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Accelerator Development Branch

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Status of Superconductor Development for the SSC Design D Dipole

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June, 1985

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1. Introduction

The development of NbTi superconductor for SSC application is being guided by a task force with representatives from Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley Laboratory and the University of Wisconsin.

The goals of this development are to obtain a high current density, fine filament material in order to achieve a commercially available product capable of operating at the design fields with low magnetization effects. This has developed into a comprehensive program which has yielded encouraging results and has involved R&D on the basic metallurgical characteristics of the production of the NbTi alloy, methods of processing the composite material in order to achieve the necessary filament size and critical current density and development of improved techniques for the measurement of short sample characteristics and magnetization effects. This technical note comprises a group of reports outlining the substantial progress in these areas and the present status of the development program.

2. NbTi Alloy Development

2.1 Recent Improvements and Expectations for the Future

The great increases in current density (and associated improvements in wire piece length and yield) observed in the last two years have their origin in improvements in the quality of the Nb-Ti alloy. A consistent view of the need for improvements in the chemical homogeneity of the alloy came about following the degraded performance of the Nb 43 wt% Ti 25 wt% Ta conductor[1] developed in the 12 Tesla program by a University of Wisconsin - Magnet Corporation of America - General Atomics team.[2] This conductor sausaged badly, had low J_c and broke up unexpectedly. These problems were traced to the presence of large local compositional inhomogeneities (of order 10 - 12 wt% in the Ta and Ti content); concern about this led to a parallel investigation of the standard binary alloy Nb 46.5 wt% Ti, where essentially similar variations were seen.[3]

Informal discussions of these results with Bill McDonald and his group at Teledyne Wah Chang took place during 1981, the work being published during 1983.[3] For these and other reasons Wah Chang instituted a major review of their melting and fabrication procedures, the results of which were felt by all purchasers of their alloy from about 1983 onwards. Many of the technical details associated with the production technology of improved alloy remain proprietary but the quality improvements of the product can be documented.

This progressive improvement in alloy quality has led to the marketing of at least two grades of alloy, with another two grades being identifiable. See Table 2.1-1. Some confusion exists about the exact meaning of these grades, not least because research on the characterization and practical

effect of these grades is still in progress and improvements in the quality of the alloy are still occurring. "Inhomogeneous" material is typical of the material supplied up to about 1982. All of the material supplied for the Fermilab Energy Doubler/Saver (ED/S) probably falls into this category. However, the later material may have been less inhomogeneous than the earlier. "Standard" material is the normal product as presently supplied. "High Homogeneity" (HiHo) alloy is a premium grade used for most of the Wisconsin developments and for the SSC procurements since early 1984. A specially improved alloy ("High Homogeneity Squared" or $HiHo^2$) has recently been developed at Wah Chang and evaluation quantities were sent to Wisconsin during May 1985.[4]

These developments on the part of Wah Chang and its user community have been very rapid. They have been extremely productive for the quality of the composite product, not only in the U.S. but also in Europe and Japan where Wah Chang sells a lot of alloy. (The HERA developments by BBC use their alloy.) However, this rapid progress has exceeded our present ability to accurately delineate the significant chemical differences between the different grades, as well as our understanding of the significance of such chemical differences for the superconducting composite properties. Much of the needed work is in progress; it is clear then that the following comments are subject to revision in the light of later experiments.

A working definition of the difference between "Standard" and "HiHo" alloy has been issued by Wah Chang. This uses flash x-radiography on 6" diameter x 1/4" thick ingot slices cut from selected regions of the ingot after forging from the melt (nominal 20" diameter) to the pre-extrusion size (6" diameter). Freckling and tree rings are permitted in the "Standard"

material; the "HiHo" material must be freckle free.[5] Spatial resolution of the radiograph is of order 1 - 2 mm; the chemical resolution of the radiograph is imprecise but of order 2 - 10 wt%. Flash radiography thus detects inhomogeneities on a rather macroscopic scale in an essentially qualitative manner.

A quantitative characterization of examples of "Standard" and "HiHo" material has been performed by the Wisconsin group, using the electron probe of 6" slices.[6] Examples of the probe results are shown in Fig. 2.1-1. The principal conclusion of this study was that the microscale inhomogeneity was very similar in the two grades, except in regions of freckling. The local composition variations are of order ± 1 wt% for both grades, the overall variations being of order ± 2 wt%. The variations in the vicinity of freckles (found only in the "Standard" grade) were of order 6 - 8 wt%.

Preliminary analysis of "HiHo^2" material suggests that the homogeneity has indeed improved: the wavelength of the chemical composition variation has lengthened by about a factor of 2 or 3. However, the absolute composition variation is about the same as in the "HiHo" material examined by Wisconsin.

The introduction of two grades of alloy by Wah Chang and the small price premium of the "HiHo" grade has met with some objection by the wire fabrication community and there has been a lively discussion of the usefulness of the "HiHo" grade. An evaluation of the critical current density performance of conductors made from different grades is provided in Section 3. It is clear, however, that the <u>idea</u> of the "High Homogeneity" alloy has been vital to the development of high J_c. The advantages remaining to be drawn from further improvements in chemical homogeneity still remain to be established; the programs studying this are in place.

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2. This resulted in a 12 T, 0.5 m bore solenoid fabricated by General Atomics.

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4. These special heats were fabricated by P. M. O'Larey, Wah Chang.

5. "Standards for Homogenized Nb-Ti Alloys", Wah Chang document, August 1984.

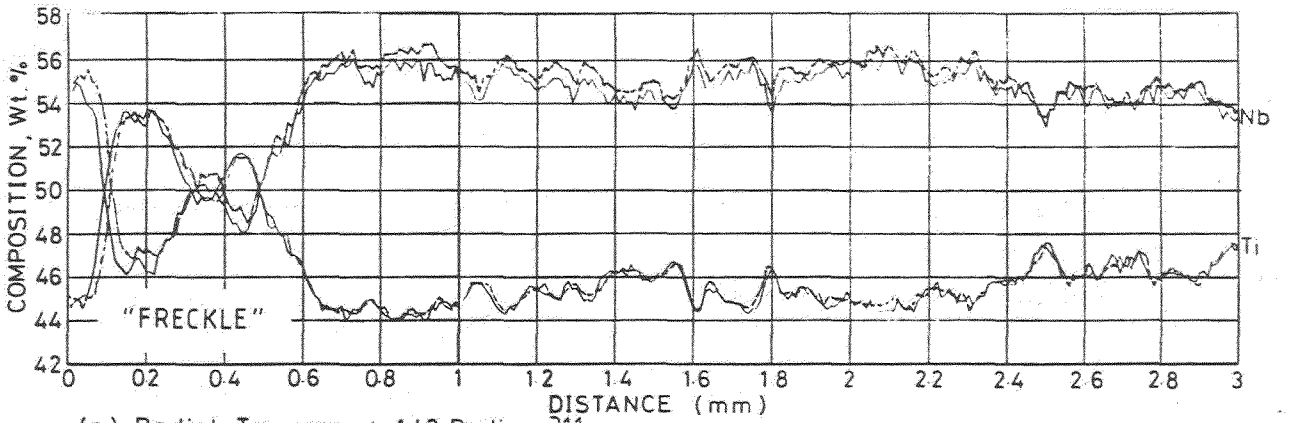
6. P. J. Lee talk to January 1985 Nb-Ti Workshop.

Table 2.1-1. Alloy Grades of NbTi

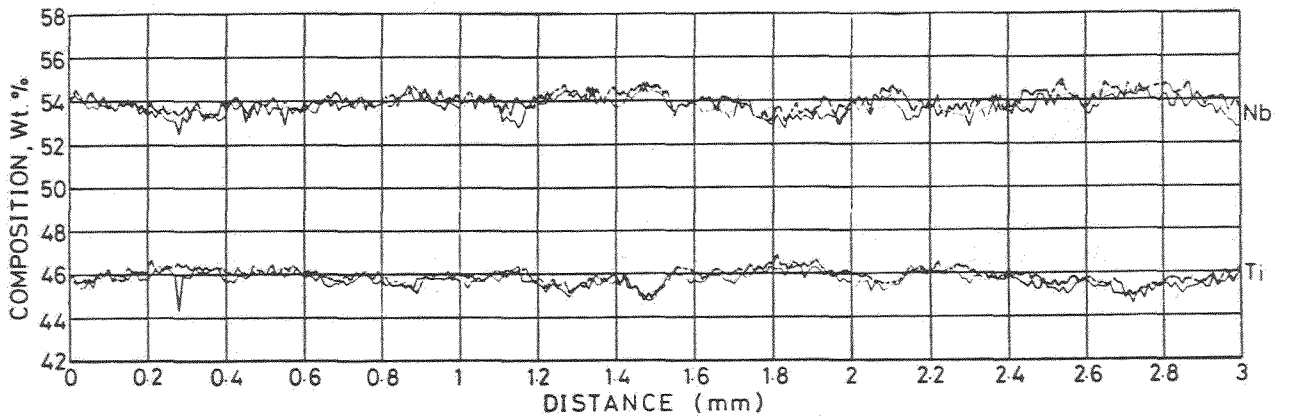
Designation	Vintage	Chemical Characterization	Comments
Inhomogeneous*	Standard quality until about 1982	Local and large scale variations of order ± 5 wt%	No longer made
Standard**	Present	Some freckling permitted: local variations of order ± 2 wt%, larger variation in freckles	Present standard production grade
High Homogeneity** (HiHo)	Present	No freckling: local variations of order ± 2 wt%	Present production grade
Special High Homogeneity* ($HiHo^2$)	Present	No freckling: local variations of order ± 1 wt%	Experimental material

* Informal designation
** Wah Chang designation

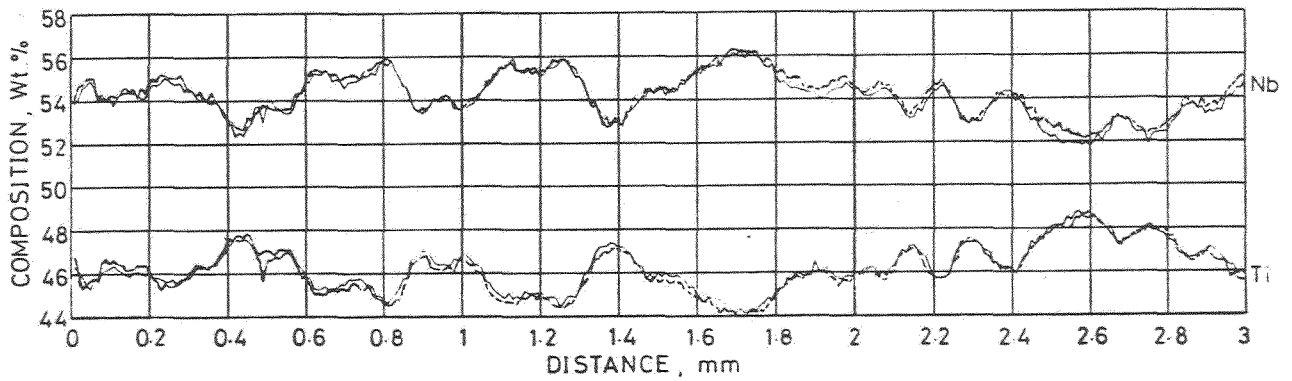
ELECTRON MICROPROBE STUDY OF 311 & 919 ROD



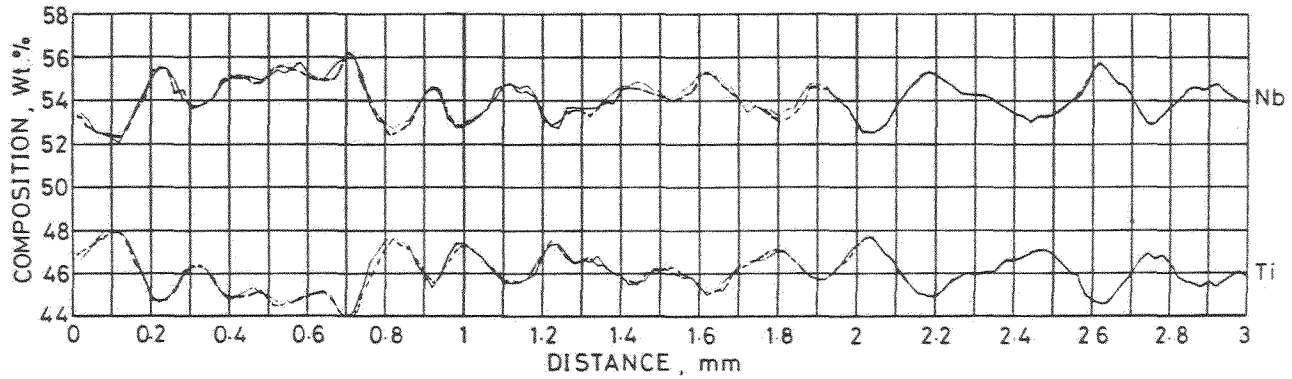
(a) Radial Traverse at 1/3 Radius 311



(b) Radial Traverse at 5/6 Radius 311



(c) Radial Traverse at 2/3 Radius 919



(d) Radial Traverse at 5/6 Radius 919

Fig. 2.1-1. Electron microprobe study of 311 and 919 rod. The rod with 311 identification number is an example of "Standard" material. The 919 rod is "HiHo".

2.2 Metallurgical Characterization of "As-Received" NbTi Rods

In one of the designs for the Superconducting Super Collider dipole magnets the requirements for the superconducting wires (their filament size and critical current densities) are significantly above the wires which are currently available on the market. In order to achieve these goals, development efforts are focused on a number of metallurgical aspects in fabrication of NbTi wires such as compound formation at the NbTi-Cu interface, heat treatment schedule during fabrication, and homogeneity of the starting alloy. Particularly the last property, the improved chemical homogeneity of NbTi in recently fabricated alloy rods, is considered to be one of the important factors in the increased critical current density of recently produced NbTi wires. However, mainly due to the single source for NbTi rods, the homogeneity of the "as-received" rods is solely dependent on the supplier and the manufacturers of NbTi wires have not attempted to develop a quality control program for the "as-received" rods.

Since it appears that the homogeneity of the alloy rods is important in achieving high values of J_c (> 2400 A/mm^2 at 5 T) in fine filamentary (<5μm) wires, a group in the Metallurgy and Materials Science Division at BNL has developed a simple metallurgical technique to distinguish between highly homogeneous and clearly inhomogeneous alloy rods. Similar work has also been done at the University of Wisconsin. In order to do this, a number of NbTi rods were received from the wire manufacturers. These samples are alloys produced during the period of the last four years. The process developed is to simply polish the surface of the rods as is done for a standard metallographic observation and etch with a solution 50 H_2O, 30 HNO_3, 10 HF.

Standard optical microscopy is then used to observe the etched surface. Since this particular etching solution attacks Ti rich regions, various features show up in the photographs depending on the degree of homogeneity of an alloy rod.

In Figs. 2.2-2 and 2.2-3, an example of a NbTi rod with high homogeneity (2.2-2) and one which shows a considerable inhomogeneity (2.2-3) are shown. In Fig. 2.2-2, the only inhomogeneity shown in the picture is very thin regions of (α-Ti) at grain boundaries. This is a Ti rich phase which comes out during the final annealing heat treatment given to the NbTi rods before the wire manufacturers receive them. These small regions of the Ti rich area are thought not to cause any problem in fabrication of high J_c wires. However, for the rod in Fig. 2.2-2, a considerable variation in contrast in the photograph is observed. These variations are due to local variations in the composition of the alloy. These local inhomogeneities originate in the casting of the alloy (nominal 20" diameter) and are sometimes called freckles. The regions are elongated as the rods are reduced in size, and an example of the elongated local inhomogeneity is illustrated in Fig. 2.2-3(b). Thus, it is shown here that if the uniformity of the starting alloy rods is important for the production of wires with highly uniform superconducting properties, the metallographic method is a simple means to examine the "as-received" rods for gross chemical inhomogeneity.

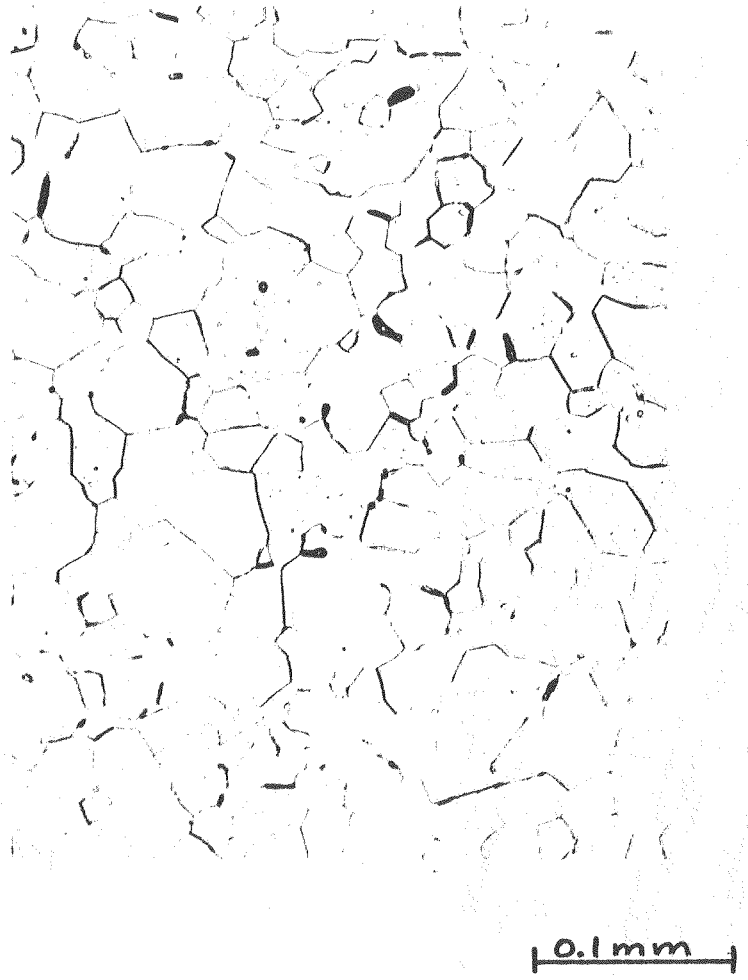


Fig. 2.2-2. An example of a 1/4 inch OD NbTi alloy rod with high homogeneity. This photomicrograph shows a transverse cross section.

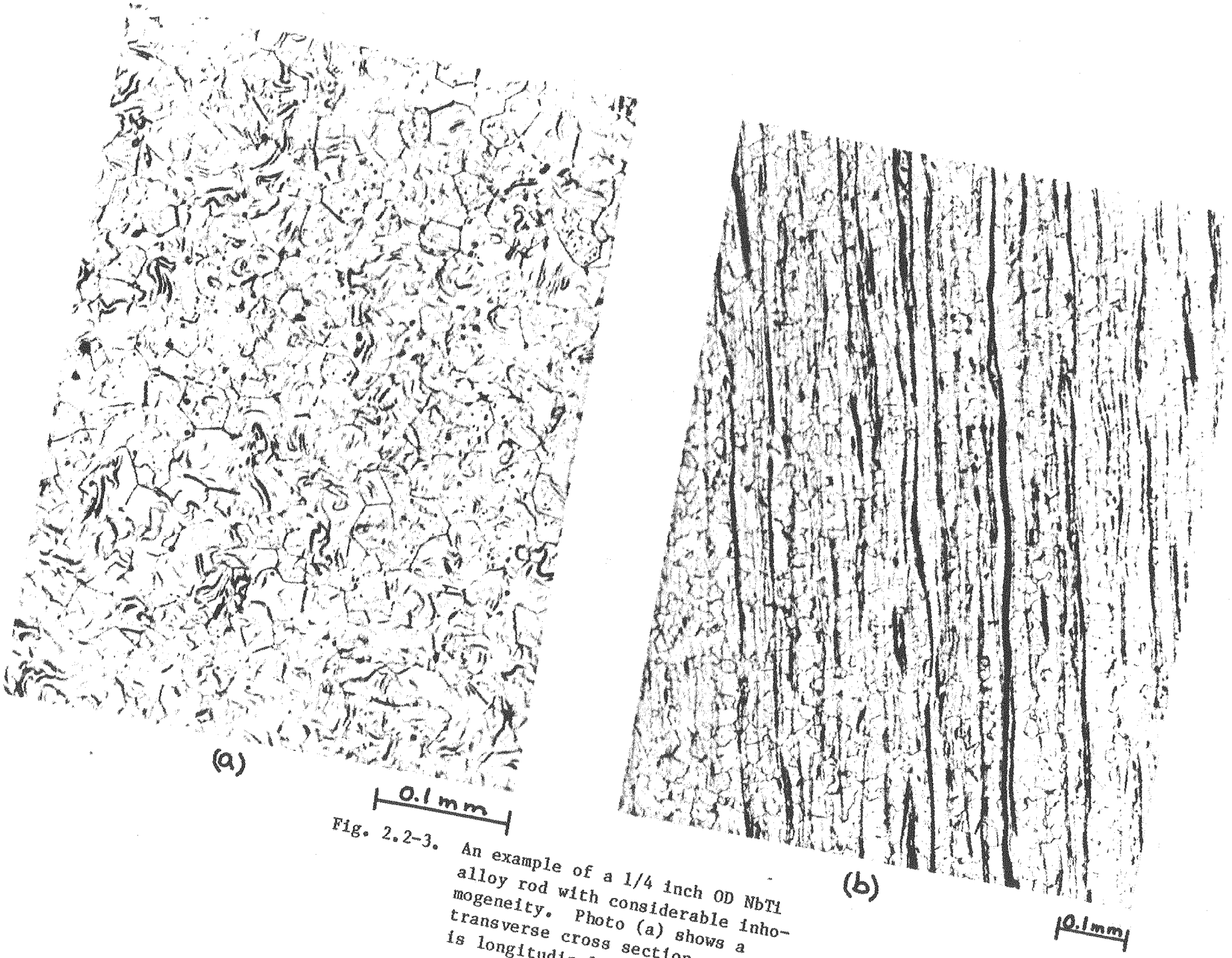


Fig. 2.2-3. An example of a 1/4 inch OD NbTi alloy rod with considerable inhomogeneity. Photo (a) shows a transverse cross section and (b) is longitudinal.

2.3 Plans to Evaluate Sources of NbTi Alloy

Until now all superconducting wire for SSC magnet fabrication has come from one U. S. Company, Teledyne Wah Change located in Albany, Oregon. This is not so surprising since Wah Chang is by far the largest and most experienced manufacturer of this alloy in the world. Furthermore, all studies of heat treatment optimization and fine filament development work have relied on use of the high homogeneity material from Wah Chang.

In spite of the fact that so far all of the alloy procurements have been from one source, there must be an evaluation of others before the SSC Project can begin. Therefore, in the near future plans will be developed to evaluate the performance of superconducting wire with alloy from other vendors. These potential vendors may include:

The Furukawa Electric Co., Ltd.
Tokyo, Japan

W. C. Heraeus GmbH
Hanau, West Germany

Kawecki-Berylco (Division of Cabot Corporation)
Reading, PA., U.S.A.

3. Improvements in Current Density Due to Heat Treatment

Prior to recent studies, the critical current density was regarded as an essentially empirical property, the fabrication processes needed to develop high current density being essentially arcane and secret.[1,2] The availability of homogeneous material transformed the situation, since it provided a reproducible source of raw material suitable for scientific study.

In the two years that such material has been available, the basic qualitative features of the metallurgy of the system have been worked out. Figure 3-1 shows the cross section of an optimized conductor of very high current density. This Transmission Electron Microscope (TEM) cross section shows the great complexity of the microstructure of an optimized conductor and the very fine scale of these microstructures. The crucial features of the microstructure are the elongated and somewhat curved ribbons which appear generally light in cross section. They are separated by a distance of about 20 nm. As may be seen from the inset in the top right-hand side of the figure, this separation corresponds approximately to the equilibrium fluxoid spacing in a field of about 5 T. The relationship of the TEM cross section to the whole composite is also indicated by the reference to the inset at the top left in the figure. Understanding these crucial features of the metallurgy of these composites has been decisive in developing the improved fabrication procedures which are responsible for the large improvements in J_c which have occurred in recent years.[3,4,5]

The base studies of the Wisconsin program to study heat treatment optimization have nearly all been done with a bundled and restacked 361 filament composite designed to reproduce as many features of the full scale production as possible. The principal feature not reproduced in this procedure is

the extrusion process which is always applied in industrial practice. However, the University of Wisconsin procedure was very successful both in increasing the critical current density and in developing a process which was directly transferable to the industrial scale. A major variable of the whole process is the number of heat treatments which can be applied during the fabrication. Important subsidiary variables are the time, the temperature and the spacing the heat treatments and these variables must be chosen so as to optimize the critical current density as well as to be consistent with an industrially feasible fabrication process.

These ideas were first put into industrial practice during 1984 with a 10-inch billet made from the first large scale heat of high homogeneity material in a collaboration organized by Lawrence Berkeley Laboratory (LBL) involving Wisconsin, Wah Chang and Intermagnetics General Corporation (IGC).[6] As a benchmark to show the benefits of the new processing techniques developed at Wisconsin, half of the billet was processed according to conventional practice. The J_c which resulted from this procedure was about 2250 A/mm^2 at 5 T. Using the new three-stage heat treatment, 2650 A/mm^2 was obtained on the industrial scale and 2740 A/mm^2 was obtained in the small lengths drawn in the Wisconsin laboratory. A fourth heat treatment applied at about the first coiling size for composite was successful in raising the J_c to 2850 A/mm^2 (5 T) and 1220 A/mm^2 (8 T). These results are collected in Table 3-1. Since the first billet, some ten further high homogeneity billets (both 10 inches and 12 inches in diameter) been produced for LBL, Fermilab, BNL and TAC. The J_c values have varied from 2500 to 2700 A/mm^2 depending on the final wire size. The yields have been excellent. Early concerns about high J_c material being more brittle have proved groundless. Piece lengths have, in fact, been considerably longer than in the earlier material.

Table 3-1. Current Densities of the First HiHo Billet

Process	Wire Size	J_c Value (10^{-14} Ωm) 5 T	8 T
Industrial Scale			
Conventional	0.805 mm	2280 A/mm^2	930 A/mm^2
	0.645	2365	1015
Three stage HT	0.805	2545	1030
	0.645	2645	1070
Laboratory Scale			
Three stage HT	0.511	2725	1140
Four stage HT	0.511	2850	1220

The influence of alloy homogeneity on J_c has been only partially evaluated at this time. Inhomogeneous material has been shown not to respond well to multiple heat treatments.[3,4,7] For example, a three stage heat treatment applied to inhomogeneous material yielded J_c (5 T) of 2100 A/mm^2 and J_c (8 T) of 760 A/mm^2, whereas identical processing applied to a high homogeneity composite yielded 2590 (5 T) and 1060 A/mm^2 (8 T), respectively.[7] The filament pack of the inhomogeneous composite sausaged, producing an optimization at a lower final drawing strain than is the case for high homogeneity composites.[8]

The practical effect of the differences between the "Standard" and "HiHo" grades is still an open question. Experiments with 1983 vintage examples of these materials were inconclusive, there being little difference between the two.[9] However, the J_c values developed with a three stage heat treatment were all less than 2400 A/mm^2 and the likelihood is that the later alloy has been of better quality. Wah Chang has since made a new set of carefully controlled alloys of "Standard", "HiHo" and "HiHo^2" quality and composites fabricated from these materials are now in process.

An important part of the whole development effort has been the rapid dissemination of results to the U. S. industrial-national lab community. Three workshops have been held, the first of these being in July 1983 at Wisconsin, the second in July 1984 at Wisconsin, the third in January 1985 at Lawrence Berkeley Laboratory and a fourth workshop in July 1985 at Wisconsin. This workshop format has yielded very rapid industrialization of the research

laboratory results. An excellent example of this is provided by the need to obtain high J_c in filaments less than 5 μm in diameter. This need only became apparent during late 1984 and was first discussed before the community at the January 1985 workshop. J_c values greater than about 2600 A/mm^2 in 4 micron filaments and less were demonstrated very quickly by several groups.[10] Within the space of less than four months after the January workshop the basic features of the formation of intermetallic compounds at the filament matrix interface and the relative importance of the extrusion in the in-process heat treatments involved in producing this intermetallic were sketched out.[11,12] A prototype conductor using the diffusion barriers produced by Supercon had achieved a J_c exceeding 2900 A/mm^2 in 3 micron filaments within about the same time frame. These developments are discussed in more detail in Section 5.

An overview of the progress achieved in the last two years is shown in Fig. 3-2. Compared to J_c values of 1800 to 2000 A/mm^2 in the conductors supplied for the Fermilab Energy Doubler/Saver, the first ten production conductors of high homogeneity materials have averaged about 2600 A/mm^2. The best values of J_c obtained so far in any conductor of Nb 46.5 wt% Ti have been obtained in experimental conductors produced at Wisconsin. These J_c values are 3300 A/mm^2 (5 T) and 1290 (8 T). These values compare very favorably to values of 3450 A/mm^2 (5 T) and 1000 A/mm^2 (8 T) obtained in the best Nb 50 wt% conductor by the Baoji Group .[13] Further increases in J_c are foreseen as the work currently in progress comes to fruition.

References

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3. West, A.W., Larbalestier, D.C., "Microstructural changes produced in a multifilamentary Nb-Ti composite by cold work and heat treatment," Metal. Trans. 15A, 843 (1984).

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5. Larbalestier, D.C., "Towards a microstructural description of the superconducting properties," to appear in IEEE Trans. on Magnetics, MAG-121, 257, 1985.

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7. D.C. Larbalestier talk to January 1985 Nb-Ti Workshop.

8. W. Warnes talk to January 1985 Nb-Ti Workshop.

9. D.C. Larbalestier talk to July 1984 Nb-Ti Workshop.

10. Samples produced by MCA, Furukawa, IGC, Supercon and University of Wisconsin-Madison had exceeded this figure in 4 μm filaments and less by April 1985.

11. D.C. Larbalestier, Li Chengren, W. Starch and P.J. Lee, "Limitation of Critical Current Density by Intermetallic Formation in Fine Filament Nb-Ti Superconductors," to appear IEEE Trans. on Nuclear Science, 1985.

12. M. Garber, M. Suenaga, W.B. Sampson and R.L. Sabatini, to appear IEEE Trans. on Nuclear Science, 1985.

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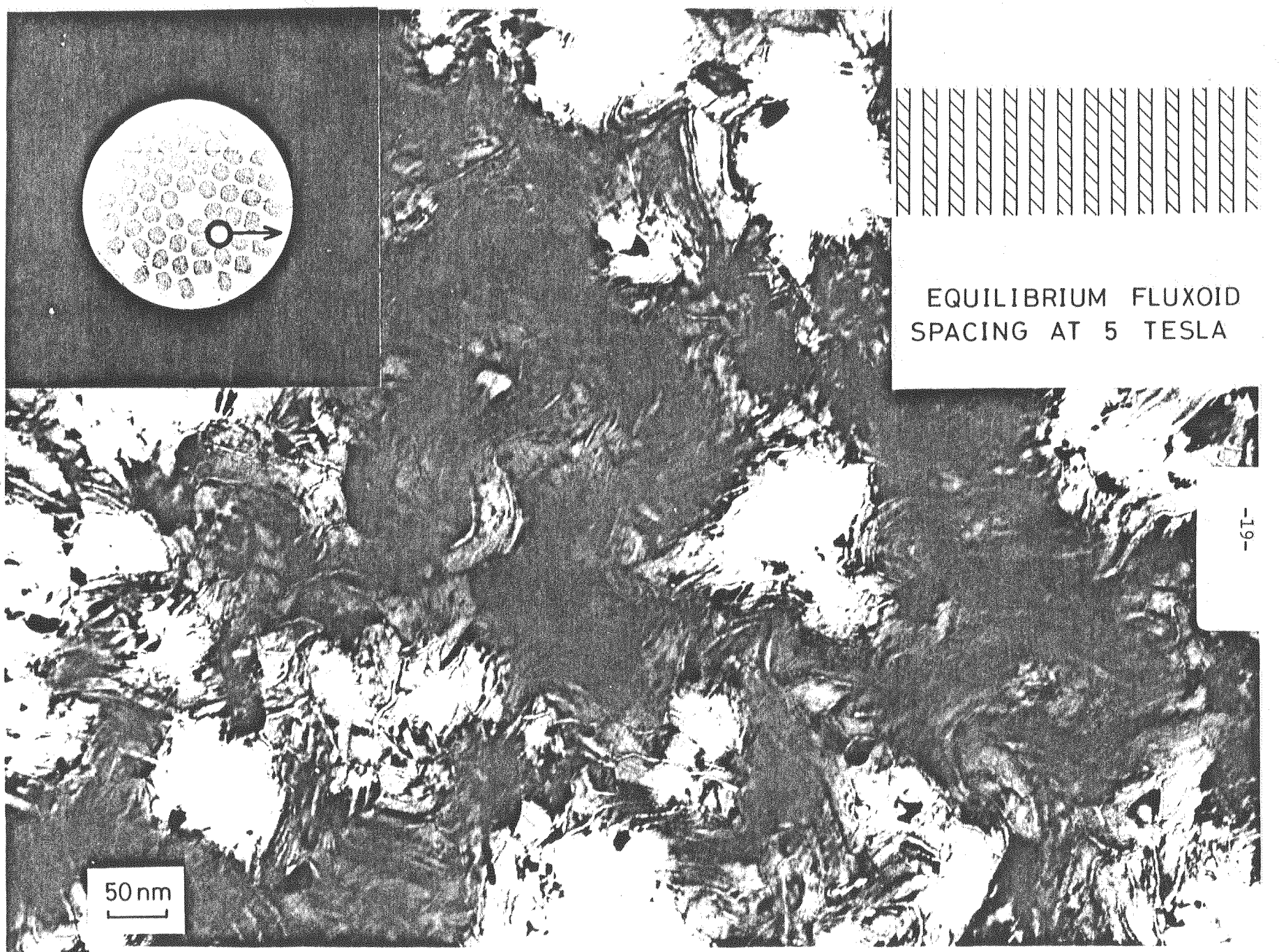


TRANSVERSE MICROGRAPH OF PORTION OF ONE FILAMENT OF NB 46.5 W/O TI COMPOSITE.

