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LASL Nb_3Ge Conductor Development

October 1—December 31, 1979

University of California

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Fourteenth Quarterly Progress Report

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ABSTRACT

The fourteenth quarterly report of the Los Alamos Scientific Laboratory program to develop Nb_3Ge as a superconductor with potential applications to superconducting power transmission lines covers the period Oct. 1 - Dec. 31, 1979. During this quarter, we concentrated on materials research aimed at improving the performance of Nb_3Ge tape conductor. A new ac-loss apparatus designed to measure hysteretic and ohmic losses in tape conductors was employed to study the losses in seventeen Nb_3Ge tape samples with currents induced around the circumference of the tapes. We discovered that tapes with Nb_3Ge thickness $\leqslant 3.0\ \mu m$ have a continuous coating of Nb_3Ge around the edges and that such tapes exhibit low total losses ($\leqslant 10\ \mu W/cm^2$ at 500 rms A/cm). Thicker layers of Nb_3Ge do not maintain edge integrity and exhibit large ohmic losses caused by the full transport current flowing through the normal substrate. Work on Nb-Ge-Ga ternaries by chemical vapor deposition has concentrated on the preparation of reproducible deposits of A-15 Nb_3Ga.

I. INTRODUCTION

The Nb_3Ge conductor development program of Los Alamos Scientific Laboratory (LASL) commenced a third phase on January 1, 1979. The long-term objective of the program is to develop a conductor suitable for application to superconducting power transmission lines (SPTLs) that is significantly superior to presently available conductors. More specifically, the aim is to exploit the record-high T_c (~23 K) of Nb_3Ge to permit operation of a SPTL in the temperature range 14-16 K. In the initial phase of the program, completed in June 1976, we developed a chemical vapor deposition (CVD) process by which short samples of Nb_3Ge could be produced with superconducting properties that meet the requirements for power transmission at T = 12 K. A description of the program accomplishments through June 30, 1976 may be found in the EPRI Final Report (TD-200).[1] The second phase, begun on July 1, 1976, concentrated on the task of modifying the basic CVD process to produce long lengths of Nb_3Ge-clad tapes with material properties matching those of our best short samples. The effort culminated in the production of a 20-m-long Nb_3Ge-clad tape. The tape consisted of a 0.64-cm-wide x 25-μm-thick copper substrate, coated uniformly with a 4.0 μm-thick layer of Nb_3Ge. Sections taken from both ends of the tape had measured values for J_c of 2.5 and 2.4 x 10^6 A/cm^2 at 13.8 K and material parameters that varied by less than 5%. Phase II was completed on June 30, 1978 and is fully described in the EPRI Final Report EL-965,[2] entitled "Development of Nb_3Ge for Power Transmission Applications." Phase III, for which this is the fourth quarterly report, is aimed at the fabrication and testing of two 1-m sections of ac-SPTL using the long Nb_3Ge-clad tapes developed in Phase II.

This report covers the period Oct. 1 - Dec. 31, 1979 and is the fourteenth quarterly report issued since the beginning of the EPRI sponsorship. In keeping with previous convention, we will refer to this report hereafter as PR-14. We reported in PR-13 the completion of our first 1-m test section of Nb_3Ge-based superconducting power transmission line. Because of scheduling problems at the power transmission line project at Brookhaven National Laboratory (BNL), we have not been able to test our cable during this quarter as originally planned. Therefore we have revised our schedule to commence portions of the materials development effort. This effort is aimed at making significant improvements in our Nb_3Ge tape material for incorporation into the second test section. During this quarter we have concentrated our efforts on two areas of materials research, ac losses and third element additions to the Nb_3Ge.

