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SUPERCONDUCTING COILS USING STRANDED CABLES

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SUPERCONDUCTING COILS USING STRANDED CABLES

by

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ABSTRACT

The performance of coils wound with stranded superconducting cables can be predicted from a knowledge of the minimum current at which propagation of normality in the cable can occur. Experiments are described in which this property has been measured on a variety of cable designs and a correlation has been obtained between the performance of short lengths of cable and large coils.

The design has been varied to obtain either a maximum average current density in the winding or the short sample current in the superconducting wires.

The behaviour of the composite conductor immediately following its transition to normality is reported.

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INTRODUCTION

The performance of superconducting coils, particularly those of large dimensions, has been seriously degraded by unpredictable premature transition to the normal state. If the superconductor is in intimate contact throughout its length with a normal conductor of high conductivity this normal material will act as a shunt at the point where a transient instability has caused the superconductor to become normal. When the transient has died away the current will either return into the superconductor or remain in the normal material. Which of these two courses is taken will depend upon the temperature of the superconductor and its thermal characteristic under the prevailing current and field conditions.

The object of stranding superconducting and normal materials together is therefore to ensure that, should a transient phenomenon cause the superconductor to go normal at a current and field below the design values, superconductivity will be restored immediately. Stekly[1] has discussed the design of coils in which the superconductor is stabilised for operation up to the short sample critical current. This paper describes techniques for optimisation of the composite conductor for stable operation up to a design current giving either the highest overall current density or most economic construction. Small scale tests are reported which can be used to determine the behaviour of cables in a practical thermal environment taking into account the temperature variation of the heat transfer coefficient and the magneto-resistance of the normal material.

Experimental data was obtained by measuring the propagation of normality in the conductor in the following three arrangements:

(1) A short length of cable freely immersed in liquid helium.

(2) A small 3-layer coil.

(3) Eight-inch bore coils having a winding depth of 2" and width of 1¼".

Tests were carried out on the first two arrangements with the samples in the field of a 1" bore superconducting solenoid.

PERFORMANCE OF CABLE FREELY IMMERSED IN LIQUID HELIUM

For these tests, the cable was mounted in a manner similar to that used for obtaining the usual short sample characteristics of the wire. Fig.1 is a photograph of a typical sample ready for test. For short sample testing, wire movement is normally restrained by taping the assembly with adhesive cotton tape. Whilst the presence of this tape does not affect the short sample performance, it decreases the minimum value of current at which normality propagates along the wire after this condition has been created artificially at one point. For propagation measurement, the cable was therefore held to the insulating tube on which it was wound by thin string at four points on each turn.

Normality was initiated by the application of a current pulse to a heater wire wound round a 1 cm length of the cable. The voltage developed across potential taps on the sample and the current through it were recorded on a multi-channel ultra-violet sensitive recorder.

Having adjusted the transverse magnetic field to the desired value, the heater was pulsed periodically as the current through the sample was raised. At low currents, voltage pulses were detected across the sample, indicating that the heater was causing normality in its vicinity but that superconductivity was restored after de-energising the heater. The current was increased to a value at which this normality propagated along the entire sample.

In composites having a relatively small amount of normal conductor, the total current transferred to the copper at this 'minimum propagating current'. As the amount of copper was increased the transfer was only partial and the current could be increased further before commutation was complete.

In the limiting case of the single superconductor surrounded by six 0.0124" diameter copper wires, the transition at high fields was completely stepless, occurring at the short sample critical current.

Propagation was impeded by the cooling effects of the potential leads on samples having a small amount of copper. In these cases, therefore, the minimum propagating current was taken as the value at which superconductivity returned as the current was decreased from a value well above the minimum propagating value.

