c are the various cooling rates, and T_{cr} is the temperature at which the cooling rate is changed. Our previous procedure for optimizing J_c and J_E in a billet was to choose a schedule (heating and cooling rates, melting and annealing temperatures and dwell times), then run a series of samples with this schedule with varying T_m, which has the most substantial influence on microstructure and hence current density. However, R_c, T_a and anneal time (t_a) can also affect J_c. For this study we used a statistically designed experiment (SDE) with these 4 factors and several levels of each in an effort to further optimize the heat treatment



Schematic heat treatment profile.

SDE heat treatment matrix

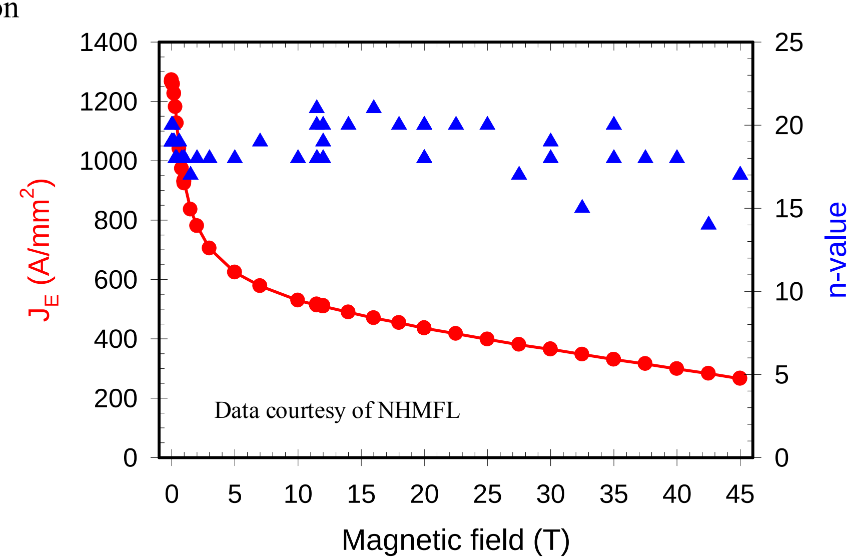
Factors:	T_m (°C)	R_{c2} (°C/m)	T_a (°C)	t_a (hr.)
Trial 1	T_{sm}	2.5	T_{ss}-30	20
Trial 2	T_{sm}	6	T_{ss}-5	80
Trial 3	T_{sm}+2	2.5	T_{ss}-30	80
Trial 4	T_{sm}+2	6	T_{ss}-5	20
Trial 5	T_{sm}+4	2.5	T_{ss}-5	20
Trial 6	T_{sm}+4	6	T_{ss}-30	80
Trial 7	T_{sm}+7	2.5	T_{ss}-5	80
Trial 8	T_{sm}+7	6	T_{ss}-30	20

profile for best current density. The table above shows the SDE, which is a low resolution Taguchi L8 matrix modified to include one four-level factor (T_m). T_{sm} and T_{ss} are the melting and solidification onset temperatures as determined by DTA data supplied by NSC. Since each precursor had different T_{sm} and T_{ss}, the wire billets made from the four precursors 521 – 524 each had a unique SDE (a total 32 heat treatments), and each had a different optimum heat treatment profile which gave maximum J_c for that billet. More complete results for the SDE can be found in reference [1]. The most important conclusion for us is that the 521 composition gives the highest J_c in wires, and the SDE revealed the proper heat treatment parameters to enable this good performance.

After completion of the SDE experiments, several more billets were manufactured using the 521 composition. A more detailed optimization of the melt temperature (T_m) was undertaken using the R_{c2}, T_a and t_a established by the SDE. The final result of these studies was the champion performance results of J_c(4.2 K, 0 T) = 6320 A/mm^2 and J_E(4.2 K, 0 T) = 1580 A/mm^2.