Fig. 3-1

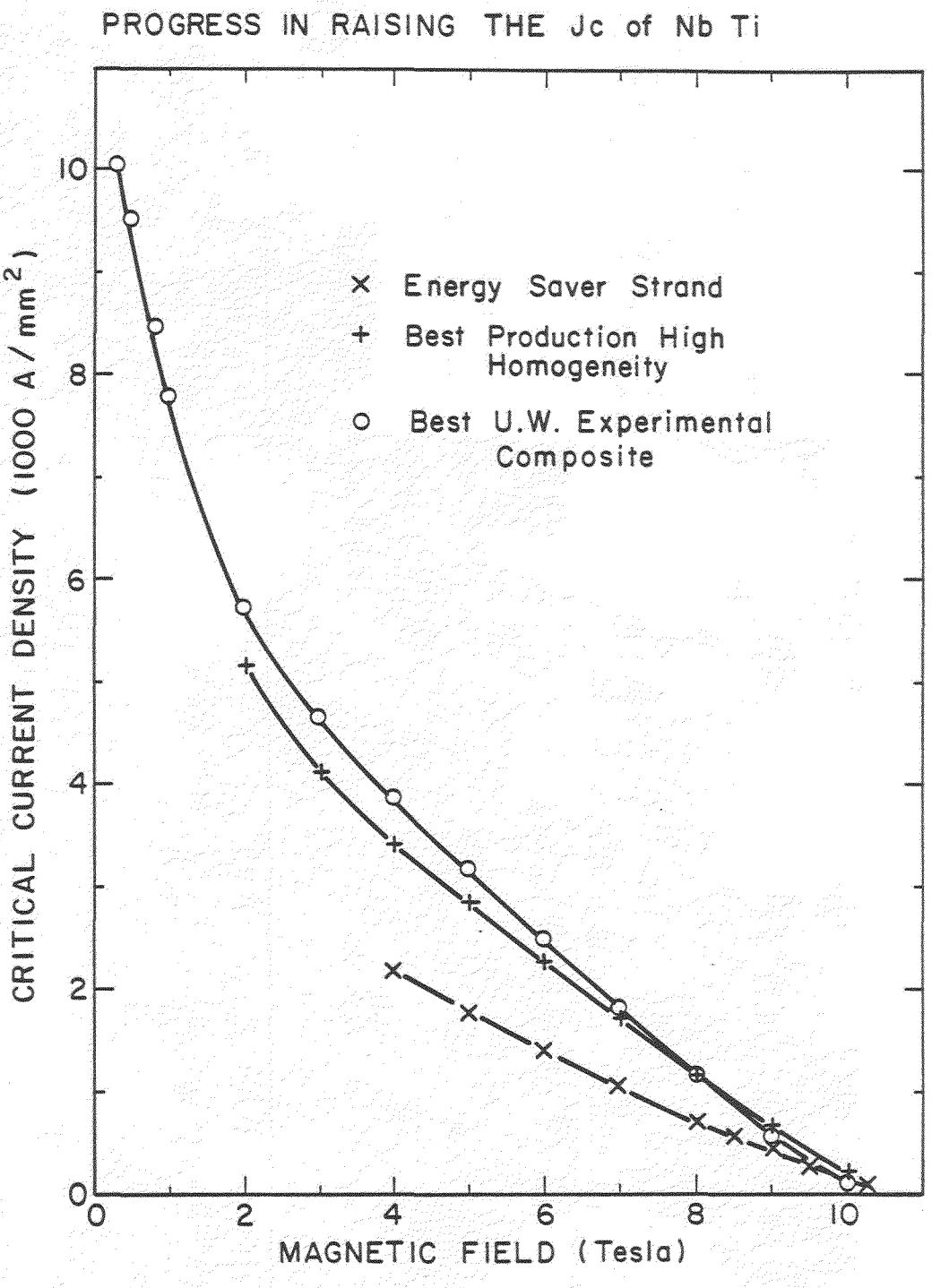

PROGRESS IN RAISING THE Jc of Nb Ti
CRITICAL CURRENT DENSITY (1000 A / mm²)
MAGNETIC FIELD (Tesla)
× Energy Saver Strand
+ Best Production High Homogeneity
○ Best U.W. Experimental Composite
0
2
4
6
8
10

Fig. 3-2

4. Status of Superconductor Procurements

4.1 Introduction

In this section are described the results of superconductor procurements for SSC dipole model magnets. Most results will pertain to LBL procurements for the LBL-BNL collaboration; however, where appropriate reference will be made to material purchased by Fermilab and TAC. Also, most of the results to be presented will relate to the conventional SSC conductors, i.e., with filament sizes in the range of 15-25 μm. Some information on fine filament NbTi material, such as quantities and delivery schedules, will be presented here; fine filament NbTi R&D will be described in Section 5.

4.2 Conventional Conductor Procurements for Model Magnet Fabrication

The "New Era" for high critical current density NbTi was initiated in 1982 with the report by the Baoji group of a J_c = 3900 A/mm^2 at 5T. (Using a more sensitive criterion for J_c, Wisconsin and BNL confirmed a value of about 3450 A/mm^2.) This announcement stimulated a new interest in binary NbTi alloys in the U.S., in particular at the University of Wisconsin. This group made an extensive analysis of conductors being produced in the U.S. and found (1) the composition of the NbTi alloy was quite inhomogeneous, and (2) this lack of homogeneity prevented these alloys from responding effectively to the multiple heat treatments used by the Baoji group.

After a series of discussions with the NbTi alloy manufacturer (Teledyne Wah Chang), a collaborative experiment aimed at testing the ideas from the University of Wisconsin was begun in August, 1983. In this experiment a 10-inch billet (Billet 5183) was ordered by LBL. A special lot of high homogeneity alloy was purchased from Wah Chang and provided to IGC for processing. After extrusion, the material was divided into two lots - one for

processing by IGC using their standard commercial process and the other held until Wisconsin could complete a J_c - optimization study and suggest an alternate treatment. As seen in Table 4.2-1, Billet 5183 processed by conventional techniques produced an improved J_c (about 2300 A/mm^2 compared with about 2000 A/mm^2 for the best Fermilab Energy Doubler/Saver and BNL CBA material.) This result was verified on two additional billets procured by LBL and processed by IGC while the University of Wisconsin staff were completing optimization studies. (See Billets 5198-1 and 5198-2 in Table 4.2-1). Wisconsin recommended a new processing schedule and IGC processed the remainder of Billet 5183 (designated 5183-2) with this schedule. As seen in Table 4.2-1, the J_c values improved significantly (from 2365 A/mm^2 to 2645 A/mm^2 for the .025" diameter strand). Based on these results, LBL ordered two additional billets (5210-1 and -2) and Fermilab ordered five billets (5209-1 through 5) from IGC in July, 1984. This material was delivered in January, 1985; the J_c values in all cases exceeded the specification value of 2400 A/mm^2. The only problem encountered was a switch of extruded rod labels at RMI, the extrusion subcontractor; as a result IGC processed the billets with the University of Wisconsin heat treat schedule, but not at the specified wire sizes.

The final order for material for Design D dipoles was placed in November, 1985, after competitive bidding won by IGC. IGC delivered 820 lbs (Inner) and 830 lbs (Outer) in April, 1985 (see Table 4.2-2); the J_c (5T) values are 2509 A/mm^2 for Inner and 2719 A/mm^2 for Outer layer material. With the exception of Billet 5210-2, all Outer layer material processed with the new heat treatment (3 x 40 hr at 375°C) has a significantly higher J_c

than Inner layer material. The Fermilab material (Billets 5209-1 through 5209-5) is equivalent to Outer layer material and also is consistent with this observation. A possible explanation for this behavior is that the additional cold working after extrusion in the case of the Outer layer material is beneficial in improving the J_c; if true, this result suggests that it may be possible to get somewhat higher J_c values in fine filament conductors which would also contain more cold working.

Another favorable result from these procurements has been the piece lengths compared with Fermilab ED/S experience. A histogram of SSC experience is shown in Fig. 4.2-1. The longer piece length greatly facilitates cabling and also simplifies testing and quality control.

There now exists a substantial data base from these production-size billets (15 billets for a total weight of approximately 5000 lbs, including the Fermilab billets), and several conclusions can be drawn:

(1) The interim SSC specification value for J_c (5T) of 2400 A/mm^2 can be met in industrial scale production. Subsequent procurements can be made with a minimum acceptable value of 2400 A/mm^2 and an incentive payment formula for performance above 2400 A/mm^2.

(2) The specification of high homogeneity NbTi appears to reduce the spread in J_c values (although a more stringent test of this hypothesis will come when more than one manufacturer is in production).

(3) The use of high homogeneity NbTi has resulted in extremely long piece lengths.

Table 4.2-1

CHARACTERISTICS AND PERFORMANCE OF WIRE PROCURED FOR SSC

Billet Designation (Cu/SC Ratio	Strand Diameter	J_c Value $10^{-14}\Omega\cdot m$ 5T	8T	Intermediate Heat Treatment	Final Heat Treatment
5183 - 1	.0318"	2280	930	IGC	IGC
(Cu/SC = 1.36/1)	.0250"	2365	1015		
5198 - 1	.0318"	2238	885	IGC	IGC
(Cu/SC = 1.35/1)					
5198 - 2	.0250	2273	880	IGC	IGC
(Cu/SC = 2.05/1)					
5183 - 2	.0318"	2545	1030	U. of Wisc.	260°C
	.0250"	2645	1070	(3 x 40 hr	
(Cu/SC - 1.36/1)				at 375°C)	
5210 - 1	.0318"	2505	1034	*	260°C
(Cu/SC = 1.25/1)					
5210 - 2	.0255"	2435	1070	*	260°C
(Cu/SC = 1.80/1)					
5212 -3	.0255"	2719	1146	U. of Wisc.	260°C
(Cu/SC = 1.77:1					
5212 -1	.0318"	2509	1083	U.of Wisc.	260°C
(Cu/SC = 1.28:1)					

* U. Wisc. heat treatment with slight variation.

Table 4.2-2.

STATUS REPORT ON SSC SUPERCONDUCTOR INVENTORY AND PROCUREMENTS FOR DESIGN D MODELS

Designation	Weight (LBS)	Strand Length (FT)	Cable Length and Designation	Status	Comments
Billet 5210-1 (Inner Cable)	426	160,617	4160 FT (XT12-2317)	Used in SLN-008,009,011	Strand J_c (5T) = 2505 A/mm^2
			2200 FT (XT14-2317)	Used in SLN-010,011	
Billet 5212-1 (Inner Cable)	Approx. 420	Approx. 160,000	Approx. 7,000 FT	Strand Complete 4-15-85. On hold at LBL awaiting firm schedule for additional model magnets.	Strand J_c (5T) = 2509 A/mm^2
Billet 5212-2 (Inner Cable)	Approx. 420	Approx. 160,000	3,200 FT (XT20-2317)	Used in SLN-010.	
			2400 FT (SC301) 1200 FT	Used in C6,7,8,9	
Billet XXXX (Inner Cable)	Approx. 200	Approx. 80,000	Approx. 3,500 FT	In process at Supercon. held at 1.0" diameter.	Material ordered by TAC. Conductor <u>could</u> be used in Design D magnets, but actual use has not been determined at this time.

Key: 4.5 m Design "D" Dipole Requires 1020 FT Inner, 1260 FT Outer

16.6 m Design "D" Dipole Requires 3550 FT Inner, 4420 Outer

Table 4.2-2 (continued)

STATUS REPORT ON SSC SUPERCONDUCTOR INVENTORY AND PROCUREMENTS FOR DESIGN D MODELS

Designation	Weight (LBS)	Strand Length (FT)	Cable Length and Designation	Status	Comments
Billet 5210-2 (Outer Cable)	Approx. 426	Approx. 241,145	4400 FT (XT13-3012)	Used in SNL-008,009,010,011	Strand J_c (5T) = 2435 A/mm^2
			1000 FT (SC #293)	Used in C2,3,4	
			1200 FT (SC #295)	367 FT sent to FNAL.	
				Used in models.	
Billet 5212-3 (Outer Cable)	Approx. 800	Approx. 452,854	2656 FT (XT15-3012) 2656 FT (XT19-3012) 2650 FT (XT21-3012) 1200 FT (SC302)	Used in SLN-010,011	Strand J_c (5T) = 2719 A/mm^2
			Approx. 4,600 FT	Strand Complete 4-15-85. Remainder held as strand at LBL awaiting firm schedule for additional model magnets.	
Billet 5209-4 5209-5B (Outer Cable)	Approx. 1305	Approx. 739,000	Approx. 24,000 FT	On hold at IGC at .460" diameter.	Fermi order.
Billet 5209-5A 5209-1B (Outer Cable)	Approx. 650 200 lbs	Approx. 350,000	Approx. 11,687 FT	On hold at IGC as .0255" diameter strand Used by BNL on July run at NEEW	Fermi Order. Strand J_c = 2500-2700 A/mm^2 at final size.

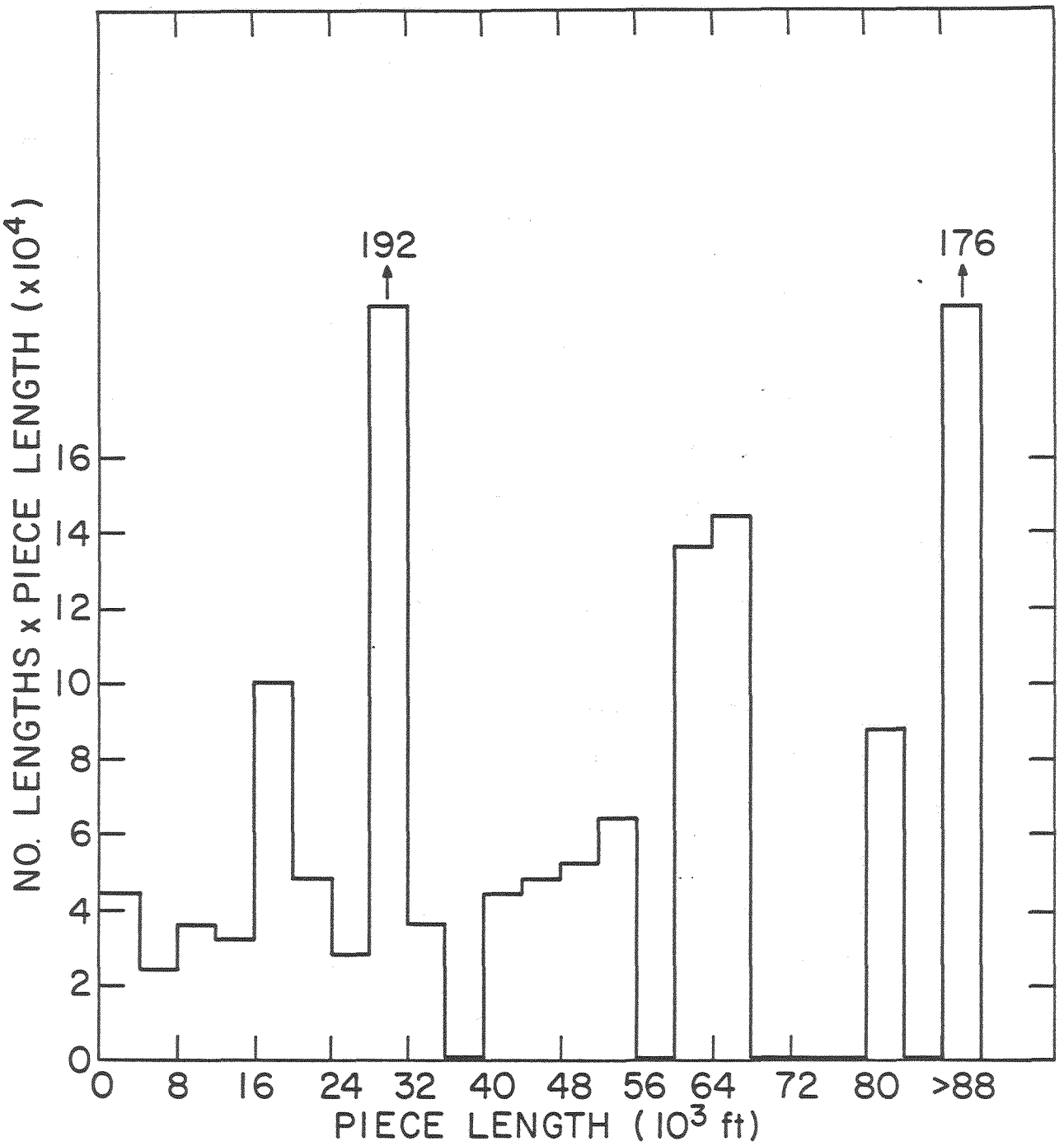


Fig. 4.2-1. Histogram of Wire Piece Lengths Produced for SSC.

4.3 Fine Filament Conductor Procurements for Model Magnet Fabrication

Figures 5.4-12 and 5.4-13 in Section 5.4 show transverse sections of the conventional SSC Inner and Outer superconductor. The pictures in the lower right are scanning electron micrographs of filaments extracted from the composites. The particles imbedded in the surface of the filaments are brittle intermetallic compounds formed during extrusion and intermediate heat treatments. (See Section 3). As these micrographs indicate, this compound formation does not seriously affect the performance of filaments in this size range (15-25 μm). However, these particles do not co-reduce and hence seriously degrade the filament integrity and J_c when these wires are drawn to fine diameters (Section 5). Therefore, if one desires fine filaments, the composite must be designed and processed with this in mind.

Several billets have been designed to yield fine filaments and are currently being processed. In addition to developing processes for fabricating fine filament NbTi and providing an economic analysis of the process, both IGC and Supercon are each providing enough fine filament material for a 16.6-m model SSC magnet (see Table 4.3-3). IGC will provide material with 2.5 μm diam. filaments in the appropriate wire sizes; the yield should be sufficient for one 16.6-m model to be built at BNL and several 1-m models to be built at LBL. Supercon will provide 400 lbs of material which can be processed to .0318" diam. wire (8 μm filaments) or .010" diam. wire (2.7 μm filaments) for use in an Inner layer 2-level cable; both options presently are being evaluated. In Phase II, Supercon will prepare 400 lbs of Outer layer material with 4,000 filaments (6 μm filament size at final wire size) or 2 μm filaments in an Outer layer 2-level cable.

Again, Phase I and II material will be sufficient for one 16.6-m dipole and several 1-m dipoles. The billets being prepared at LBL for hydrostatic extrusion will provide material for several additional 1-m model dipoles.

Recently, BNL issued an order to Oxford Superconducting Technology (OST) for enough material with a 5 μm filament size to build one additional 16.6-m model (see Table 4.3-3). Thus, material presently being procured will provide for the construction of three 16.6-m dipoles and at least six 1-m dipoles. From the standpoint of cable availability, dipole magnet construction could start as early as January, 1986.

Table 4.3-3
NbTi Superconductor R&D and Procurements for
SSC Reference Design D Dipole Magnets

Project Phase	Conductor Description	Billet Size & Cu:SC Ratio	Final Wire Size & Filament Size	Preliminary Results (J_c@ 5T)	Expected Quantity	Expected Delivery
Intermagnetics General Corporation, Waterbury, CT.						
Internal R&D	single extrusion of 1953 filaments with diff. barrier	3.5" dia. billet 1.4:1	0.011" wire 4.3 μm filaments	2835 A/mm^2	-	Completed
Phase I	double extrusion of 7 x 858 filaments with diff. barrier	6" dia. billet 1.8:1	0.0255" wire 5 μm filaments	2450 A/mm^2	100 lbs.	Aug. 1985
Phase II	double extrusion of 19 x 2400 fil. with diff. barrier	10" dia. billet 1.3:1	0.0318" wire 2.5 μm filaments	-	400 lbs. for inner coils	Dec. 1985
	double extrusion of 19 x 1260 fil. with diff. barrier	10" dia. billet 1.8:1	0.0255" wire 2.5 μm filaments	-	400 lbs. for outer coils	Dec. 1985
Supercon Inc., Shrewsbury, MA						
Internal R&D	single extrusion of 127 filaments with diff. barrier	2 " dia. billet 0.75:1	0.002" wire 3 μm filaments	2950 A/mm^2	-	Completed
Phase I	single extrusion of 4400 filaments with diff. barrier	12" dia. billet 1.3:1	0.0318" wire 8 μm filaments or 0.010" wire 2.7 μm filaments in cable-of-cables	2950 A/mm^2 (0.013" wire)	400 lbs. for inner coils	Nov. 1985
Phase II	single extrusion of 4200 filaments with diff. barrier	12" dia. billet 1.8:1	0.0255" 6 μm filaments or 0.009" wire 2 μm filaments in cable-of-cables	-	400 lbs. for outer coils	Nov. 1985

Table 4.3-3 (continued)
NbTi Superconductor R&D and Procurements for
SSC Reference Design D Dipole Magnets
(continued)

Project Phase	Conductor Description	Billet Size & Cu:SC Ratio	Final Wire Size & Filament Size	Preliminary Results (J_c@5 T)	Expected Quantity	Expected Delivery
Lawrence Berkeley Laboratory						
	hydrostat. extrude 19 x 2000 filaments w/o diff. barrier	6.5" dia. billet 1.3:1	0.0318" wire 2.7 μm filament	-	200 lbs. for inner coils	Nov. 1985
	hydrostat. extrude 19 x 1000 fil. w/o diff. barrier	6.5" dia. billet 1.8:1	0.0255" wire 2.7 μm filaments	-	200 lbs. for outer coils	Nov. 1985
	hydrostat. extrude 19 x 1000 fil. with diff. barrier	6.5" dia. billet 1.8:1	0.0255" wire 2.7 μm filaments	-	100 lbs. for outer coils	Nov. 1985
Oxford Superconducting Technology, Carteret, N.J.						
RFQ for completed cable	double extrusion of 55 x 211 fil. with diff. barrier	11" dia. billet 1.3:1	0.0318" wire 5 μm filaments	-	340 lbs. for inner coils	Jan. 1986
	double extrusion of 55 x 108 fil. with diff. barrier	11" dia. billet 1.8:1	0.0255" wire 5 μm filaments	-	370 lbs. for outer coils	Jan. 1986
Requirements for magnet construction						
	Inner Coils	1.3:1	0.0318" wire	1m-long models: 16.6 m-long magnets:	13 lbs. 220 lbs.	
	Outer Coils	1.8:1	0.0255" wire	1 m-long models: 16.6 m-long magnets:	15 lbs. 240 lbs.	

4.4 Development of a Specification for Reference Design D Superconducting Wire and Cable

The attachment to this report is a copy of the latest specification for superconducting wire for the Design D dipole. In some sense this is a universal SSC specification because it has been used also by the proponents of Reference Design C magnets at TAC. It should be noted in that document that the specified parameters are underlined; they may change with subsequent procurements. Definitions and measurement techniques for each parameter are also given in either the specification itself or its appendix. The specification for superconducting wire has received the critical comments of members of the Superconductor Working Group.

In the near future when there is more experience with the testing of Design D magents and with fabrication of cable for them, a specification will be prepared for the completed bare cable conductor. Appropriate parts of the wire specification will be included in it. In the long range, procurements for SSC conductor will be for completed cable with the vendors responsible for all cable mechanical and electrical properties.

5. Fine Filament R&D

5.1 Introduction to the Associated Problems

Conventional production of NbTi superconductor consists of hot extrusion (at 500-600°C) of NbTi rods in a copper matrix. During this extrusion and the prior heating of the billet, a layer of titanium-copper intermetallic compound perhaps 1-2μm thick can form around the filaments. This brittle intermetallic layer does not co-reduce and thus can become nearly equal to the filament diameter at final wire size; this results in extensive filament breakage and sometimes strand breakage. This problem can be eliminated by enclosing the NbTi rods at extrusion size in a barrier material, such as Nb or Ta, which prevents the titanium-copper formation.[1] This barrier need be only be 0.1 to 0.2 mm thick, and will be reduced to an insignificant fraction of the filament cross section at final filament size.

Another problem can arise from the introduction of foreign particles during the billet preparation operations. Any "dirt" consisting of micron size particles or any inclusions of this size in the NbTi rods or the copper components can result in filament breakage at the final wire size. This type of problem is insidious since processing may proceed successfully until the final wire size is approached. Also, the size of inclusion which is tolerable depends upon the desired filament size, e.g., a one micron diameter inclusion is acceptable for a 20 micron filament, but not for a 2 micron filament. This problem can be eliminated by careful selection of raw materials and by clean room practice in billet assembly.

When a large number of rods are stacked in a billet, as is necessary to achieve fine filaments, a large void fraction is present and this can lead to

non-uniform reduction in the extrusion step. The filaments are necked down locally and this also leads to filament breakage. This problem can be eliminated by compacting the billet before extrusion.

When these potential problems are eliminated by proper processing and quality control, there is no metallurgical reason why a J_c value of greater than 2400 A/mm^2 cannot be achieved in filaments less than 2.0 μm in diameter. In fact, the increased total reduction in area of the NbTi filaments may mean that it is possible to introduce more heat treat/cold work cycles and hence raise the value of J_c.

1. P. Dubots et. al., Proc. ICEC 8, 505(1980).

5.2 Studies of Intermetallic Formation on Filaments

At BNL groups in the Metallurgy and Materials Science Division and the Superconducting Materials R&D Section of the Magnet Division have collaborated on a study of intermetallic formation on filaments.[1] Their studies originated from a wish to understand the variations in performance of a large number of superconducting wire samples produced for the CBA Project at BNL. The basis for their study is given in Fig. 5.2-1 where about 250 wire samples are shown with a histogram of J_c (5T) values and a scatter plot of I_c (5T) vs. quality factor, n. Detailed metallurgical analysis was then done of wire samples with low J_c ($\approx$ 1400 A/mm^2) and those with higher values ($\approx$ 2200 A/mm^2). Scanning electron microscope (SEM) photos of these are shown in Figures 5.2-2 and 5.2-3. The conclusions reached in this study indicated that in low-J_c wire there was evidence for necking or sausaging of the filaments and the occurrence of numerous particles or nodules. Chemical analysis of the particles showed the presence of Cu and Ti in the ratio of 4:1 with a small amount of Nb. It is believed, therefore, that the particles are Cu_4Ti compound produced during extrusion or major heat treatments. The study also showed that drawing down the wires (or filaments) to sizes where the harder particles formed a large fraction of the filament diameter produced a sizable reduction in J_c from original values. Wires without particle formation did not show this degradation.

Related studies have been done by the Applied Superconductivity Center at the University of Wisconsin-Madison.[2] One recent experiment there used an industrially extruded composite from Billet 5183 which has been used extensively for studies of heat treatment optimization. (See Section 4.2.)

Previous heat treatments had been based on filament sizes of about 20 μm. For this new experiment a similar heat treatment schedule was applied to reduced wire sizes, of approximately 9-10 μm. Whereas a larger number of heat treatments improved the current density performance of wire with 20 μm filaments, an increase in the number of heat treatment steps for wire with 9-10 μm filaments produced much lower J_c values. The results are summarized in Table 5.2-1. These degraded J_c values are consistent with an increase in filament sausaging brought about due to the formation of Cu-Ti intermetallic compounds. Figures 5.2-4 through 5.2-6 illustrate through photomicrographs and SEM photos the cases of 20 μm filaments without sausaging and typical 9 μm filaments with this effect.

Results at Wisconsin show that intermetallic compound formation occurs primarily during the extrusion process. However, another experiment was done to look at intermetallic formation only from heat treatment. In this experiment a laboratory billet was formed and reduced without extrusion. The only subsequent heat treatments were for the purpose of optimizing J_c. Table 5.2-2 summarizes the J_c performance for various composites with different filament diameters and heat treatments. The basic conclusion reached in this experiment is that intermetallic compound formation capable of producing sausaging in small filaments can be produced during the required heat treatment steps, independent of hot extrusion. Photos also illustrating the results are shown in Figures 5.2-7 through 5.2-9. These conclusions show

the importance of developing a reliable, cost-effective diffusion barrier technology to prevent the intermetallic formation under any processing conditions.

1. M. Garber, M. Suenaga, W. B. Sampson and R. L. Sabatini, "Effect of Cu_4Ti Compound Formation on the Characteristics of NbTi Accelerator Magnet Wire", to appear in IEEE Trans. on Nuclear Science, 1985.

2. D. C. Larbalestier, Li Chengren, W. Starch and P. J. Lee, "Limitation of Critical Current Density by Intermetallic Formation in Fine Filament NbTi Superconductors", to appear in IEEE Trans. on Nuclear Science, 1985.

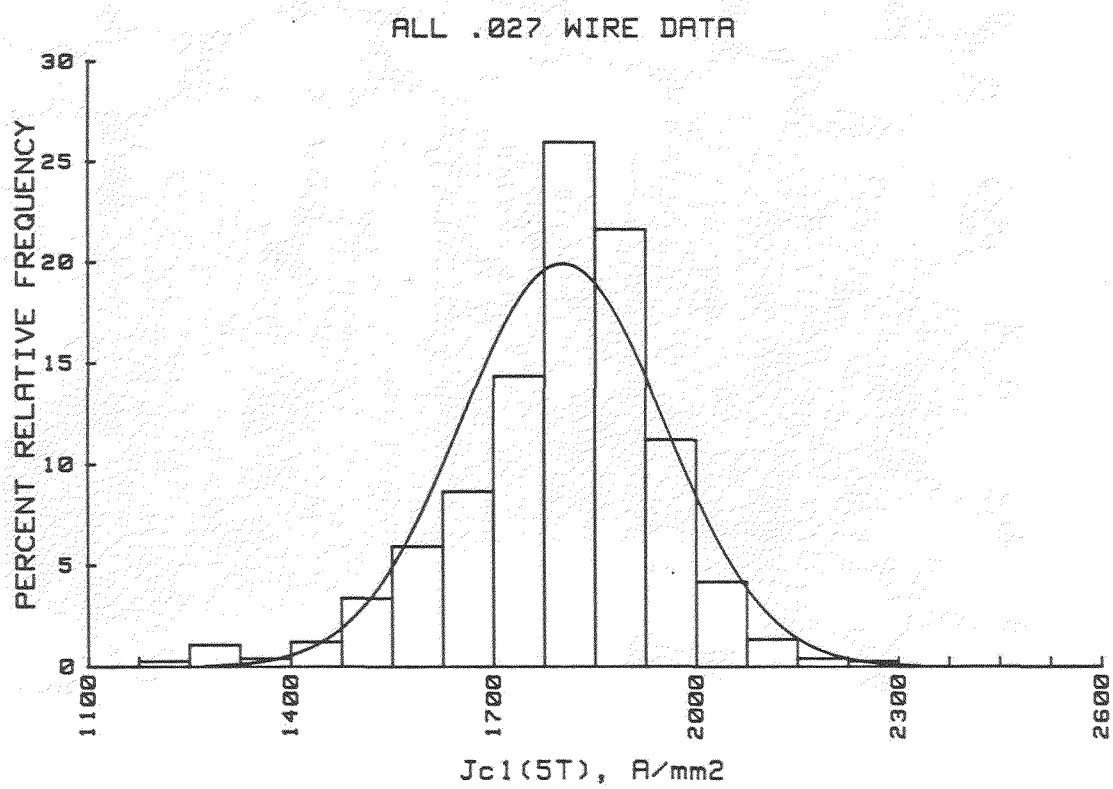
Table 5.2-1. Effect of number of heat treatments of 40 hrs/390 C on the J_c of an industrially extruded composite.

# of H.T.	Fil. dia µm	J_c (5T) A/mm^2	J_c (8T) A/mm^2
3	9	2410	1050
4	10	2410	1020
	9	2215	975
5	10	1965	810
	9	1760	740
6	10	1865	680
	9	1665	620

Table 5.2-2 Effect of heat treatment time and number on the J_c of a laboratory produced composite having no extrusion step.

Composite	Filament µm	Heat treatment schedule	J_c (5T) A/mm^2	J_c (8T) A/mm^2
CB1210	21	6 x 10 hrs	2705	1145
CB1710	4.0		2640	1080
	3.2		2265	995
CB1230	19	6 x 40 hrs	3190	1135
CB1730	5.3		1920	--
	3.2		1320	510
CB1233	5.3	9 x 40 hrs	1590	1020
	4.5		935	324

Note: all H.T. were at 375°C.