PERFORMANCE OF CABLE WHEN WOUND INTO A SMALL COIL

Previous tests have shown that a gaseous environment reduces the minimum propagating current of composite conductors by a factor of 2 or 3, thus indicating the importance of ensuring that the conductor is in contact with liquid. Since the liquid will be vapourised by a transient normality it is essential that there must be adequate provision for the removal of the gas and its rapid replacement by more liquid. To enable the performance of large coils to be predicted it is necessary to carry out propagation tests on the cable under the appropriate thermal conditions. This was done using a three-layer coil with a mesh between layers to allow helium access. The layers were 1¼" wide, the width proposed for the large coils, wound on to a ½" diameter insulating tube. Adhesive Melinex tape was wound round the outside of the coil to prevent radial ingress of liquid. A heater was wound around the centre turn of the middle layer. The coil was then assembled in the bore of the solenoid and the minimum propagating current found in the same manner as for the sample in free liquid.

EIGHT-INCH COILS

The large coils built to check that their performance could be predicted from the small coil tests were 8" bore, 12" outside diameter, and 1¼" wide. Copper mesh $\frac{1}{32}$" thick was inserted between the coil and the end cheeks to give the helium access to all the layers. The interlayer insulation in the earlier coils was 0.01" thick stainless steel mesh, and on the later ones 0.01" thick Terylene net.

The coils were wound with cable which had been insulated with Terylene yarn approximately 0.001" thick. A heater was incorporated in the inside layer to initiate a normal region for the determination of the minimum propagating current.

EXPERIMENTAL RESULTS

Tests on Short Samples of Cable

The first type of cable on which a complete set of tests has been carried out is a 3-strand cable.

The cable was made by twisting together two 0.010" diameter Nb 25% Zr wires, copper plated to 0.013" diameter, together with one 0.0124" diameter copper wire, followed by an indium dip. The short sample performance and minimum propagating current for an experimental length of uninsulated cable is shown in Fig.2 (Cable A).

A long length of cable was then manufactured. The copper plating in this cable was reduced to 0.001" thick and the copper wire was 0.0126" diameter. One of the superconducting wires was Nb 25% Zr and the other Nb 33% Zr. The results for this cable (Cable B) are also shown in Fig.2, together with the minimum propagating current curve obtained after the cable had been insulated with Terylene yarn. It is to be noted that although the short sample characteristic of cable B was better than that of cable A, its propagating current was less. The resistance of the copper in the cables was determined from the potential measurements and is shown in Fig.3. The resistivity of the copper in cable B was significantly higher than that of cable A, thus accounting for the lower propagating current. The curves also show the significant contribution of magneto-resistance.

Small Coil Tests

Fig.4 shows the performance of a number of three layer coils all wound with cable B but having different interlayer insulation. The full curve is that obtained for the cable in free liquid. There is fair agreement between the sample in free liquid and the three-layer coils. It has not been established whether the deviation from the curve is due to the different interlayer insulation or to constructional variables.

Large Coil Performance

An 8" pancake coil consisting of 1596 turns of cable having the load line shown in Fig.4 was then wound and energised. As the current was raised the heater was repeatedly pulsed and the first sign of sustained normality occurred at 58 amps when the wire in the vicinity of the heater remained normal after the heater had been de-energised. The current was increased again without further pulsing of the heater. At 64 amps, the region of normality propagated and resistance measurements indicated that it now extended for a distance of approximately four turns. On reducing the current, complete superconductivity was restored at 57 amps. This performance was perfectly repeatable.

Improvements in Cable Performance

It has been shown that appropriate heat-treatment of the superconductor after final drawing can improve the short sample performance of NbZr superconductors[2]. Unfortunately when heat treated wire is wound into a coil, the degradation is so increased that the coil performance is inferior to that for a similar coil using untreated wire. If, however, a heat treated wire is used in conjunction with a shunting normal conductor, regions subject to a transient change to normality will be neither sustained nor propagated below a certain value of current which is determined solely by the thermal conditions.

The performance of a cable could thus be improved by using heat treated superconductors. To utilise the enhanced short-sample performance it is also necessary to increase the copper section and the cooling surface. Accordingly the number of copper conductors was increased from 1 to 2 and a central 0.005" wire was included to obtain a satisfactory mechanical arrangement for stranding. A five-strand cable, of only slightly larger diameter than the three-strand was in this way developed. Fig.5 shows the performance of two such cables. In cable C the central 0.005" wire is a resistance wire whereas in D it is a superconductor. The resistance of the copper in cable D is higher than that in cable C resulting in a falling off in performance at the higher fields.

