R. M. Scanlan
April 8, 1987

SSC-MAG-138
SSC-N-318

FY87 SSC CONDUCTOR AND CABLE R&D PLAN

Introduction

The R&D Plan described here is the cumulation of a number of workshops and meetings with the various interested parties. Three workshops (Madison, Nov. 1986, Berkeley, Jan. 1987, and Madison, Feb. 1987) were held which focussed on recent experimental results, SSC specification parameters, and key R&D issues, respectively. In addition, meetings with CDG personnel have helped define the priorities, e.g., critical current, mechanical properties, and filament size. Finally, V. Karpenko has provided key dates for conductor procurements, at which time the R&D information must be available in order to make an impact. These requirements have been discussed with the three U.S. wire manufacturers and I have received their input on both the technical and cost aspects of this program. I will now discuss the main components of the proposed program, including (1) Purpose, (2) Goals, (3) Plans, and (4) Costs for several program options.

Purpose

The purpose of this R&D program is to identify the optimum set of parameters which will provide SSC cable with (1) adequate margin for high yields in manufacturing, and (2) adequate design margins in terms of high I_c, low cable degradation and good mechanical properties.

Plan

This R&D program is a logical sequence to the previous SSC-related programs in which many of the same parameters were investigated, but over a much wider range. In addition, this program seeks to determine the optimum balance between critical current, filament size, filament spacing, and cable manufacturability. These issues were discussed at length during the Feb. workshop at Madison; the conclusions and recommendations from this workshop are included in the workshop report written by D. Larbalestier and attached as Appendix A. The R&D program proposed for FY87 incorporates the recommendations from the Madison Workshop Report.

In addition, it includes the fabrication of one billet of outer layer strand by each manufacturer. This is necessary in order to (1) allow the manufacturers to optimize the thermomechanical processing for the outer layer material, since the optimum probably will be different from that found for the inner layer strand, and (2) to provide the manufacturers with experience in fabricating outer layer cable in preparation for fixed price production contracts.

New Results - Three new results, not available at the time of the workshop, are relevant to this program and will be summarized. OST delivered approximately 400 lbs. of inner layer wire with 1.5/1 Cu/SC ratio and with a strand $J_c(5T) = 2700\ A/mm^2$ and an average piece length of about 10,000 ft. The filament size was 5 μm. Also, Furukawa delivered both inner layer and outer layer cable made for the SSC program under a U.S.-Japan High Energy Physics Agreement. The strand for this cable had a filament diameter of 4.7 μm and was produced with good piece lengths. The $J_c(5T)$ values were $> 2750\ A/mm^2$ for the outer layer strand and $> 2500\ A/mm^2$ for inner layer strand. Both of these results reaffirm our belief that strand can be made to SSC specification. In addition, results of an experiment on filament spacing was completed by E. Gregory et al., and will be published in Cryogenics. He prepared a series of billets using "the Fermi Kit" approach and varied the filament spacing. The results showed that the $J_c(5T)$ could be increased from $2000\ A/mm^2$ to $2500\ A/mm^2$ simply by changing the spacing to diameter ratio (s/d) from that in the Fermi Kits (0.35) to 0.13. This result corroborates earlier results which show that filament spacing is an important parameter that must be controlled and optimized.

Filament Size - Two filament sizes will be investigated, 6 μm and 9 μm. The present SSC specification calls for a filament size of 6 μm and a minimum filament spacing of 1 μm. These parameters insure that proximity effect coupling at the injection field is eliminated and also that the s/d value is safe with respect to preventing filament sausaging. A filament size of 9 μm will be investigated as an alternative which may provide a higher J_c with good mechanical properties. In addition, a 9 μm filament size can be achieved in the SSC strand sizes via the "Fermi Kit" approach and this may reduce the cost of the conductor.