A major objective of the Nb_3Ge program is to develop a tape superconductor based on Nb_3Ge with properties significantly superior to those of Nb_3Sn for application to power transmission line technology. Heretofore, we have concentrated our efforts on the problem of improving the current carrying capacity of our tape conductors at temperatures $T \geqslant 12$ K. In these tapes, we have achieved critical current densities J_c that surpass those attainable in any other conductor at $T \geqslant 12$ K by at least a factor of two. However, an equally important problem is that of reducing ac losses in these conductors to an acceptable level for use in ac-power transmission. These losses can be separated into two categories: hysteretic losses from irreversible flow of quantized vortices through the superconductor; and ohmic losses associated with current flow through normal conductors. We have previously attacked and solved the problem of hysteretic losses in Nb_3Ge by a combination of metallurgical techniques, which raise J_c, and surface treatments, which inhibit vortex entry into the superconductor.[2]

The second source of losses has proven to be a more difficult problem; it is a problem encountered in the Brookhaven National Laboratory (BNL) double helix design for an ac power transmission line, where the transport currents are driven not along the axis of the tape but helically around the tape axis.[3] This drives large transport currents circumferentially around the edges of the tapes and leads to unacceptably large ohmic losses in the normal substrates of presently available Nb_3Sn conductors. Our tapes consist of a 0.64-cm-wide, 25-μm-thick ribbon of copper (or other normal metal) which is coated uniformly with a 2-to-6-μm-thick layer of Nb_3Ge by the chemical vapor deposition process (CVD). Our process for producing Nb_3Ge should eliminate the ohmic loss problem because the Nb_3Ge should completely shield the normal conductor around the tape circumference. Unfortunately, initial ac-loss measurements on our conductors performed at BNL indicated that the Nb_3Ge does not carry currents around the edges. During this quarter we have made significant progress on this problem by discovering a correlation between edge continuity and substrate material and Nb_3Ge thickness.

We designed and constructed a new ac loss apparatus capable of measuring both hysteretic and ohmic losses on tape samples in a geometry in which currents are induced circumferentially around the cross-section of the tape. Our previous apparatus could only measure the hysteretic component.[1] The new apparatus is also capable of measuring losses as a function of temperature over 4 K $\leqslant$ T $\leqslant$ 20 K.

We have measured the power loss P_L on 17 samples as a function of ac-current amplitude, although we are primarily interested in P_L at 500 rms A/cm, as this is the rated current level for the BNL cable; losses less than 10 $\mu W/cm^2$ at this level are considered acceptable. In our samples we varied the Nb_3Ge thickness as well as the substrate--copper, nickel, niobium, and stainless steel. The results of our study indicate that the edges are continuous and shield the substrate on samples whose Nb_3Ge-layer thickness is $\leqslant$ 3.0 μm. Also,thicker Nb_3Ge coatings maintain their integrity on substrates (e.g. stainless steel) that place the coat under substantial compression. For one sample on which edge integrity was maintained, total ac-losses were measured as a function of temperature and were observed to remain $\leqslant$ 10 $\mu W/cm^2$ @ 500 rms A/cm up to 12.0 K. This is an encouraging result, and further work will be carried out to ensure reproducible continuous edges. Details are provided in Sec. II.

We have previously explored the possibility of using third element additions to Nb_3Ge in order to stabilize the compound,[2] leading to a more homogeneous, reproducible product. Third element additions have been observed to enhance the upper critical field H_{c_2} in Nb_3Sn . A likely candidate for this approach is the element gallium which would substitute for germanium in Nb_3Ge. Nb_3Ga forms in the A-15 structure and is a high-T_c superconductor ($T_c \sim$ 20.0 K). Earlier, we were unable to achieve the proper stoichiometry in the Nb-Ge-Ga system due to problems encountered in the chlorination of gallium to produce $GaCl_3$. During this quarter, we have returned to this problem with a different approach, employing a $GaCl_3$ saturator instead of in-situ chlorination. An extensive investigation this quarter reveals that this technique is not feasible due, probably, to the formation of the dimer $(GaCl_3)_2$, which is not reduced by hydrogen at the coating temperature. We have, therefore, elected to redesign the chlorinator system for further attempts. This effort is described more fully in Sec. III.

