# TECHNICAL PROGESS REPORT

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ON

# PROPERTIES AND DESIGN OF MULTIFILAMENTARY NbTi COMPOSITE SUPERCONDUCTORS (New Title)

Contract No. DE-ACO2-86ER40296

to

U. S. Department of Energy
Division of High Energy Physics

October 31, 1989

BATTELLE
505 King Ave
Columbus, OH 43201

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## INTRODUCTION

For the past three years we have been conducting research in support of multifilamentary conductor development for Superconducting Supercollider (SSC) applications. We have been concerned not only with alloy design -- NbTi-base alloys for the superconductor and Cu-base alloys for the stabilizer -- but also with the design of the multifilamentary strand itself.

Superconductor Materials (Task I): A proposal submitted to the Division of High Energy Physics on April 12, 1985, suggested that the incorporation of Mn into the alpha-phase precipitates that are developed in NbTi for flux-pinning purposes, would reduce proximity coupling between the precipitates and the beta-phase matrix, and thereby enhance flux-pinning strength. Work on the proposed research commenced on August 28, 1986.

The existence of proximity effect on the average superconducting properties of alpha + beta-phase NbTi was demonstrated in a paper entitled **CALORIMETRIC STUDIES OF THE SUPERCONDUCTING TRANSITION AS A FUNCTION OF THERMOMECHANICAL PROCESSING IN FINE FILAMENT Cu/NbTi COMPOSITES** (published, 1988) -- see Appendix A.

In the first phase of the alloying study, Nb-46.5Ti was alloyed with up to 6 wt.% Mn. The results of this work formed the basis of a paper entitled **EFFECT OF**

**MANGANESE ADDITIONS ON THE PHYSICAL AND SUPERCONDUCTING PROPERTIES OF Nb46.5Ti ALLOYS (published, 1988)** -- see Appendix B. In the second phase, currently under way, the properties of monofilamentary strands consisting of 0.5 wt.% Mn dissolved into NbTi(46.5 - 57.5 wt.%Ti) are being examined. Some preliminary results were described in a paper entitled **LOW TEMPERATURE SPECIFIC HEAT OF NbTi AND NbTiMn (to be published)** -- see Appendix C.

Stabilizer Materials (Task II): At a NbTi Workshop held at the Lawrence Berkeley Laboratory in January, 1986, we became aware that interfilamentary coupling, caused by superconductive proximity effect between the filaments across the intervening Cu matrix, was a serious problem to the magnet designer. Since we had already been thinking about the superelectron-decoupling potency of the Mn localized magnetic moment in an alpha-Ti environment, a possible solution to the Cu-matrix proximity-effect problem was immediately to hand. A theoretical paper predicting the utility of dilute Cu-Mn (as an interfilamentary alloy) as an antidote for proximity-effect coupling was presented to the subsequent NbTi Workshop which was held at the University of Wisconsin, Madison, in November 1986. A paper validating these predictions, entitled **STABILIZER DESIGN CONSIDERATIONS IN FINE-FILAMENT Cu/NbTi COMPOSITES (published 1988)** was presented at the International Cryogenic Materials Conference (ICMC) in June, 1987 -- see Appendix D. In the meantime, a proposal to study stabilizer design considerations in more detail was submitted to the Division of High Energy Physics on April 3, 1987. Work on that proposed program commenced on August 28, 1987. Under that program rapid advances are being made in the field of stabilizer materials and strand performance. Very practical aspects have appeared in: **(1) A CONDUCTOR WITH UNCOUPLED 2.5 UM DIAMETER FILAMENTS DESIGNED FOR THE OUTER CABLE OF SSC DIPOLE MAGNETS (published, 1989)**, and **(2) THE EFFECT OF PROCESSING ON THE FILAMENT ARRAY IN MULTIFILAMENT SSC STRAND (to be published).** This work (see Appendix E) was performed in collaboration with a superconductor manufacturer. More fundamental aspects of the research have been discussed at subsequent NbTi Workshops, in particular the the most recent one which was held at Asilomar in January of this year. In addition the following papers were presented at the CEC/ICMC Conference held in Los Angeles during July 24-28, this year: (1) **CRITICAL FIELD ENHANCEMENT DUE TO FIELD PENETRATION IN FINE-FILAMENT SUPERCONDUCTORS;** (2) **THEORY OF FLUX PENETRATION EFFECTS BELOW $H_{c1}$ IN MULTIFILAMENTARY SUPERCONDUCTORS;** (3) **MAGNETIC STUDIES OF PROXIMITY-EFFECT COUPLING IN VERY CLOSELY SPACED FINE-FILAMENT NbTi/CuMn COMPOSITES;** (4) **AC LOSS MEASUREMENTS OF TWO MULTIFILAMENTARY NbTi COMPOSITES (all accepted for publication)** -- see Appendix F. The AC-loss activity stemmed from the hysteresis measurements that were being taken in support of the coupling studies. But they were in fact performed in response to a request from a VAMAS Technical Working Group. We hope to be able to continue to participate formally in these international studies by incorporating them as a task in the proposed continuation program.

