CONF-760829--4

INVESTIGATION OF STABILITY OF COMPOSITE SUPERCONDUCTORS IN TYPICAL COIL CONFIGURATIONS*

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For Presentation

Applied Superconductivity Conference
Stanford, California
August 17-20, 1976

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CONTRACT NO. W-7405-ENG-26

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INVESTIGATION OF STABILITY OF COMPOSITE SUPERCONDUCTORS IN TYPICAL COIL CONFIGURATIONS*

J. R. Miller, J. W. Lue, and L. Dresner†

ABSTRACT

The stability of various composite conductor designs in realistic coil environments has been examined. We measure the velocity of propagation or contraction of a normal region, the full recovery current, and the minimum propagating current in a coil segment. We examine the dependence of these measurements on background field, transport current, electrical insulation, cooling passage size and orientation, and proximity of other conductors. Comparison of experiment and calculation provides indirect information about local heat transfer to the helium bath and direct information about safe operating current limits for particular coil designs.

I. INTRODUCTION

It is impossible to discuss the stability of a magnet wound with a composite superconductor in terms of conductor characteristics only. The details of heat transfer to the helium bath and of magnet structure must, of course, be carefully considered. Even then any statement about stability must be conditional upon the nature and duration of expected heat inputs.

Nevertheless it is possible and important to separate out the factors affecting stability that can be related directly to the conductor and its exposure to boiling helium. This is the type of information that is required by the buyer writing conductor specifications, and it is a baseline from which a magnet designer may begin his design.

It is the purpose of this study to examine aspects of stability that are determined solely by a conductor in contact with boiling helium and to develop methods of using this information to extrapolate to realistic magnet coil situations. The approach has been an iterative process using both theoretical and experimental information.

II. EXPERIMENTAL TECHNIQUE

In addition to measuring the conductor stability limits (full recovery current I_{FR} and minimum propagating or maximum recovery current I_M), we measured the recovery velocities at currents between these limits and propagation velocities at currents larger than the minimum propagating current. Such measurements increase our certainty about the stability limits and give insight to possible differences in details of heat transfer, for instance, in the different current regions.

Measurements of propagation and recovery velocity are performed using two different sample holders for positioning the test conductor in the applied field. A holder such as the one pictured in Fig. 1 fixes the sample into a relatively open helix whose axis is oriented parallel to the applied field. A conductor on this holder is unaffected by inter-turn heat flow, and though the exposure to helium can be varied over a wide range by masking, channel size has no influence. Such an apparatus then can be used to measure the limits of stability in a situation almost entirely determined by conductor design.

Another apparatus used may be described as a bifilar pancake sample holder. In this apparatus, pictured in Fig. 2, heat flow between adjacent turns of the conductor may have an effect. In addition, the passages admitting helium to the conductor are finite. This holder is designed so that it can be oriented at any angle relative to horizontal. The bifilar mounting eliminates problems due to reaction of the current carrying sample to an external field.

Both sample holders and the measuring techniques used with them can be described schematically by Fig. 3. Several resistance heaters may be bonded to the test conductor; some provide localized heat input, and others are stretched out on one side of a conductor to distribute heat input over a long section. Propagation velocities are measured by selecting a suitable current and background field and by applying a localized heat input. The growth of a normal region is monitored by voltage taps at specific intervals along the conductor and recorded as traces of voltage vs time on a Biomation 1015 transient recorder. Similarly, recovery velocities are measured by creating a normal zone with a distributed heat source and then allowing the normal region to collapse from the ends when the external heat is removed. Typical voltage vs time records are shown in Fig. 4 for both propagation and recovery.

