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CRITICAL CURRENT MEASUREMENTS OF ISABELLE SUPERCONDUCTING CABLES,* M. Garber, W.B. Sampson, and M.J. Tannenbaum, Brookhaven National Laboratory — Short sample critical measurements on ISABELLE superconducting cables are described. The purpose is to provide a basis for assessing magnet performance and to provide Quality Assurance data on materials purchases. The measurements are made on 1 m samples in a dipole magnet. Voltages on the V-I curve are determined to a precision of several tenths of a microvolt. The critical current is defined as that at which $\rho = 1 \times 10^{-12}\Omega\text{cm}$[1] and is determined to a precision of 1 to 2%. Similar techniques are employed in determining the critical currents of the wires of which the cables are made. The relation between cable and wire critical currents will be discussed. It is found that well insulated, slowly ramped cables of the ISABELLE design are stable for currents up to approximately $\rho = 2 \times 10^{-12}\Omega\text{cm}$. The value of current corresponding to the resistivity determines the limit of magnet performance. Additional properties of the cabled conductors such as the normal state resistance and the longitudinal quench propagation velocity are also measured.

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* Work performed under the auspices of the U.S. Department of Energy.

[1] W.B. Sampson et al., "Superconducting Synchrotron Magnets", Particle Accelerators, 1, 173, 1970.

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ISABELLE Project Memorandum

CRITICAL CURRENT MEASUREMENTS OF ISABELLE SUPERCONDUCTING CABLES

M. Garber, W.B. Sampson, and M.J. Tannenbaum

I. Introduction

In this note we describe the essential features of short sample critical current measurements on ISABELLE superconducting cables. The purpose of these measurements is threefold: to provide a basis of comparison assessing magnet performance, to provide Quality Assurance data on purchased materials, and to evaluate metallurgical R and D aimed at understanding and improving conductor performance.[1] Additional properties of the cabled conductors are also studied in these experiments, such as quench propagation velocity[2],[3] effect of compaction pressure, heat pulse stability, etc; these will be reported on in future Notes.

The method of measurement is very similar to that employed previously for braids. It has been improved in several respects with a view to achieving results which are reliable to 1 or 2%. While further refinements are still to be made, it was thought appropriate at this time to report results for the first group of cables submitted for test.

II. Definition of Critical Current, I_c

No two laboratories measure or define critical current in quite the same way. Not infrequently, disagreement arises when intercomparisons are made. This is due primarily to the fact that the transition from superconducting to normal state as a function of current is spread out over a range of values, (unless there is a non-intrinsic quench, brought about by improper mounting, for example). In the earliest work, and occasionally in contemporary papers, the critical current is taken as that at which some minimum detectable voltage is developed across a sample, without regard to sample length or cross sectional area. In a complex modern conductor, a twisted multifilamentary structure embedded in a copper matrix, the initial appearance of resistance is likely a reflection of inhomogeneities in superconducting properties from point to point along the conductor. This results in a ve small sharing of current by the copper matrix. The initial onset is therefor not a true indication of the abrupt disappearance of resistance that characte izes the truly lossless state.

In order to express this behavior quantitatively, it was pointed out some time ago[4] that an appropriate manner of expression is in terms of an effective resistivity, ρ, defined in the usual way:

$$\rho \equiv \frac{V}{\ell} \cdot \frac{A}{I} \qquad (1)$$

where V = voltage developed between taps
ℓ = length of sample between taps
I = current
A = cross sectional area (including copper matrix)

The minimum detectable value of ρ is usually in the range 10^{-13} to 10^{-12} ohm cm. As the resistivity increases, thermal dissipation produces a sudden, irreversible transition to the completely normal state, i.e., a quen The current at which this occurs, I_q, depends primarily on the amount of coppe stabilizing material, the rate of current ramping, and details of the cooling environment. Typically, I_q occurs at values of ρ in the range 10^{-11} to 10^{-10} ohm cm for well cooled small wires, and at somewhat lower values for high current conductors. Within the above range of values, viz., 10^{-13} to 10^{-10} ohm cm, the measured variation of ρ with current can generally be well approximated by the equation

$$\rho = \text{const} \cdot I^{n} \qquad (2)$$

where n is a large number - usually between 15 and 30.*

The range of current over which measureable, reversible resistive behavior occurs can be as large as 50% or as small as 1 or 2%, but typically in conductors of the kind we are interested in , it is approximately 10%. At the high end of this range, not only is the conductor very close to being unstable under any circumstances, but the resulting dissipation in any large scale device would be prohibitively large. Sampson et al[4] proposed that a practical and operational definition of the critical current is that at which the average resistivity as defined in Equation 1) is 10^{-12} ohm cm.

$$\rho(I_c) \equiv 10^{-12} \text{ ohm cm} \qquad (3)$$

Up to this value of ρ the V-I curve is generally reversible, and the dissipation is acceptably small. Table I gives the voltage drop and dissipation for an ISABELLE conductor ($A = .0837$ cm^2) under the assumed conditions indicated.