The effect of increasing the amount of copper surrounding a single heat treated superconductor has been experimentally determined. The basic superconductor was a 0.01" diameter Nb 25% Zr wire, copper plated to 0.013" diameter. The minimum propagating currents measured on short lengths of cable freely mounted in liquid helium are shown in Fig.6. A table has also been drawn up to obtain a measure of the current density which would be obtainable in a coil at 20 and 40 kG. (Table I). It has been assumed that there will be 0.01" insulation between all layers. These results show that if the performance obtained on the samples can be reproduced in coils, a current density in the coil of the order of 1.7×10^4 amps/cm^2 should be obtainable at 20 kG with a nine-strand cable. A cheaper arrangement, however, could be obtained by using the seven-strand cable at 200 amps per superconductor, but the winding would require slightly more space. These figures are based on the minimum propagating current of bare cables whereas insulated cables will be used in coils. The effect of the temperature drop through the Terylene yarn is small, however, as shown by the curves in Fig.2.

TABLE I

Total No.of Strands	Diameter of Superconductor incl. plating (Inches)	No. of Copper Wires	Dia.of Copper Wires (Inches)	Diameter of Cable (Inches)		Cable Currents (Amps)		Av. Current Density in winding (Amps/cm^2 $\times 10^4$)	
				Bare	Insulated	20 kG	40 kG	20 kG	40 kG
1	.013	–	–	.013	.015	34	26	1.3	1.0
13	.013	12	.004	.021	.023	71	50	1.4	1.0
9	.013	8	.0076	.0282	.0292	130	86	1.7	1.1
7	.013	6	.0124	.0378	.04	200	100	1.45	0.75

Current Sharing

The manner in which the current is shared between the superconductor and the normal conductor has been deduced from the voltage and current recordings and the current in the superconductor is plotted against the total current for a number of cables in Fig.7. These show that in the case of the cable stranded with 0.004" copper wires the current transferred entirely to the copper at fields of 40 kG and below. This was because the heat generated by current flowing in the copper was always sufficient to maintain the superconductor in a normal state. In the case of the cable stranded with 0.0124" diameter copper wires, however, the temperature rise was such as to cause very little reduction in the current carried by the superconductor up to a total current of 190 amps which was the limit of the power supply.

CONCLUSIONS

Tests of the type reported here enable superconducting coils to be designed with a predictable performance. The following criteria can be ascertained from the data obtained:

(a) The design of cables to give the maximum current density, averaged over the winding space, for a specified field strength. This is important when the available winding space is limited.

(b) The design of cable to give the optimum average current density whilst operating at the short sample current. In large diameter coils this normally gives the shortest length of superconductor and therefore probably the cheapest arrangement.

(c) The value of current at which normality could propagate and the conditions under which complete or partial current commutation would take place. Cables having less normal material than would be required to obtain gradual commutation can be used satisfactorily providing the current does not exceed the minimum propagating value.

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REFERENCES

1. STEKLY, Z.J.J. and ZAR, J.L. Stable superconducting coils. Avco-Everett Res. Lab. Report no.210, 1965.

2. TREUTING, R.G., WERNICK, J.H. and HSU, F.S.L. Effect of heat-treatment on NbZr superconducting alloys. In Kolm, H. and others, eds. High magnetic fields. New York, Wiley, 1962. p.597.