III. CALCULATIONS

The minimum propagating current is calculated by the equal-area method of Maddock, James, and Norris.[1] Various boiling heat transfer coefficients are used[2] and the effects of current sharing are included in the calculation of the joule heat production. The thermal conductivity of the matrix is taken to be proportional to temperature in accordance with the Wiedemann-Franz law, which is assumed to hold for non-zero magnetic fields.[3] The propagation and recovery velocities are calculated by a new method[4] which includes not only the physical effects just mentioned, but also the temperature variation of the specific heats of both copper and the superconductor.[5] The theory as described in Ref. 4 contains no adjustable parameters. Agreement with the experiment is generally poor, but can be improved markedly by an ad hoc correction to the heat transfer coefficient for the effect of transient heat transfer. The correction factor has the form $\exp\ Cv(T_{as}-T)/(T_{as}-T_b)$, where C is a constant to be chosen to achieve a good fit to the data, v is the propagation velocity (positive for an expanding normal zone, negative for a recovering zone), T_{as} is the temperature in the normal region far from the propagating front, T_b is the helium bath temperature, and T is the temperature in the metal at a point being traversed by the front. For an expanding zone, this is equivalent to a maximum correction to the heat transfer coefficient of a factor exp (Cv) at the head of the wave ($T = T_b$). At the tail of the wave ($T = T_{as}$), the correction factor equals 1.

Manuscript received August 17, 1976.

*Research sponsored by the Energy Research and Development Administration under contract with Union Carbide Corporation.

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IV. RESULTS AND DISCUSSION

Figure 5 displays a representative set of data on a particular conductor with relatively high copper fraction. These data were taken using a helical sample holder similar to that of Fig. 1. The dashed curves represent the fits to data obtained using the methods of calculation described. The fit is reasonable though not perfect. It should be noted that this fit was obtained by modifying the boiling curve of Lyon[2] using the expression given earlier with $C = 5.6$; this type of fitting was carried out with all data with more or less the same degree of success.

Table I describes the conductors tested and summarizes the results of these tests. The calculated ratios of maximum recovery current to full recovery current, I_M/I_{FR}, are based on three different heat transfer curves suggested by Lyon, Brentari and Smith. and Butler et al.[2] The theory gave values of I_M/I_{FR} in the range 1.3-1.6; the experiments gave values near 1.3. Because the heat transfer coefficient for insulated conductor surfaces is not well known, calculations were not done for insulated conductors.

TABLE I
Measured and Calculated Recovery Currents

Sample & Holder	B (T)	I_M (A)	I_{FR} (A)	$\dot{Q}_m$[d] (W/m²)	$(I_M/I_{FR})_{exp}$	$(I_M/I_{FR})_{Th}$
S10-30 bare (λ_{sc}=0.091 A=5.65 mm²) Helical	3.0	670	500	0.20	1.34	1.29[a] 1.36[b] 1.28[c]
11.4-1530 bare (λ_{sc}=0.42 A=3.31 mm²) Helical	6.0	320	---	---	---	1.58[a] 1.35[b] 1.50[c]
	7.5	280	---	---	---	1.57[a] 1.32[b] 1.49[c]
11.4-1530 Insulated (λ_{sc}=0.42 A=3.31 mm²) Bifilar Pancake	4.5	205	160	0.42	1.28	
	5.5	195	150	1.43	1.30	

[a] Using heat transfer curves of Lyon[2]

[b] Using heat transfer curves of Brentari[2]

[c] Using heat transfer curves of Butler[2]

[d] $\dot{Q}_m \equiv I_{FR}^2\rho/f_{cu}AP$

A comparison of stability of the same conductor in both the helical configuration and in the pancake configuration is shown in Fig. 6. Here the data were forced to have the same crossing point on the current axis by plotting $V/\sqrt{f}$ vs $I/\sqrt{f}$ where f is the fraction of surface exposed to helium in each case. The logic behind this choice is that for the conductor paramaters at hand, the maximum recovery current is roughly proportional to $\sqrt{f}$, but since the velocity in the region just above this current should be proportional to I, we also divide the corresponding velocity by $\sqrt{f}$. If there are no other factors of influence, all the data should fall on the same curve; however, as is evident from the figure, velocities measured on the pancake sample fall below those for the helical smaple in the same region. This can be explained in terms of inter-turn heat flow since in the bifilar pancake sample experiment the sample always has a superconducting and thus a cold section of sample lying adjacent to it.

When the pancake was tilted relative to the vertical, data like those in Fig. 7 were produced. Apparently the variation in the cooling with changing channel orientation had some effect. It should be noted that a tilt of the pancake relative to the vertical also causes a reorientation of the conductor in the background field. A field component parallel to the conductor current will increase the critical current; the reorientation of the field from being parallel to the wide face towards being parallel to the narrow face will decrease the critical current.[6] However, for 15° of tilt these two competing effects are both small. Thus the observed shift of the velocity vs current curves in Fig. 7 would seem to be due mostly to the variation in cooling.

