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Short Sample Results for Cable S/C 374
The Effect of Cold Welds

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1. Description of the Cable.

S/C 374 (BNL SI 63) is a recent inner type cable made from IGC wire, billet 5251-1000. Each strand has approximately 7250 filaments of mean diameter 6 microns. s/d, the interfilamentary spacing parameter, is approximately 0.2. The copper/superconductor ratio is 1.5. The cable was made at LBL and is a backup cable for dipole DD-11. Its twin, S/C 375, is intended for use in a 17 m dipole, DD-16, and in a series of 1.8 m magnets, DSS-13 through 17.

R. Scanlan suggested that we test the effect of cold weld splices in strands on the performance of cables. He prepared samples of this particular cable in which 1, 2, and 3 strands have such splices. Strand samples from each of the 8 spools from which the cable was made were tested in order to determine Ic degradation. Also, the dependence of resistance on current was measured for the cold welded strands.

2. Strand Test Results.

Complete test data are given in Table 1. The power supply which was used did not permit Ic determinations at 5T; the values listed were obtained by linear extrapolation from the higher field data. This is usually a good approximation between 4 and 7T and in the present case was valid to 8T. Fig. 1 shows a plot of Ic vs. B for the strands which have the highest and lowest critical currents. The spread in currents is so small that the mean value obtained by weighting the values according to the corresponding number of strands in the cable agrees with a simple average to within 0.1%. Table 2 summarizes the average values of various quantities. The Jc values are calculated using the measured average diameter of 0.0318 inches and C/S = 1.5 (our measured mean value was 1.49 whereas IGC measured 1.51). The RRR values varied between 99 and 155.

Table 2.

Mean Strand Data for IGC 5251-1000

Field	Ic	Iq	n	Jc	Zero field resistance
5	580	-	-	2830	R295 = 548.1
6	460	495	36	2244	RRR = 117
7	338	370	33	1648	C/S = 1.49
8	218	248	27	1064	

3. Cable Test Results.

__Perpendicular__. The critical current was measured for three different pieces of cable; data for several runs are combined into one set. Figure 2 presents the results in our usual report format. For a description of the test procedure see reference 1. Comparison of the wire and cable critical currents gives the degradation:

$$1 - \frac{12789}{23 \times 580} = 4.1\%$$

This value is based on a wire critical current which is not self-field corrected. This is the same convention always used in the past.

Parallel. In this test configuration the field is a maximum at the middle of the broad faces of the cable and measures the critical current of the cable in a region where there is relatively little mechanical distortion. Figure 3 shows the results of this experiment. The four data points correspond to two applied fields, and two directions of current flow for each field. The fit of the points to a straight line shows the correctness of the self-field calculation. Table 3 gives a comparison of the parallel cable results with the wire results. The parallel cable Ic's are somewhat greater than the wire values due to the fact that no self-field correction is applied to the strand currents.

Table 3.

Parallel Cable Ic's

B(tesla)	Parallel Cable,Ic	23 x Wire Ic
5	13511	13340
6	10697	10580
7	7884	7774

4. Training Tests.

Training is observed in short sample experiments on cables with high Jc's and low copper-to-superconductor ratios. This was first discussed in Reference 2. The standard test conditions are: cable pressure = 10 kpsi and current ramp rate = 1000 A/sec.

Figure 4 shows the training for cable 374. Two quenches are required to reach Ic. This fits well on the curve of training vs. C/S ratio described in reference 2 and reproduced in Figure 5. The plateau or limiting quench current for cable 374 is much higher than Ic compared with cables in which C/S = 1.3 or less. Consequently more training steps are required to reach it. In these respects cable 374 shows a similar behavior to other cables in which C/S = 1.5 and to HERA cables, in which C/S = 1.7 or 1.8.

5. Effect of Cold Welds.

Cables in which one or more strands were cold welded had similarly shaped V-I curves to those of weld-free cable, but with lower critical and quench current. Table 4 lists the observed critical currents.

Table 4.

Comparison of Cables Containing Cold Welded Strands (5T, 4.22K).

# Spliced Strands	Ic
0	12790
1	12250
2	11800
3	11150

The reduction in critical current was approximately proportional to the number of spliced strands. A graph of the data, Figure 6, shows a straight line through the origin.

