AD/SSC/Tech. No.

Accelerator Development Department

BROOKHAVEN NATIONAL LABORATORY

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SSC Technical Note No. 71

SSC-N- 496

Analysis of Commercial Cabling at New England Electric Wire Corporation Under Contract to Oxford Superconducting Technology

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INTRODUCTION

In August of 1987 a production lot (4400 ft.) of RHIC cable was manufactured at New England Electric Wire (NEEW) Corporation under contract to Oxford Superconducting Technology (OST). The cable produced showed an excessive degree of degradation (I_a Degradation = 24%) even though the wire met the specifications and the cabler was set up as in the past for other more successful production runs. The following outlines the investigation undertaken by Brookhaven National Laboratory (BNL) to determine the cause(s) of this degradation along with the conclusions arrived at and the changes recommended and made to minimize cabling degradation in the future.

PART 1 - WIRE

WIRE SPECIFICATIONS

The wire specifications governing this purchase order are given in Table 1.

Table 1.

Requirements for RHIC Superconducting Wire

Requirement	Required Value and Tolerance
Minimum critical current at 5T	253 A
Maximum critical current at 3T	1.5 times measured critical current at 5T
Maximum R_{295}	745 micro-ohms/cm
Minimum RRR	90
Wire diameter	0.0255 ± 0.0001 inches
Nominal copper-to-non-copper ratio	2.25:1

INCOMING INSPECTION OF WIRE

One (1) sample of wire was taken from each "heat" (10 heats) and given the standard incoming inspection. This consisted of: a visual inspection of the wire's surface appearance, measuring the wire's diameter with a micrometer, measuring the filament twist pitch (2 + - 0.1 twists/inch), checking the filament twist direction (clockwise), measuring the wire's springback (Acceptance Test Procedure [ATP] No. 015) and performing a sharp bend test (ATP No. 016).

The wire diameter was consistantly on the high side (.0256") but in spec. The springback tests are summarized in Table 2. Consultation with the Lawrence Berkeley Laboratory (LBL) on our springback measurement results confirmed that a springback of up to

1100 degrees for a 0.0255" diameter wire is acceptable. The sharp bend tests showed no damage to the wire's copper jacket or its NbTi filaments (see Fig. 1 & 2).

Table 2.

Sharp Bend and Sringback Tests

Wire No.	Sringback	Sharp Bend
1797 - 3A1(4)-603-11	920°	Passed
1797 - 1C1-603-51	920°	Passed
1797 - 1A3-603-45	916°	Passed
1797 - 2C1A-603-27	1020°	Passed
1797 - 3B7-603-36	930°	Passed
1797 - 2A1-603-1	980°	Passed
1797 - 2B3-603-21	1000°	Passed
1797 - 2C4-603-25	988°	Passed
1797 - 3A2-603-6	1020°	Passed
1797 - 1B2-603-49	988°	Passed
1797 - 3A2(1)-603-169	996°	Passed

In conclusion, it was determined that the wire passed all the present mechanical tests for acceptance.

The wire was electrically inspected by Dr. M. Garber of BNL. A summary of his tests results are given in Table 3 below.

Table 3.

Electrical Test Results

Specification =	≥ 253	≥ 2500	≤ 745	≥ 90
Sample No.	I_c(5T)	J_c	R(295)	RRR
2C4	258	2520	732.7	124
2A1	252*	2469*	731.8	135
2C1A	250*	2449*	728.9	150
1A3	258	2520	728.6	135
1C1	253	2476*	730.6	144
3A1C4	258	2520	731.0	153
1B2	254	2481*	725.6	148
3B7	259	2539	727.0	136
3A2	261	2554	728.8	143
2B3	251*	2451*	724.1	142
Average	255	2498	728.9	141

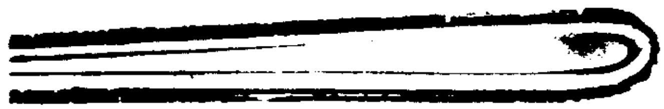


Figure 1.
Oxford Wire - 1797
Typical Sharp Bend/W Cu Jacket.

Figure 2.
Oxford Wire - 1797
Typical Sharp Bend Acid Etched.

From Table 3 it can be seen that of the ten (10) samples tested: half (*) were just below specification and the balance were just above specification. The average of the ten samples met the specifications.

In conclusion, it was determined that although the wire met the specification electrically, the test results indicated a "marginal" wire.

Even though the wire appeared to meet the minimum requirements of the BNL specification, it was decided to conduct additional investigations of the wire. Samples of wire used in a number of "good" and "bad" cables (cables with low and high percentages of degradation) were subjected to tensile tests by Brookhaven's Metallurgy Department. The Ultimate Tensile Strength (UTS) showed considerable variation among samples. However, when one computes the Ultimate Load per NbTi filament (neglecting copper's contribution, all filaments of the same size carry the same load. See Table 4.

Table 4.

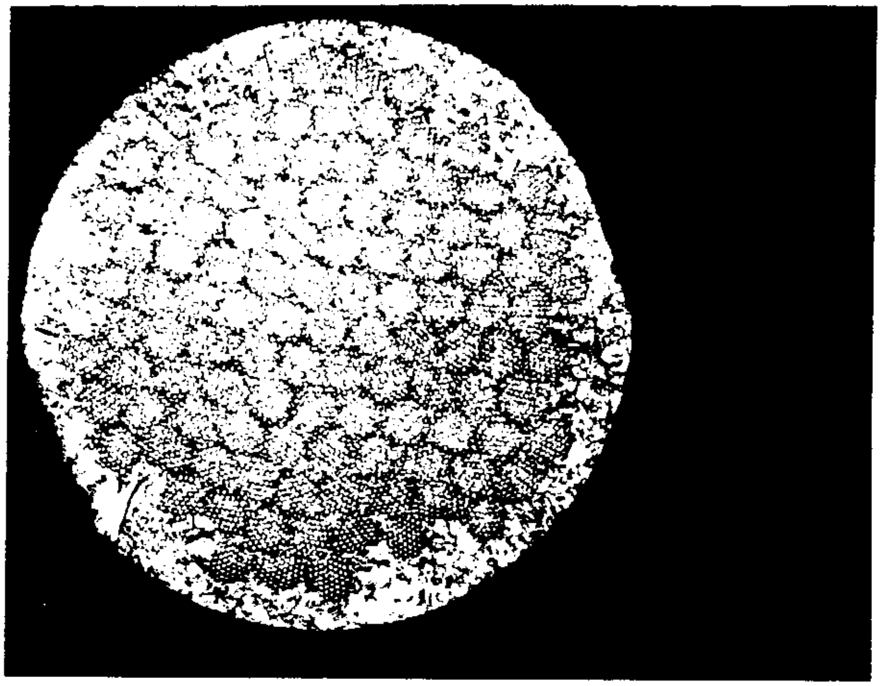
Sample Mfr./ Billet Number	Cable/ Mfr.	Cable Deg. (%)	Ult. Ten. Strength (Psi)	Filament Size (μm)	Cu/S	No. of Filaments	Avg. Ult. Load Fil. (Lb./Fil)
OST	S0-53	3.3		5	1.78	6036	0.0092
1579	-54	4.4	109,316				
	-55	4.1	108,728				
	-56	4.1					
	LBL						
OST	S0-70	11.33		5	1.84	5909	0.0089
1725	-71	13.09	102,067				
	-72	13.09	103,634				
	LBL						
OST	S0-88	-		5	2.297	5090	0.0093
1797	S0-89	24.0	92,859				
	S0-90	22.0	93,055				
	NEE						
Sup.	S0-76	14.86		5	1.97	5650	0.0087
348E	S0-77	17.30	95,798				
	S0-78	18.05	96,386				
	LBL						
Fur.	S0-38	6.4		5	1.68	6261	0.0090
SG-6104	S0-41	7.8	109,707				
	S0-42	5.8	110,295				
	S0-43	6.2					
	NEE						

From the table it is clear that although the wires were made by different manufacturers, using different assembly techniques and heat treatments, the tensile strength of the NbTi filaments round off to be equal. If all wire samples had had the same number of filaments, all wires would have had about the same tensile strength.