High field I_c/J_E characterization

Routine measurements of I_c and J_E have been carried out in self field at OST, with occasional good samples measured at 4.2 K and up to 16 T in OST's critical current test facility. The best wire samples have been further studied at the highest available d.c. fields in the National High Magnetic Field lab in Tallahassee, Florida. The figure at right is an OST 2212 wire made with the optimized precursor composition and heat treatment. The 45 T result of engineering current density equal to 266 A/mm^2 is quite exciting in terms of potential for high field magnets. This value is higher than J_E in the best Nb_3Sn at 22 T, presently the highest field available in an all superconducting magnet.



Mechanical property improvement

OST has no capability for measuring mechanical properties. The original plan was to collaborate with NIST and/or NHMFL to have these measurements made, but these collaborations have not yet resulted in measurements at either lab.

Insulation development

As part of this effort OST has experimented with a range of insulation materials and two different techniques. Ceramic coatings were tried but were not successful, primarily due to lack of adhesion after the high temperature oxygen heat treatment. A variety of yarn materials were braided on the wire. Most degraded badly in the heat treatment, and some chemically reacted with the 2212 melt, through mechanisms that have been studied and reported elsewhere

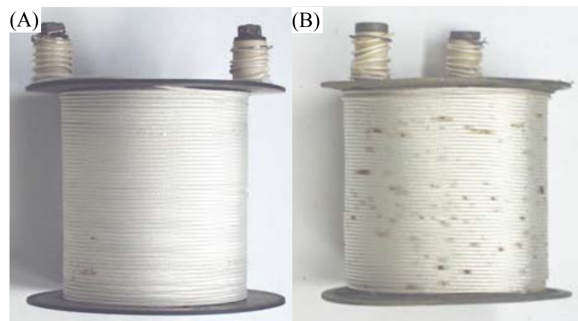
[3]. We did find a ceramic yarn that was successfully braided, has not degraded short sample performance, and has enabled successful wind-and-react coils. [4] High voltage breakdown testing has been done on braided and reacted 1 mm strands in accordance with IEC standard 60851-5. Five samples were tested and the average measured breakdown voltage was 1679±19 V. Note that in a coil the braid is infiltrated with epoxy, and the breakdown performance may exceed this value.

TEST COIL PARAMETERS

Name	ID (mm)	OD (mm)	Height (mm)	No. Turns	No. Layers	Wire Length (m)	Self Field J_E (A/mm^2)	Self Field (T)	Coil Ic % short sample
W1	13	24.4	44.0	120	4	7	356	--	
W2	53.2	62.5	73.0	202	4	37	353	0.8	87%
W3	53.1	71.2	73.0	425	8	83	289	1.27	71%
W4	53.0	81.9	73.0	628	12	133	375	2.3	74%

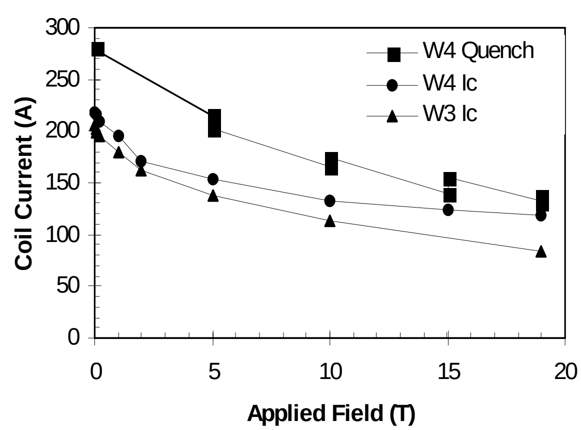
Small coil development

Several hundred meters of 1.0 mm strand were ceramic fiber braided to use in a series of wind-and-react test coils. The table above compares parameters for four coils. Coil W1 was small and intended to provide a first tightly wound coil test with minimum length of wire. Coils W2 through W4 were intended to provide progressively thicker winding sections, having 4, 8 and 12 layers. Note that coils W1 through W3 all used wire from the same billet; W4 used wire from a billet with the same design but a higher performance as a result of a better precursor powder [1]. After winding, all coils were heat treated using a schedule identical to that used for short sample I_c optimization. The photographs show coil W3 before heat treatment and coil W4 after heat treatment. There is some spotting in the braid after heat treatment, which is likely due to slight leaking. This requires further study. The heat treated coils W2, W3, and W4 were epoxy impregnated by our collaborators at NHMFL using equipment and procedures established for our 5 T 2212 insert coil which reached 25 T [5].