The above experiment is a DC one. The spliced strands appear to carry little or no current. This is simply understood if the cold weld resistance is much greater than that of a strand at Ic. The latter is $10^{-12}\ \ell/A = 1.4 \times 10^{-8}$ ohm for $\ell = 70$ cm and $A = .00512\ cm^2$. The V-I curves of the six cold welds were measured at 0 and 5T. The results are shown in Figure 7. At voltages of order 5 μV the cold welds limit the current to 25 amps or less at 5T, whereas the weld-free samples carry about 600A at this voltage.

In the preceding DC experiment the quench current exceeds the critical current, as it generally does in cables with no cold welds. However, for high ramp rates an interesting, different behavior is observed: the quench current is greatly reduced, to values equal to or less than the critical current. This is illustrated in Table 5 for cables with 0 and 3 cold welds. Cables with 1 or 2 cold welds behave like the cable with 3 cold welds: the quench current at 1 kA/sec. is a little higher than Ic but much less than the DC quench current.

Table 5.

Ramp Rate Effect. T = 4.36K B = 5.75T

Number of cold welds:	0	3
Critical current:	9400	8250
DC quench current:	9900	8850
Quench current at 1 kA/sec:	10600	8300

This behavior can be understood as follows. With no cold welds the 23 strands carry equal currents at all ramp rates. At high ramp rates, currents well above the DC quench current are reached before the strands become unstable. This effect depends on C/S: the higher C/S is the greater the difference between quench current and Ic. The presence of a cold weld in a strand causes it to act as an open circuit for DC currents. For high ramp rates, however, inductive impedance causes all strands to carry current equally. The relatively high resistance of a cold weld then produces a local hot spot and a premature quench.

References:

1. Test Methods for Cable Critical Current and Normal State Resistance - BNL ADD Tech. Note # ______, M. Garber and W. B. Sampson.

2. Talks by W. B. Sampson to the Advisory Panel on Industrial Participation, Madison, Wisconsin, Feb. 1987 and to the SSC Conductor Workshop, Madison, Wisconsin, Nov. 1987.