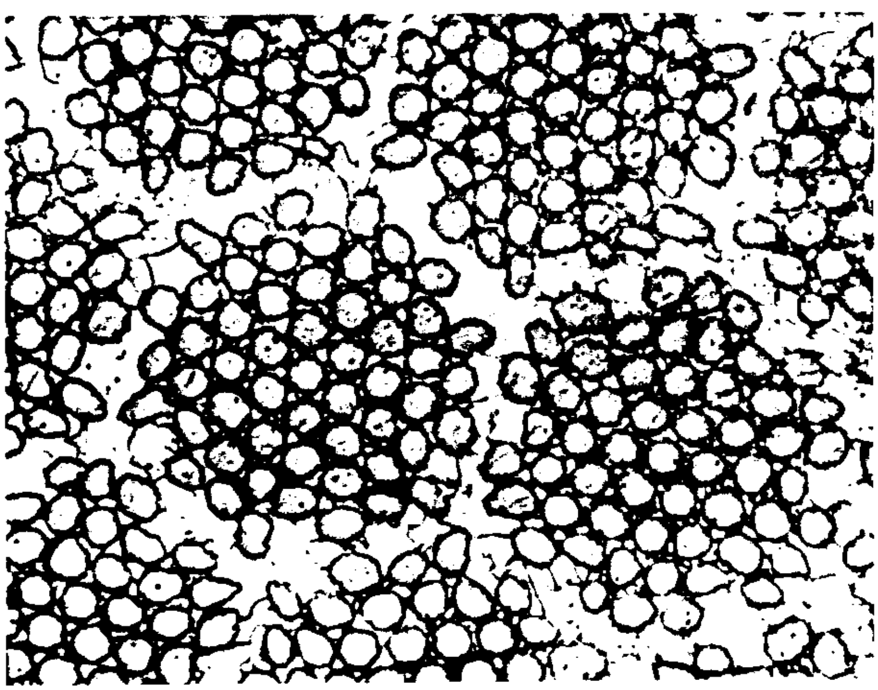
In addition to the tensile tests, Metallurgy made high and low magnification photomicrographics of these wires (see Fig. 3 through Fig. 9). As reported by Mr. C. Klamut in a memorandum dated September 9, 1987, it appears that the strongest wires made the best cables and that having NbTi distributed uniformly through the entire cross section may have been a contributing factor.

Even though Fig. 6 shows that the OST wire used in this cabling run exhibited distortion of some filaments and slight sausaging, the wire appears to be typical for NbTi conductor.

The decision was made to further investigate the sharp bend test. Three (3) samples of the OST wire were taken and subjected to excessive compression in the Sharp Bend Test Fixture. The samples taken were: 1797-1A5, 1797-3A2(5), and 1797-1C(3). The gap in the fixture was first reduced from 0.062" to 0.052" (0.010"). Each wire sample was given the sharp bend test and inspected under a microscope before and after acid etching. None of the samples showed any damage or degradation. The procedure was then repeated with the fixture gap reduced from 0.062" to 0.047" (0.015"). Again, none of the samples showed any damage or degradation.

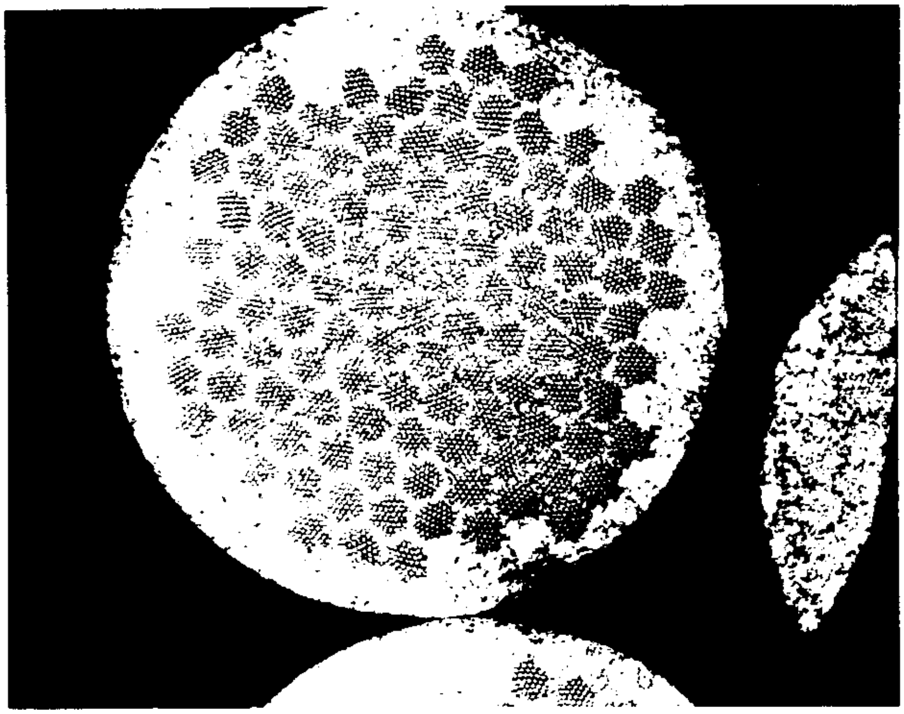


Cu-Nb Etch **OST 1579** **125x**

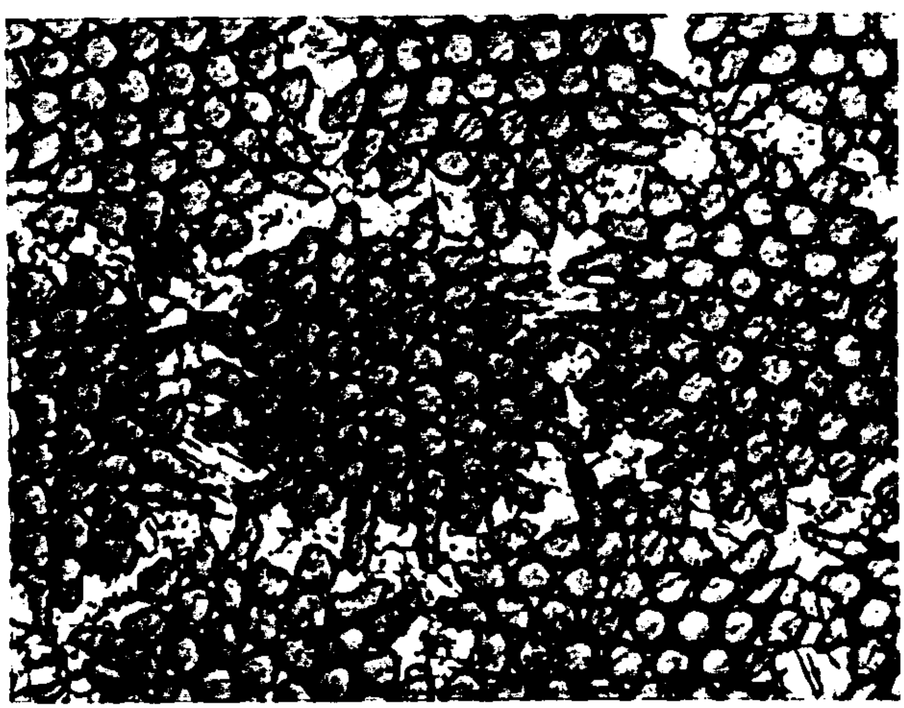


Cu-Nb Etch **OST 1579** **1000x**

Figure 3.