Cold worked Rod - The cold work range available for optimizing J_c after extrusion is less for the SSC inner layer conductor, and may be marginal for achieving $J_c(5T) > 2750$ A/mm^2 using smaller than 12" diameter billets. (This has been confirmed by IGC with billets 5183, 5210, and 5212, and by Furukawa with billets KO1, 2, and KI1-6.) It may be easier to meet the new inner layer J_c spec. (1650 A/mm^2 at 7T) with less cold work than the old value at 5T; however, using cold worked rod may help provide additional margin. On the other hand, there is some risk that cold worked rod may (1) increase sausaging during extrusion due to a greater mechanical mismatch between the NbTi and Cu, or (2) produce more mechanical problems in drawing or cabling. These questions should be resolved upon completion of the present matrix of billets, which includes four billets with cold worked rods. The complete R&D billet matrix is shown in Table I.

Program Timing and Costs

Work is underway at Supercon and contracts are being finalized at IGC and OST for the first series of billets (annealed rod, 6 μm and 9 μm filament sizes). The funding for this work was included in the initial LBL FY87 budget and the total will be about $420K. The remaining six inner billets to complete the cold worked rod segment of the matrix will cost an additional $420K ($318K in FY87 and $102K in FY88). The costs are summarized in Table II. The three outer layer billets will cost another $195K ($140K in FY87 and $55K in FY88). These costs are somewhat higher than the original estimate made in Nov. 1986 due to (1) two-thirds of the billets are inner layer and hence require more NbTi, and (2) we are proposing 12" diameter billets rather than 10" diameter billets in order to obtain more cold work and hence higher J_c values. Assuming the add-on contracts are in place by Jun. 1987, we should have the results of the strand optimization studies by Dec. 1987 and the results of the cabling studies by Feb. 1988. These results would then be used to set the specifications for the cable procured for the FY98 dipole program.

Table I - R&D Billet Matrix

Company	Billet	Fil. Size	Fil. s/d	NbTi Rod A = annealed CW=cold worked	Cu/SC Ratio	Strand
Supercon	1	6	.15	A	1.5/1	Inner
	2	6	.15	CW	1.5/1	Inner
	3	9	.15	A	1.5/1	Inner
	4	9	.15	CW	1.5/1	Inner
	5	6 or 9*	.15	A	1.8/1	Outer
IGC	1	6	.20	A	1.5/1	Inner
	2	6	.20	A	1.5/1	Inner
	3	9	.20	A	1.5/1	Inner
	4	9	.20	A	1.5/1	Inner
	5	6 or 9*	.20	A	1.8/1	Outer
OST	1	6	.17	A	1.5/1	Inner
	2	6	.17	CW	1.5/1	Inner
	3	9	.17	A	1.5/1	Inner
	4	9	.17	CW	1.5/1	Inner
	5	6 or 9*	.17	A	1.8/1	Outer

*Filament size will be chosen based on best results obtained on Inner layer billets.

Table II - FY87 SSC Conductor R&D Program Costs

Scope: Three - U.S. manufacturers with parallel R&D programs.
Two filament sizes X 2 cold work conditions X 3 manufacturers defines a 12 billet Phase I Program.
One (optimized) filament size X 3 manufacturers defines 3 additional billets to optimize Outer layer cable.

Note: Costs for 6 billets were included in original LBL FY87 plan and are not included below.

I. Industrial contracts for work to be completed in FY87 (progress payments).

Task	Completion Date		Cost
1. Procure raw materials	8 wks. ARO	6 billets @ $30K/billet 3 billets @ $23K/billet	= $250K
2. Preliminary materials processing (monolith extrusions)	14 wks. ARO		$135K
3. Multifilamentary extrusions	18 wks. ARO		$ 73K
	FY87 Industry Subtotal:		$458K

II. Industrial Contract costs for work completed in FY88:

Task	Completion Date	Cost
1. Wire drawing and testing	24 wks. ARO	$ 70K
2. Cable manufacturing	30 wks. ARO	$ 60K
3. Analysis and final report	38 wks. ARO	$ 30K
FY88 Industry Subtotal:		$160K

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INDUSTRIAL R&D PROGRAM FOR SSC CABLE

Report of a program developed at a workshop on conductor R&D for advanced accelerators held February 5, 1987 at the University of Wisconsin-Madison.