TABLE 1

Date: 2-16-88

S. C. Wire Test

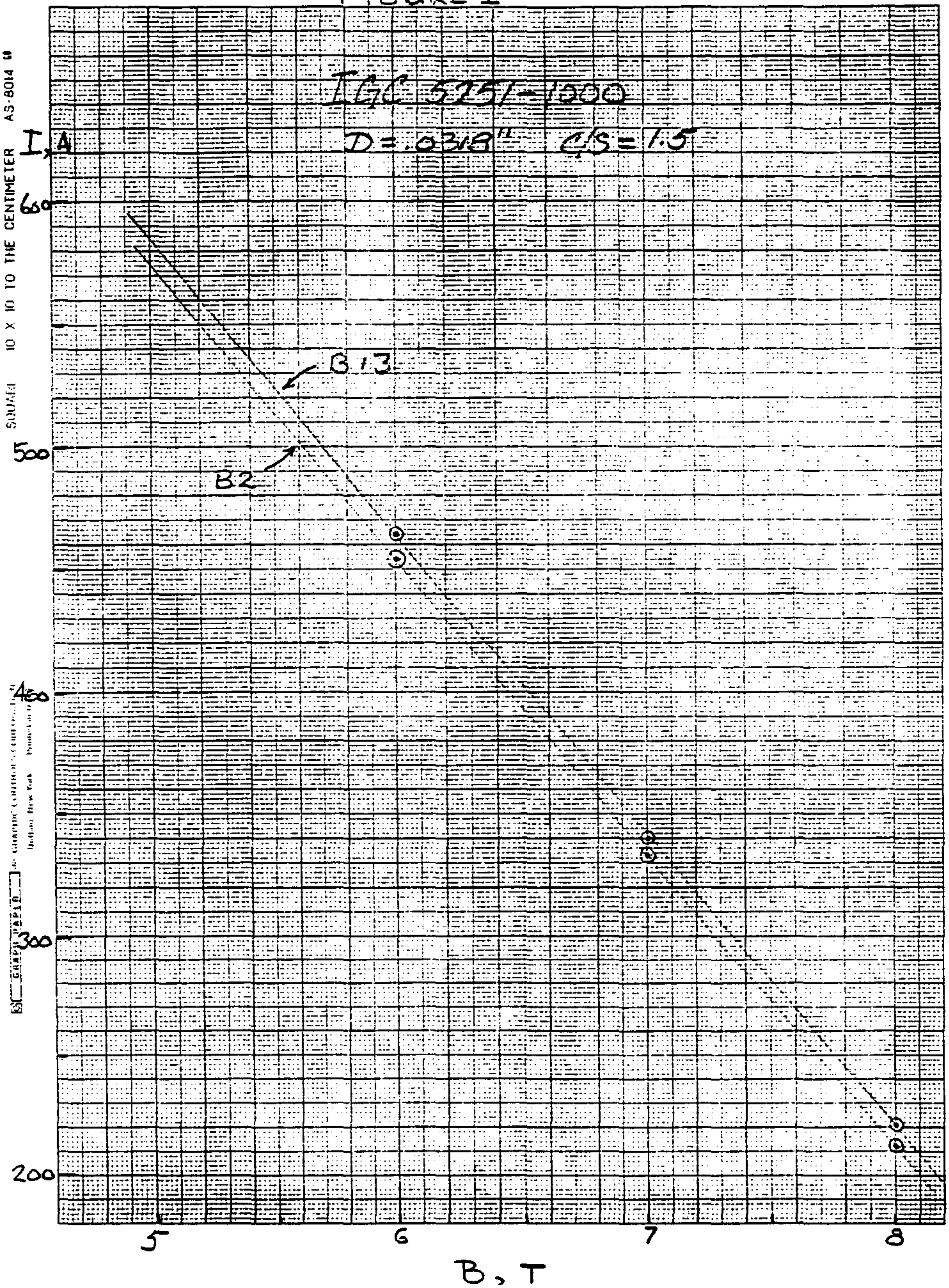
Manufacturer: IGC 5251-1000

Description: Dia. (in.) .0318" Nominal C/S 1.5 Fil. dia. (μm) 6 No. Fils. 7250

Comments: 5T values are linear extrapolations
This wire used in S/C 374 & SK 375

Sample & # strands in S/C 374	B (kG)	I_c (A)	I_q (A)	n	J_c (A/mm²)	R(295) (μΩ/cm) (B=0)	RRR (B=0)	C/S_R (B=0)
B1 #=5	50	576	-	-	2810	543.4	99	1.52
	60	457	490	37	2231			
	70	336	367	35	1639			
	80	218	247	29	1063			
B2 #=3	50	575	-	-	2805	542.7	99	1.53
	60	454	492	35	2215			
	70	333	368	32	1624			
	80	212	248	23	1034			
B5 #=5	50	582	-	-	2840	548.6	130	1.48
	60	462	>500	38	2256			
	70	341	372	38	1662			
	80	221	250	30	1079			
B7 #=1	50	576	-	-	2810	551.3	100	1.47
	60	457	488	35	2230			
	70	333	367	29	1625			
	80	220	248	29	1073			
B9 #=3	50	584	-	-	2849	547.6	152	1.48
	60	463	499	34	2257			
	70	339	373	33	1655			
	80	219	251	26	1070			
B13 #=1	50	585	-	-	2854	549.5	155	1.47
	60	464	498	38	2262			
	70	340	372	34	1661			
	80	221	251	27	1076			
B15 #=4	50	584	-	-	2849	550.4	102	1.47
	60	463	495	40	2258			
	70	337	372	32	1645			
	80	218	251	25	1063			
B17 #=1	50	577	-	-	2815	551.1	101	1.47
	60	457	492	34	2227			
	70	335	366	31	1633			
	80	216	245	24	1052			