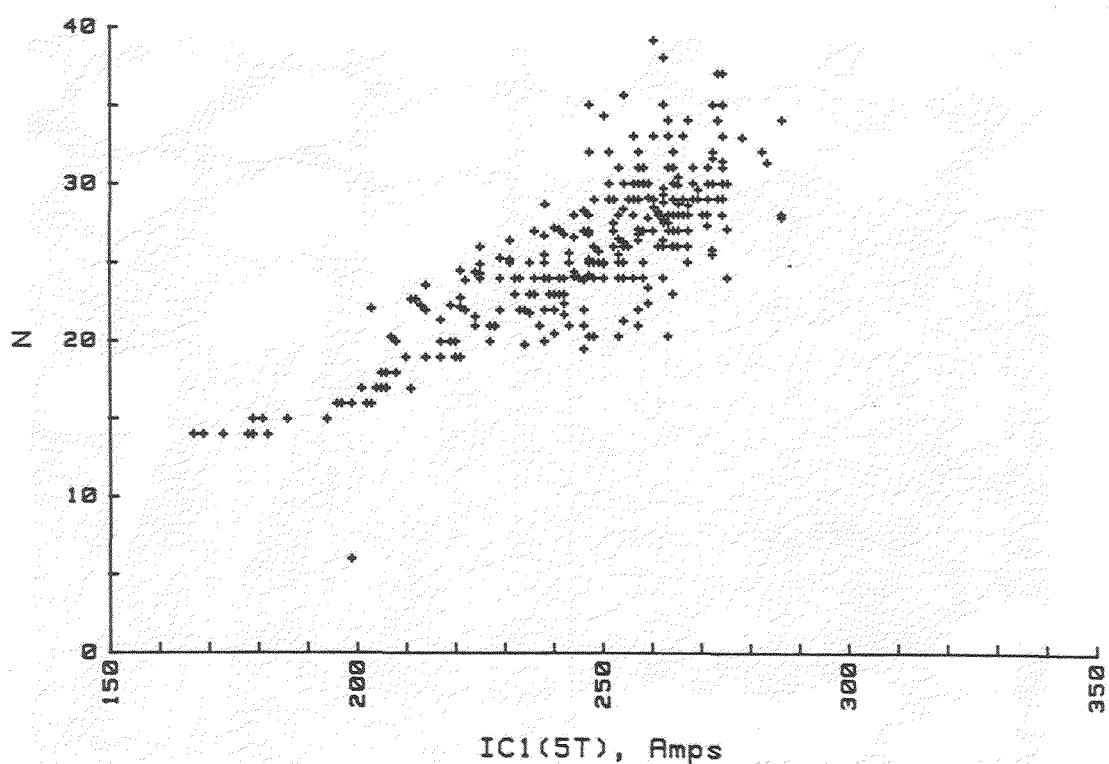
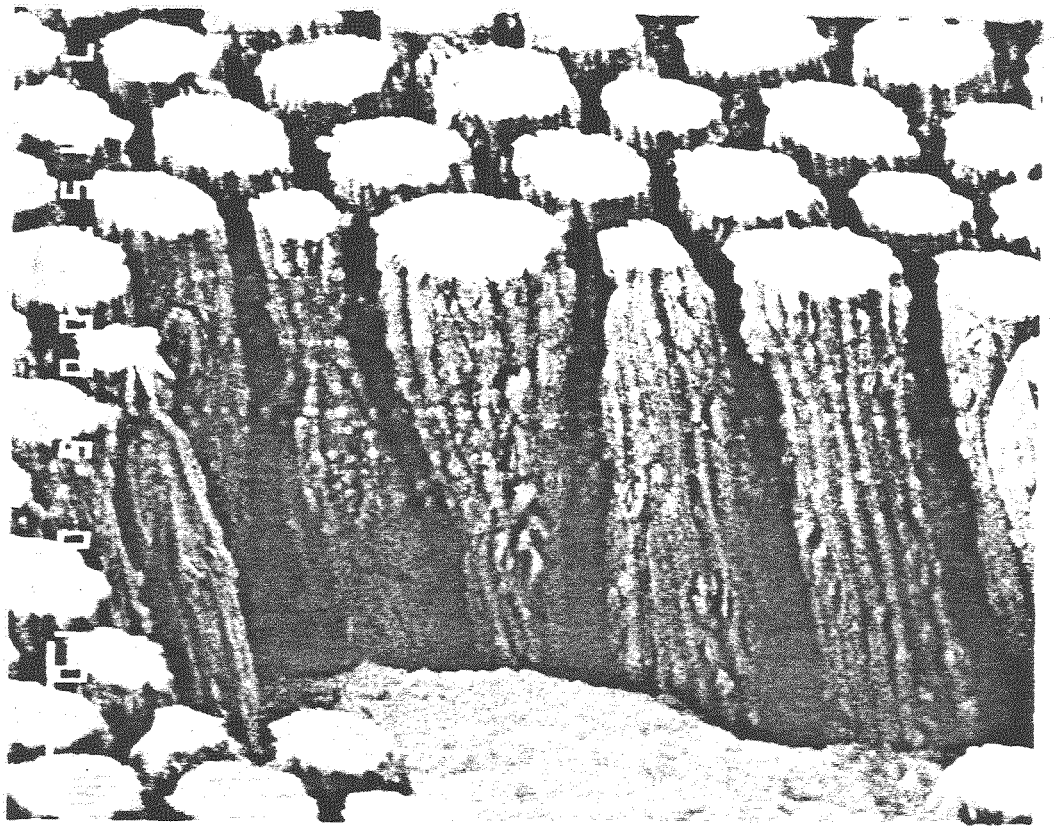


Fig. 5.2-1. Short sample results for CBA wires.



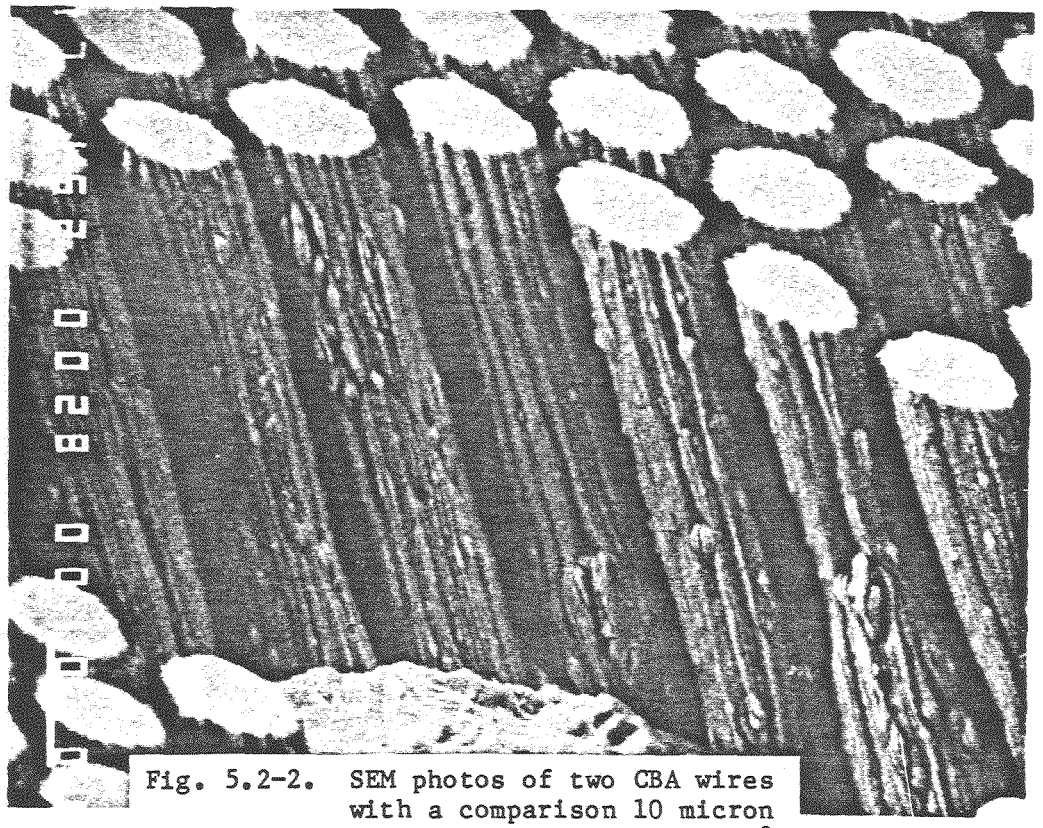


Fig. 5.2-2. SEM photos of two CBA wires with a comparison 10 micron scale. Top J_c = 1400 A/mm^2, n = 19; bottom J_c = 2200 A/mm^2, n = 35

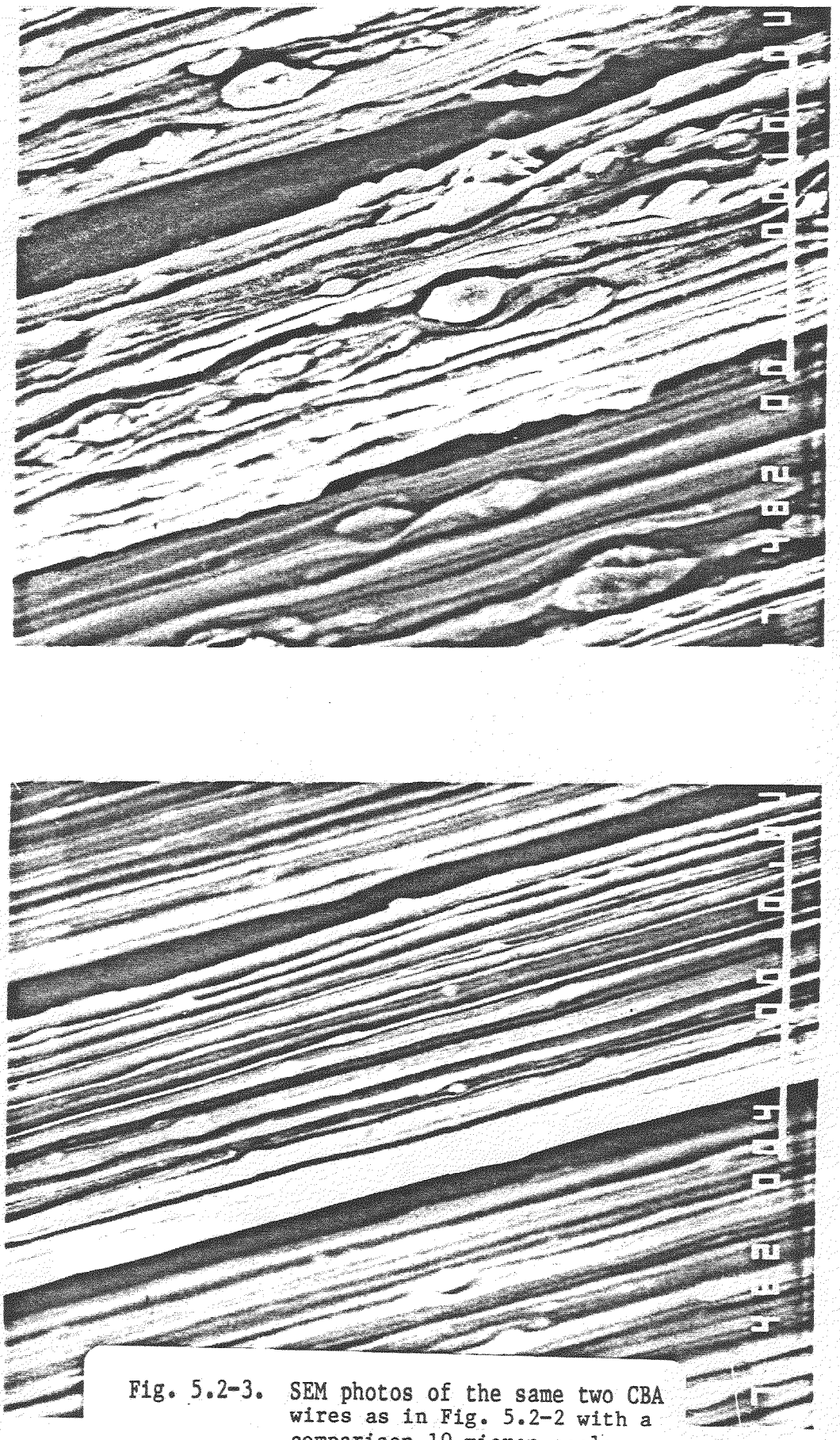


Fig. 5.2-3. SEM photos of the same two CBA wires as in Fig. 5.2-2 with a comparison 10 micron scale. Top J_c = 1400 A/mm^2, n = 19 bottom J_c = 2200 A/mm^2, n = 35.

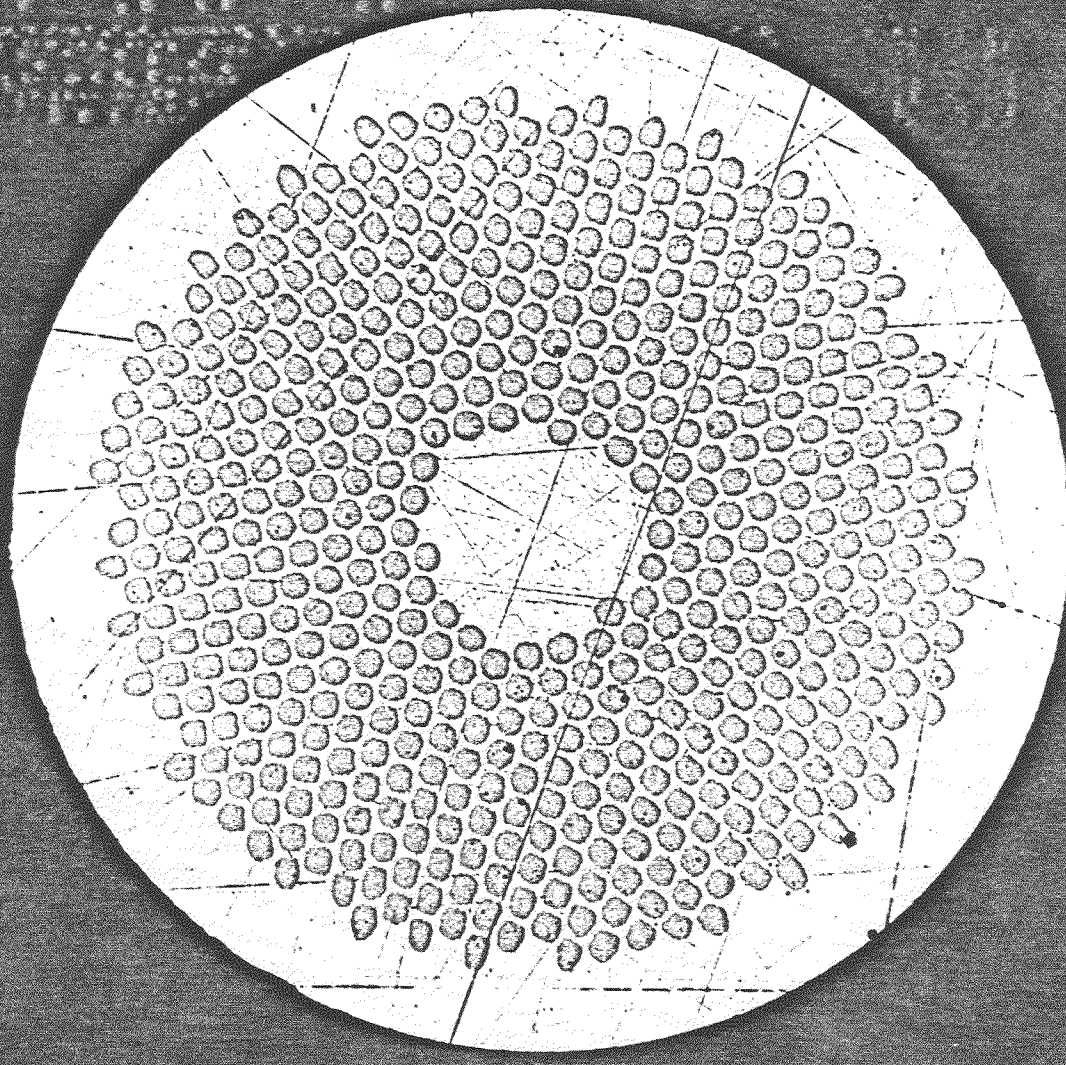


Fig. 5.2-4. Cross section of Billet 5183 composite. J_c at 5T = 2725 A/mm^2 with a 20 μm filament diameter. The rather uniform cross section of the filaments is evident.

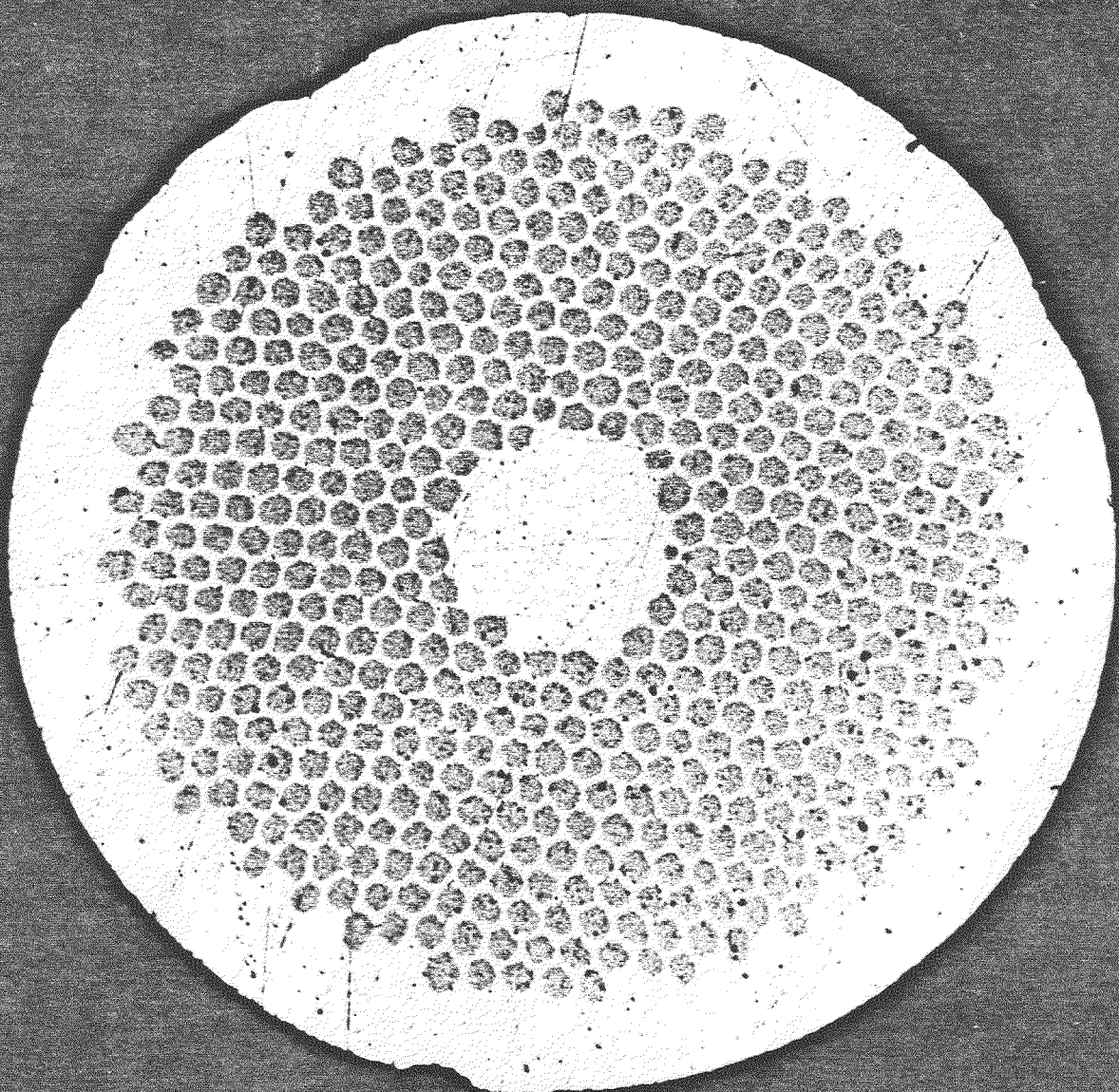


Fig. 5.2-5. Cross section of sausaged low J_c composite from Billet 5183 with 6 heat treatments. J_c at 5T = 1665 A/mm^2 at 9 μm filament diameter.

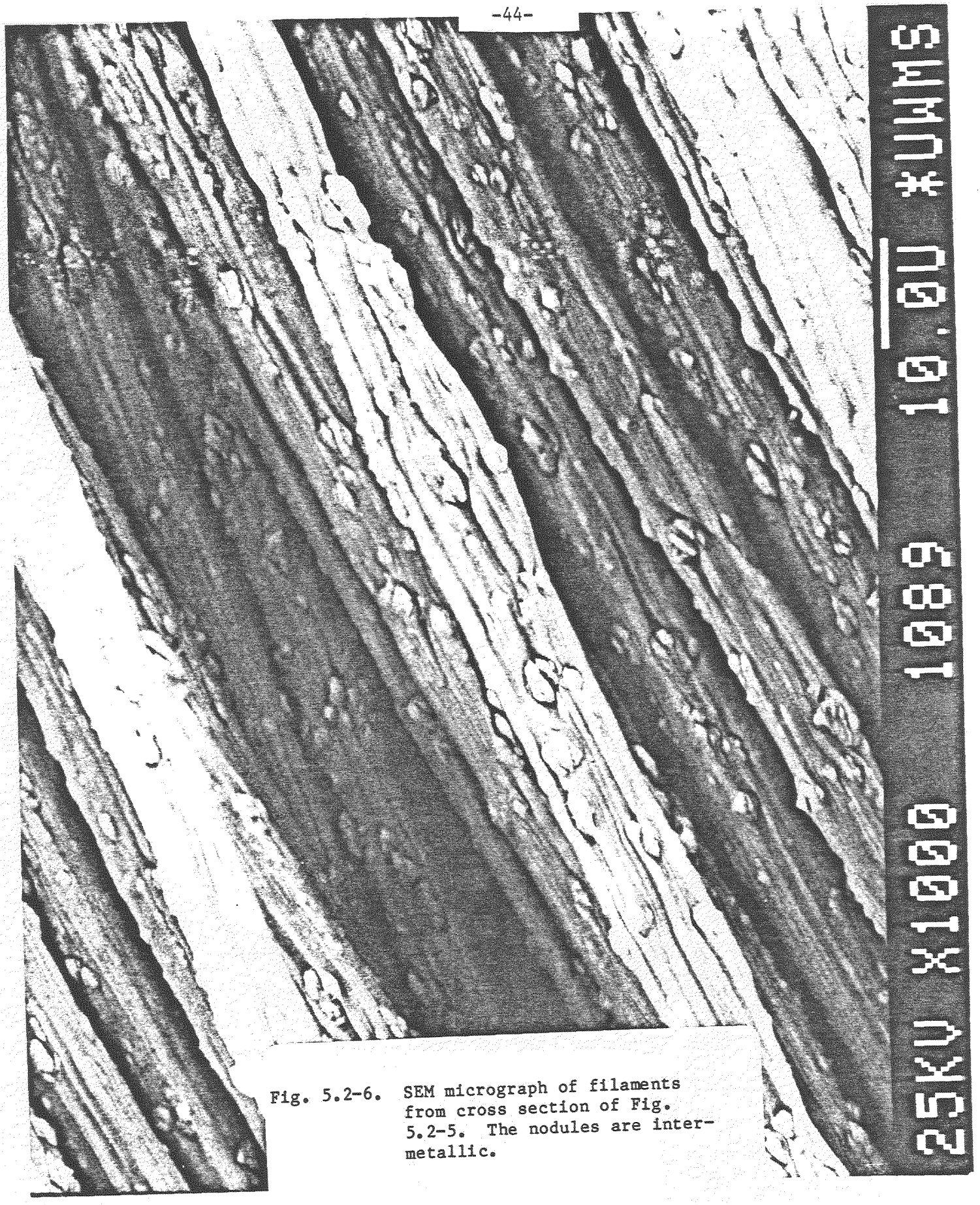


Fig. 5.2-6. SEM micrograph of filaments from cross section of Fig. 5.2-5. The nodules are intermetallic.

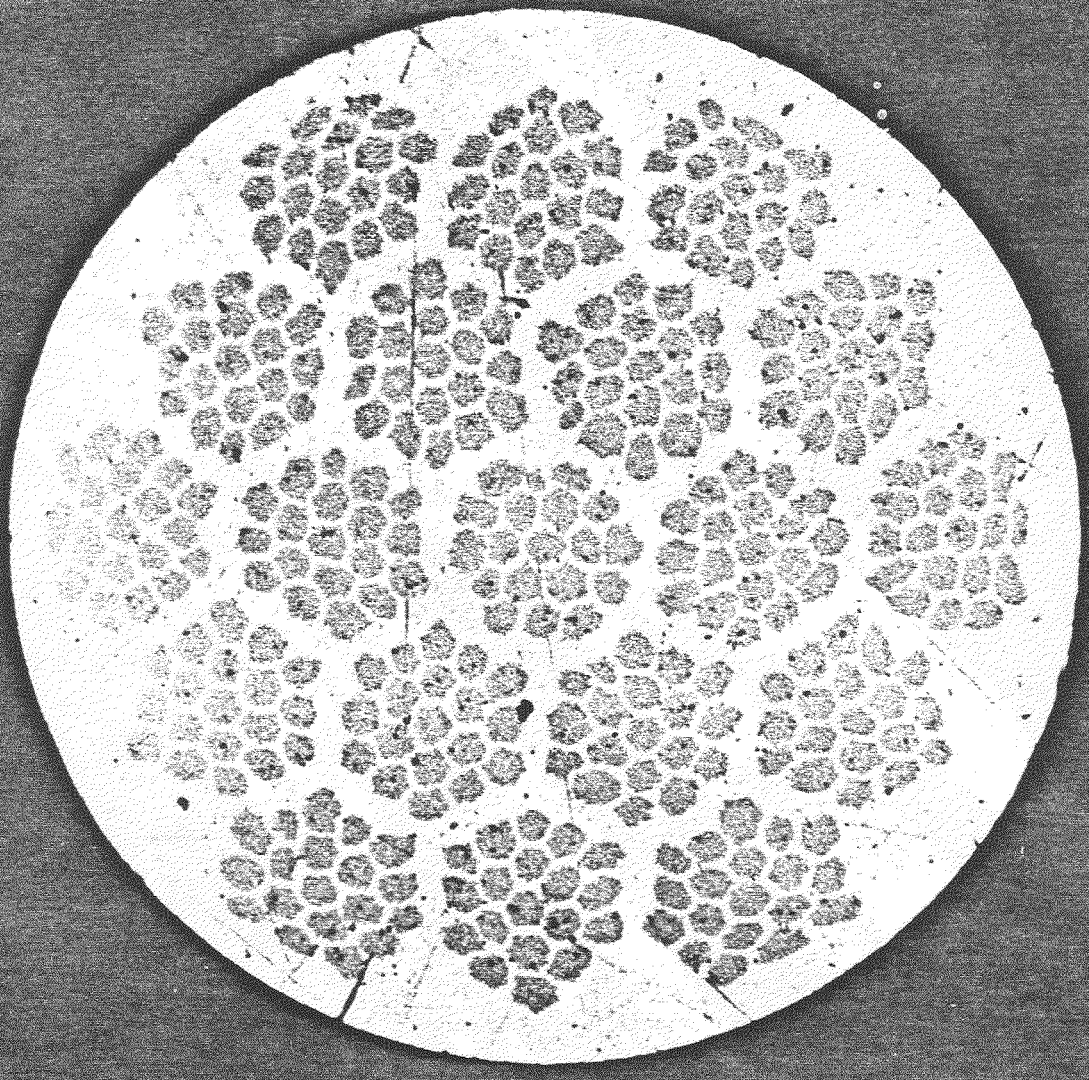


Fig. 5.2-7 Cross section of badly sausaged Billet CB1233 at 4.5 μm filament diameter. Note the non-uniform cross sections. J_c (5T) = 1590 A/mm^2.

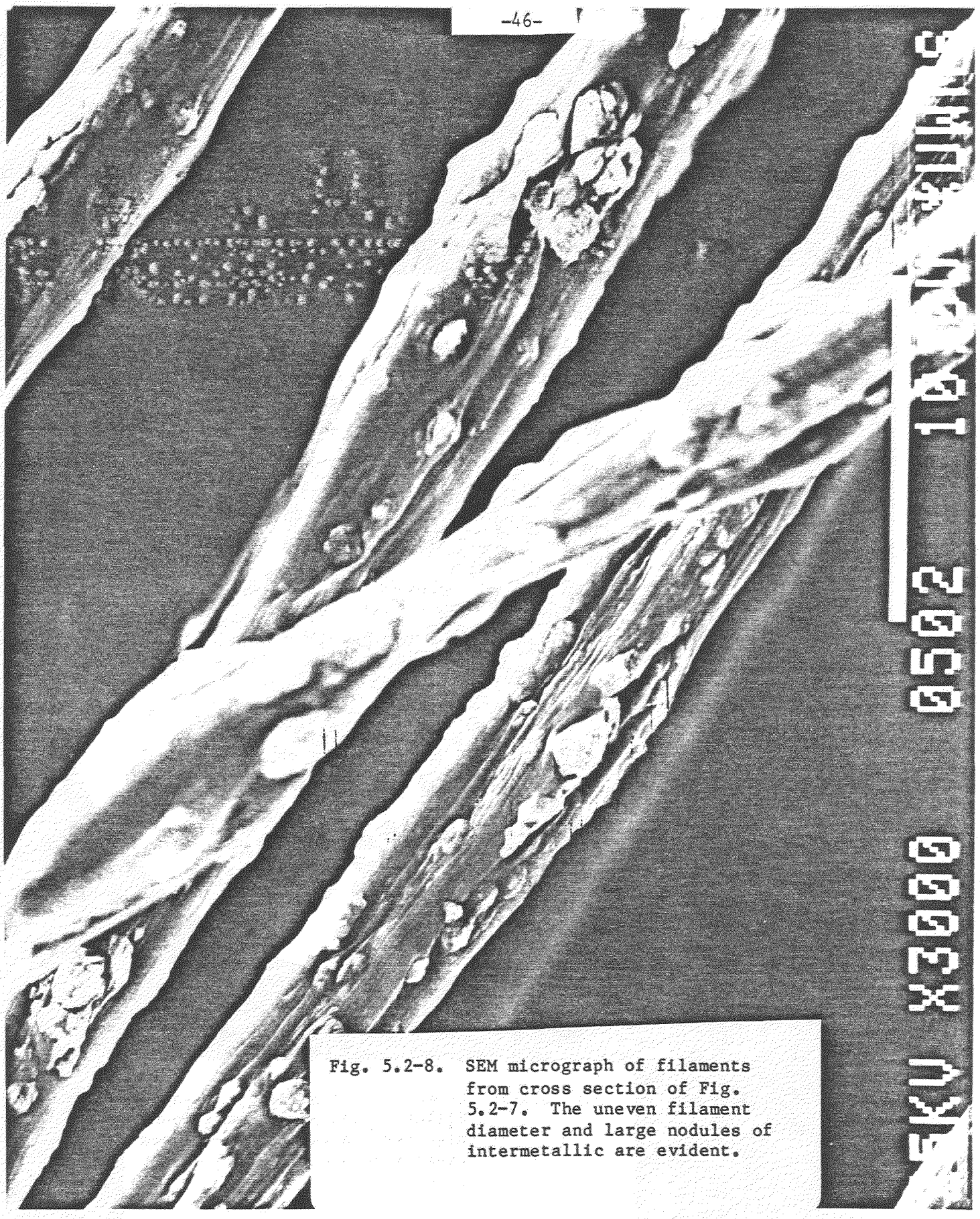


Fig. 5.2-8. SEM micrograph of filaments from cross section of Fig. 5.2-7. The uneven filament diameter and large nodules of intermetallic are evident.