Photographs of (A) coil W3 before and (B) coil W4 after reaction.

All coils were initially tested at 4.2 K, self field. Coils W3 and W4 were subsequently tested in background fields using the NHMFL 20 T, 200 mm bore resistive magnet. Critical current was determined using a criteria of 0.1 μV/cm. For the three larger coils a calibrated cryogenic Hall probe was used to directly measure axial field. Coil constants were calculated for these coils using a standard short solenoid model, and the Hall probe data agreed with these calculations to within a few percent, indicating no shorted turns and verifying the integrity of the insulation. Also, the self field I_c in the coils was compared with the I_c for short samples of wire in the coils, the coil



I_c(B) performance of coils W3 and W4. The upper curve is initial quench current behavior of W4. The I_c curves were obtained at 0.1μV/cm.

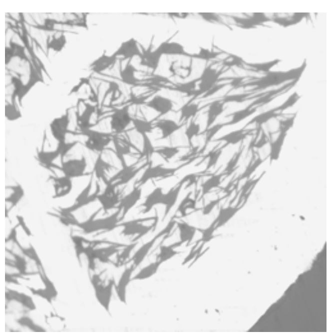
% of short sample is shown in the table

The figure at right shows the in-field $I_c(B)$ data obtained at 4.2 K and 0.1 μV/cm for coils W3 and W4. W3 was well behaved, with stable, reproducible V(I) transitions. W4 quenched at the very start of the V(I) transition during the first 11 current ramps. The top curve in the figure shows the quench currents obtained. For W4 we made multiple current ramps at each test field, hence the multiple data points at a given field. After 11 quenches at various increasing fields between 0.05 and 19 T this coil developed a resistive baseline. After this, at various decreasing fields, we were able to obtain I_c data at 0.1 μV/cm, although these I_c values were substantially lower than the initial quench currents, as shown in the figure. The degraded I_c values still exceeded the reproducible I_c values in W3, made from a lower performing strand. After testing, the outer lead-out in W4 showed visible signs of damage; we speculate this lead is the source of quenching and subsequent resistance.

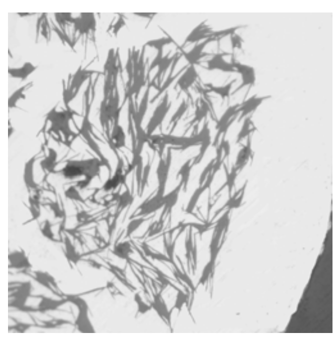
In a 19 T background field coil W3 added 0.47 T, and W4 added 0.99 T at I_c(0.1 μV/cm). Note that these coils were made to demonstrate a wind-and-react fabrication method, and were not designed as field generating coils. Future efforts will focus on adding maximum field using these Bi-2212 wires. As prior measurements have shown, this wire is capable of J_E values over 250 A/mm^2 at 45 T and over 400 A/mm^2 at 25 T [6]. Such J_E performance coupled with the now demonstrated techniques for wind-and-react coils make this a promising material for continued high field coil development.

Microstructure characterization

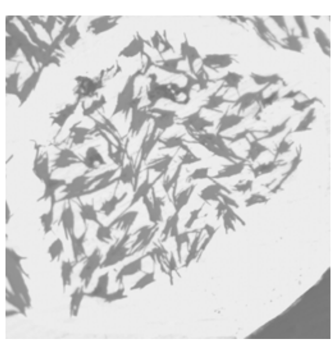
Light metallography and SEM examinations have been done for the whole range of conductor trials made in this study. One example is the characterization done in support of the powder composition trials. These micrographs below show the dramatic differences in filament morphology which occur with different precursor powder compositions, as a result of different melt and recrystallization behaviors [1]. It is of interest to note that higher Sr/Ca ratio correlates with a greater 2212 grain aspect ratio, and a greater number of 2212 whiskers which



521: Sr/Ca =2.18, J_e = 1340 A/mm^2



523: Sr/Ca =2.31, J_e = 1120 A/mm^2



522: Sr/Ca =1.75, J_e = 794 A/mm^2

524: Sr/Ca =1.34, J_e = 342 A/mm^2

The cross-sections of round 521-524 wires with peak J_e after the optimized heat treatment.

grow between filaments.