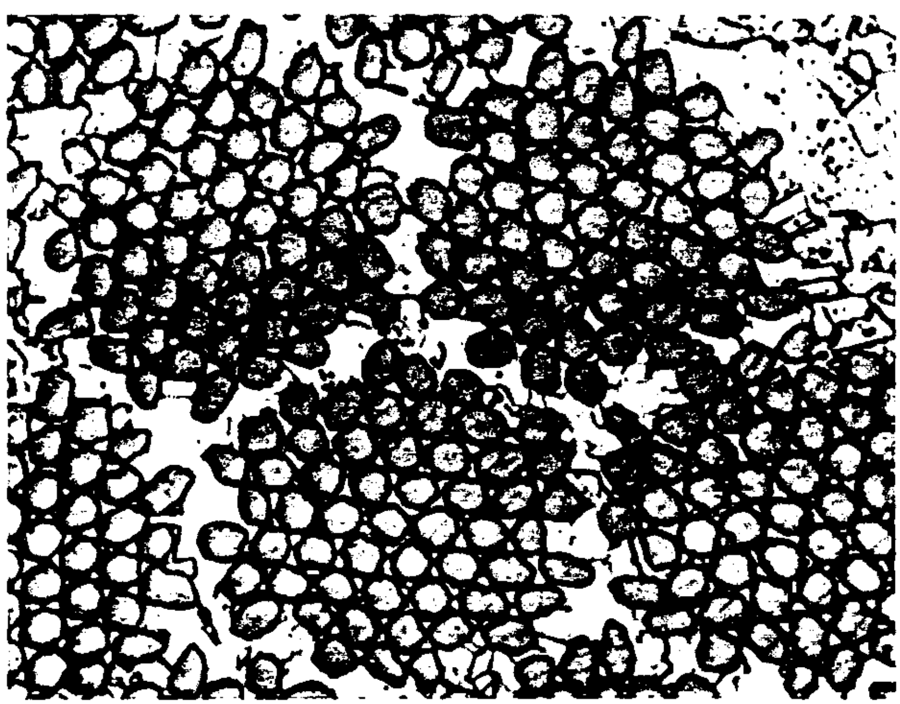
Cu-Nb Etch OST 1725 125x



Cu-Nb Etch OST 1725 1000x

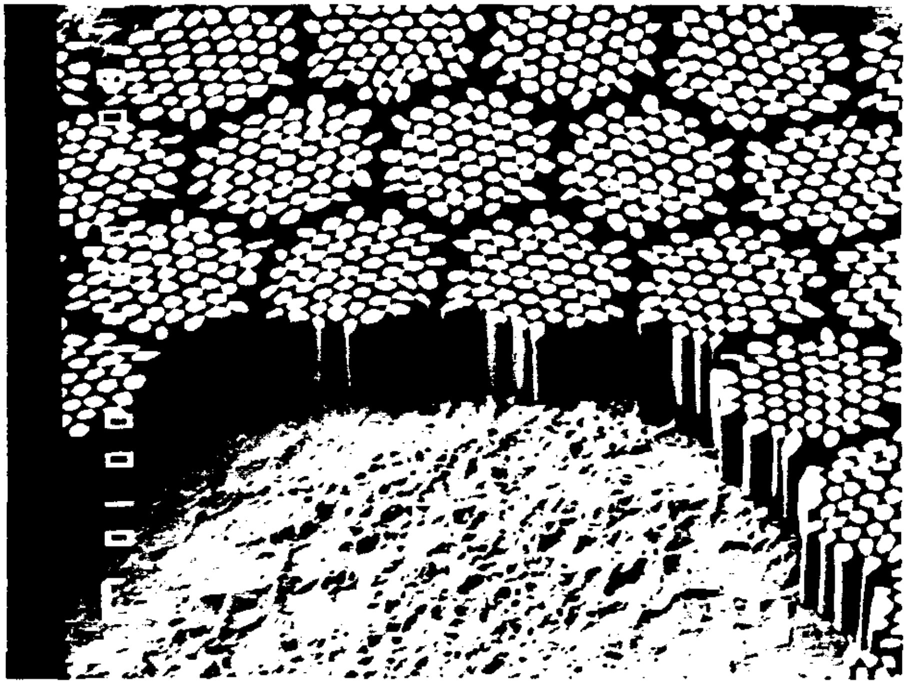
Figure 4.

Cu-Nb Etch OST 1797 125x

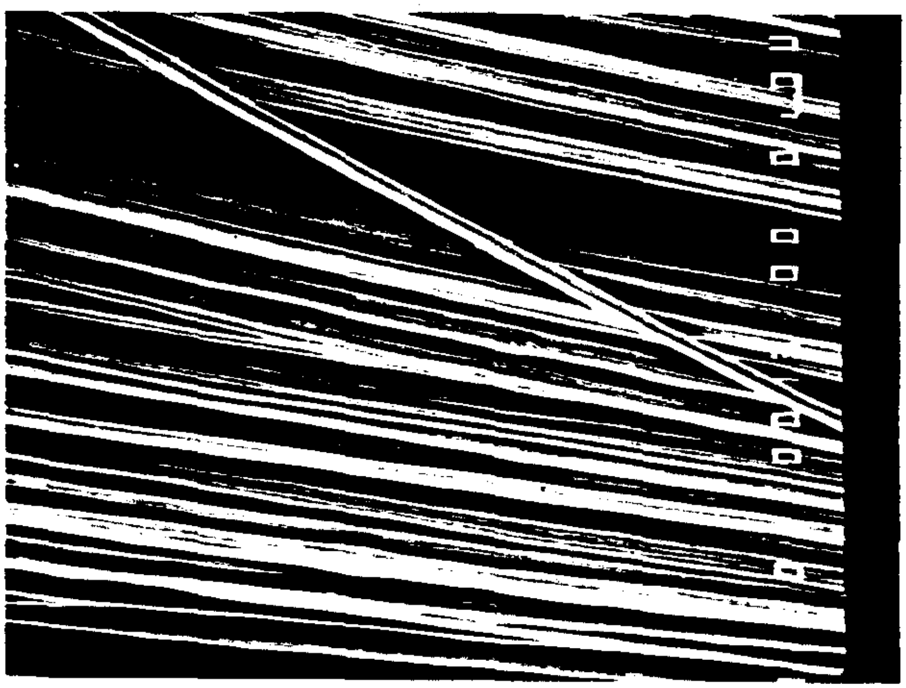


Cu-Nb Etch OST 1797 1000x

Figure 5.