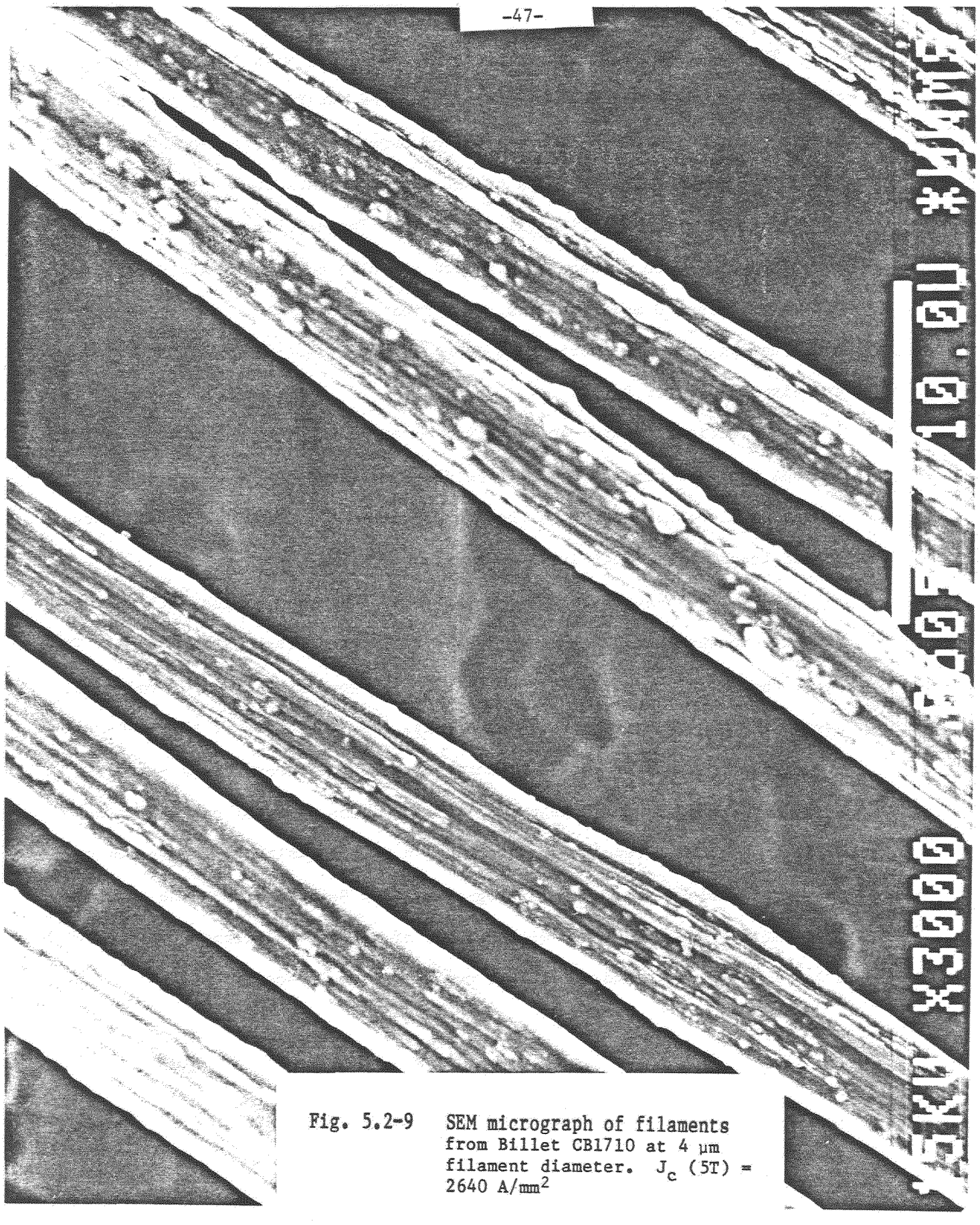


Fig. 5.2-9 SEM micrograph of filaments from Billet CB1710 at 4 μm filament diameter. J_c (5T) = 2640 A/mm^2

5.3 Summary of DOE-funded R&D

The potential problems of producing NbTi wire with fine filaments and the proposed solutions were discussed with the superconducting material manufacturers between December, 1983 and August, 1984. In September, 1984, both IGC and Supercon responded to LBL with proposals to investigate the production of high- J_c, fine filament NbTi. The deliverable items include material with which J_c can be optimized and also can be used to construct Reference Design D model magnets. The final reports will include an economic analysis of the fabrication methods. Some details of these projects are listed in Table 4.3-3.

A practical problem to be solved in producing fine filament NbTi for the SSC Design D configuration is to devise a method of stacking a large number of elements to produce the end product. (See Fig. 5.3-10.) There are at least three promising approaches.

First, one can stack a large number of rods in a single billet, and this is the approach being investigated by Supercon (see Table 4.3-3). To date, they have stacked a 12-inch billet with approximately 4000 rods and have completed the extrusion successfully. Small amounts of this material are being processed to .0318" diameter wire (8μm filament size) and .010" diameter wire (2.7 μm filament size). A decision on final configuration will be made after results are complete on this optimization study and on two-level cable experiments in progress. (See Section 6.3.) The second phase of the Supercon study will consist of another 12" diameter billet with a 1.8:1 Cu:SC ratio and a filament number yet to be specified.

IGC proposed to investigate a double extrusion approach as well as a large stack approach. LBL agreed to fund the double extrusion approach and IGC elected to proceed in parallel with the single stack approach using their internal funding. In the LBL-funded program, (see Table 4.3-3) IGC has completed both Phase I extrusion (an initial 6" diameter billet with 7 NbTi rods and a second 6" billet with 7 x 858 NbTi filaments). Approximately 100 lbs of this material was drawn to final wire size in August, 1985, and will be cabled in order to produce samples for I_c and magnetization measurements. IGC is proceeding with Phase II and has procured the raw material for two 10-inch first stage billets. Material from these billets will then be restacked to produce a 10-inch billet of Inner layer and a 10-inch billet of Outer layer material. This wire should be ready for cabling in December, 1985. If this phase is successful, there will be enough cable for one 16.6-m model dipole and several 1-m models.

A promising alternative to the use of conventional hot extrusion with diffusion barriers is cold hydrostatic extrusion. Production-size hydrostatic presses providing extrusion services are available in Europe (but not in the U.S.), and the costs are competitive with conventional extrusion. The maximum billet diameter is 6.5", but billets to 62" long can be extruded. (See Table 5.3-3 for complete list of parameters available at LDM in Holland; similar services are available at National Standard in Scotland.) Hence, one can process approximately the same weight of material using hydrostatic extrusion as can be produced from a 10" diameter conventional extrusion. However, the yield of useful material can be much higher in the hydrostatic extrusion case because of reduced end losses. This factor is especially important in a double extrusion process.

In order to evaluate, both technically and economically, the potential of hydrostatic extrusion for producing fine filament NbTi, LBL personnel are assembling three billets for hydrostatic extrusion (see Table 4.3-3). The elements for stacking the first two billets are being prepared at LBL using a bundle and draw approach. NbTi rods are clad with Cu, then 19 of these rods are loaded into another Cu tube, drawn and bundled to form the billet stacking elements. The billets will be sent to National Standard for extrusion and then returned to the U. S. where they will be drawn to wire. (See schedule in Fig. 5.3-11.) An additional billet will be prepared using excess first stage material from IGC (Phase I); this will provide some material containing diffusion barriers for comparison with the other two billets.

At the conclusion of this R&D phase in November, 1985, there will be a data base on both cost and technical feasibility of various fine filament options. This will allow the SSC management to evaluate the fine filament option and to begin incorporating fine filament NbTi into the SSC long range plan.

Table 5.3-3. Lists of parameters available for hydrostatic extrusion at at LDM in Holland.

LDM
DATA SHEET

-Hydrostatic extrusion press.

Type	ASEA QEN 40
Press force	40 MN

-Container

Max. pressure	1400 MPa
Max. operating pressure	1300 MPa
Length	1600 mm

-Billet dimensions

Billet diameter	ø 160 mm or ø 80 mm
Billet length	400 mm 850 mm
and	1200 mm
Tube extrusion billet	790 mm -----

Other billet dimensions on request

-Extrusion data

Extrusion ratios at room temp: 10 : 1 up to 25 : 1
at elev. temp: 40 : 1 up to 600 : 1

Ram speed (16 steps)	from 0,0014 to 0,023 m/s.
Ram diameter	ø 180 mm
Produkt diameter max.	ø 60 mm
Adiabatic temp. rise of produkt	~0,25° C/MPa
Incl. extrusion die angle	40° up to 110°
Incl. billet cone angle	Incl. extrusion die angle minus 6°-10°
Billet nose diam.	Rod diam. minus 1 mm
Time for press adaptation	~30 minutes : to special tooling
Inert gas-protection	: N2

Direct watercooling of product

Optional: coiling of product : ~ 1000 to 1500 mm.

Number of extrusions/per hour depending on:

- -number of extrusions per order
- -warm or cold extrusion
- -specific product experience
- -Billet heating rate °C/min
- -extrusion speed selection
- -data collection
- -special lubrication requirements
- -product cooling rate
- -sampling procedures

Billet Heating Equipment

-ASEA fully controllable medium frequency billet-heater
-Dimension : ø 170 length 2400 mm.
Electric data: 600 kW 470 Hz.

-Smit Net frequency billet-heater (step-control)
Dimension ø 165 length 1317 mm.
Electric data: 540 kW 50 Hz.

Rod drawing equipment

-Chain drawbench: 400 KN length 30 m.
Ranging from 48 mm, inlet diameter down to 10 mm
-Vertical Bull Block: 180 KN Drum diam. 2130 mm
Ranging from 33 mm inlet diam. down to 3,5 mm
-Horizontal Bull Block 45 KN Drum diam. 915 mm
Ranging from 15 mm inlet diam. down to 2 mm.

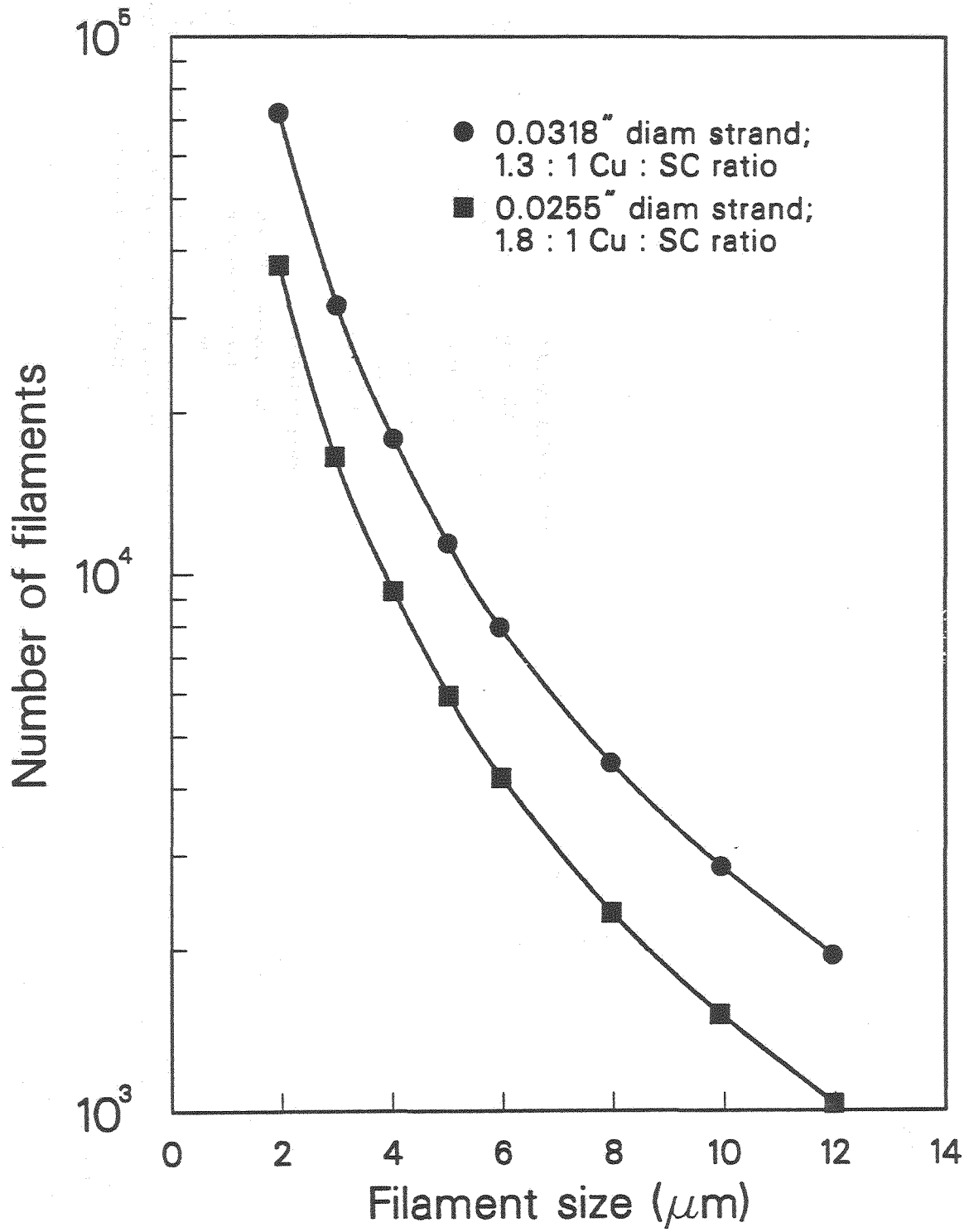


Fig. 5.3-10 Number of filaments required for SSC Reference Design D Conductor.

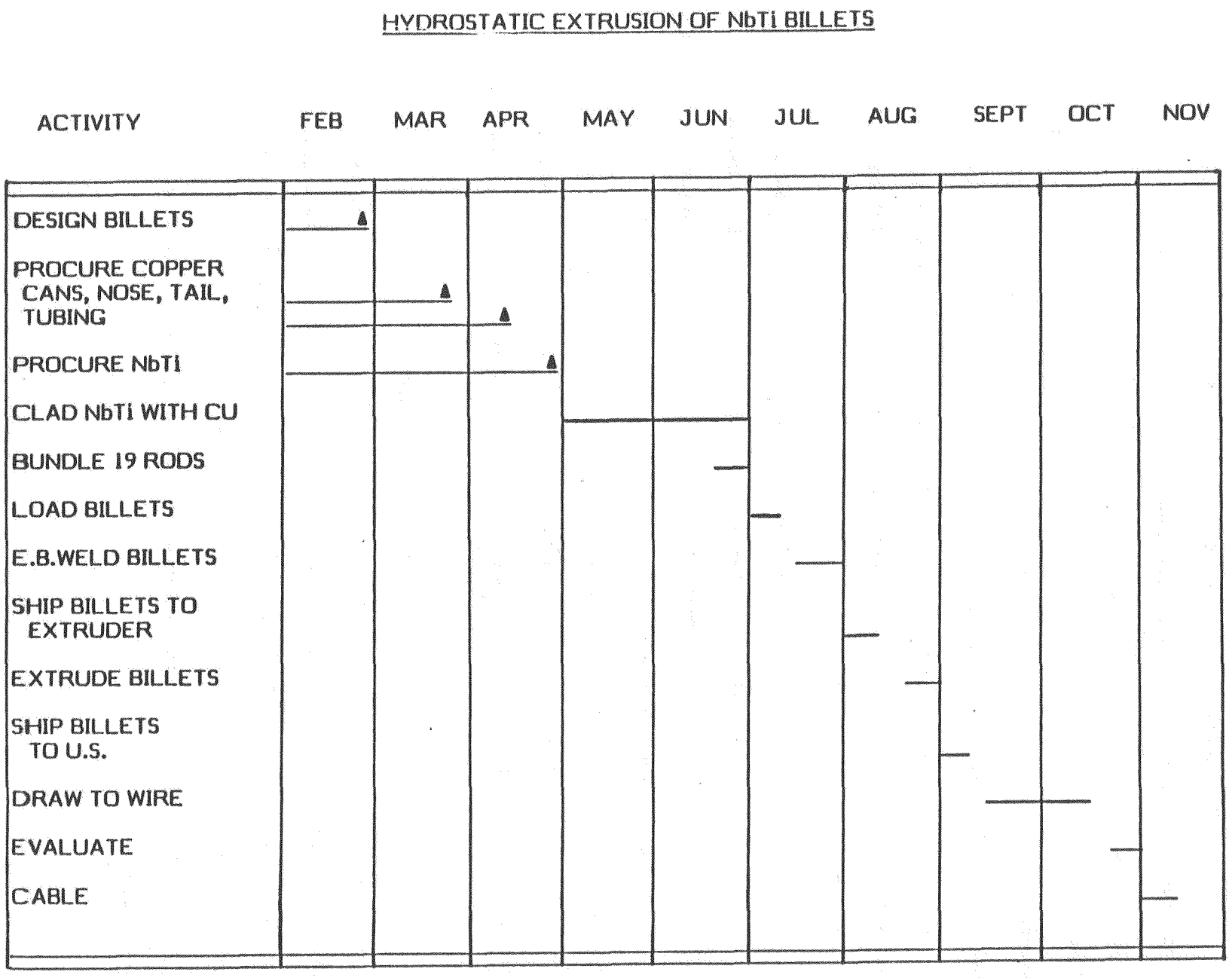


Fig. 5.3-11 Schedule for preparation and hydrostatic extrusion of LBL NbTi R&D billets.

5.4 Summary of Fine Filament Wire Performance From Several Manufacturers

In Section 5.3 the DOE-funded research being done by U.S. Superconductor manufacturers to fabricate conductor for SSC magnets was described. Here will be a summary of recent results from that research and a description in the context of wire with good electrical properties being manufactured for SSC Reference Design D model magnet fabrication and conductor for the HERA Project at DESY. Furthermore, conductors have been provided for examination that were originally intended for other projects and development tasks, or were completed using internal industrial R&D funds.

Table 5.4-4 is a concise summary of many wire samples all measured using facilities at BNL and the University of Wisconsin since about December 1984 with a consistent set of measuring criteria. All of the headings in the table are defined in the current SSC wire specification and its accompanying Appendix A. (See attachment to this report. Also see Section 7.). The measured wire samples are separated into three general categories. Photomicrographs of most samples described in the table are shown in Figures 5.4-12 through 5.4-20.

A. Production Wire for Magnet Model Fabrication

So far IGC fabricated five billets of superconductor to be used to fabricate model magnets for SSC Reference Design D. Tests of wire samples from these production lots are summarized. The design filament sizes for inner and outer layer SSC wire were 23 and 18 μm, respectively. It should be noted there that the design value of J_c (5T) = 2400 A/mm^2 is exceeded in every case.

A sample of HERA wire manufactured by Vacuumschmelze (VAC) is also listed. It is representative of one of the best samples of superconductor wire manufactured for that project. A filament size in the conductor is 12 μm. A sample was sent to BNL for evaluation to show the capability of VAC as a potential superconductor manufacturer.

B. Small Production for Special Purposes

Several interesting wire samples in this category have been tested at BNL during the past few months. The first listed by Brown Boveri Corporation (BBC) had its origin in wire used to fabricate a small quantity two-level-cable conductor for HERA cold iron model dipoles. The sample using NbTi (Ta) alloy was manufactured in a small quantity for Fermilab to see whether the ternary alloy would enhance the current density especially at higher fields. Since the time it was ordered advances in wire fabrication technology have produced better material. However, it did represent a significant improvement over wire produced until about 1983 for the Fermilab ED/S and BNL CBA Projects.

In about 1981 Airco (now Oxford Superconducting Technology or OST) produced a very interesting fine filament superconductor as a qualification test for the Tore II Supra Project in France. Samples drawn to smaller wire (or filament) sizes with recent heat treatment techniques were provided to BNL for evaluation in January 1985 and showed promising results especially considering the date of manufacturing. These samples represent some of the earliest produced to optimize performance under rapid cycling conditions. The wire used a Nb barrier around the filaments and CuNi for interfilament

spacing. Contamination of the alloy with Zr from grinding wheels used in a centerless grinding operation likely led to filament breakage and the rapid fall-off of J_c with reduction in filament size.

C. Special R&D for SSC

Since January 1985 four superconductor manufacturers have provided samples for evaluation of performance. Most of these have been produced with fine filaments. Furukawa in an effort to assist with the SSC Project provided small filament material drawn down from prototype wire intended for use in superconducting generator development in Japan. It represented the first sample measured at BNL with filament size of $\leq$ 5 μm and J_c (5T) > 2400 A/mm^2.

Magnet Corporation of America (MCA) when challenged by the SSC fine filament R&D undertook internally funded research to produce the samples listed. These are remarkable since they were produced using 8-inch diameter billets used in standard production at MCA but with special attention to the conditions of extrusion and heat treatment.

The more recent samples from IGC and Supercon show the best characteristics of fine filament superconductor produced so far and result from DOE-funded research described in Section 5.3.

The results in Table 5.4-4 represent a remarkable collection when considered in the context of possible future materials for the SSC magnet program. Approximately one year ago the state of the art for production current density for NbTi superconductors was J_c (5T) = 2400 A/mm^2 with 20 μm filaments. This table describes samples with $J_c \approx$ 3000 A/mm^2 and filament

sizes as small as 3 microns. These results are further summarized in Figure 5.4-21 where J_c at 5T and filament size are compared for the category C samples.

Table 5.4-4. Electrical Properties of Superconducting Wire
Fabricated for SSC and HERA Model Magnets, Special Purposes and R&D

Note: The listed Cu:SC Ratio is the value used to calculate J_c. In most cases a design value (D) is used but in others it is felt that a measured value (M) will give the most accurate determination of J_c.

Manufacturer	Comments	Date Received	Wire Dia. (Inches)	Fil. Dia. (Microns)	Cu:SC Ratio	J_c at 5T, 4.2K (A/mm^2)	n at 5T	J_c at 8T, 4.2K (A/mm^2)	n at 8T	R_{295} ($\mu\Omega/cm$)	RRR
					D-Design M-Measured						
A. Production Wire for Model Magnet Fabrication											
1. IGC	For SSC Design D; inner wire	1/85 (Billet 5210-1)	0.0318	23	1.29-M	2505	-	1028	-	-	140
		4/15/85	0.0318	23	1.3 -D	2509	-	1077	-	-	130
	For SSC Design D; outer wire	1/85 (Billet 5210-2)	0.0255	18	1.8 -M	2435	-	1070	-	-	138
		4/15/85 (Billet 5212-3)	0.0255	18	1.8 -D	2719	-	1147	-	-	96
2. VAC	For HERA	1/9/85	0.0325	12	1.8 -D	2454	34	988	28	486	118

Table 5.4-4. Electrical Properties of Superconducting Wire
(continued)

Manufacturer	Comments	Date Received	Wire Dia. (Inches)	Fil. Dia. (Microns)	Cu:SC Ratio	J_c at 5T, 4.2K (A/mm^2)	n at 5T	J_c at 8T, 4.2K	n at 8T	R_{295} ($M\Omega/cm$)	RRR
Small Production for Special Purposes											
1. BBC	Origin-HERA cold iron dipole fabrication	12/10/84	0.011	11	1.0 -D	2518	43.3	1287	33.5	5600	32
2. IGC	For Fermilab using NbTi(Ta) alloy	3/19/85	0.0319	13	1.5 -D	2204	46.1	885	30.8	553	119
					OST Below: Cu + CuNi:SC)						
3. OST (Airco)	For Tore II Supra qualification test; manufactured in 1981; drawn down for BNL	1/24/85	0.0358	5	2.7 -D	2411	17.6	843	21	509	94
			0.0225	3	2.7 -D	2235	10.8	-	-	1302	88
			0.0179	2.5	2.7 -D	1563	5.5	-	-	2119	83
			0.0142	2	2.7 -D	1086	4.5	-	-	3357	63
			0.0078	1.1	2.7 -D	974	.5	-	-	10902	61

Table 5.4-4. Electrical Properties of Superconducting Wire

(continued)

Manufacturer	Comments	Date Received	Wire Dia. (Inches)	Fil. Dia. (Microns)	Cu:SC Ratio	J_c at 5T, 4.2K (A/mm^2)	n at 5T	J_c at 8T, 4.2K (A/mm^2)	n at 8T	R_{295} ($\mu\Omega/cm$)	RRR
C. Special R&D for SSC											
1. Furkukawa	Origin-superconductor generator R&D using Nb50 wt. %Ti; drawn down for BNL	1/85	0.0284	8.9	1.65-D	2680	28.7	1011	21.1	701	32
			0.0160	5	1.65-D	2485	29.4	952	24.3	2164	28
			0.0088	2.7	1.65-D	2205	26.1	805	24.1	7384	24
	For BNL Magnetization studies	3/29/85	0.0089	2.8	1.09-D	2381	24.5	842	18.2	8501	25
2. IGC	Preliminary sample for DOE funded R&D	4/85	0.0115	4.3	1.39-M	2835	31.5	1210	29.2	4321	72
3. MCA	Standard MCA billet; special extrusion and heat treatment for SSC	2/19/85	0.0304	25	0.98-D	-	-	940	38.2	712	116
			0.008	7	0.9 -M	2695	39.8	1075	30.5	11146	73
			0.0045	4	0.9 -M	2554	31.0	1002	25.2	34986	54
	For BNL magnetization studies	4/1/85	0.0045	4	1.1 -D	2497	31.2	994	25.0	31800	76
4. Supercon	Preliminary sample for DOE-funded R&D	5/85	0.00206	3	0.75-M	2950	39.2	1200	33.1	15943	52

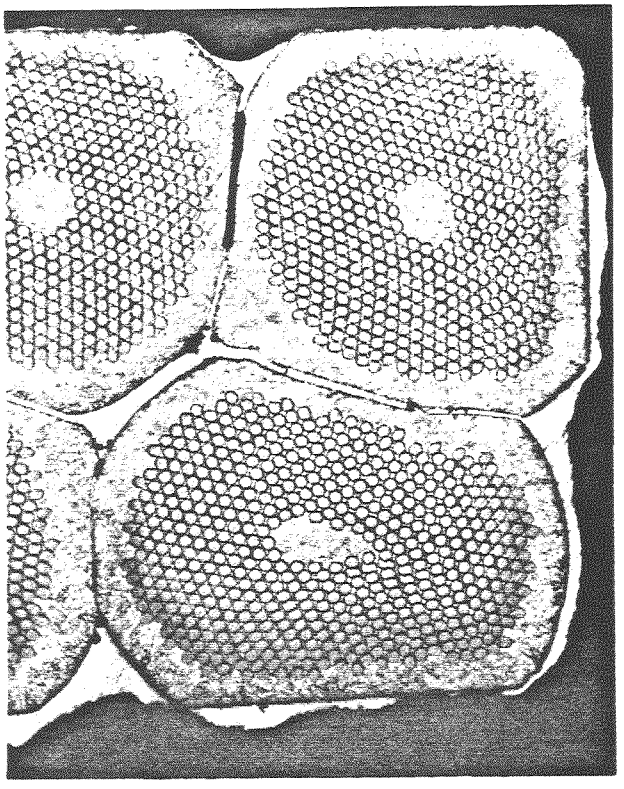
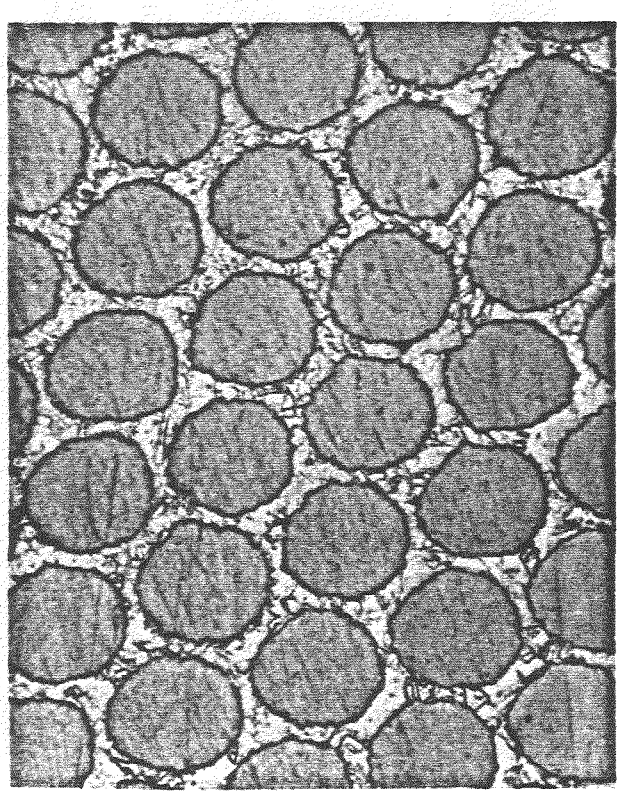
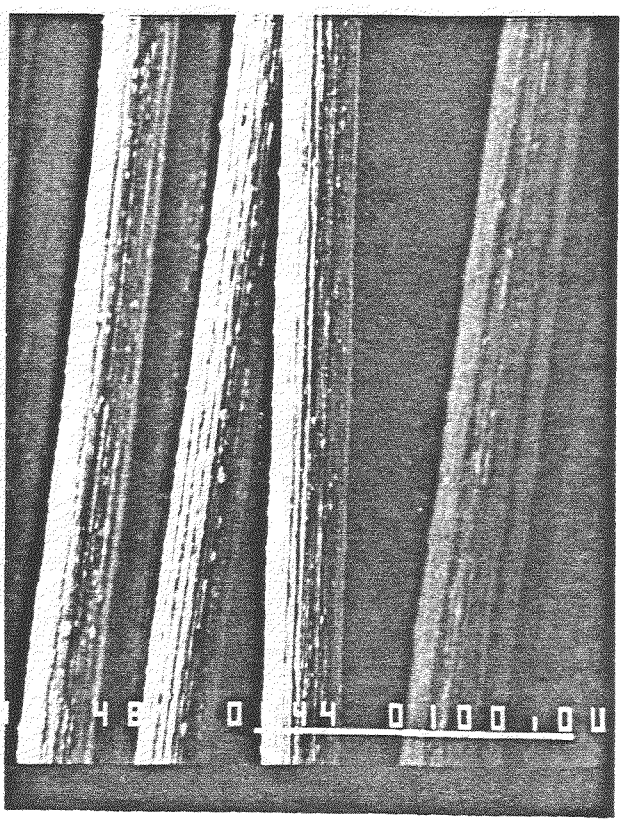


Fig. 5.4-12 Photomicrographs and SEM photo of Design D inner cable and wire referred to in Table 5.4-4 as item A.1. The cable cross section showing the thin keystone edge has a magnification of 75X. The 23 micron filaments are shown at 750X and the etched filaments are shown against a 100 micron scale.





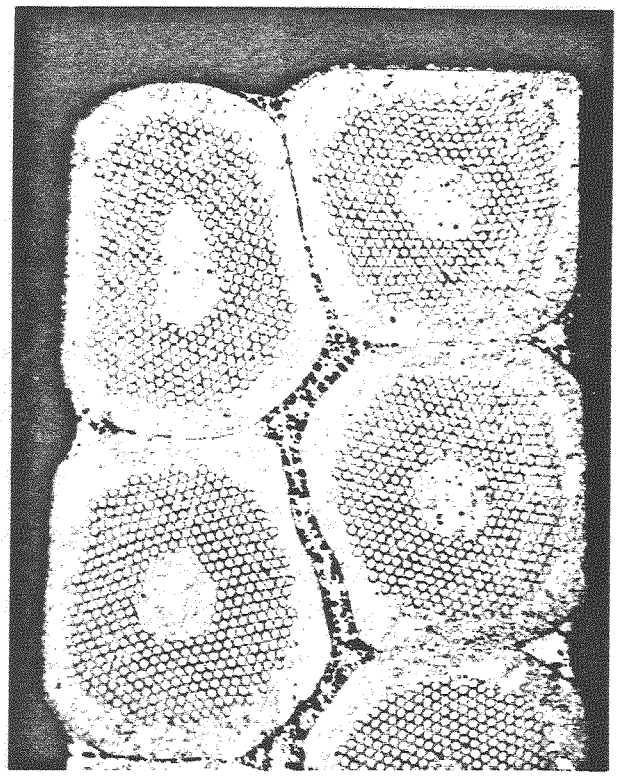
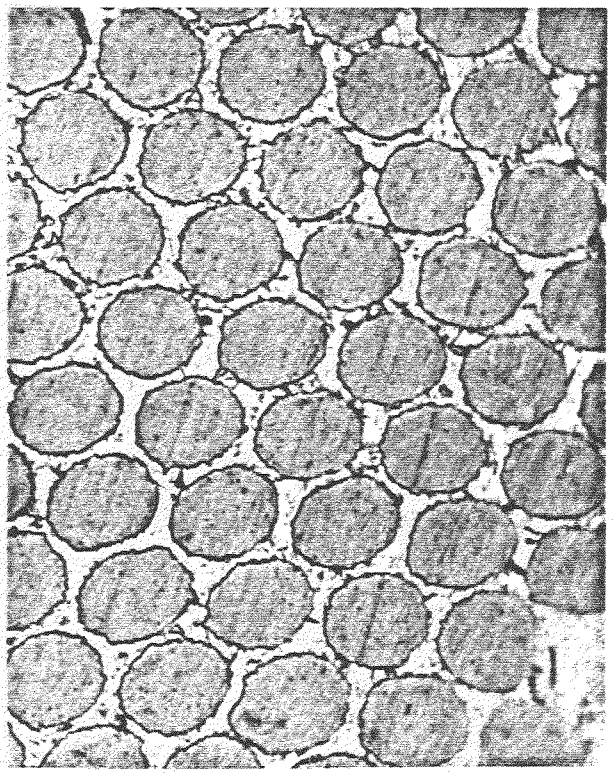
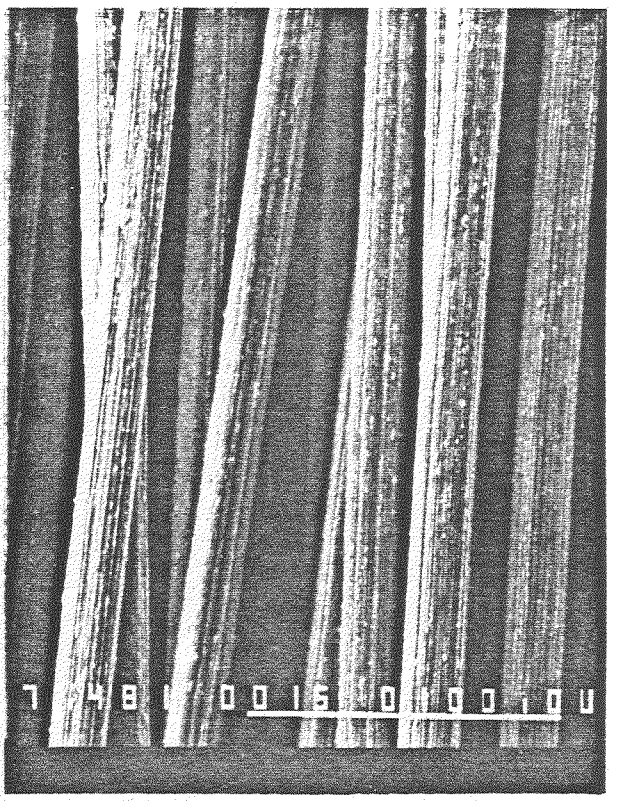


Fig. 5.4-13 Photomicrographs and SEM photo of Design D outer cable and wire referred to in Table 5.4-4 as item A.1. The cable cross section showing the thin keystone edge has a magnification of 75X. The 18 micron filaments are shown 750X and the etched filaments are shown against a 100 micron scale.