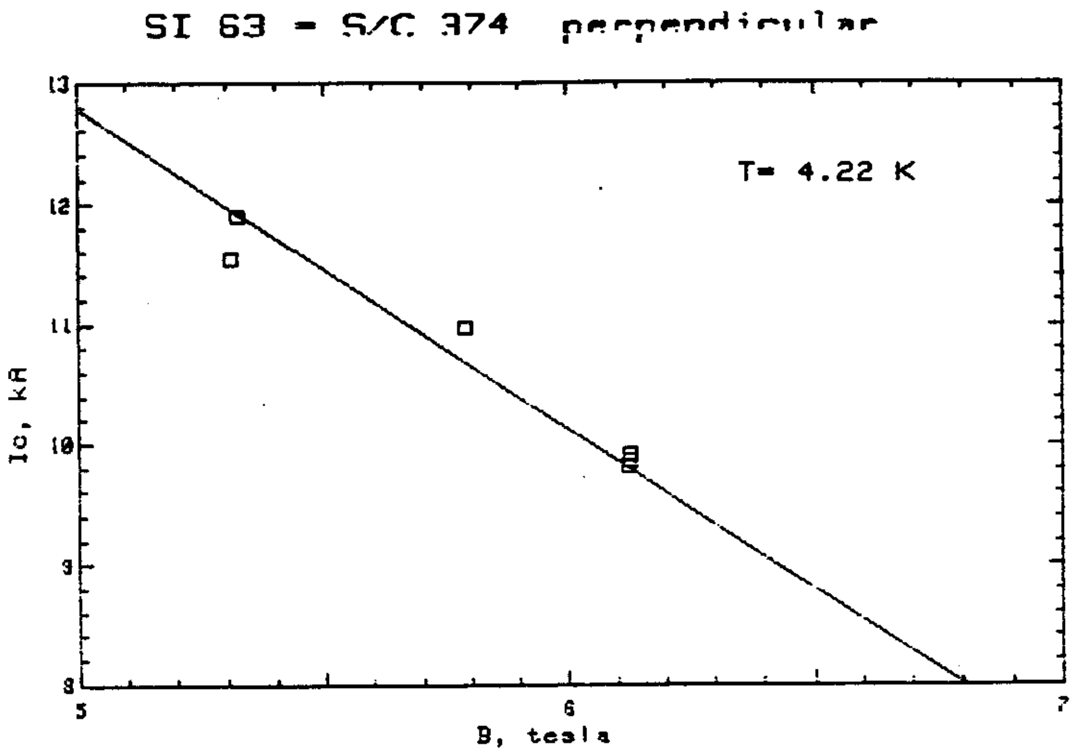
FIGURE 1



IGC 5251-1000
D=.0318" C/S=1.5
I, A
600
500
400
300
200
B1,3
B2
5
6
7
8
B, T
SQUARE 10 X 10 TO THE CENTIMETER AS-8014
GRAPH PAPER

FIGURE 2

Run No. 1591   FEB 5 88



Measurements

B	T	It	Iq	n
5.31	4.364	10955	11837	31
5.33	4.364	11297	11837	29
5.79	4.359	10400	10885	23
6.12	4.360	9250	9750	22
6.13	4.347	9407	9888	23
6.13	4.347	9361	9888	26

R(295)= 25.1 uohms/cm   RRR= 63
R(10) = .40 "   C/S= 1.49

Calculated results for T= 4.22

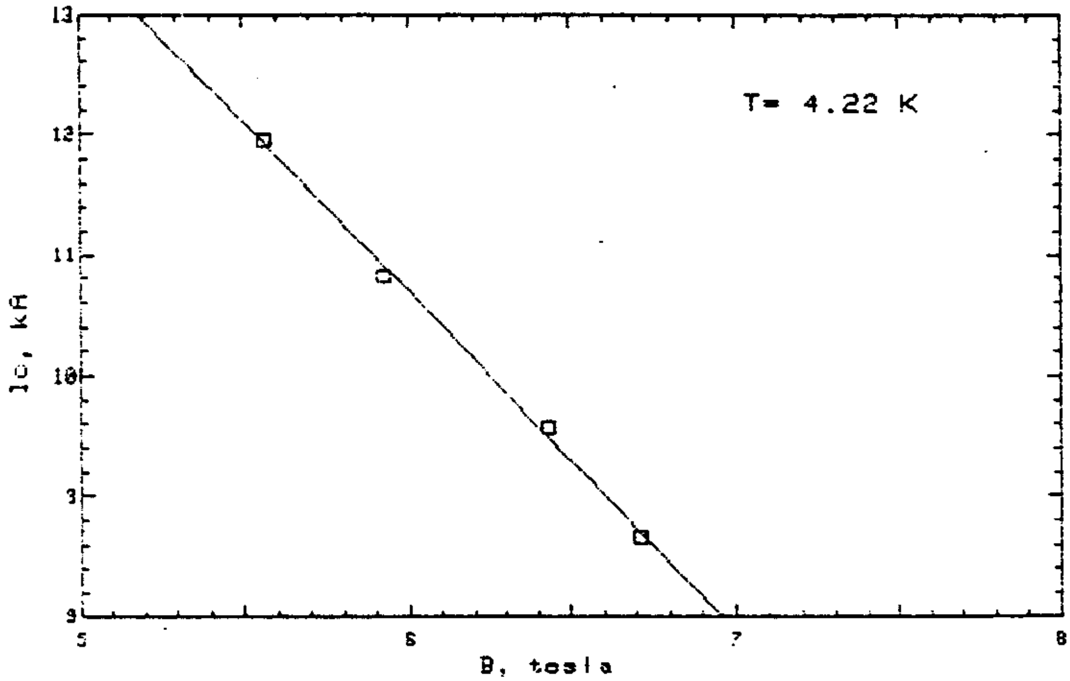
B	Ic	Jc
5	12789	2700
6	10126	2138
7	7463	1576