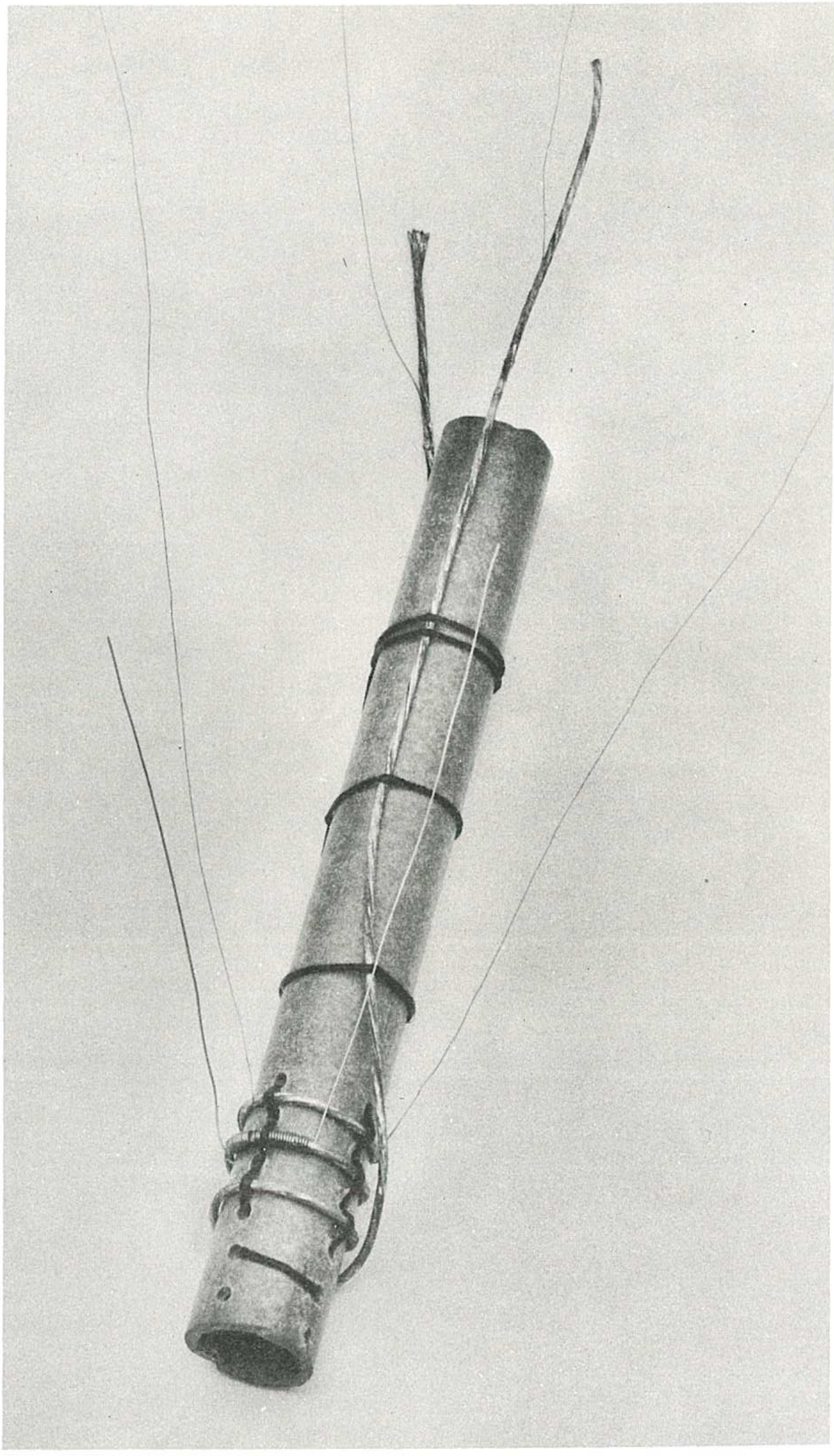

Fig. 1 (CLM-P83)
Photograph of cable sample assembled on insulating tube for minimum propagating current measurements