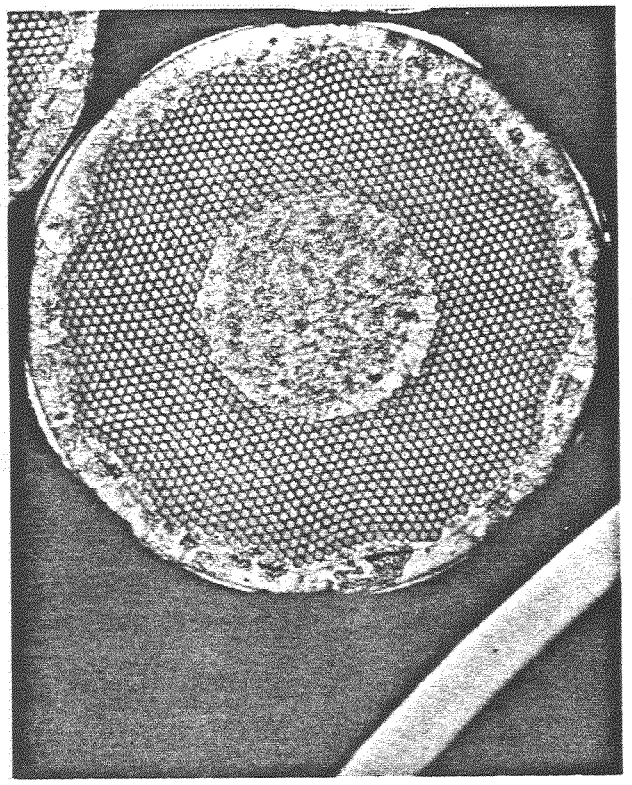
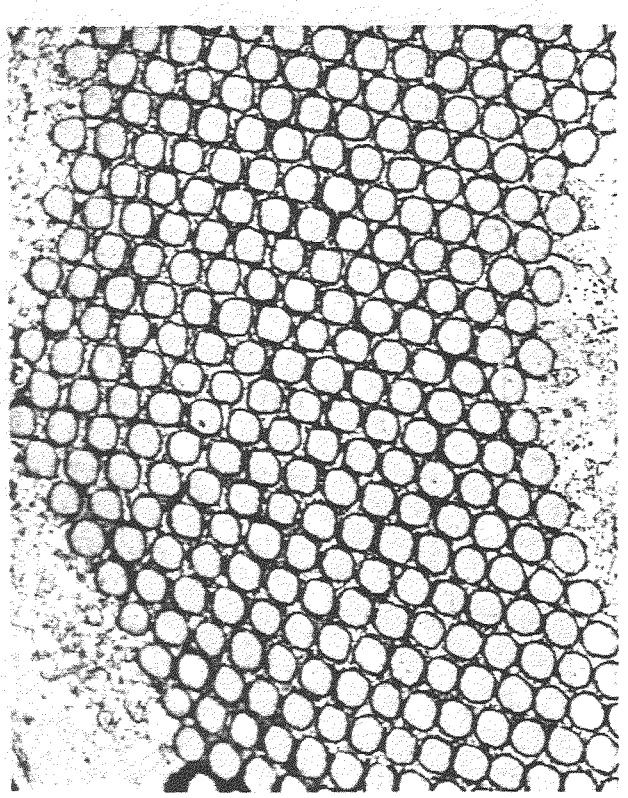
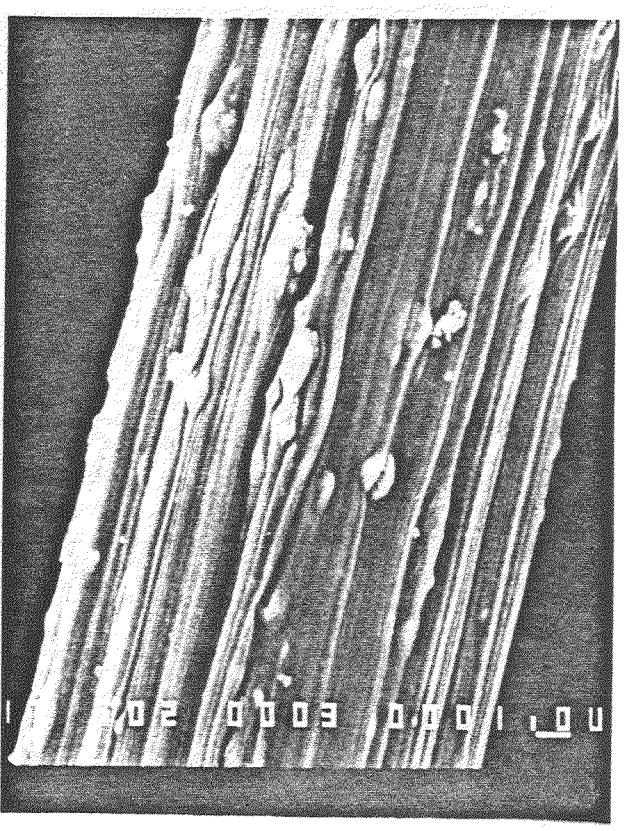


Fig. 5.4-14 Photomicrographs and SEM photo of HERA wire produced by VAC referred to in Table 5.4-4 at item A.2. The entire wire is shown with a magnification of 100X; the enlarged filaments of 12 microns are shown at 400X. The etched filaments are shown against a one micron scale.





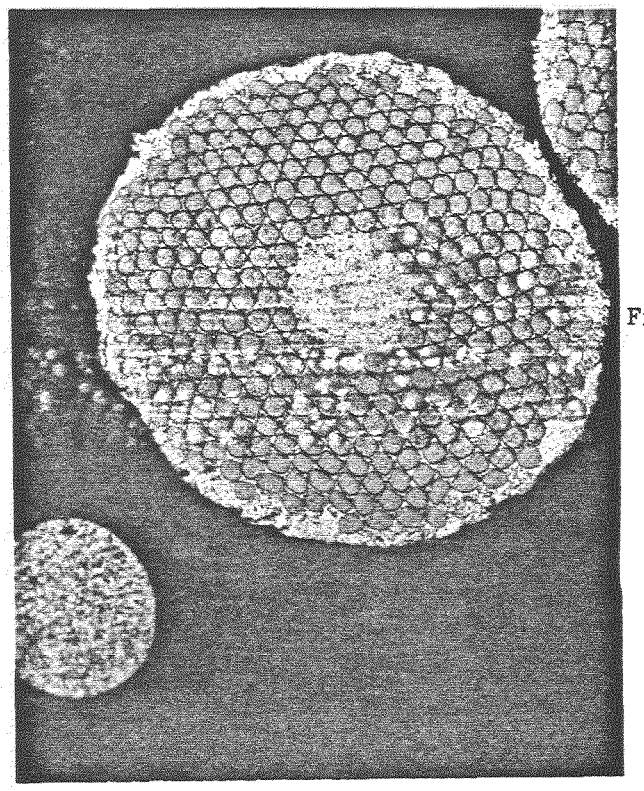
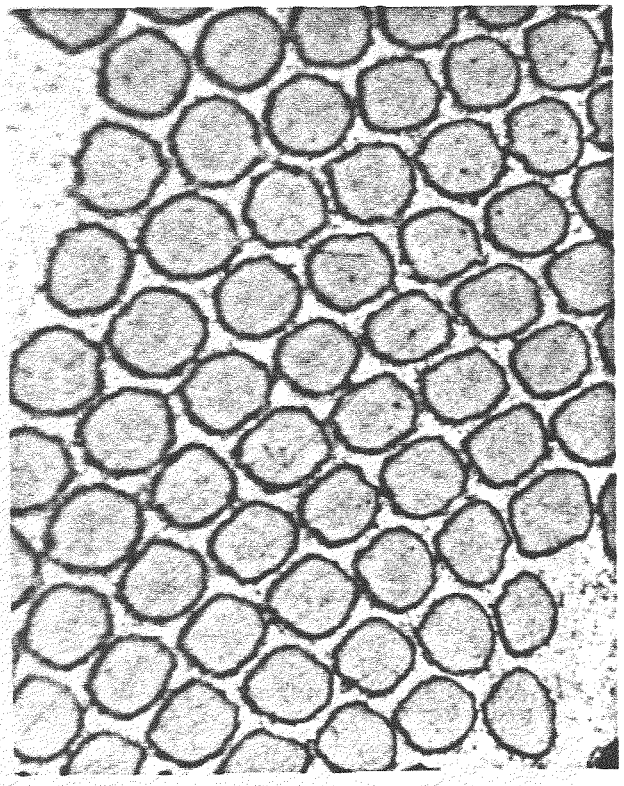
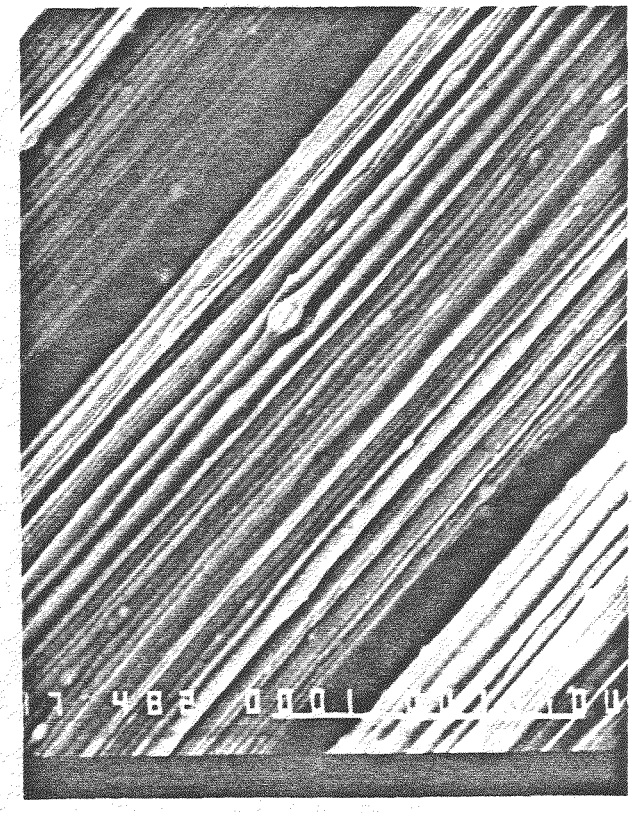


Fig. 5.4-15 Photomicrographs and SEM photo of BBC wire referred to in Table 5.4-4 as item B.1. The overall wire and filament region are shown with magnifications of 250X and 1000X. The etched filaments are shown against a 10 micron scale.





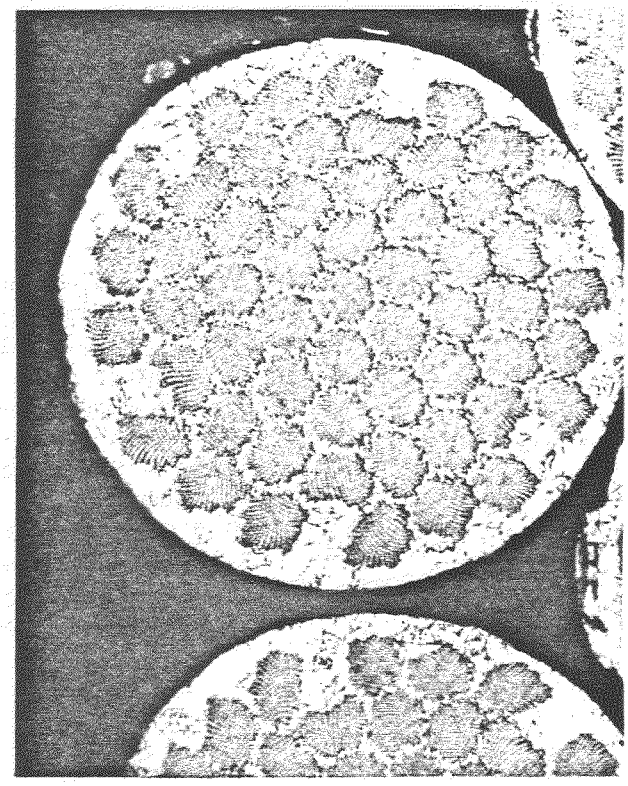
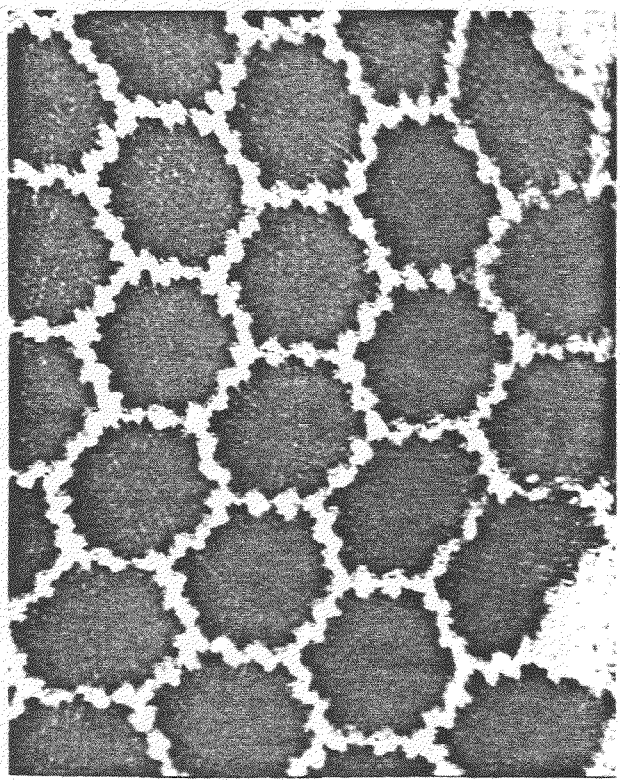
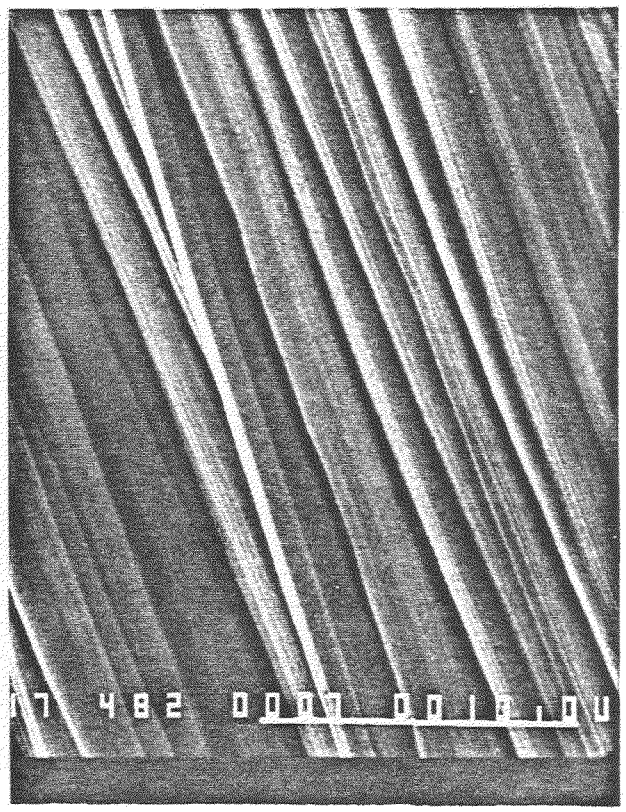


Fig. 5.4-16 Photomicrographs and SEM photo of OST (Airco) wire referred to in Table 5.4-4 as item B.3. The wire shown here has a diameter of 0.0078 inches with 1.1 micron filaments. The overall wire has a magnification of 400X and the filament regions 1000X. The etched filaments are shown against a 10 micron scale.





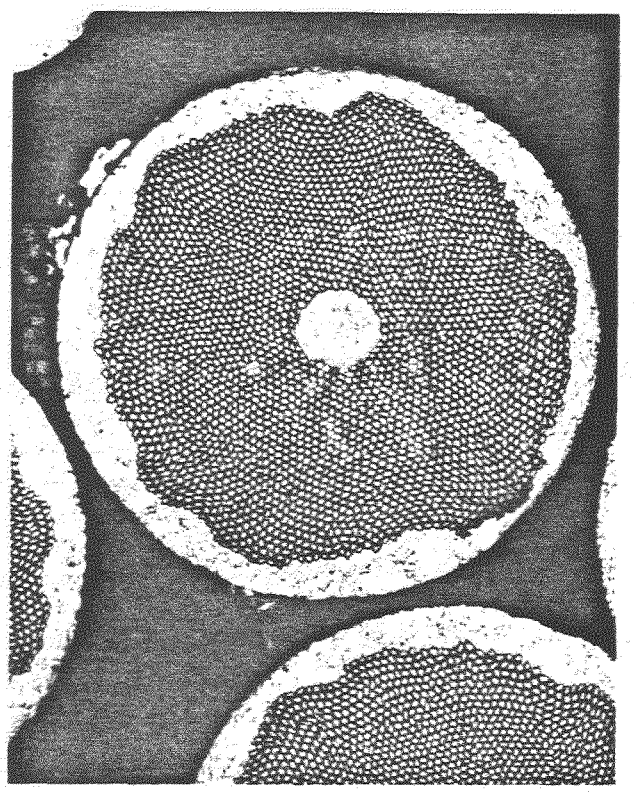
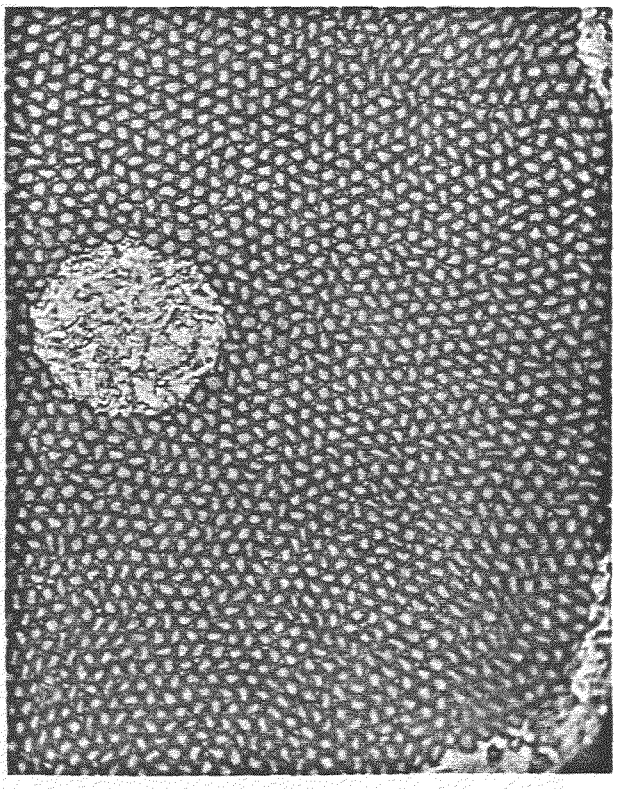
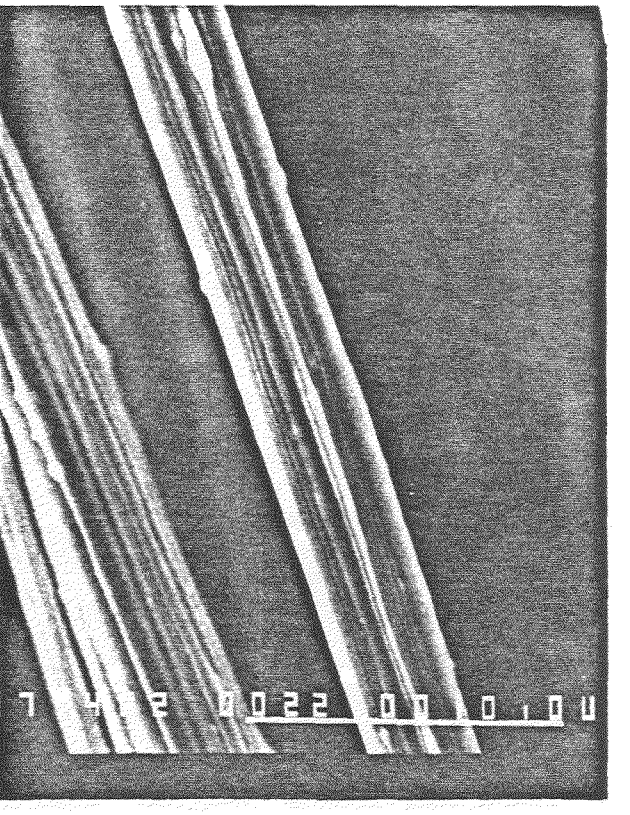


Fig. 5.4-17 Photomicrographs and SEM photo of Furukawa wire referred to in Table 5.4-4 as item C.1. These photos are of samples from long lengths of 0.0089 inch diameter wire with 2.9 micron filaments fabricated for BNL magnetization measurements. The overall wire is shown with a magnification of 350X and the filament region at 1000X. The etched filaments are shown against a 10 micron scale.





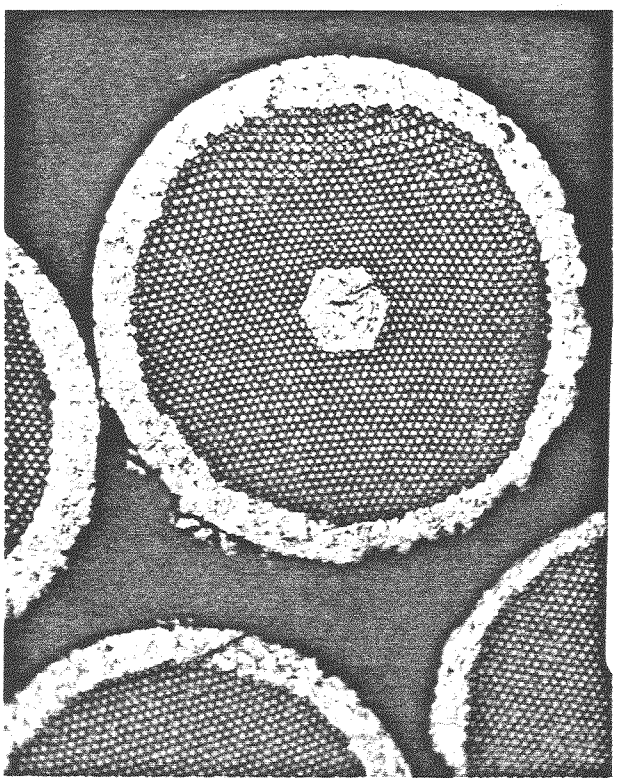
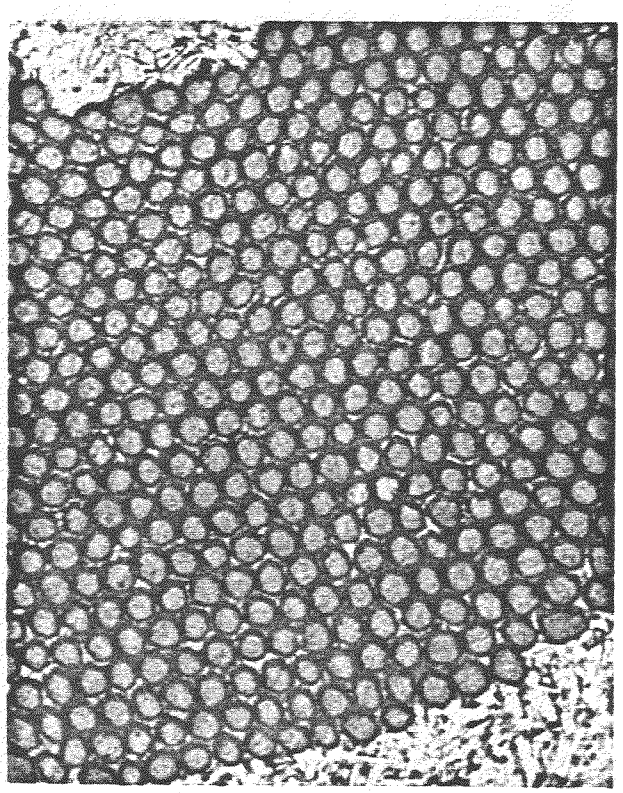
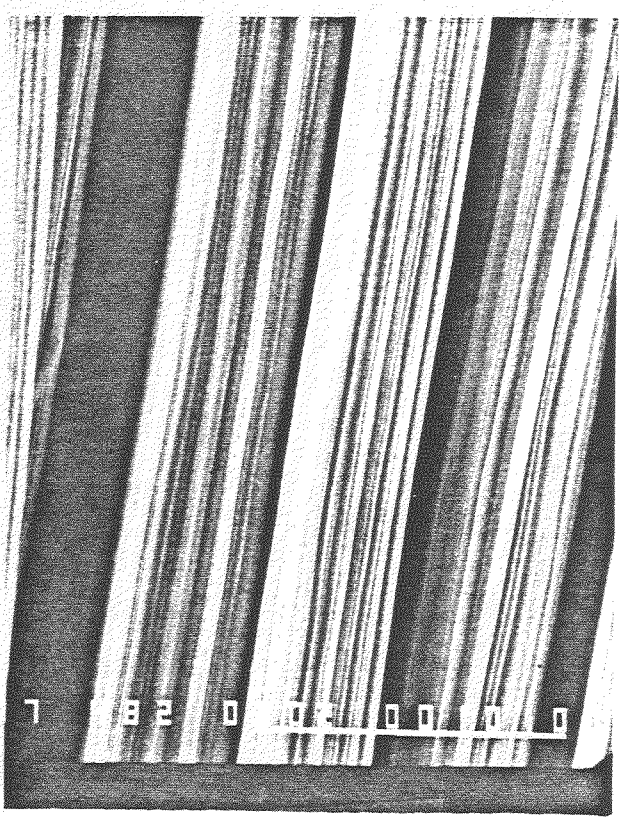


Fig. 5.4-18 Photomicrographs and SEM photo of wire from IGC referred to in Table 5.4-4 as item C.2. The overall 0.0115 inch diameter wire is shown at a magnification of 250X and the filament region at 1000X. The etched filaments are shown against a 10 micron scale.





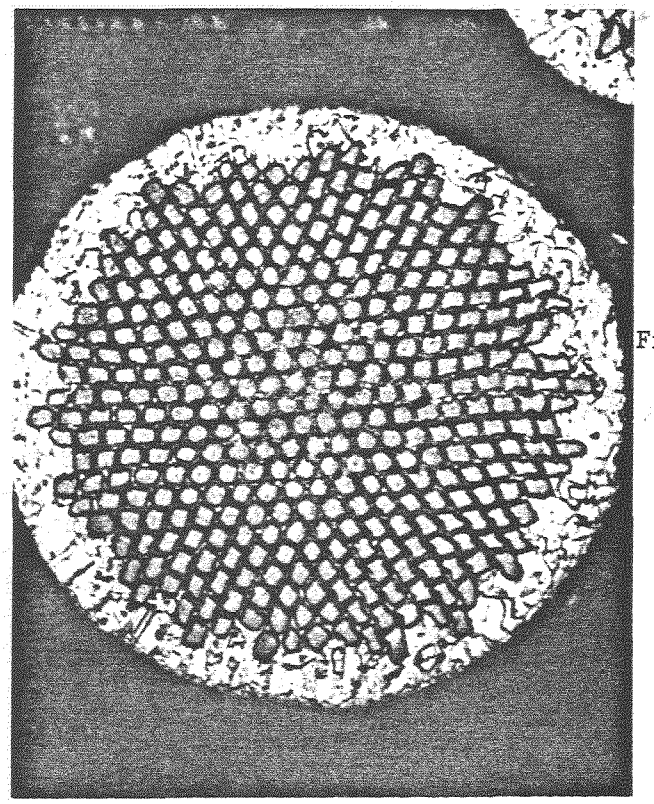
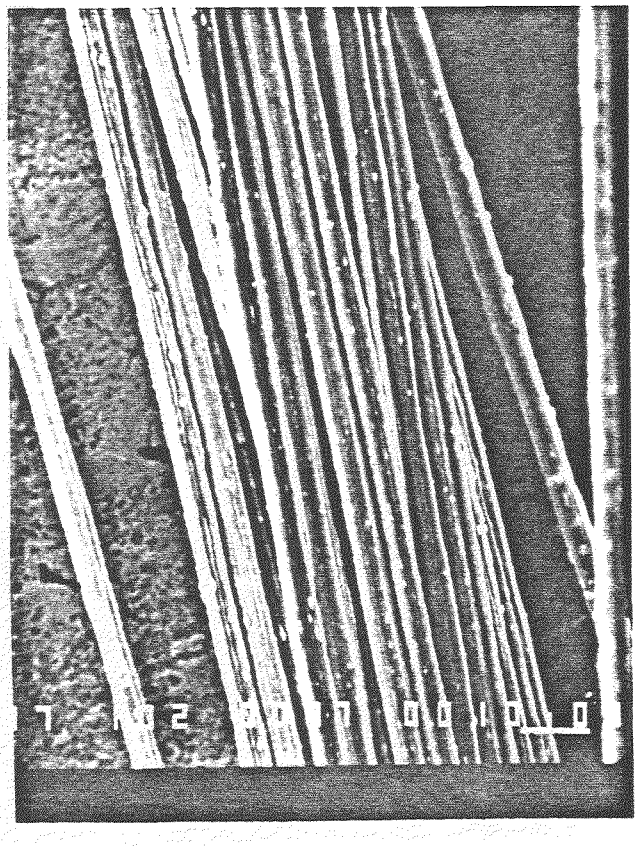
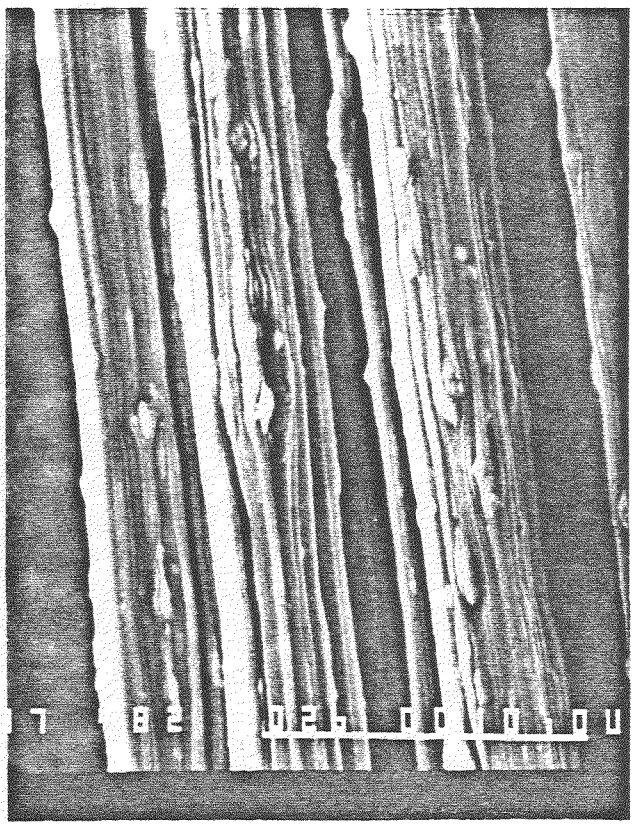


Fig. 5.4-19 Photomicrograph and SEM photos of wire from MCA referred to in Table 5.4-4 as item C.3. These photos are of samples taken from a long length of 0.0045 inch diameter wire with 4 micron filments fabricated for BNL magnetization measurements. The overall wire is shown with a magnification of 750X. The etched filaments are shown against 10 micron scales.