Table I

Voltage Drop and Dissipation at I = 5000A

ρ, ohm cm	10^{-12}
V/ℓ, μV/cm	.060
P/ℓ, W/km	30

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*Other approximations are equally good for the relatively small range of

Analogous considerations apply to measurements of individual wire samples; the critical currents are determined in a similar way (Appendix).

Occasionally there is a desire to refer to the currents at which $\rho = 1 \times 10^{-12}$, 2×10^{-12}, 5×10^{-12}, etc. In these cases we use the notation I_c, I_{c2}, I_{c5}, etc., respectively.

It might be noted that NBS and ASTM standards committees have proposed using an electric field criterion for I_c, i.e., V/ℓ equal to some standard reference value. This definition appears to us to be less physical: for one thing it is cross section dependent. In any case, their proposed standard is limited at present to measurements below 600A.

III. Cable Description

The ISABELLE cable has been described by Palmer et al[5]. For purpose of reference some dimensions of interest are given in Table II. The ca is made from 23 wires, each .0268" in diameter.

Table II

ISABELLE Cable Dimensions

Keystone (Uninsulated)		
Width	.307 in.	7.80mm
Inner Thickness	.0465	1.18
Outer Thickness	.0525	1.33
Mean Thickness	.0495	1.26
Included Angle	1.11°	
Spiral Angle	15° to 15.5°	
Cable Areas		
Keystone Area	.0152 in^2	.0980 cm^2
Conductor Area (Normal to current)	.0130	.0837
Superconductor Area (1/2.8 total)*	.00463	.0299
Wire Areas		
Overall per wire	.0268 in^2	3.64×10^{-3} cm^2
Superconductor area	2.02×10^{-4}	1.30×10^{-3}
Average Filament Diameter (based on 2000 filaments)	3.6×10^{-4} in	9.1×10^{-3} mm

For a cable which can carry 5kA (say, at 5T) the superconducting critical current density is 1.67×10^5 A/cm^2. Individual wires tested prior to cabling have current densities (at 5T) of 2×10^5 A/cm^2. This is close to the state of the art.

*In recent cables this ratio is about 1/2.65.

IV. Experimental Description

Physical Arrangement. The cable test samples are bifilar, formed from two straight lengths soldered together at one end. Insulation is either of the form used on magnet conductors (see ref 5) or, for bare cables, a strip of .010" mylar is sandwiched between the bifilar legs. The sample is clamped in a slotted micarta piece using modest pressure - a few hundred psi. The samples measured to date have shown little or no mechanical training.

The sample is mounted in a 1 m dipole magnet. (Interestingly enough this is a 2-layer cos θ design magnet.[6]) Results reported in this note are for B perpendicular to the wide surface of the cable - see Fig. 1. This is the standar Q.A. configuration.

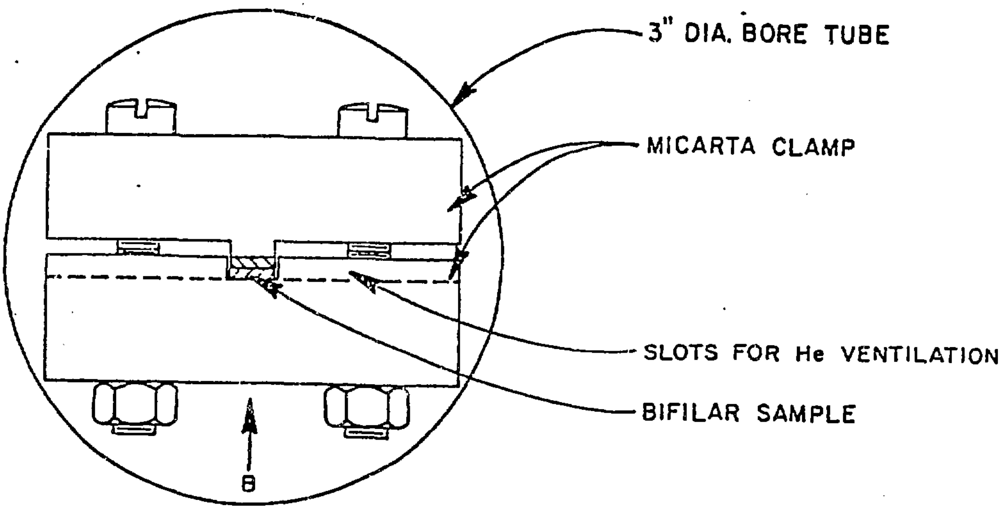

Figure 1. Schematic of sample, clamp-holder, and magnetic field direction.

Joints. Current leads are soldered to the sample well out of (i.e., above) the dipole. The bifilar joint is in the magnetic field as the samples have been shorter than the magnet to date. Typically, the resistance is $\sim 3 \times 10^{-9}$ ohm, so the joint dissipation is less than 0.1W over an area of several square centimeters. There is no evidence that quenches occur preferentially at the the joint. Runs in which the sample is made using a hairpin loop at the turn-around end - i.e., a continuous sample - give the same results. The latter construction is not as easy as the first, as the hairpin must be secured mechanically, and therefore it is not preferred.

In the future, a longer sample holder will be employed and the joint will be located entirely out of the field at the bottom of the dipole.