We have also continued attempts, reported in PR-13, to produce a very homogeneous sample of Nb_3Ge for examination by heat capacity measurements. This is discussed in Sec. IV.

The results of calculations of ac losses for various tape cross-sections are given in an appendix.

II. AC LOSSES

Apparatus and Procedure

In PR-13, we described our new ac-loss probe, which allows losses to be measured on short (3-5 cm) lengths of tape samples. Currents are induced around the circumference of the sample by a 50-Hz magnetic field that is aligned parallel to the tape axis. A flat pickup coil surrounds the sample and is tightly coupled to it. As previously discussed,[1,2] the pickup signal contains a loss component caused by flux movement through the sample surface and an inductive component, generally at least two orders of magnitude larger, caused by flux linkage external to the sample surface. The inductive component is cancelled out by a second inductive pickup coil that surrounds the sample but is very loosely coupled to it. The procedure for "bucking" out the inductive component is crucial to the accuracy of the loss measurement because any small phase shift introduced between the bucking signal and pick-up signal will add or subtract a component that is in phase with the loss signal. Because the inductive signal is so much larger, phase shifts of a small fraction of a degree can lead to large errors. If one is only interested in measuring the hysteretic component of the loss then a universal feature of the critical-state-model, a kink occurring in the loss waveform at the maximum current amplitude, can be used to adjust the phase of the two signals. This procedure suffers from an inability to measure any ohmic-like (nonhysteretic) components of the loss. This was not a serious disadvantage when we were measuring tubular samples coated uniformly on the outside with Nb_3Ge. However, for the tape samples, there is reason to suspect that the coating may not be continuous around the edges, leading to large transport currents being driven through the normal substrate. The ohmic losses caused by these currents may be substantially higher than the hysteretic losses.

The primary problem in measuring the total losses, hysteretic plus ohmic, is to establish a credible procedure for setting the proper phase relation between the pickup and inductive signals. We elected to accomplish this by employing a standard sample of 0.64-cm-wide, 25-μm-thick niobium tape. Assuming that the losses are negligible in the niobium for field amplitudes $\leqslant H_{c1}$, we adjusted both phase and amplitude of the inductive signal to give a null resultant when added to the pickup signal. We found that when the field amplitude was increased sufficiently to yield a hysteretic loss signal no further phase adjustment was required to achieve the waveform required by the critical state model for pure hysteretic loss. Because niobium is not expected to exhibit any ohmic losses in the superconducting state, we believe that this procedure establishes the proper phase relation between the two signals. However, the usefulness of this procedure for measuring losses in our Nb_3Ge coated tapes depends on the ability to warm up the probe and change samples without changing the phase relation. This was demonstrated by a series of five loss measurements on the niobium sample at an induced current of 500 rms A/cm. Between measurements, the probe was removed from the Dewar and warmed up. The sample was removed and then reinserted into the pickup coil. For the five tests, measured ac losses varied by $\leqslant 1.0\ \mu W/cm^2$. The same test was periodically repeated once a week over a period of six weeks with the same results. These tests establish confidence that small changes in the geometrical arrangement of pickup and compensating coils caused by changing samples do not alter the phase relations significantly. After this demonstration, we felt confident in setting the phase with the niobium tape for each series of measurements on the Nb_3Ge samples.

Results

In Fig. 1 we show plotted the power losses vs induced current σ. The round symbols indicate the total losses determined in the manner described above. For this sample, the losses at 500 rms A/cm are very large ($\sim 60\ \mu W/cm^2$), and the loss waveform exhibited "ohmic" characteristics. This same behavior was characteristic of a large number of our samples and is, we believe, associated with "cracked" or discontinuous edge material. This belief was corroborated by measurements we made on this same sample after both edges were sliced off with scissors. The losses measured on the "edgeless" sample were not significantly different from those plotted in Fig. 1. Also shown in Fig. 1, by the triangular symbols, are the hysteretic losses measured on the sample after the phase was changed to give the canonical hysteretic loss signal. It is apparent that the hysteretic component ($\sim 10\ \mu W/cm^2$ @ 500 rms A/cm) is only a small fraction of the total loss.