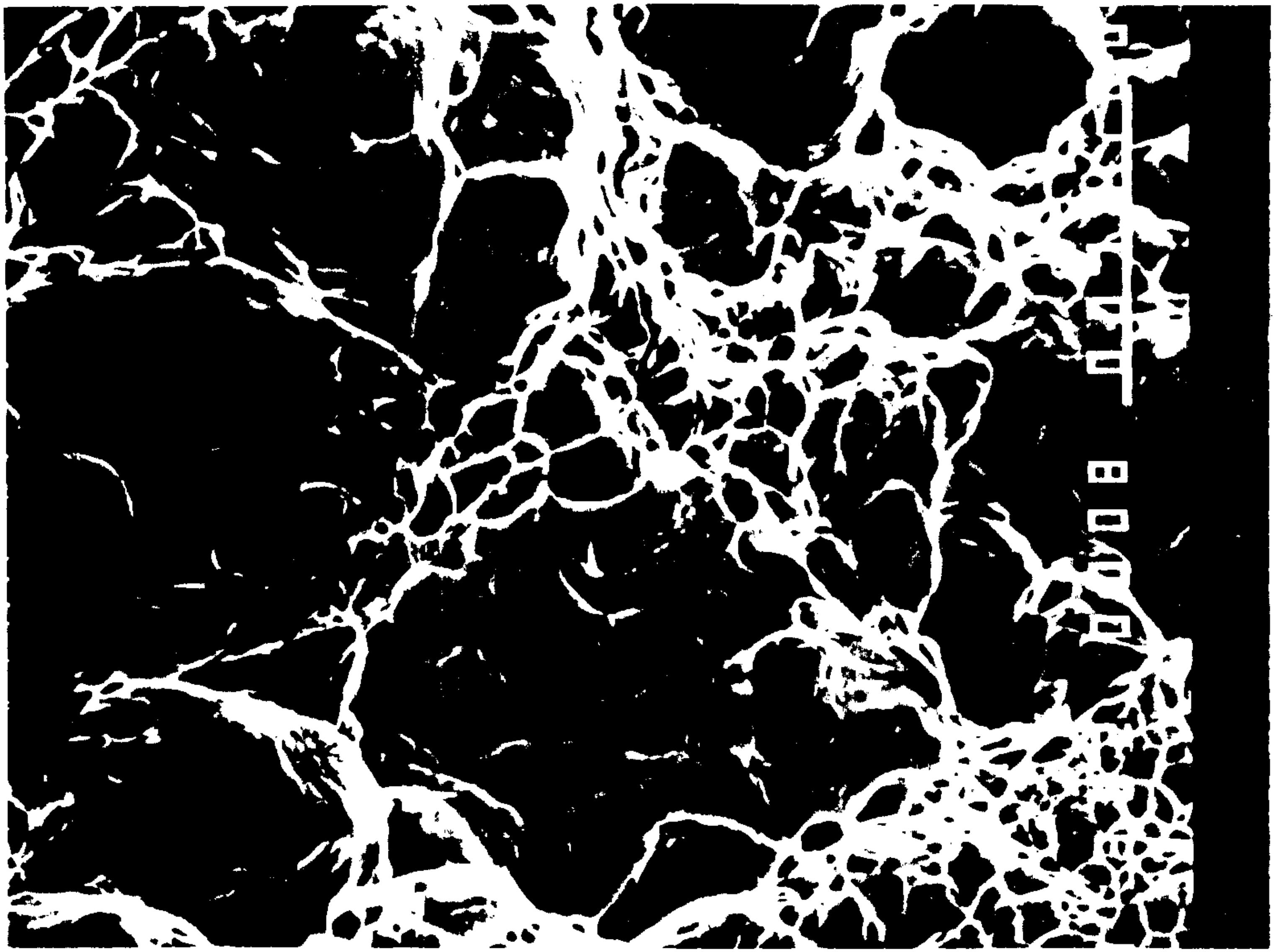


Nitric Etch OST 1797 500x



Nitric Etch OST 1797 500x

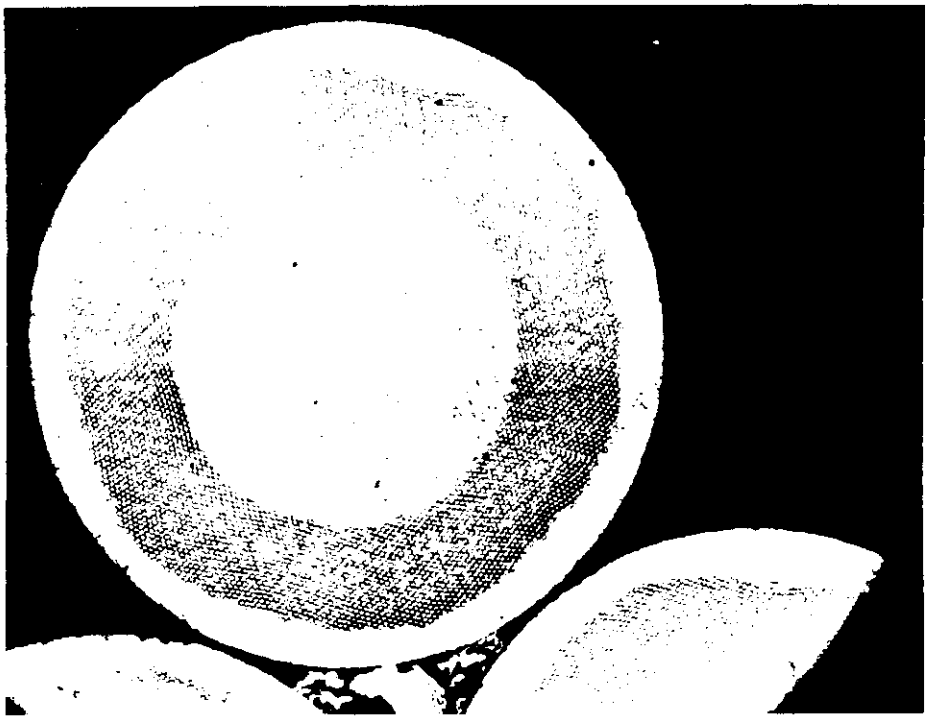
Figure 6.



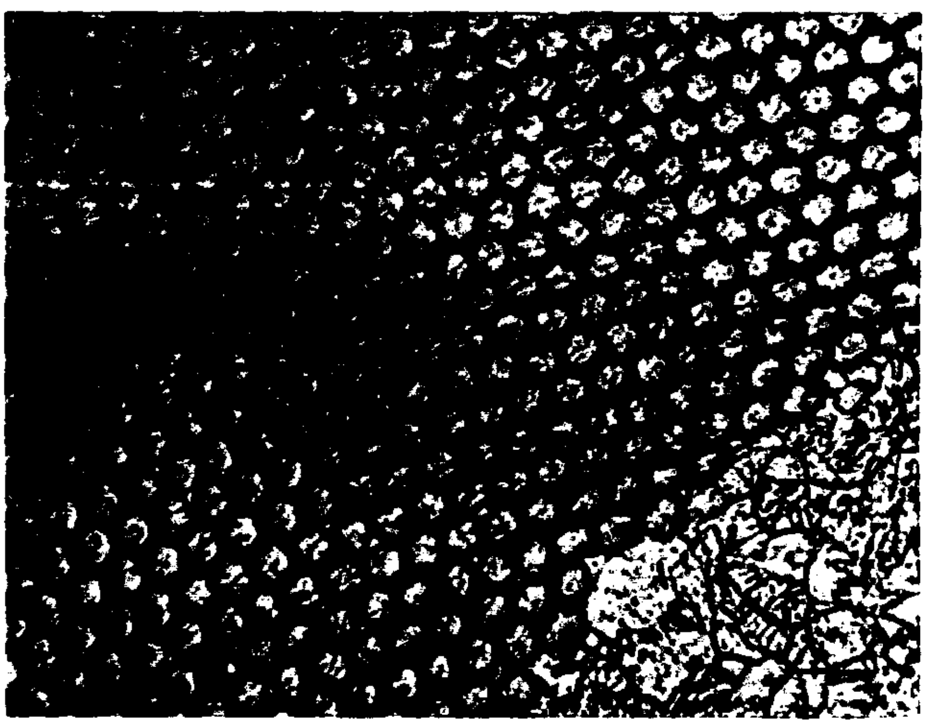
OST 1797 **3000x**

Fracture Surface

Figure 7.

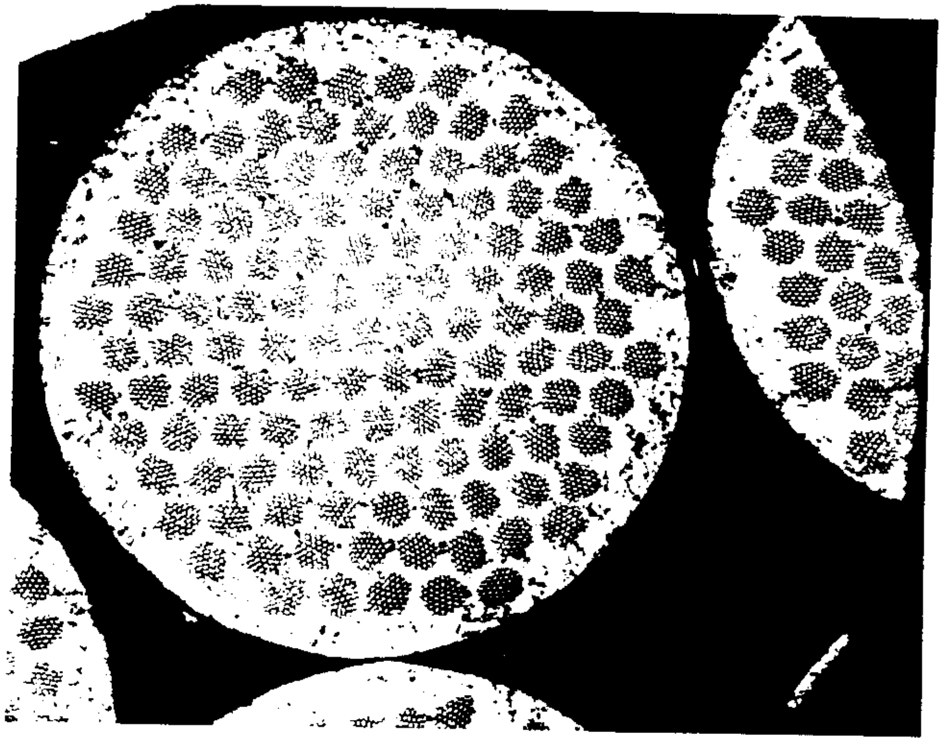


Cu-Nb Etch SUP 348E 125x

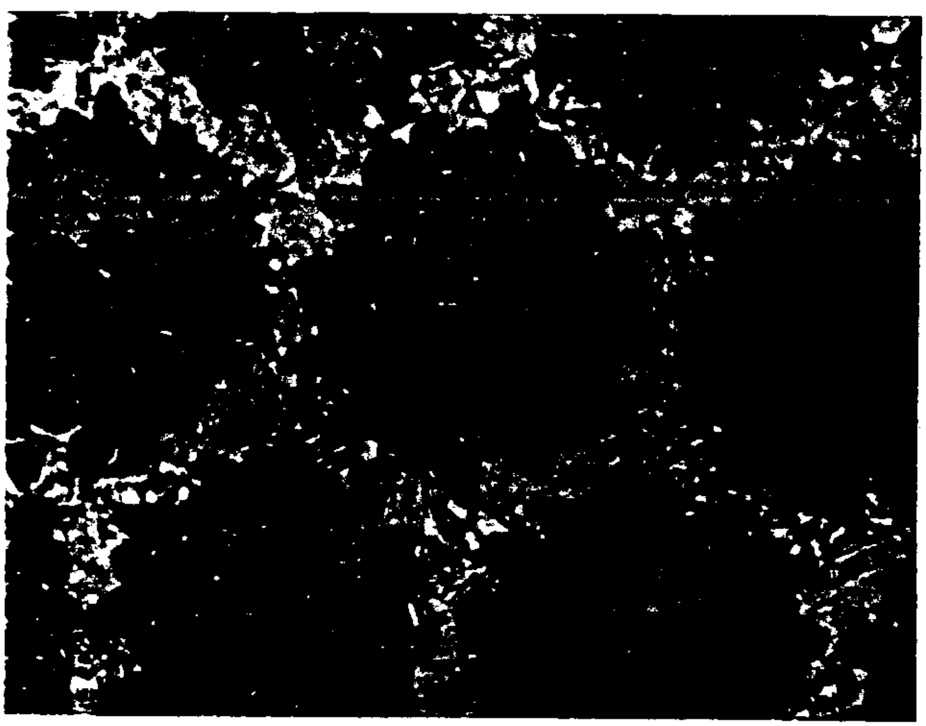


Cu-Nb Etch SUP 348E 1000x

Figure 8.