Comments: IGC 5251-1000. 6 um fils. Cabled at LBL.

FIGURE 3

Run No. 1591 FEB 5 88

SI 63 - S/C 374 parallel



Measurements

B	T	It	Iq	n
5.56	4.345	11400	0	0
6.44	4.350	9030	0	0
5.93	4.345	10300	0	0
6.71	4.350	8150	0	0

R(295)= 25.1 uohms/cm RRR= 63
R(10) = .40 " C/S= 1.49

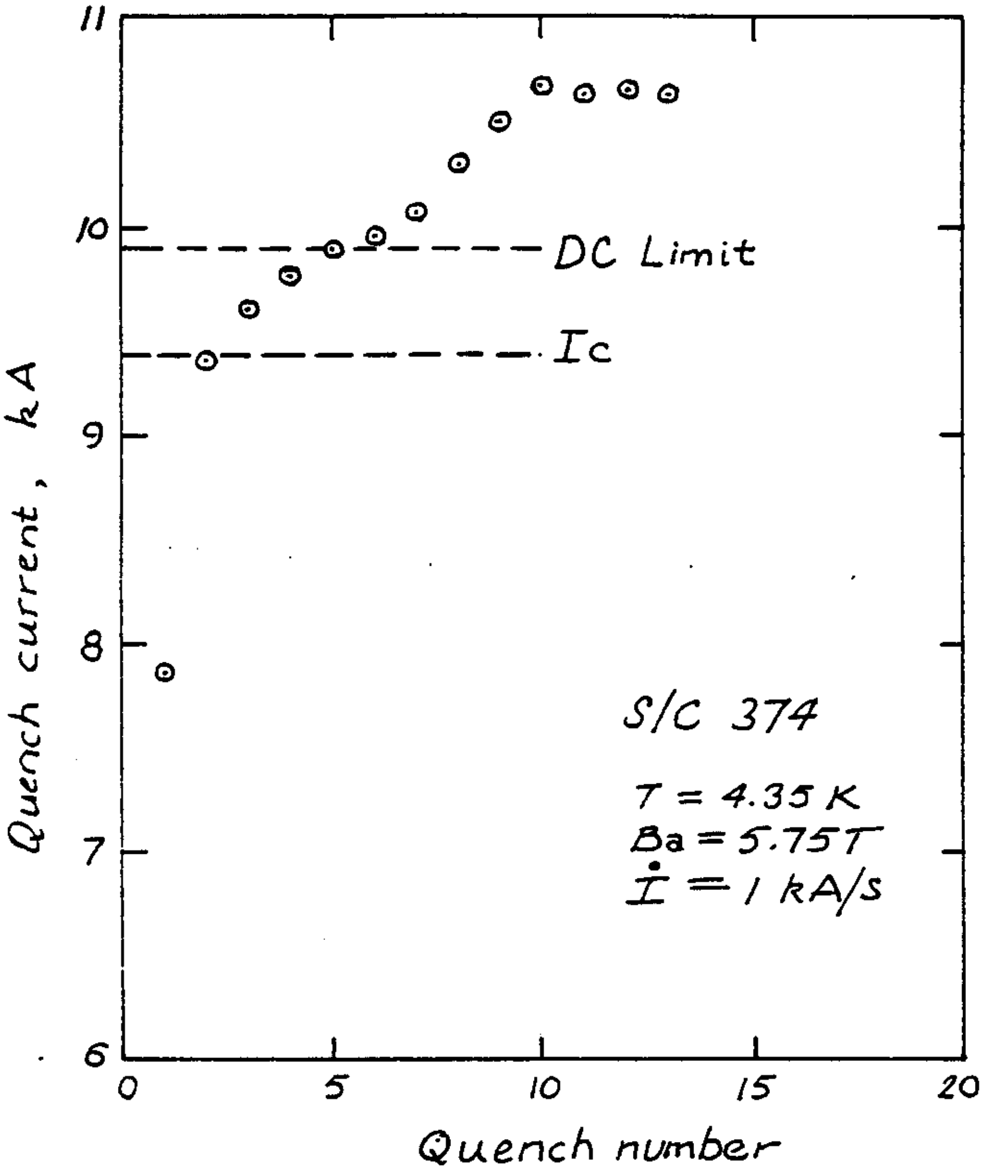
Calculated results for T= 4.22

B	Ic	Jc
5	13511	2852
6	10697	2258
7	7884	1664

Comments: IGC 5251-1000. 6 um fils. Cabled at LBL. Parallel HI and LO data.