During this quarter we measured the ac losses on seventeen samples of our Nb_3Ge tape material, including samples taken from all of the long tapes used in wrapping our first 1-m test cable. We observed two distinctly different types of behavior. One class of samples showed loss characteristics similar to the results of Fig. 1, with a large ohmic loss observable at the lowest induced currents. The second class of samples, however, exhibited negligible

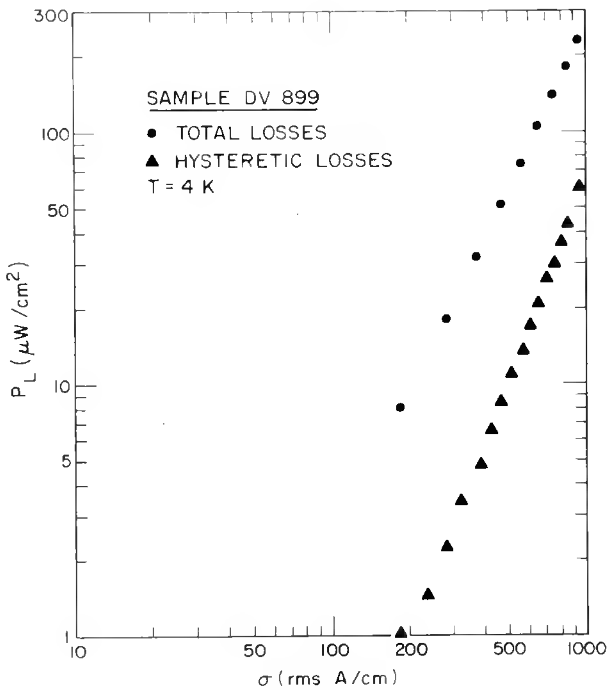

Fig. 1.
Plots of total ac losses (• -symbol) and of the hysteretic components (▲-symbol) as functions of the induced current for sample DV 899 at 50 Hz and 4 K.

losses at low induced currents and a pure hysteretic loss waveform above a threshold current value. These samples behave identically to the niobium tape when measured at the same phase setting. Clearly, the edges on the second class of tapes are continuous and their normal substrates are being shielded from the ac field. In Fig. 2 we have plotted total losses as a function of σ for one of these samples. The loss at 500 rms A/cm for this sample is only $\sim$ 4.5 μW/cm^2. On some of these tapes we were able to observe a "break-through" in which the current penetrated into the normal substrate above a certain current level.

In studying the results for the 17 samples we were able to ascertain some systematics in the loss behavior. These results are summarized in Table I.

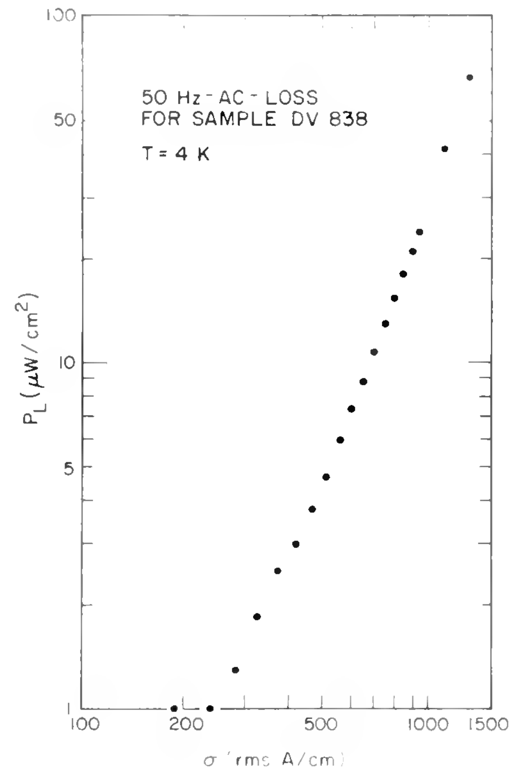

Fig. 2.
A plot of total ac loss as a function of induced current at 50 Hz and 4 K for sample DV 838.