Workshop participants:

Art Greene	BNL	Bill Sampson	BNL
Bill Hassenzahl	DOE	Ron Scanlan	LBL
Vic Karpenko	SSC-CDG	Bruce Strauss	Powers Associates
David Larbalestier (Chair)	U.W.	Dave Sutter	DOE
Al McInturff	FNAL	Clyde Taylor	LBL
Bob Remsbottom	U.W.	Maury Tigner	SSC-CDG

Report by David Larbalestier
March 17, 1987

APPENDIX I

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Report by David Larbalestier
March 17, 1987

I. Workshop Purpose

The purpose of the meeting was twofold:

A. To discuss the technical issues involved in the procurement of high current density, fine filament Nb-Ti strand and cable.

B. To decide on an industrial R&D program of about 15 billets which would address the outstanding technical issues in such a way that large scale procurements of cable meeting SSC requirements would be possible at the conclusion of such a program.(1)

II. Technical Issues

A. Critical Current Density

There was general agreement on the following three propositions:

1) High J_c remains a major goal of the SSC conductor. It confers margin in several very important areas: manufacturing margin against filament sausaging, barrier defects and cable degradation, as well as any future need to increase the Cu:NbTi ratio.

2) The SSC specs are currently 2750 A/mm^2 at 5 T (appropriate for outer conductor) and 1100 A/mm^2 at 8 T (appropriate for inner conductor).(2) A goal of the immediate R&D program should be to raise the attainable J_c to 3000 A/mm^2 (5 T) and 1300 A/mm^2 (8 T), in order to provide appropriate manufacturing margin.

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(1) The program which emerged from our discussions covers the industrial production of cable from 4 different conductor designs. It covers the inner conductor only, since this is the harder of the 2 conductors to cable and to produce with high J_c. A realistic aim for the program is to use it to establish the parameters defining an optimized cable which meets SSC requirements on a time scale compatible with the SSC schedule (i.e. before June 1988). Full industrialization will require a future procurement of multiple billets of the same design.

(2) The most recent specifications are SSC-MAG-118 for strand and SSC-MAG-119 for cable. These are included in annex. The most recent revision was made 1.13.87. Several participants noted inconsistencies in these specifications as written. Strand I_c (and J_c) is specified at both 5T and 8T. Cable I_c is specified at both 5T and 7T. The most appropriate integer field values for the SSC are 7T for the inner conductor and 5T for the outer conductor. Since most measurements and most characterizations have been performed at 5T and 8T, definition continues to be made at these 2 values. Nevertheless, logic suggests that we should collectively consider moving to a new definition, this being at 7T for the inner conductor and 5T for the outer conductor. A low field magnetization or transport J_c measurement would provide the second specification point. This latter measurement has not yet been explicitly addressed by the SSC specification.

3) The J_c specs are hardest for the inner .0318" dia conductor because the available strain from 12" to .0318" dia is less than optimum. If better optimized fabrication procedures can be developed for the inner conductor, they should be easily implemented for the outer conductor because of its greater strain.

Larbalestier reviewed various processing options for the inner conductor aimed at avoiding the strain limit and raising J_c. He presented results showing that the J_c was very sensitive to the prestrain before the first heat treatment. J_c(5T) values of 3050 A/mm^2 were obtained in a 55 filament conductor from 3 H.T. when the prestrain was 6.6. Raising the prestrain to 7.7 raised J_c to 3300 A/mm^2. The limited strain space of the SSC inner conductor unfortunately restricts the billet prestrain to 4.5-5.5. A potential method of increasing the filament prestrain is to use cold-worked rod in the billet. However the experimental evidence on the usefulness of this procedure is unclear. Although recrystallization does not occur during extrusion, there may be so much recovery as to render the use of cold-worked rod valueless.