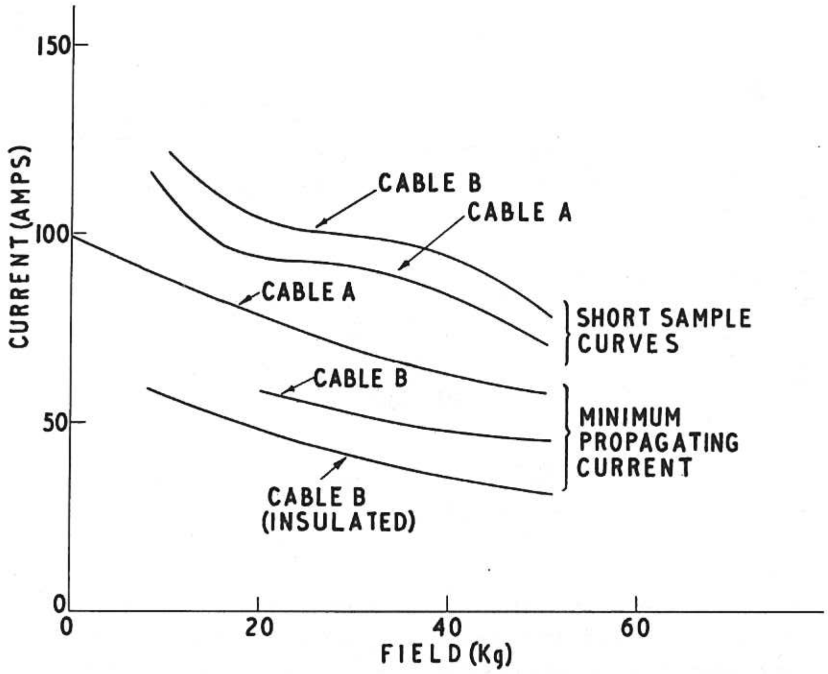

Fig. 2 (CLM-P83)

Short sample and minimum propagating current for three-strand cable

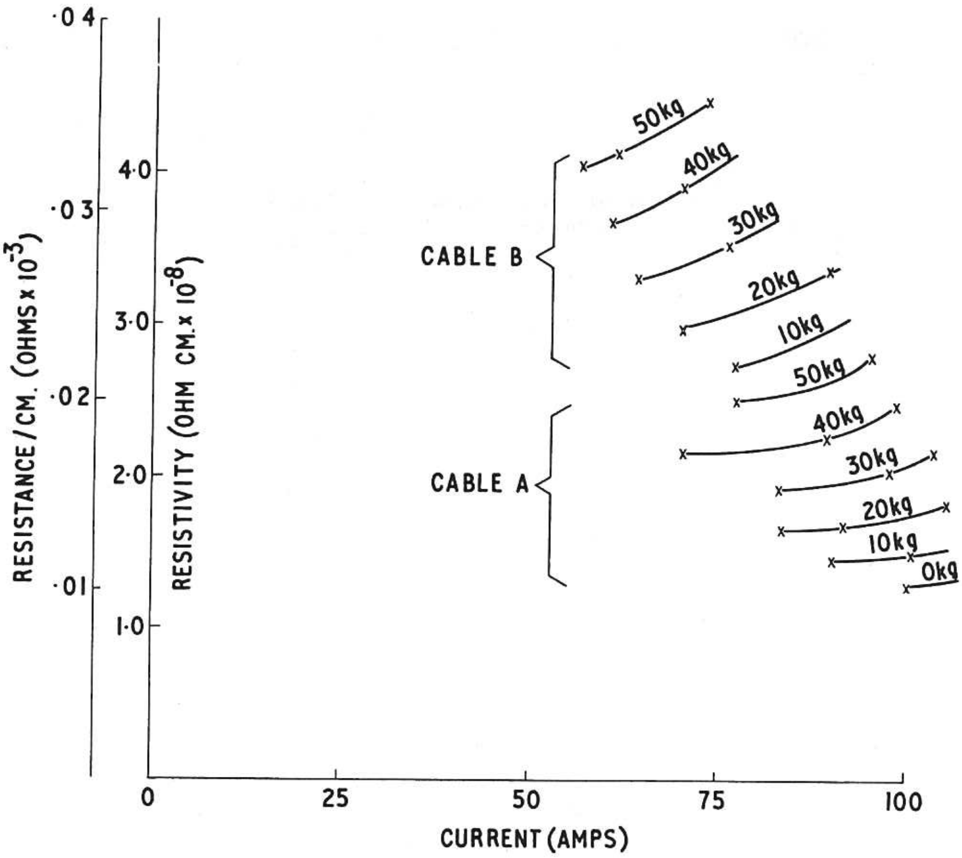

Fig. 3 (CLM-P83)

Resistance of copper on three-strand cable plotted against current flowing through it