Electrical Measurement. The critical current is determined by measuring th V-I curve for a length of sample (one side of the bifilar sample) which is in a uniform region of field. At present this length is about 30 cm. The V-I curve measured in a point-by-point manner as noise during ramping is too great to all the voltage to be determined with the required precision. The effect of unfiltered power supply ripple is eliminated by averaging each voltage measurement o an integral number of line cycles, for a period of about 1 second (this ripple current is about 100 A p-p at 5000 A dc; however, the resulting noise voltage i about 1 mV in comparison with dc signal levels of ∿ 1 μV). Base line voltage during the course of a measurement is determined at low currents, below 3500 A typically, where V is essentially zero. The dc voltages obtained in this way a accurate to about 0.2 μV, not counting long term drifts.

Typical parameters of a measurement have been given in Table I. The range measureable ρ-values is usually between 1 and 5 x 10^{-12} ohm cm, the greatest uncertainty being at the low values. In order to obtain greater precision in the determination of I(10^{-12} ohm cm) the following extrapolation technique is used. The point-by-point V-I data are converted to a log ρ vs log I graph. For the range of data generally encountered this graph is a fairly straight line. The intercept with the line log ρ = -12 gives the critical current. A precision of ± 1% (i.e., about 50 A) is realized on repeated trials. Figures 2 and 3 are illustrations of this method from a recent run. These data and analyses were obtained using an interactive computer technique: the base line determination a the straight line fit to the log ρ - log I data were done by hand; the paramete of these lines, drawn on a digital x-y plotter, were read back digitally to the computer by means of an opto-electronic probe.

Temperature Correction. The measurements are made in a vertical cryostat in pool boiling helium. The temperature of this bath generally runs between 50 and 100 millikelvin high owing to the overpressure required to force gas through the four high current leads (magnet and sample). The dependence of critical current on temperature is known to be well represented, at fixed field, by the empirical linear equation:

$$\frac{I_c(T)}{I_c(T_r)} = \frac{T_{c,B} - T}{T_{c,B} - T_r} \qquad (4)$$

$T_{c,B}$ is the critical temperature at field B, T_r is a reference temperature, and $I_c(T_r)$ is the critical current at T_r. By means of this expression data taken at different temperatures can be corrected to a common reference temperature, say 4.224 K, the boiling point of helium at one atmospher For NbTi, at 50 kG, $T_{c,B}$ = 6.9 K. Putting in these numbers we get:

$$I_c(T_r) = I_c(T)\left(1 - \frac{T-T_r}{2.6}\right) \qquad B = 5T,\ T_r = 4.224K \qquad (5)$$

For $T-T_r$ = 0.1 K and $I_c(T)$ = 5000, $I_c(4.2)$ = 5190; i.e., there is a 4% decrease in I_c per 100 mK rise in temperature (in a magnet the effect on the quench current is half as great since B is proportional to I).

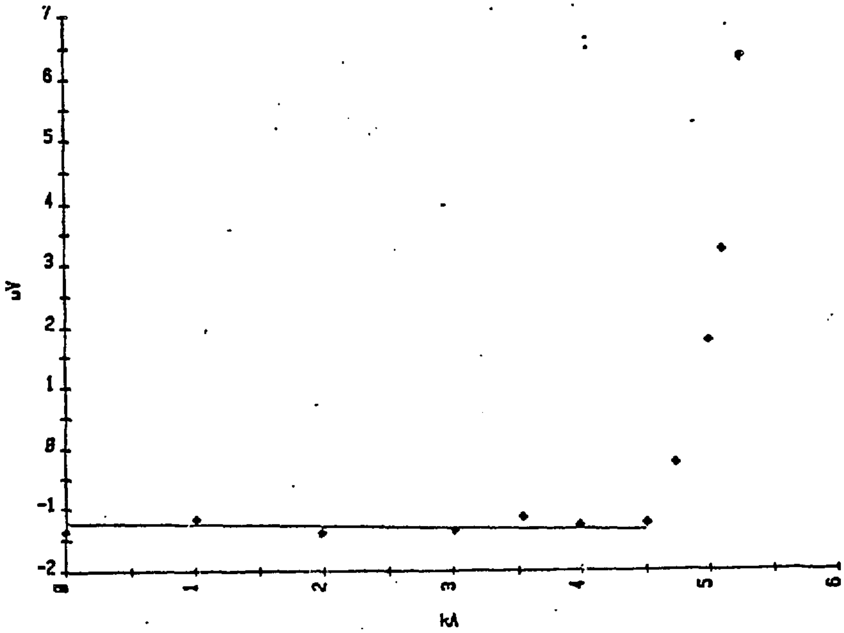

Figure 2. V-I curve for a cable sample. Taken with an HP 3456 DVM, 9825 computer, and 7225 plotter. Baseline was drawn by hand and read using the plotter, opto-electronic pen, and computer. Measured at 5T, 4.2K; length of sample = 20 cm.