In recent months, two important new discoveries have been made: The first has to do with the manner in which coupling magnetization varies with "position" around the M(H) hysteresis loop. The coupling magnetization is predominantly paramagnetic, occurring along the trapping branches of the loop. Coupling magnetization is negligibly small along the shielding branches, and hence should not itself play in important role during SSC beam injection. Most of the parasitic magnetization that exists during beam injection derives from the filamentary magnetization (residual magnetization) independent of the extent of coupling. The second discovery hinges on a way of dealing with this residual magnetization. We are currently looking, in a preliminary way, at the elimination of residual magnetization by the addition to the strand of a small volume fraction of unalloyed Ni. Our thoughts on this subject are expressed in a paper that was presented at the Los Angeles ICMC Conference entitled: **DESIGN OF COUPLED OR UNCOUPLED MULTIFILAMENTARY SSC-TYPE STRANDS WITH ALMOST ZERO RETAINED MAGNETIZATION AT FIELDS NEAR 0.3 T (to be published)** -- see Appendix G.

## RESEARCH SUMMARY

The following statements highlight the major accomplishments of the research performed under this program. Reprints of publications arising from the work are attached as Appendix' A to G.

### Low Temperature Specific Heat of NbTi and NbTiMn Alloys

Low temperature specific heat measurements were performed on a series of annealed-and-quenched binary NbTi alloys in the concentration range 43 ~ 54 wt.% Nb, which includes most compositions of technical interest. As a result of this work we were able to assess the influence of Mn on the calorimetrically measured properties of NbTi. Two series of alloys were considered: (i) Mn content fixed at 0.5 wt.% and with Nb between about 40 and 53 wt.%; (ii) almost fixed Ti content and with Mn between 0 and 5 wt.%. It was demonstrated that Mn causes a decrease in the electronic specific heat coefficient and a concomitant decrease in $T_c$. In that regard the effect of Mn on $T_c$ ($dT_c/dc$ = -0.22 K/at.%) is comparable to those of Cr, Mo, and Re (for which $dT_c/dc$ = -0.2 K/at.%). From this it was possible to generalize that Mn in bcc NbTi acts like any other nonmagnetic transition-element and influences $T_c$ through its influence on the band density of states.

### AC Loss Measurements of Two Multifilamentary NbTi Composite Strands

As a contribution to an interlaboratory comparative testing program conducted in support of the Versailles Agreement on Advanced Materials and Standards (VAMAS), transverse-field DC hysteresis loss measurements were made at liquid-helium temperatures at fields of up to 3T (30 kG) on two samples of multifilamentary NbTi composite strand, comparable in filament diameter but one with, and the other without, a Cu-Ni barrier between the filaments. The results were analyzed, and magnetically deduced critical current density values obtained (for comparison with directly measured transport data) using various standard techniques. Based on these studies, the question of AC-loss criteria was systematically addressed.

## Magnetic Studies of Proximity Effect Coupling in Very Closely Spaced Fine-Filament NbTi/CuMn Composites

Magnetization studies were conducted on a 22,900 filament composite (local fil. spacing/fil.dia. ratio of about 0.19) drawn down to filament diameters in the range of 0.5 to 2.5 $\mu$m. The various techniques that have been used to explore the onset of proximity-effect coupling between the filaments across the Cu-0.5wt.%Mn matrix were systematically discussed. These trechniques are: (i) departures from linearity of plots of (a) M(H) loop area vs. fil.diam.; (b) M(H) loop height at a given field vs. fil. diam.; (ii) comparisons of the M(H) loop heights of clad material with those of a series in which all the matrix has been removed by etching; (iii) an inter-comparison of the M(H) loops taken at field sweeps below the $H_{c1}$ of NbTi. It is demonstrated that proximity-effect, when it occurs in the matrix, may do so over a wide range of applied magnetic field strength, but that the most sensitive test of its presence is by susceptibility measurement in very low magnetic fields -- i.e. below the "$H_{c1}$" of the matrix.