B. Filament Size

Several propositions received general assent:

1) Tigner said the minimum filament size (d) was 5 μm diameter. The correctors for the SSC could easily accommodate d of 5-10 μm. If real advantages (eg. increased J_c) could be derived from 10-20 μm filaments, then it would probably be beneficial to redesign the correctors to accommodate a larger d.
2) There is a tendency for J_c, the mechanical properties and the yields to decline as the filament size declines from 10-15 μm to 5 μm. The reasons for this are not well understood at this time. Only the diminished magnetization of finer filaments provides a driving force for finer filaments.
3) Filament sausaging is the major problem to control. We do not yet understand whether local ratio, diffusion barrier quality, grain size, heat treatment or other unknown variables are dominant.
4) Fine filaments mean large numbers of filaments and increased problems in billet stacking. This choice raises the cost and perhaps diminishes the yield. Scanlan described the wire length experience obtained on SSC and RHIC billets with $d < 8$ μm. Wire lengths have increased rapidly but need considerable further improvement.
5) Consistency of low field magnetization is desirable. Significant sausaging is therefore undesirable, even if the 5 T and 8 T transport current specifications are met.

There was general agreement in discussion that the filament size range needing study was approximately 5 to 10 μm. Tigner commented that it was worth a few million dollars of R&D to really understand how to get the best and most consistent cable properties.

C. Local Ratio

Much work has been done recently by the 3 wire manufacturers on the local ratio, s/d, (where s is the inter-filament spacing). Investigations of the influence of s/d upon filament quality and J_c have figured extensively in the SBIR supported work of IGC and Supercon. Although many participants in the workshop have seen reports of this work in SBIR proposals, there is as yet no permanently accessible description of the experiments. It is thus hard to evaluate critically. At present Supercon prefers an s/d ratio of order 0.15, IGC one of order 0.2.

Agreement was obtained on the following propositions:

1) s should be 1 μm minimum (as in the present version of the SSC specification).(3)
2) Smaller s/d ratios produce better filament quality.

However, Taylor described a qualitative argument showing that too low an s/d ratio was bad for stability.(4) Since much of the SBIR work was conducted with 2" or 4" dia billets and both Supercon and IGC received Phase II awards with some component of s/d R&D in them, there was some hope that further information could be quickly obtained. Greene described some CBA kit work done by Supercon and Scanlan some SSC R&D billet results which confirmed that reduced s/d ratio produced better properties in large scale billets.

D. Diffusion Barrier

General agreement was obtained on the following points:

1) Nb foil is the only proven diffusion barrier. However, other potential alternatives exist eg. sputtered Nb, V and Ni.
2) Cold drawn Nb barriers are unsatisfactory. Hot extruded foil is the preferred present method but is not always fully effective.
3) Good diffusion barriers are required in order to achieve 3000 A/mm^2 (5 T) and 1300 A/mm^2 (8 T).
4) Significant experimental variables exist in the cladding process: billet machining, billet and foil cleaning and thickness, quality and number of the Nb foil wraps.
5) The residual resistance ratios of clad Nb-Ti composites are considerably higher than unclad composites.

Larbalestier presented results on monofilament clad rod (procured by Scanlan from TWCA for experimental billets by IGC and UW) in which the clad rod was inferior to large filament unclad rod. The n values of the as drawn rod were low (<20 at 5T), indicating considerable lengthwise

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(3) Sampson commented in review that this figure is conservative: 0.75 μm spacing would have negligible effect on field quality.

(4) Several participants requested a detailed version of this argument.

variation of I_c. The reasons have not yet been identified, in spite of much work. Scanlan described conductors to be delivered to LBL in the next 3-4 months. Conductors from IGC, Supercon and OST will all have been fabricated from hot extruded 5.75" dia clad monofilament. Conductors from Furukawa will have been prepared in a generally similar way. The experience of these billets will be very important in evaluating the quality of barrier technology.

E. Cu:Nb-Ti Ratio

Minor changes to the SSC spec were made at an SSC conductor R&D working group held Jan. 13, 1987 under Scanlan's chairmanship at LBL. The ratio for the inner conductor was changed from 1.3±0.1:1 to 1.3+0.1/-0.0:1. This was stimulated by concerns about the stability of the 1.3:1 inner conductor.