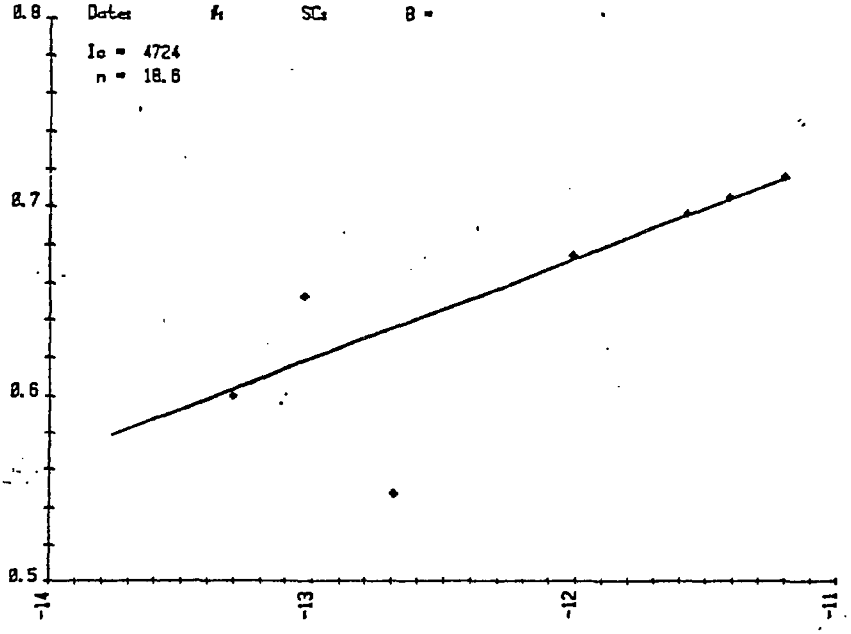

Figure 3. log ρ - log I plot of data of Figure 2. Straight line

For fields other than 5T the appropriate value of $T_{c,B}$ must be used. In the range of fields of interest to us, $4T \leq B \leq 6T$, say, a good approximation is:

$$T_{c,B} = 2.6(12 - B)^{1/2} \qquad (6)$$

For $B = 5.5T$, $T_{c,B} = 6.6K$.

Equation (6) is based on previous work with NbTi braids. Preliminary data indicate that it is not much different for the material used in the cables. The true zero field transition temperature, 9.5K, is somewhat higher than the value derived from Eq. 6 because there is a "tail" in the low field portion of the B vs $T_{c,B}$ curve.

Self Field Effects The fact that rather large currents are involved in a typical measurement leads to a non negligible perturbation of the magnetic field experienced by the sample, the so-called self field. Historically, this has led to considerable debate and disagreement in the interpretation of results for example, between suppliers and users with respect to quoted and realized performance. As with wire, see Appendix, we wish to adopt a precise operational approach in reporting our critical current data: the critical current is given for an external field of 50 kG, applied normal to the wide surface of a bifilar sample as described in Figure 1. This procedure leads to a slight underestimati of the ideal critical current, due to the self field. In order to obtain an ide of the size of this effect a calculation of the self field has been made assumin a uniform distribution of current over the cable cross section and using the program MAGFLD[8], modified to include a constant external field. Contours of constant field magnitude, $|B|$, are plotted as shown in Figure 4. The fields are largest in the upper right corner of this figure.

We estimate, by visual inspection, that the average field over a single wire in this region is about 51.5 kG, for cable current of 5000 A. This implies that the measured critical current is low by 3%, i.e., about 150 A, since a reasonably good approximation for small variations of critical current with field in this region of field is

$$\frac{dI_c}{I_c} = \frac{dB}{B} \qquad (7)$$

In view of the complicated nature of this calculation we are loath to apply a self field correction, prefering instead to report the observed current, for the stated external field and sample configuration (but nonetheless correcting for temperature). Over a range of fields the self field correction is not constant since the critical current decreases as the external field increases, cf Equatio 7. The region of greatest interest to us, viz., from 50 to 60 kG is sufficient small, however, that the self field error is essentially the same over this rang of field. Errors of interpretation would become serious only in the event we we concerned with low external fields and high currents.

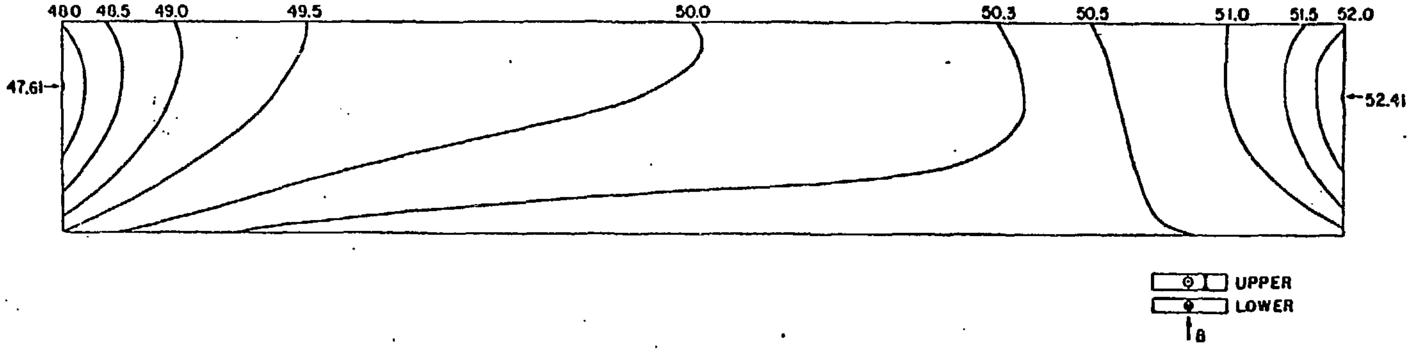

Figure 4. $|B|$ = constant contours for one conductor of a bifilar pair. Upper conductor is shown, space between conductors = 0.2 mm. I = 5000A, out of figure. External field = 5T upward.