Cu-Nb Etch   Furukawa 8G 6104-1   125x



Cu-Nb Etch   Furukawa 8G 6104-1   1000x

Figure 9.

PART 2 - CABLE

CABLE SPECIFICATIONS

The cable specifications governing this purchase order are given in Tables 5 & 6.

Table 5.

Mechanical Requirements for RHIC Superconducting Cable

Requirement	Required Value and Tolerance
Cable mid-thickness	0.0459 ± 0.0005 inches
Cable width	0.386 ± 0.002 inches
Keystone angle	1.2 ± 0.2 degrees
Maximum cable twist	90°
Cable lay direction	Left
Cable lay pitch	2.9 ± 0.2 inches

Table 6.

Electrical Requirements for RHIC Superconducting Cable

Requirement	Required Value & Tolerance
Minimum critical current at 5T	6460 A
Maximum critical current at 3T	1.50 times measured value at 5T
Maximum R_{295}	26.4 micro-ohms/cm
Minimum RRR (R_{295}/R_{10})	55

ANALYSIS OF CABLE

Samples of cable were taken from SO-0088 [400' for cabler "set up"] and the transition cable that followed SO-0088 and preceded SO-0089. Samples were also taken from SO-0089 and SO-0090. Table 7 lists the mean thickness (Tm) of the cable analyzed. All the measurements listed were taken at BNL. The "10" Stack Measurements taken at NEEW were as follows:

SO-0088 = .04588
SO-0089 = .04566
SO-0090 = .04568

The Mean Thickness (Tm) measurements recorded at NEEW on their Cable Measuring Machine (CMM) averaged the following:

SO-0089 = .04564
SO-0090 = .04563

Table 7

Mean Thickness of Cable Analyzed

Sample Identification	BNL Meas. "10" Stack	Remarks: T_{mspec} = 0.0459" ± 0.0005"
Sample 1	0.04661"	Over spec. by 0.00021"
Sample 2	0.04556"	In spec. but under nominal by 0.00034
Sample 3	0.04400"	Under spec. by 0.0014"
SO-88	0.04587"	In spec. on nominal
SO-89	0.04580"	In spec. below nominal by 0.0001"
SO-90	0.04580"	In spec. below nominal by 0.0001"

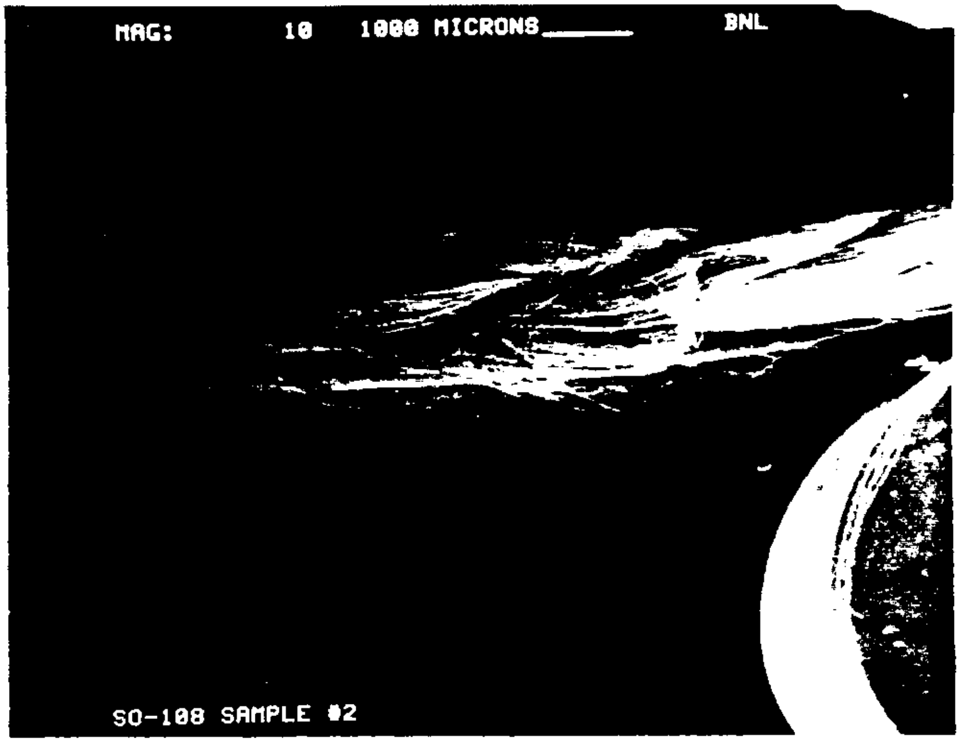
As can be seen, all cables were made within the specifications and both measuring devices agreed with each other within acceptable tolerances.

In addition to mean thickness measurements, these samples (each 10" - 12" long) were acid etched and examined under a microscope. Extensive filament damage was observed (see Fig. 10). The broken strands were noted and recorded (see Worksheets 1 thru 6). As one can see, there is no pattern to the breaks and the same strand, in most cases, did not break in every "pitch length" section of the cable. However, the breaks in each strand did appear along the same corner of the thin edge. One sample of cable was removed from the spool and its orientation noted and traced back to the turkshead roller (Fig. 11). This sample shows that the strand is breaking as it comes out of the thin edge and lays on the long flat side.

From this analysis one may conclude that the broken strands were not caused by over compressing of the cable as Tm was well within the cable specifications. The breaks are random and form no pattern with regard to which strands break. Furthermore, all breaks are consistant in their location within the cable.

CABLER ANALYSIS

To determine if the wire can be cabled and if the cabler is the cause of the degradation, OST wire was sent to LBL for cabling on their experimental cabling machine. On August 31, 1987 cables SO-0091, SO-0092, SO-0093, and SO-0094 were received at BNL and tested. The cable degradation ranged from 9% to 11% with no major filament damage. In order to check the cabler "set up" and compare the cabling procedures of BNL and LBL, and to also manufacture the needed RHIC cable, Brookhaven representatives traveled to LBL and cabled SO-0095 [2200'] and SO-0096 [4627']. These cables show a degradation of 9% and 12% respectively. Acid etched samples of all cables made at LBL showed no broken wires. However, a "fuzzy" appearance caused by many random broken filaments was noticed. This "fuzzy" appearance was also present on all cables made at NEEW (see Fig. 12).



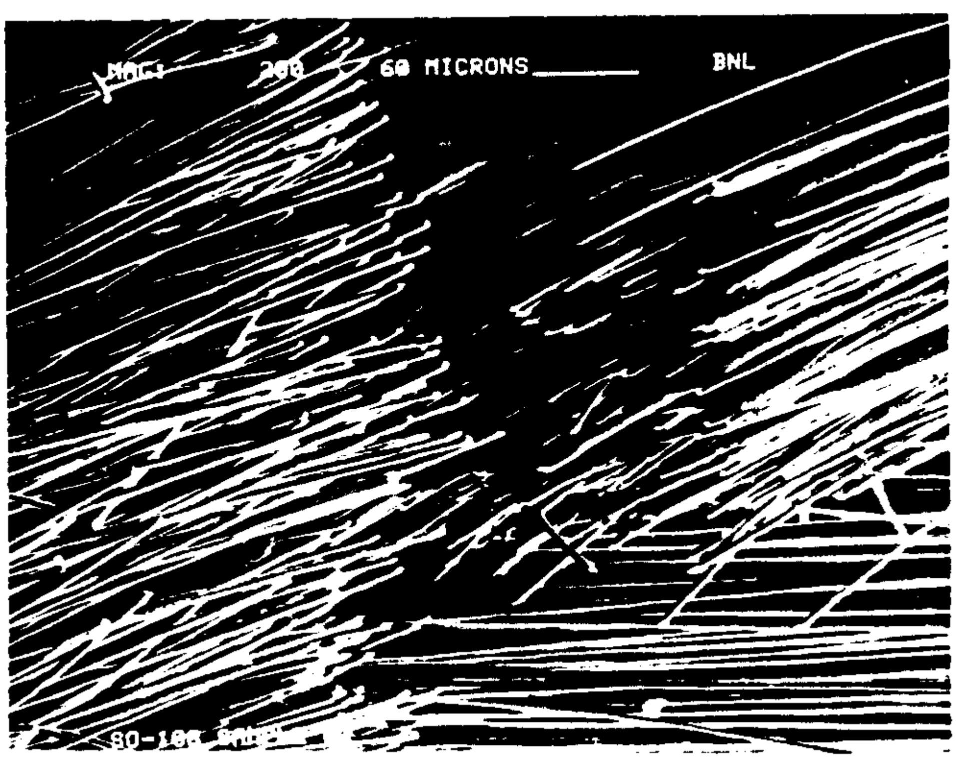


Figure 10.
A Typical Broken Strand.