The conclusions which we draw from the results are as follows:

1. Without exception, all Nb_3Ge material with thicknesses > 4.0 µm deposited on copper substrates exhibit large losses. An examination of loss waveforms on these tapes shows the presence of ohmic (copper) losses even at low currents. This can be true only if the edges are cracked.

2. Without exception, <u>all</u> Nb_3Ge material with thicknesses $\leqslant$ 3.0 µm exhibit low losses. The loss waveforms show perfect shielding of the copper by the Nb_3Ge, i.e., edge integrity.

3. Material with thicknesses $\geqslant$ 4.0 µm on stainless steel and on niobium substrates exhibit low losses. Because niobium is superconducting at 4.0 K, this does not necessarily imply edge integrity for samples on niobium, but it does for samples on stainless steel. An examination of these results in conjunction with the relative coefficients of thermal expansion for Nb_3Ge and the various substrates suggests that a substantial compressive stress on the

TABLE I

AC POWER LOSSES IN Nb_3Ge TAPES

Sample	Nb_3Ge Thickness (μm-per side)	Substrate Material	P_L @ 4K, 500A/cm(rms) (μW/cm²)
DV 899	5.0	Copper	52.0
DV 824	6.0	Nickel	100.0
DV 837-10	4.5	Copper	50.2
DV 828	6.0	Copper	90.4
DV 898	4.5	Copper	100.0
DV 901	4.5	Copper	100.0
DV 900	5.0	Copper	100.0
DV 838(1)	2.8	Copper	8.1
(2)	2.8	Copper	4.7
(3)	2.8	Copper	5.0
(4)	2.8	Copper	5.4
DV 913(1)	2.5	Copper	3.8
(2)	2.5	Copper	0.66
(3)	2.5	Copper	3.0
DV 912	2.7	Copper	4.5
DV 868-2	5.5	Niobium	1.1
DV 851-1	6.5	Stainless Steel	3.3

Nb_3Ge coat may be necessary to maintain edge integrity. However, a further examination of samples coated on stainless steel, showed that many of the samples exhibited "breakthrough" at rather low values of induced current. This was not true of thin layers ($\leqslant$ 3.0 μm of Nb_3Ge) on copper. Further studies of these correlations are planned. This is an important step toward producing Nb_3Ge tapes with acceptable losses for ac power transmission.

We succeeded in measuring the temperature dependence of the ac-losses on sample DV 913. Figure 3 shows the losses at two different current amplitudes σ, plotted as a function of temperature. The losses at the lower level (280 rms A/cm) remain small ($\leqslant$1.3 μW/cm^2) and nearly temperature independent up to $\sim$15 K. This current amplitude is less than the current required to nucleate flux lines in the bulk of the Nb_3Ge, and thus the losses remain negligible up to $\sim$15 K, where the surface barrier becomes equal to σ. The higher current amplitude (500 rms A/cm) is sufficient to allow flux penetration at 4 K. The increasing losses with temperature rise reflect the decreasing critical current density $J_c(T)$. Both samples exhibit a "breakthrough" of flux into the substrate above a certain temperature.