## Design of Coupled or Uncoupled Multifilamentary SSC-Type Strands With Almost Zero Retained Magnetization at Fields Near 0.3 tesla

Multifilamentary Cu-matrix strands with interfilamentary spacing as small as 0.2 um can be almost fully decoupled by the addition of 0.5 wt.% Mn to the interfilamentary Cu. It has been discovered that the elimination of coupling does little to reduce residual strand-magnetization at the injection field of about 0.3 T when that field is approached, as usual, along the shielding branch of M(H). This residual diamagnetic magnetization (say $M_R$) of the winding material is responsible for unwanted distortion (multipole formation) of the dipolar field. It is demonstrated that

$M_R$ can be localled cancelled to zero by associating the strand with a small volume-fraction (less than 2%, depending on filament diameter) of pure Ni or any other low-field-saturable ferromagnetic material. The presence of the Ni has little effect on the shape of the M(H) hysteresis loop of the strand, other than to shift its wings uniformly in the +M ( when H is positive) and -M directions, respectively. It is recommended that, in practice, the Ni could be administered as: (a) additional filaments, (b) interfyilamentary barriers, or (c) an electroplated layer on the outside of the strand.

## CONCLUSION

Research funded under the subject contract has contributed strongly to the SSC program. The publications themselves make up a short recent history of SSC strand development, viz: (i) the recognition of field-quality problems associated with strand magnetization; (ii) the identification of proximity-effect coupling as a contributor to magnetization-loop height and hence (erroneously) as a contributor to excess magnetization; (iii) the recognition that proximity-effect had a relatively minor effect on the actual strand magnetization during the field-increasing segments of the magnetization cycle (the SSC-operating mode); (iv) the discovery that a small addition of Ni to the strand could go a long way towards eliminating total strand magnetization during field-increase and hence towards increasing the SSC bore-field quality.

The results of the research should contribute towards a higher quality lower cost SSC magnet.

Appendix A – G

Papers

APPENDIX A

CALORIMETRIC STUDIES OF THE SUPERCONDUCTING TRANSITION AS FUNCTION OF THERMOMECHANICAL PROCESSING IN FINE FILAMENT Cu/NbTi COMPOSITES

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## APPENDIX B

## EFFECT OF MANGANESE ADDITIONS ON THE PHYSICAL AND SUPERCONDUCTING PROPERTIES OF Nb46.5Ti ALLOYS

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# APPENDIX C

## LOW TEMPERATURE SPECIFIC HEAT OF NbTi and NbTiMn ALLOYS

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APPENDIX D

STABILIZER DESIGN CONSIDERATIONS IN FINE FILAMENT Cu/NbTi COMPOSITES

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APPENDIX E

A CONDUCTOR WITH UNCOUPLED 2.5 um DIAMETER FILAMENTS DESIGNED FOR THE OUTER CABLE OF SSC DIPOLE MAGNETS

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AND

THE EFFECT OF PROCESSING ON THE FILAMENT ARRAY IN MULTIFILAMENT SSC STRAND

CONF paper removed.

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## APPENDIX F

AC LOSS MEASUREMENTS OF TWO MULTIFILAMENTARY NbTi COMPOSITE STRANDS

MAGNETIC STUDIES OF PROXIMITY-EFFECT COUPLING IN VERY CLOSELY SPACED FINE-FILAMENT NbTi/CuMn COMPOSITES

CRITICAL FIELD ENHANCEMENT DUE TO FIELD PENETRATION IN FINE-FILAMENT SUPERCONDUCTORS

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# APPENDIX G

## DESIGN OF COUPLED OR UNCOUPLIED MULTIFILAMENTARY SSC-TYPE STRANDS WITH ALMOST ZERO RETAINED MAGNETIZATION AT FIELDS NEAR 0.3 T

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