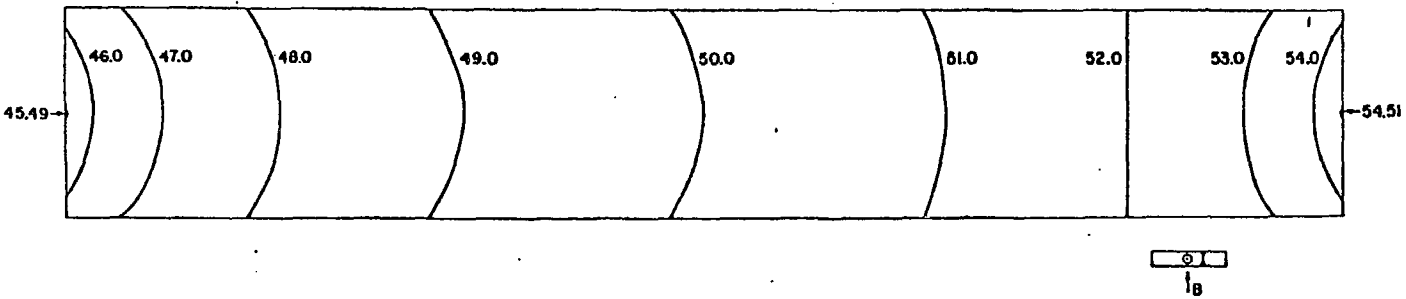

Figure 5. $|B|$ = constant contours for a single conductor. I = 5000A, out of figure. External field = 5T upward.

Angular misalignment between the applied field direction and the normal to the cable surface will produce a change in the self field. In the bifilar configuration this effect is not symmetrical with angle, or alternatively with current direction. This can be inferred from the shape of the contours of Figure 4. In practice this manifests itself as a difference in the observed critica currents when the current direction is reversed. The magnitude of this differenc varies from run to run but is generally 50 to 100A. Quoted data refer to the average of the forward and reverse critical currents. Calculations similar to those illustrated in Figure 4 but with the external field at various angles to th cable normal show this is a correct procedure. The observed differences in critical current correspond to angular misalignments of the probe and dipole of 5° to 10°.

It is of interest to compare the self fields in the bifilar configuration we use with those for a single isolated cable. The latter corresponds, for example, to "hairpin" sample configurations. The results are shown in Figure 5. By visual inspection the maximum self field is 6 - 7% in this case. Thus the bifilar sample is closer to the actual magnet situation.

V. Results for Cables; Comparison with Wire Data

Data for cables tested to date are given in Table III. Critical currents have also been measured in a number of ways differing from the Quality Assurance procedure described above:

- Sample of bifilar racetrack form[2]
- Fully insulated ISABELLE cable, bifilar legs epoxy molded
- Varying ramp rate, up to 200 A/sec.

The last named involves a sacrifice of precision at the lowest voltages, but the upper part of the V-I curve prior to quench can be determined. The results of the various experiments can be summarized as follows:

1) The quench current is determined by the degree of insulation and the rate of current increase. Bare conductor samples ramped rapidly, say at 100 A/s or faster, quench at ρ-values of the order of 10^{-11} ohm cm. Well insulated samples which are ramped very slowly (point-by-point method) reach ρ-values of approximately 2×10^{-12} ohm cm. In intermediate cases, i.e., well insulated, rapidly ramped samples and bare samples ramped slowly, the quench current occurs at an effective resistivity of approximately 5×10^{-12} ohm cm. This behavior is indicated by Figure 6. Only the quench current for the well insulated, slowly ramped case is relevant to magnet performance.

2) The current at $\rho = 1 \times 10^{-12}$ ohm cm is taken as the definition of I_c. However, the V-I curve is stable up to $\rho \approx 2 \times 10^{-12}$ ohm cm ($\pm$ 10%). This corresponds to another 3 to 4% of current above I_c.

The results and conclusions just stated pertain to the present cabled conductors. The relatively stable, training-free behavior of these samples is probably due in no small part to the extra copper: about one third more than fo wire used in formerly braided conductors. In addition, the residual resistance ratio of the copper is about 50 for the cabled conductors compared with a value c about 25 in the braids. Measurements on wires similar to those used in making cables are given in Table IV. The current per wire in cables is about 15% lower than that of the starting wire. Why this is so is not yet understood, nor why the critical currents of wires removed from a cable appear to be greater than in the cable. Self field effect in the wire measurement is not much different from that in the cable measurement. The technique of wire measurements is described in the Appendix.