AC loss measurements

Although this remains of interest, our focus to date has been on optimizing this wire for DC field applications. No AC loss measurements have yet been performed.

CONCLUSIONS: HTS MRI System

The original aim of demonstrating an open geometry HTS MRI system running at 0.2 T was not completed due to changes in the partner companies as well as a substantial shift in the MRI market during the course of the project. Substantial technical progress was made toward a high performance, low cost dip coated HTS tape. Based on the measured performance and the cost structure for conductor manufacture established by this program, the project economics for the target system were judged to be not commercially attractive.

CONCLUSIONS: Multifilamentary Round Wire for Magnets

Our first wire objective, to achieve $J_c > 6000$ A/mm^2 at 4.2K, self field through use of best precursor composition and heat treatment was accomplished. We achieved $J_c = 6320$ A/mm^2 in wire using the best precursor and our best heat treatment optimization to date.

Our second wire objective, to achieve $J_E > 1600$ A/mm^2 at 4.2K, self field was very nearly achieved, with a value of 1580 A/mm^2 attained. We further demonstrated in field J_E values of 475 A/mm^2 at 25 T, and 266 A/mm^2 at 45 T.

Our third objective, to achieve J_c and J_E values in small coils containing at least 100 m of wire that are greater than 60% of short sample performance, was attained. Wind-and-react coils with 83 and 133 meters of wire achieved J_c and J_E performance greater than 70% of short sample.

Regarding the 9 SOW tasks shown below, we completed all planned work for tasks 1-4 and 6-8. Tasks 5 and 9 were not completed due to lack of resources.

1. Powder composition optimization
2. Billet ceramic fraction optimization
3. Heat treatment optimization
4. High field I_c/J_E characterization
5. Mechanical property improvement
6. Insulation development
7. Small coil development
8. Microstructure characterization
9. AC loss measurements

PROSPECTS for FUTURE APPLICATIONS

The 2005 U.S. COHMAG report emphasizes that continued progress toward higher magnetic fields holds significant potential for general advances in science and technology [7]. One specific recommendation this report makes for high field technology development is the goal of a 30 T superconducting magnet for NMR. Commercial high field superconducting magnets for NMR, made with continued advances in Nb_3Sn wires, are available with fields up to 22.5 Tesla at 2.2 K [8], [9]. The most recent internal tin Nb_3Sn conductors have enabled a commercial 22.3 T magnet for 950 MHz NMR spectroscopy [10], [11]. While Nb_3Sn can probably enable 23.5 T for 1 GHz NMR, it is unlikely that such Nb_3Sn magnets can be pushed higher than 25 Tesla because of limits on the upper critical field (B_{c2}).

The results established for multifilamentary round wire in the last 2 years of this project have attracted significant interest in the high field magnet community. Two different application areas have very strong potential, and serious magnet development has begun in both these areas. The first area is high field solenoid magnets for laboratory magnets and NMR magnets. The second is high field dipole magnets for high energy physics and particle accelerator magnets. OST is engaged in active collaborations in both of these areas, and wire manufactured within this program have been supplied at no charge to these collaborators for their development work.

One active collaboration is with the National High Magnetic Field laboratory in Tallahassee, Florida. There is an active development effort underway at NHMFL aimed at a 30 T powered NMR system, which requires a new, higher field superconducting wire to enable this level of magnetic field. The leading candidate for this magnet is 2212 round wire. Over the last 2 years of this SPI project which were aimed at such wire, OST supplied approximately 300 meters of round wire for the development effort in Tallahassee. The NHMFL program is presently being scaled up in terms of resources and level of effort. The present plan calls for approximately 2 kilometers of OST 2212 wire to be supplied in 2006 – 2007 to support the high field development effort. It is interesting to note that the present generation 30 T and higher d.c. magnets at NHMFL are all resistive, water cooled magnets which require 20 MW of electric power to run. The electricity cost to operate these magnets, one at a time over two shifts, 5 days a week is close to $5M annually. It is estimated that a powered 30 T superconducting magnet using 2212 wire would require a power supply < 1 kW, for a twenty thousand times reduction in electric power operating budget.