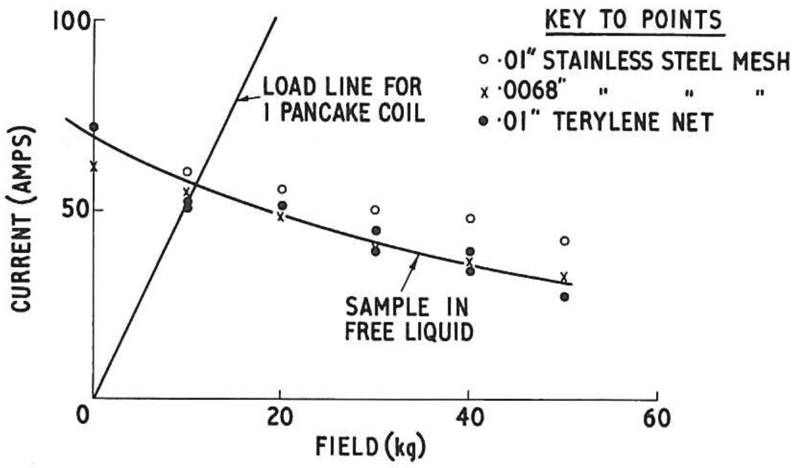

Fig. 4 (CLM-P83)
Minimum propagating current of three-strand cable together with points obtained on three-layer coils having different interlayer insulation. Also shown is the load line for a single coil 8 inch i.d., 12 inch o.d., 1¼ inch wide, wound with three-strand cable.

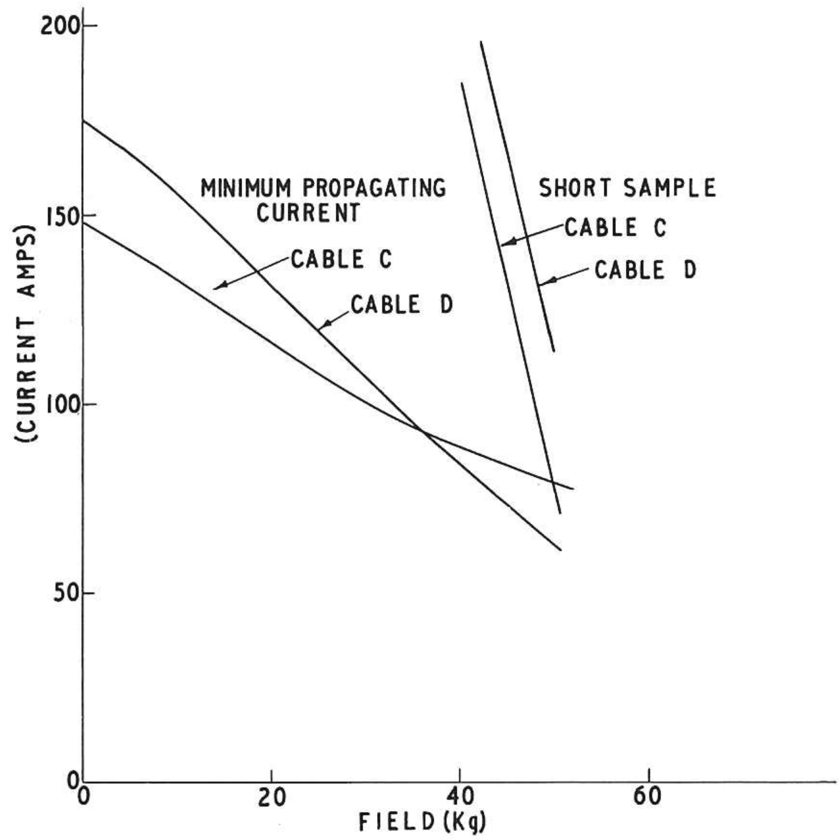

Fig. 5 (CLM-P83)
Short sample and minimum propagating current for five-strand cable