Sampson described recent experiments on the training of cable short samples having various Cu:Nb-Ti ratios. His results showed that about 20 training quenches were needed to get a 1.2:1 cable up to short sample critical current. The number of quenches declined significantly as the ratio increased, being 10 at 1.3:1, 3 at 1.4:1 and $<$ 1 at $>$ 1.5:1. He proposed that changing the ratio of the inner conductor from 1.3:1 to 1.5:1 would produce a considerably greater margin of stability.

There was considerable discussion of this proposal. The physical basis for the results is unclear, since there was no correlation with the electrical conductivity of the copper stabilizer (for example, a 1.8:1 cable with higher resistance than a 1.3:1 cable showed no training, while the 1.3:1 cable did). Conductor enthalpy does not appear to be the deciding factor since the enthalpy of Nb-Ti is significantly greater than that of Cu. Change from 1.3:1 to 1.5:1 is not obtained for nothing: it requires an 8.7% increase in J_c to maintain I_c constant. However, if magnet stability is enhanced, then less J_c margin is required. It is also possible that cabling degradation may be lower for the higher ratio conductor.

A number of points were raised in discussion. Taylor argued for maintaining the ratio at 1.3:1 and for doing some billets with very high conductivity Cu. The placement of Cu within the conductor was discussed. Various proposals for continuing the stability work were briefly discussed.

F. Cabling

There was general agreement on the following:

1) Cabling is substantially a new task for the 3 wire manufacturers. They are now ready to take it up.
2) Cabling degradation is being put on a more quantitative basis now that full account is being taken of peak field effects in cable testing. Degradation is variable: values of 0-10% are

currently being obtained at LBL.(5)

3) Optimization of the conductor means optimization of the cable, not the strand.

Scanlan described recent cabling experience at LBL. Much good cable has been made, but 3 failures have occurred. One was with IGC 2.5 μm filament conductor. The strand failed the sharp bend test, however. Two billets, whose strand failed the spring back tests, did not cable acceptably. The most worrying failure, since it remains unexplained and was undiagnosed by the strand mechanical property tests, was with a large filament (15-20 μm) IGC conductor (B5209-5). This passed the sharp bend and springback tests but developed hairline edge cracks after cabling. Additional mechanical property evaluation by Scanlan and postmortem microscopy by Larbalestier's group revealed no peculiarities. Two cabling runs had produced identical results; a third is planned by Scanlan to investigate this further.

III. Industrial R&D Program

A. Discussion

Discussion of the proposed industrial R&D program was initiated by Strauss with a Needs/Wants matrix:

Property	Need	Want
J_c (Outer)	2750 A/mm^2 (5 T)	> 3000 A/mm^2 (5 T)
(Inner)	1100 (8 T)	> 1300 (8 T)
Filament dia	5 - 10 μm	5 μm
Strand Piece Length	> 10,000 feet	>40,000
Barrier	Yes	Yes
Cu:NbTi	> 1.3:1 inner(6)	Same
	> 1.7:1 outer(7)	Same

Scanlan showed a 6 billet matrix planned for the LBL funded R&D program covering some of the above points: variable filament size, inner and outer conductor, hot extruded Nb barriers and final delivery of 100 lbs. of cable from each 400 lb. billet.
An extensive discussion of the industrialization aspects of the R&D Program followed, with comments by all participants. Various concerns were paramount, amongst them:

1) The parameter space of the SSC specification, particularly with respect to J_c and d is not well-understood. A safety margin is required for effective manufacturing.
2) From the manufacturing point of view, multiple billets of the

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(5) Subsequent comments by Sampson: Accurate degradation numbers require that <u>all</u> strands be measured. This has very seldom been done. A real degradation (that is when full account is taken of self field) of 8-10% is probably to be expected.

(6) The majority view was that this should be raised to 1.5:1.

(7) The outer conductor is specified as 1.8 ± 0.1:1.

same design are desirable. This permits a true learning curve to be ascended. Ascending a learning curve is ineffective, however, if the product is not yet properly defined. In view of point (1) above, this seems to be the present case.