V. SUMMARY

The full recovery current, the minimum propagating current, and normal zone velocities were measured for several conductors in different environments. The velocities of normal zone propagation and contraction can be fitted reasonably to theoretical calculations only by an ad hoc correction for the effects of transient heat transfer. The stability limits are improved by tilting the conductor pancake towards vertical. The effect of inter-turn heat flow in the bifilar pancake was also observed.

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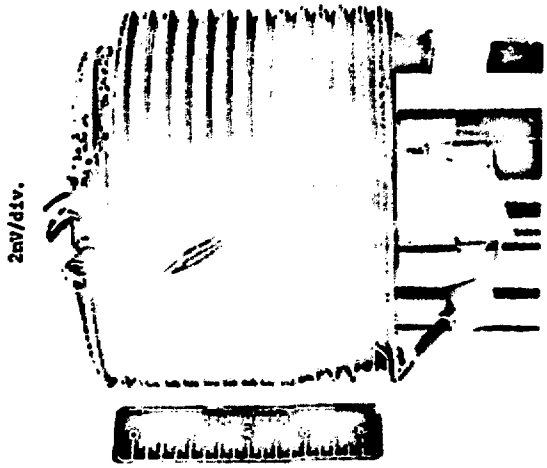


Fig. 1. Helical sample holder. Test conductor lies in the bottom of the Vee groove.

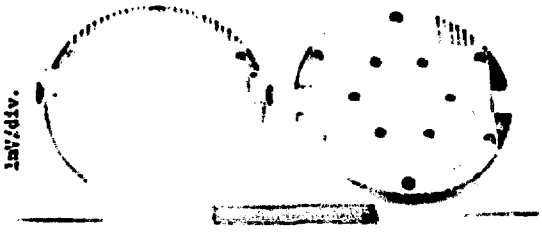


Fig. 2. Bifilar pancake sample holder, opened to show mounted sample and helium channels.

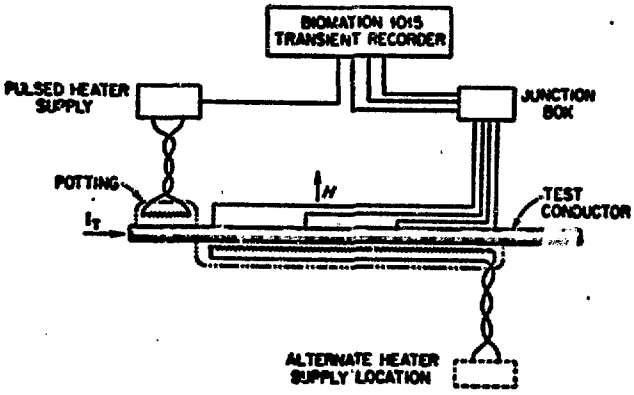
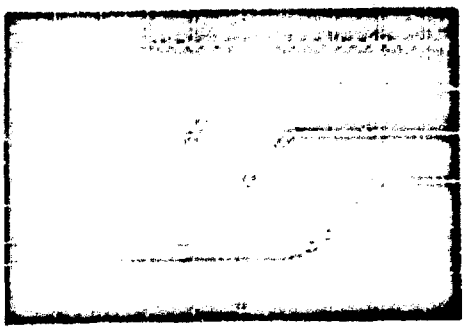


Fig. 3. General schematic of stability experiment.



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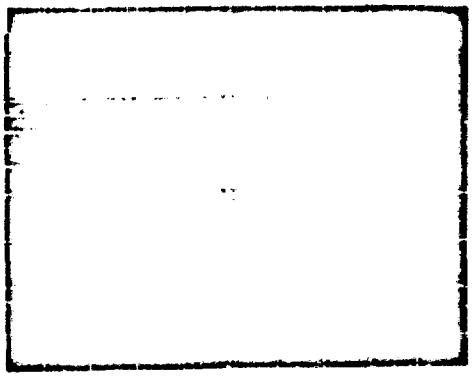
(a)



0.05 s/div.
(b)

Fig. 4. Typical voltage vs time traces showing (a) linear propagation through four sequential zones and (b) linear recovery through four sequential zones.