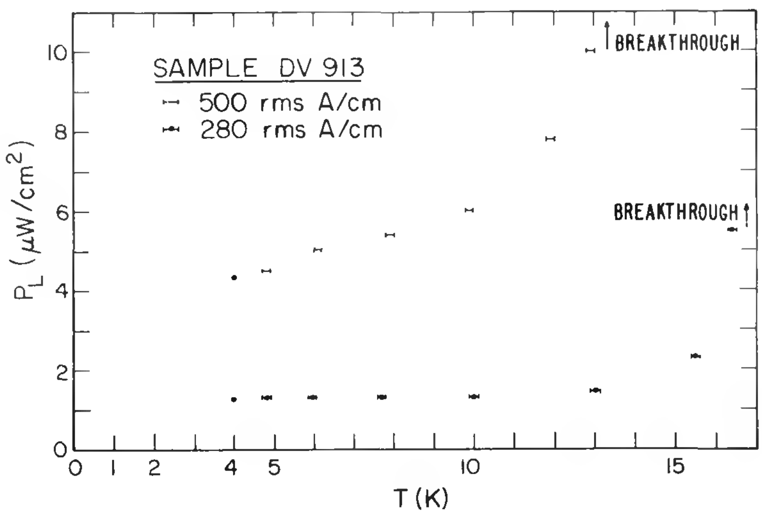

Fig. 3
Plots of total ac losses at two induced current levels as functions of temperature for sample DV 913 at 50 Hz.

III. Nb-Ga SYSTEM

In preparation for depositing Nb-Ge-Ga ternary alloys, the deposition of binary Nb-Ga is being studied. Several attempts were reported about 18 months ago at depositing Nb-Ga-Ge alloys.[2] The superconducting properties of these alloys were rather poor as an apparent result of failure to achieve 3:1 stoichiometry in the Nb to (Ga + Ge) ratio. We feel that further attempts to deposit ternary alloys without first establishing the optimum conditions for binary Nb_3Ga are rather futile. Our previous attempt employed the low temperature chlorination of gallium in a nickel chamber as a source of $GaCl_3$. Observation during chlorination and examination of the residue remaining in the chlorinator suggest that two different mechanisms were probably responsible for failure. First the presence of a reactive salt in the chlorinator implies that chlorides other than $GaCl_3$ are being generated and that these chlorides are not volatile at the chlorination temperature (325^oC). In addition, observation of the reaction products suggests that the conversion of Cl_2 to chlorides was incomplete, resulting in an excess of HCl in the deposition chamber.

In order to avoid the pitfalls described above, we decided to employ a $GaCl_3$ saturator using commercial $GaCl_3$ instead of in situ chlorination. In this arrangement the $GaCl_3$ is held at a constant temperature somewhere below its normal boiling point (203^{o}C) and argon is passed over it to transport the vapor present. In this type of system, the amount of vapor transported is proportional to the argon flow over a limited range of flows. By this technique, we expected to have reasonable control over the delivery of $GaCl_3$ without any possibility of chlorine passing through into the system to create excess HCl.

Several runs were carried out, with observations quite different from those expected. At temperatures significantly below the boiling point of $GaCl_3$ (100-120^{o}C), vapor began to evolve from the saturator with no flow of carrier gas. At higher temperatures, a large amount of vapor evolved independent of the amount of argon carrier passed through the saturator. Tape samples were prepared at various saturator temperatures from 85^{o}C to 170^{o}C and their structure determined by x-ray diffraction. Those prepared at the lower saturator temperatures were bcc niobium, indicating little effective transport of $GaCl_3$, apparently contradicting the observation of noticeable smoke in the exhaust system. Those prepared at the higher saturator temperatures were a mixture of bcc and A-15 structures, while those prepared at the highest saturator temperature were single phase A-15. The lattice spacings of the A-15 phase ranged from $\sim$5.26 A to 5.19 A, indicating a range of gallium compositions from $<$ 2 at.% to $\sim$18 at.%. No attempt was made to achieve compositions greater than 18 at.% since the delivery of $GaCl_3$ was not controllable above this level, and a great deal of smoke was observed in the exhaust system.