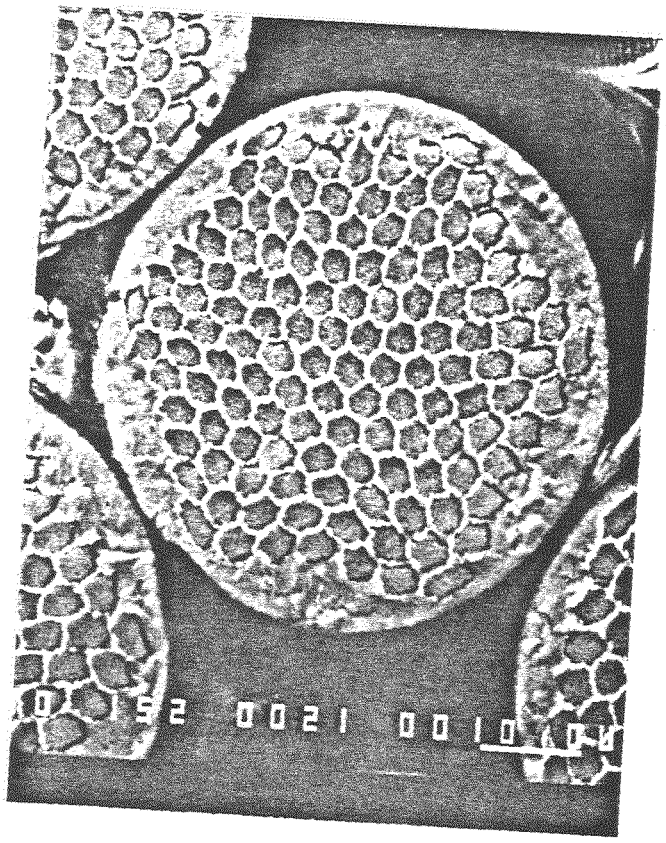
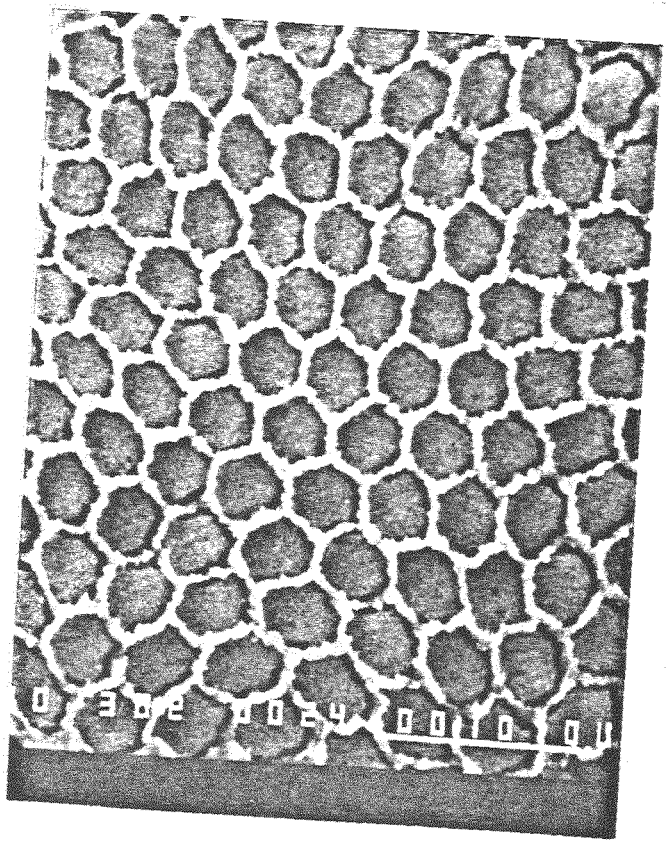
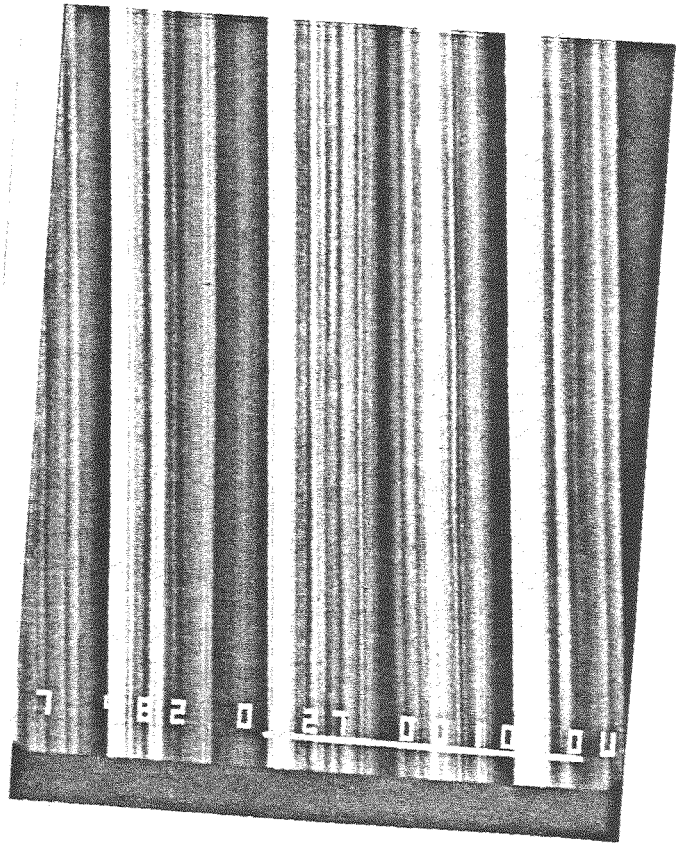


Fig. 5.4-20 SEM photos of Supercon wire referred to in Table 5.4-4 as item C.4. The overall 0.00206 inch diameter wire, the filament region and the individual etched filaments are each shown against 10 micron scales.





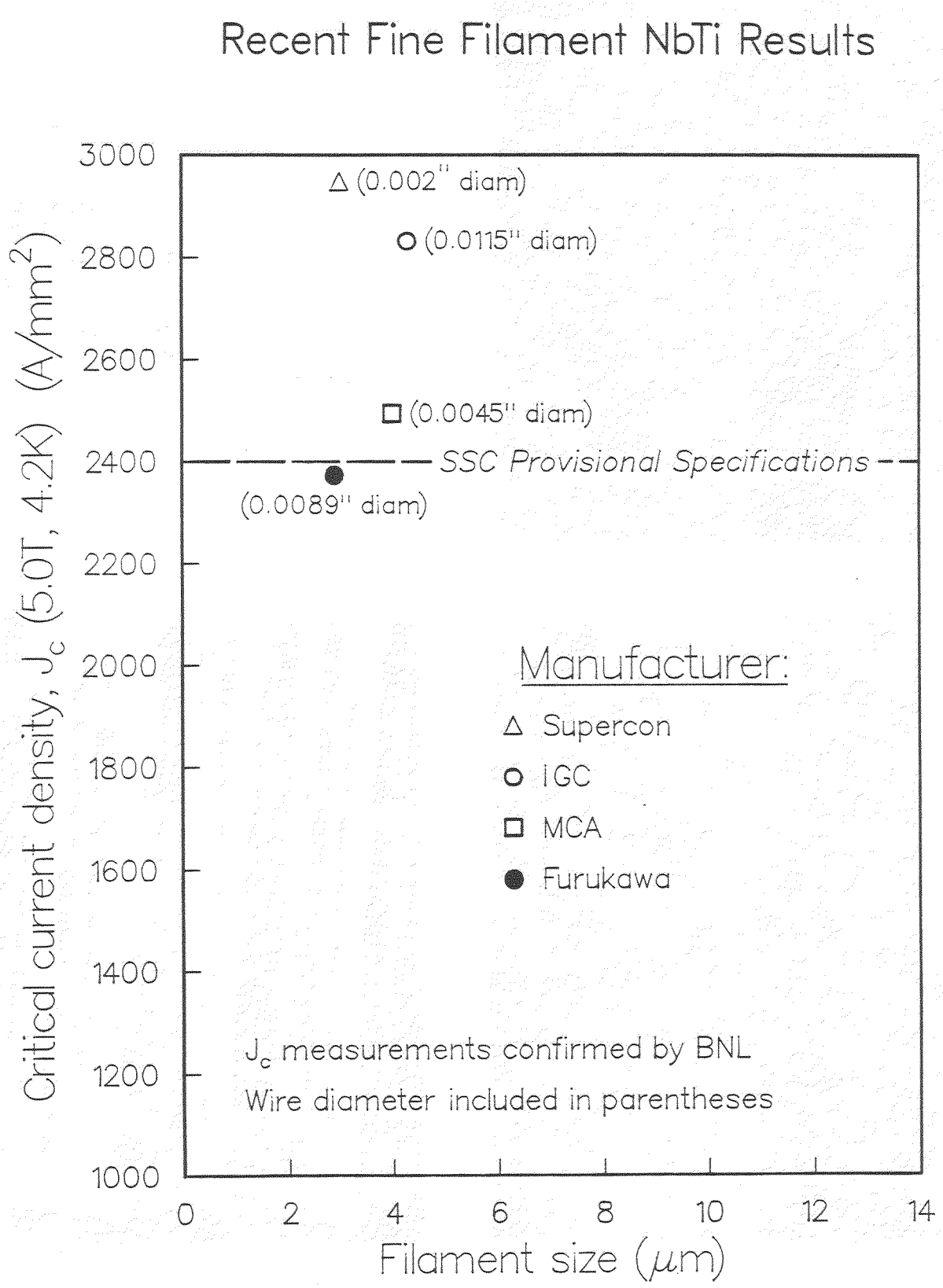

Recent Fine Filament NbTi Results
Critical current density, J_c (5.0T, 4.2K) (A/mm^2)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
△ (0.002" diam)
○ (0.0115" diam)
□ (0.0045" diam)
SSC Provisional Specifications
(0.0089" diam)
Manufacturer:
△ Supercon
○ IGC
□ MCA
● Furukawa
J_c measurements confirmed by BNL
Wire diameter included in parentheses
0
2
4
6
8
10
12
14
Filament size (μm)

Fig. 5.3-21

5.5 Magnetization Measurements on Small Filament Wires

At injection the field quality of a cosθ type dipole is determined by the magnetization currents present in the superconductor. A large number of conductor samples have been measured to test the scaling of magnetization with current and filament size.[1,2] Of paramount interest is the scaling with filament size since there have been reports in the literature of conductor with very small filaments whose magnetization was larger than expected. This phenomenon was observed in some samples with fine filaments but only in cases where the transport current is also relatively low. For conductors with the same effective transport current the magnetization is directly proportional to filament size.

This is illustrated in Fig. 5.5-22 where conductors ranging in filament size from 23 μm to 2.8 μm are shown. (The techniques for measuring magnetization will be described in Section 7.4.) The larger filament conductors are characteristic of the cable now being used to fabricate SSC Design D magnets while the smaller filament wires are developmental types representing the next generation of SSC conductor. All of these conductors had an effective transport current of approximately 2500 A/mm^2 before cabling. The reason that usually high magnetization values are often observed in fine filament wires of low current capability is due to the fact that magnetization is a bulk property unaffected by filament breakage or necking, whereas transport current is directly affected by such geometric defects. Thus a sample with severe necking due to compound formation will have a much larger magnetization than would be expected from the measured current. In fact, it is not the magnetization that is high but the current that is low. It has been possible to

demonstrate that magnetization measurement made as part of a short sample test program can be used to forecast the injection field harmonics of magnets before they are built.[2] When the filament size is very small (< 5 μm) the magnetization curve will be asymmetric due to reversible effects (see Fig.5.5-23) and this must be taken into account when calculating the effect on the field distribution. Preliminary indications are that the degradation produced by cabling and compaction do not correspondingly reduce the magnetization but only affect the transport current due to local necks produced at the cable edges.

1. A. K. Ghosh, K. E. Robins and W. B. Sampson, "Magnetization Measurements on Multifilamentary Nb_3Sn and NbTi Conductors", IEEE Trans. on Nuclear Science, May 21, 1985, p. 238.

2. A. K. Ghosh, W. B. Sampson and P. Wanderer, "Magnetization, Critical Current and Injection Field Harmonics in Superconducting Accelerator Magnets", IEEE Trans. on Nuclear Science, 1985.

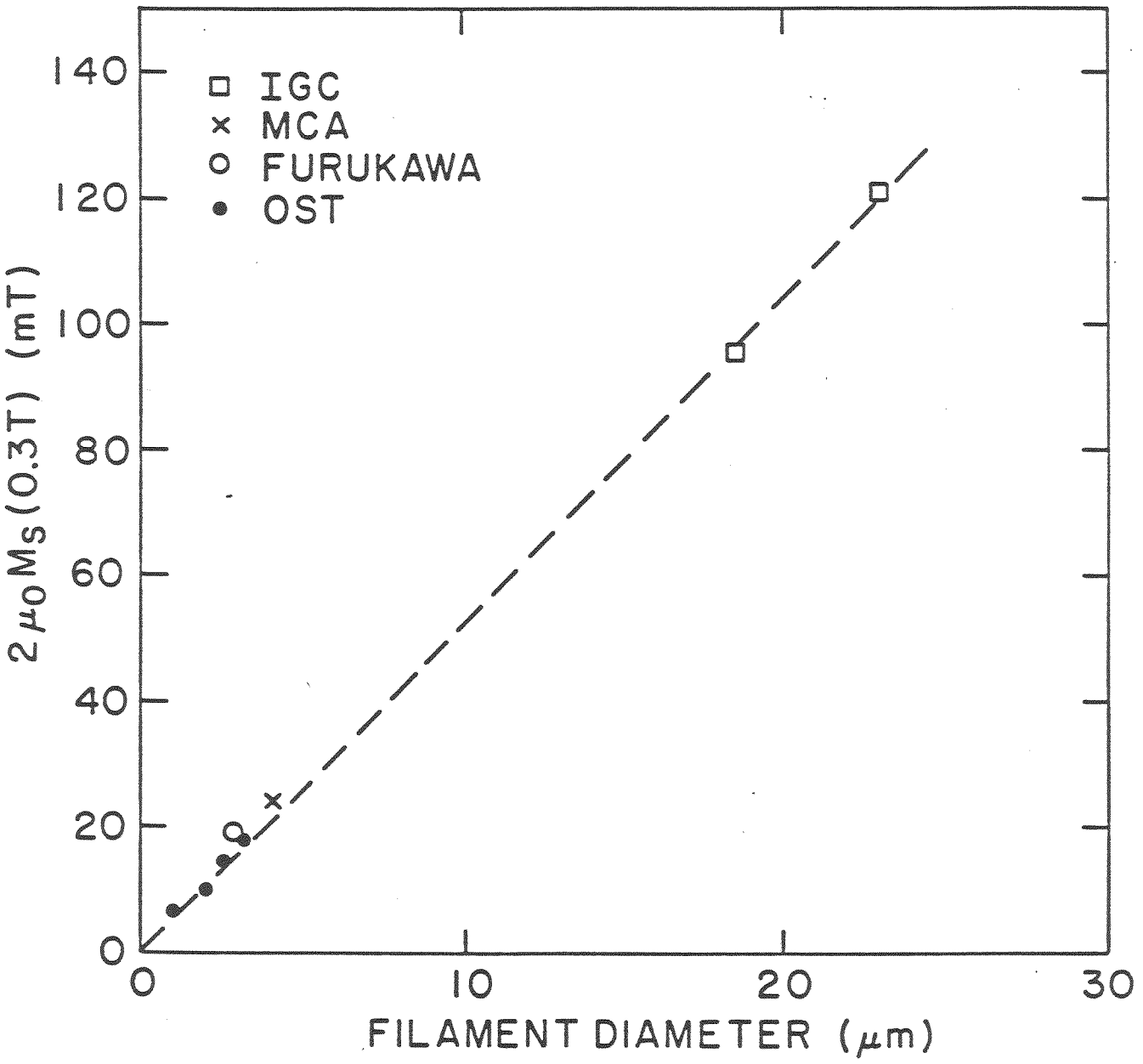


Fig. 5.5-22. Variation of measured magnetization with filament size for samples with transport current $J_c \approx 2500$ A/mm^2.

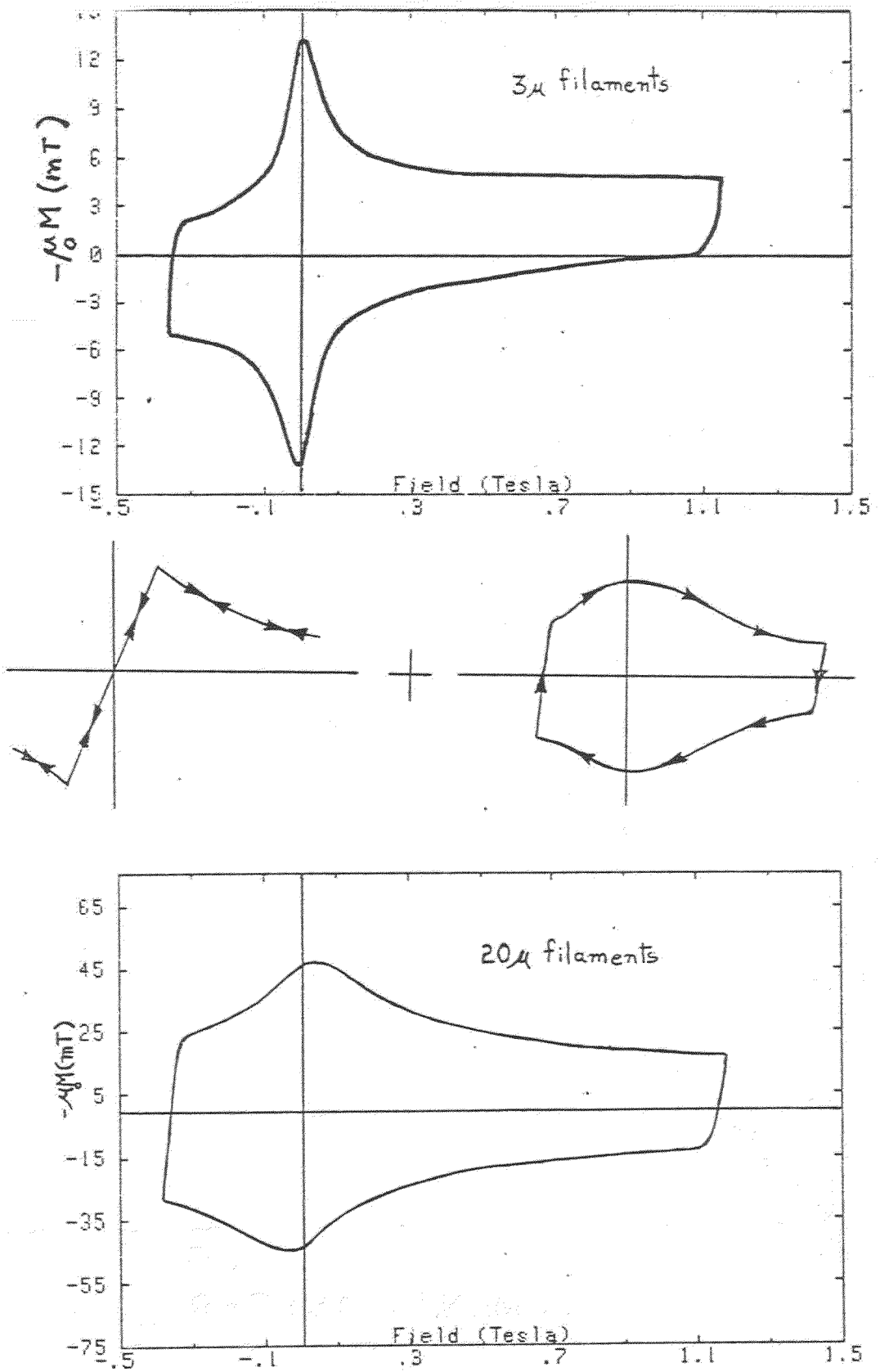


Fig. 5.5-23 The results of reversible and hysteresis effects on the magnetization of samples with two different filament sizes (3μm and 20μm).

6. Cable Fabrication

6.1. Introduction to Reference Design D Cable Fabrication.

At the commencement of the LBL-BNL collaboration on Design A dipoles, both BNL and LBL had active programs for cable R&D and cable procurement. In an effort to reduce duplication of effort within the collaboration, the decision was made to assign to LBL primary responsibility for cable R&D. The BNL team continues to provide support to this effort in the areas of cable property measurements (both mechanical and electrical) and liaison with New England Electric Wire (NEEW). In addition, many of the quality control and record maintenance systems developed for the CBA project at BNL are being adopted for use in SSC cable procurements.

6.2 Conventional Cable Fabrication

During this past year, the cable development effort has been proceeding along two paths - cabling experiments at LBL and process improvements at NEEW. An experimental cabling machine has been built at LBL that can produce long continuous lengths of cable (up to about 5,000 ft. with the present spool system) at production speeds (e.g., 12 ft./min.). In addition, the machine has several features not found on conventional machines, but essential for developing the optimum cabling parameters. These include variable planetary motion for the supply spools, precise tension control for the individual strands, capacity for 36 spools, and easy adjustment of cable twist pitch or cabling direction.

Several trial runs were made at NEEW between February and November, 1984. Many of the early trials were disappointing, especially for the 30-strand Outer cable. Many crossovers occurred and only about 450 ft. of cable could be produced before crossovers recurred. In order to determine

whether there was some practical limit on strand number with the 30-strand cable, a 36 strand cable was attempted at LBL and was successful. Additional trials on the LBL experimental cabling machine showed that two conditions contributed to crossovers - uneven tension from strand to strand and a small mandrel diameter (0.250"). When these two conditions were corrected at NEEW, the crossover problem disappeared. Additional problems were encountered and the solutions adopted are described Table 6.2-1. After these changes were made, a total of approximately 8,000 of cable was feet fabricated at NEEW and 12,000 feet of cable was made at LBL at speed of a 10-12 ft./min. and a yield of over 95%. This speed is comparable to that used at NEEW on ED/S and CBA cable and the recent yields are better than 95% vs. about 80% for the older projects. The increased yield is due (1) to improved wire lengths and quality, and (2) to improved cabling parameters and techniques. At this time, it is felt that the Design D cable can be made for the same cost, or perhaps less, than the ED/S and CBA cable.

6.3. Cabling R&D

Currently, at LBL there is investigation of several new cables which could have advantages for SSC dipoles. These include two level cables, internal wedge cables, and internal flat cables. The two-level cable is of interest from the standpoint of fine filaments and increased cable flexibility. For example, use can be made of the 4,000 filament material being produced by Supercon as a .0318" diameter strand with 8 μm diameter filaments, or the wire diameter can be reduced to .010" (filament diameter = 2.7 μm), to fabricate a 7 element cable, and then fabricate a 23 strand cable from these elements. At LBL, a mechanical model of this cable was produced using surplus Isabelle strand material. The cabling was completed without

problems and at a typical production line speed of 10 ft./min. As soon as the new material is completed by Supercon, this experiment will be repeated with high-J_c strand material and electrical measurements will be made.

Use of an internal wedge in the SSC cables may produce a keystoned cable without the I_c degradation experienced in conventional cables (see Section 7). Finally, internal flat cables[1] offer the advantages of higher effective modulus in compression and perhaps less I_c degradation. Short lengths have been made at LBL and BNL; however, scale-up to production is quite challenging. Several internal flat techniques are currently being evaluated at LBL.

6.4 Sharing Cable Fabrication Techniques

On August 27 and 28, 1985, a workshop was held at LBL for the purpose of transferring to interested industrial participants the techniques for fabricating Design D cable. It is intended for the superconductor manufacturers to take responsibility for cable manufacturing so future purchases can be for completed cable conductor with guaranteed performance and dimensions.

1. A.R. Borden and R.C. Wolgast, ASC Knoxville, 1982

Table 6.2-1

PROBLEMS ENCOUNTERED IN PRODUCTION OF SSC CABLE AND SOLUTIONS ADOPTED

PROBLEM	CAUSE	SOLUTION	COMMENTS
Periodic Crossovers of Strands During Cabling	a) Uneven Strand Tension	Recommend NEEW Rebuild Cabling Machines	After Changes, 8000 FT of Cable Made at NEEW and 12,000 FT of Cable Made at LBL Without Crossovers.
	b) Mandrel Design	Developed New Mandrel Design at LBL	
Excessive Variability in Cable Keystone Angle	a) Worn Turksheads (T.H.)	Used New BNL Turksheads at NEEW	All Cable Made After Changes Have Keystone Angle Within Spec
	b) Variability in Turkshead Assembly	Developed New Operating Mode for Turkshead	
Difficulty Reported By BNL in Winding Dipoles From 30 Strand Cable	c) Cable Twist Pitch (T.P.) Too Long	Reduced Outer Cable Twist Pitch From 2.9" to 2.7" and Inner Cable T.P. from 3.125" to 2.9"	Improved Cable Mechanical Properties With Slight Change In Metal Density (Approx. 0.5%). No Additional Degradation In I_c Due to Tighter T.P.
Sharp Edge on Cable Damaging Insulation	Turkshead Assembly Procedure	Tendency Greatly Reduced With New T.H. Operating Mode. Brushing Station Incorporated in BNL Cleaning Line	No Problem in Insulation for 4.5 m Dipoles

7. Critical Current and Magnetization Measurements

7.1 Techniques for Measuring Strand I_c

The measurement of the critical current of strand before cabling is straight forward since there is no problem with sensitivity and the current is relatively low (< 1000 amps). A four wire technique is used with the voltage points situated far enough inside the current contacts to ensure that no current transfer voltages are included in the V vs. I data. A small superconducting solenoid with reasonable field homogeneity can be used for the background field.

The critical current, I_c, is usually defined as the current at which the effective resistivity of the strand is equal to 10^{-14} ohm-m for the total wire cross section. Strands, particularly very fine ones, will often carry current considerably in excess of I_c, before quenching. The form of the voltage vs. current relationship is used to determine I_c, and the "quality index", n, which is defined in Fig. 7.1-1. In practice, this measurement is usually computerized and a typical result is shown in Fig. 7.1-2. If the uniformity of the sample is in question additional voltage taps can be used to segment the sample. The normal state resistance of the strand is measured at room temperature and just above the transition temperature as part of the standard test. These resistances are then used to compute the copper-to-superconductor ratio (for comparison with specifications and etch and weigh measurements) and the residual resistivity ratio (RRR). Details of these techniques are included in Appendix A of the specification for SSC superconducting wire attached to this report and in references 1 and 2.

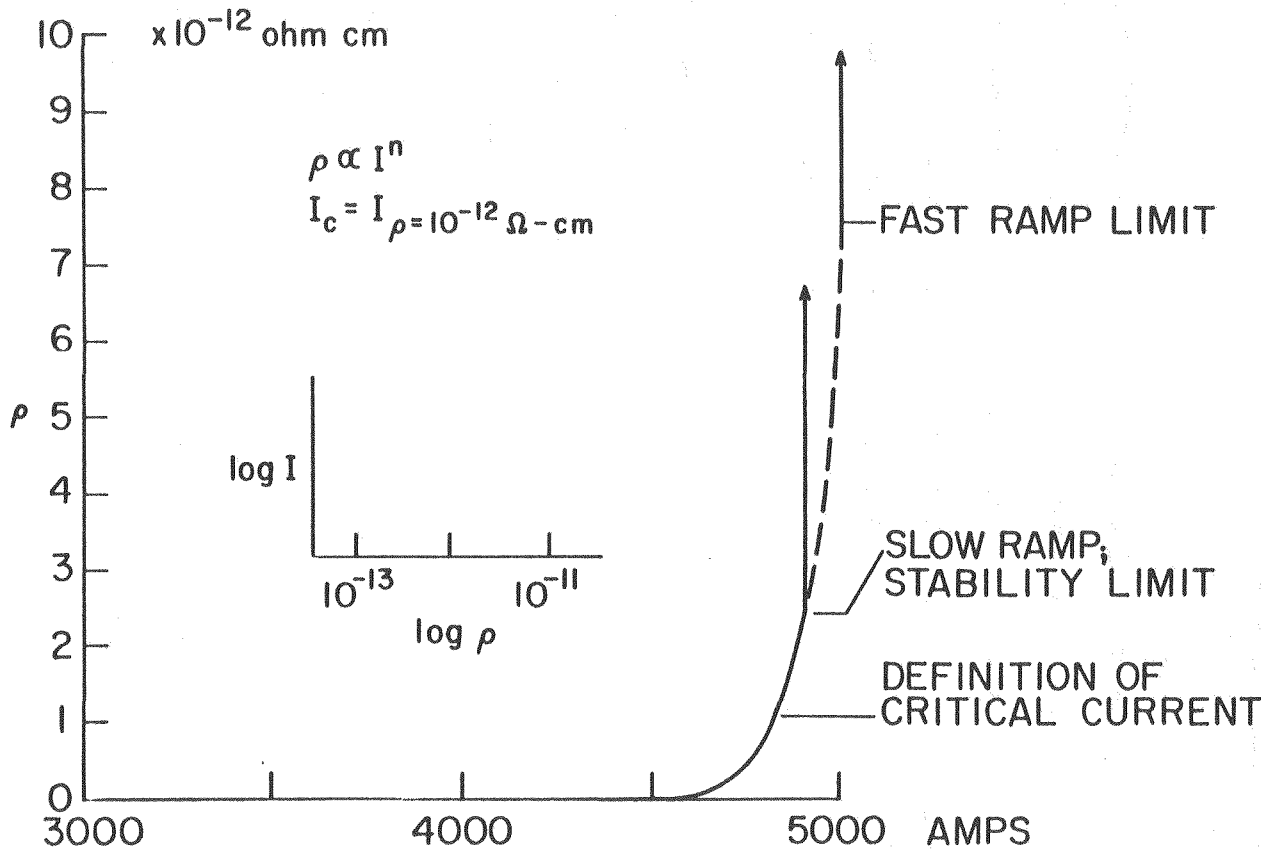


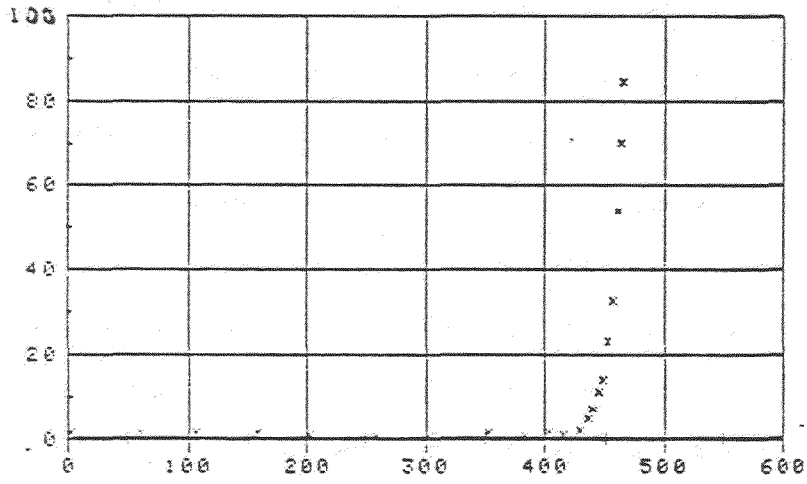
Fig. 7.1-1. Schematic drawing of the voltage (or resistivity) vs. current relationship to determine I_c.

RUN 3823 TAC B:SPOOL Sp: 3 Probe:B 6-5-85

Field = 50kG Dia.= .0268in. C/S= 1.21 Mfr C/S= 1.3

Amps	uVolts	Rho	Amps	uVolts	Rho	Amps	uVolts	Rho
1.0	1.7	74.2	350.4	1.6	.2	442.7	11.1	1.2
59.8	1.0	.7	382.0	.6	.1	446.4	14.0	1.5
105.3	1.4	.6	401.8	1.8	.2	450.9	23.0	2.5
155.8	1.6	.4	414.4	1.0	.1	454.5	32.9	3.5
201.0	1.2	.2	427.6	2.0	.2	459.2	54.0	5.7
256.7	.6	.1	434.0	4.9	.5	461.6	70.2	7.4
300.8	.7	.1	438.7	7.1	.8	463.2	84.4	8.8

Ic1= 441.7 Iq= 465 n= 45.1 Jc= 2683 A/mm2



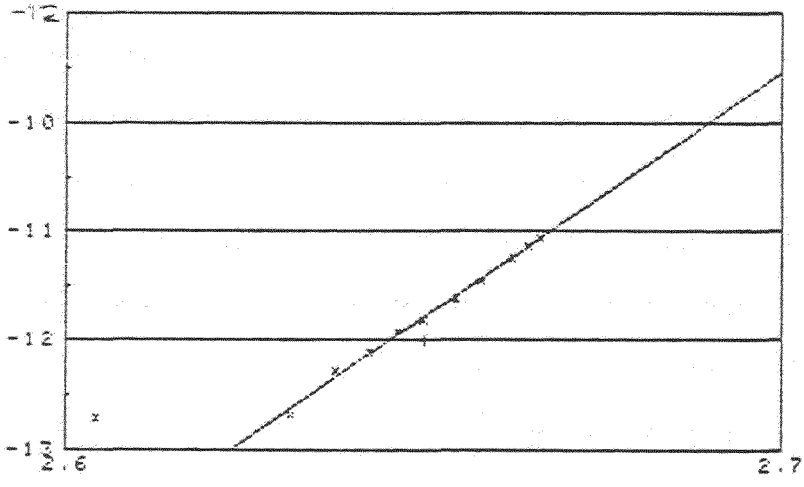


Fig. 7.1-2. Sample data sheet from BNL wire critical current measurement. The upper graph shows V in μV vs I in A. The lower graph shows log ρ vs. log I.

7.2 Techniques for measuring cable I_c

While the measurement of I_c for cables is in principle the same as for wires there are a number of practical considerations which make it much more difficult. Sensitivity is a problem since it is not easy to get a long section of cable in a uniform field. In addition, very high current (~ 10kA) power supplies are hard to filter adequately and the cables must be held rigidly to prevent "training" effects. The sensitivity question is addressed by using a dipole magnet for the applied field. This provides a "gauge length" of 70 cm or so which is sufficient when voltmeters of high sensitivity are used. A robust clamping fixture prevents conductor motion but full scale cables still quench at a current which is only slightly above the 10^{-14} ohm-m level. A typical voltage-current curve for an SSC cable is shown in Fig. 7.3-4.

An advantage of using a dipole to provide the magnetic field is that the critical current can be measured with the field both parallel and perpendicular to the wide face of the cable. "Anisotropy" measurements are useful in determining the optimum parameters for cable pitch, compaction etc. The resistance measurements at room temperature and 10K provide the copper-to-superconductor ratio and the RRR for the cable. The use of small "spot" heaters on the cable make it possible to measure the velocity of propagation of normal zones which can then be used in magnet protection analysis. The details of the cable measurements are given in reference 3. When comparing the results of critical current measurements with magnet performance it

should be remembered that under ideal conditions a cable will carry current in excess of I_c, and that the peak field and field orientation must be taken into account. The quoted values of critical current are the "worst case" values with the field perpendicular to the cable and no correction for the "self field" effect.