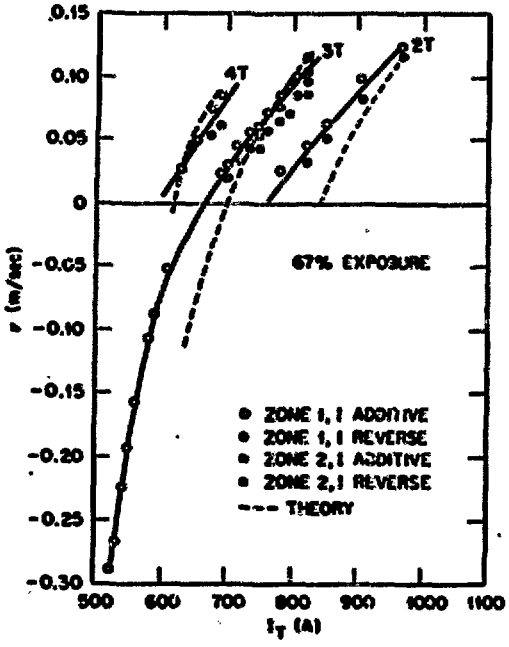


Fig. 5. Velocity of propagation/recovery vs transport current (helical sample holder).

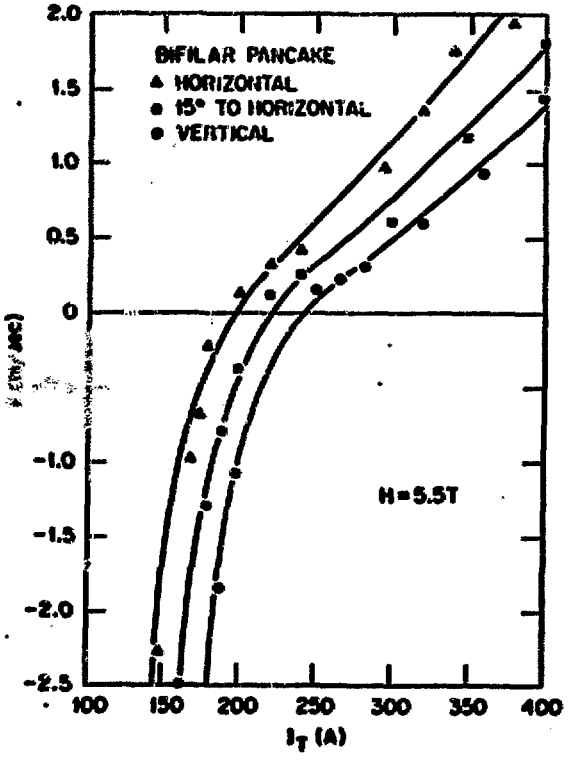


Fig. 7. Effect on velocity vs transport current caused by tilting the pancake sample holder.

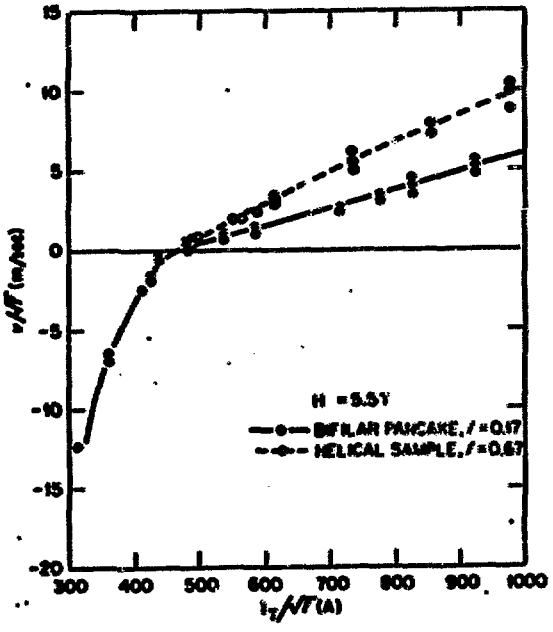


Fig. 6. Reduced velocity vs reduced current for identical conductors on sample holders that allow different exposure to helium.