Worksheet No. 1

Sample 1 (Cabler Set up) X = NG = clean breaks.

Tracer	Section 1	Section 2	Section 3
1			
2			
3		X	
4			
5			
6		X	
7			X
8			
9	X		
10			
11	X		X
12			
13		X	
14		X	
15			
16			
17		X	
18			
19			
20			
21	X	X	X
22	X		
23			
24	X		X
25	X	X	
26			
27			
28			X
29			
30		X	X

Section ⟶ 1 | 2 | 3 Going from left to right.

Mean thickness of cable: T_m = 46.61 mils.

Worksheet No. 2

Sample 2 (Cabler Set up)   X = NG = clean breaks.

Tracer	Section 1	Section 2	Section 3	Section 4
1				
2				
3				
4				
5		X		
6				
7	X	X		
8				
9				
10				
11				
12				
13				
14				
15		X		X
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30		X		

Section ⟶ 1 2 3 4 Going from left to right.

Mean thickness of cable: T_m = 45.56 mils.

Worksheet No. 3

Sample 3 (Cabler Set up) X = NG = clean breaks.

Tracer	1	No sign of any major damage. A few broken filaments.
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	
	11	
	12	
	13	
	14	
	15	
	16	
	17	
	18	
	19	
	20	
	21	
	22	
	23	
	24	
	25	
	26	
	27	
	28	
	29	
	30	

Mean thickness of cable: T_m = 44.00 mils.

Worksheet No. 4

Sample 4 (SO-88) X = NG = clean breaks.

Tracer	Section 1	Section 2	Section 3
1			
2			
3			
4			
5			
6			
7			
8			
9	X		
10	X		X
11	X	X	
12			
13	X	X	X
14			
15	X		
16			
17			
18			
19		X	
20			X
21			
22			
23			
24		X	
25		X	
26			X
27			
28		X	
29			
30		X	

Section ⟶ 1 2 3 Going from left to right.

Mean thickness of cable: T_m = 45.87 mils.

Worksheet No. 5

Sample 5 (SO-89) X = NG = clean breaks.

Tracer	Section 1	Section 2	Section 3
1			
2			
3		X	X
4	X	X	
5			X
6			
7	X		
8	X		
9			
10			
11		X	
12	X		X
13	X	X	X
14	X	X	X
15	X	X	
16			X
17			
18		X	
19			
20			
21	X	X	
22	X	X	
23		X	
24			
25			
26			
27			
28			
29			
30			

Section ⟶ 1 2 3 Going from left to right.

Mean thickness of cable: T_m = 45.80 mils.

Worksheet No. 6

Sample 6 (SO-90) X = NG = clean breaks.

Tracer	Section 1	Section 2
1		
2		
3		
4	X	X
5		
6	X	
7		
8	X	X
9		
10	X	X
11	X	
12		X
13		X
14	X	
15	X	X
16	X	
17	X	X
18		X
19	X	
20	X	X
21	X	
22		X
23	X	
24		
25		
26		
27		X
28		
29	X	
30		

Section ⟶ 1, 2 Going from left to right.

Mean thickness of cable: T_m = 45.80 mils.

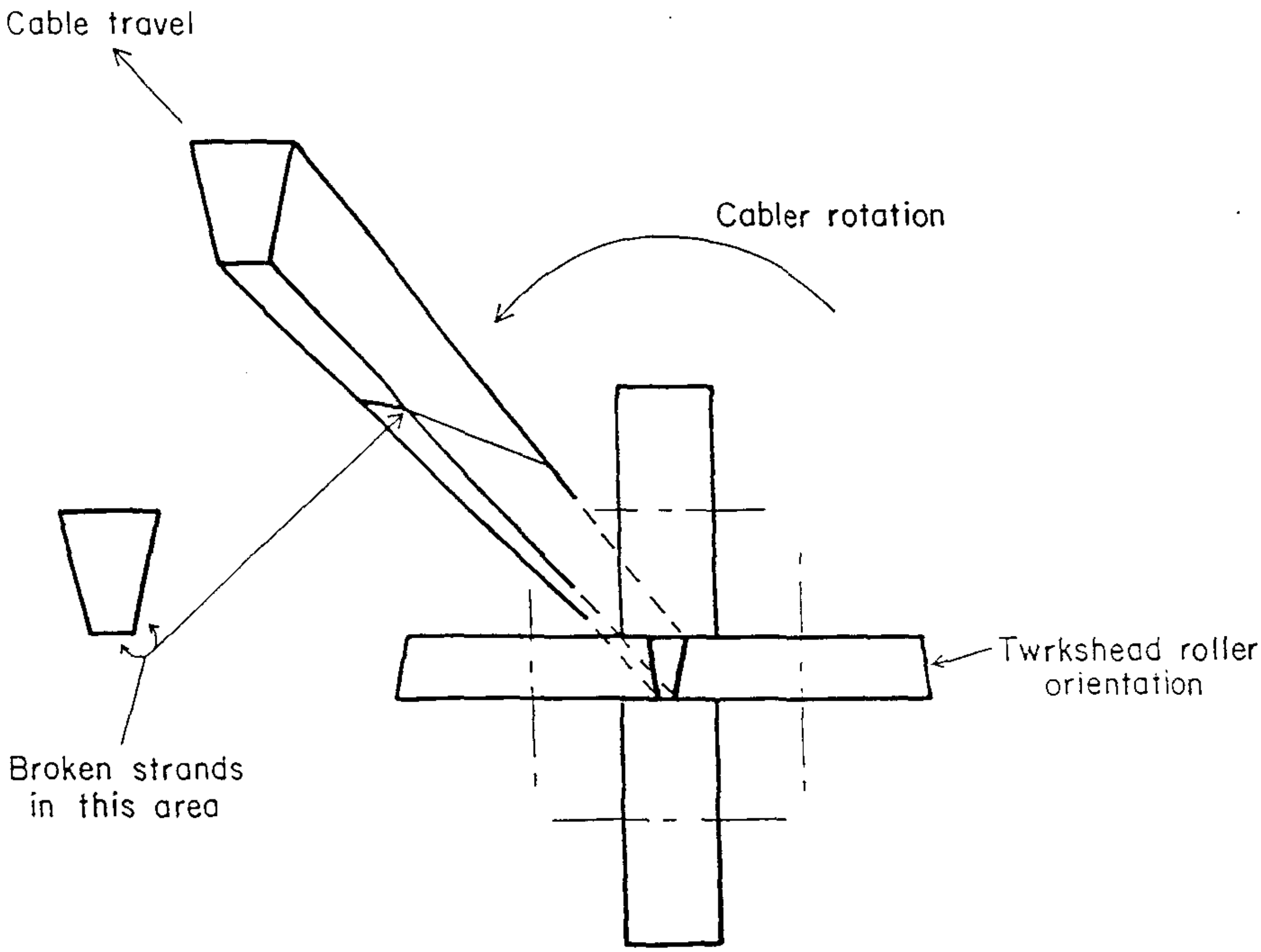


Figure 11.