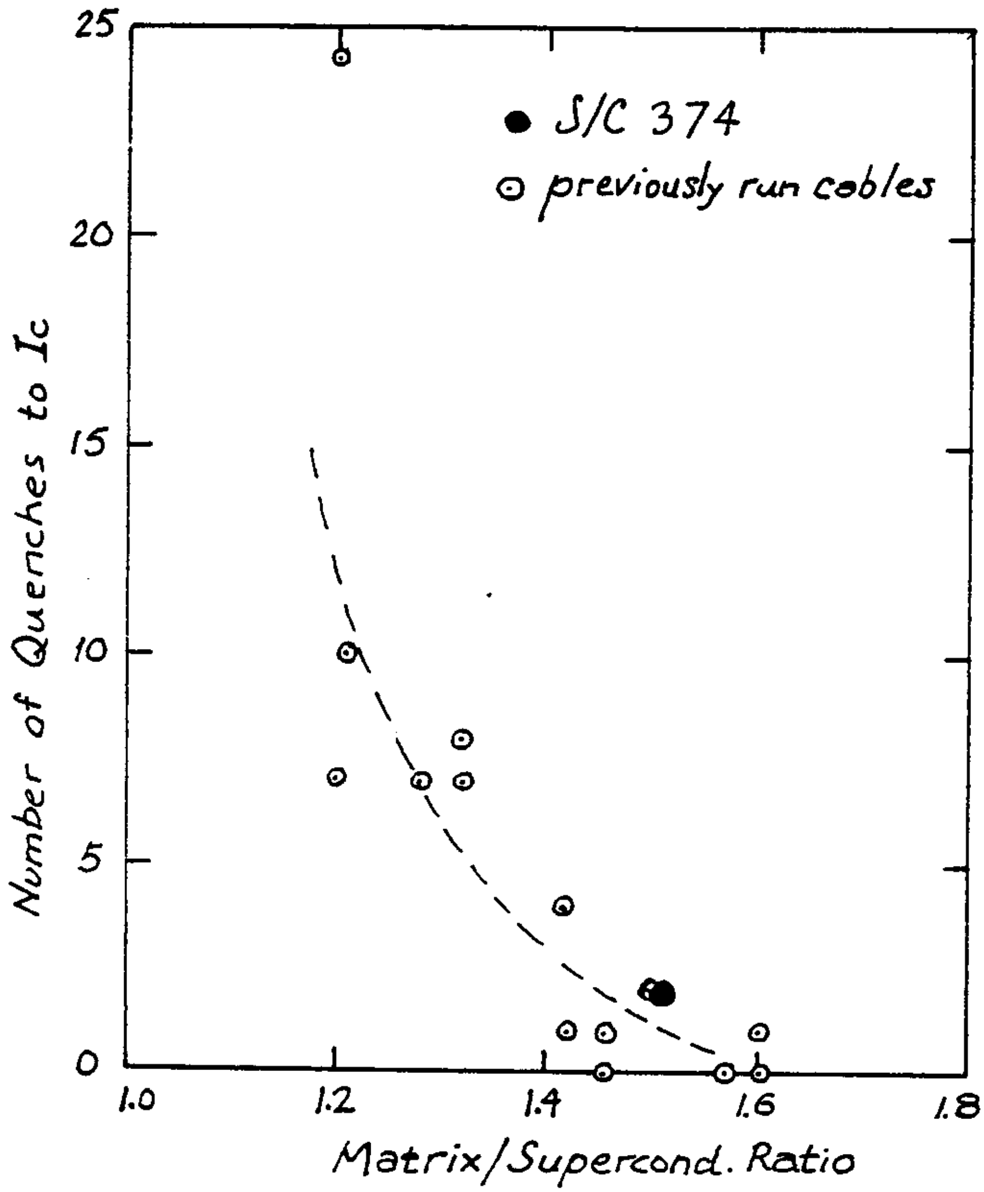
CFF.170 1.26 1.71

FIGURE 4



11
10
9
8
7
6
0
5
10
15
20
Quench current, kA
Quench number
DC Limit
Ic
S/C 374
T = 4.35 K
Ba = 5.75T
İ = 1 kA/s

FIGURE 5



25
20
15
10
5
0
1.0
1.2
1.4
1.6
1.8
S/C 374
previously run cables
Number of Quenches to I_c
Matrix/Supercond. Ratio