In order to understand the very unexpected behavior of the $GaCl_3$ saturator, several thermodynamic calculations were carried out by R. Behrens of LASL Group CMB-3. These calculations showed that decomposition of the $GaCl_3$ to Ga_4Cl_9, $GaCl_2$, or GaCl is thermodynamically unfavorable. Polymerization of the $GaCl_3$ to $(GaCl_3)_2$, however, is extremely favorable, and the vapor pressure of the dimer is expected to be 1 atm between 100 and 150^{o}C. This agrees well with the observed evolution of vapor between 100 and 120^{o}C. Using the Al-Cl system as an analogy, the vapor pressure of the $(GaCl_3)_2$ is expected to increase slowly as the temperature increases, accounting for the increasing amount of smoke in the exhaust as the saturator temperature is raised. By further analogy to the Al-Cl system, one would expect the dimer, $(GaCl_3)_2$, to dissociate increasingly to $GaCl_3$ as the temperature is raised, achieving an equal mixture of $GaCl_3$ and $(GaCl_3)_2$ somewhere between 700° and 1000°C. Comparison of the measured composition of the deposit with the estimated gas composition indicates that reduction of the $GaCl_3$ is less than 30% efficient. This may be compared to near 100% efficiency in reducing $GeCl_4$. If we assume, for the present, that only $GaCl_3$, and not $(GaCl_3)_2$, can be reduced by hydrogen, then this low effective activity for gallium may be understood in terms of the balance between $GaCl_3$ and $(GaCl_3)_2$.

Because the evolution of $(GaCl_3)_2$ makes delivery of $GaCl_3$ from a saturator nearly impossible to control, we have returned to in situ chlorination of gallium. On the basis of our previous experience, the process has been altered in the following ways: First, the gallium metal is contained in a quartz crucible inside the nickel chlorinator, preventing direct reaction between the nickel and the gallium. Second, no carrier gas is used, resulting in an atmosphere of pure Cl_2, $GaCl_3$ and $(GaCl_3)_2$ above the Ga. Third, chlorination is carried out at 500°C instead of 325°C. Our first attempts at using this chlorinator have been successful in delivering $GaCl_3$; however, a plugging problem is observed to develop downstream in the apparatus after 1 to 2 h of operation.

IV. Nb_3Ge HEAT CAPACITY

As discussed in PR-13, substantial effort has been expended attempting to prepare a Nb_3Ge sample with the sharpest possible heat capacity transition in order to observe any effect of sample homogeneity on γ and N(0). Using the x-ray linewidth of the (611) peak as an indication of sharpness, all possible variables in coating procedure were controlled as closely as possible to insure material homogeneity. The cooling chamber length was shortened so that only a $\pm$ 5°C temperature variation existed over its length, and the chosen composition was approached from the germanium rich side instead of the usual germanium deficient side.

In addition to the measures described above, sample preparation techniques were altered. Careful examination of linewidths has shown that material on the copper tape is almost three times as sharp as ground powder. A long-term anneal of powder for 330 h shows that about half of this sharpness is recovered during the first 40 h at 800°C. Additional annealing up to the 330 h time showed little additional improvement. This may suggest that the grinding process used to produce the powder results in some damage to the structure. The ideal solution would be to measure an unground foil, removed from the copper substrate; however, the mass of such a piece is too small for an accurate measurement. The sample chosen for measurement was deposited at 855^{o}C under the conditions described above, and the pressed powder pellet was annealed for 330 h @ 800^{o}C. The measurement is presently underway and will be reported in the next quarterly.

V. PERSONNEL

L. R. Newkirk and F. A. Valencia are responsible for development and testing of the conductor, M. P. Maley and J. D. Thompson for ac-loss measurements and cable fabrication, and R. J. Bartlett and R. V. Carlson for critical current and bend test measurements.

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3. M. Garber, J. F. Bussiere, and G. H. Morgan "Design of Double Helix Conductors for Superconducting AC Power Transmission" Magnetism and Magnetic Materials (Joint MMM-Intermag Conf., Pittsburgh) AIP Conf. Proc. #34, 84, 1976.