Broken Strand Orientation

(Looking Upstream Into The Turkshead)

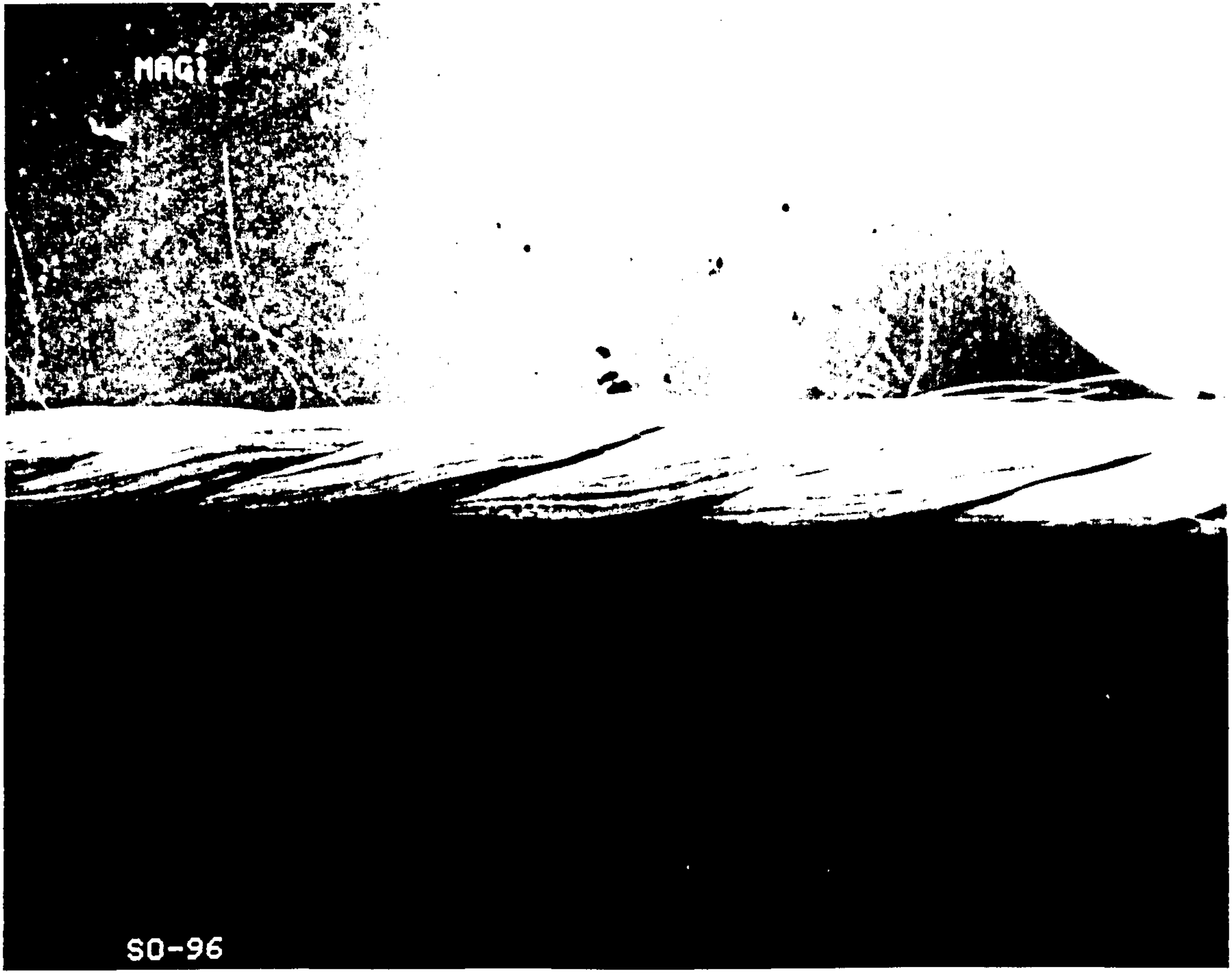


Figure 12.
A Typical Cable Manufactured at LBL.

From these experiments it was concluded that although the wire met all specifications, its filaments appeared to be fragile and susceptible to random breakage due to handling and cabling. The cabling at NEEW appeared to be the cause of the excessive and concentrated filament breakage along the cable's narrow edge.

CABLER MODIFICATIONS

During mid October Brookhaven representatives visited NEEW to review their cabling machine and cabling operation. From this trip a list of proposed modifications to their Kraft Cabler was made. A copy of the actual recommendations made appears as Appendix A. Figure 13 is a schematic representation of our suggested design changes covered under items 1 and 2 in Appendix A. All proposed modifications were made with the exception of item 4, as NEEW claimed that the existing clutch would suffice to permit pulling cable without carriage rotation. These modifications were completed by mid November. During the implementation period, Brookhaven engineering developed a check off list entitled:

CHECK OFF LIST

SSC & RHIC
Cabling Machine Set-Up and Operation
For
New England Electric Wire Corporation

This check off list was reviewed by LBL to assure their agreement for use in the cabling of SSC cable at NEEW. The purpose of the check off list is to assure the proper set-up and operation of NEEW's Kraft Cabler Machine to produce quality cable with uniform and consistent properties for both the SSC and RHIC Projects. To test out this procedure and NEEW's modifications, Brookhaven representatives visited NEEW in late November and ran a series of experiments using some of the remaining OST wire.

BNL CABLING TESTS OF OST WIRE

A series of cables were made to determine the optimum "Pinch Point plus Gap" (PP + Gap) setting for the cabler's mandrel. The "pinch point" is that distance along the cabler's Z axis (longitudinal axis) at which the wires are "pinched" between the tip of the mandrel and the rollers within the turkshead. The pinch point is determined by closing the gap between the tip of the mandrel and the turkshead rollers until the cable ceases to pull smoothly through and starts to "jurk" through the turkshead. The turkshead is then moved away from the mandrel an optimum amount to produce good cable. It was determined that LBL's setting of PP + Gap = 0.030" was not

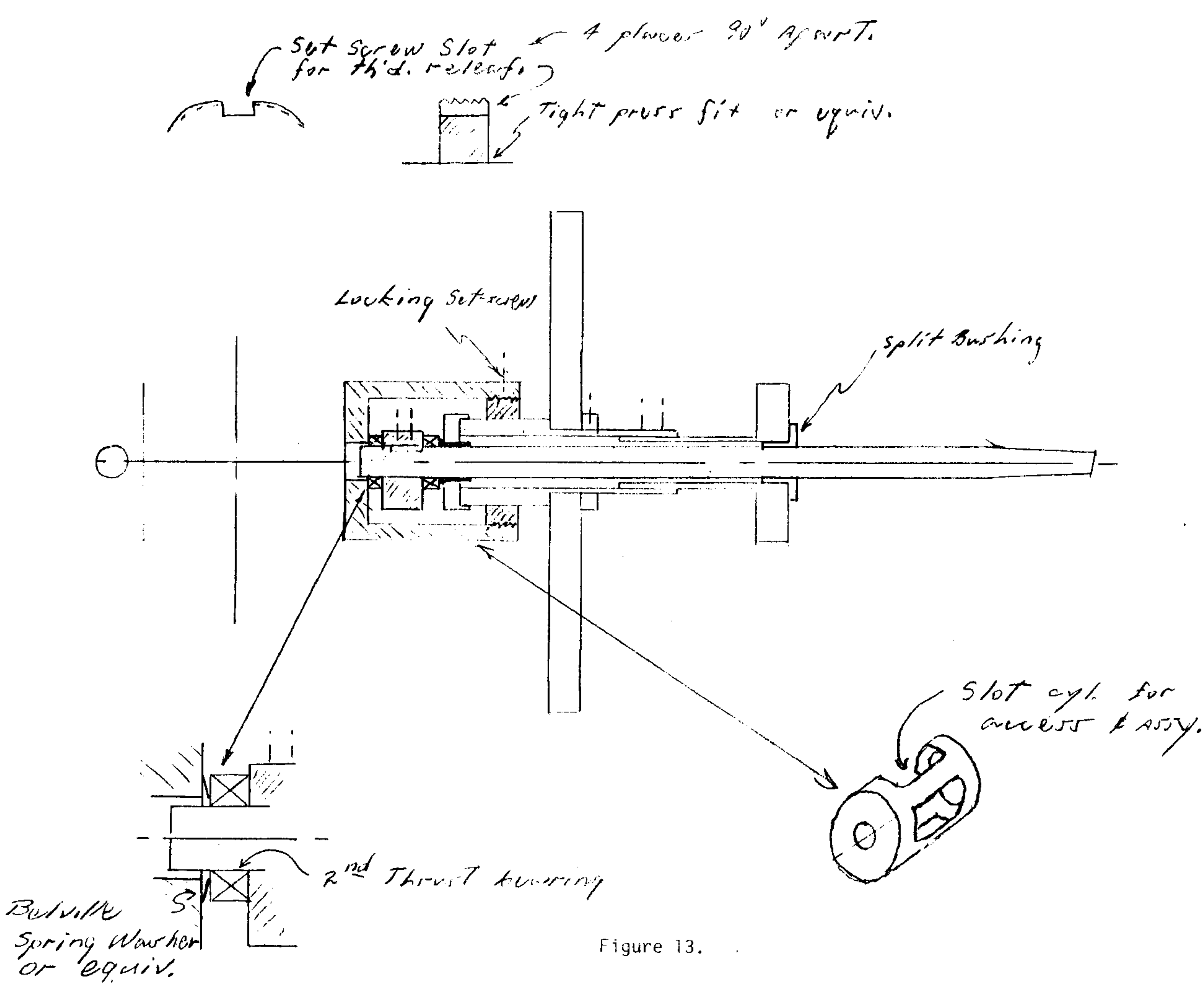

Set Screw Slot
for th'd. releaf.
4 places 90° Apart.
Tight press fit or equiv.
Locking Set-screws
Split Bushing
Slot cyl. for
access & assy.
2nd Thrust bearing
Belville
Spring Washer
or equiv.