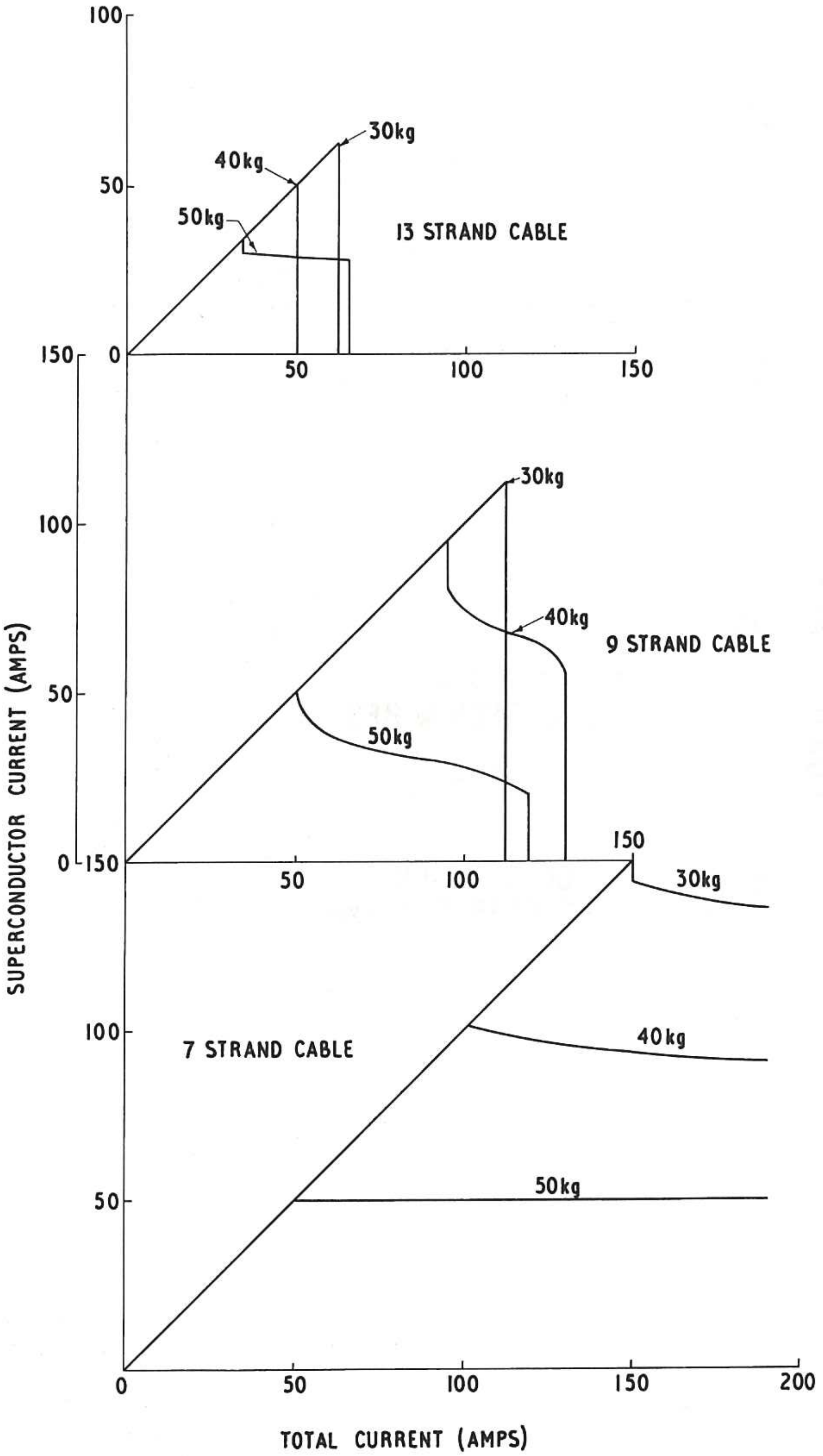

Fig. 7 (CLM-P 83)

Current through the superconductor plotted against total current through the composite conductor. **Top** 13-strand cable **Centre** 9-strand cable **Bottom** 7-strand cable