APPENDIX

Calculation of Normal Substrate Losses

It is instructive to compare the power losses due to the normal substrate in our tape conductors for four different cases. Case 1, Fig A1, is that of a bare copper substrate of thickness t and width w that is subjected to an ac field B which is aligned along the tape axis (perpendicular to the plane of the cross-section). This case would approximate the situation in which the Nb_3Ge coating was severely fractured in many places, so that there is no continuous superconducting path around the tape. Case 2 corresponds to adding continuous superconducting layers on both sides of the substrate but with no edge coverage. Case 3 is a tape covered with a continuous layer of Nb_3Ge with the exception of a narrow crack of width t'. Case 4 is that of a tape covered completely around with Nb_3Ge. For comparison purposes the losses will be estimated for all of these cases with the following assumed values for the various parameters:

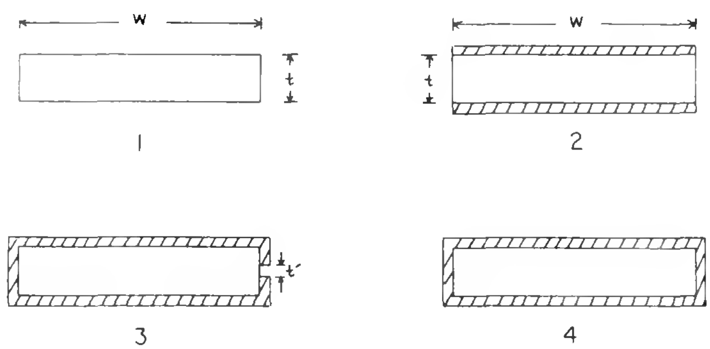

Fig. A1.
Illustratons of the various models of tape cross-sections upon which the calculations are based. Cross-hatching indicates Nb_3Ge; the central rectangle of each figure is copper.

resistivity $\rho_{cu} = 10^{10}$ Ω-m

frequency f = 50 Hz

applied field amplitude B_o = 0.1 T ≈ 560 rms A/cm

thickness $t = 2.5 \times 10^{-5}$ m

width $w = 5\times10^{-3}$ m

Case 1. For high conductivity copper at 50 Hz, the skin depth $\delta > t$ and we may use a straightforward application of Faraday's law to derive:

$$P_L(1) = \frac{B_o^2 \omega^2 t^3}{6} \quad W/m^2 \tag{A1}$$

and inserting the values listed above gives, $P_L(1) \approx 3\,\mu W/cm^2$.

Case 2. The superconducting layers on the faces will carry currents that completely shield the center of the tape from the external field. However, these large shielding currents must transfer at the edges completely through the normal substrate in a layer of thickness δ at the copper edge. This problem can be solved by a standard eddy current treatment and its solution has been given by Garber et al[3] as:

$$P_L(2) = (2\mu_o\rho\omega)^{1/2}\, t/w\, B_o^2/\mu_o^2 \tag{A2}$$

assuming $t \ll \delta \ll w$ ($\mu_o = 4\pi \times 10^{-7}$).

Application of this expression to our problem gives, $P_L(2) \approx 890\,\mu W/cm^2$. This value is more than two orders of magnitude larger than $P_L(1)$, a result that may seem surprising. However, although the driving emf is the same for both cases, because most of the current circuit is superconducting in Case 2 its resistance is smaller by the factor t/w. This results in a current which is larger by the factor w/t and losses that are larger by a similar factor.

Case 3. Although this problem is difficult to solve analytically, we can make a good approximation by assuming that the current flow is identical to that assumed in Case 2, i.e. that the full shielding current flows through the copper within δ of the surface over the length t'. With this assumption eq A2 is applicable with t' replacing t, and the losses will be smaller by the ratio t'/t. If we assume that the crack causes current to transfer through the copper over a distance of ~2 μm; then $P_L(3) \sim 75\mu W/cm^2$, a value comparable with those measured in our samples at this current level.

Case 4. In this case the losses are purely hysteretic and the copper is completely shielded. The Bean London model of hysteretic losses gives an expression for 50 Hz:

$$P_L\ (4) = 2.38 \times 10^{-4}\ (t/w)\ (B_0^3/\mu_0^3\ J_c)\ W/m^2 \qquad \text{(A3)}$$

where J_c is the critical current density of the superconductor. Using the appropriate values in A(3) gives $P_L(4) \sim 3.0\ \mu W/cm^2$ a value in agreement with our measurements on samples that maintain edge integrity.