1. M. Garber and W. Sampson, "Test Method for Normal State Resistance of NbTi Superconducting Wire", BNL Magnet Division Note 115-4.

2. M. Garber and W. Sampson, "Test Method for Short Sample Critical Current Determination of Twisted Multifilamentary Superconducting Wire", BNL Magnet Division Note 116-4.

3. M. Garber and W. B. Sampson, "Critical Current Anisotropy in NbTi Cables IEEE Trans. on Nuclear Science, 1985.

7.3 Summary of Electrical Properties of Production Cable

Table 7.3-1 provides a summary of the electrical characteristics of the superconductor cable manufactured so far for SSC Reference Design D model magnets at BNL. The results are plotted in Figures 7.3-3 through 7.3-7. The measured properties of the cable exceed the required design value, some by a considerable margin. However, there are two features which currently are somewhat puzzling and will require additional study. These features will be summarized briefly here.

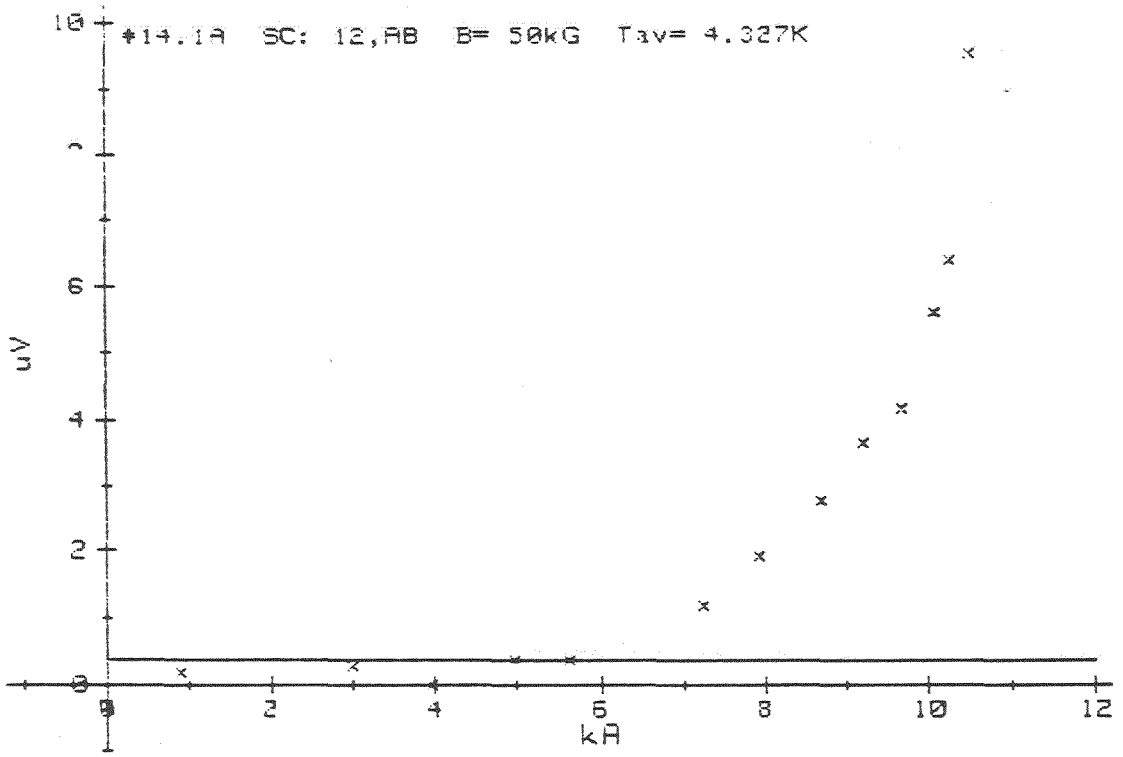
The superconductor cables for the inner layer coil (XT-012 and XT-014-2317HH) exhibit substantial training when not clamped with stresses above 10,000 psi. It is suspected that this characteristic may be due to the reduced amount of copper in the cable and the high critical currents. (The Cu:SC Ratio is 1.3:1.) This training is unusual in comparison with other similar conductors with higher copper ratios and similar critical currents which are clamped not nearly as well and do not train. The cable sample holders at BNL have recently been strengthened to enable measurement without training. Also, the satisfactory training characteristics of the 1 m and 4.5 m long model Design D dipole magnets have reduced the concerns about the operational stability of a magnet with this conductor.

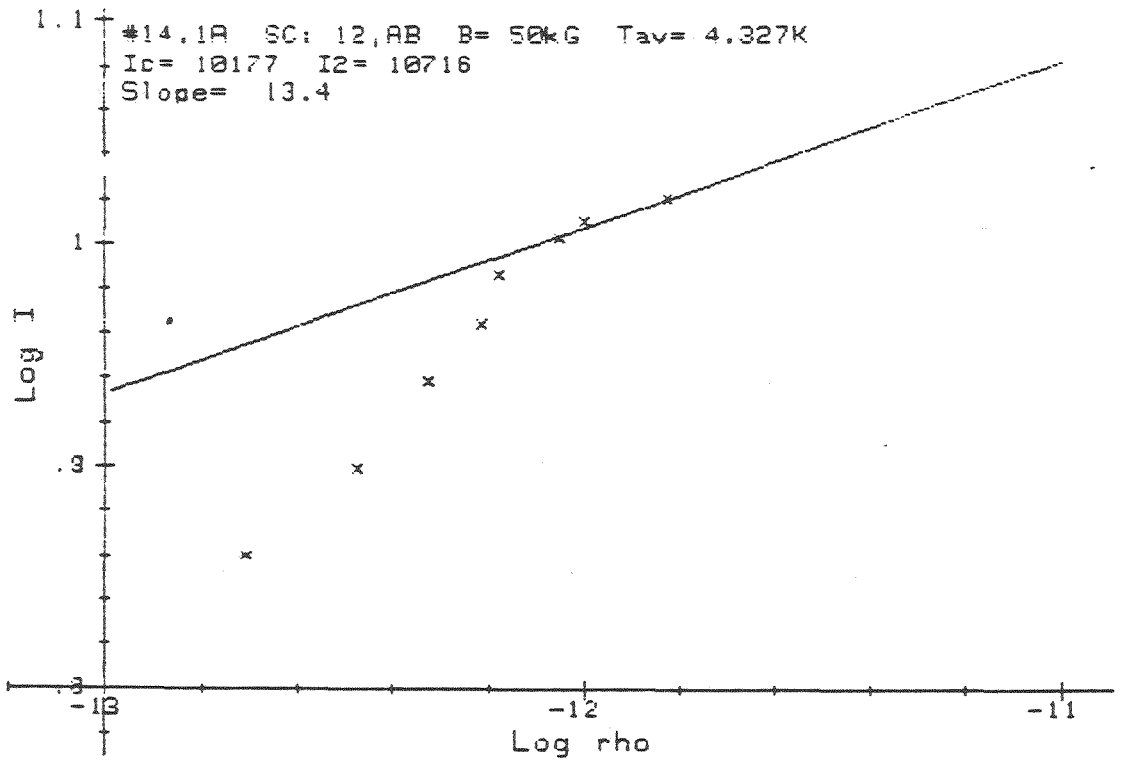
The V-I curve for the inner cable also exhibits somewhat anomalous behavior. A comparison of typical inner and outer V-I curves are given in Figures 7.3-3 and 7.3-4. Note the increase in V at relatively small I compared with the normal appearing curve for the outer cable. This characteristic also appears to be related to the reduced copper in the conductor but the reasons for this type of performance are unclear at present in spite of numerous follow-on tests.

The outer conductor such as XT-013-3012HH performs in a classic manner under electrical test. See Fig. 7.3-6. However, a surprise has developed there. Cable XT-015-3012HH was produced at LBL with a mid-thickness of 0.4 mils over the maximum tolerance. In order to preserve the field quality characteristics of the magnets LBL was requested to reroll the cable. This rerolling was done with completely satisfactory results from the mechanical standpoint. However, the electrical results were disappointing. A size reduction during reroll of 0.5 mils resulted in a large degradation (D) when measured the customary way, but substantial reduction of I_c-parallel as shown by the value of the anisotropy (A) in Table 7.3-1 and in the summary given in Fig.7.3-7. This cable will not be used to fabricate model magnets. More work must be done to understand the effects of mechanical shaping on the characteristics of the Design D cable.

Table 7.3-1 Electrical Properties of Superconducting Cable for SSC Reference Design D

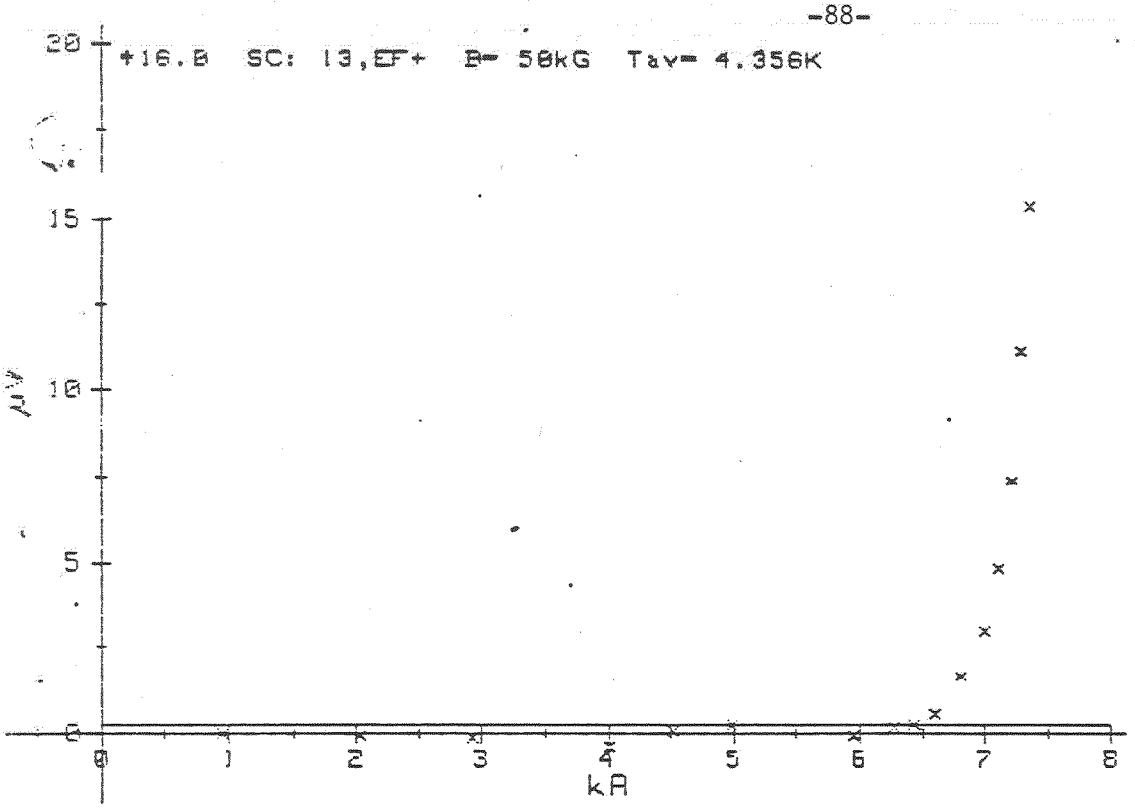
	Meas. Date	$I_{c\perp}$ 5T, 4.2K (amps)	n at 5T	A (%)	D (%)	R_{295} (μΩ/cm)	RRR	Comments
INNER CABLE Design Values	-	> 10453	-	-	< 15 incl. in I_c	-	> 70 estimated	
XT-012-2317HH	5/9/85	10600	13	12	16.5	26.8	69	manufactured at NEEW
XT-014	5/9/85	10500	11	12.5	17	26.8	76	manufactured at LBL
XT-020	6/6/85	11120	19.7	11.3	13.5	27.0	71	manufactured at LBL
XT-022	8/15/85	10450	10	4	17	27.0	-	manufactured at LBL
OUTER CABLE Design Values	-	> 7202	-	-	< 15 incl. in I_c	-	> 70 estimated	
XT-013-3012HH	3/13/85	7480	34	4.3	14.5	28.2	81	manufactured at NEEW
XT-015	5/17/85	8180	28	4.7	15	28.4	72	manufactured at LBL
	5/29/85	7510	14	-11	22	28.5	61	after re-rolling; not used for magnet fabrication
XT-019	6/6/85	8130	18.2	2.8	15.3	27.9	73	manufactured at LBL
XT-021	6/26/85	8280	26.0	2.8	13.9	28.1	68	manufactured at LBL
XT-023	8/22/85	6980	15	11.5	20.7	-	-	manufactured at NEEW
XT-025	10/29/85	7350	19	8	-	28.5	73	manufactured at NEEW





#14.2A B= 50kG ID=12,AB L=68.6 IC=10592 I2=11154 N=13.4 08-MAY-1985 17:01

Fig. 7.3-3 Data format from cable tests of XT-012-2317HH at 5.0T with the magnetic field perpendicular to the large surface of the conductor. The anomolous increase of V at small currents is evident in the top graph.



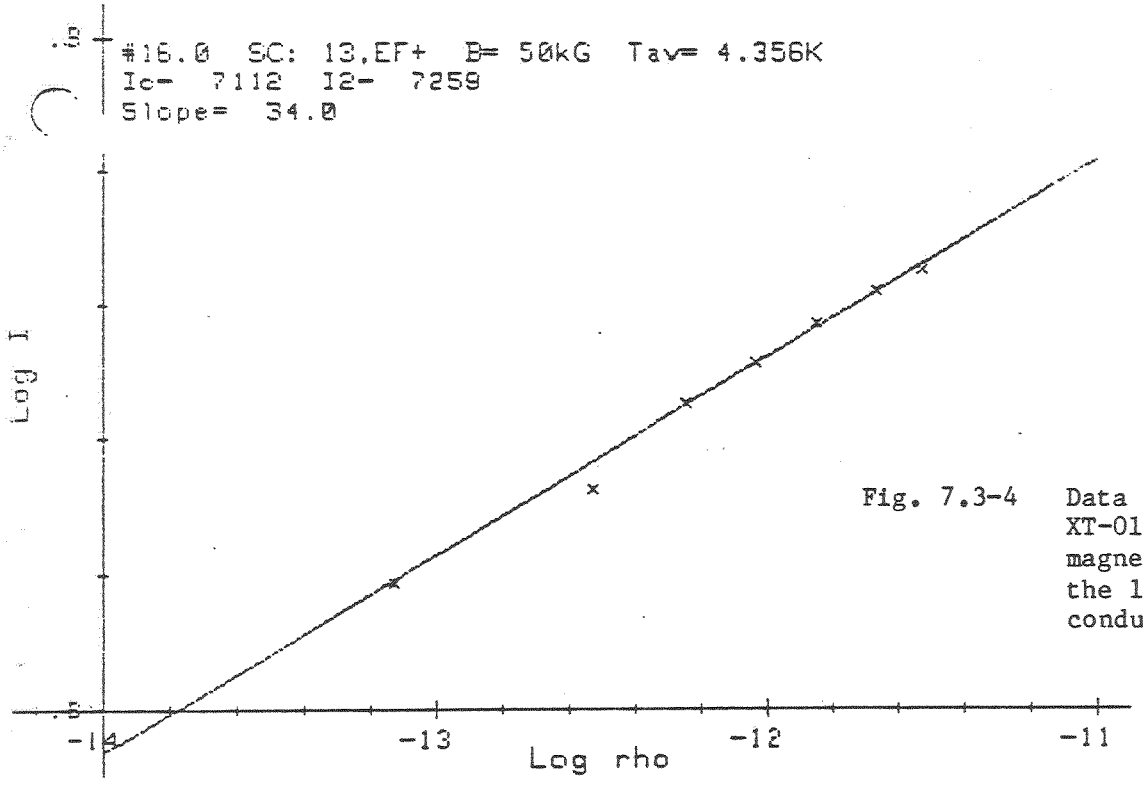


Fig. 7.3-4 Data format from cable tests of XT-013-3012HH at 5T with the magnetic field perpendicular to the large surface of the conductor.

#16.0 B= 50kG ID=13.EF+ L=68.6 IC= 7489 I2= 7643 N=34.0 25-FEB-1985 14:13

	I	V	I	V	I	V	I	V	I	V	I	V
1	950	-.02	2023	-.07	2919	-.13	4015	-.36	4510	.08	4988	.27
7	5947	-.04	6281	.22	6435	.28	6587	.59	6805	1.67	7001	3.00
13	7101	4.83	7202	7.39	7283	11.17	7337	15.45				

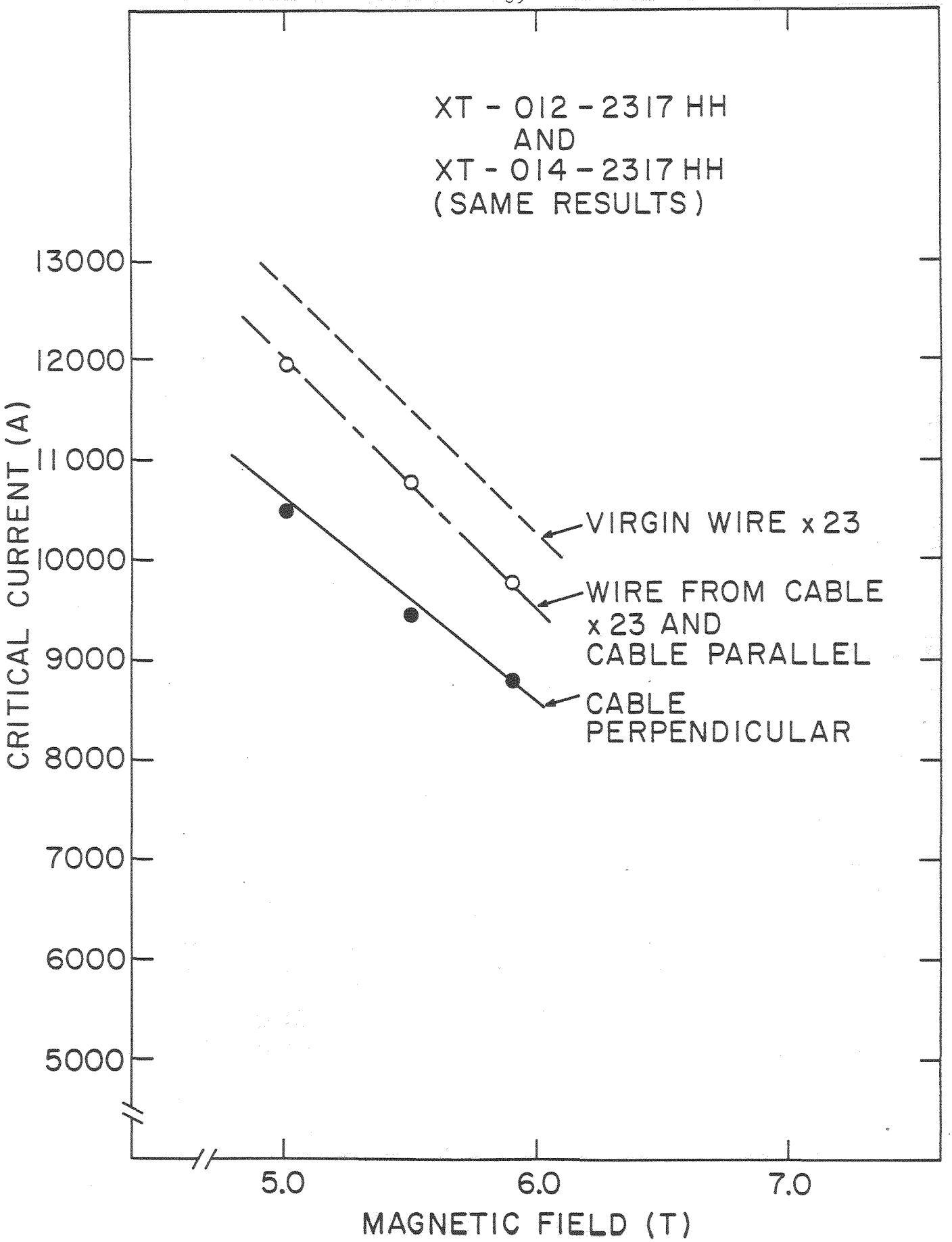


Fig. 7.3-5. Critical current vs. magnetic field results for inner Design D cable and component wire.

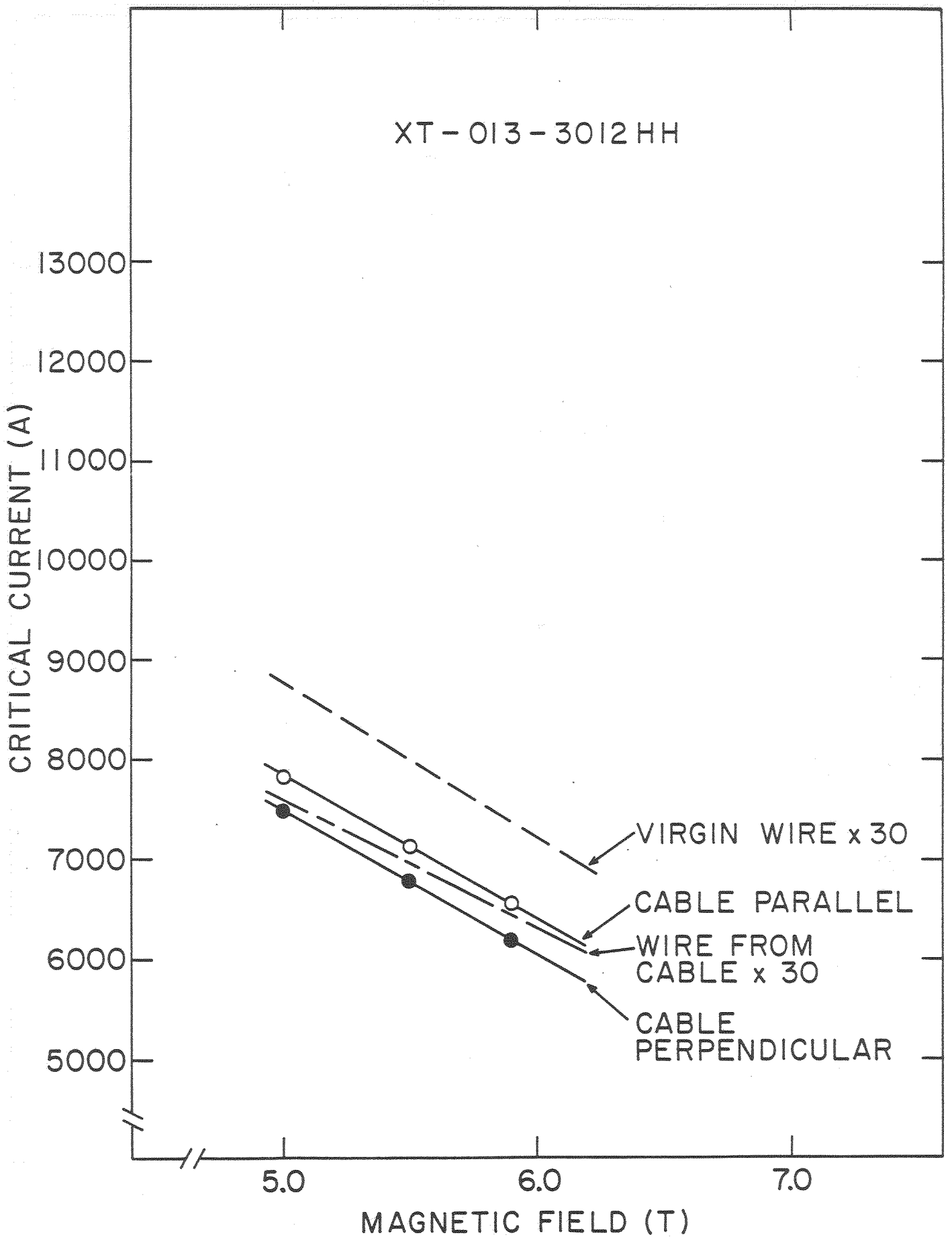


Fig. 7.3-6. Critical current vs. magnetic field results for outer Design D cable XT-013-3012HH and component wire.

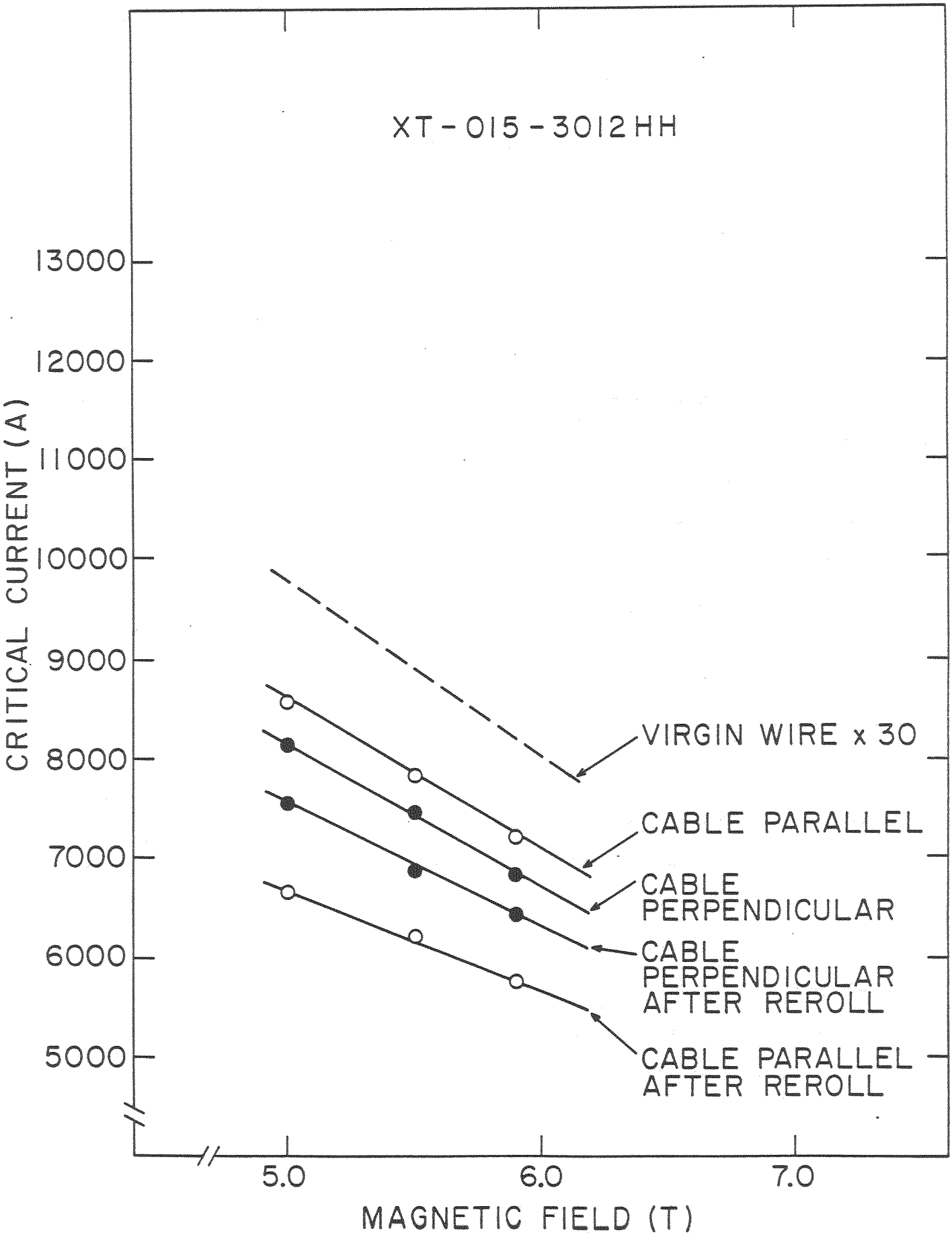


Fig. 7.3-7. Critical current vs. magnetic field results for outer Design D cable XT-015-3012HH and component wire.

7.4 Techniques for Measuring Magnetization

The methods used to measure the magnetization of superconductors are essentially the same as those used to measure the susceptibility of any material. Basically, the effect of the presence of the conductor is compared to a similar volume of vacuum under the same magnetic conditions. This is normally done by placing a specimen of conductor in a suitably shaped pickup coil and observing the effect on the integrated output of the coil. In practice, because of the very small signals involved two bucked pickup coils are used which have been carefully matched to give no output when the applied field is varied. A sample of conductor is then introduced into one of the coils and its effect on the field in that coil is observed as the applied field is swept through the cycle of interest.

In the case of cable samples, long, thin pickup coils which closely fit the sample, give the best sensitivity. In order to include several transposition lengths of cable in the pickup coils, samples of approximately one-half meter are used and a dipole is best suited for providing the energizing field. This also allows any anisotropy in the magnetization to be studied by rotating the conductor which is aligned axially in the magnet. Coupling between filaments due to bridging or lack of twisting will show up as enhanced magnetization. Similarly, coupling between strands can be studied by varying the rate of change of field.

Figures 7.4-8 and 7.4-9 show schematically the measuring techniques and the shape of the coils used in the magnetization apparatus. While the absolute calibration of a magnetization apparatus can be complicated by demagnetization factors and geometrical details, the comparison of cable

samples for relative magnetization is straightforward as long as care is taken to preserve the sample size and shape. For this reason developmental conductors which are not yet available as cables are tested in the form of "simulated cables". These are formed by assembling multiple lengths of straight wire in an array which corresponds to the shape and volume of the standard 30 cm long cable specimen.

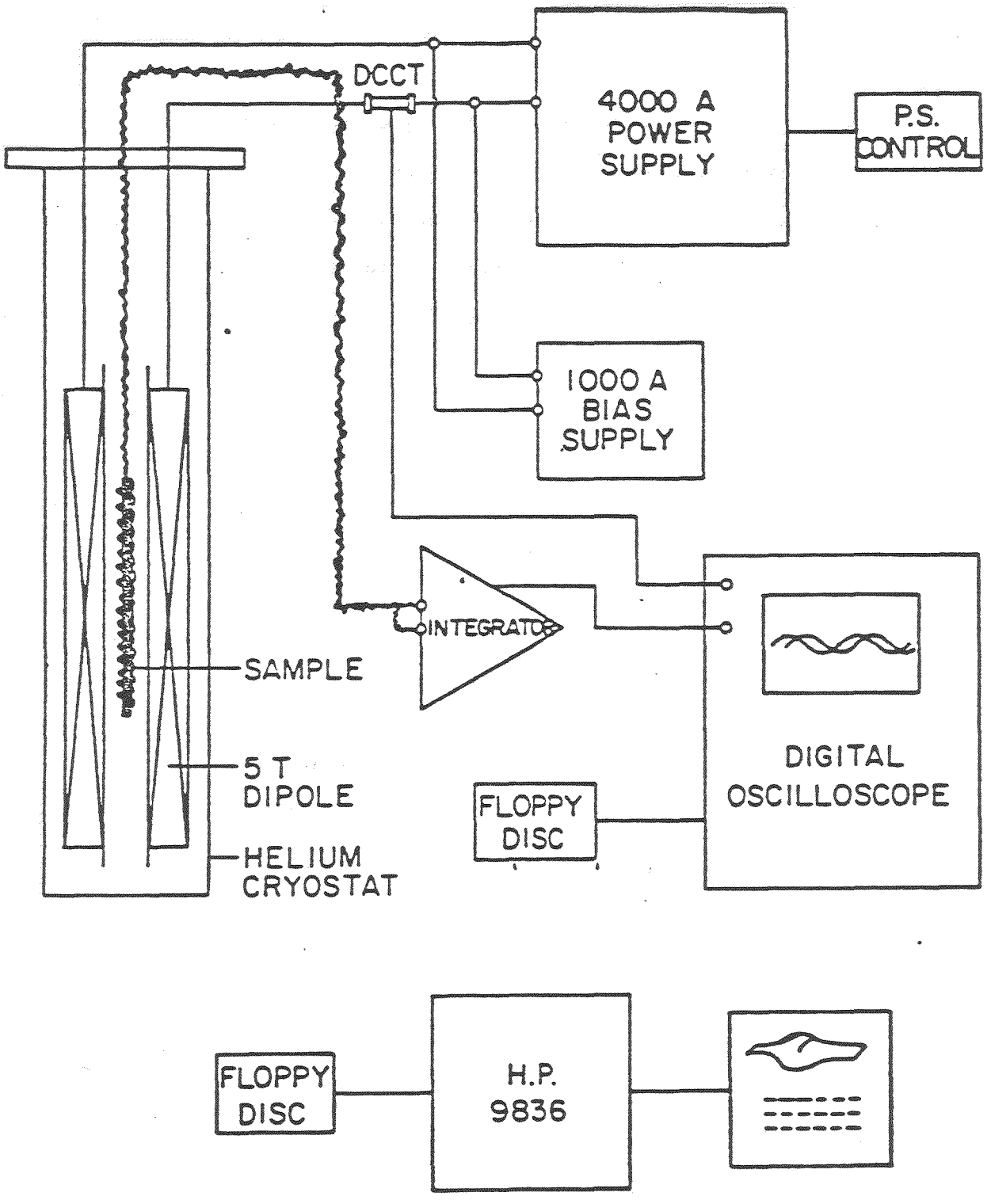


Fig. 7.4-8. Schematic of magnetization measuring technique.