FIGURE 6

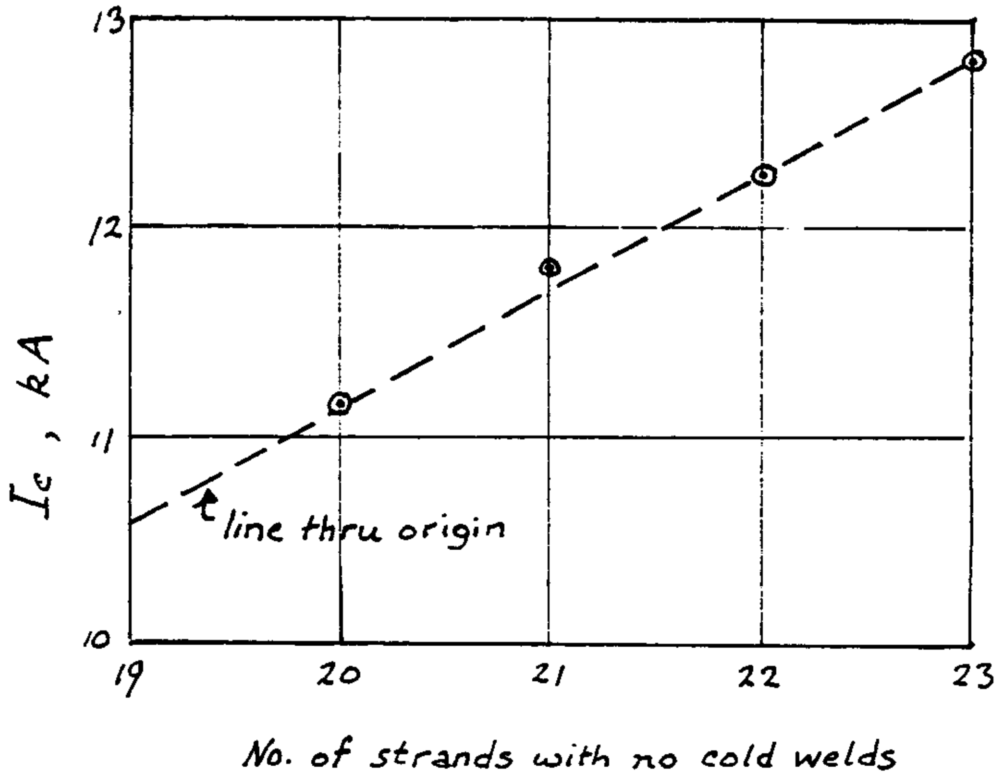
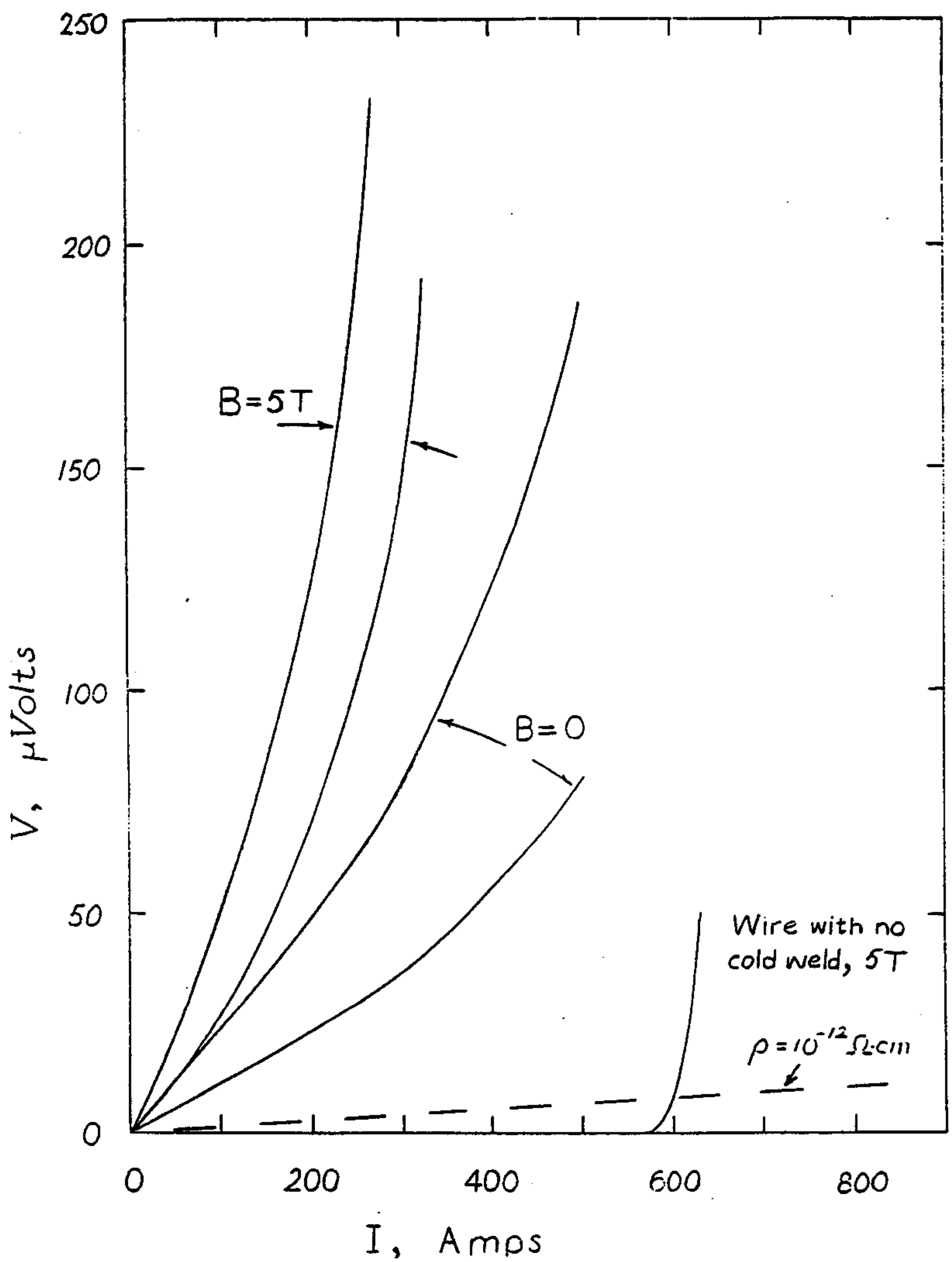

13
12
11
10
I_c , kA
19
20
21
22
23
line thru origin
No. of strands with no cold welds

FIGURE 7



250
200
150
100
50
0
0
200
400
600
800
V, μVolts
I, Amps
B=5T
B=0
Wire with no cold weld, 5T
ρ=10⁻¹² Ω·cm