Table III

Short Sample Measurements on Cables (T = 4.224K)

Cable[1]	I(5T) amps	I(5.5T) amps	R(295) micro-ohm/cm	R(10K,0T) micro-ohm/cm	R(10K,5T) micro-ohm/cm	rrr(0T)[3]	Used in Magnet
I3-MN	4600		34.1	.59	.96	57.8	LM1
I4-MN	4750		33.2	.61	1.06	54.4	LM1
C001MN	4900		34.9	.68	1.08	51.4	
C002MN	4740		34.8	.68	1.05	51.1	LM2
C003MN	4800	4200	34.5	.70	1.05	49.3	LM2
C004MN	4780		34.7	.66	1.07	52.6	LM2
C005MN	4760	4140	35.1	.72	1.16	48.7	LM3
C006MN	4530	3995	34.9	.68	1.08	51.4	LM3
C007MN	4900		34.7	.71	1.07	48.9	
XC001AA[2]	5270		36.8	.55	.97	66.9	
XC002AA	5280	4690	35.3	.53	.97	66.7	

NOTES:

1. "MN" = MCA wire and NEL cabling, "AA" = Airco wire and cabling.
2. Airco cable produced in short length, Cu/SC ratio = 1.5. Sample XC002AA had no staybrite.
3. The rrr of MCA wire is 60 - 70 before cabling, for Airco or IGC wire it is 100 to 120.
4. The critical current per wire is typically 4800/23 = 209A.

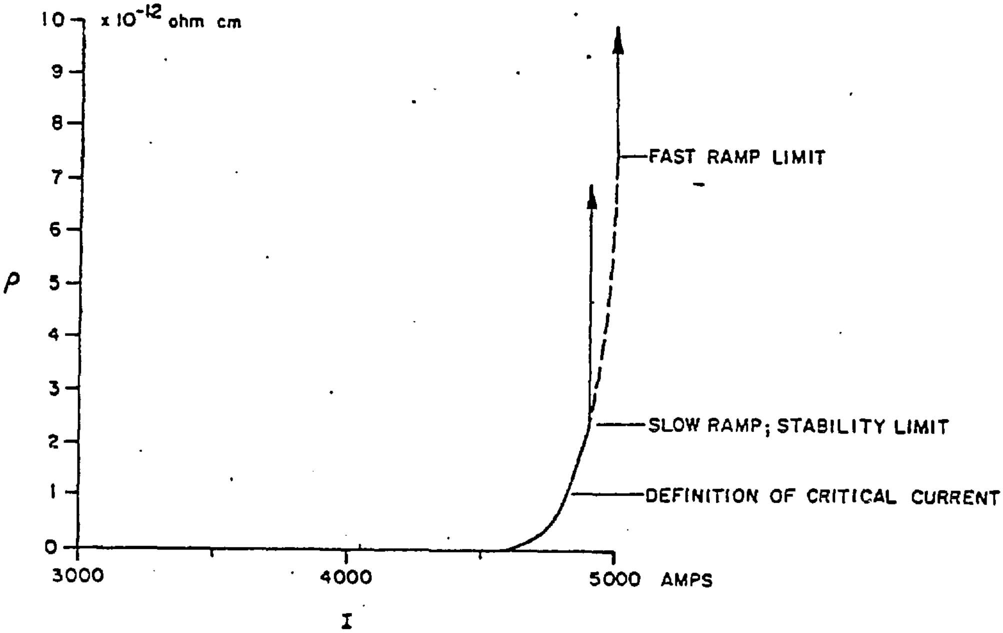

Figure 6. Schematic summary of cable short sample behavior

Table IV

Short Sample Measurements on .0268" Wire for Cables

Mfr ID	I(5T,4.22K) amps	R(295K) mohm/cm	rrr	Notes
	MCA Production Samples (from FNAL)			
173-1-1	225			
174-1-4A	228	.763	72.1	
174-1-4B	226			
174-1-4C	222			
175-2-17	245			
176-1-3	221	.745	68.1	
176-2-4A	242			
177-1-9	241			
179-1	248			Used in CM2
179-1-4	247			
180-2-1	235			Used in CM3
180-2-1A	235			
187-1-8	249			
187-1-10	255			Used in CM3
188-1-11	240			
189-2-5	240	.761	65.6	
190-1-5	238	.749	60.5	
190-1-5A	244			
190-2-12	243			
190-2	252			

Table IV (continued)

IGC Wire Samples

Samples marked "*" were sent by IGC for R & D evaluation. Others are production samples from FNAL.

Mfr ID	I(5T, 4.22K) amps	R(295K) mohm/cm	rrr
325-4	254		
325-7	257		
*327-1	234		
327-3	281	.729	99.4
327-9	267	.728	109.2
*327-11	268		
*329-15	262		
*335-5	276		
336-2	233		
336-9	246		
337-29	234		
*339-13	301		
*342-14	207		
343-12	277		
343-16	283		

Airco

The following are samples of the wire used in XC001AA and XC002AA. This wi had a Cu/SC ratio of 1.5. It was used for evaluation. A higher Cu/SC ratio wil be used in production.