Figure 13.

adequate for NEEW's cabler. It should be noted, however, that LBL had no trouble making cable from this OST wire at PP + 0.030" and greater. In fact, LBL with their "fixed" (non rotating) mandrel, could make cable with a gap large enough to permit wire cross-overs. It was determined that NEEW's Kraft Cabler required a PP + Gap = 0.060" or greater to reduce cable degradation caused by broken wires. A combination experimental and production cabling run was made during December with LBL at NEEW. LBL, using Brookhaven's Check Off List and recommended PP + Gap = 0.070", cabled 4900' of SO-0118 [IGC 15 µm/1.8:1 Cu/S wire] while BNL ran two (2) short lengths of cable using the same cabler set-up and settings. The Brookhaven samples were SO-0117 [Supercon 7 µm/2.25 Cu/S wire] and SO-0119 [OST 5 µm/2.25 Cu/S wire]. These cables exhibited the following degradations:

SO-0117 = 11.26% (Sup wire) Figure 14
SO-0118 = 14.44% (IGC wire) Figure 15
SO-0119 = 9.03% (OST wire) Figure 16

From this it can be seen that the modifications to NEEW's Kraft Cabler and the new more precise set-up procedure has greatly reduced the cabling degradation of the OST wire.

SUMMARY

Though marginal in electrical test results, the wire used in this cable run passed all present incoming inspection procuedures and tests. As wire, it appears to be typical of NbTi conductor. In cable, the wire displays a "fuzzy" appearance which is attributable to many random broken filaments throughout the cable. This leads the author to conclude that the wire is marginal and inferior to past wire procurements.

The initial cabling run at NEEW caused the excessive degradation in the cable due to poor set up and alignment procedures. These procedures may have been adequate in the past due to a more forgiving wire (wire of higher quality). The fact that this wire, cabled at LBL, demonstrated a much lower degradation (9% - 11% vs. 24%) showed that much of the degradation was caused in the cabling process. After modifying the NEEW cabler, and using a more precise set up procedure, this wire was successfully cabled with degradations in the same range as that of LBL (9% - 11%). Severe filament damage was eliminated. The cable still exhibited a "fuzzy" appearance which was not present in subsequent cable runs with different wire. A presentation of the material presented in this paper was made to Brookhaven's Cable Task Force Group. It was noted, by the author, that further review of cable samples made at NEEW indicates that increasing the PP + Gap to 0.090" may further improve the cabler's performance while allowing more room for error in setting up the

Figure 14.
Supercon 7μm.

Figure 15.
IGC 15μm.

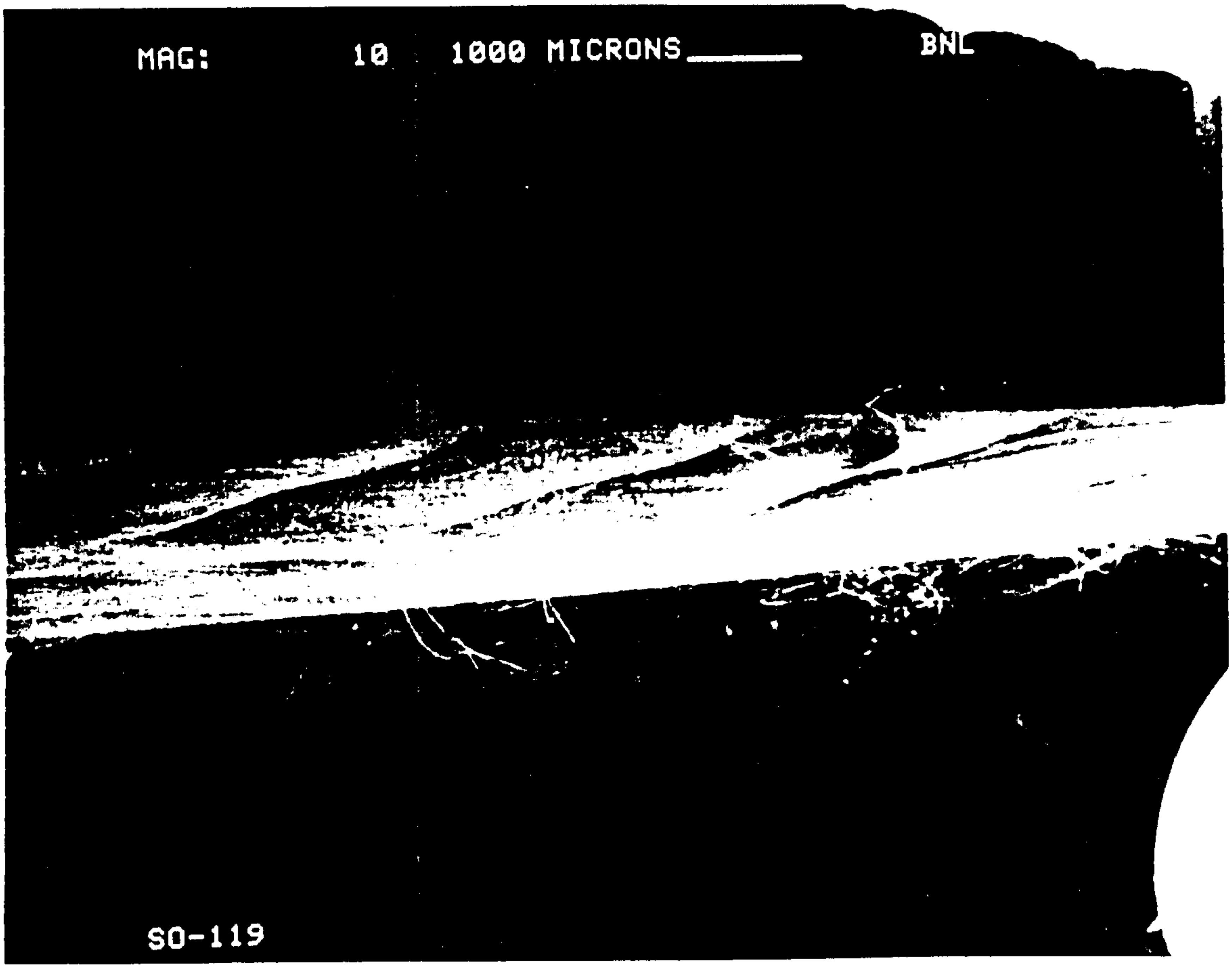


Figure 16.
OST 5μm.

machine. Also emphasized at this meeting was the fact that NEEW's rotating mandrel and wire tensioning method may be a contributing factor in preventing a further reduction in cable degradation. At LBL's request and as part of SSC cable development, NEEW is presently modifying their cabler to eliminate mandrel rotation.

CONCLUSION

(1) It was proven that the cabling process caused a major part of the cable degradation and that the alignment of the X, Y, and Z axes with respect to the mandrel is extremely critical. The mandrel should be "fixed" so as to eliminate rotation.

(2) The wire was of inferior quality and did not lend itself to cabling into a high performance cable.

(3) The modifications to NEEW's cabler and set up procedures greatly reduces the cabler caused degradation but in no way is a final solution to the degradation problem.

APPENDIX A

PROPOSED MODIFICATIONS
TO
KRAFT CABLER
AT
NEW ENGLAND ELECTRIC WIRE CORPORATION

Proposed Modifications
to
Kraft Cabler
at
New England Electric Wire Corporation

The following proposed modifications to the Kraft Cabler are intended to assure the quality, consistency, and repeatability of cable manufacture on this machine to both SSC and RHIC specifications.

1) Modify the mandrel clamp so that the mandrel may be located and locked in a predetermined position along the Z axes (longitudinal axis). Locate the mandrel so that the wire/ mandrel tangent angle is the same as at LBL.

2) Fabricate a split bushing, for set-up only, to support and align the mandrel on the machine's centerline. This bushing will be installed in the appropriate Wire Guide Plate and removed after the turkshead has been centered on the mandrel's axis.

3) Add Jack Screws to the Turkshead Support Frame to provide precise adjustment and locking of the turkshead's X-Y axis. A level, or equivalent, is to be used to eliminate any "pitch and roll" of the turkshead assembly.

4) Install a Track Puller between the existing turkshead and capstand. An alternate to this might be the installation of a clutch which allows the pulling of cable by the capstand while the carriage remains stationary. The purpose of this is to permit the taking of "10" Stack Measurement Samples right after the turkshead without "losing" the cable and in so doing, reduce the amount of wire/cable waste.

5) Modify or replace the existing brush oiler with a drip oiler that is equivalent to the one used at LBL.