3) A strong industrial base requires that at least two and hopefully all three wire manufacturers be able to make wire to the SSC specifications. This led to agreement that the major variables should be studied by all manufacturers.
4) The key issues in meeting the J_c specifications are filament size, barrier quality and thermo-mechanical processing.
5) The conductor goes into a magnet. Design of the conductor must be optimized for the magnet. On the technical implementation of this point there were 2 divergent views. One favored the 1.3:1 conductor since the I_c requirement can be met with lower J_c. The second favored a 1.5:1 conductor, since the stability margin of the conductor is believed higher. After considerable discussion, the latter view prevailed.(8)

B. Proposed Program

A proposed industrial R&D program of 15 billets (5 per manufacturer) emerged from this discussion:

1) All billets will have hot extruded Nb foil barriers.
2) Two filament sizes (6 μm and 9 μm) will be investigated.
3) Single stack billets stacked from a) cold-worked and b) annealed rod will be fabricated, one each with 6 μm and 1 each with 9 μm filament size.
4) Points (2) and (3) define 4 billets. The manufacturer will be free to choose a 5th billet duplicating 1 of the above 4 billets.
5) The billets will all be for inner conductor wire (0.0318" dia) and have a Cu:Nb-Ti ratio of 1.5:1.
6) The strand will be made into cable.
7) Mechanical specifications for the strand and cable will follow the current SSC draft specification for inner conductor except as noted above.
8) The minimum filament spacing will be 1 μm. The local s/d ratio can vary from 0.15 to 0.2 at the discretion of the manufacturer.
9) No fixed quantity of delivered cable is required. However, the target shall be the delivery of > 100 lbs of finished cable per billet. The billets shall be for the purpose of exploring the parameter space determining the industrial production of high current density, fine filament cable. Extensive samples of the monofilament and the multifilament conductors may be taken for experiments by the Wisconsin and other groups.

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(8) Karpenko and Tigner commented subsequently that the workshop was not convened to consider the stability performance of the magnet and its conductor. The discussion that took place on this subject was not definitive. Stability is very important but it needs to be addressed by separate experiments. Choice of a ratio of 1.5:1 for this program does not imply a permanent choice of 1.5:1 for SSC inner conductor.

IV. Postscripts

This report was circulated in draft form (2.9.87) to all participants. Appropriate additions and clarifications have been made to the text. Some reflections on the meeting not covered in the text above are:

1. The proposed program investigates the parameter space believed crucial for the SSC cable. It is thus primarily an industrial R&D program, rather than an industrialization of SSC cable production. The parameters of the program have been drawn so that the transition to full industrial production will be as straight-forward and rapid as possible.
2. The program covers only the inner conductor, since this is by common agreement the more difficult conductor. Greene and Scanlan emphasized that outer cable also needs to be made.
3. This program is only one element in the R&D supporting advanced accelerator conductor development. Parallel R&D by LBL, BNL and FNAL is investigating other topics, such as alternate barriers, other filament sizes and methods for decoupling filaments.

SSC-MAG-118
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0783M
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SPECIFICATION FOR NbTi SUPERCONDUCTOR WIRE FOR SSC DIPOLE MAGNETS

1. Technical Requirements

1.01 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.

1.02 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 4.222 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 2750 A/mm^2 at 5 T and 1100 A/mm^2 at 8 T.

1.03 Filament Size: The filament size shall be 6 microns. In order to insure that the filaments are electrically decoupled, the filament spacing shall be greater than 1.0μm in the billet design.

1.04 Copper-to-non-copper 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.

$$\frac{A_{Cu}}{A_{SC}} = \frac{\rho_{SC}}{\rho_{Cu}} \left(\frac{\text{Total Weight}}{\text{Superconductor Weight}} - 1\right)$$

ρ_{SC} = Density of Superconductor = 6.02 gm/cm^3

ρ_{Cu} = Density of Copper = 8.95 gm/cm^3

1.05 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 values for resistances and tolerances are given in Table I.