OST also maintains active collaborations with four laboratories using 2212 for high field dipole magnet development aimed at particle accelerators. The labs are Lawrence Berkeley Lab, Fermi Lab, Brookhaven Lab, and the Texas A&M University magnet devlelopment lab. OST's round 2212 wire has been supplied to all of these groups. One purchase order has been received for 2 km of wire, and another is presently being negotiated. There are active project development efforts underway in all of these laboratories aimed at growing the 2212 dipole magnet development effort. The most ambitious of these is aimed at an energy tripler set of magnets for the LHC accelerator at CERN; a detailed engineering proposal has estimated that using 2212 round wire, a ring of dipole magnets could be operated at 24 T. This is a significant advance over present efforts to double the energy of the LHC using Nb_3Sn dipole magnets.

In conclusion, there is strong interest from the high field magnet community in the U.S. in pushing superconducting magnet technology to unprecedented levels using 2212 round wire. Thanks to the support of the DOE SPI program, OST has taken significant steps in conductor development that support these efforts and the prospects for new applications of high fields.

REFERENCES

1. H. Miao, K.R. Marken, M. Meinesz, B. Czabaj, S. Hong, M.O. Rikel, and J. Bock, "Studies of Precursor Composition Effect on Jc in Bi-2212/Ag Wires and Tapes", Adv. Cryog. Eng. V50, p. 673 (2006).
2. Rikel, M.O., Wesolowskii, D., Polyanskii, A.A., Cai, X.Y., Marken, K., Miao, H. and Hellstrom, E.E., Physica C 372-376, 1839 (2002).

3. D.E. Wesolowski, M.O. Rickel, J. Jiang, S. Arsac and E.E. Hellstrom, "Reactions between oxides and silver sheathed $Bi_2Sr_2CaCu_2$ conductors", Supercond. Sci. & Techn. V18, p. 934 (2005).
4. K.R. Marken, H. Miao, M. Meinesz, B. Czabaj and S. Hong, "Progress in Bi-2212 Wires for High Magnetic Field Applications", IEEE Trans. Appl. Supercond. V16, 992 (2006).
5. H.W. Weijers, U.P. Trociewitz, K. Marken, M. Meinesz, H. Miao and J. Schwartz, "The Generation of 25.05 T using a 5.11 T Bi2Sr2CaCu2Ox Superconducting Insert Magnet", Supercond. Sci. Technol. vol. 17, p. 636, 2004.
6. H. Miao, K. R. Marken, M. Meinesz, B. Czabaj and S. Hong, "Development of Round Multifilament Bi-2212/Ag Wires for High Field Magnet Applications", IEEE Trans. Appl. Supercond., vol. 15, p. 2554, 2005.
7. U.S. National Research Council's Committee on Opportunities in High Magnetic Field Science, "Opportunities in High Magnetic Field Science", National Academies Press, Washington, D.C., 2005.
8. Alan Street, "Superconducting magnets: at the heart of NMR", Spectroscopy Europe, vol. 15, no. 1, pp. 10-13, 2003.
9. S.W. Van Sciver and K.R. Marken, "Superconducting magnets above 20 tesla", Physics Today, vol. 55, no. 8, pp. 37-44, 2002.
10. Oxford Instruments Superconductivity, "Oxford Instruments announces the world's first 950 MHz magnet for Nuclear Magnetic Resonance is at field", press release, August 31, 2005.
11. S. Hong, M.B. Field, J.A. Parrell and Y. Zhang, "Latest improvements of current-carrying capability of Nb-Sn", IEEE Trans. Appl. Supercond. vol. 136 pp. 1146, 2006.