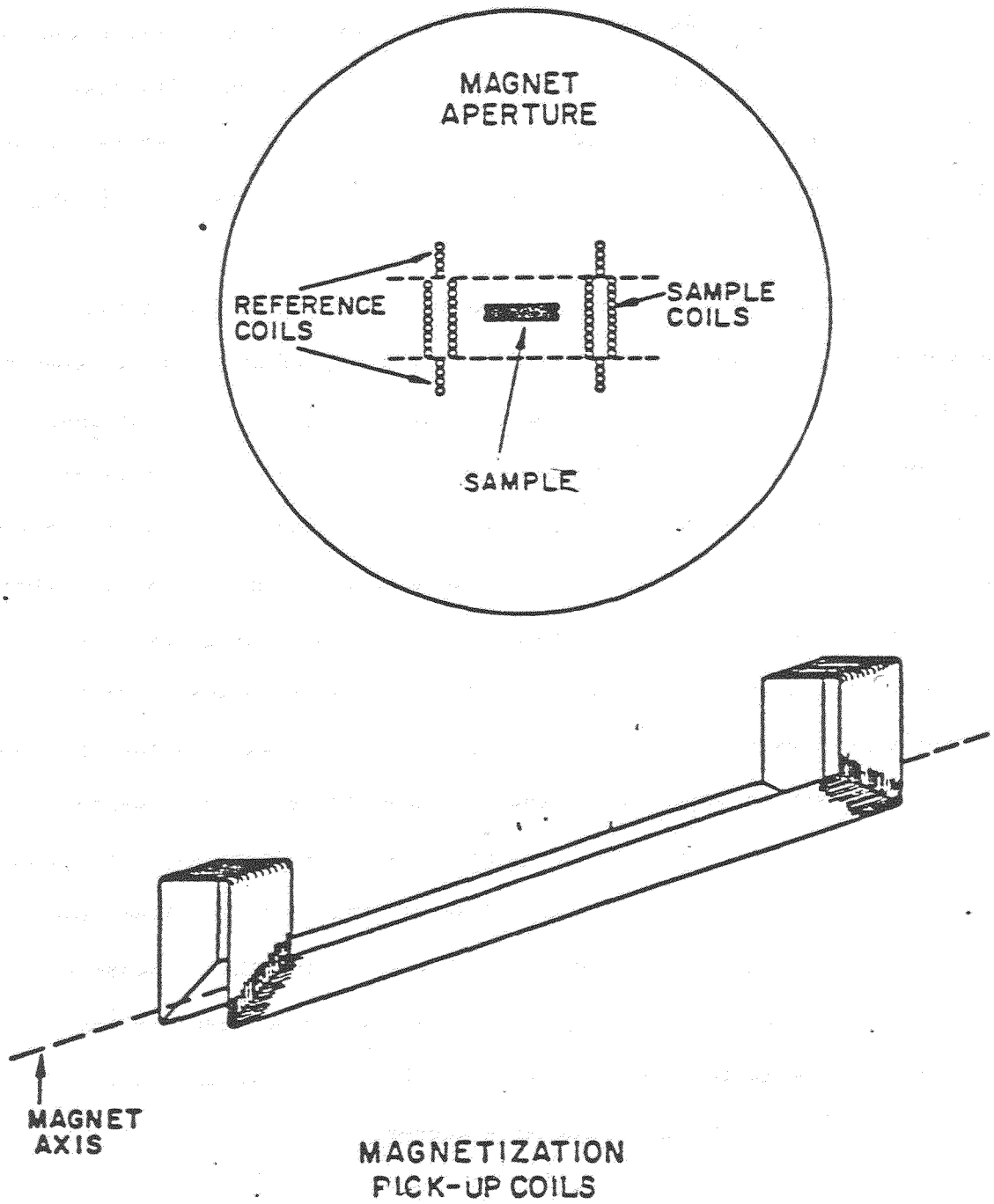


Fig. 7.4-9 Schematic of the magnetization pick-up coils.

8. Cable Mechanical Measurements

8.1. Techniques for Measuring Keystone Angle and Mid-Thickness

A. Keystone Angle Measurement:

A device has been developed at BNL to assist in the measurement of the angle of keystoned cable.[1] It measures the angle of an individual cable cross section under a compressive load (usually 2000 psi); various tensions can be applied up to 100 lb. A picture of the device is given in Fig. 8.1-1.

The device relies on a measurement of the vertical position of an upper plate which is pressed onto the cable with a hydraulic cylinder connected to it by a pivot. Two LVDT's (Linear Variable Differential Transformers) sense the position of the plate and give a digital readout of the deviation from a calibration standard which is used previously to zero the LVDT's. The cable is secured inside an accurately machined slot to maintain its dimensional integrity. The device is capable of measuring to thousandths of a degree, although its reproducibility on an individual cable sample is probably a factor of ten worse than this. This device is very satisfactory for measuring cable keystone angles which must be known to tenths of a degree.

At the present time the cable keystone angle is measured for a sample of each cable length manufactured. However, when the techniques for rolling the cable are finally established, measurements with this frequency will likely be unnecessary. Checks for reproducibility of keystone angle have been made along an individual length of cable and variations are seen to be of the order of a few hundredths of a degree.

B. Mid-Thickness Measurement:

The basic techniques for measuring the cable mid-thickness have been in use throughout the Fermilab ED/S Project and throughout the magnet development phase of the CBA Project at BNL. The method relies on cutting a bare cable sample into ten sections, each 5 inches long. These sections are then placed with alternating keystone direction into a slot designed to match the cable width. The stack height is then measured under a compressive load of 2000 psi.

The measurements are sometimes done using larger fixtures at BNL, but also using a portable device with tooling accurately machined to match. This portable device has been used at NEEW and LBL during cable manufacturing. The BNL fixture is pictured in Fig. 8.1-2.

8.2 Summary of Mechanical Properties of Production Cable

Using the techniques developed for measuring the cable keystone angle and mid-thickness described previously these methods were used to measure the mechanical properties of cable produced for SSC Design D models. The resulting measurements are summarized in Tables 8.2-1 and 8.2-2. One may note there the tendency for the cable width as measured to be slightly above the design value. Currently this is a minor concern and will probably be remedied with improvements to the measuring techniques for cable width.

The cable keystone angle is generally within the specified values in spite of different techniques for grinding the Turkshead rollers used to produce this shape. The cable mid-thickness is very important for molding uniform sized field quality coils and several measurements of that parameter

are shown. Measurements are made now of cable samples taken between individual coils as they are wound and molded to check on the uniformity of the component cable. The outer cable XT-015-3012 HH was found to be substantially oversized at receiving inspection. Subsequent rerolling corrected the mechanical oversize condition. However, this rerolling adversely affected the electrical characteristics of this cable as was described in Section 7.

Fermilab is developing an automatic method for measuring the cable keystone angle and mid-thickness during production. Prototype devices have been built at Fermilab and at BNL. Fermilab staff are now debugging both of these pieces of apparatus and will evaluate their performance for a cable production environment. It is possible that the mid-thickness measurements could be used to control automatically the setting of the Turkshead rollers.

1. A. Bertsche, "Keystone Angle Measuring Devices", Magnet Division Note 95-4, 1984.

Table 8.2-1. Mechanical Properties of Inner Superconducting Cable for SSC Reference Design D

Note: All measurements here are without tension applied to the cable.

	Measurement Date	Mid-Thickness (inches)	Width (inches)	Keystone Angle (degrees)	Comments
Inner Cable (Piece Length) Design Values and Tolerances	-	0.0574 ±0.0005	0.366 ±0.001	1.6 ±0.15	
XT-012-2317HH (880 Ft; 3363 Ft)	2/8/85	0.0576	0.371	1.79	Receiving inspection
	2/22/85	0.0575	0.373	1.75	Recheck
	4/16/85	0.0573	0.370	1.77	Recheck
	5/16/85	0.0574	-	-	Coil beginning SLN-I-005
	5/16/85	0.0573	-	-	Coil end SLN-I-005
	6/4/85	0.0574	-	-	Coil end SLN-I-010
XT-014 (2200 Ft)	5/3/85	0.0583	0.372	1.65	Receiving inspection
	5/16/85	0.0583	0.370	1.63	Coil end SLN-I-006
	6/4/85	0.0584	-	-	Coil beginning SLN-I-008
	6/4/85	0.0585	-	-	Coil beginning SLN-I-009
XT-020 (3090 Ft)	6/4/85	0.0576	0.373	1.68	Receiving inspection
	7/23/85	0.0580	0.371	1.69	Coil end SLN-I-011
	7/29/85	0.0579	0.370	1.70	Coil end SLN-I-012
XT-022	8/6/85	0.0574	0.371	1.73	Receiving inspection

Table 8.2-2. Mechanical properties of Outer Superconducting Cable for SSC Reference Design D

Note: All measurements here are without tension applied to the cable.

	Measurement Date	Mid-Thickness (inches)	Width (inches)	Keystone Angle (degrees)	Comments
Outer Cable (Piece Length) Design Values and Tolerances	-	0.0459 ± 0.0005	0.383 ± 0.001	1.2 ± 0.15	
XT-013-3012HH (4953 Ft)	2/22/85	0.0464	0.388	1.35	Receiving inspection
	5/3/855	0.0462	0.386	1.34	Coil end SLN-0-004
	5/8/855	0.0463	0.385	1.34	Coil end SLN-0-005
	5/8/855	0.0463	0.387	1.36	Coil end SLN-0-006
	5/10/85	0.0464	0.387	1.36	Coil end SLN-0-007
XT-015 (2656 Ft)	5/10/85	0.0467	0.388	1.32	Receiving inspection
	5/13/85	0.0468	-	1.30	Recheck
	5/21/85	0.0456	0.387	1.30	Receiving inspection after reroll
XT-019 (2656 Ft)	6/4/85	0.0458	0.388	1.43	Receiving inspection
	6/12/85	-	0.386	1.44	Recheck
	7/23/85	0.0460	0.387	1.44	Coil end SLN-0-009
	7/29/85	0.0458	0.386	1.44	Coil end SLN-0-010
	7/29/85	0.0458	0.386	1.45	Coil end SLN-0-011
	7/29/85	0.0461	0.386	1.44	Coil end SLN-0-012
XT-021 (2650 Ft)	6/24/85	0.0462	0.386	1.24	Receiving inspection
	7/10/85	0.0461	0.388	1.25	Recheck
	7/23/85	0.0462	0.388	1.28	Coil end SLN-0-013
	7/23/85	0.0462	0.387	1.27	Coil end SLN-0-014
XT-023	8/15/85	0.0458	0.381	1.08	Receiving inspection
XT-025	10/28/85	0.0458	0.389	1.01	Receiving inspection

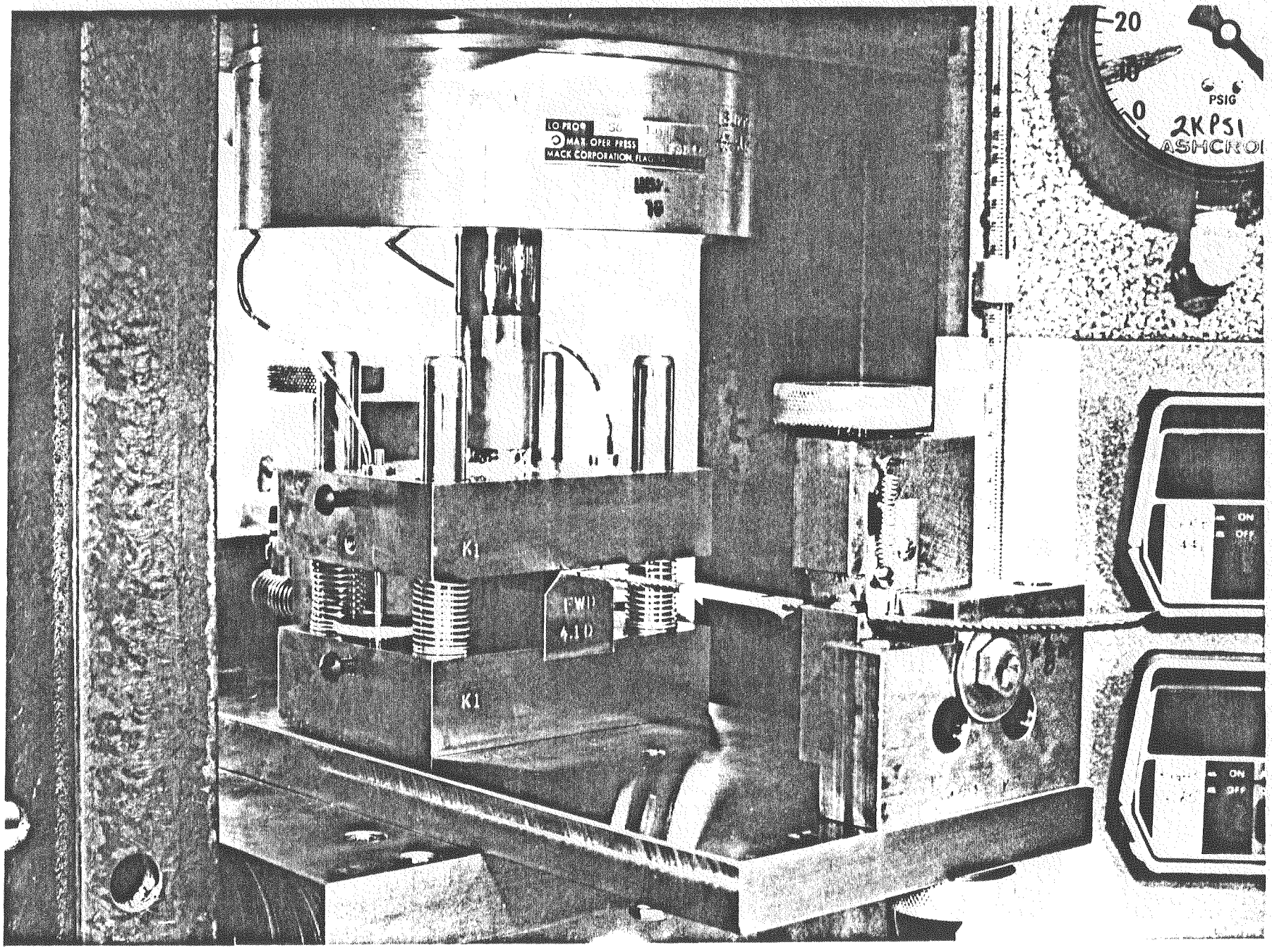


Fig. 8.1-1. Device Used to Measure Cable Keystone Angle.

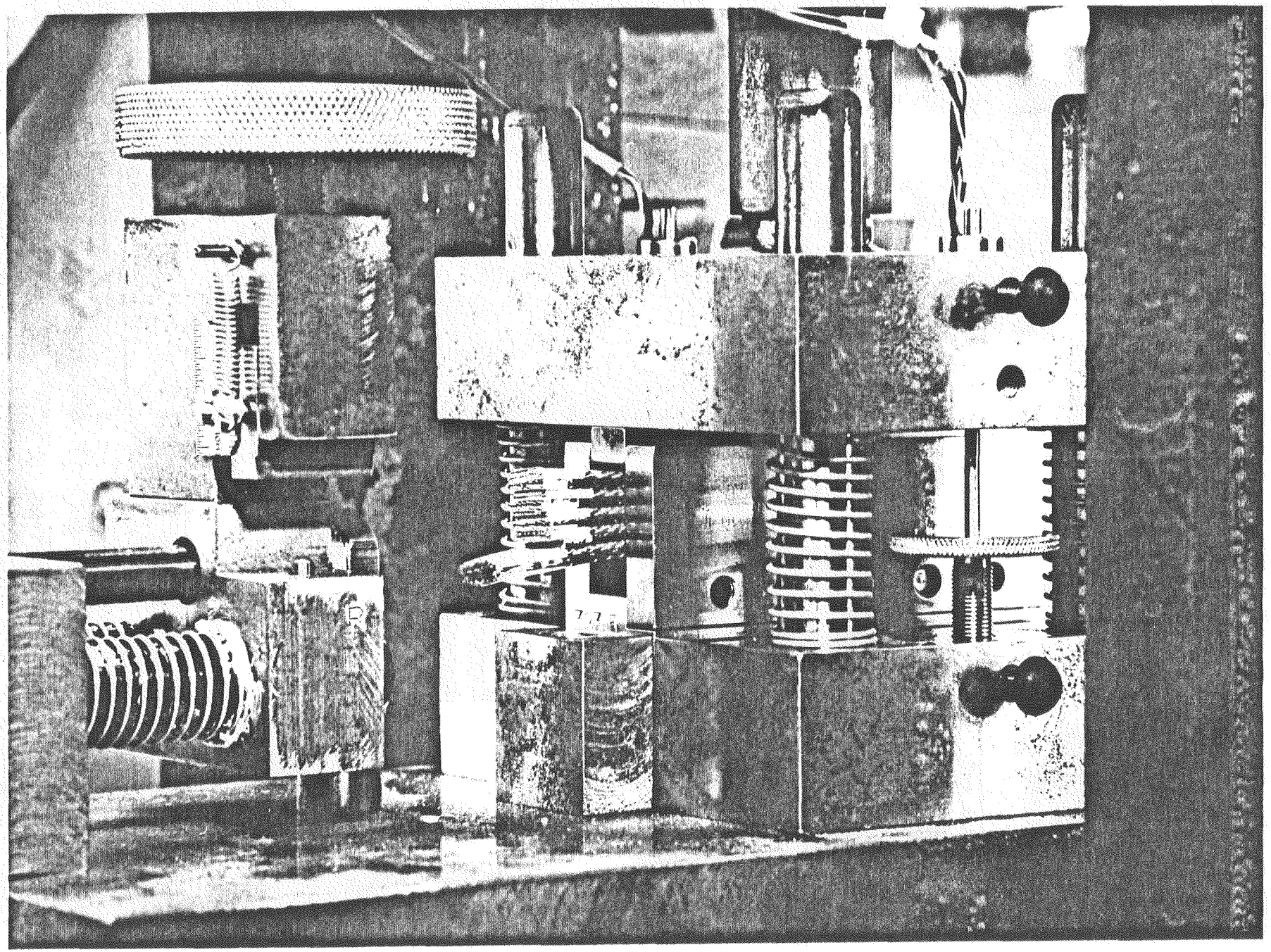


Fig. 8.1-2. Device Used for Measuring Cable Mid-thickness at BNL.

6/6/85

ATTACHMENT

SPECIFICATION FOR NbTi SUPERCONDUCTOR WIRE FOR SSC DESIGN D DIPOLE MAGNETS

1. Technical Requirements

1.1 Conductor Type: The conductor shall be a composite of NbTi filaments in an oxygen-free copper matrix. The superconductor composition shall be Nb 46.5 ± 1.5 wt.% Ti, and shall be high homogeneity grade or equivalent.

1.2 Critical Current: The conductors shall have a critical current greater than the values listed in Table I. These values refer to a test temperature of 4.224 K and a critical current criterion of $\rho = 10^{-14}$ ohm - m, based on the total wire cross section area and with the applied magnetic field perpendicular to the wire axis. The currents given in Table I and the conditions defined above correspond to a current density in the superconductor of 2400 A/mm^2 at 5 T and 953 A/mm^2 at 8T.
A possible incentive factor for improvement of the current density performance above that specified is:

2% price increase for each current density increase of 100 A/mm^2 (~ 4%) at 5T.

1.3 Filament Size: The vendor can choose a nominal filament size of 5 microns or less.

1.4 Copper-to-Superconductor Ratio: The copper-to-superconductor area ratio is determined by first weighing a length of wire and

then weighing the filaments after dissolving the copper matrix in the same wire. The ratio is defined by the equation and constants below; the required values and tolerances are given in Table I.

$$\frac{\text{Area of Copper}}{\text{Area of Superconductor}} = \frac{\text{Density of Superconductor}}{\text{Density of Copper}} \times \left[\frac{\text{Total Weight}}{\text{Weight of Superconductor}} - 1\right]$$

Density of Superconductor = 6.02 gm/cm^3

Density of Copper = 8.95 gm/cm^3

1.5 Resistance at Room and Transition Temperatures:

The resistance of the wire at room temperature (or normal state resistance) is usually expressed as R at 295K or R_{295}. It is an important parameter for magnet construction and depends on the content and purity of the copper. The resistance of the wire at transition temperature, usually expressed as R at 10K or R_{10} can also provide a convenient independent check of the copper-to-superconductor ratio. The procedures for measuring R_{295} and R_{10} are described in Appendix A of this specification. The guideline values for resistances and tolerances are given in Table I.

1.6 Copper Residual Resistivity Ratio: The RRR for wire at final size, equal to R_{295}/R_{10}, is defined by the values of R_{295} and R_{10} given in Table I. The target values for RRR as given there are greater than 80 for the inner layer wire and greater than 90 for the outer layer wire.

Table I. Requirements for Inner and Outer Layer Superconducting Wire

Requirement Value	Inner Layer	Outer Layer
Minimum Critical Current at 5T	535 A	282 A
Minimum Critical Current at 8T	212 A	---
Copper-to-Superconductor Ratio	(1.3 ± 0.1):1	(1.8 ± 0.1):1
Wire Diameter	0.0318 ± 0.0001 in.	0.0255 ± 0.0001 in.
Guideline Value		
R_{295} (micro-ohms/cm)	580 ± 15	800 ± 15
Maximum R_{10} (micro-ohms/cm)	7.0	9.0

1.7 Twist Pitch: The wire shall be twisted to produce a twist pitch of 1.0 ± 0.1 twists per inch at the final wire size. All wire shall be twisted clockwise so that the filaments follow the same rotation as a right-hand screw thread.

1.8 Final Anneal: The wire shall be annealed at 260°C for 3 hours followed by a furnace cool. This heat treatment will take place after the final drawing and twisting and shall be performed in a protective atmosphere so that the copper is not oxidized. Annealing is required to prepare the wire for subsequent cabling.

1.9 Surface Condition: The wire surface shall be free of all surface defects, slivers, folds, laminations, dirt, or inclusions. No NbTi filaments shall be visable.

2.0 Minimum Lengths: The minimum acceptable length at final wire size shall be 2500 ft. This minimum length shall be determined after all lead and end defects have been removed by cropping. These defects include areas of distorted cross section due to wire point by swaging, any foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion.

2. Seller's Quality Assurance, Inspection and Tests

2.1 Seller Responsibility: The seller shall establish a quality assurance program that assures manufacture of a product that complies with this specificaiton. The seller shall provide the purchaser with seller's sampling plan and inspection schedule and a description of the means whereby he will maintain control over his own and his subcontractor's fmanufacturing processes, inspection and testing, handling and storage. Included shall be means for identification of conforming material, serialized identification by lot of finished product, and procedures for the segaretation of nonconforming material. The seller's record-keeping system shall be such that traceability exists for all QC records and material used in the conductor from the time raw materials are received by the

seller until the final conductor is completed. In particular, detailed records shall be maintained for billet extrusion conditions (time and temperature of pre-heat, extrusion temperature and speed, post extrusion cooling if any, etc.) and wire annealing conditions.

2.2 Test Witnessing: The purchaser reserves the right to witness manufacturing steps, tests, and inspections established under the seller's quality assurance program, and all other testing performed at the seller's plant and his subcontractor's plants to demonstrate compliance with this specification. Any information of a proprietary nature must be identified in the seller's bid response. The seller will not be required to disclose this proprietary information, but will be required to show that adequate records and quality controls are maintained in these proprietary steps.

2.3 Sample Testing: The seller shall measure the critical current for samples from each continuous length of wire at B = 5T and 8T, and T = 4.224 K. If a temperature of 4.224 K is not possible, measurements may be made at another temperature and a conversion constant must be supplied. The conversion constant must be approved by the buyer. A 5-foot sample of wire adjacent to each length used by the seller for critical current measurements shall be sent to the buyer. These samples shall be identified by

billet number, spool number, original continuous wire length, and purchase order number. Samples will be checked by the buyer that they conform to all aspects of the specification, both mechanical and electrical. ASTM B-714-82 and Item 1.2 of this specification will form the basic method and criteria for measurement of the critical current of these samples. The techniques described in Appendix A of this specification are consistent with the ASTM procedures for determining the short sample critical current and will be employed by the buyer to verify the measurements. In addition, Appendix A describes the practical test methods to be used for determining the wire normal state resistance and resistance at transition temperature.

2.4 Certification: The seller must provide a written statement with each wire shipment certifying that it meets all of the buyer's specifications.

3.0 Spooling and Shipping: Wire shall be level-wound. Spools shall be labeled with wire length, weight, billet number and purchase order number. Spools shall be packaged so that neither spools nor wire are damaged in shipment.

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APPENDIX A. VERIFICATION OF ELECTRICAL PROPERTIES OF SUPERCONDUCTING WIRE

A. Short Sample Test Method for Critical Current Determination of Twisted Multifilamentary Wire.

1. General Outline; Definition of Critical Current

The V-I curve is determined as a function of increasing current until a sufficient voltage necessary to define I_c is obtained. This measurement is carried out in specified external fields, 5T or 8T typical, applied normal to the wire axis, and in a temperature bath of liquid helium at 4.224 K. For currents less than the quench current the V-I curve is reversible.

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

$$R = 10^{-14}/(\pi D^2/4) \text{ ohms/m}$$

where D is the wire diameter in meters. The effective resistivity of the wire is 10^{-14} ohm•m.

2. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical former so that it fits in a solenoid magnet (see Section 4 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. 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, for example, use of a G-10 or stainless steel 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).

3. Procedure (See Fig. 3)

The sample length (between voltage taps) should be $\gtrsim$ 25 cm. This corresponds, typically, to a voltage drop of several microvolts. This is readily measured with the aid of a suitable pre-amplifier or digital voltmeter. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The amplifier signal should be recorded on a 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 stable, well-filtered power supply. The current should be measured to an accuracy of ± 0.5%. Use of a low resistance normal metal shunt connected across the sample is feasible provided the resulting correction for sample is accurately known (1% in I_c). Electronic circuitry for quench protection is preferable.

Frequently a quality index, n, is estimated using either the equation $V = \text{constant} \times I^n$ or $\rho = \text{constant} \times I^n$.

4. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to ± 0.5%. The direction between field and wire axis must be 90° ± 6° everywhere. This range of angles corresponds to a variation in I_c of 0.5%.

5. Temperature Bath Correction

The specification temperature is 4.224 K, 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 an accuracy of ± 0.010 K(10 mK). A deviation of 25 mK from 4.224 K corresponds to an error in I_c of 1%. For larger temperature excursions of 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 is the transition temperature at the specified magnetic field. (T_c = 6.9 K at 5T and 5.7 at 8T.) I_m is the current measured at temperature T_m, and I_c is the critical current at the specification temperature, T = 4.224 K.

B. Test Method for Normal State Resistance of NbTi Superconducting Wire

1. General Outline; Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of NbTi multifilamentary composite wire which is used to make

high current superconducting cables. The composite matrix is copper. The resistance per unit length is determined at room temperature (295 K) and just above the transition temperature ($T_c \sim 9.5$ K). These quantities are designated R_{295} and R_{10}, respectively, and are measured with an accuracy of 0.5%. The ratio R_{295}/R_{10} is defined to be the residual resistance ratio, RRR.

R_{295} is determined chiefly by the copper matrix. For a given wire diameter it provides a measure of the volume copper-to-superconductor ratio (Cu/SC) of the wire.

R_{10} is determined chiefly by the residual resistance of the copper matrix. The ratio RRR provides a measure of the elecrical purity of the copper matrix.

2. Apparatus Description

A four wire method is used to determine the resistance. The wire sample is mounted on a probe which is also used for superconducting critical current measurements. It has leads which are suitable for carrying ~ 600 A from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a digital voltmeter of 0.1 μV resolution. It is helpful during the low temperature measurement to use and X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time (see Section 4 below).

Current in the range 0.1 to 1.0 A is provided by a well regulated and filtered DC power supply. It is measured by a shunt of 0.2% accuracy.

In the room temperature measurement a thermocouple device of 0.1°C accuracy is used to determine the ambient temperature.

3. Sample Mounting

The test specimen is wound on a grooved former. The ends are soldered to the copper terminations of the current leads over a minimum length of 1". Voltage taps are soldered to the specimen at a distance of at least 1". Voltage taps are soldered to the specimen at a distance of at least 1" from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% this length should be 50 cm or more. The voltage leads should follow the sample in a non-indictive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively in the former.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. A typical value is 0.5A. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is raised so that the lowest point in the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. As the sample warms, the voltmeter reading will go suddenly from zero to a finite value corresponding to its normal state resistance. The latter is substantially independent of temperature from the transition temperature, T_c, to 15 K, so that the voltage remains constant long enough to be read and is recorded. With a reasonably designed probe and former it may take 1 or 2 seconds for the specimen to go normal. The resistance will remain in the residual resistance region several times longer than this. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible.

5. Room Temperature Correction

Normally occurring room temperature variations may produce significant variations in the measured resistance. Designating this resistance as R_m and the ambient temperature as T_m(°C), the resistance at the reference temperature of 295 K is calculated as follows:

$$R_{295} = R_m/[1 + 0.0039\ (T_m - 22)]$$

The effect of the NbTi is neglected for the purpose of this correction.

6. Copper-to-Superconductor Ratio

The copper-to-superconductor (Cu/SC) ratio is related to R_{295}. Therefore, an independent check can be made of this ratio measured by a weighing technique and by measuring R_{295}. The range of acceptable values of R_{295} is determined by the Cu/SC ratio and the wire diameter.

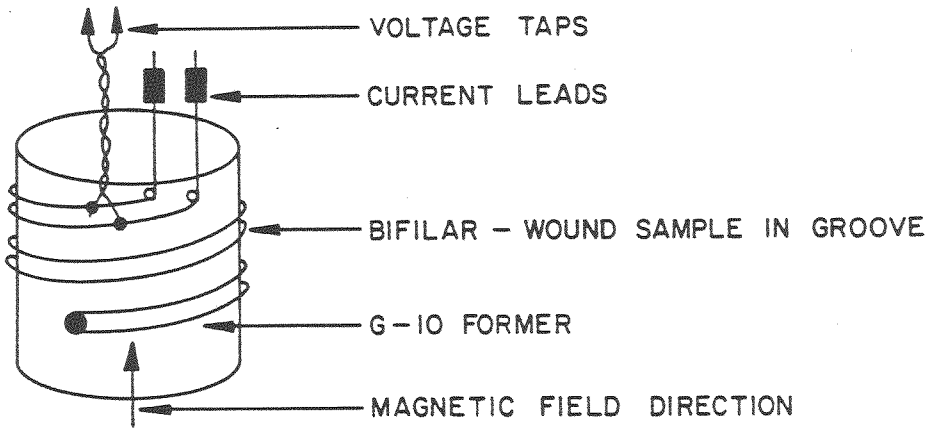

FIG. 1 Non - inductive sample mounting arrangement

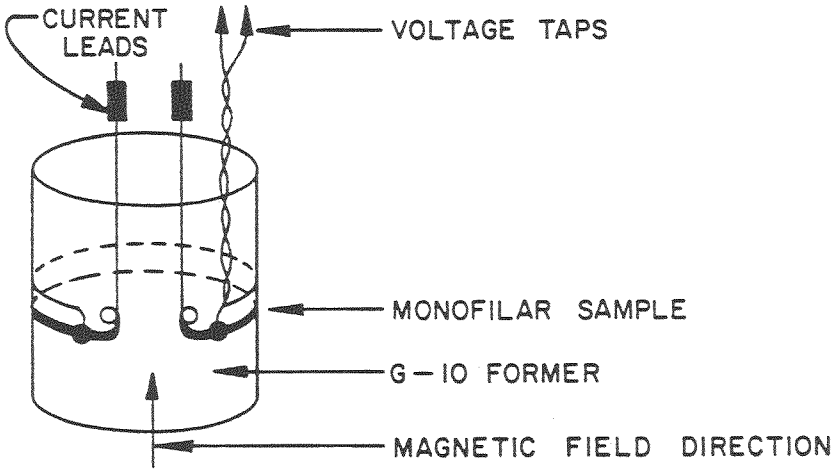

FIG. 2 Alternative sample mounting arrangement

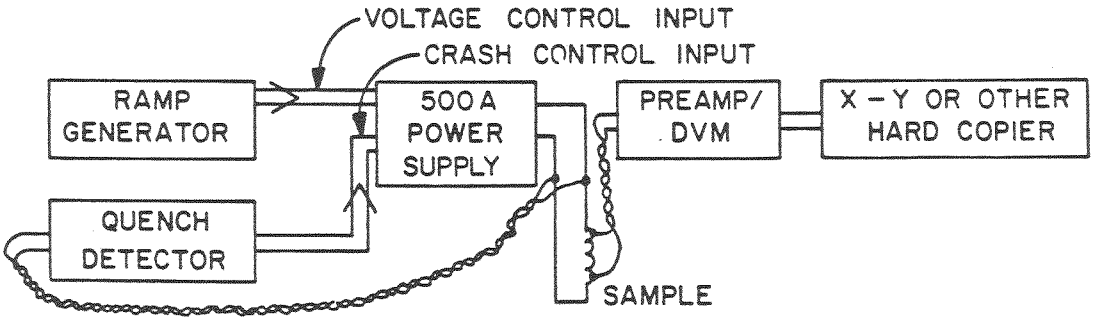

FIG. 3 Schematic of Electrical Measurement Apparatus