1.06 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 83 for the inner layer wire and greater than 89 for the outer layer wire.

Table I. Requirements for Inner and Outer Layer
Superconducting Wire

Requirement	Inner Layer	Outer Layer
Minimum Critical Current at 5 T	613 A	323 A
Minimum Critical Current at 8 T	248 A	130 A
Copper-to-Superconductor Ratio	(1.3 - 0.0 + 0.1):1	(1.8 ± 0.1):1
Wire Diameter	0.0318 ± 0.0001 in.	0.0255 ± 0.0001 in.
Maximum R_{295} (micro-ohms/cm)	580	800
Maximum R_{10} (micro-ohms/cm)	7.0	9.0

1.07 Twist Pitch: There are two options for twist pitch depending upon which cabling method will be followed.

Option A requires the wire to be twisted to produce a twist pitch of 2.0 ± 0.1 twists/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. Requirements on twisting shall apply over the full length of delivered wire (no leaders with variable twist are allowed).

Option B requires that the wire be delivered in the untwisted condition.

1.08 Final Anneal: The wire may be ordered in the annealed or unannealed condition. If the wire is ordered in the unannealed condition, samples for testing purposes shall be annealed for 3 hrs. at 230°C in order to verify that the R_{10} and RRR values are satisfied.

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

1.10 Minimum Lengths: At least 90% of each order shall be delivered in lengths greater than 10,000 ft. The remaining 10% may be made up of lengths between 1000 ft. and 10,000 ft. If more than 10% of the ordered quantity falls below 10,000 ft. in length, the additional short lengths may be accepted, but at a reduced price which reflects the added costs associated with testing and cabling short lengths. 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 swag- ing, and foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion.

1.11 Mechanical Properties: The wire shall survive a sharp bend test without any visible sign of cracking at the outer diameter of the sharp bend.

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 specification. 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 manufacturing 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 segregation 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 = 5 T and 8 T, and T = 4.222 K. If a temperature of 4.222 is not possible, measurements may be made at another temperature and a conversion constant must be supplied. The conversion constant must be approved by 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 to insure 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 normal state resistance and copper-to-superconductor ratio of the wire.

The seller shall measure the bend strength of a sample from each continuous length of wire. This test shall be performed according to the procedure in Appendix B.

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.

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 an irreversible transition or quench occurs. This measurement is carried out in specified external fields, 5 T or 8 T typical, applied normal to the wire axis, and in a temperature bath of liquid helium at 4.222 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:

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

where D is the wire diameter in centimeters. 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). Either bifilar or monofilar mounting arrangement may be used, if the procedures outlined below are followed. A non-inductive (bifilar) form will provide adequate length, reduce inductive voltage signals, and provide for ease of connection; see Fig. 1. Shorter, monofilar mounts may be used if adequately sensitive signal detectors are available; voltage taps are arranged as in Fig. 2 in this case. Means must be provided for constraint of mechanical motion without interfering with coolant contact: use of a G-10 former with grooved location of wire and careful tensioning during mounting. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

3. Procedure (See Fig. 3)

The sample length (between voltage taps) should be $\geq$ 25 cm. This corresponds, typically, to a voltage drop of several microvolts. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The amplifier signal should be recorded on an X-Y recorder (or if desired in a digital memory device). The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of ± 5%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is < 1%. Electronic circuitry for quench protection is preferable. Frequently, a quality index, n, is estimated using the equation $V = \text{constant} \times I^n$.

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 4.222 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 a precision of ± 0.010 K (10mK). Deviations of 25 mK or less from 4.222 K correspond to an error in I_c of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

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

where T_c is the transition temperature at the specified magnetic field. (T_c = 7.2 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, $T (= 4.222$ 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 electronic 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 the required current 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 0.5 μV resolution. It is helpful during the low temperature measurement to use an 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 0.5% 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 form. 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" from the current joint. Voltage taps are soldered to the specimen at a separation 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-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

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 0.5 A. 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 of 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:

$$R_{295} = R_m / [1 + .0039\ (T_m - 22)]$$

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

6. Copper/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.