B-765-1	268	.775	119
B-765-2	267	.773	120

Wires removed from cable XC002AA had critical currents between 240 and 246A

VI. Other Results

Further work will be reported in future notes: critical currents for fields parallel to the cable face, variation of critical current with field, propagation velocities, etc. A preliminary result is given in Figure 7, viz., the variation of BI_c with field for two wire samples, indicating the degree to which the approximation BI_c = constant is valid.

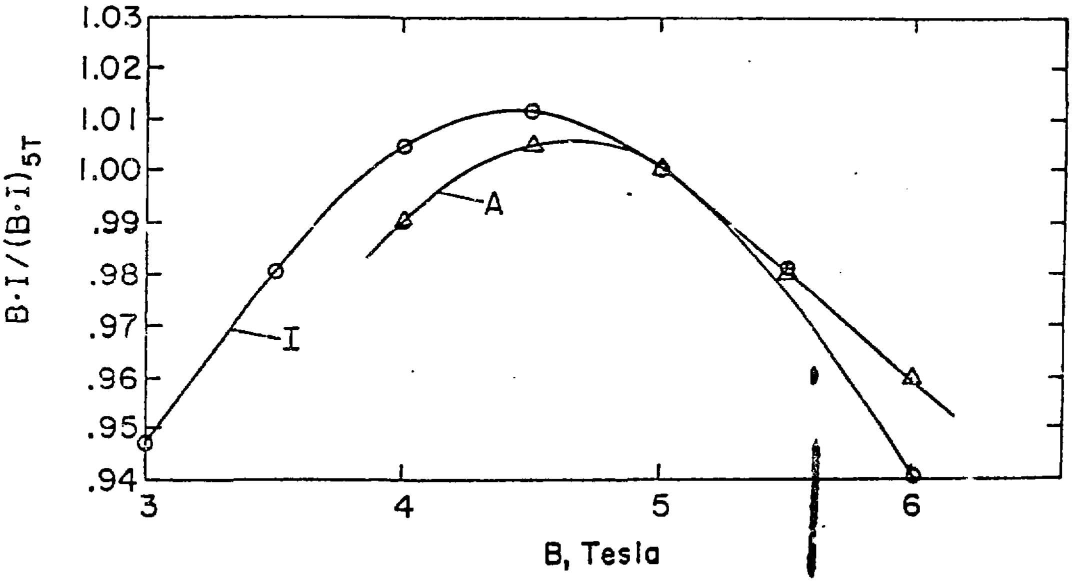

Figure 7. Variation of BI_c vs B for 2 wires. Normalizing values for BI, at 5T are 867 T-A for wire "A" and 1200 T-A for wire "I".

VII. Short Sample Data; Cable Specifications; Predicting Magnet Quench Currents

For purposes of Quality Assurance the following parameters adequately characterize a conductor:

Table V

Short Sample Quality Assurance ("Traveler") Data

I_{c1}	Critical current ($\rho = 10^{-12}$ ohm cm), at $B = 50$ and 55kG
I_{c2}	Critical current ($\rho = 2\times10^{-12}$ ohm cm), at $B = 50$ and 55kG
T	Temperature of the critical and quench current measurements
R(R.T.)	DC resistance per centimeter at 295 K
R(10K)	DC resistance per centimeter at 10 K
R(10K, 5T)	DC resistance per centimeter at 10 K and $B = 50$kG

This list is designed to be a necessary and sufficient one. In order to obtain values of the critical current at temperatures, fields, and resistivities other than those of the measurement, previously given information may be used or simple rule of thumb estimates may be made. This information is summarized in Table VI.

In preparing a performance specification the quantities which can be determined in a meaningful way are those listed in Table V. The measurement procedure is specified according to the description given above. Corrections to standard experimental conditions of temperature, magnetic field, and resistivity may be made following Table VI.

Similar remarks are relevant in discussing predictions of expected magnet performance. A short sample B-I curve for the appropriate temperature is constructed using the I_{c2} values. Intersection of this curve with the magnet load line should give the maximum field.

Table VI

Variation of I_c with T, B, and ρ

	Approximate Expressions for $B = 50$kG, $T = 4.2$K	Reference for General Case
Temperature	$\Delta I/I = 4\%$ per 0.1 K	Equations 4 and 6
Field	$\Delta I/I \approx -2.5\%$ per kG	Figure 7
Resistivity	$3\% \le (I_{c2}-I_{c1})/I_{c1} \le 4\%$ [for $24 \le n \le 18$ - i.e., most cases in practice]	Equation 2

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APPENDIX

(Appendix IV from ISA Spec. No. 89)

BNL Short Sample Test Procedure For Critical Current Determination Of 0.0268"D Twisted Multifilamentary Wire

1. Purpose

The purpose of this test procedure is Quality Assurance of wire suitable for superconducting cable production. The critical current, I_c, and normal state resistivity are the principal electrical parameters for assessing acceptability.

2. General Outline; Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is carried out in an external field of 50 kG, applied normal to the wire axis, and in a temperature bath of liquid helium at 4.22K.

The critical current is defined as that at which the resistance per unit length, R_c, is:

$$R_c = 2.75 \times 10^{-10} \text{ ohm/cm}$$

This is based on a specified wire diameter of 0.0268" and an effective resistivity of 10^{-12} ohm cm.

3. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical former so that it fits in a solenoid magnet (see section 5 below). A non-inductive (bifilar) form is advisable in order to obtain adequate length, reduce inductive voltage signals, and provide for ease of connection; see Fig. 1. Shorter, monofilar mounts may be used if adequately sensitive signal detectors are available; voltage taps are arranged as in Fig. 2 in this case. Means must be provided for constraint of mechanical motion without interfering with coolant contact - use of a G-10 former with grooved location of wire and careful tensioning during mounting. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length).

4. Electrical Measurement (See Fig. 3)

The sample length (between voltage taps, or gauge length) should be $\gtrsim 50$ cm. This corresponds, for a critical current of 240A, to a voltage $\gtrsim 3.3$ V. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective rsistivity to a precision of 10%.

The amplifier signal should be recorded on an x-y recorder (or if desired in a digital memory device). The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. Typically, current is supplied by a commercial, well-filtered 500A, 20V SCR supply. The current should be measured to a precision of $\pm$ 0.1 amp. Every determination of I_c should be repeated at least once. Means for quench protection are essential for this purpose: the current source should be disconnected or crashed within approximately 20 millisec of the onset of a quench, i.e., when R_c increases suddenly, typically between 10^{-8} and 10^{-7} ohm/cm. Use of a low resistance normal metal shunt is parallel with and at the sample is feasible provided the resulting correction for sample current is accurately known (1% in I_c). Electronic circuitry for quench protection is preferable, however.

5. Magnetic Field

The external magnetic field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample gauge length of 50 $\pm$ 0.25 kG. This range of field corresponds to a range of I_c of 1%. The direction between field and wire axis must everywhere be 90° $\pm$ 6°. This range of angles corresponds to a variation in I_c of 1/2%.

6. Temperature Bath

The specification temperature is 4.224K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath)with a precision of $\pm$ 0.010K (10 mK). Deviations of 25 mK or less from 4.22K correspond to an error in I_c of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

$$\frac{I_c}{I_m} = \frac{T_c - T}{T_c - T_m}$$

where T_c, = 6.9K, is the transition temperature at 50kG, I_m is the current measured at temperature T_m, and I_c is the critical current at temperature T(= 4.224K).

7. Other Measurements

Other measurements are optional, but two more are very desirable:

a. The normal state electrical resistance at room temperature and at 10K. This provides a measure of the quantity of copper and its purity. It i a required measurement for cables. The resistance can be measured at 10K by slowly lifting the sample probe above the liquid helium bath leval.

b. The critical current at a higher field, preferably 60 kG. This provides a check on the metallurgical state of the NbTi.

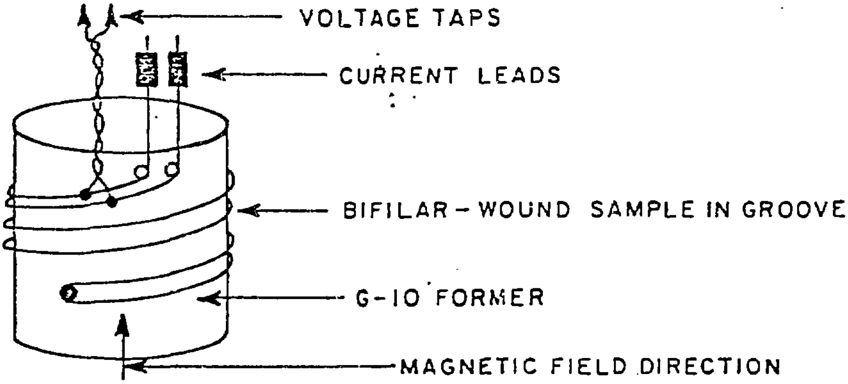

FIG. 1 Non-inductive sample mounting arrangement.

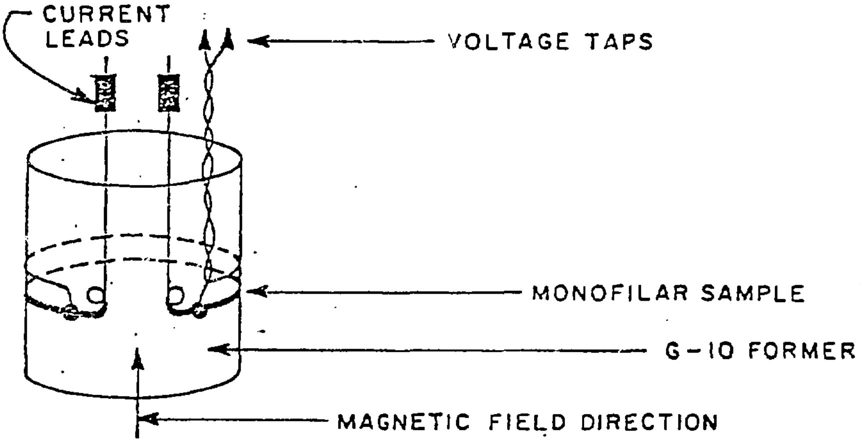

FIG. 2 Alternative sample mounting arrangement