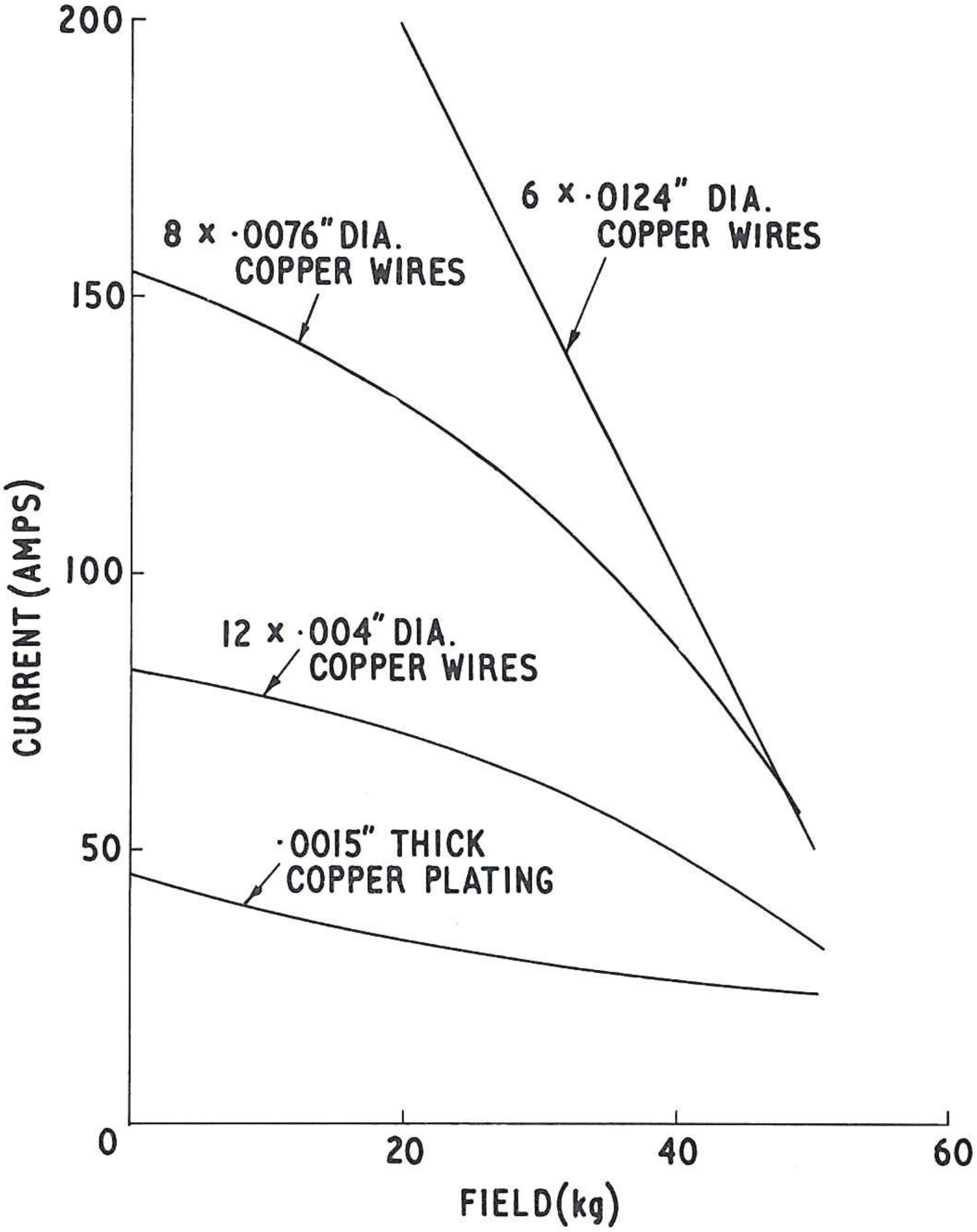

Fig. 6 (CLM-P83)

Minimum propagating current for the following composite conductors: (1) 0.010 inch dia. Nb 25% Zr wire copper plated to 0.013 inch dia. after heat treatment at 650°C for five minutes; (2) as (1) but surrounded by 12 strands of 0.004 inch dia. copper strands (13–strand cable); (3) as (1) but surrounded by 8 strands of 0.0076 inch dia. copper strands (9-strand cable); (4) as (1) but surrounded by 6 strands of 0.0124 inch dia. copper strands (7-strand cable)